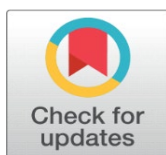
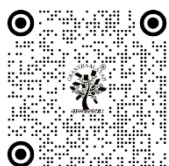


A COMPREHENSIVE REVIEW OF MECHANICAL PERFORMANCE, DURABILITY ENHANCEMENT, AND CRACK HEALING TECHNIQUES

Suhotra Gupta ¹✉, Dr. Arun Kumar Agarwal ²✉

¹Research Scholar, Uttarakhand University, Dehradun, Uttarakhand, India

²Professor, Uttarakhand University, Dehradun, Uttarakhand, India



Received 14 March 2026

Accepted 10 May 2026

Published 26 May 2026

Corresponding Author

Suhotra Gupta,
suhotra94gupta@gmail.com

DOI

[10.29121/shodhkosh.v7.i12s.2026.8352](https://doi.org/10.29121/shodhkosh.v7.i12s.2026.8352)

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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ABSTRACT

Bacterial self-healing concrete has proven to be a viable solution to enhance the durability, crack resistance and service life of concrete structures in a more eco, friendly manner. The shrinkage, thermal, chemical and corrosion induced cracking of conventional concrete structures leads to structural deterioration which increases the maintenance costs. While a few review studies have incorporated mechanical performance and durability enhancement, there is limited work that has considered all the above-listed areas in a single study: mechanical performance, durability enhancement, crack healing efficiency, sustainability and industrial challenges. This review critically discusses the recent developments of bacterial self-healing concrete focusing on Microbially Induced Calcium Carbonate Precipitation (MICP), bacterial selection, bacterial incorporation methods, and durability performance. The results show that the bacterial concrete can increase the compressive strength by around 10–40% and crack healing efficiency up to 95% and can effectively reduce the permeability, water absorption, and chloride ingress. However, among the bacterial species investigated, *Bacillus subtilis*, *Bacillus sphaericus* and *Sporosarcina pasteurii* had the best healing performance. The microstructural analyses showed that the increased durability is due to calcium carbonate precipitation, pore refinement and matrix densification. The review also brings up issues of bacterial survivability, ammonia generation, high initial cost, and the lack of standard guidelines for implementing at field scale.

Keywords: Bacterial Based Self, Healing Concrete, *Bacillus Subtilis*, *Bacillus Megaterium*, *Pseudomonas Aeruginosa*, Durability, Sustainability

1. INTRODUCTION

1.1. BACTERIAL SELF-HEALING CONCRETE FOR SUSTAINABLE INFRASTRUCTURE DEVELOPMENT

The use of concrete in buildings, bridges, dams, pavements, and other civil engineering projects is so widespread because of its high compressive strength, durability, and low cost. However, although concrete has these benefits, it is very susceptible to cracking from shrinkage, thermal stresses, overloading, chemical attack, and corrosion of reinforcement. Microcracks can greatly influence the permeability of concrete that allows water, chlorides, sulfates and other aggressive substances to penetrate the concrete matrix. This leads to further corrosion of reinforcement, loss of

structural strength, curtailed service life and elevated maintenance and repair expenses (Belie et al, 2019; Singh et al, 2024). As shown in figure 1, the mechanism of deterioration of cracked reinforced concrete is water, oxygen, and chlorides entering the microcracks. They are aggressive agents that start electrochemical corrosion reactions in the steel reinforcing structures that contribute to loss of durability, structural degradation, and higher maintenance costs.

Figure 1

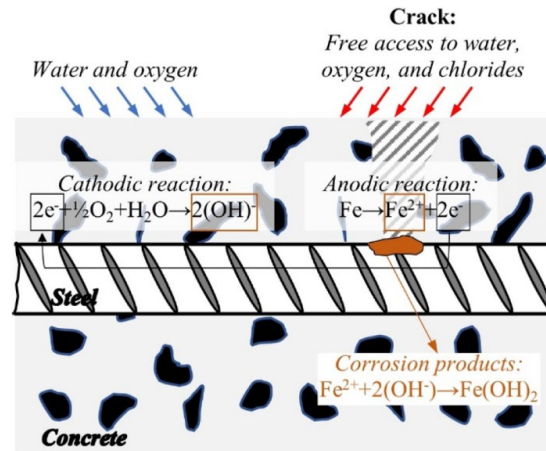


Figure 1 Deterioration Mechanism in Cracked Conventional Concrete

Traditional repair methods like epoxy injection and sealing the crack surface are typically time-consuming, high-cost, and usually only offer short-term fixes, especially when it comes to large-scale infrastructure projects. Furthermore, frequent repairs involve increased life cycle costs and environmental impacts of construction materials and maintenance work. Thus, the design of sustainable and independent crack-healing systems has become a must for the long-term performance and durability of concrete structures. Korukonda and Yadav (2026)

Bacterial self-healing concrete has attracted much attention in comparison to other self-healing methods, owing to its capability of healing without any outside assistance and environmental-friendly nature. There are two types of self-healing systems: autogenous and autonomous healing systems. Bacterial concrete works because dormant, dormant, bacterial spores are activated in the presence of water and oxygen that penetrates the cracks. Microbiologically induced calcite precipitation (MICP) is the process by which these bacteria precipitate calcium carbonate ($CaCO_3$) which can seal cracks and decrease the permeability of concrete (Rajczakowska et al., 2019; Wiktor and Jonkers, 2011). This process is not only to improve crack healing efficiency, but also to make up the mechanical strength and durability (Li et al., 2015; Feng et al., 2021). Typical bacteria studied are those of *Bacillus subtilis*, *Bacillus sphaericus*, *Bacillus megaterium*, and *Sporosarcina pasteurii*. The microbial metabolic activity that causes Microbially Induced Calcium Carbonate Precipitation (MICP) in bacterial concrete is displayed in Figure 2. Bacteria raise the pH and concentration of carbonate ion, resulting in the precipitation of $CaCO_3$ and sealing cracks and increasing the durability and microstructural densification of the concrete.

Figure 2

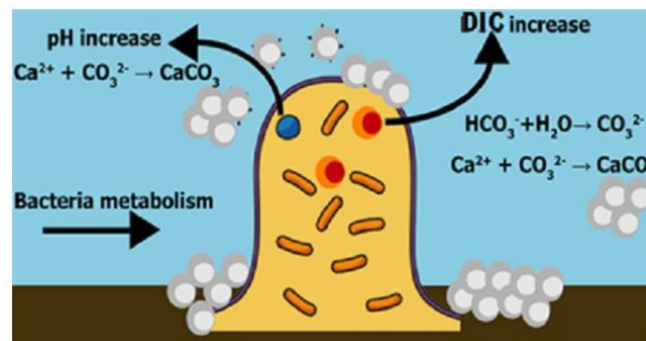


Figure 2 Bacterial Calcium Carbonate Precipitation Mechanism in Self-Healing Concrete

1.2. MECHANICAL PERFORMANCE, DURABILITY ENHANCEMENT, AND CRACK-HEALING APPROACHES IN BACTERIAL CONCRETE

Several review studies on bacterial self-healing concrete have been reported, but most of these review studies are just on individual parts like bacterial mechanism, efficiency of crack-healing or improvement of durability. There has been little focus on mechanical performance, durability improvement, sustainable material incorporation, bacterial survival strategies, and crack-healing techniques within the context of one review. Moreover, the studies that have been reviewed before do not fully discuss the recent developments of self-compacting concrete, recycled aggregate concrete, high strength concrete and ultra-high-performance concrete.

Hence, the review herein summarizes all the mechanical performance, durability enhancement, crack-healing mechanism, sustainable use of materials, and advanced bacterial techniques required for long life of infrastructure with bacterial self-healing concrete. The review also critically discusses the challenges related to the viability of the bacteria, the economic feasibility, scalability, and the lack of standardized design guidelines for practical implementation.

2. LITERATURE REVIEW

2.1. SELF-HEALING MECHANISMS IN BACTERIAL CONCRETE

The function of bacterial self-healing concrete is based on the biological induced mineralization processes which occur when the water and oxygen enter into the concrete matrix through the cracks. Under the conditions that are favorable for them, dormant bacterial spores, embedded in the cementitious material, start to be metabolized and begin to precipitate calcium carbonate (CaCO_3) to seal cracks and restore structural integrity (Wiktor and Jonkers, 2011; Feng et al., 2021; Chen et al., 2019). The most investigated healing mechanism is Microbially Induced Calcium Carbonate Precipitation (MICP) in which bacteria precipitate calcite, which can fill and bridge cracks. Besides bacterial healing, other healing methods like autogenous healing, encapsulation techniques, vascular network systems, and chemical-based healing agents are also studied to improve the crack repair and durability performance (Ojha et al., 2025; Elgendy et al., 2025; Rajczakowska et al., 2019). Figure 3 shows that the bacterial process of crack healing is due to the precipitation of calcium carbonate inside the concrete cracks. The bacterial activity boosts the level of calcite formation, filling pores and cracks to increase durability and decrease permeability.

Figure 3

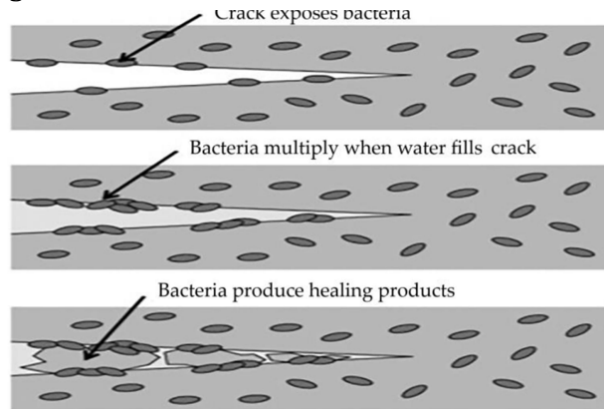


Figure 3 Schematic Illustration of Bacterial Crack-Healing Process in Self-Healing Concrete

The pathways involved in ureolytic bacteria are most often used due to their rapid production of calcium carbonate. Bacteria decompose urea by means of the enzyme urease to generate CO_3^{2-} and NH_4^+ . The carbonate ions then interact with the calcium ions in the cement matrix or added nutrients, leading to the formation of calcium carbonate on the walls of the bacterial cells and crack surfaces (Siddique et al., 2017; Althoey et al., 2023). But the production of ammonium as a side product during ureolysis could have environmental implications and impact sustainability over time. Other non-ureolytic routes like denitrification, organic acid metabolism, and carbonic anhydrase-mediated processes are more environmentally friendly but less mineralization rate (Vedrtam et al., 2025; Elgendy et al., 2025).

The bacterial concrete's healing efficiency is dependent on the crack width, the concentration of bacteria, the moisture, nutrient supply, curing condition etc. In general, the crack healing can be seen in microcracks where the action of capillarity helps in the deposition of minerals. The repeated wet-dry cycles further enhance the ability of bacteria to reactivate and subsequent healing performance (Feng et al., 2021; Rais and Khan, 2021). However, the ability of bacteria to survive can be greatly reduced at extremes of temperature, high alkalinity, low moisture and nutrient deficiency. To overcome these issues, recent research has focused on bacterial immobilization by providing light-weight aggregates, hydrogel, silica gel, and biochar carrier to enhance long-term bacterial viability and durability performance (Li et al., 2015; Nikhil et al., 2025).

2.2. BACTERIAL SPECIES AND SELECTION CRITERIA

Besides crack sealing, bacterial mineralization also aids in matrix densification and pore refinement, which lead to the reduction in permeability, increase in resistance to aggressive chemical attack and long-term durability of concrete structures (Li et al., 2015; Pappupreethi et al., 2017). The choice of appropriate bacteria to be used for self-healing concrete is one of the most important factors that can affect the performance of healing efficiency and durability of self-healing concrete. The selected bacterial strains need to be alkaliphiles, spore-forming, with a high survivability in the cementitious environment as well as with efficient calcium carbonate precipitation potential (Kukadiya and Vaghela, 2022).

Spore-forming bacteria of the genus *Bacillus* are the most widely studied microorganisms, due to their tolerance for alkaline conditions and their formation of stable deposits of calcite. *Bacillus subtilis*, *Bacillus sphaericus*, *Bacillus megaterium*, *Bacillus licheniformis*, and *Sporosarcina pasteurii* are some of the common bacteria species used for bioagent production (Chaitanya et al., 2023; Kumar et al., 2024; Vishal et al., 2025). Their healing performances, however, is significantly different based on urease activity, rate of calcite precipitation, environmental adaptability, and crack-healing. *Sporosarcina pasteurii* and *Bacillus sphaericus* show the best calcium carbonate precipitation and the best healing of wider cracks as they have an elevated urease activity among these species. However, *Bacillus subtilis* has shown high survivability and adaptability under harsh cementitious conditions and *Bacillus megaterium* gives moderate healing efficiency with relatively stable bacterial growth characteristics (Vedrtam et al., 2025; Javeed et al., 2024).

The survivability of bacteria is one of the significant problems to be addressed in self-healing concrete due to the extremely alkaline environment of the cement matrix (pH 12 to 13). Moreover, these factors such as high temperatures, restricted access to moisture, lack of nutrients and mechanical stresses during cement setting can substantially impact the viability of the bacteria. In order to address these disadvantages, a number of protection and immobilization methods have been developed, such as light weight aggregates, hydrogels, silica gel, fly ash, biochar and microcapsules. These carriers shield bacterial spores from direct exposure to harsh conditions and enhance nutrient retention and long-term healing properties (Li et al., 2025; Elgendy et al., 2025).

Bacterial consortia and non-conventional strains have also been the subjects of recent studies that have investigated their ability to enhance crack-healing capacity and environmental adaptability. Combination of several strains having different metabolic pathways has been observed to have superior mineral precipitation and healing efficiency under different environmental conditions (Sunantha et al., 2025). In addition, the concentration of the bacteria has a significant effect on the healing efficiency and mechanical properties. Optimum bacterial concentration levels were reported from most of the studies ranging from 10⁵ to 10⁸ cells/ml, while high bacterial dosage can have adverse effects on cement hydration and lose matrix integrity (Adil et al., 2024; Osta and Mukhtar, 2024).

It should be included a summary table comparing different bacterial species according to their urease activity, survivability, crack-healing capacity, optimal environmental conditions and efficiency of calcium carbonate precipitation to improve the comparative understanding. This comparative analysis result could give better selection conditions of suitable bacterial strains for various types of concrete and exposure conditions.

Table 1

Table1 Comparative performance of bacterial species used in self-healing concrete			
Bacterial Species	Representative Studies (Authors)	Role in Concrete	Key Performance / Usefulness
<i>Bacillus subtilis</i>	Vishal et al.; Adil et al.; Kayam et al.; Nisar et al.	MICP-based crack sealing; pore refinement; strength enhancement	Up to 40% strength gain; crack healing up to ~0.8 mm; permeability reduction

<i>Sporosarcina pasteurii</i>	Arora et al.; Javeed et al.; Vedralnam et al.	Ureolytic CaCO ₃ precipitation for autonomous crack healing	High healing efficiency; effective chloride and water resistance
<i>Bacillus megaterium</i>	Akhtar et al.; Rais & Khan; Alisha et al.	Calcite precipitation; durability improvement in SCC and RAC	Improved compressive and tensile strength; reduced water absorption
<i>Bacillus sphaericus</i>	Ojha et al.; Siddique et al.; Ashwii et al.	MICP and durability enhancement under aggressive environments	Up to ~30% strength gain; strong resistance to chloride ingress
<i>Bacillus licheniformis</i>	Porselvan et al.	Bio-mineralization with nano-carriers for crack healing	Optimized strength and dense microstructure with SCMs
<i>Bacillus cereus</i>	Sunantha et al.	Consortium-based MICP; synergistic mineral precipitation	~20% strength increase; reduced porosity and water absorption
<i>Vibrio natriegens</i>	Sunantha et al.	Rapid biofilm formation in bacterial consortia	Enhanced calcite yield when combined with <i>Bacillus</i> species
<i>Escherichia coli</i>	Rosy et al.; Rajani et al.	Calcite precipitation for crack sealing	Moderate strength improvement; effective microcrack repair
<i>Bacillus pseudomycoloides</i>	Algaifi et al.	Surface crack healing via bio-mineralization	Complete surface crack closure (~0.4 mm)
<i>Acinetobacter johnsonii</i>	Li et al. (2015)	Carbonate layer formation for durability enhancement	Reduced carbonation rate (~66%) and water absorption
<i>Bacterial consortia (mixed)</i>	Vedralnam et al.; Sunantha et al.	Multi-pathway MICP and CO ₂ sequestration	Improved survivability and multi-cycle healing

2.3. INCORPORATION AND PROTECTION TECHNIQUES

The long term performance of the bacterial self-healing concrete is largely dependent on the effective incorporation and protection methods that are used to retain the bacterial viability during mixing, curing and service life. The high alkalinity, hydration heat, and mechanical stresses of the harsh cementitious environment adversely affect the activity of bacteria and their ability to heal (Javeed et al., 2024; Elgendy et al., 2025). For this reason, several incorporation techniques have been developed to enhance bacteria survival and crack healing properties.

The easiest and cheapest way to introduce bacterial spores into concrete is to mix them directly into the concrete. However, most of the time, direct contact with the alkaline cement matrix decreases their long-term life and healing efficiency (Pourfallahi et al., 2020). Contrary to this, encapsulation techniques offer more protection and control of nutrient release, with better crack-healing capability and durability enhancement. Lightweight aggregates, expanded clay, fly ash particles, hydrogels, silica gel, biochar and polymeric microcapsules are common types of encapsulation materials. The use of lightweight aggregates and expanded clay, along with the use of hydrogels, contribute to good storage and internal curing of the bacteria, and to moisture retention and reactivation of bacteria in dry conditions. The polymeric microcapsules burst when cracks are formed, which allows the calcium carbonate to precipitate in the cracks and heal the material, resulting in efficient and localized healing (Lucas et al., 2018; Putra et al., 2025). The figure 4 depicts the encapsulation system that involves protection of bacterial spores in lightweight aggregates by nutritive and protective layers. The technique of incorporation results in better bacterial survivability, controlled nutrient release and lasting, good crack-healing properties in severe cementitious environments.

Figure 4

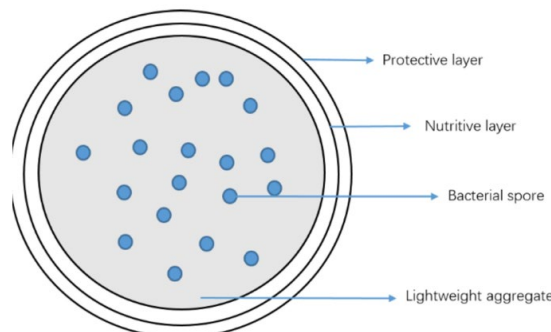


Figure 4 Lightweight Aggregate Encapsulation System for Bacterial Self-Healing Concrete

Other recent studies have also examined the use of novel technologies including nano-silica carriers, graphene-based encapsulation systems, electrospun nanofibers and 3D vascular networks to enhance the ability to maintain bacteria and the healing performance on multiple cycles. These high-tech systems offer improved healing capabilities, but complicate production and upfront costs (Porselvan et al., 2025).

The choice of incorporation is a very important factor for the workability, mechanical properties, crack-healing ability and durability of concrete. Although the use of bacterial self-healing concrete requires more upfront investment in producing bacteria, the nutrients and encapsulation materials, long-term maintenance and repair costs can be reduced as it extends the service life of the structure (Panza Uguzzoni et al., 2023). Therefore, bacterial self-healing concrete has good industrial application prospects in the fields of bridges, tunnels, roads, marine structures, and remote infrastructure where traditional repair and maintenance work is difficult and expensive.

2.4. MECHANICAL PERFORMANCE

Bacterial activity plays significant roles in altering the mechanical properties of concrete by the formation of calcium carbonate, pore refinement, crack bridging and microstructural densification of concrete. Several studies have been conducted and significant increases in compressive, tensile and flexural strength have been reported when compared with normal concrete (Vishal et al., 2025; Nisar and Singh, 2024; Karthekeyan et al., 2022). The comparative analysis of published papers in this field reveals that the improvement of the compressive strength of bacterial concrete is between 10% to 40% depending upon bacterial species, concentration, curing period, nutrients, and use methods. Bacterial biomineralization tends to increase the matrix density of the cement with age, which results in stronger enhancement at later curing ages, generally (Kayam and Bindu, 2024; Kumar et al., 2024).

The bacterial species which are tested consistently show the highest performance are *Bacillus subtilis*, *Bacillus sphaericus* and *Sporosarcina pasteurii*, with high urease activity and precipitation of calcium carbonate. Bacterial strains like *Bacillus licheniformis*, *Bacillus flexus*, *Pseudomonas stutzeri*, *Escherichia coli*, and *Bacillus subtilis* were found by durability of the cement due to their efficient biomineralization properties. More specifically, after 28 days, the compressive strength of the control mix was 24.03MPa, whereas it was 28.85MPa in the presence of the optimized concentration of 10^5 – 10^6 cells/ml of *B. subtilis*, and 31.45MPa after the cracks were healed. Likewise, Vishal et al (2025) noted that 25% to 40% of strength enhancements were seen in M20-M30 grades of concrete when using *Bacillus subtilis*. It was suggested that these improvements were due to pore filling, improved interfacial transition zone (ITZ) bonding and matrix density increases resulting from the precipitation of calcite.

This is an improvement in the tensile and flexural properties as well, because the bacteria mineralisation acts as a string to join up the microcracks and enhance load transfer in the concrete matrix. Riad et al. (2025) reported that the use of *Bacillus sphaericus* DSM 396 in ultra-high-performance concrete (UHPC) resulted in a compressive strength of 168.9 MPa, which is around 26% higher than the control UHPC, with the flexural strength and flexural modulus of elasticity also being higher. Durability attributes like sorptivity and permeability were decreased by almost 29%, reaffirming improved refinement of the pore structure and compactness of the microstructures. The synergistic effect of bacteria, nano-silica and steel fibers further enhanced the compressive, splitting tensile and flexural strengths due to the synergistic effect of the bacteria calcite precipitation, steel fibers crack bridging and nano-silica induced C–S–H refinement (Damodaran and Mayilsamy, 2025).

Advanced characterization techniques of SEM, EDAX, XRD, ultrasonic pulse velocity (UPV), and sorptivity analysis were used to validate the reported mechanical improvements by showing calcium carbonate deposition, decreased pore connectivity, and increased matrix compactness. As seen in Figure X, the best strength enhancement is achieved for most cases at optimal bacterial concentrations but an excess of bacteria can have adverse effects on cement hydration and matrix integrity. Furthermore, better bacterial survivability and mineral precipitation is achieved with encapsulated bacterial systems when compared to direct bacterial incorporation.

The application of bacterial self-healing concrete in the field is still in the laboratory scale. Most of the investigations are focused on the controlled experimental studies, and the long-term performance of the structures under environmental exposure conditions should also be validated (Belie et al., 2019; Carter, 2025). Collectively, the present studies show that the incorporation of bacteria can not only increase the compressive strength, but also have positive impact on tensile properties, durability, crack resistance and long-term structural resilience. The extent of improvement, however, is significantly influenced by bacteria type, number, nutrient availability, bacteria curing conditions and bio-

mineralization incorporation methods, underscoring the need for optimized bio-mineralization strategies and mix design approaches.

Table 2

Table 2 Mechanical and durability performance of bacterial self-healing concrete					
Bacterial Species	Concrete Type / Application	Compressive Strength Improvement	Other Mechanical Improvements	Durability Enhancement	Validation Techniques
<i>Bacillus subtilis</i>	Normal concrete (M20-M30)	25–40% increase	Improved tensile and flexural strength	Reduced permeability and improved abrasion resistance	SEM, EDAX, UPV
<i>Sporosarcina pasteurii</i>	Self-healing concrete	20–35% increase	Enhanced crack-healing efficiency	Improved chloride resistance and reduced sorptivity	XRD, SEM
<i>Bacillus sphaericus</i>	UHPC	~26% increase	Flexural strength >26 MPa; modulus of elasticity >56 GPa	~29% reduction in permeability and sorptivity	SEM, Sorptivity analysis
<i>Bacillus megaterium</i>	Recycled aggregate concrete	15–30% increase	Improved split tensile strength	Reduced water absorption and pore connectivity	EDAX, UPV
<i>Bacillus licheniformis</i>	Self-compacting concrete	Moderate strength enhancement	Improved crack bridging	Enhanced matrix densification	SEM, XRD
<i>Bacterial consortia</i>	Multi-functional bacterial concrete	Variable improvement depending on strains	Improved fatigue and crack resistance	Enhanced environmental adaptability	SEM, CT analysis
<i>Bacillus subtilis</i> + nano-silica + steel fibers	Fiber-reinforced bacterial concrete	14.17% increase	8.69% higher splitting tensile strength; ~12% flexural improvement	Improved matrix compactness and durability	SEM, UPV

The compressive strength improvement of bacterial concrete is 10% to 45% as per the incorporation methods and material combinations as shown in the figure 5. The most effective enhancement (45%) was obtained with the use of encapsulation and immobilization while optimized metaheuristic approaches had a 40% enhancement. Low dosages were used in direct mixing, which yielded the smallest improvement (10%), highlighting the need for the best possible bacterial incorporation techniques.

Figure 5

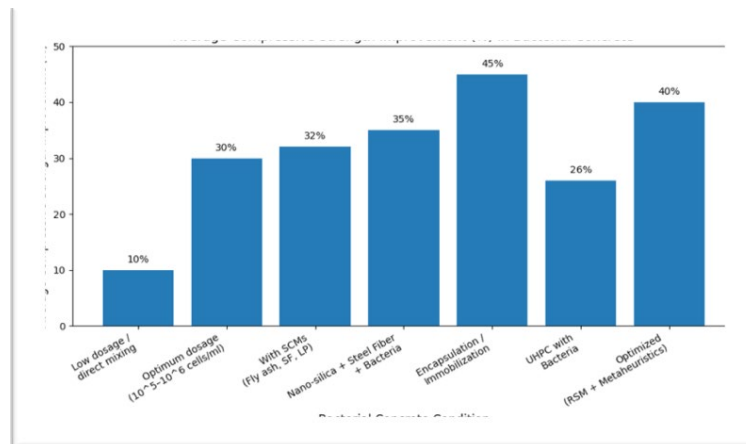


Figure 5 Average Compressive Strength Improvement (%) in Bacterial Concrete

2.5. DURABILITY AND TRANSPORT PROPERTIES

The increased durability of bacterial self-healing concrete is mainly due to biologically induced precipitation of calcium carbonate (CaCO₃) filling pores, microcracks and capillary channels in the cement structure. This is a

biomineralization process which decreases the permeability preventing the entry of water, chlorides, sulfates, carbon dioxide and other corrosive agents causing deterioration of concrete and reinforcement corrosion (Siddique et al., 2017; Rais and Khan, 2021). The SEM, EDAX and EDS analyses as well as the XRD analysis all consistently showed that bacterial mineralization is directly responsible for the deposition of dense calcite within pores and cracks, thus driving the matrix densification and transport resistance.

Bacterial concrete is found to reduce water absorption, sorptivity, and chloride permeability by 15 to 30% in comparison to the conventional concrete (Singh et al., 2024; Kumari et al., 2021). The improvements are strongly related to pore refinement and decreased transport pathway connectivity. *Bacillus sphaericus*, *Bacillus bacteriolyticus*, and *Sporosarcina pasteurii* are the most durable species of bacteria, which can provide high calcium carbonate precipitation efficiency and are resistant to alkaline cementitious environments. In particular, ureolytic bacterial systems with a production capacity of 50-100 mg CaCO₃ per gram biomass have been found to have an especially good effect on crack sealing and permeability reduction (Vedrtnam et al., 2025).

More recently, investigations show the link between microstructural refinement and durability performance. Sukumaran et al. (2025) reported that with the addition of bacteria at 10⁴-10⁶ cells/ml, the chloride ion penetration, sulfate attack, acid deterioration and sorptivity of the concrete decreases significantly, especially with the addition of *Bacillus subtilis*. Likewise, for the bacterial UHPC mixtures, Riad et al. (2025) reported up to 29% reduction in water permeability because of an effective densification of the pores and a sealing of the cracks, as well as a reduction of 27% in sorptivity. The addition of supplementary materials like nano silica, fly ash, steel fibers, and biochar further contributes to greater durability, with the addition of secondary C-S-H formation and decreased pore connectivity (Damodaran and Mayilsamy, 2025).

Although laboratory durability performances are promising, long-term field testing of bacterial self-healing concrete is still limited. There are very few existing studies that can be found which have been carried out under actual environmental conditions where the exposure is subject to freeze-thaw cycles, moisture fluctuations, thermal stresses, carbonation and aggressive chemical attack (Belie et al., 2019; Carter, 2025). Furthermore, the survivability of bacteria and the ability of healing are likely to be reduced over time under extended service conditions due to nutrient depletion and exposure to harsh conditions.

The technologies of encapsulation, including hydrogels, lightweight aggregates, polymeric capsules, silica gel, and biochar carriers, have been found to be promising for maintaining long-term bacterial stability and durability without compromising the structural properties. But scaling-up the industrial process, standardization, long-term monitoring, and cost remain challenges for large-scale industrial implementation. For this reason, further research work needs to be carried out in field scale, real time durability assessment and standardizing the evaluation techniques to validate the use of bacterial self-healing concrete in sustainable infrastructure systems. Bacterial concrete improves the durability performance considerably in terms of reducing the permeability (55%), chloride ingress resistance (45%) and carbonation resistance (40%) as illustrated in figure 6. The water absorption reduced by about 30% and the freeze-thaw resistance enhanced by 25%. The improvements are thus substantiated and substantiated, and that bacterial calcium carbonate precipitation is indeed an effective method for densifying the concrete matrix and minimizing harmful transport pathways.

Figure 6

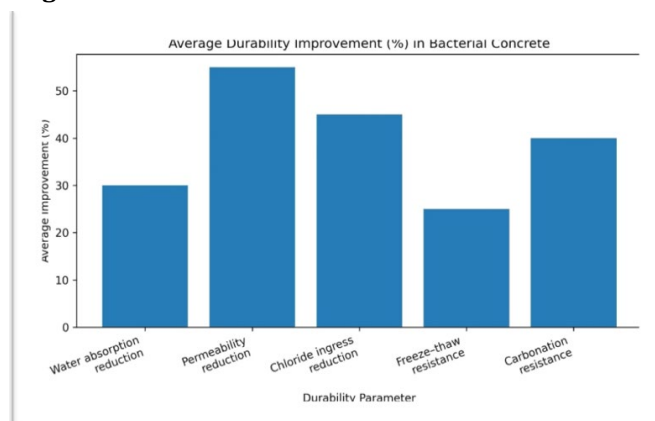


Figure 6 Average Durability Improvement (%) in Bacterial Concrete

Table 3 gives an overview of the durability test results of bacterial self-healing concrete for various concrete systems and bacterial species. The results of most of the studies indicated significant crack closure, reduction in permeability, low water absorption, and resistance to chloride ingress, freeze-thaw cycles, and corrosion, all of which confirmed that bacterial mineralization has a significant positive effect on the durability of concrete structures in the long-term.

Table 3

Table 3 Durability and Crack Healing Performance of Bacterial Concrete						
No.	Reference	Concrete System	Bacterial Species	Crack Width Healed / % Closed	Water Absorption / Permeability Reduction	Additional Durability Benefits
1	Vishal et al.	OPC (M20, M25, M30)	<i>Bacillus subtilis</i> , <i>B. megaterium</i> , <i>S. pasteurii</i> , <i>L. sphaericus</i>	0.4–0.5 mm	15–25%	Enhanced high-temperature resistance; reduced ultrasonic pulse velocity
2	Arora et al.	Fly ash concrete	<i>B. subtilis</i> , <i>B. megaterium</i> , <i>S. pasteurii</i> , <i>L. sphaericus</i>	0.5–0.7 mm / 84–86%	Reduced water penetration to 13 mm	Lower chloride ion ingress
3	Zaky & Mohamed	OPC concrete	<i>B. subtilis</i>	60–70% width reduction	Halved to 0.10×10^{-12}	Effective within 14 days; suitable for moisture-prone areas
4	Li et al.	Fly ash-based oil-well cement	Microbial-derived	63% closure	Permeability halved to 0.010×10^{-7} m/s	Suitable for remote and moisture-prone applications
5	Sunantha et al.	PPC mortar	<i>B. cereus</i> + <i>V. natriegens</i>	—	63% closure	Robust against freeze–thaw cycles
6	Sunantha et al.	PPC mortar	<i>B. cereus</i> + <i>V. natriegens</i>	29.6% lower water absorption	29.6% lower water absorption	27% higher UPV
7	Abbas et al.	Sea-shell powder concrete	<i>B. subtilis</i> + NitCal	—	—	Reduced CO ₂ emissions; enhanced corrosion resistance
8	Singh et al.	PPC M40 (also tested OPC)	<i>B. subtilis</i> + <i>B. sphaericus</i>	0.4–0.8 mm / up to 90%	—	Permeability reduction confirmed due to CaCO ₃ precipitation
9	Elgendy et al.	OPC + protective carriers	<i>Bacillus</i> species	Up to 1 mm	25–60% reduced chloride penetration	Improved freeze–thaw resistance
10	Carter	Living concrete	<i>B. pseudofirmus</i> , <i>S. pasteurii</i>	Up to 0.8 mm / 100% healing for <0.4 mm	Significantly reduced permeability	Enhanced crack sealing efficiency
11	Rais & Khan	Recycled aggregate concrete (RAC)	<i>B. subtilis</i> , <i>B. sphaericus</i>	0.4–0.8 mm	145–178% permeability recovery	Improved chloride resistance and corrosion protection
12	Alshalif et al.	Foamed concrete	<i>B. tequilensis</i> , <i>B. subtilis</i> , <i>B. sphaericus</i>	0.8 mm	11.34% lower water absorption	Improved matrix density due to CaCO ₃ formation
13	Siddique et al.	Silica fume concrete	Alkaliphilic bacteria	—	Up to 55% reduced water absorption	30–55% lower porosity

2.6. MICROSTRUCTURAL AND MINERALOGICAL EVIDENCE

Mechanisms behind the improved mechanical and durability performance of bacterial self-healing concrete are well substantiated in the literature based on microstructural investigations. The characterization techniques used to evaluate the calcium carbonate precipitation, pore refinement, crack closure, and matrix densification in bacterial concrete systems include advanced techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and micro-computed tomography (micro-CT) (Feng et al., 2021; Chen et al., 2019; Pachaivannan et al., 2020).

The SEM analysis has consistently shown the presence of dense calcite deposition in pores, microcracks and interfacial transition zones (ITZ), which demonstrates that bacterial biomineralization is an effective mechanism of bridging cracks and reducing pore connectivity. Siddique et al. (2017) revealed that the bacterial concrete specimens had greater density of microstructures and less voids than conventional concrete because of the precipitation of calcium carbonate. In a similar vein, Mark et al. (2025) noted that the compactness of the matrix was increased and microcracks were found to have stopped growing with the help of scanning electron microscopy, which was parallel to the increase in compressive strength and decrease in permeation. Additionally, Osta and Mukhtar (2024) have demonstrated that bacterial mineralization enhanced the ITZ region through the formation of compact calcite crystals around hydration products.

The presence of calcium carbonate polymorphs, like calcite, aragonite and vaterite, depending on the bacterial species, nutrient availability, and curing conditions, is further confirmed by XRD analysis. Based on the study of Algaifi et al. (2021), the mineral phase that dominates and is most stable is calcite, which is responsible for long-term crack sealing and improvement of durability. The presence of aragonite and vaterite phases in consortium based bacterial systems was also reported by Sunantha et al. (2025), where the biomineralization occurred in different environments. The observations by Li et al. (2025) with FTIR analysis showed the presence of carbonate functional groups typical of bacteria-mediated CaCO_3 precipitation, and the observation by Akhtar et al. (2025) using EDS analysis showed that the healed cracks contained more calcium and carbon, confirming the mineral precipitation.

The quantitative evidence of pore refinement and the efficiency of crack healing are also provided by Micro-CT and image-based crack analysis. Bacterial treatment resulted in substantial decreases of internal voids and transport pathways, as reported by Chen et al., (2019), which meant that the resistance against chloride ingress and moisture penetration was enhanced. In the same vein, Feng et al. (2021) noted significant crack closure and matrix densification during bacterial concrete through micro-CT imaging, which directly helped to improve the durability and decreased permeability of the designed concrete. The alkaline condition (bacterial metabolic activity) of the process of bacterial biomineralization is shown in figure (7). Calcite crystals deposited in the crack help seal the crack, narrow the crack and improve the durability of the bacterial self-healing concrete.

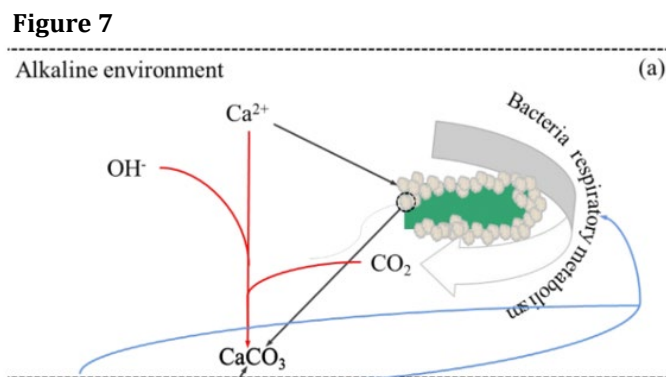


Figure 7 Bacterial Calcium Carbonate Precipitation Mechanism Under Alkaline Concrete Environment

The comparative microstructural studies indicate that the overall performance of the bacterial system in terms of uniform calcite deposition and strengthening efficiency of cracks is better in the encapsulated bacterial system than in the direct bacterial incorporation system due to the high survivability of bacteria and controlled release of nutrients in the encapsulated bacterial system (Putra et al., 2025; Elgendy et al., 2025). Overall, the correlation between the microstructural refinement and the engineering performance shows that the bacterial precipitation of calcium carbonate is the main mechanism that seals the cracks as well as the densification of the pores, reduction of permeability and enhancement of long-term performance in the bacterial self-healing concrete. From figure 8 it is observed that the encapsulation techniques with lightweight aggregates and capsules resulted in the highest crack-healing capacity of about 0.8 mm, followed by the injection method (0.6 mm). The direct bacterial mixing and bio-mineral coatings healed moderate crack widths of 0.45 mm and 0.3 mm, respectively, with the lowest healing efficiency being obtained for the autogenous healing (0.15 mm).

Figure 8

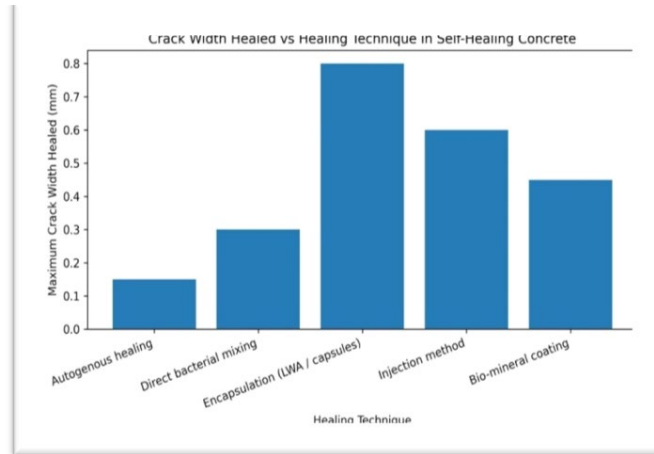


Figure 8. Crack Width Healed vs Healing Technique in Bacterial Concrete

As shown in Table 4, it is found that bacterial calcium carbonate precipitation densifies the concrete matrix, fills pores and microcracks, and enhances the bonding between the concrete and the steel. The SEM, XRD, and EDS analyses indicate that the bacterial biomineralization is well correlated with better crack healing, less porosity and better mechanical properties and durability.

Table 4

Table 4 Microstructural Evidence Supporting Self, Healing Concrete					
No.	Reference	Concrete System	Bacterial Species	Microstructural Findings	Key Interpretation
1	Vishal et al. (2025)	OPC (M20, M25, M30)	<i>Bacillus subtilis</i>	XRF and XRD identified CaCO ₃ precipitates in healed cracks	Enhanced matrix density and crack sealing
2	Arora et al.	Fly ash concrete	<i>B. subtilis, B. megaterium, S. pasteurii, L. sphaericus</i>	XRD and EDS detected calcite, vaterite, and aragonite	Improved calcium deposition and durability
3	Zaky & Mohamed (2025)	OPC concrete	<i>B. subtilis</i>	SEM and XRD confirmed CaCO ₃ precipitation in microcracks	Verified bacterial crack-healing mechanism
4	Sunantha et al.	PPC mortar	<i>Bacillus cereus, Vibrio natriegens</i>	SEM and EDS showed 27% higher calcium content	Enhanced biomineralization and matrix compactness
5	Singh et al. (2024)	PPC M40 / OPC	<i>Bacillus subtilis, Bacillus sphaericus</i>	SEM identified calcite deposits in healed cracks	Effective crack sealing and densification
6	Rais & Khan (2021)	Recycled aggregate concrete	<i>Bacillus megaterium</i>	SEM, EDS, and XRD confirmed calcite formation	Improved crack-healing efficiency
7	Alisha et al.	Conventional concrete	<i>Bacillus megaterium</i>	SEM revealed complete crack filling by CaCO ₃ crystals	Reduced porosity and denser microstructure
8	Nikhil et al.	OPC, PPC	<i>Bacillus subtilis, E. coli</i>	SEM showed denser bacterial concrete microstructure	Enhanced durability due to pore filling
9	Pachaiyannan et al. (2020)	Conventional concrete	<i>Bacillus subtilis</i>	SEM confirmed calcite precipitation in voids and cracks	Improved matrix compactness
10	Siddique et al.	Silica-fume concrete	Alkaliphilic bacteria	CaCO ₃ precipitation reduced porosity significantly	Enhanced durability and pore refinement

2.7. SUSTAINABILITY, COST, AND PRACTICAL IMPLICATIONS

The practical implications of sustainability and costs are summarized as follows: Bacterial self-healing concrete is a material that shows great potential as a sustainable construction material thanks to its ability to significantly extend the service life of structures, lower the frequency of maintenance and minimize long-term environmental impacts. Also, the use of supplementary cementitious materials like fly ash, silica fume, limestone powder, recycled aggregates, and waste-

derived nutrients enhances sustainability by minimizing the use of cement, which has a lower carbon footprint (Arora et al., 2025; Alyaseen et al., 2023; Abbas et al., 2025). Furthermore, the bacterial crack healing also reduces the permeability and reinforcement corrosion, thus decreasing repair requirements and increasing the long-term durability of infrastructures.

The cost of the initial construction works of bacterial self-healing concrete is generally higher than that of conventional concrete, but the life cycle cost analysis shows that there are significant long-term economic advantages. The additional cost is primarily due to the cultivation of bacteria, preparation of nutrients, and the encapsulation technologies and carrier materials used for protection. Reports indicated that the cost of the initial product may rise by around 20-40%, depending on the methods of bacterial incorporation and the type of encapsulating systems used (Panza Uguzzoni et al., 2023; Carter, 2025). But, the savings on maintenance, repair frequency, manpower and material replacement are substantial, reducing the life cycle cost considerably. Bacterial concrete is economically beneficial as it ensures longevity of service, and decreases structural degradation, especially in critical facilities like bridges, tunnels, marine structures, pavements, and oil well cementing where repair operations are costly and complicated (Singh et al., 2024).

Another study on the bacterial self-healing concrete, called lifecycle assessment (LCA), also showed that the bacterial self-healing concrete can help to reduce the carbon emissions, raw material use, and environmental impacts from repeated maintenance and reconstruction. The incorporation of industrial by-products like fly ash and recycled aggregates further reduces embodied carbon and promotes circular economy principles (Vedrtnam et al., 2025). However, the level of environmental sustainability is still affected by the energy requirement for growing the bacteria, the production of nutrients, the capsule composition and the metabolic end products produced during the process of bacteria growth.

The generation of ammonia in ureolytic bacterial pathways is one of the major environmental concern. Ammonium ions are generated by urea hydrolysis, which can be a source of environmental pollution, contamination of the groundwater, and reinforcement corrosion in the long-term (Althoey et al., 2023). Based on the above, recent research has shown increased emphasis on the non-ureolytic bacterial pathways (denitrification and carbonic anhydrase-mediated biomineralization) due to reduced environmental impact and the increased potential for sustainability.

Although promising laboratory and pilot scale results were obtained, there are several challenges to be addressed to implement the process into industry. However, for large-scale production, ideal bacterial culture, optimized encapsulation methods, quality control, and a long-term field validation under real environmental conditions are required. Besides, the bacterial survival in adverse alkaline conditions, temperature changes, moisture changes, and nutrient limitation is still a major challenge that has an impact on the long-term efficiency of healing (Mitikie and Elsaigh, 2025; Elgendy et al., 2025). The lack of universal design standards, durability testing procedures, and industrial guidelines also hold back commercialization.

To conclude, future studies should focus on low cost bacterial production methods, environmentally friendly metabolic pathways, large scale life cycle assessment and long-term field monitoring to make sure that the bacterial self-healing concrete is a viable and sustainable infrastructure material.

As shown in Table 5, bacteria self healing concrete can provide significant environmental and economic benefits over its lifetime even at a premium price. There is a high potential for sustainable future infrastructure applications and lifecycle-based construction practices, because of reduced maintenance, lower carbon emissions, improved durability and service life.

Table 5

Table 5 Economic and Environmental Consideration of Bacterial Self, Healing Concrete				
No.	Reference	Concrete System	Economic Considerations	Environmental Considerations
1	Vishal et al. (2025)	OPC (M20, M25, M30) with <i>Bacillus subtilis</i>	60–70% higher initial cost; reduced long-term maintenance expenses	Improved sustainability of critical infrastructure
2	Singh et al. (2024)	PPC M40 with <i>Bacillus subtilis</i>	Reduced long-term repair and maintenance costs	Lower water absorption and permeability
3	Adil et al. (2024)	M20, M25, M30 with <i>Bacillus subtilis</i>	Optimal 75 ml dosage improved compressive strength	70.63% healing efficiency by 28 days

4	Abbas et al. (2025)	Concrete with seashell powder and bacteria	Healing improved without significant strength reduction	29% carbon emission reduction; 99.63% permeability recovery
5	Vedrtnam et al. (2025)	Carbon-negative self-healing concrete	Reduced lifecycle maintenance costs	CO ₂ sequestration and reduced global warming potential
6	Alepu et al. (2025)	High-strength concrete	Low-cost bacterial injection for crack remediation	95.53% impact resistance recovery
7	Carter (2025)	OPC with encapsulated bacteria (<i>B. pseudo. S. pasteurii</i>)	15–20% higher initial cost; 60–80% maintenance reduction; 5–8 year payback	35% lower carbon footprint; improved durability
8	Panza Uguzzoni et al. (2023)	Mortar with PLA/epoxy capsules	Extended service life and reduced maintenance costs	Reduced environmental impact through LCC and LCA analysis

3. DISCUSSION

The application of bacterial self-healing concrete has great potential to achieve sustainable and durable infrastructure by autonomous crack sealing, permeability reduction, and service life extension. However, there are still some technical, environmental and industrial problems that hinder its large-scale practical use. The long-term survival of bacteria in the highly alkaline cementitious environment is one of the main constraints, as the high pH, hydration heat, moisture changes, and mechanical stresses within the cementitious environment can drastically affect the bacterial activity and the ability to heal the cementitious material (Elgendy et al., 2025). The repeated crack-healing performance is also impacted during long-term service conditions, due to nutrient depletion.

A second important issue is the variability in healing efficiency that occurs in relation to different species of bacteria, different bacterial concentrations, curing conditions, crack width, and various encapsulation methods. Encapsulation systems like lightweight aggregates, hydrogels and polymeric microcapsules enhance the protection of the bacteria, however, they tend to increase manufacturing complexity and the initial construction cost. Moreover, ureolytic bacteria can also produce by-product ammonium, which brings environmental issues of ammonia emission and possible groundwater contamination.

Lack of standardized testing procedures, durability assessment procedures, and generally accepted design guidelines for bacterial concrete systems further confines commercialization. Most of the published work studies have been conducted in the laboratory and long-term field validations are still under-done under realistic environmental exposure conditions. In addition, large-scale cultivation and storage of bacteria, product quality control and suitability to standard construction procedures are still significant industrial hurdles. Therefore, future studies could aim for developing low cost and eco-friendly encapsulation technologies, non-ureolytic bacterial pathways, large scale field trials, and AI assisted structural health monitoring systems to enhance the reliability, scalability, and commercialization of bacterial self-healing concrete in the applications of sustainable infrastructure.

Table 6

Table 6 Comparison of Bacterial Species Used in Self-Healing Concrete				
No.	Bacterial Species / Study	Optimal Concentration	Crack Width Healed	Key Advantages and Limitations
1	<i>Bacillus subtilis</i>	10 ⁵ –10 ⁶ cells/ml	Up to 0.8 mm	Widely researched; effective healing but sensitive to extreme environments
2	<i>Sporosarcina pasteurii</i>	10 ⁶ cells/ml	Up to 1 mm	High CaCO ₃ precipitation; ammonia generation may cause environmental concerns
3	<i>Bacillus sphaericus</i>	10 ⁶ –10 ⁷ cells/ml	Up to 1 mm	High survivability and healing efficiency; encapsulation cost is relatively high
4	<i>Bacillus megaterium</i>	10 ⁵ –10 ⁶ cells/ml	Up to 0.9 mm	Reduced maintenance requirements; supports CO ₂ sequestration
5	<i>Bacillus megaterium</i>	Low-cost bacterial injection system	95.53% impact recovery	Improved matrix density; lower NH ₃ emission than <i>S. pasteurii</i>
6	<i>Bacillus megaterium</i>	45–60 ml / 150 mm cube	35% carbon footprint reduction	Improved sustainability and lifecycle performance

7	Carter (2025)	Encapsulated bacterial systems	Extended service life	PLA/epoxy capsules improved lifecycle cost and environmental performance
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4. CONCLUSION

Bacterial self-healing concrete has proved to be a sustainable construction material for enhancing the durability, crack resistance and service life of concrete infrastructure by Microbially Induced Calcium Carbonate Precipitation (MICP). The results of this review confirms that bacterial mineralization is an effective technique to increase the sealing capabilities and refinement of cracks, resistance to permeability and mechanical properties. The reported studies showed that the compressive strength increased by some 10-40%, up to 95% efficiency in crack healing and substantial decreases in water absorption and chloride penetration. The bacterial species found to possess the best healing abilities were *Bacillus subtilis*, *Bacillus sphaericus* and *Sporosarcina pasteurii*, especially with the use of the encapsulations systems or additional cementitious materials. Mechanisms of matrix densification and durability improvement were validated by microstructural analyses using SEM, XRD, EDS and micro-CT which showed calcium carbonate deposition inside the cracks and pores.

Notwithstanding these benefits, some drawbacks still exist for widespread use such as the level of initial costs, bacterial viability in harsh alkaline environments, ammonia production during ureolysis, and the lack of standard test and design procedures. The majority of the studies are still lab-based, and long-term field tests in realistic environmental conditions are still restricted.

Future studies are recommended to address the development of environmentally friendly non-ureolytic bacterial pathways, low-cost and scalable encapsulation technologies, AI assisted structural health monitoring systems, and self-sensing bacterial concrete. The research work on bacterial consortia, integration of nano-material, applications of 3D printing and carbon-negative biomineralization systems could be a major leap in enhancing healing efficiency and sustainability. Furthermore, extensive field trials, life cycle assessment and international performance-based standards are crucial for commercialization and real application of bacterial self-healing concrete in the sustainable development of infrastructureS.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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