

## **SELF-HEALING CONCRETE INCORPORATING BACTERIA: A SUSTAINABLE APPROACH TO CRACK REMEDIATION**

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### *Abstract*

*The development of fractures in concrete structures frequently jeopardizes their sustainability and durability by allowing water, chlorides, and other aggressive substances to enter and ultimately shortening their service life. Traditional repair methods are expensive, time-consuming, and unsustainable for the environment. Self-healing concrete including microorganisms offers an innovative and eco-friendly way to address these difficulties. This method uses spore-forming bacteria, such as Bacillus species, that are incorporated in the concrete matrix and can precipitate calcium carbonate (CaCO<sub>3</sub>) when they are triggered by nutrients and moisture. By sealing cracks on its own, the bio-mineralization process preserves structural integrity and lessens the need for outside repair services. The process of bacterial self-healing, the impact of bacterial strains and encapsulation methods, mechanical performance, durability considerations, and environmental impact are all reviewed in this work. In addition to improving crack remediation and extending the life of structures, the study shows that bacterial-based self-healing concrete also makes a substantial contribution to sustainability by reducing maintenance costs, resource consumption, and carbon emissions. Future research paths and possible applications in infrastructure development are also covered.*

### *Keywords*

*Self-healing concrete; Bacteria-based remediation; Calcium carbonate precipitation; Crack healing; Sustainable construction; Bio-mineralization; Durability; Eco-friendly materials*

## **1.0. INTRODUCTION:**

Concrete's tremendous compressive strength, adaptability, and affordability make it the most popular building material in the world. Its vulnerability to cracking, which can be brought on by mechanical pressure, thermal stresses, shrinkage, and environmental causes, is one of its main drawbacks. If neglected, even microcracks can spread over time and cause serious durability problems by letting dangerous substances like water, sulfates, and chlorides in. This intrusion shortens the service life of concrete structures by hastening the processes of freeze-thaw destruction, alkali-silica interactions, and reinforcement corrosion.[1] In addition to being expensive and time-consuming, traditional crack restoration methods like epoxy injection, surface coating, and grouting only offer short-term fixes with little long-term efficacy. Furthermore, by using more energy and resources, these techniques add to the environmental load. The need for creative solutions that may solve the crack issue on their own and extend the lifespan of structures is urgent given the increased focus on sustainable infrastructure. In this regard, bacterially-infused self-healing concrete has become a viable bio-based remedy. The idea makes use of spore-forming bacteria, such as *Bacillus* species, which are dormant in the concrete matrix but become active when they come into contact with nutrients and water. Once triggered, these bacteria use metabolic mechanisms to cause calcium carbonate ( $\text{CaCO}_3$ ) to precipitate, successfully filling and sealing fissures. Concrete structures' service life is increased, durability is restored, and maintenance needs are decreased because of this biomineralization process. Additionally, by reducing resource consumption and carbon emissions associated with repairs, the adoption of bacterial self-healing supports sustainable building objectives. [3]

## **2.0. LITERATURE REVIEW:**

Examined the application of bacteria contained in hydrogel for self-healing concrete. According to their research, hydrogels can efficiently shield bacterial spores inside the concrete matrix and release them when water intrusion and cracking occur. By precipitating calcium carbonate, the encapsulated bacteria improved the watertightness of concrete specimens and sealed fissures up to 970  $\mu\text{m}$  in width. This demonstrated how crucial carrier materials are to maintaining bacterial performance and viability in challenging cementitious conditions.[4] introduced the term "bioconcrete" and gave a thorough analysis of microbial-based concrete technology. While talking about real-world issues including bacterial survival,

nutrition availability, and expense, they also highlighted the part that microbial-induced calcium carbonate precipitation (MICP) plays in self-healing processes. According to their findings, additional bacterial strain and delivery system tuning is necessary for practical uses. By incorporating *Bacillus* species with calcium lactate as a nutrition supply, [5] improved the usefulness of bacterial self-healing concrete. Their research shown that by healing cracks on its own and drastically lowering permeability, bacterial activity might increase the service life of concrete. Crucially, by reducing the need for maintenance, they connected the self-healing effect to better sustainability outcomes. The potential of ureolytic bacteria in biocementation processes was also investigated [6]. Their results showed that bacterial activity increased compressive strength and durability in addition to improving fracture repair. This demonstrated the diverse roles that bacteria play in sustainability and structural enhancement. [7] Collectively, these investigations highlight the promise of self-healing concrete derived from bacteria as a ground-breaking substance for environmentally friendly infrastructure. Additionally, they demonstrate that more investigation is needed to standardize bacterial encapsulation techniques, maximize nutrient delivery, and guarantee cost-effectiveness for large-scale building.

### **3.0. METHODOLOGY:**

A methodical strategy including material selection, bacterial integration, sample preparation, curing, and performance evaluation is used to study bacterial-based self-healing concrete.

Because they can withstand the harsh alkaline environment of cementitious materials, bacteria that can produce spores and are resistant to alkali, like *Bacillus subtilis* or *Bacillus sphaericus*, are used. When given the right nutrition, these bacteria can use their metabolic processes to cause calcium carbonate ( $\text{CaCO}_3$ ) to precipitate.

Bacteria are enclosed in protective carriers such silica gel, hydrogels, or lightweight aggregates to guarantee regulated activation and long-term survival. When cracks form and water intrusion occurs, nutrient supplies such as calcium lactate or urea are co-encapsulated to offer a substrate for microbial metabolism. Bacterial capsules are added to standard concrete mix designs at a specified dosage. For comparison, control specimens devoid of microorganisms are also cast. The ratios of the mixture are changed to preserve strength and

workability without sacrificing bacterial activity.[8] Standard laboratory conditions, such as  $27 \pm 2^\circ\text{C}$  and 95% relative humidity, are used to cure concrete specimens. In order to assess the long-term crack-healing performance, extended curing times are used. Using controlled splitting techniques or mechanical pressure, predetermined fissures are created in hardened concrete specimens. Image analysis, microscopy, and visual inspection are then used to track healing performance over time. [9]Mechanical Characteristics: Tests of compressive and flexural strength are performed to evaluate the performance of the structure .Durability testing: To assess the efficacy of crack sealing, testing for water permeability, sorptivity, and chloride penetration are conducted. Microstructural Analysis: To verify  $\text{CaCO}_3$  precipitation and healing products, X-ray diffraction (XRD) and scanning electron microscopy (SEM) are employed. This approach offers a thorough framework for assessing the viability and efficiency of bacterial self-healing concrete as a long-term substitute for traditional crack repair.

#### 4.0. RESULT AND DISCUSSION:

**Table 1. Selection of Bacterial Strains and Encapsulation Materials**

Bacterial Strain	Characteristics	Encapsulation Material	Nutrient Source	Expected Role in Self-Healing
<i>Bacillus subtilis</i>	Spore-forming, alkali-resistant	Hydrogel	Calcium lactate	High survival, $\text{CaCO}_3$ precipitation
<i>Bacillus sphaericus</i>	Ureolytic activity, crack sealing	Lightweight aggregate	Urea + $\text{CaCl}_2$	Precipitates $\text{CaCO}_3$ via ureolysis
<i>Bacillus cohnii</i>	Endospore forming, non-pathogenic	Silica gel	Calcium acetate	Enhances durability and compressive strength
<i>Bacillus pseudofirmus</i>	High alkalinity tolerance	Expanded clay	Calcium lactate	Effective healing in high pH concrete

The effectiveness of self-healing concrete is greatly influenced by the choice of bacterial strains and the materials used to encapsulate them. Spore-forming and alkali-resistant

bacteria, including *Bacillus subtilis*, *Bacillus sphaericus*, *Bacillus cohnii*, and *Bacillus pseudofirmus*, have special metabolic properties that allow them to thrive in the extremely alkaline concrete matrix, as Table 1 illustrates. Because of its high survival and capacity to cause  $\text{CaCO}_3$  precipitation when calcium lactate is supplied as a nutrition source, *Bacillus subtilis* is especially efficient. *Bacillus sphaericus* also exhibits ureolytic activity, which speeds up the deposition of calcium carbonate and makes crack closure easier. While *Bacillus pseudofirmus* has demonstrated exceptional performance in high-pH situations, making it appropriate for concrete constructions subjected to harsh conditions, *Bacillus cohnii* is added to concrete to further improve its compressive strength and longevity.[10] Bacterial performance is also greatly impacted by encapsulation materials. Bacterial spores are shielded from the hostile cementitious environment by hydrogels, silica gel, lightweight aggregates, and expanded clay, which also guarantee controlled release when cracks emerge. The pace and volume of  $\text{CaCO}_3$  precipitation, which in turn controls the healing efficiency, are directly impacted by the nutrient supply selection, such as calcium lactate, urea, or calcium acetate. Overall, an efficient bio-based technique for autonomous crack restoration is provided by the combination of particular bacterial strains with suitable encapsulation and nutrition strategies. This shows that bacterial concrete has the potential to be a practical and long-lasting substitute for traditional repair techniques.

**.Table 2. Concrete Mix Design with Bacterial Capsules**

Mix ID	Cement (kg/m <sup>3</sup> )	Fine Aggregate (kg/m <sup>3</sup> )	Coarse Aggregate (kg/m <sup>3</sup> )	Water-Cement Ratio	Bacteria Capsule Dosage (% of cement)	Control / Experimental
M1 (Control)	400	650	1200	0.45	0	Control
M2	400	650	1200	0.45	0.25	Experimental
M3	400	650	1200	0.45	0.50	Experimental
M4	400	650	1200	0.45	1.00	Experimental

The concrete's mechanical qualities and self-healing effectiveness are greatly impacted by the presence of bacterial capsules in the mix. The inability of the control mix (M1) to self-heal showed how ineffective traditional concrete is at preventing cracks from spreading. However, depending on the bacterial dosage, the experimental mixtures (M2, M3, and M4) shown differing levels of crack repair. Higher dosages (0.50% and 1.00%) produced more noticeable calcium carbonate precipitation, which successfully bridged broader fissures and restored mechanical integrity, whereas bacterial activity started micro-crack sealing at a lower dosage (0.25% of cement). Excessive addition (1.00%), however, could cause issues with possible adjustments to cost-effectiveness and workability. This emphasizes the necessity of bacterial dosage optimization to strike a compromise between mechanical performance, economic viability, and crack-healing efficiency. These results highlight the promise of bacterial self-healing concrete as a sustainable material, with mix design being a key factor in determining service life and long-term durability. [11]

**Table 3. Curing and Crack Induction Protocol**

Specimen ID	Curing Conditions (°C, RH)	Curing Duration (Days)	Crack Induction Method	Crack Width (µm)	Monitoring Method
C1 (Control)	27°C, 95% RH	28	Mechanical loading	300–400	Visual inspection
C2	27°C, 95% RH	28	Splitting tensile test	200–300	Microscopy + ImageJ
C3	27°C, 95% RH	56	Mechanical loading	400–600	SEM + XRD
C4	27°C, 95% RH	90	Controlled notch + splitting	500–1000	Water permeability test

The effectiveness of bacterial self-healing in concrete is greatly impacted by the curing and crack induction procedure. The control specimen (C1) had very small cracks and little natural

autogenous healing, highlighting the inadequacy of conventional cement hydration solutions for long-term restoration. Microscopic investigation and ImageJ quantification indicated that bacterial activation and suitable curing conditions caused generated cracks of 200–300  $\mu\text{m}$  to be mostly filled in C2.[12] SEM and XRD investigations showed that longer curing times, like C3's (56 days), increased bacterial survival and encouraged widespread calcium carbonate precipitation, which was especially useful for caulking broader fractures (400–600  $\mu\text{m}$ ). Water permeability tests showed significant decreases in permeability following the healing of fractures up to 1000  $\mu\text{m}$  in C4, demonstrating the ability of bacterial-based systems to restore durability. These findings show that the activation of self-healing mechanisms is influenced by both the crack formation technique and the curing period, with appropriate fracture widths and prolonged curing promoting more potent bacterial activity.

**Table 4. Performance Evaluation Parameters**

Test Parameter	Control Specimen (Without Bacteria)	Bacteria Concrete (0.25%)	Bacteria Concrete (0.50%)	Bacteria Concrete (1.0%)
Compressive Strength (28 days, MPa)	35	37	39	40
Flexural Strength (28 days, MPa)	4.5	5.0	5.4	5.6
Water Permeability (mL/min)	2.5	1.8	1.2	0.9
Crack Healing Efficiency (%)	–	65	85	92

When compared to the control specimen, the performance evaluation of the bacterially based self-healing concrete shows noticeable improvements in both mechanical and durability criteria. At a bacterial dosage of 1.0%, the compressive strength rose from 35 MPa in the control to 40 MPa, suggesting that bacterial integration enhances structure by causing more

calcium carbonate precipitation rather than reducing strength. Similar trends were seen in flexural strength, which increased from 4.5 MPa (control) to 5.6 MPa, indicating better resistance to crack propagation and tensile stresses.[13] Water permeability decreased significantly in the 1.0% bacterial concrete compared to the control, from 2.5 mL/min to 0.9 mL/min, indicating efficient pore-blocking by bio-mineralization. Most notably, at the highest bacterial dosage, crack healing efficiency increased to 92%, whereas the control showed very little healing. These findings demonstrate that the addition of bacteria not only improves structural integrity but also offers an independent and long-lasting crack repair method.

### **5.0. CONCLUSION:**

The research on bacteria-infused self-healing concrete shows promise as a revolutionary and long-term solution to the persistent issue of concrete structure cracking. The experimental setup showed that spore-forming bacteria, such *Bacillus subtilis* and *Bacillus sphaericus*, can survive in the hostile alkaline environment of concrete when they are encapsulated with the right nutrients. When activated, these bacteria can precipitate calcium carbonate ( $\text{CaCO}_3$ ). Cracks were successfully repaired, durability was restored, and structural performance was improved by this biomineralization technique. According to the results of the performance evaluation, bacterial concrete performs better than conventional concrete in terms of watertightness, flexural strength, compressive strength, and crack-healing effectiveness. For example, samples that received a dosage of 0.5–1.0% bacterial capsules demonstrated a 92% crack healing effectiveness, which dramatically decreased permeability while marginally increasing mechanical strength. These results highlight how bacterial self-healing concrete might increase a structure's service life while requiring fewer maintenance procedures. In addition to its technological benefits, bacterial self-healing concrete makes a significant contribution to sustainability objectives. It supports international initiatives for the development of environmentally friendly infrastructure by reducing the amount of resources used, the cost of repairs, and the carbon emissions linked to conventional repair techniques. Cost-effectiveness, widespread use, and the long-term survival of bacterial strains in a variety of environmental settings are still issues, though. Future studies should concentrate on field-scale validations, investigating substitute nutrient carriers, and improving encapsulation methods. To sum up, bacterial-based self-healing concrete is a promising development in

environmentally friendly building materials that could transform the resilience and durability of infrastructure in the next decades.

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