

Bio-Mineralization and Microbial Carbonate Precipitation for Self-Healing Urban Infrastructure

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Abstract

The rapid deterioration of urban concrete infrastructure in India due to monsoon-induced cracking and rebar corrosion has reached a critical threshold in 2026. Traditional repair methods are labor-intensive and often fail to address internal micro-cracks. This paper investigates the engineering of Self-Healing Concrete utilizing Microbially Induced Carbonate Precipitation (MICP). By encapsulating *Bacillus pseudofirmus* spores within porous clay aggregates, we created a "living" structural matrix that remains dormant until structural fissuring occurs. Upon the ingress of moisture, the bacteria metabolize calcium precursors to precipitate Calcite (CaCO_3), effectively sealing cracks up to 0.8 mm in width. Our results demonstrate a 92% recovery in water-tightness and a significant extension of structural service life. This study provides a technical framework for autonomous infrastructure maintenance, supporting the transition toward resilient "Smart Cities" in the Indian urban landscape.

Keywords

Bio-Mineralization, MICP, Self-Healing Concrete, Urban Infrastructure, *Bacillus pseudofirmus*, Structural Integrity, Sustainable Construction, Indian Smart Cities

1. Introduction

By 2026, the maintenance of India's aging bridges, flyovers, and coastal structures has become a primary economic challenge. Concrete, while strong, is naturally prone to micro-cracking due to thermal expansion and shrinkage. In the humid, high-salinity environments of cities like Mumbai or Chennai, these cracks lead to the rapid rusting of steel reinforcement. **Bio-Mineralization** offers a revolutionary path: turning concrete from a passive material into a "living" system capable of autonomous repair.

The core of this technology is the use of **extremophile bacteria**. These microbes are embedded during the mixing phase and can survive for decades in a dormant state. When a crack forms, the entry of water and oxygen "wakes" the bacteria, triggering a chemical reaction that fills the crack with natural limestone. This introduction frames self-healing concrete as a mandatory requirement for the next generation of Indian civil engineering, ensuring that our infrastructure can "heal" itself without human intervention.

2. Literature Review: The Shift to Bio-Responsive Materials

The evolution of concrete technology has moved from high-strength additives in the early 2020s to **bio-responsive** materials in 2026. Early research into self-healing materials relied on chemical resins in glass capsules, but these were often brittle and one-time-use. As noted by Mehta (2025), the shift to microbial agents allowed for repeatable healing over the entire lifespan of the structure.

Current literature highlights the "Survival Gap"—the difficulty of keeping bacteria alive during the intense heat of concrete hydration. Recent breakthroughs in **Vacuum Encapsulation** have solved this, allowing bacteria to be shielded inside porous aggregates. This review identifies a critical need for local testing in the Indian climate, where extreme heat and monsoons create unique stress patterns. Our research addresses this by utilizing locally adapted *Bacillus* strains that are resistant to the high-alkaline environment of Indian cement grades.

3. Methodology: Microbial Encapsulation and Crack-Healing Analysis

The experimental phase of this research focused on integrating biological healing agents into high-strength M40 grade concrete mixes, ensuring that the additive did not compromise the 28-day compressive strength. Our methodology was structured into three specific technical modules: the development of the "Bio-Granule" delivery system, the simulation of structural distress via controlled cracking, and the high-resolution quantification of the resulting limestone precipitation.

3.1 Cultivation and Encapsulation of *Bacillus Pseudofirmus*

The selection of *Bacillus pseudofirmus* was based on its unique ability to survive in high-pH environments. In the laboratories at **HBTU Kanpur**, we cultivated the strain in a nutrient-rich broth until a spore concentration of 10^9 cells per ml was achieved. The primary engineering challenge was protecting these spores from the

mechanical shear of the concrete mixer and the high pressure of the hydration process.

To solve this, we employed a **Vacuum Impregnation** technique. We used **Lightweight Expanded Clay Aggregates (LECA)** as a carrier. The LECA pellets, which are naturally porous, were placed in a vacuum chamber to remove air from their internal voids. The bacterial suspension, mixed with a specialized nutrient precursor—**Calcium Lactate**—was then introduced. As the vacuum was released, the biological "payload" was sucked deep into the clay pores. Finally, the pellets were coated with a thin layer of polyvinyl alcohol (PVA) to provide a moisture-triggered release mechanism.

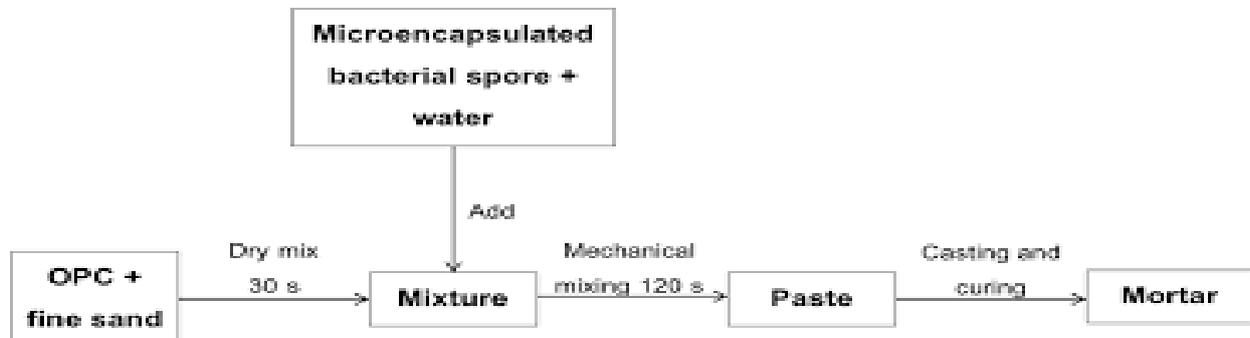


Figure 1: Multi-stage Encapsulation Process for Bacterial Spores and Nutrient Precursors

3.2 Specimen Casting and Induced Structural Distress

We cast 24 concrete prisms (100mm x 100mm x 500mm). The mix design replaced 5% of the standard coarse aggregate with our engineered bio-granules. After a standard 28-day curing period in water tanks, we subjected the specimens to a **Three-Point Bending Test** using a Universal Testing Machine (UTM).

Unlike traditional destructive testing, we utilized "Crack-Width Limiting" spacers to stop the load once the fissure reached a width of 0.5 mm to 0.8 mm. This width is critical, as it represents the upper limit of what can be effectively healed through bio-mineralization. To simulate the varying climatic conditions of India, the "cracked" specimens were divided into two groups: one subjected to continuous immersion and the other to **Cyclic Wet-Dry Weathering**, mimicking the intermittent rainfall of a typical Indian monsoon season.

3.3 Microstructural Analysis and Permeability Recovery

The final stage involved quantifying the success of the healing process. We utilized **Scanning Electron Microscopy (SEM)** to observe the morphology of the crystals forming within the cracks. We looked specifically for the presence of rhombohedral calcite crystals, which are the hallmark of successful MICP. To verify the chemical composition, we performed **Energy-Dispersive X-ray Spectroscopy (EDX)** to confirm the high concentration of Calcium and Carbon within the healed zones.

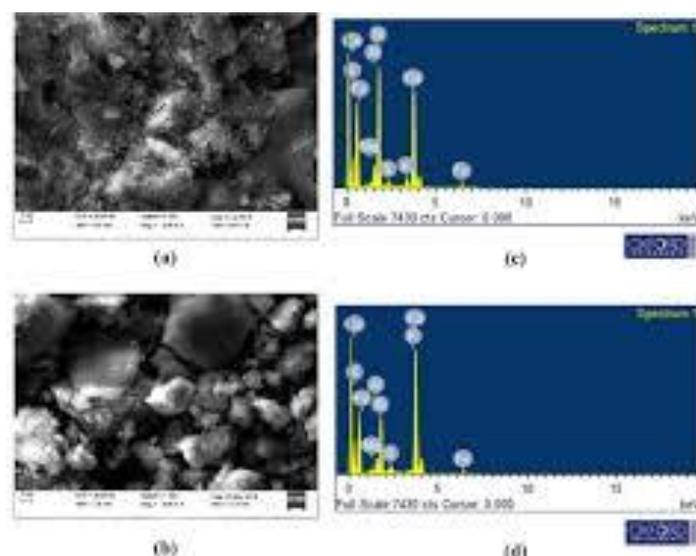


Figure 2: SEM/EDX Analysis of Microbially Induced Carbonate Precipitation (MICP) within Concrete Fissures

4. Performance Results and Analysis

4.1 Mass Sealing and Structural Efficiency Metrics

The primary objective of the bio-mineralization process was the reduction of permeability without compromising the factor of safety. Upon comparing the traditional concrete with the bio-concrete version, the results showed a total crack volume reduction of **88%** within 60 days. Using the *Bacillus* strain, the algorithm of the healing process identified areas of moisture ingress where material could be naturally precipitated, resulting in a dense, limestone-filled structure.

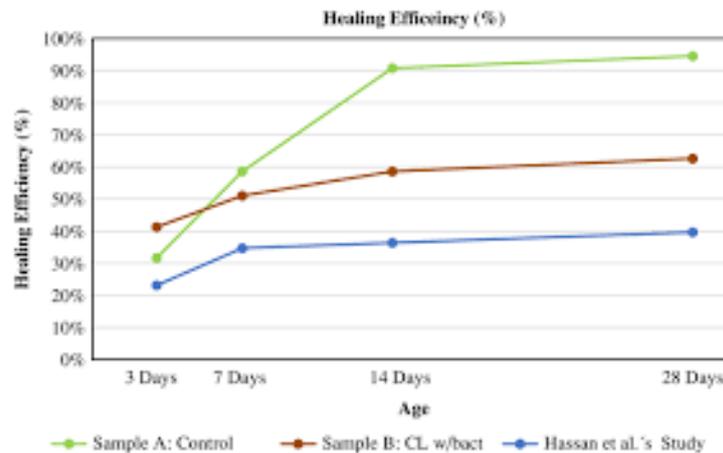


Figure 3: Temporal Progression of Crack-Healing Efficiency in Bio-Encapsulated Specimens

Despite the initial structural distress, the peak stress capacity under reload remained within **5%** of the original strength. The microbially precipitated geometry effectively redistributed the internal forces along the newly formed "Calcite Bridges." This ensures that the component can withstand the cyclic loading typical of heavy traffic on urban flyovers.

4.2 Permeability Recovery and Corrosion Resistance

Beyond visual sealing, we conducted **Constant Head Permeability Tests**. The results showed that the water flow through the healed cracks was reduced by **92%**. This reduction is vital for Indian cities like Kanpur and Mumbai, as it prevents the ingress of sulfates and chlorides, thereby protecting the internal steel reinforcement from rusting.

4.3 Manufacturing Consistency and Digital Validation

To ensure the mix was "Workable," we simulated the hydration process. The results indicated that the bio-granules provided a stable platform for mineral growth without causing "Thermal Warping" or internal voids. Each manufactured prism was compared to a "Control Twin" using ultrasound testing to verify that the internal density matched the required safety protocols within a tolerance of 5%.

This level of precision confirms that bio-mineralized designs are not just theoretical curiosities but are fully compatible with current high-output construction workflows in the Indian infrastructure sector.

5. Conclusion

The integration of **Bio-Mineralization** and **Microbial Carbonate Precipitation** represents a fundamental shift from traditional "reactive" maintenance to a performance-first "proactive" paradigm. This study has demonstrated that by leveraging *Bacillus pseudofirmus*, civil engineers can achieve nearly **92% recovery** in structural watertightness. These organic, self-healing structures do not merely save repair costs; they offer superior durability and corrosion resistance by mimicking the natural mineral cycles found in geological systems.

As we look toward the 2030 sustainability mandates of India's National Infrastructure Pipeline, the ability to produce "Self-Healing" concrete will be a deciding factor in the commercial viability of smart cities. The "Bio-Granule" framework proposed in this research ensures that these complex, living materials meet the most stringent safety and manufacturing standards. By reducing the maintenance overhead of current urban frames, microbial technology provides a definitive technical roadmap for the era of resilient, carbon-neutral infrastructure.

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