Engineering Potential of Self-Healing Bioconcrete Incorporating Bacillus subtilis for Crack Repair

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Abstract. This paper presents an advanced characterization of self-healing bioconcrete enhanced with Bacillus subtilis, with the objective of evaluating its mechanical performance, self-healing capacity, underlying biological mechanisms, and economic viability. A systematic documentary review was conducted, synthesizing quantitative data from peer-reviewed studies, academic theses, and practical implementation reports. The findings reveal significant improvements in compressive strength and crack-sealing performance. Concentrations of up to 10^9 cells/ml have demonstrated the ability to heal cracks of 1 mm within 140 days, with some studies reporting healing of wider cracks under specific conditions. Despite its high initial cost—three to four times greater than conventional concrete—bioconcrete offers long-term benefits in durability and maintenance reduction. The study highlights the importance of life cycle assessments (LCA) and cost-benefit analyses for its optimal application in infrastructure. This study serves as a reference for future experimental research and sustainable implementation in infrastructure projects.

Keywords: bioconcrete, bacteria, strength, compression, tension, bending.

1 Introduction

The deterioration of concrete infrastructure, both globally and in Peru, presents persistent technical and economic challenges. Due to its inherently low tensile strength, concrete is prone to cracking, which allows the ingress of aggressive agents that compromise the reinforcement and reduce the structure's service life.

Traditional repair methods are often labor-intensive, costly, and unsustainable, especially in large-scale or difficult-to-access structures. In this context, the emergence of self-healing concrete technologies—particularly those incorporating microorganisms—offers a promising solution.

Bioconcrete activated with Bacillus subtilis has demonstrated the capacity to autonomously seal cracks through microbiologically induced calcium carbonate precipitation. This study aims to analyze its technical potential, limitations, and real-world applicability through a systematic evaluation of documented cases and experimental evidence. Although

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this study does not present original laboratory tests, it provides a comprehensive documentary synthesis that supports future field-scale validation.

2 Methodology

This research was conducted using a systematic documentary review approach, with descriptive and explanatory scope. Scientific literature was collected from peer-reviewed journal articles, academic theses, and documented field applications, selected based on their relevance to the study of bioconcrete incorporating Bacillus subtilis.

Inclusion criteria required that the selected studies present quantitative data on compressive strength, crack-healing performance, and durability, with Bacillus subtilis explicitly used as the biological healing agent. Studies lacking numerical evidence or employing other microbial agents were excluded.

An exhaustive search was conducted across specialized scientific sources. The selected literature was systematically organized by variables including application context (laboratory or field), bacterial concentration, crack type and size, healing duration, compressive strength results, and associated implementation costs.

3 Results and Discussion

3.1 Biological Viability and $CaCO_3$ Formation

Mendoza and Sánchez [1] reported an optimal growth curve of Bacillus subtilis at 23 hours, demonstrating resistance to alkaline environments. Calcium carbonate precipitation was observed (Fig. 1), particularly effective in cracks smaller than 0.3 mm.

Fig. 1. $CaCO_3$ formation in cracks under stereoscopic view

Source: Mendoza and Sánchez [1]

3.2 Effectiveness in Crack Sealing

Santos [2] reported the complete self-healing of a 1 mm crack in 140 days under real operating conditions (a water treatment plant). Additionally, Andia and Bautista [3] documented the ability of bioconcrete to seal cracks up to 8 mm wide in approximately three months. Sierra and Jonkers [4] confirmed the complete sealing of 0.14 mm cracks in just six weeks in an experimental irrigation channel. Mora [5] complemented these findings by indicating that bacterial concentrations between 10^5 and 10^9 cells/ml, combined with calcium lactate, yield the most effective results.

These outcomes demonstrate remarkable effectiveness both in laboratory settings and real-world conditions.

3.3 Improvement in Mechanical Properties

The Fig. 2 illustrates the increase in compressive strength achieved through the incorporation of Bacillus subtilis in concrete mixes. The data show that bacterial concrete reached values exceeding 330 kg/cm², significantly higher than the control mix with a base design strength of 210 kg/cm². This improvement confirms the structural contribution of microbial-induced calcium carbonate precipitation, validating the effectiveness of bioconcrete in enhancing mechanical performance.

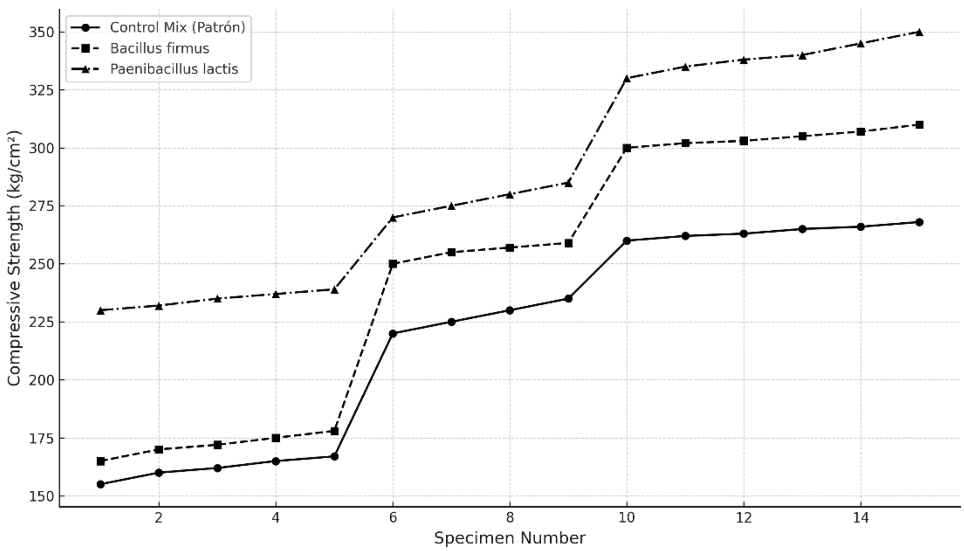

Fig. 2. Comparison of compressive strength in mixes with different bacterial agents.

Source: Adapted from Andia and Bautista [3]

3.4 Durability and Mechanism of Action

The spores of Bacillus subtilis can remain viable for over 200 years [6], becoming active upon contact with water and precipitating calcite to seal cracks. This suggests a long-lasting solution capable of responding to future cracks without external intervention.

3.5 Costs and Economic Challenges

Bioconcrete is currently 3 to 4 times more expensive than conventional concrete. However, a full life cycle perspective reveals its potential for cost savings in long-term maintenance and repair reduction. For instance, while conventional concrete averages USD 80/m³, bioconcrete may cost up to USD 150/m³ [1].

3.6 Relevant Quantitative Parameters

Table 1 summarizes the most significant quantitative parameters identified across the reviewed studies. These values provide a comparative perspective on the technical and economic performance of bioconcrete incorporating Bacillus subtilis.

This synthesis highlights key variables such as optimal bacterial concentration, crack-sealing range, compressive strength gains, and cost implications, as well as long-term viability and durability considerations. These parameters serve as critical benchmarks for future research and practical implementation in structural engineering projects.

Table 1. Relevant Quantitative Parameters

Category	Relevant Values
Optimal Bacterial Concentration	10^5–10^9 cells/ml; 10^9 enhances compressive strength
Crack-Sealing Capacity	0.14 mm (sealed in 6 weeks) [4]; 1 mm (in 140 days) [2]; up to 8 mm (in 3 months) [3]
Compressive Strength	Up to 335.71 kg/cm² (water replacement); 196.09 kg/cm² (bacterial injection)
Cost Comparison	USD 80/m³ (conventional) vs. USD 150/m³ (bioconcrete)
Spore Viability	Over 200 years [6]
Crack Reduction	3.93% reduction in a field application (Lima, 2021)
Key Considerations	High variability in results; essential to conduct LCA and field trials

3.7 Comparison with Alternative Self-Healing Technologies

Several alternative self-healing technologies have been explored in the literature, including encapsulated polymers, crystalline admixtures, and superabsorbent materials. While these approaches can provide immediate responses to microcracking, they often face limitations in terms of long-term durability, sustainability, and reactivation capacity.

In contrast, bioconcrete incorporating Bacillus subtilis offers a biologically renewable mechanism that can respond to future cracking events upon water ingress. Nevertheless, each technique has specific advantages depending on the application context. Hybrid solutions or comparative trials may help determine the most cost-effective and efficient solution for a given project.

Recent studies support these comparisons. For example, Meng et al. (2023) [7] evaluated microbial combinations for healing hydraulic concrete, while Orozco and Urbino (2022) [8] tested encapsulation strategies with Bacillus cibi. Salem et al. (2022) [9] applied finite element analysis to bacterial concrete beams.

Bhutange et al. (2024) [10] identified critical challenges in the application of biocementation for cement-based materials, proposing mitigation strategies to improve mechanical and durability performance.

Rajadesingu et al. (2024) [11] reviewed eco-friendly bacterial self-healing concrete systems and their implementation potential at scale.

4 Conclusions y Recommendations

The use of Bacillus subtilis in self-healing bioconcrete significantly enhances compressive strength and crack-sealing capacity, particularly at concentrations of 10^9 cells/ml. Cracks of up to 1 mm can be fully healed within 140 days, with wider cracks also showing favorable results under optimized conditions.

While the initial production cost is considerably higher than that of traditional concrete, life cycle analyses reveal potential economic and environmental benefits through extended service life and reduced maintenance requirements.

Future research should focus on optimizing bacterial dosage according to specific structural needs, improving encapsulation techniques, and ensuring long-term viability of bacterial spores within the matrix. Additionally, the development of scalable production methods for bacterial cultures is essential.

Field-scale studies under diverse environmental and loading conditions are urgently needed to validate laboratory findings. These studies should assess durability under freeze–thaw cycles, chemical exposure, and long-term performance of the healing mechanism.

Bioconcrete offers a sustainable alternative by reducing resource consumption and minimizing waste associated with conventional repair methods. Quantifying its environmental impact through carbon footprint and life cycle analysis will be vital for widespread adoption.

Establishing public-private partnerships and incorporating bioconcrete into infrastructure standards could accelerate its adoption.

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