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Integration of Smart Materials: Enhancing Concrete Durability through Bacterial Solutions

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Abstract

Concrete, an essential material in modern infrastructure, is very susceptible to cracks, resulting to structural failures and costly maintenance. Traditional restoration approaches are costly and ecologically hazardous. This study examines the use of microbially induced calcite precipitation (MICP) as a self-healing mechanism for concrete, using Bacillus Subtilis and Calcium Lactate as smart materials to enhance durability. The primary aim is to increase the lifetime and sustainability of concrete by allowing it to autonomously repair fractures. This research meets the current inequality in concrete durability by optimizing the bacterial solution, which is incorporated inside the concrete mix and activated during immersion curing. The self-healing efficacy is assessed by assessing the recovery of fracture widths and the average restoration width, with findings showing over 90% fracture healing after 28 days. Additionally, compressive and tensile strength experiments demonstrate that bacterial concrete exceeds conventional concrete in both mechanical strength and fracture healing ability. The watertightness restored by bacterial concrete was above 82%, indicating its exceptional resistance to water penetration and environmental degradation. This research proves the potential of bacterial solutions in concrete as a sustainable, cost-effective option for long-term infrastructure maintenance, opening the path for more durable, self-healing concrete systems in the construction sector. Future study will concentrate on enhancing bacterial compositions and evaluating durability under varied environmental circumstances.

Keywords: Self-healing concrete, Bacillus Subtilis, Calcium Lactate, Microbially induced calcite precipitation (MICP), Durability, Fracture healing, Sustainability.

1. Introduction

Modern infrastructure depends significantly on concrete owing to its adaptability and strength; still, it is naturally capable of splitting, which impairs its durability and structural integrity. Traditional restoration procedures are generally expensive, costly in terms of resources and ecologically detrimental, prompting the quest for sustainable solutions to extend concrete's lifetime. In recent years, the idea of microbially induced calcite precipitation (MICP) has arisen as a potential self-healing mechanism. This technology uses bacteria, such as Bacillus subtilis, to repair fractures autonomously by producing calcium carbonate in the presence of calcium supplies like calcium lactate, thereby restoring the concrete's structural integrity. Adding these microorganisms as part of smart materials in concrete has shown favorable outcomes, significantly enhancing self-healing effectiveness and mechanical qualities. Research has showed that healing rates may reach 90%, and the overall watertightness and durability of concrete are strengthened. Furthermore, the use of chemical healing agents and bio-immobilized compounds has showed promise in enhancing traditional concrete’s performance. The combined impacts of bacterial solutions and smart materials provide a sustainable and cost-effective option for concrete maintenance, coinciding with larger objectives of sustainability and resource efficiency in the building sector. This work expands upon previous advancements by focusing on the connection between bacterial solutions and smart materials to increase concrete's durability and self-repair capabilities. By altering the quantities of microbes and nutrients, this technique customizes the self-healing process to particular environmental circumstances that concrete buildings experience. Objectives of the research include: Investigating the effectiveness of MICP via Bacillus subtilis and Calcium Lactate as a self-healing mechanism in concrete. Evaluating the compressive and tensile strength of bacterial concrete compared to standard formulations. Examining the possibility of bacterial concrete as a sustainable method to increase the lifetime of infrastructure. Preliminary studies reveal that bacterial-infused concrete not only maintains but may also enhance its mechanical qualities, making it a viable alternative to conventional

concrete. This study intends to pave the path for more durable and eco-friendly infrastructure by establishing the advantages of bacterial solutions in concrete, creating a fresh standard for sustainable civil engineering techniques.

2. Literature Reviews:

A novel and environmentally responsible method to increase the lifetime and resilience of concrete buildings is self-healing concrete. Higher maintenance costs and worse structural performance are common outcomes of using traditional concrete due to its fracture and degradation proneness. Innovative approaches to these problems have recently emerged, such as microbial-induced calcite precipitation (MICP). This method makes use of certain bacterial strains, including Bacillus Subtilis, that seal fractures and enhance mechanical characteristics by precipitating calcium carbonate when calcium lactate is present. With recuperation efficiency over 90%, the watertightness and durability were substantially enhanced, according to Chandana et al. (2023). Dilshad et al. (2022) brought attention to the use of smart materials in conjunction with bacterial solutions; their research showed that this combination enhanced the overall strength and fracture regeneration of concrete structures. Further investigation is needed to completely comprehend the environmental and structural efficacy of bacterial concrete in the long term, since there are still some unknowns. Duan et al. (2023) studied the use of recycled coarse aggregates (RCA) as microbial carriers, presenting a sustainable technique for enhancing healing efficacy while addressing ecological issues. While encapsulation strategies, as tested by Jonkers et al. (2010), enhanced bacterial activity inside concrete, certain methods diminished total strength. Researchers Pelletier et al. (2013) found that sodium silicate capsules and other self-healing materials might recover as much as 26% of their initial strength upon fracturing. Although less successful than microbial therapies, these discoveries contribute to the larger knowledge of self-healing processes. There has been a lot of progress, but there has to be more study into developing durable, environmentally friendly concrete systems by optimizing bacterial compositions and enhancing the integration of smart materials.

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3. Methodology:

3.1 Materials Preparation

The materials utilized in this attempt composed Ordinary Portland Cement (OPC), 53 grade, noted for its remarkable strength and durability. The cement's qualities were defined by an initial setting time of 32 minutes, a full setting time of 560 minutes, soundness of 8 mm, and normal consistency of 32%. Fine particles utilized were river sand with a specific gravity of 2.59, and coarse aggregates constituted of gravel with a specific gravity of 2.6 to obtain a balanced composition. The bacterial strain employed for this investigation was Bacillus subtilis, a gram-positive, rod-shaped bacterium chosen for its demonstrated capacity to precipitate calcium carbonate, a vital element in the self-healing process of fractures in concrete.

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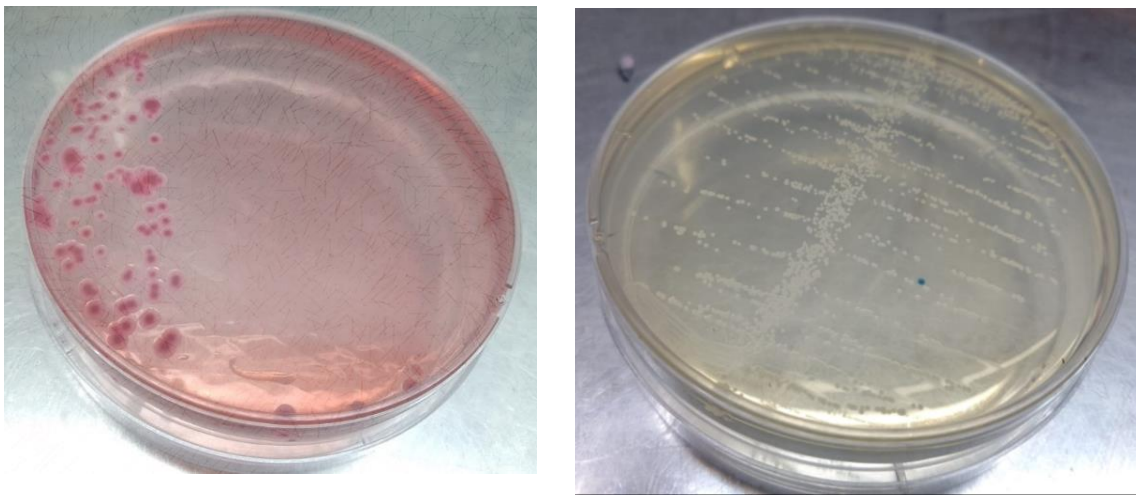


Figure :1 Bacillus Subtilis Growth in Culture Preparation for Bacterial Concrete

3.2 Preparation of Bacterial Concrete

Ingredients, including cement, fine and coarse aggregates, water, and calcium lactate, were properly weighed to attain correct compound proportions for bacterial concrete. Bacillus subtilis was cultivated in a nutrient-rich medium under optimal conditions to obtain a high cell concentration. The bacterial culture was treated to retain feasibility and was placed into the concrete mix, permitting effective microbial-induced calcite precipitate and self-healing.

3.3 Concrete Mix Preparation

The fundamental concrete mix was developed as M20 grade for structural reasons. Bacillus subtilis and Calcium Lactate were combined into the mixture in four variations: 10 ml Bacillus subtilis (BS) with 2.5% Calcium Lactate (CL), 15 ml BS with 2.5% CL, 10 ml BS with 0.5% CL, and 15 ml BS with 0.5% CL. After combining, the concrete was subjected to immersion curing to activate microbiological activities, enabling calcium carbonate precipitation to heal cracks.

3.4 Specimen Casting and Curing

Specimens were molded into 150x150x150 mm blocks for compressive strength testing and 150x300 mm cylinders for fracturing tensile strength tests. The bacterial concrete mix, comprising Bacillus subtilis and Calcium Lactate, was compressed inflexibly to minimize honeycombing. The specimens experienced immersion curing to assurance correct hydration, which stimulated bacterial activity for calcium carbonate precipitation. Curing was conducted at intervals of 7, 14, and 28 days, and assessments were carried out at each stage to evaluate the mechanical characteristics and self-healing efficacy of the bacterial concrete.

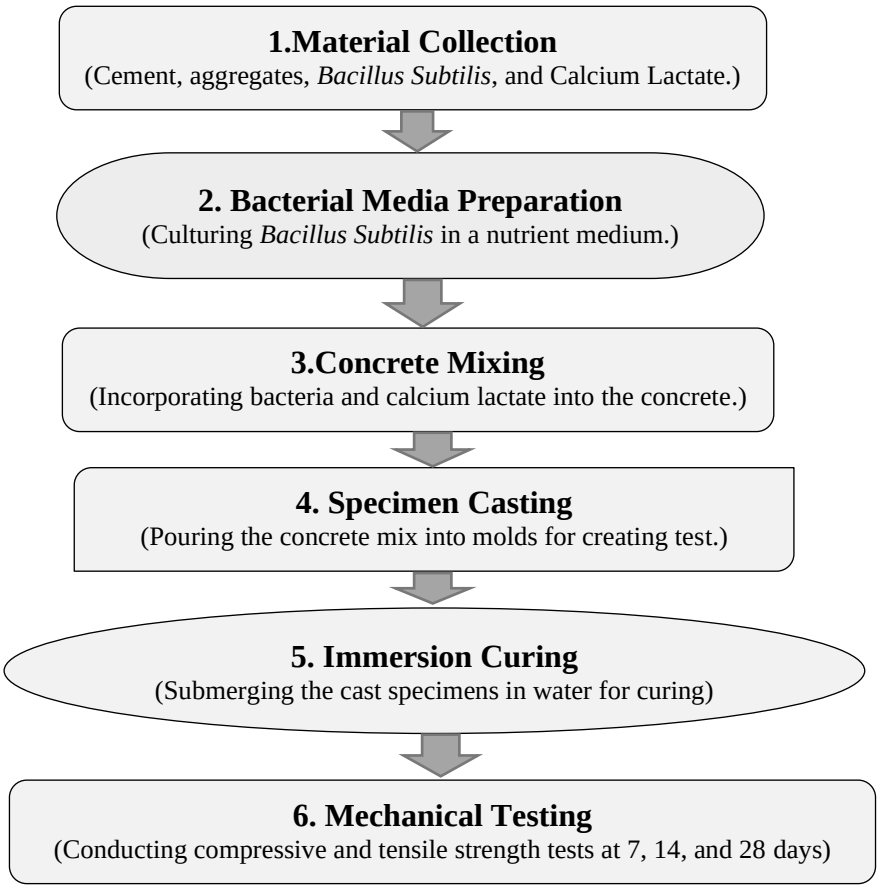


Figure 2: Working Methodology Flow Chart for Bacterial Concrete Preparation and Testing

4. Result:

4.1 Mechanical Properties

The mechanical attributes of the concrete samples were examined using compressive strength tests and fracturing tensile tests, done in accordance with ASTM C39 M and ASTM C496 standards. The investigations were done on both conventional concrete and bacterial concrete containing various concentrations of Bacillus Subtilis (BS) and Calcium Lactate (CL). The findings indicate analogous patterns across all concrete varieties, emphasizing the influence of bacterial presence on the mechanical characteristics. Comparative evaluations demonstrated considerable gains in compressive and tensile strength for bacterial concrete compared to conventional formulations, demonstrating the efficiency of microbial interventions in enhancing concrete performance.

Table: 1 Compressive and Splitting Tensile Strength Results for Conventional and Bacterial Concrete Mixes

Test Conducted		Conventional Concrete	Bacterial Concrete			
			10ml BS +0.5% CL	15ml BS +0.5% CL	10ml BS +2.5% CL	15ml BS +2.5% CL
Compressive Strength (kN/m^2)	**7 days**	13.22	17.15	19.55	9.19	21.97
	14 Days	17.68	23.46	26.96	10.57	31.13
	28 Days	19.40	32.68	30.02	11.63	34.57
Splitting Tensile Test (kN/m^2)	**7 days**	2.56	1.40	1.93	1.15	1.66
	14 Days	2.88	1.93	2.66	1.45	2.22
	28 Days	3.02	2.13	2.93	1.90	2.47

4.2 Self-Healing Efficiency:

The self-healing efficiency of bacterial concrete was a primary focus of this study. When fractures occurred in the concrete, water penetration triggered the latent Bacillus Subtilis bacteria confined inside the matrix. The bacteria metabolized the provided calcium lactate, resulting in microbial-induced calcite precipitation (MICP), where calcium carbonate was precipitated to cover and close the fractures. This technique restored the structural integrity of the concrete. To assess the self-healing efficiency, fracture widths were monitored over time using microscopic imaging and digital measuring methods. The recovery % was estimated by comparing the original and ultimate fracture diameters. Experimental findings demonstrated that bacterial concrete had healing efficiencies surpassing 90% after 28 days of immersion curing, considerably outperforming conventional concrete.



Figure 3: Crack Repair in Cube via Mycobacterial Self-Healing Action.

Visual studies of "before" and "after" healing indicated the closure of visible cracks, while chemical investigation verified the existence of calcium carbonate deposits at the fracture locations. The reaction mechanism for MICP may be expressed as:

$$Ca(C_3H_5O_2)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2C_3H_6O_3$$

This self-healing mechanism not only avoided further deterioration but also enhanced resistance to environmental elements, such as moisture interruption and chemical attacks, hence increasing the service life of the concrete. These results highlight the promise of bacterial concrete as a sustainable, resilient alternative to traditional formulations. Future study will concentrate on refining the measuring methodologies and researching applications under mixed environmental circumstances.

5. Comparative Analysis with Conventional Concrete

Bacterial concrete exhibited superior performance compared to conventional concrete in terms of strength, durability, and self-repair capabilities. The combination of Bacillus Subtilis and calcium lactate considerably enhanced the capacity of bacterial concrete to autonomously repair fractures, diminishing the need for expensive and ecologically detrimental maintenance. This self-healing process not only increased the concrete's resilience to environmental deterioration but also offered enhanced protection against water permeability and chemical assaults. These properties are particularly essential in difficult situations where standard concrete commonly suffers from moisture infiltration and concurrent reinforcing degradation. This comparative research demonstrates the promise of bacterial concrete as a sustainable and resilient solution for current building projects.

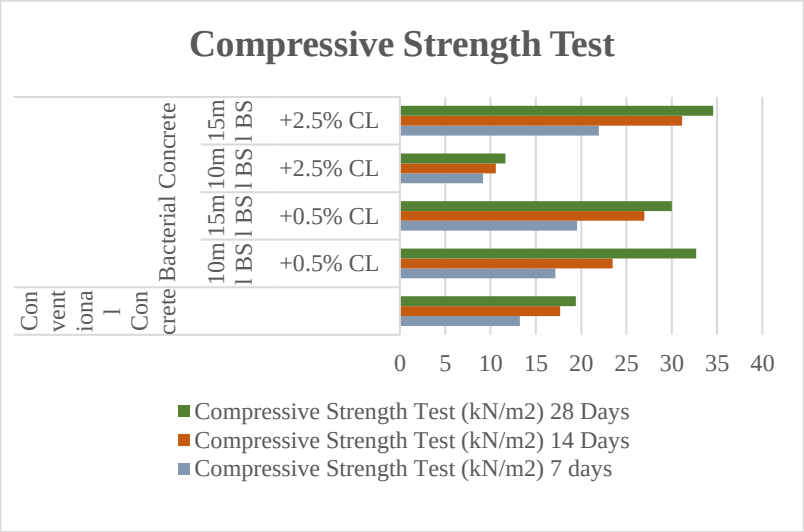


Figure 4: Comparison of Compressive Strength between Conventional and Bacterial Concrete Samples.

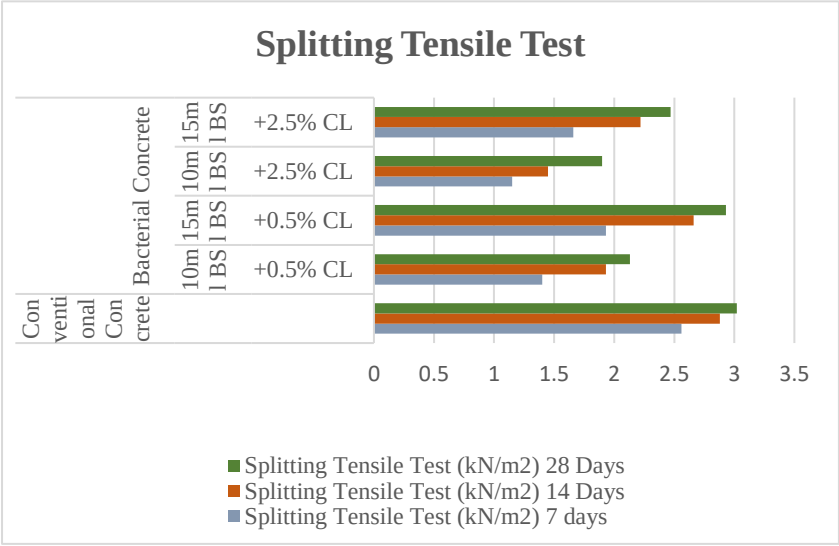


Figure 5: Comparison of Tensile Strength between Conventional and Bacterial Concrete Samples.

The effectiveness of self-healing in bacterial concrete is integrally connected to the metabolic activity of the bacteria, which prosper when given with appropriate nutrition and water during curing. The research indicates that bacterial concrete has much greater fracture closure rates and superior mechanical strength compared to conventional concrete. These innovations not only increase the service life of buildings but also contribute to sustainable and resilient infrastructure. By mitigating the long-term environmental and economic implications of concrete degradation, bacterial concrete provides a feasible option for modern building, harmonizing with sustainability objectives and challenging significant issues in structural maintenance.

6. Conclusion:

The combination of smart materials, specifically bacterial solutions, represents a transformational leap in concrete technology, substantially encouraging the durability and sustainability of concrete buildings. This work indicates that adding Bacillus Subtilis into concrete introduces Microbial-Induced Calcium carbonate Precipitation (MICP), providing independent self-healing capabilities. This method effectively closes fractures, limiting hazards connected with water entrance and chemical attacks, therefore increasing the lifetime of buildings. Comparative study with conventional concrete reveals the enhanced performance of bacterial concrete, notably in terms of mechanical strength, fracture healing, and resistance to environmental deterioration. These results emphasize its capacity as a sustainable option for current building, harmonizing with global objectives for resilient infrastructure. Future study should concentrate on refining bacterial formulations, assessing long-term performance across varied environmental conditions, and increasing applicability to larger-scale construction projects. By addressing these areas, bacterial concrete may be further developed as a cost-effective, eco-friendly option, establishing a new benchmark for sustainable building practices in the construction sector. This research emphasizes the significance of novel materials in overcoming the constraints of conventional concrete, opening the path for a more sustainable future in civil engineering.

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