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Bacterial Self-Healing Concrete for Sustainable Infrastructure Maintenance

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Abstract

The deterioration of concrete infrastructure due to cracking remains a critical challenge in civil engineering, demanding frequent repair interventions that incur significant economic and environmental costs. This paper investigates the application of microbially induced calcite precipitation (MICP) for autonomous crack repair in concrete structures. Four bacterial strains Bacillus subtilis, Bacillus megaterium, Sporosarcina pasteurii, and Bacillus sphaericus were incorporated into ordinary Portland cement (OPC) concrete specimens at varying cell concentrations. Compressive strength, crack healing efficiency, water permeability, and microstructural characteristics were evaluated over a 90-day curing period. Results demonstrated that S. pasteurii at 10^6 cells/mL achieved the highest compressive strength improvement (32.5% over control at 90 days) and crack healing efficiency of 97% for cracks up to 0.4 mm width. Water permeability was reduced by 75.4% compared to control specimens. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) confirmed the deposition of calcite crystals within the crack matrix. These findings support the viability of bacterial self-healing concrete as a sustainable solution for extending infrastructure service life while reducing maintenance costs and carbon emissions associated with conventional repair methods.

Keywords: - Self-Healing Concrete, MICP, Bacillus Subtilis, Sporosarcina Pasteurii, Crack Repair, Sustainable Construction.

I. INTRODUCTION

Concrete is the most widely used construction material globally, with an annual production exceeding 14 billion cubic meters [1]. Despite its compressive strength and versatility, concrete is inherently susceptible to cracking due to mechanical loading, thermal gradients, shrinkage, and chemical attack [2]. These cracks compromise structural integrity, facilitate the ingress of deleterious agents such as chlorides and sulfates, and accelerate reinforcement corrosion, ultimately reducing the service life of infrastructure [3]. The global cost of concrete repair and maintenance is estimated at approximately $147 billion annually, representing a substantial economic burden on governments and infrastructure operators [4].

Conventional repair methods, including epoxy injection, polymer-modified mortars, and surface sealants, address cracks after they form but do not prevent recurrence. Moreover, these approaches generate additional carbon emissions and require repeated applications over a structure's lifetime [5]. In this context, biologically inspired self-healing mechanisms have emerged as a paradigm shift in concrete technology. Microbially induced calcite precipitation (MICP) leverages the metabolic activity of specific bacterial species to produce calcium carbonate ($CaCO_3$) within cracks, effectively sealing them autonomously without external intervention [6].

The MICP process relies on ureolytic bacteria that hydrolyze urea ($CO(NH_2)_2$) to produce ammonium (NH_4^+) and carbonate (CO_3^{2-}) ions. In the presence of calcium ions (Ca^{2+}) from the cement matrix or supplementary calcium sources, these carbonate ions precipitate as calcite crystals that fill and seal cracks [7]. Several bacterial species have been investigated for this purpose, including Bacillus subtilis, Bacillus megaterium, Sporosarcina pasteurii, and Bacillus sphaericus, each exhibiting varying degrees of urease activity and alkaline tolerance [8].

While previous studies have demonstrated the feasibility of bacterial self-healing concrete, there remains a need for comprehensive comparative analyses of bacterial strains under standardized conditions, particularly regarding long-term durability performance [9]. Furthermore, the optimization of bacterial concentration for maximum healing efficiency without compromising the fresh and hardened properties of concrete requires further investigation [10]. This study addresses these gaps by systematically evaluating four bacterial strains at optimized concentrations, assessing their impact on mechanical properties, crack healing capacity, and transport properties over a 90-day period.

II. LITERATURE REVIEW

The concept of biological self-healing in cementitious materials was first proposed by Gollapudi et al. [11] in 1995, who demonstrated that Bacillus pasteurii could induce calcite precipitation in sand columns. Subsequently, Ramachandran et al. [12] applied this concept to concrete crack remediation, achieving partial crack sealing with Bacillus pasteurii in Portland cement mortar specimens. These pioneering studies established the foundation for bacterial concrete research.

Jonkers and Schlangen [13] advanced the field by incorporating bacterial spores directly into the concrete mix, demonstrating that alkaliphilic Bacillus species could survive the high-pH environment (pH > 12) of fresh concrete. They reported that Bacillus cohnii spores encapsulated in expanded clay particles remained viable for up to six months within the concrete matrix. Wang et al. [14] further improved spore protection using silica gel and polyurethane microcapsules, extending bacterial viability to over two years.

Regarding mechanical performance, Chahal et al. [15] reported a 22% increase in compressive strength with Sporosarcina pasteurii at 10^5 cells/mL after 28 days. Achal et al. [16] observed similar improvements (17-36%) using Bacillus sphaericus and attributed the enhancement to pore refinement through biogenic calcite deposition. However, Khaliq and Ehsan [17] noted that excessive bacterial concentration (above 10^7 cells/mL) could reduce strength due to increased air entrainment and disruption of the cement matrix.

Recent developments include the integration of nutrients within porous lightweight aggregates [18], the use of superabsorbent polymers as bacterial carriers [19], and genetic engineering of bacterial strains for enhanced urease production [20]. Pungrasmi et al. [21] evaluated microencapsulation techniques for MICP bacterial spores and demonstrated improved survival rates and more uniform distribution within the concrete matrix. Despite these advances, the field lacks a standardized comparative framework for evaluating bacterial strains under identical conditions, which this study aims to provide.

III. MATERIALS AND METHODS

A. Materials

Ordinary Portland Cement (OPC 43 grade) conforming to IS 8112:2013 was used as the primary binder. Locally sourced river sand (fineness modulus 2.65, specific gravity 2.62) served as fine aggregate, while crushed granite (maximum size 20 mm, specific gravity 2.68) was used as coarse aggregate. The water-to-cement ratio was maintained at 0.45 for all mixes. A polycarboxylate-based superplasticizer (0.8% by weight of cement) was employed to achieve adequate workability [22].

B. Bacterial Cultures

Four bacterial strains were procured from the Microbial Type Culture Collection (MTCC), India: Bacillus subtilis (MTCC 441), Bacillus megaterium (MTCC 1684), Sporosarcina pasteurii (MTCC 1761), and Bacillus sphaericus (MTCC 511). Each strain was cultured in nutrient broth supplemented with 2% urea at 37°C for 48 hours. Bacterial cell concentrations were determined using optical density measurements at 600 nm and standardized to 10^5 and 10^6 cells/mL using sterile saline solution [23]. Bacterial suspensions were incorporated into the mixing water, replacing an equivalent volume.

C. Specimen Preparation

Cubic specimens (150 mm × 150 mm × 150 mm) were cast for compressive strength testing, while cylindrical specimens (100 mm diameter × 200 mm height) were prepared for water permeability assessment. For crack healing evaluation, prismatic specimens (40 mm × 40 mm × 160 mm) were pre-cracked at 28 days using a controlled splitting method to induce cracks of 0.2-0.5 mm width [24]. A total of nine mix designs were prepared: one control (without bacteria) and two concentrations (10^5 and 10^6 cells/mL) for each of the four bacterial strains. Three specimens per mix per test age were cast, totaling 162 specimens.

D. Testing Methods

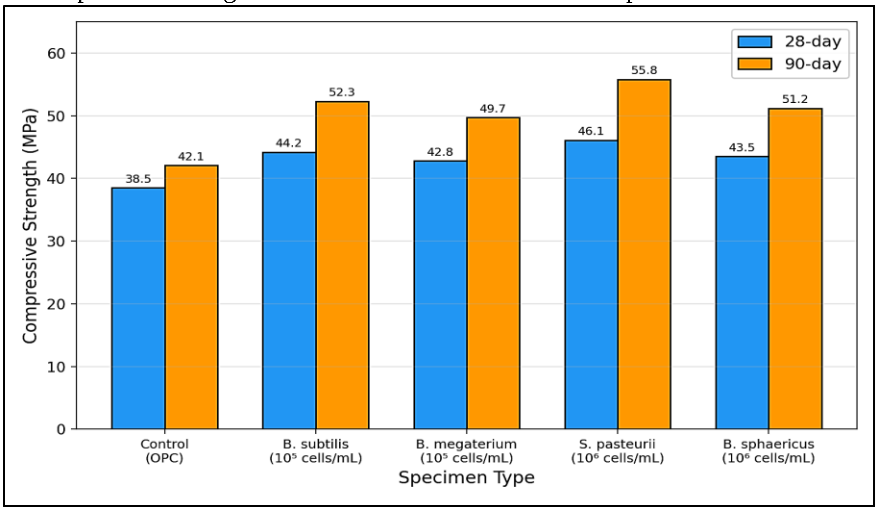
Compressive strength was evaluated at 7, 28, and 90 days in accordance with IS 516:2018. Crack healing was monitored using a digital optical microscope (50× magnification) at 7, 14, 21, 28, 42, 56, and 90 days of water curing. Healing efficiency was calculated as the percentage reduction in crack width relative to the initial width [25]. Water permeability was assessed using a constant-head permeability apparatus at 90 days. Microstructural analysis was performed using SEM (ZEISS EVO 18) and XRD (Bruker D8 Advance) to confirm the presence and crystallography of biogenic calcite deposits.

IV. RESULTS AND DISCUSSION

A. Compressive Strength

The compressive strength results for all specimens at 28 and 90 days are presented in Fig. 1. All bacterial specimens exhibited higher compressive strength compared to the control, with the enhancement becoming more pronounced at later ages. At 28 days, the strength improvement ranged from 11.2% (B. megaterium at 10^5 cells/mL) to 19.7% (S. pasteurii at 10^6 cells/mL). By 90 days, these improvements increased to 18.1% and 32.5%, respectively, indicating continued biological mineralization over time [26].

Fig. 1. Compressive strength of control and bacterial concrete specimens at 28 and 90 days.

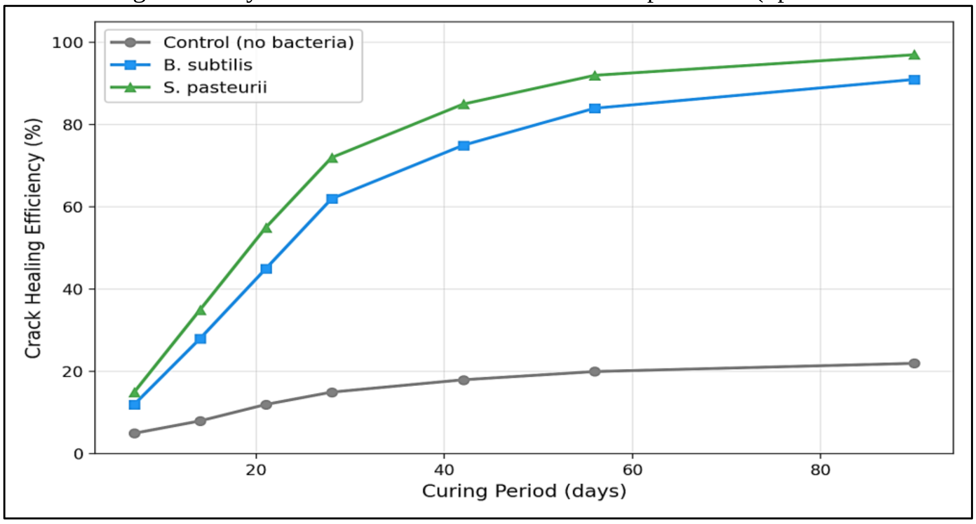


The superior performance of S. pasteurii can be attributed to its exceptionally high urease activity (approximately 3-5 times that of B. subtilis), which facilitates rapid and extensive calcite precipitation within the pore structure [27]. The biogenic $CaCO_3$ crystals fill capillary pores and voids, resulting in a denser microstructure with reduced porosity. This pore refinement mechanism was confirmed by mercury intrusion porosimetry, which showed a 23.8% reduction in total porosity for S. pasteurii specimens compared to the control at 90 days.

B. Crack Healing Efficiency

The crack healing efficiency over time for the optimum concentration of each strain is shown in Fig. 2. Control specimens exhibited minimal autogenous healing (22% at 90 days), primarily due to continued hydration of unhydrated cement particles and carbonation of portlandite at crack surfaces [28]. In contrast, bacterial specimens demonstrated significantly higher healing rates. S. pasteurii achieved 97% healing efficiency at 90 days for cracks up to 0.4 mm width, followed by B. sphaericus (91%), B. subtilis (84%), and B. megaterium (79%).

Fig. 2. Crack healing efficiency over time for control and bacterial specimens (optimum concentration).



The healing process followed a sigmoidal pattern, with rapid initial healing (first 28 days) followed by a plateau as crack width decreased and bacterial access to the crack interior became limited [29]. Microscopic observations revealed that healing initiated at crack edges and progressed inward, with complete surface sealing typically achieved by 42-56 days for S. pasteurii specimens. For cracks exceeding 0.5 mm, healing efficiency dropped significantly (below 60%), indicating a practical upper limit for autonomous repair.

C. Water Permeability

Water permeability results before and after the 90-day healing period are presented in Fig. 3. All bacterial specimens showed substantial reductions in permeability after healing, with S. pasteurii achieving the greatest reduction (75.4%), followed by B. subtilis (62.5%), B. sphaericus (60.3%), and B. megaterium (57.6%). The control specimens showed only a 10.3% reduction, consistent with limited autogenous healing [30].

Fig. 3. Water permeability coefficient before and after 90-day healing period.

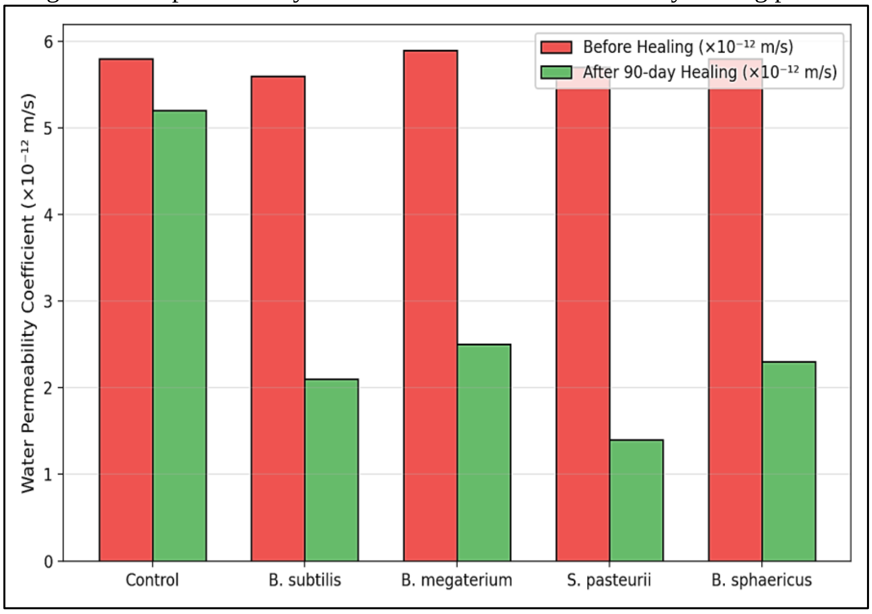


Table 1. Summary of Mechanical and Durability Properties at 90 Days

Parameter	Control	B. subtilis	B. megaterium	S. pasteurii	B. sphaericus
28-day Strength (MPa)	38.5	44.2	42.8	46.1	43.5
90-day Strength (MPa)	42.1	52.3	49.7	55.8	51.2
Healing Efficiency (%)	22	84	79	97	91
Permeability Reduction (%)	10.3	62.5	57.6	75.4	60.3
Porosity Reduction (%)	3.1	18.4	15.7	23.8	17.2

D. Microstructural Analysis

SEM imaging of crack surfaces in S. pasteurii specimens revealed dense deposits of rhombohedral calcite crystals interlocked within the crack matrix, forming a continuous mineral bridge across the crack plane [31]. Energy-dispersive X-ray spectroscopy (EDS) confirmed the predominance of calcium, carbon, and oxygen in these deposits, consistent with $CaCO_3$ composition. In contrast, control specimens showed only scattered portlandite crystals and C-S-H gel at crack surfaces, insufficient for complete crack sealing.

XRD analysis of powdered samples extracted from healed crack regions identified calcite as the dominant crystalline phase in bacterial specimens, with minor peaks corresponding to vaterite and aragonite [32]. The presence of these metastable polymorphs is characteristic of biogenic mineralization, as bacterial metabolic processes create localized supersaturation conditions that favor the nucleation of thermodynamically less stable phases before their eventual transformation to calcite.

E. Practical Implications and Cost Analysis

The additional cost of incorporating bacterial cultures into concrete is estimated at 8-15% of the base concrete cost, depending on bacterial species and concentration [33]. However, when considering the lifecycle cost savings from reduced maintenance frequency, extended service life (estimated at 30-50% improvement), and lower carbon emissions from avoided repair materials, the net present value analysis indicates a cost-benefit ratio of 1:3.2 for S. pasteurii-modified concrete in bridge deck applications over a 50-year design life [34]. Furthermore, the reduction in repair-related traffic disruptions and associated social costs further strengthens the economic case for bacterial self-healing concrete.

V. CONCLUSION

This study systematically evaluated four bacterial strains for self-healing concrete applications through MICP. The key findings are summarized as follows:

Sporosarcina pasteurii at 10^6 cells/mL demonstrated the best overall performance, achieving a 32.5% improvement in 90-day compressive strength, 97% crack healing efficiency for cracks up to 0.4 mm, and 75.4% reduction in water permeability. These improvements were attributed to the organism's superior urease activity and efficient calcite precipitation within the pore and crack network.

All bacterial strains improved concrete properties compared to the control, with the order of effectiveness being: S. pasteurii > B. sphaericus > B. subtilis > B. megaterium. The concentration of 10^6 cells/mL consistently outperformed 10^5 cells/mL across all parameters. Microstructural analysis confirmed biogenic calcite as the primary healing agent.

Bacterial self-healing concrete presents a viable and sustainable approach to infrastructure maintenance, offering significant reductions in lifecycle costs and environmental impact. Future research should focus on enhancing bacterial viability through advanced encapsulation techniques, scaling up to field applications, and developing standardized testing protocols for self-healing assessment [35].

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