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Self-Healing Concrete: A Sustainable Approach

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Abstract—**The development of sustainable infrastructure requires construction materials that offer both enhanced service life and minimized maintenance requirements. Conventional concrete is prone to micro-crack formation due to structural loading and environmental weathering, which facilitates the ingress of moisture and aggressive chemicals, leading to durability failure. This paper investigates the performance and mechanism of self-healing concrete as a sustainable approach to mitigate crack propagation. The experimental program evaluates autonomous healing techniques, focusing on bacterial concrete using Bacillus sphaericus incorporated via calcium alginate beads, and chemical healing mechanisms involving sodium silicate microcapsules. Mechanical properties, including compressive strength recovery, split tensile strength, and flexural healing indices, were analyzed at 7, 14, and 28 days of curing. Long-term durability and sealing efficacy were verified through water absorption, chloride penetration resistance, and permeability tests on pre-cracked and healed specimens. The results demonstrate that bacterial self-healing concrete achieves up to 85% crack healing efficiency for crack widths up to 0.35 mm, while simultaneously providing significant strength restoration. Furthermore, the integration of autonomous self-healing technologies contributes to environmental sustainability by reducing the carbon footprint associated with frequent structural repairs, minimizing cement utilization, and enhancing structural longevity.**

***Index Terms*—Self-Healing Concrete, Bacterial Concrete, Bacillus sphaericus, Sodium Silicate Microcapsules, Healing Index, Concrete Durability, Strength Recovery, Sustainable Infrastructure.**

I. INTRODUCTION

Concrete is the most widely consumed construction material in modern infrastructure development due to its excellent compressive strength, durability, and versatility. However, despite its structural advantages, concrete possesses an inherent vulnerability to tensile stresses, which regularly results in micro-crack formation. These cracks emerge from various phenomena including plastic shrinkage, thermal gradients, structural overloading, and dry weathering. While micro-cracks may not immediately compromise structural integrity, they establish preferential pathways for water, chloride ions, sulfates, and other aggressive agents. This ingress accelerates steel reinforcement corrosion and concrete degradation, drastically lowering the service life of infrastructure.

Traditional repair methods involve regular structural monitoring followed by manual concrete patching, epoxy injections, or surface coatings. However, manual maintenance exhibits serious drawbacks: it is highly labor-intensive, economically burdensome, difficult to execute in inaccessible structural regions, and contributes to further carbon dioxide emissions. Given that global cement manufacturing accounts for roughly 7-8% of anthropogenic $CO2$ emissions, expanding the service life of existing structures via autonomous self-healing mechanisms has emerged as a major strategy for environmentally responsible construction.

Self-healing concrete represents an innovative paradigm shifting modern engineering from passive prevention to active autonomous restoration. This advanced concrete mimics biological healing by automatically repairing cracks without human intervention. Self-healing mechanisms are broadly classified into autogenous healing (inherent chemical reactions of unhydrated cement) and autonomous healing (engineered interventions using bacteria or chemical capsules). In bacterial concrete (bio-concrete), specific spore-forming bacteria from the genus Bacillus are embedded alongside organic nutrients. When cracks occur and water penetrates the matrix, the dormant spores activate, metabolizing nutrients to precipitate calcium carbonate (calcite), which physically seals the fissure.

Chemical autonomous healing utilizes microcapsules containing healing agents like sodium silicate or polyurethane. Structural cracking ruptures these microcapsules, releasing the fluid into the crack plane where it reacts with the surrounding matrix to produce hardening gels. While independent studies have evaluated individual bacteria or microcapsule systems, comparative and integrated performance tracking concerning both mechanical recovery and durability preservation remains limited. This experimental study provides a comprehensive investigation into the strength recovery and sealing efficiency of bacterial and chemical self-healing concrete. By optimizing encapsulation parameters and mix proportioning, this research aims to validate self-healing concrete as a robust, long-term approach for sustainable global infrastructure.

II. LITERATURE REVIEW

The development of autonomous self-healing technologies in cementitious systems has experienced substantial growth over the past decade, driven by the structural requirement for resilient materials and low-maintenance designs.

2.1 Microbial Self-Healing (Bacterial Concrete)

Microbiological calcite precipitation, or Microbiologically Induced Calcite Precipitation (MICP), represents a prominent autonomous healing approach. Researchers have focused heavily on alkaliphilic, spore-forming bacteria such as Bacillus sphaericus and Bacillus pasteurii. These strains can survive within the highly alkaline environment of concrete (pH 12–13) for decades in a dormant state. Previous investigations demonstrate that when cracks open up to 0.4 mm, the ingress of oxygen and moisture triggers spore germination. The bacteria hydrolyze urea or lactate, reacting with dissolved calcium to produce calcium carbonate crystals. Studies confirm that bacterial direct-incorporation can lead to a slight initial reduction in strength due to biomass volume, but using lightweight aggregates or calcium alginate hydrogel beads for encapsulation completely neutralizes this effect while enhancing crack sealing efficiency.

2.2 Chemical Self-Healing via Microcapsules

Autonomous chemical healing relies on core-shell microcapsules distributed uniformly within the fresh concrete matrix. The shells, frequently synthesized using urea-formaldehyde or glass polymers, protect liquid cores containing chemical agents like sodium silicate, epoxy resins, or cyanoacrylates. When a propagating crack encounters a microcapsule, the localized stress concentration fractures the shell. The released sodium silicate reacts immediately with free calcium hydroxide present in the concrete matrix, producing additional Calcium Silicate Hydrate (C-S-H) gel. Experimental reviews show that chemical encapsulation ensures rapid seal times and high initial strength recovery, though the maximum sealable crack width is typically smaller than that achieved through biological approaches.

2.3 Combined and Comparative Analyses

Recent literature has increasingly shifted toward comparing the durability gains of autonomous systems against standard control mixes. While autogenous healing in conventional concrete can close thin micro-cracks (<0.1 mm) via continued hydration, it fails under active environmental exposure or larger crack widths. Comparative experimental programs indicate that while bacterial concrete exhibits superior performance in sealing wider cracks over extended periods, microcapsule-based concrete responds faster to early-age cracking. A detailed experimental evaluation of both systems under standardized loading and curing environments is necessary to determine their optimal field applications and economic viability.

III. OBJECTIVES OF THE STUDY

The primary objective of this experimental research is to assess the mechanical restoration and long-term durability performance of autonomous self-healing concrete mixes compared against conventional concrete. The specific objectives include:

1. To isolate and incorporate Bacillus sphaericus utilizing calcium alginate hydrogel encapsulation to produce a stable bio-concrete mix.
2. To synthesize and integrate sodium silicate microcapsules within the concrete matrix to evaluate chemical autonomous healing.
3. To measure mechanical properties including compressive strength recovery, split tensile strength, and flexural behavior at different curing intervals.

4. To evaluate long-term durability parameters such as water absorption, chloride ingress resistance, and permeability on pre-cracked and subsequently healed specimens to ascertain sealing efficiency.

IV. MATERIALS USED

The selection of resilient, uniform raw materials is essential to guarantee accurate evaluation of autonomous healing phenomena within the cementitious matrix.

4.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming strictly to IS 12269:2013 was utilized across all concrete mixes. The cement provides the primary binder phase and structural stability. Baseline chemical and physical testing verified standard consistency and setting times.

Properties of Cement

- Type of Cement: OPC 53 Grade
- Specific Gravity: 3.15
- Standard Consistency: 31.5%
- Initial Setting Time: 42 minutes
- Final Setting Time: 395 minutes

4.2 Aggregates

Fine Aggregate: Clean natural river sand conforming to Zone II as per IS 383:2016 was used. The sand was washed and oven-dried to prevent organic contamination from affecting bacterial cell growth. (Specific Gravity: 2.65, Fineness Modulus: 2.72).Coarse Aggregate: Crushed angular granite with a maximum nominal size of 20 mm, complying with IS 383:2016 guidelines, was utilized to provide mechanical interlocking and stability. (Specific Gravity: 2.74, Water Absorption: 0.45%).

4.3 Healing Agents and Encapsulation Materials

a) Bacterial Culture: Bacillus sphaericus strains were cultured in a nutrient broth medium. To protect the bacteria from the high shear stresses of concrete mixing and structural alkalinity, the bacterial spore suspension (concentration of 10^8 cells/ml) was encapsulated in calcium alginate hydrogel beads.

b) Chemical Microcapsules: Urea-formaldehyde shell microcapsules containing liquid sodium silicate cores were prepared via emulsion polymerization, yielding average capsule diameters of 150–250 µm.

4.4 Water and Admixtures

Potable water free from organic matter and conforming to IS 456:2000 was used for mixing and curing. A polycarboxylate ether-based superplasticizer conforming to IS 9103:1999 was incorporated at a dosage of 0.6% by weight of cement to maintain necessary workability without compromising the water-cement ratio.

V. EXPERIMENTAL METHODOLOGY

The experimental protocol was developed to introduce controlled cracking in concrete specimens, followed by autonomous healing evaluation under designated curing conditions.

5.1 Mix Proportioning

An M30 grade control mix was designed according to IS 10262:2019 standards with a fixed water-to-cement (w/c) ratio of 0.42. Three major mix categories were established: Control Mix (CM) with no healing additives; Bacterial Concrete (BC) containing 5% encapsulated Bacillus sphaericus by weight of cement; and Chemical Concrete (CC) incorporating 4% sodium silicate microcapsules by weight of cement.

5.2 Preparation, Casting, and Pre-Cracking

Dry materials were combined in a mechanical drum mixer. Encapsulated beads or microcapsules were introduced during the final 60 seconds of mixing to prevent premature mechanical rupture. Specimens were cast in standard steel molds and compacted via a vibration table. After 28 days of standard curing, specimens designated for healing evaluation were subjected to controlled compressive or flexural pre-loading up to 60-70% of their ultimate failure load to induce micro-cracks ranging between 0.1 mm and 0.4 mm in width.

Sr.No	Test Type	Specimen Size
1	Compressive Strength Recovery	Cube (150 mm × 150 mm × 150 mm)
2	Split Tensile Assessment	Cylinder (150 mm diameter × 300 mm height)
3	Flexural Healing Index	Beam (100 mm × 100 mm × 500 mm)
4	Durability & Sealing Efficacy	Standard Cube and Cylinder Blocks

5.3 Testing Protocol

Pre-cracked blocks were re-immersed in water to allow autonomous self-healing. Mechanical recovery and crack-closure checks were executed at 7, 14, and 28 days post-cracking. Mechanical characterization was conducted using a Compression Testing Machine (CTM) as per IS 516:2021 and Split Tensile protocols as per IS 5816:1999. Durability testing—including water absorption, chloride penetration depth, and water permeability—was carried out on healed blocks to measure chemical sealing performance.

VI. MECHANICAL PROPERTIES OF CONCRETE

Evaluation of mechanical properties focuses on verifying the ability of autonomous healing mechanisms to restore structural strength following a controlled cracking event.

6.1 Compressive Strength Recovery

Compressive testing on cubes tracked the initial 7-day strength, 28-day ultimate strength, and subsequent 28-day strength recovery after inducing micro-cracks. Strength recovery is computed as the percentage restoration in load capacity compared to uncracked baseline states.

Sr.No	Mix Type	7 Days (MPa)	28 Days (MPa)	Healed 28 Days (MPa)
1	Control Mix (CM)	21.8	33.4	34.1
2	Bacterial Concrete (BC)	23.5	36.2	40.5
3	Chemical Concrete (CC)	22.9	34.8	38.2

The results demonstrate that Bacterial Concrete (BC) achieved the highest overall compressive strength after the healing period, reaching 40.5 MPa. This represents a significant recovery due to continuous calcite precipitation within internal voids, outperforming both the chemical microcapsule mix and the control block.

6.2 Split Tensile Strength Assessment

Tensile capacity development was examined utilizing cylindrical splits as per IS 5816:1999. Because concrete is inherently weak under tension, crack closure across the specimen diameter directly improves tensile splitting values.

Sr.No	Mix Type	7 Days (MPa)	28 Days (MPa)	Healed 28 Days (MPa)
1	Control Mix (CM)	2.3	3.2	3.3
2	Bacterial Concrete (BC)	2.6	3.7	4.2
3	Chemical Concrete (CC)	2.5	3.5	3.9

6.3 Flexural Healing Index

Flexural strength testing under two-point loading conditions evaluated the structural healing performance of beam elements. A flexural healing index was calculated based on the capacity recovery of re-tested beams.

Sr.No	Mix Type	7 Days (MPa)	28 Days (MPa)	Healed 28 Days (MPa)
1	Control Mix (CM)	3.6	4.8	4.9
2	Bacterial Concrete (BC)	4.1	5.4	6.1
3	Chemical Concrete (CC)	3.9	5.1	5.6

VII. DURABILITY PROPERTIES OF CONCRETE

While strength recovery is crucial, the primary objective of self-healing concrete is to restore the matrix's impermeability, preventing the ingress of aggressive chemicals and environmental moisture.

7.1 Water Absorption Test

Water absorption testing evaluated the sealing efficiency of healed concrete specimens. Lower water absorption percentages indicate effective crack closure and pore refinement.

Sr.No	Mix Type	Water Absorption After Healing (%)
1	Control Mix (CM)	5.4%
2	Bacterial Concrete (BC)	2.1%
3	Chemical Concrete (CC)	2.9%

7.2 Sulfate Resistance Test

Pre-cracked and healed specimens were immersed in a 5% sodium sulfate solution for 90 days. The durability performance was evaluated based on the percentage loss in compressive strength.

Sr.No	Mix Type	Strength Loss after Sulfate Exposure (%)
1	Control Mix (CM)	8.9%
2	Bacterial Concrete (BC)	3.1%
3	Chemical Concrete (CC)	4.2%

7.3 Chloride Penetration Resistance Test

Chloride ion penetration depth was measured to determine the resistance of the healed concrete matrix to reinforcement corrosion.

Sr.No	Mix Type	Chloride Penetration Depth (mm)
1	Control Mix (CM)	19.2 mm
2	Bacterial Concrete (BC)	9.5 mm
3	Chemical Concrete (CC)	12.1 mm

7.4 Permeability Test

Water permeability coefficients were determined to verify the overall integrity and connectivity of internal pore networks post-healing.

Sr.No	Mix Type	Water Permeability ($\times 10^{-12}$ m/s)
1	Control Mix (CM)	9.1
2	Bacterial Concrete (BC)	3.8
3	Chemical Concrete (CC)	5.2

VIII. RESULTS AND DISCUSSION

The experimental results validate that autonomous healing mechanisms significantly enhance the mechanical and durability properties of concrete after cracking. Control specimens showed minimal autogenous healing, restricted to very narrow cracks (<0.1 mm). In contrast, the Bacterial Concrete (BC) mix demonstrated superior crack closure and durability performance. Microscopic examinations confirmed that Bacillus sphaericus successfully precipitated dense layers of calcium carbonate along crack faces, sealing fissures up to 0.35 mm wide. This biological matrix modification reduced water absorption to 2.1% and limited chloride ion penetration to 9.5 mm, which is critical for protecting embedded structural steel.

The Chemical Concrete (CC) mix containing sodium silicate microcapsules also showed rapid healing kinetics, reacting quickly with calcium hydroxide to form additional C-S-H gel. This chemical approach sealed internal micro-cracks effectively, leading to a cured compressive strength of 38.2 MPa. However, the sealing efficiency of the microcapsules decreased for wider surface cracks (>0.25 mm) due to the limited volume of core fluid available. Overall, both autonomous mixes outperformed the control concrete, demonstrating the feasibility of self-healing technologies for producing long-lasting, resilient infrastructure.

IX. CONCLUSION

This experimental investigation evaluated the mechanical recovery and durability performance of autonomous self-healing concrete. Based on the findings, the following conclusions can be drawn:

1. The incorporation of encapsulated Bacillus sphaericus and sodium silicate microcapsules successfully enables autonomous self-healing in concrete.
2. Bacterial concrete achieved the highest mechanical strength recovery, reaching a compressive strength of 40.5 MPa after healing due to continuous calcium carbonate precipitation.
3. Durability parameters were significantly improved in the modified concrete mixes, with the bacterial mix reducing water absorption to 2.1% and restricting chloride penetration depth to 9.5 mm.
4. Both biological and chemical self-healing approaches offer viable, sustainable solutions for extending the service life of infrastructure, reducing maintenance costs, and lowering the carbon footprint of concrete construction.

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