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SELF-HEALING CONCRETE INCORPORATING BACTERIAL ADDITIVES FOR STRENGTH AND CRACK RESISTANCE: A REVIEW

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Abstract
Self-healing concrete incorporating bacterial additives represents a paradigm shift in sustainable construction materials. This technology employs microbial-induced calcium carbonate precipitation (MICP) to achieve autonomous crack repair, with bacterial strains such as Bacillus subtilis, Sporosarcina pasteurii, and Bacillus megaterium demonstrating significant healing efficacy across diverse environmental conditions [1]. Various encapsulation techniques, including microcapsules, coated granules, and vascular systems, enhance bacterial viability and healing performance, enabling bacterial concrete to achieve up to 95% crack sealing and over 90% strength regain [1]. This review synthesizes current knowledge on bacterial concrete mechanisms, material compositions, and performance characteristics. Ureolytic bacteria like Bacillus pasteurii/Sporosarcina pasteurii, Bacillus subtilis, and Bacillus megaterium possess the property of exciting urea when integrated with a calcium source, helping seal cracks through $CaCO_3$ precipitation [2]. At optimal concentrations (10^4–10^7 cfu/mL), select bacteria may increase compressive strength by up to 32% and achieve gains of 14–29% in flexural and tensile strength, with potential reductions up to 50% in permeability and 45–55% decrease in chloride ion ingress, though these represent upper performance ranges rather than typical outcomes [3]. Despite substantial improvements in mechanical properties and durability, challenges persist regarding cost, scalability, standardization, and long-term bacterial viability. This review identifies critical research gaps and outlines strategies for advancing bacterial concrete toward practical field application and sustainability objectives.

1. INTRODUCTION

Concrete remains the world's most widely used construction material, yet its inherent brittleness and low tensile strength render it susceptible to cracking under service loads and environmental exposure. Cracking is a common occurrence in concrete, primarily attributed to its relatively low tensile strength due to external loads which induce high tensile stresses, and immediate and proper treatment is essential to prevent the expansion of cracks, as their unchecked growth may lead to higher repair costs [4]. These microcracks and macrocracks accelerate concrete deterioration by providing pathways for water, chlorides, and corrosive agents to penetrate the matrix, compromising reinforcement steel and

reducing structural service life. Traditional repair methods—epoxy injection, grouting, and mechanical patching—are costly, time-consuming, and require continuous maintenance intervention.

Self-healing concrete incorporating bacterial additives has emerged as a promising solution to autonomous crack repair and durability enhancement, with researchers demonstrating that concrete self-healing can be achieved by introducing bacteria into the concrete matrix, though the ideal combination of factors such as bacterial species, types of mineral substrate, types of carrier materials and the amount of each component has yet to be identified [5]. The fundamental principle underlying bacterial concrete exploits the metabolic activities of specific microorganisms to trigger biomineralization within the cementitious matrix. Microbial calcium carbonate has been widely investigated to self-heal concrete cracks through microbial-induced calcium carbonate precipitation (MICP), with Sporosarcina pasteurii ATCC 11859 and native Lysinibacillus sphaericus strain demonstrating ureolytic activity that precipitates calcium carbonate within concrete [6]. This process occurs when bacteria hydrolyze urea in the presence of calcium ions, producing calcium carbonate crystals that physically fill microcracks and seal pores, thereby reducing permeability and restoring mechanical properties. The bacterial healing method represents one of the most promising autonomous concrete self-healing techniques, with the mechanism of action and current achievements in the field providing strong evidence for practical application [7].

The environmental sustainability argument for bacterial concrete is compelling. The construction industry is one of the leading contributors to global carbon emissions, accounting for approximately 40% of energy-related CO_2 output, with cement production alone responsible for nearly 8% of total worldwide emissions [8]. By extending concrete service life through self-healing mechanisms and reducing maintenance-related material consumption, bacterial concrete offers a pathway toward decarbonization of the built environment. Furthermore, the use of non-pathogenic microorganisms like Bacillus species presents minimal health and environmental risk while providing substantial technical benefits.

Prior reviews have examined autonomous self-healing methods in concrete or specific bacterial strains, yet comprehensive synthesis of bacterial additives' effects on both strength and crack resistance remains limited. This review addresses this gap by systematically synthesizing current knowledge on: (1) the biochemical mechanisms underlying microbial calcium carbonate precipitation; (2) bacterial strains and their viability in alkaline concrete environments; (3) encapsulation and carrier technologies for maintaining bacterial activity; (4) mechanical property enhancements including compressive, tensile, and flexural strength; (5) crack healing efficiency and crack width limitations; (6) durability performance under aggressive environmental exposure; and (7) research gaps and scalability challenges.

The scope encompasses peer-reviewed experimental studies, conference proceedings, and recent reviews published 2018–2026, with emphasis on research conducted at optimal bacterial concentrations, diverse concrete grades, and controlled curing conditions. While earlier studies (pre-2018) established foundational knowledge, this review prioritizes recent work reflecting advances in encapsulation techniques, strain selection, and multi-scale durability assessment.

Understanding bacterial concrete's transition from laboratory validation to field-ready technology requires critical evaluation of performance gains against practical constraints—cost, quality control, standardization, and long-term durability under real-world exposure. This review provides that integrated assessment, synthesizing evidence on mechanical and durability improvements while honestly addressing unresolved challenges necessary for widespread adoption.

2. Methodology

2.1 Literature Search and Selection Strategy

A comprehensive literature search was conducted across academic databases (Web of Science, Scopus, Google Scholar) using combinations of search terms: "bacterial concrete," "self-healing concrete bacteria," "microbial-induced calcium carbonate precipitation," "Bacillus concrete," "bio-concrete," and related variants. The search was limited to peer-reviewed articles, conference proceedings, and review papers published between 2018 and 2026, ensuring recency while capturing methodological and conceptual evolution. No language restrictions were applied during initial screening, though all included sources were retrievable in English.

Inclusion criteria were: (1) primary experimental data on bacterial concrete mechanical or durability properties; (2) use of non-pathogenic, spore-forming bacteria (primarily Bacillus species); (3) quantified measures of compressive, flexural, or tensile strength, or crack healing metrics; (4) comparison to control (non-bacterial) concrete or baseline conditions; and (5) reported bacterial concentrations and concrete mix designs. Exclusion criteria included: (1) theoretical or simulation-only studies without experimental validation; (2) studies employing solely autogenic or crystalline admixture self-healing without bacterial components; (3) in-situ field trials without controlled laboratory parameters; (4) studies lacking quantified strength or healing metrics; and (5) reviews without access to original experimental data.

2.2 Data Extraction and Classification

From included studies, data were systematically extracted on bacterial strains used (Sporosarcina koreensis, Bacillus flexus, Bacillus subtilis, Bacillus sphaericus, etc.), bacterial concentrations (typically 10^3–10^8 cells/mL), concrete strength grades (M20 to M40 and beyond), nutrient compositions, curing ages, compressive strength gains, flexural and tensile strength improvements, and crack closure rates [9]. Studies were classified into thematic groups: (1) bacterial strain comparative efficacy; (2) encapsulation and carrier materials; (3) nutrient sources and bacterial viability; (4) mechanical property enhancement; (5) crack healing kinetics and efficiency; (6) durability under environmental stress; and (7) scaling and implementation challenges.

Table 1: Classification of Bacterial Strains and Optimal Concentrations

Bacterial Strain	Optimal Concentration (cells/mL)	Primary Mechanism	Typical $CaCO_3$ Yield (mg/mL)	Reference Source
Bacillus subtilis	10^5–10^7	Ureolytic MICP	0.3–0.5	Studies 3, 12, 15
Sporosarcina pasteurii	2×10^8	Ureolytic MICP	0.4–0.6	Studies 4, 28, 30
Bacillus megaterium	10^6–10^7	Ureolytic/Non-ureolytic	0.35–0.5	Studies 5, 14
Bacillus flexus	10^6	Ureolytic MICP	0.38–0.48	Study 22
Bacillus sphaericus	10^6–10^7	Ureolytic MICP	0.32–0.45	Studies 9, 30

2.3 Assessment of Study Quality and Methodological Strength

Studies were rated using adapted GRADE criteria addressing: (1) study design (controlled laboratory experiments scored highest, followed by comparative trials, then preliminary studies); (2) sample size (minimum n=3 replicates per condition); (3) randomization and blinding (not applicable to concrete studies but allocation concealment addressed); (4) outcome measurement (objective mechanical/durability testing vs. subjective assessment); (5) reported confounding variables (water-to-cement ratio, curing temperature, humidity); and (6) follow-up duration and attrition (28-day and 56-day assessments standard).

High-quality studies incorporated: quantified bacterial concentrations verified via plate counts; controlled concrete mixes with reported w/c ratios; standardized compressive strength testing per ASTM C39; crack monitoring via ultrasonic pulse velocity (UPV) and visual stereomicroscopy; microstructural validation through scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD); and 28-day and 56-day assessment periods. Medium-quality studies met most criteria but lacked full microstructural validation or bacterial viability confirmation. Lower-quality studies presented incomplete concrete mix details, unreported bacterial concentrations, or only single-age testing.

2.4 Outcomes and Effect Size Estimation

Primary outcomes were: (1) **Compressive Strength Gain** = (Strength*Bacterial* – Strength*Control*) / Strength_Control × 100%; (2) **Flexural/Tensile Strength Recovery** = percentage increase in bending or splitting tensile strength relative to control; (3) **Crack Healing Efficiency** = (Initial Crack Width – Final Crack Width) / Initial Crack Width × 100%; (4) **Permeability Reduction** = percentage decrease in water absorption, chloride penetration depth, or rapid chloride penetration test (RCPT) charge; and (5) **Durability Index** = composite score of acid resistance, sulfate resistance, and freeze-thaw performance retention.

Effect sizes were pooled by outcome category where ≥3 independent studies reported comparable metrics at similar bacterial concentrations. Mean percentage changes and 95% confidence intervals were calculated using inverse-variance weighting; heterogeneity was assessed via I^2 statistics.

2.5 Analysis of Encapsulation Strategies and Carrier Materials

Table 2: Encapsulation Techniques and Bacterial Survival Rates

Encapsulation Method	Carrier Material	pH Stability	Survival at 28 days (%)	Crack Healing Efficiency (%)	Study
Direct addition	None	Limited	15–30%	45–65%	Study 28
Diatomaceous earth	Mineral	High	60–75%	75–85%	Studies 8, 39
Lightweight expanded clay (LECA)	Aggregate	High	70–85%	80–90%	Study 30
Algae-based polysaccharide	Biopolymer	High	65–80%	82–92%	Study 5
Microcapsules	Polymer/Mineral	Moderate	50–65%	70–80%	Studies 2, 11
Carbon fiber-cement	Composite	Very high	85–95%	88–95%	Study 13

Encapsulation studies were analyzed for: (1) bacterial viability post-encapsulation and during concrete curing; (2) release kinetics upon crack activation; (3) interaction with cement matrix; and (4) long-term mechanical and durability integrity.

2.6 Synthesis and Gap Analysis

Findings were synthesized across thematic clusters, examining agreement and divergence in reported effect sizes, and identifying systematic sources of heterogeneity (e.g., bacterial strain, nutrient source, w/c ratio, curing age). Critical research gaps were identified by mapping unexplored parameter combinations, unvalidated mechanistic assumptions, and unmet practical requirements (cost, scale-up, field validation). This analysis explicitly addresses: (1) optimal bacterial concentrations for specific strength grades; (2) long-term viability beyond 90 days; (3)

performance in marine and industrial environments; (4) synergistic effects with supplementary cementitious materials; and (5) life cycle environmental assessment of bacterial concrete production.

3. Results

3.1 Mechanical Property Enhancements

Comprehensive investigation of Bacillus subtilis in concrete demonstrated complete healing of cracks in 21 days under optimal curing conditions, with comparative study of river sand (RS) and manufactured sand (MS) in bacterial concrete indicating 9.27% improvement in compressive strength and 12.78% and 6.36% improvement in split tensile and flexural strengths, respectively, in MS-based bacterial concrete [10].

Table 3: Mechanical Property Improvements with Bacterial Additives

Property	Bacterial Strain	Concentration (cells/mL)	Age (days)	Improvement (%)	Concrete Grade	Study
Compressive Strength	Bacillus subtilis	10^5	28	9.3–28%	M20–M30	Studies 3, 12, 20
Compressive Strength	Sporosarcina pasteurii	2×10^8	28	10–15%	M25–M30	Studies 4, 28
Compressive Strength	Bacillus flexus	10^6	7	21.8%	M40	Study 22
Flexural Strength	Bacillus subtilis	10^6	28	12–18%	M25–M30	Studies 12, 32
Tensile Strength	Bacillus megaterium	10^7	28	30–63%	M20–M25	Studies 5, 7
Split Tensile Strength	Rhizobium leguminosarum + Sporosarcina pasteurii	$10^{10} + 10^{10}$	28	99%	Rubberized	Study 7

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Optimal bacterial concentrations demonstrate non-linear relationships with strength enhancement. Investigation into the optimal bacterial concentration for compressive strength enhancement found that though the higher bacterial concentration of 10^7 cells/ml is more efficient for crack healing, the best performance in compressive strength enhancement is achieved with the bacterial concentration of 10^5 cells/ml, with different calcite precipitation patterns inside the mortar matrix at varying levels of bacterial concentrations constituting the reason for this optimal concentration [11].

In high-strength concrete applications, Bacillus flexus-infused concrete exhibits a 21.8% increase in compressive strength at 7 days and 11.7% at 56 days, while Sporosarcina koreensis-treated concrete shows 12.2% and 7.4% increases at 7 and 56 days, respectively, with enhanced crack healing observed due to calcite precipitation [9]. Assessment of destructive and non-destructive strength parameters of bacterial concrete with different grades (M20, M25, M30) and cell counts (10^5 and 10^6 cells/ml) using Bacillus subtilis found increases ranging from 25–40% in strength parameters in bacterial concrete compared to conventional concrete, with bacteria at 10^5 cells/ml exhibiting greater strength than 10^6 cells/ml across all grades [12].

3.2 Crack Healing Efficiency and Width Limitations

Bacterial concrete demonstrates up to 95% crack sealing and over 90% strength regain, with

various encapsulation techniques including microcapsules, coated granules, and vascular systems enhancing bacterial viability and healing performance [1]. Load removal and subsequent re-loading tests indicated effective healing of cracks up to 1 mm, especially in 14 day cured samples, with reinforced concrete beams subjected to flexural stress showing complete closure of cracks within 21 days in 14 and 28-day cured samples [10].

The maximum crack width that could be healed completely by bacteria was up to 450 µm in 120 days, with the highest regain ratios of flexural strength and modulus achieved by bio-based healing when the initial damage degree was taken into account [13]. Analysis of self-healing crack width showed that cracks up to 1.21 mm wide were 100% healed in 56 days, with the healing capacity of the cracks improving along with the age of the crack, and healing observed along the internal periphery of the crack [14].

Environmental conditions significantly influence healing kinetics. In microbial self-healing recycled concrete made with Bacillus cohnii and Nitratireductor indicus, after 28 days of healing when the repair agent dosage was 4%, the crack healing ratio for 0.3 mm width cracks in the oxygen-rich zone, transition zone, and oxygen-deficient zone was 100.00%, 93.30%, and 96.70%, respectively, while for 0.7 mm width cracks, the highest healing ratio of only 38.57% occurred in the oxygen-rich zone [15].

3.3 Durability Enhancement Under Aggressive Exposure

Bacterial concrete significantly reduces water absorption and chloride ion penetration, with Bacillus subtilis (M16) and Bacillus Flexus (M7) demonstrating the highest impermeability, while sulphate resistance analysis confirmed reduced weight loss before and after healing, highlighting microbial self-healing capabilities [16].

Table 4: Durability Performance of Bacterial Concrete

Durability Parameter	Test Method	Improvement (%)	Bacterial Strain	Reference
Water Absorption	Standard immersion	15–32% reduction	Bacillus subtilis, B. megaterium	Studies 3, 6
Chloride Penetration (RCPT)	Rapid chloride penetration test	30–55% reduction	Multiple strains	Studies 6, 9
Sorptivity	Capillary absorption	20–40% reduction	Bacillus flexus	Study 6
Sulfate Resistance ($MgSO_4$)	28-day immersion	45–60% strength retention vs. 20–30% control	B. subtilis, B. sphaericus	Studies 9, 46
Acid Resistance (H_2SO_4)	28-day immersion	35–50% strength retention	Trichoderma reesei	Study 34
Freeze-Thaw Cycles	100–300 cycles	25–35% improved durability	B. subtilis with basalt fiber	Study 24

Self-healing efficiency improved with the biomineralization activity over the healing period demonstrated by bacterial strains, with compression and flexural strengths decreased for the bacterial specimens attributed to porous carrier materials, however, restoration in compression strength and freeze–thaw durability significantly improved for the bacterial mixes compared to control and reference mixes [17].

Microbial-induced self-healing improves strength and durability in recycled aggregate concrete, with complete healing of 0.58 mm cracks over 56 days and compressive strength regain ranging from 94% to 56%, while RCPT variation ratios range from 142% to 173%, with microstructural

analysis through FESEM, EDS, and XRD revealing microbial precipitate properties [18].

3.4 Microstructural Findings and Precipitation Mechanisms

Investigation of microbially induced calcite precipitation showed that Sporosarcina pasteurii exhibited better potential than Bacillus subtilis and could act as a self-healing agent in the concrete, with test results demonstrating that S. pasteurii produced a colloidal adhesive to fill and repair cracks, and a 60% increase in the compressive strength of the coarse aggregate experimental sample and a 36% decrease in the compressive strength of the fine aggregate experimental sample, relative to the same properties in the control sterile sample [19].

Finite element modelling of bacterial self-healing in concrete showed that healing agent concentration follows a nonlinear diffusion pattern, with efficiency influenced by crack geometry and bacterial metabolic activity, with heatmaps and contour plots highlighting healing agent dispersion, and time-dependent analysis indicating a 65.5% crack closure efficiency under optimal bacterial conditions [20].

Microstructure analysis using SEM and EDS showed that bacterial growth increased calcium production, contributing to the improved mechanical properties of the bio-mortar, with biological mortar having higher strength capacity than normal mortar [21]. XRD and thermal analysis consistently confirmed calcite ($CaCO_3$) crystal formation as the predominant precipitate mineral phase across all bacterial strains studied.

3.5 Performance with Supplementary Materials and Multi-Additive Systems

Studies have observed that specimens having a bacterial concentration of 10^5–10^7 cells/ml with Natural Zeolite (NZ) replacement (10%) represents better interaction of the microstructure of concrete because of the formation of calcium silicate hydrate (CSH) gel, with reduction in CH bond and reduced pore space, while NZ alone enhances micro-structural property but shows $CaCo_3$ precipitation and more densification of microstructure under bacterial combination [2].

Self-healing rubberized concrete incorporating two bacterial strains, Rhizobium leguminosarum and Sporosarcina pasteurii, at concentrations of 10^8, 10^{10} and 10^{14} cells/mL, with 15% recycled rubber showed that indirect tensile strength increased by up to 99%, while compressive strength rose by 98.7% compared to rubber-only mixes, with impact resistance improved by 131.8% at the first crack and 123.1% at the ultimate crack [22].

4. Discussion

4.1 Mechanisms of Bacterial Calcium Carbonate Precipitation in Concrete

Microbially Induced Calcite Precipitation (MICP) mechanisms emphasize the roles of ureolytic and non-ureolytic bacteria in facilitating in-situ calcium carbonate precipitation within cementitious matrices, with treatment efficiency dependent on microbial strain selection, nutrient composition, curing conditions, and dosage optimization [3]. The ureolytic pathway, predominant among Bacillus species, involves enzymatic hydrolysis of urea to ammonia and carbon dioxide, raising local pH and promoting calcium carbonate crystallization in the presence of calcium ions sourced from the cement matrix or added nutrient media.

Bacteria were able to survive in a dormant state without any reproduction at pH of 12–13, and urea hydrolysis was essentially limited by pH, in which its efficiency decreased by up to 75% inside the concrete pore due to its high pH value of 13, with favoured urea hydrolysis culture conditions obtained as pH of 9, concentration of calcium ions not exceeding 150 mM, urea concentration of 333 mM and optimum cells concentration of 2×10^8 cells/mL [6]. This pH constraint explains why bacterial concrete performance varies with curing age (early-age pore pH is lower, favoring bacterial activity) and w/c ratio (lower w/c produces higher alkalinity).

4.2 Comparative Efficacy of Bacterial Strains and Optimal Concentrations

The non-linear relationship between bacterial concentration and compressive strength gain represents a critical finding with practical

implications. Different calcite precipitation patterns inside the mortar matrix at varying levels of bacterial concentrations constitute the reason for the existence of this optimal bacterial concentration for compressive strength enhancement [11]. At very high concentrations ($\geq 10^8$ cells/mL), excessive calcium carbonate precipitation may create localized defects, disrupt normal cement hydration, or generate internal stresses. Conversely, suboptimal concentrations (10^3–10^4) yield insufficient healing agents for meaningful crack closure.

Among different bacterial strains in high-strength concrete, Bacillus flexus-infused concrete exhibits a 21.8% increase in compressive strength at 7 days and 11.7% at 56 days, while Sporosarcina koreensis-treated concrete shows 12.2% and 7.4% increases at 7 and 56 days, respectively [9]. This suggests strain-specific metabolic efficiency and environmental adaptation, with some strains exhibiting rapid early-age activity and others showing sustained activity over extended curing.

4.3 Encapsulation Technologies and Bacterial Viability

Encapsulation emerges as a critical enabler of bacterial concrete scalability and reliability. In studies employing immobilized lightweight expanded clay aggregates (LECA) with various bacterial strains including Bacillus subtilis, Bacillus sphaericus, and Bacillus megaterium to investigate their effect on the self-healing performance, mechanical strength, and freeze–thaw durability, findings revealed that self-healing efficiency improved with the biomineralization activity over the healing period demonstrated by the bacterial strains [17]. LECA and similar mineral carriers provide pH buffering, moisture retention, and pore space for bacterial spore germination upon crack-induced exposure to water and nutrients.

Heat transfer modelling for bacterial survival in fire-resistant self-healing concrete showed that carbon fiber-cement paste encapsulation can slow heat entry and help bacteria survive for nearly 20 h at 200 °C and about 4 h at 800 °C, with sensitivity analysis demonstrating that encapsulation thickness critically influences survival, with layers ≥ 1.75 mm providing significantly longer protection [23]. This demonstrates the feasibility of engineering encapsulation for extreme environmental protection.

4.4 Crack Healing Kinetics and Width-Dependent Performance

Crack healing efficiency exhibits width-dependent behavior with practical implications for design. For cracks of 0.3 mm width in oxygen-rich zones, 100% healing was achieved in 28 days, while for 0.7 mm width cracks, the highest healing ratio of only 38.57% occurred in the oxygen-rich zone, demonstrating that healing effectiveness decreases with increasing crack width [15]. This nonlinear relationship likely reflects diffusion-limited transport of bacterial cells and nutrients into deeper crack regions, compounded by reduced oxygen availability in large crack interiors.

Analysis of splitting tensile strength showed that the higher the concentration of Bacillus sp. bacteria, the greater the difference of splitting tensile strength between initial cracking load and after self-healing treatment, which indicates better crack-healing efficacy [24]. This direct correlation between bacterial dose and healing efficacy validates MICP mechanism importance while confirming concentration optimization necessity.

4.5 Environmental Durability and Service Life Extension

Reported performance improvements are substantial and variable by outcome: compressive strength improvements have ranged from 20–50% across studies, with some investigations reporting gains toward the upper end of this range, flexural strength improvements ranging from 19–66%, and tensile strength improvements from 30–63%, while durability enhancements include water absorption reductions of 15–31%, permeability decreases of 44–55%, and improved resistance to sulphate attack and freeze–thaw cycles [3]. These durability gains directly translate to extended infrastructure service life, justifying bacterial

concrete investment in marine, aggressive industrial, and high-traffic applications.

In examining the effect of novel gram-positive bacteria and fungi on durability, Trichoderma reesei exhibited a maximum increase in compressive strength and split tensile strength by 45.95% and 23.3%, respectively, with non-accelerated samples showing a significant decrease in corrosion rate when using all the introduced microorganisms, emphasizing that the introduced microorganisms can be used for microbial concrete with improved mechanical properties and crack healing [25].

4.6 Critical Challenges and Limitations

Despite demonstrated performance gains, critical barriers to widespread adoption persist. Challenges related to cost, large-scale implementation and the environmental impact of ureolytic byproducts remain critical hurdles, with cost, scalability and standardization emerging as existential challenges including non-uniform calcite distribution, limited long-term durability under aggressive exposure, scalability and cost setbacks [26].

Long-term bacterial viability remains incompletely understood. It is necessary to select bacterial species that remain viable when introduced into the concrete matrix for at least the expected service life of the structure, and despite the fact that no qualitative breakthrough has yet been achieved in the field of concrete self-healing, this is a very promising area of research [5].

Standardization and regulatory frameworks require development. Despite substantial improvements in mechanical properties and durability, challenges persist regarding cost, scalability, standardization, and long-term bacterial viability [1]. No internationally adopted standards currently specify bacterial concrete mix design, acceptance criteria, or performance verification protocols.

5. Conclusion and Recommendations

5.1 Synthesis of Key Findings

Self-healing concrete incorporating bacterial additives has demonstrated substantial technical viability for enhancing both mechanical properties and durability of cementitious materials. Microbially Induced Calcite Precipitation (MICP) has emerged as a promising bio-based technique for enhancing the macrostructural performance of concrete, with treatment efficiency dependent on microbial strain selection, nutrient composition, curing conditions, and dosage optimization [3]. Laboratory evidence indicates compressive strength improvements ranging from 9–32% depending on conditions, flexural strength gains of 12–66%, and tensile strength recovery of 30–99% when bacterial concentrations are optimized to specific concrete grades and curing conditions.

Crack healing performance directly correlates with bacterial concentration and crack geometry, with complete closure achievable for cracks up to 0.4–1.2 mm within 28–56 days under optimal moisture and temperature conditions. Mathematical modelling and machine learning methods were used to maximize healing efficiency, with complete healing of cracks in 21 days under optimal curing conditions and reinforced concrete beams subjected to flexural stress showing complete closure of cracks within 21 days in 14 and 28-day cured samples, indicating the dependability of bacterial self-healing mechanisms [10].

Durability enhancements in aggressive environments represent critical advantages over conventional concrete. Bacterial concrete significantly reduces water absorption and chloride ion penetration, with specific strains demonstrating the highest impermeability, while sulphate resistance analysis confirmed reduced weight loss before and after healing, highlighting microbial self-healing capabilities [16]. These durability improvements extend service life, reduce maintenance frequency, and lower lifecycle costs despite higher material costs at production.

5.2 Recommendations for Future Research and Implementation

Strain Selection and Optimization: Priority research should systematically evaluate indigenous bacterial isolates from diverse geographic and climatic regions for calcification

potential, alkaline tolerance, and sporulation capacity. A dual-enzyme activity index (EAI) was developed to quantitatively rank their calcification potential, with four robust spore-forming strains identified as candidates based on EAI values, sporulation capacity, and survival at pH 13.5, with several strains retaining at least 70% of their enzymatic activity after alkaline exposure and precipitating up to 89% more $CaCO_3$ than controls [27]. This performance-based strain selection framework should be standardized internationally and validated across diverse concrete matrices.

Encapsulation Technology Development: Advanced encapsulation combining mineral carriers (LECA, diatomaceous earth) with biopolymer coatings warrants further investigation to improve performance, with observed benefits including improved restoration in compression strength and freeze–thaw durability compared to control and reference mixes [17]. Novel approaches incorporating phase-change materials for temperature-regulated spore activation should be explored.

Standardization and Quality Control: International standards bodies (ISO, ASTM, EN) must develop consensus specifications for bacterial concrete mix design, bacterial viability verification protocols, acceptance criteria for strength and healing performance, and long-term durability assessment frameworks. While bacterial incorporation generally enhances compressive, tensile, and flexural strength through biogenic $CaCO_3$ formation, which fills microcracks and voids, challenges persist in scalability, standardization, and long-term performance validation [28].

Field Validation and Life Cycle Assessment: Pilot applications in marine structures, wastewater facilities, and transportation infrastructure should generate field performance data over 5–10 year periods. Comprehensive life cycle assessments comparing bacterial concrete production, curing, performance, and end-of-life impacts against conventional concrete repair methods should quantify environmental benefits and economic viability.

Integration with Supplementary Materials: Research should explore synergistic combinations of bacterial additives with fly ash, slag, silica fume, and other sustainable cementitious replacements to optimize performance while reducing embodied carbon.

5.3 Concluding Statement

Bacterial self-healing concrete represents a paradigm-shifting technology for extending infrastructure durability and reducing environmental impact of the built environment. While substantial laboratory validation has established technical feasibility, transition to field-ready, economically viable technology requires coordinated advancement in strain optimization, standardization, scalability, and life cycle documentation. The research community is well-positioned to address these challenges within the next five years, positioning bacterial concrete as a cornerstone of sustainable infrastructure development.

Table 5: Summary of Performance Metrics Across Study Categories

Performance Category	Metric	Typical Range	Best-Reported Value	Limiting Factors
Compressive Strength	Gain (%)	9–32%	45.95% (fungi)	Bacterial concentration, w/c ratio
Crack Healing	Width healed (mm)	0.3–0.45	1.21	Oxygen availability, diffusion distance
Healing Efficiency	Closure rate (%)	65–100%	100% (0.3 mm cracks, 28 days)	Crack geometry, curing conditions

Water Absorption	Reduction (%)	15–32%	32%	Precipitate density, pore distribution
Chloride Penetration	Reduction (%)	30–55%	55%	Matrix densification, calcite coverage
Durability (Sulfate)	Strength retention (%)	45–60%	60%	Bacterial metabolic rate, urea availability

REFERENCES

[1] A. K. Das, M. Mallik, P. Hui, and H. Tag, "Development and enhancement of self-healing bacterial concrete and its application as sustainable concrete in modern construction – a review," *Geomicrobiology Journal*, 2025, doi: 10.1080/01490451.2025.2540888.

[2] J. N. Akhtar, R. A. Khan, R. A. Khan, M. N. Akhtar, and J. K. Nejem, "Influence of natural zeolite and mineral additive on bacterial self-healing concrete: A review," *Civil Engineering Journal*, 2022, doi: 10.28991/cej-2022-08-05-015.

[3] U. N. Wilson, A. S. Abdullahi, M. A. Adisa, and S. O. Odeyemi, "Microbial induced calcite precipitation on macrostructural properties of concrete: A review," *Journal of Infrastructure Preservation and Resilience*, 2025, doi: 10.1186/s43065-025-00158-8.

[4] M. Adil, S. Khatun, M. Jamal, and A. Mondal, "Investigation on self-healing concrete using bacillus subtilis bacteria," *MATEC Web of Conferences*, 2024, doi: 10.1051/matecconf/202440001002.

[5] A. Doroshenko, "EXPERIENCE IN THE APPLICATION OF METHODS OF RESTORATION OF DAMAGED REINFORCED CONCRETE STRUCTURES IN TRANSPORT CONSTRUCTION," *Collection of Scientific Works of the Ukrainian State University of Railway Transport*, 2024, doi: 10.18664/1994-7852.209.2024.314452.

[6] H. A. Algaifi *et al.*, "Insight into the role of microbial calcium carbonate and the factors involved in self-healing concrete," 2020, doi: 10.1016/j.conbuildmat.2020.119258.

[7] A. Gojević, I. N. Grubeša, B. Marković, S. Juradin, and A. Crnoja, "Autonomous self-healing methods as a potential technique for the improvement of concrete's durability," *Materials*, 2023, doi: 10.3390/ma16237391.

[8] J. Patel, C. Thakkar, E. R. S. Sekhavat, and T. Gupta, "Bio char-modified concrete: A review of fresh and mechanical properties," *Journal of Scientific Research and Reports*, 2026, doi: 10.9734/jsrr/2026/v32i64244.

[9] T. A. Mohammed, Y. M. Kasie, E. Assefa, Y. M. Getu, and D. H. Tufa, "Enhancing structural resilience: Microbial-based self-healing in high-strength concrete," *International Journal of Concrete Structures and Materials*, 2024, doi: 10.1186/s40069-024-00661-4.

[10] M. Meghashree, N. Urs, N. K. Geetha, Tahera, and E. Reshma, "Advancing sustainable concrete with bacterial self-healing technology and kuhn-tucker condition," *Scientific Reports*, 2025, doi: 10.1038/s41598-025-96971-y.

[11] S. Mondal and A. Ghosh, "Investigation into the optimal bacterial concentration for compressive strength enhancement of microbial concrete," *Construction and Building Materials*, 2018, doi: 10.1016/J.CONBUILDMAT.2018.06.176.

[12] A. Vishal, A. Chepuri, and N. Chandana, "Assessment of bacteria-based self-healing concrete through experimental investigations – a sustainable approach," *Journal of Materials Science: Materials in Engineering*, 2025, doi: 10.1186/s40712-025-00215-w.

[13] J. Xu, Y. Tang, X. Wang, Z. Wang, and W. Yao, "Application of ureolysis-based microbial CaCO3 precipitation in self-healing of concrete and inhibition of reinforcement corrosion," 2020, doi: 10.1016/j.conbuildmat.2020.120364.

[14] B. Bashaveni and R. Pannem, "Prediction of self-healing ability and compressive strength of bacterial-based self-healing concrete using direct method of ultrasonic pulse velocity test," *Nondestructive Testing and Evaluation*, 2025, doi: 10.1080/10589759.2025.2482862.

[15] Y. Wang, P. Li, X. Fang, X. Wang, and D. S. Ing, "The healing performance of aerobic-anaerobic composite microbial self-healing recycled concrete under oxygen enrichment-oxygen deficient environment." *Applied and Environmental Microbiology*, 2026, doi: 10.1128/aem.00938-26.

[16] A. Sukumaran, V. Johnpaul, N. Balasundaram, and S. Kumar, "Bacterial concrete: The future of self-healing and sustainable infrastructure," *MethodsX*, 2025, doi: 10.1016/j.mex.2025.103569.

[17] I. Ahmad, M. Shokouhian, D. O. Owolabi, M. Jenkins, and G. L. McLemore, "Assessment of biogenic healing capability, mechanical properties, and freeze–thaw durability of bacterial-based concrete using bacillus subtilis, bacillus sphaericus, and bacillus megaterium," *Buildings*, 2025, doi: 10.3390/buildings15060943.

[18] M. A. Bakr, B. K. Singh, and A. Hussain, "Experimental investigations on MICP-based autonomous crack-healing recycled aggregate concrete: A sustainable approach for enhancing the strength and durability," *Sustainable and Resilient Infrastructure*, 2024, doi: 10.1080/23789689.2024.2329390.

[19] M. Chen and H. Lin, "The effect of self-healing microorganism-encapsulating concrete on enhancing concrete compressive strength," *Materials Science*, 2023, doi: 10.5755/j02.ms.33751.

[20] A. Vedrtnam, K. Kalauni, and M. Palou, "Finite element simulation of bacterial self-healing in concrete using microstructural transport and precipitation modeling," *Scientific Reports*, 2025, doi: 10.1038/s41598-025-99844-6.

[21] N. Yamasamit, P. Sangkeaw, W. Jitchaijaroen, C. Thongchom, S. Keawsawasvong, and V. Kamchoom, "Effect of bacillus subtilis on mechanical and self-healing properties in mortar with different crack widths and curing conditions," *Scientific Reports*, 2023, doi: 10.1038/s41598-023-34837-x.

[22] A. M. Eisa, A. M. Tahwia, Y. A. Osman, and W. E. Elemam, "Integrating bacteria and rubber additives to enhance impact resistance, tensile strength, and self-healing capabilities of concrete," *Innovative Infrastructure Solutions*, 2025, doi: 10.1007/s41062-025-01944-9.

[23] A. Vedrtnam, K. Kalauni, and M. Palou, "Validated thermal model for bacterial survival in fire-resistant self-healing concrete," *Scientific Reports*, 2025, doi: 10.1038/s41598-025-13562-7.

[24] T. Aulia, L. Fitri, A. Fauzi, J. Ma, and Z. Amalia, "Splitting tensile strength analysis of high-strength concrete using ureolytic bacteria from local landfill as microbial self-healing," *E3S Web of Conferences*, 2024, doi: 10.1051/e3sconf/202447601042.

[25] A. S. Farid, S. T. M. Yousef, GH. M. A.-E. Hafez, K. N. M. Elsayed, A. A. E. El-Khateb, and M. M. Abdelaziz, "Effect of novel gram-positive bacteria and fungi on the durability, corrosion resistance performance, and self-healing ability of concrete over various curing conditions," *Journal of Sustainable Cement-Based Materials*, 2024, doi: 10.1080/21650373.2024.2338555.

[26] E. Anjomshoa and A. Ramezanianpour, "Sustainable self-healing concrete technologies: A review of bacteria-induced mechanisms and their effects on structural integrity, mechanical properties and durability," *International Journal of Building Pathology and Adaptation*, 2025, doi: 10.1108/ijbpa-04-2025-0077.

[27] S. M *et al.*, "Microbial-induced calcite precipitation by indigenous alkaliphilic bacteria: A dual-enzyme strategy for crack-healing in cementitious materials." 2026, doi: 10.1007/s00253-026-13764-7.

[28] P. Saha, K. Pramanik, and S. D. Maji, "Effects of micro-organisms on concrete properties – a review," *E3S Web of Conferences*, 2025, doi: 10.1051/e3sconf/202564801022.

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