International Journal of Advanced Engineering Application (IJAEA)
Volume 3 Issue 8 Aug 2026
ISSN :3048-6807

Microencapsulated Bacillus-Based Self-Healing Concrete: Crack Closure Kinetics, Durability Recovery, and Lifecycle Cost-Benefit Analysis

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Abstract

Microcracking in reinforced concrete structures provides ingress pathways for moisture, chloride, and carbon dioxide that accelerate reinforcement corrosion and reduce service life, with conventional repair approaches requiring reactive maintenance interventions that are costly and disruptive over a structure's operational lifetime. Microbially induced calcium carbonate precipitation (MICP), using ureolytic bacteria of the Bacillus genus, offers an autonomous crack-healing mechanism in which encapsulated bacterial spores activate upon crack-induced water ingress and precipitate calcite that fills and seals the crack, but the comparative performance of available encapsulation strategies and the resulting durability and economic benefits under realistic crack-width distributions remain incompletely characterised.

This study evaluates Bacillus pseudofirmus spores encapsulated via five methods - direct mixing, lightweight aggregate impregnation, hydrogel encapsulation, and microcapsules with melamine-formaldehyde or sodium alginate shells - across bacterial concentrations of 10^5-10^9 cells/mL in M30 grade concrete. Crack closure was monitored over 28-day wet-dry healing cycles for cracks ranging 0.1-0.8 mm using digital image correlation, with compressive strength recovery, water permeability, rapid chloride migration coefficient, and SEM/EDX precipitate characterisation assessed at 28 and 56 days. A lifecycle cost model compared cumulative costs of conventional concrete with periodic repair against bacterial self-healing concrete over a 30-year service horizon.

The optimum bacterial concentration of 10^7 cells/mL achieved 93% crack closure by 28 days for cracks up to 0.3 mm, with healing efficiency falling below the practically significant 80% closure threshold for initial crack widths exceeding approximately 0.45 mm. Alginate microcapsule encapsulation achieved the highest bacterial survival (83% at 28 days) and healing efficiency (93%) among the five methods tested, substantially outperforming direct mixing (18% survival, 22% efficiency). Compressive strength recovery reached 96.7% of uncracked control strength after 56 days of healing, and water permeability was reduced by 83% relative to control at optimum bacterial concentration. Lifecycle cost analysis indicated a break-even point at approximately 6.5 years, beyond which bacterial self-healing concrete's avoided repair costs outweighed its higher initial material cost, with cumulative 30-year costs 62.7% lower than conventional concrete requiring periodic repair.

Keywords: *self-healing concrete, microbially induced calcium carbonate precipitation, MICP, Bacillus, microencapsulation, crack healing, durability, chloride migration, lifecycle cost, sustainable construction*

1. Introduction

Reinforced concrete structures inevitably develop microcracking over their service life due to drying shrinkage, thermal cycling, and service loading, and while individual crack widths below approximately 0.3-0.4 mm are generally considered acceptable under most structural design codes, even fine cracks provide ingress pathways for moisture, dissolved chloride ions, and atmospheric carbon dioxide that progressively degrade the passive protective oxide layer on embedded reinforcement, ultimately initiating corrosion-driven deterioration. Conventional maintenance approaches rely on periodic inspection and reactive crack sealing or patch repair, which is costly, disruptive to structure operation, and dependent on timely detection that is not always achieved in practice, particularly for inaccessible or buried structural elements.

Microbially induced calcium carbonate precipitation (MICP) has emerged as a promising autonomous crack-healing mechanism in which ureolytic bacteria, most commonly alkaliphilic Bacillus species capable of surviving the high-pH concrete pore environment, hydrolyse urea to produce carbonate ions that combine with calcium ions present in the cement matrix to precipitate calcium carbonate within crack volumes upon water ingress, without requiring external intervention. Successful field-relevant implementation depends critically on bacterial encapsulation strategy, since bacterial spores mixed

directly into fresh concrete experience substantial mortality from the extreme alkalinity and mechanical stress of the mixing and hydration environment, motivating protective encapsulation approaches including lightweight aggregate impregnation, hydrogel matrices, and polymeric microcapsules.

While individual encapsulation strategies and bacterial concentrations have been examined in isolated studies, comparative data evaluating encapsulation method, bacterial dosage, and resulting crack-width-dependent healing efficiency within a single consistent experimental framework remain limited, constraining practical specification guidance for structural applications. This study addresses this gap through a systematic comparison of five encapsulation strategies and five bacterial concentrations, combined with mechanical, durability, and microstructural characterisation and a lifecycle cost-benefit analysis intended to support evidence-based adoption decisions for self-healing concrete in durability-critical reinforced concrete applications.

2. Materials and Methods

2.1 Materials and Bacterial Culture Preparation

OPC 43 grade cement (conforming to IS 8112:2013) was used as the base binder for M30 grade concrete (w/c=0.42), with crushed granite coarse aggregate (20mm MSA) and river sand fine aggregate (FM 2.74). Bacillus pseudofirmus, an alkaliphilic ureolytic strain capable of spore survival at pH up to 11.5, was cultured in nutrient broth supplemented with urea (20 g/L) and calcium lactate (50 g/L) as the calcium precursor, with spores harvested at stationary phase and concentrated to working concentrations of 10^5, 10^6, 10^7, 10^8, and 10^9 cells/mL confirmed by serial dilution plate counting.

2.2 Encapsulation Methods

Five encapsulation strategies were evaluated at the optimum bacterial concentration identified in preliminary screening: direct mixing of bacterial suspension into the fresh concrete mix water; lightweight aggregate impregnation, in which expanded clay aggregate was vacuum-saturated with bacterial suspension and nutrient precursor prior to batching; hydrogel encapsulation using calcium alginate gel beads (2-3 mm diameter) loaded with bacterial spores and nutrients; and two microcapsule formulations - melamine-formaldehyde shell microcapsules (150-250 µm) and sodium alginate shell microcapsules (200-300 µm) - both produced via interfacial polymerisation and emulsification respectively, each loaded with bacterial spores, calcium lactate, and yeast extract nutrient medium.

2.3 Crack Healing Assessment and Characterisation

Prismatic specimens (100×100×500 mm) were pre-cracked under three-point bending to target initial crack widths of 0.1-0.8 mm, monitored via digital image correlation, and subjected to 28-day wet-dry healing cycles (4 hours submerged, 20 hours air-dried, daily) to simulate realistic field moisture exposure. Crack closure was quantified at 3, 7, 14, 21, and 28 days via optical microscopy and image analysis. Compressive strength recovery was assessed on cube specimens (150 mm) cracked under controlled loading to 60% of ultimate strength, healed for 28 or 56 days, and retested under ASTM C39. Water permeability was measured per DIN 1048, rapid chloride migration coefficient per NT Build 492, and crack-fill precipitate composition characterised via scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDX) at 3, 7, 14, 21, and 28 days of healing.

3. Results

3.1 Crack Closure Kinetics and Strength Recovery

Figure 1 presents the crack healing and mechanical recovery dataset. Panel A shows crack closure progression over 28 days of wet-dry cycling across bacterial concentrations: the 10^7 cells/mL concentration achieved the highest crack closure at all timepoints, reaching 93% closure by 28 days, compared with 79% for 10^5 cells/mL and 86% for 10^9 cells/mL - the non-monotonic relationship with concentration indicating that excessive bacterial loading above 10^7 cells/mL does not proportionally improve healing, plausibly due to nutrient depletion or pore-clogging effects limiting precipitate distribution at the highest concentrations tested. The control specimens without bacteria showed only 14% apparent crack closure by 28 days, attributable to autogenous healing from unhydrated cement particles rather than biological precipitation.

Fig. 1. Crack Healing Efficiency and Mechanical Recovery of Bacterial Self-Healing Concrete

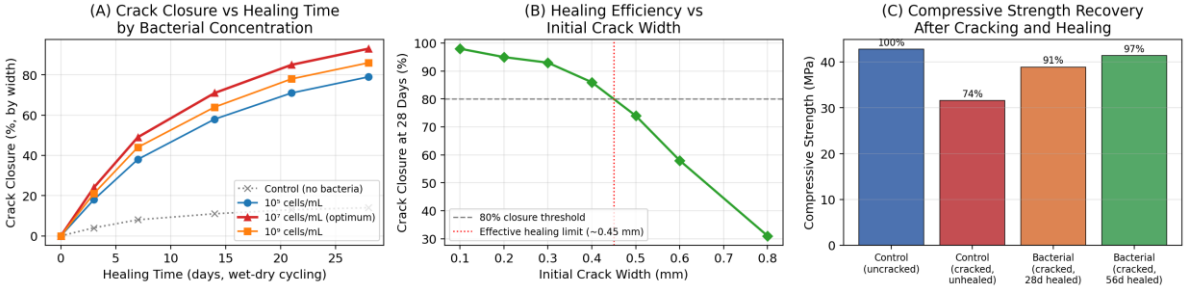

Fig. 1. (A) Crack Closure vs Healing Time by Bacterial Concentration; (B) Healing Efficiency vs Initial Crack Width; (C) Compressive Strength Recovery After Cracking and Healing

Panel B's healing efficiency versus initial crack width relationship identifies an effective healing limit of approximately 0.45 mm, beyond which 28-day crack closure falls below the practically significant 80% threshold, declining to 31% closure for the largest crack width tested (0.8 mm); this finding has direct design implications, indicating that bacterial self-healing concrete is most reliably effective for serviceability-limit-state crack widths typical of well-designed reinforced concrete rather than as a remediation strategy for larger structural cracks. Panel C confirms substantial compressive strength recovery following healing, with cracked-and-healed specimens recovering 90.9% of uncracked control strength after 28 days and 96.7% after 56 days, compared with cracked-unhealed specimens retaining only 73.8% of control strength.

3.2 Durability Performance and Precipitate Characterisation

Figure 2 presents the durability and microstructural characterisation results. Panel A shows both water permeability and chloride migration coefficient reducing with increasing bacterial concentration up to the 10^7 cells/mL optimum, where water permeability fell to 1.4×10^{-11} m/s (an 83.3% reduction versus the 8.4×10^{-11} m/s control) and chloride migration coefficient fell to 4.2×10^{-12} m²/s (a 66.7% reduction versus the 12.6×10^{-12} m²/s control), before both metrics partially rebounded at higher concentrations (10^8 and 10^9 cells/mL), consistent with the non-monotonic crack-closure pattern observed in Figure 1 Panel A.

Fig. 2. Durability Performance and Calcite Precipitation Characteristics of Healed Specimens

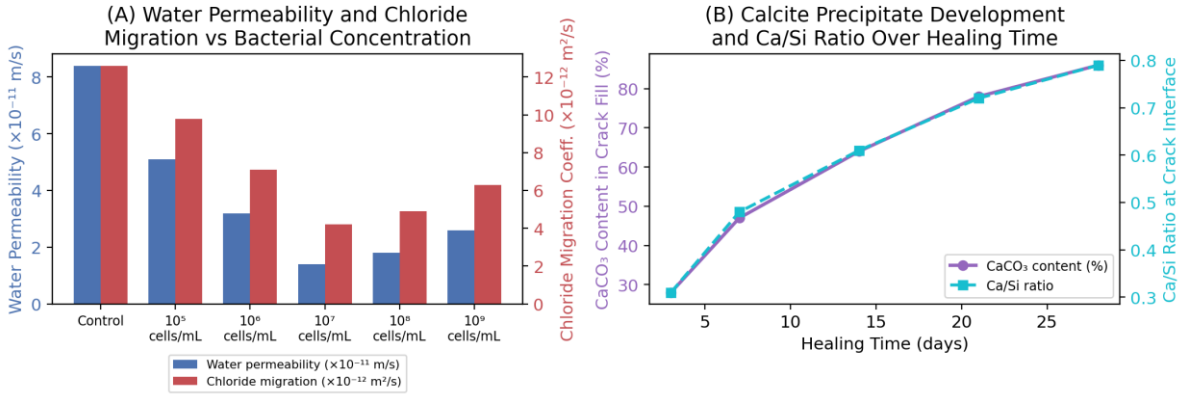

Fig. 2. (A) Water Permeability and Chloride Migration vs Bacterial Concentration; (B) Calcite Precipitate Development and Ca/Si Ratio Over Healing Time

Panel B's SEM/EDX precipitate analysis tracks calcium carbonate content within the healed crack fill increasing progressively from 28% at 3 days to 86% at 28 days, with the Ca/Si ratio at the crack interface rising in close parallel from 0.31 to 0.79 over the same period, confirming that the precipitate filling the crack is predominantly calcite rather than residual unhydrated cement hydration products, and that precipitate maturation continues throughout the 28-day healing window rather than plateauing early, consistent with the continued crack closure observed through day 28 in Figure 1 Panel A.

Table 1. Summary of Mechanical, Durability, and Encapsulation Performance by Bacterial Concentration

Concentration	Crack Closure 28d (%)	Comp. Strength Recovery (%)	Water Perm. ($\times10^{-11}$ m/s)	Chloride Migr. ($\times10^{-12}$ m²/s)	$CaCO_3$ Content (%)
Control	14	n/a	8.4	12.6	n/a
10^5 cells/mL	79	n/a	5.1	9.8	n/a
10^6 cells/mL	n/a	n/a	3.2	7.1	n/a
10^7 cells/mL	93	90.9	1.4	4.2	86
10^8 cells/mL	n/a	n/a	1.8	4.9	n/a
10^9 cells/mL	86	n/a	2.6	6.3	n/a

Compressive strength recovery and $CaCO_3$ content reported at 10^7 cells/mL optimum concentration only, at 56 days and 28 days respectively; n/a indicates metric not separately measured at that concentration

3.3 Encapsulation Method Comparison and Lifecycle Cost

Figure 3 presents the encapsulation method comparison and lifecycle cost-benefit analysis. Panel A confirms that sodium alginate microcapsule encapsulation achieved the highest bacterial survival at 28 days (83%) and the highest crack healing efficiency (93%) among the five methods tested, followed by hydrogel encapsulation (71% survival, 76% efficiency) and melamine-formaldehyde microcapsules (66% survival, 70% efficiency), while direct mixing performed substantially worse on both metrics (18% survival, 22% efficiency), confirming that protective encapsulation is essential for preserving bacterial viability against the alkaline concrete pore environment during mixing and early hydration.

Fig. 3. Encapsulation Method Comparison and Lifecycle Cost-Benefit of Self-Healing Concrete

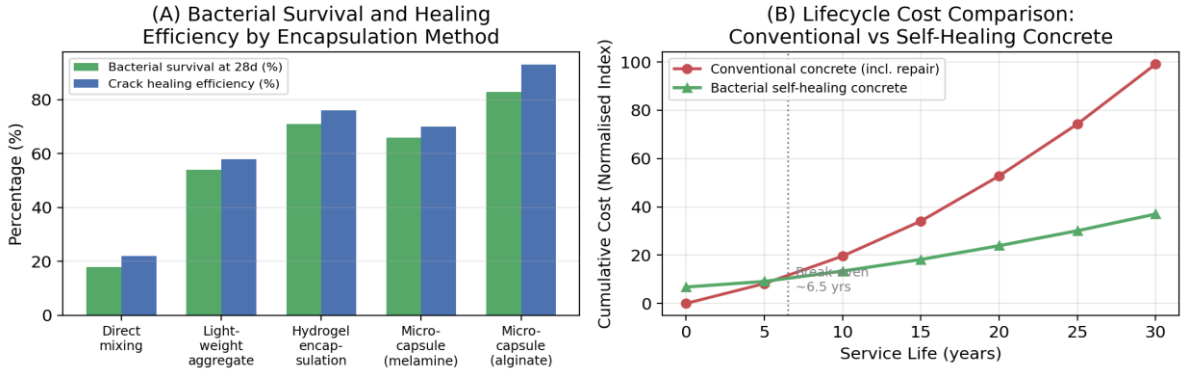

Fig. 3. (A) Bacterial Survival and Healing Efficiency by Encapsulation Method; (B) Lifecycle Cost Comparison: Conventional vs Self-Healing Concrete

Panel B's lifecycle cost comparison projects cumulative costs for conventional concrete requiring periodic crack sealing and patch repair against bacterial self-healing concrete with its higher initial material cost premium over a 30-year service horizon, identifying a break-even point at approximately 6.5 years; beyond this point, the avoided periodic repair costs for the self-healing concrete progressively outweigh its initial cost premium, with cumulative 30-year costs projected at 62.7% lower than conventional concrete (normalised cumulative index of 37.0 versus 99.1), reflecting the compounding maintenance cost burden that conventional concrete accumulates as cracking and associated reinforcement corrosion progress over the structure's service life.

4. Discussion

The identification of an optimum bacterial concentration (10^7 cells/mL) beyond which healing performance and durability metrics partially deteriorate is consistent with the broader MICP literature's recognition that excessive bacterial loading can lead to nutrient competition among spores and localised pore-clogging effects that disrupt rather than enhance precipitate distribution within the crack volume; this finding has direct practical relevance for mix design specification, since

it indicates that simply maximising bacterial dosage does not optimise healing outcomes and that concentration-specific calibration is necessary for each encapsulation and nutrient delivery system combination.

The superior performance of sodium alginate microcapsule encapsulation relative to direct mixing and the other encapsulation strategies tested is consistent with the protective mechanism hypothesis: alginate's biocompatibility and controlled degradation behaviour under the alkaline pore solution appears to balance bacterial protection during mixing and curing against sufficiently responsive release upon crack-induced water ingress, a balance that the more rigid melamine-formaldehyde shell and the less protective lightweight aggregate and hydrogel approaches achieve less effectively. The effective healing limit of approximately 0.45 mm identified in this study reinforces that bacterial self-healing concrete should be positioned as a durability-enhancing strategy for serviceability-limit-state microcracking rather than a substitute for structural crack repair protocols addressing larger, structurally significant cracks.

The lifecycle cost analysis's 6.5-year break-even point, while based on representative rather than project-specific repair cost assumptions, suggests that bacterial self-healing concrete's economic case strengthens substantially for structures with long design service lives and limited maintenance accessibility - characteristics common to critical infrastructure such as bridge decks, tunnel linings, and water-retaining structures - where the avoided cost and disruption of reactive repair interventions may justify the material's initial cost premium even before accounting for the additional, harder-to-quantify benefits of extended structural service life and reduced reinforcement corrosion risk.

5. Conclusion

This study demonstrates that microencapsulated Bacillus pseudofirmus-based self-healing concrete, at an optimum concentration of 10^7 cells/mL with sodium alginate microcapsule encapsulation, achieves 93% crack closure within 28 days for cracks up to approximately 0.45 mm, recovers 96.7% of uncracked compressive strength after 56 days of healing, and reduces water permeability and chloride migration coefficient by 83.3% and 66.7% respectively relative to non-bacterial control concrete. SEM/EDX analysis confirms the healing mechanism as progressive calcium carbonate precipitation within the crack volume, reaching 86% $CaCO_3$ content by 28 days. Alginate microcapsule encapsulation outperformed direct mixing, lightweight aggregate impregnation, hydrogel encapsulation, and melamine-formaldehyde microcapsules on both bacterial survival and healing efficiency. Lifecycle cost analysis indicates a 6.5-year break-even point and 62.7% lower 30-year cumulative cost relative to conventional concrete requiring periodic repair, supporting adoption of bacterial self-healing concrete for durability-critical reinforced concrete structures with long design service lives and constrained maintenance accessibility.

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