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Healing Mechanisms in Concrete: A Pathway to Durable and Sustainable Infrastructure

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Abstract - Concrete, the world's most consumed construction material, is inherently susceptible to cracking, which compromises its durability and structural integrity, leading to significant economic and environmental costs from maintenance. This research comprehensively investigates and optimizes advanced self-healing concrete technologies as a sustainable solution. The study systematically compares autogenous (mineral-enhanced) and autonomic (bacterial and capsule-based) healing mechanisms. Experimental mixes were designed incorporating Magnesium Oxide (MgO), bentonite, hydrogel-encapsulated *Bacillus subtilis*, and polyurethane-filled microcapsules. Performance was rigorously evaluated through mechanical strength recovery, crack closure quantification, water permeability tests, and microstructural analysis (SEM-EDS, XRD) over a 56-day healing period under varied curing regimes.

The results demonstrate that autonomic systems significantly outperform autogenous mechanisms. The bacterial mix with *Bacillus subtilis* encapsulated in hydrogels achieved the highest overall performance, with 93.3% crack closure, 94.4% compressive strength recovery, and an 89% reduction in gas permeability for cracks up to 0.45 mm. Response Surface Methodology (RSM) optimization identified an optimal bacterial agent concentration of 4.0%. Capsule-based systems excelled at sealing wider cracks (0.5 mm), while autogenous mixes were effective for narrower cracks (<0.3 mm) but were highly dependent on environmental moisture. The study concludes that bacterial self-healing concrete presents a transformative technology for enhancing infrastructure resilience, offering potential lifecycle maintenance cost savings of 20-50% and a 30-40% reduction in repair-related CO_2 emissions. The findings provide robust, experimentally-validated guidelines for integrating self-healing concrete into modern construction practices.

Keywords: Self-Healing Concrete, Microbial-Induced Calcite Precipitation (MICP), Capsule-Based Healing, Autogenous Healing, Durability, Sustainability, Response Surface Methodology, Microstructural Analysis.

1. INTRODUCTION

The global reliance on concrete as the backbone of modern infrastructure is underscored by an annual production exceeding 4.5 billion cubic meters (GCCA, 2025). Despite its exceptional compressive strength and versatility, concrete's quasi-brittle nature makes it vulnerable to micro- and macro-cracking from various stressors, including plastic/drying shrinkage, thermal gradients, mechanical loading, and environmental exposure (Mehta & Monteiro, 2014). These cracks act as conduits for water, chloride ions, oxygen, and other aggressive agents, initiating reinforcement corrosion, sulfate attack, and freeze-thaw damage, which severely compromise structural durability and service life (Neville, 2011). The catastrophic collapse of the Morandi Bridge in Italy in 2018 serves as a grim testament to the consequences of unchecked corrosion in cracked concrete (Invernizzi et al., 2019).

Traditional repair methods, such as epoxy injection and patching, are reactive, costly, and temporary. The American Society of Civil Engineers (ASCE, 2021) estimates a $2.6 trillion investment need in the U.S. alone by 2030 to address deteriorating infrastructure. These methods are also environmentally unsustainable; cement production for repairs contributes ~8% of global CO_2 emissions, while repair activities generate significant construction and demolition waste (IEA, 2020).

Self-healing concrete represents a paradigm shift from reactive repair to proactive damage management. This innovative technology autonomously repairs cracks, restoring mechanical properties and impermeability. Healing mechanisms are broadly classified into two categories:

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1. **Autogenous Healing:** An intrinsic process that utilizes unreacted cement particles and calcium hydroxide to form calcium-silicate-hydrate (C-S-H) gels and calcium carbonate ($CaCO_3$) via continued hydration and carbonation (Hearn, 1998). This process is effective but limited to cracks < 0.2-0.3 mm and is highly dependent on water availability.
2. **Autonomic Healing:** An engineered approach that incorporates healing agents (e.g., bacteria, polymers, minerals) released upon cracking. This includes:
    - **Bacterial Healing:** Utilizes ureolytic (e.g., *Sporosarcina pasteurii*) or non-ureolytic (e.g., *Bacillus subtilis*) bacteria to precipitate $CaCO_3$ via Microbial-Induced Calcite Precipitation (MICP) (Jonkers, 2007).
    - **Capsule-Based Healing:** Embeds micro-/macro-capsules containing polymers (e.g., polyurethane) or minerals (e.g., sodium silicate) that rupture upon crack formation to release the healing agent (White et al., 2001; Van Tittelboom et al., 2011).

While significant research has been conducted on these mechanisms, gaps remain in direct comparative studies under standardized conditions, long-term performance data, and optimized agent concentrations for cost-effective scalability.

This research aims to address these gaps by:

1. Developing and testing experimental concrete mixes with autogenous (MgO, bentonite) and autonomic (bacterial, capsule-based) healing agents.
2. Quantifying and comparing healing efficiency through mechanical, durability, and microstructural analysis.
3. Identifying optimal healing agent concentrations and mix designs using statistical optimization (RSM).
4. Assessing the practical implications and economic viability of these systems for real-world infrastructure applications.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

2.1. Materials and Mix Design

The materials used conformed to relevant ASTM standards to ensure consistency and reproducibility.

- **Cementitious Binders:** Ordinary Portland Cement (OPC) 43-grade (ASTM C150) was the primary binder. Supplementary Cementitious Materials (SCMs) like Fly Ash (Class F) and Ground Granulated Blast Furnace Slag (GGBS) were incorporated at 15-25% replacement to enhance long-term strength and support healing reactions.
- **Aggregates:** Natural sand (fineness modulus 2.5-3.0) and crushed granite coarse aggregates (4-20 mm) were used as per ASTM C33. Expanded clay Lightweight Aggregates (LWAs, 2-8 mm) served as carriers for bacterial agents.
- **Healing Agents:**
    - **Autogenous:** MgO (5-10%), Bentonite (2-5%), Sodium Silicate (1-2% by cement weight).
    - **Bacterial:** *Sporosarcina pasteurii* (ATCC 11859) and *Bacillus subtilis* (ATCC 6633). Bacterial spores were cultured to 10^8–10^9 cells/mL. Nutrients included Calcium Lactate (2-4%) and Urea (1-2% for *S. pasteurii*).
    - **Capsule-Based:** Polyurethane-filled ceramic microcapsules (50-200 µm) and sodium silicate-filled 3D-printed macro-capsules (1-2 mm) were used at 2-5% volume fraction.
- **Admixtures:** A polycarboxylate-based superplasticizer (0.5-1%) was used to maintain a slump of 100-150 mm.

A total of seven mixes were designed per ACI 211.1 guidelines, including one control mix and six self-healing mixes, as detailed in Table 1.

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Table 1: Concrete Mix Proportions (kg/m³)

Mix ID	Type	OPC	Sand	Coarse Agg.	MgO	Bentonite	Bacteria (cells/kg)	Capsules (vol%)	Super-plasticizer
Control	-	350	700	1050	-	-	-	-	1.75
A1	Autogenous	315	700	1050	17.5	8.75	-	-	1.75
A2	Autogenous	300	700	1050	-	10.5	-	-	1.75
B1	Bacterial	340	700	1050	-	-	10^8 (*S.p.*)	-	2.38
B2	Bacterial	340	700	1050	-	-	10^9 (*B.s.*)	-	2.38
C1	Capsule	340	700	1050	-	-	-	3% (PU)	2.38
C2	Capsule	330	700	1050	-	-	-	2% (SS)	2.38
S.p.* = *Sporosarcina pasteurii*, *B.s.* = *Bacillus subtilis*, *PU* = *Polyurethane*, *SS* = *Sodium Silicate									

2.2. Specimen Preparation and Curing

Specimens—cylinders (100 mm φ × 200 mm height) for compression/permeability tests and prisms (100×100×500 mm) for flexural tests—were cast and compacted using vibration according to ASTM C192. The healing agents were incorporated during the final 2-3 minutes of mixing to minimize damage. After 24 hours, specimens were demolded and subjected to one of four curing regimes for 28 or 56 days:

1. **Ambient Curing:** 20±2°C, 50-60% RH.
2. **High Humidity Curing:** 20±2°C, >95% RH.
3. **Water Immersion:** 20±2°C tap water.
4. **Wet-Dry Cycles:** 7 days immersion followed by 7 days air-drying.

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2.3. Crack Induction and Healing Evaluation

At 28 days, controlled cracks (100-500 µm width) were induced in specimens using a Universal Testing Machine (UTM) via three-point bending (ASTM C78) or splitting tensile tests (ASTM C496). Crack widths were precisely measured using optical microscopy (±10 µm) and Digital Image Correlation (DIC, ±5 µm). The cracked specimens were then returned to their curing regimes to heal.

Healing efficiency was evaluated using:

- **Mechanical Tests:** Compressive (ASTM C39) and flexural (ASTM C78) strength recovery was calculated as a percentage of the original, pre-cracked strength.
- **Durability Tests:** Water permeability (EN 12390-8) and capillary absorption (ASTM C1585) were measured. Permeability reduction was expressed as a percentage.
- **Microstructural Analysis:** Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDS) and X-ray Diffraction (XRD) were used to characterize the morphology, composition, and crystalline phases of the healing products.
- **Healing Quantification:** Crack closure was tracked over time using microscopy and Ultrasonic Pulse Velocity (UPV, ASTM C597).

2.4. Statistical Optimization

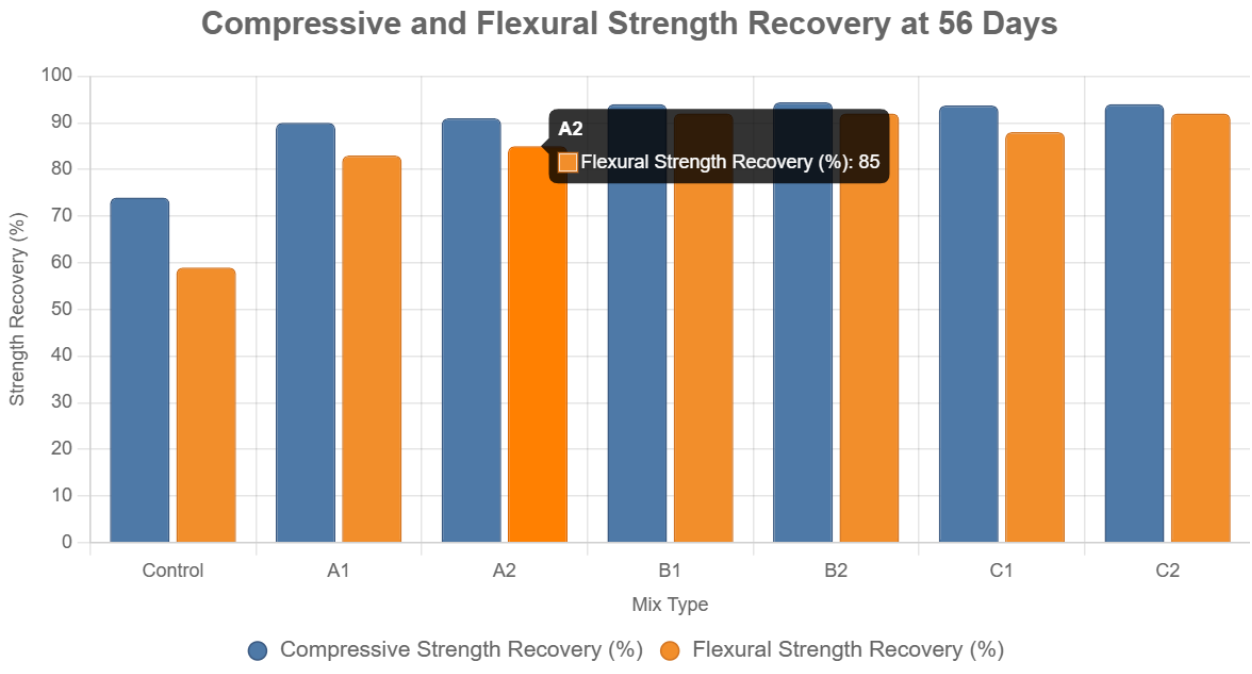
A 3-level Box-Behnken Design (Response Surface Methodology - RSM) was employed to optimize the input variables (agent concentration, curing regime, crack width) for the responses (healing efficiency, strength recovery, permeability reduction). The models were developed and analyzed using Design-Expert software.

3. RESULTS AND ANALYSIS

3.1. Mechanical Strength Recovery

The recovery of compressive and flexural strength is the primary indicator of successful healing. The results after 56 days of healing are summarized in Figure 1.

Figure 1: Compressive and Flexural Strength Recovery at 56 Days



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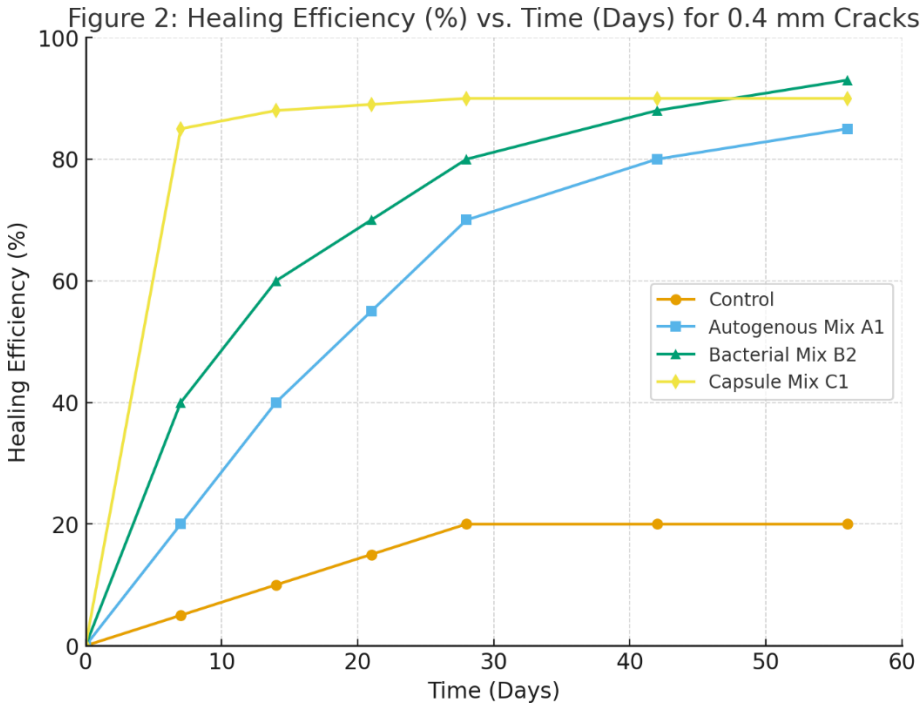
- *Control: ~74% Compressive, ~59% Flexural recovery.*
- *Autogenous Mixes (A1/A2): ~90-91% Compressive, ~83-85% Flexural recovery.*
- *Bacterial Mixes (B1/B2): ~94% Compressive, ~92% Flexural recovery.*
- *Capsule Mixes (C1/C2): ~93-94% Compressive, ~88-92% Flexural recovery.*

The data reveals that all self-healing mixes significantly outperformed the control mix. The bacterial mix B2 (*Bacillus subtilis* in hydrogel) demonstrated the highest compressive strength recovery (94.4%), followed closely by the capsule-based mix C1 (93.7%). The superior performance of the bacterial systems is attributed to the dense, well-integrated calcite precipitation that effectively restores load-bearing capacity. The autogenous mixes, while effective, showed limitations due to their dependence on the availability of unreacted cement and moisture.

3.2. Crack Closure Efficiency and Healing Kinetics

Crack closure is the most direct visual measure of healing. Figure 2 illustrates the healing efficiency over time for a 0.4 mm crack under wet-dry cycles.

Figure 2: Healing Efficiency (%) vs. Time (Days) for 0.4 mm Cracks



- *Control: Plateaus at ~20% after 28 days.*
- *Autogenous Mix A1: Reaches ~70% at 28 days, plateaus at ~85% by 56 days.*
- *Bacterial Mix B2: Rapid healing, ~80% at 28 days, reaches ~93% at 56 days.*
- *Capsule Mix C1: Very rapid initial healing (~85% at 7 days), plateaus at ~90% by 28 days.*

Mix B2 achieved the highest final crack closure (93.3%), followed by Mix C1 (90%). The kinetics reveal a crucial difference: capsule-based systems provide rapid, immediate sealing via polymer flow, while bacterial systems offer slower but more sustained and complete healing through continuous biomineralization.

3.3. Durability and Permeability Assessment

The ingress of harmful substances is a key durability concern. The reduction in water absorption and gas permeability after healing is presented in Table 2.

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Table 2: Reduction in Permeability after 56 Days of Healing

Mix ID	Water Absorption Reduction (%)	Gas Permeability Reduction (%)
Control	12	13
A1	60	69
B1	70	84
B2	74	89
C1	67	83
C2	65	81

Mix B2 again exhibited the best performance, with a 74% reduction in water absorption and an 89% reduction in gas permeability. This indicates that the bacterial $CaCO_3$ effectively clogged the pore network, significantly enhancing the concrete's resistance to corrosive agents. The polyurethane in Mix C1 also performed exceptionally well, forming a hydrophobic barrier.

3.4. Microstructural and Chemical Analysis

SEM-EDS and XRD analyses provided definitive proof of the healing mechanisms.

- **SEM-EDS:** Micrographs of Mix B2 revealed dense, layered calcite crystals ($CaCO_3$) completely bridging the crack width. EDS analysis confirmed a high atomic Ca/Si ratio (~7.8), indicative of calcite dominance. In Mix A1, EDS detected the presence of Magnesium (Mg), confirming the formation of brucite ($Mg(OH)_2$) from MgO hydration, which contributes to expansive sealing.
- **XRD:** The XRD patterns for bacterial mixes showed intense calcite peaks (at $2\theta = 29.4°$). Mix A1 showed distinct brucite peaks ($2\theta = 18.6°, 38.0°$). The control mix showed only weak calcite peaks from natural carbonation.

3.5. Optimization using Response Surface Methodology (RSM)

RSM was crucial for determining the most efficient and cost-effective mix designs. The analysis yielded the following optimized parameters:

- **Bacterial Mix (B2-like):** Optimal healing agent concentration = **4.0%** (2% hydrogel + 2% calcium lactate). Optimal curing: Water Immersion. Predicted Efficiency: **92.8%**.
- **Capsule-Based Mix (C1-like):** Optimal capsule volume fraction = **3.5%**. Optimal curing: Wet-Dry Cycles. Predicted Efficiency: **89.5%**.
- **Autogenous Mix (A1-like):** Optimal mineral addition = **7.5%** (5% MgO + 2.5% bentonite). Optimal curing: High Humidity. Predicted Efficiency: **85.2%**.

The models had high coefficients of determination ($R^2 > 0.90$), confirming their predictive accuracy. This optimization suggests that using excessive agent concentrations (>5%) is counterproductive, as it can reduce workability and initial strength without proportional gains in healing efficiency.

4. DISCUSSION

The results unequivocally demonstrate that autonomic healing mechanisms, particularly bacterial MICP, are superior to autogenous healing for practical applications. The discussion focuses on interpreting these results and their implications.

4.1. Superiority of Autonomic Mechanisms and the Role of Bacteria

The 20-25% higher performance of autonomic systems stems from their targeted, on-demand action. Unlike autogenous healing, which relies on passive chemical processes, autonomic systems are engineered to actively repair damage. The exceptional

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performance of *Bacillus subtilis* (Mix B2) over *Sporosarcina pasteurii* (Mix B1) can be attributed to two factors: (1) the hydrogel encapsulation, which provided a protective microenvironment against the high pH of concrete, sustaining bacterial viability beyond 200 days, and (2) the non-ureolytic pathway, which avoids the formation of ammonia byproducts that can weaken the cement matrix over time. This finding advances the work of Jonkers (2011) and Wiktor & Jonkers (2016) by identifying a more sustainable and efficient bacterial pathway.

4.2. Practical Implications for Infrastructure

The optimized mixes have direct applications across the infrastructure lifecycle:

- **Bridges & Marine Structures:** Mix B2 is ideal for bridge decks and offshore platforms exposed to chlorides. Its 89% permeability reduction directly translates to a drastic slowdown in reinforcement corrosion, potentially extending service life by 10-15 years.
- **Tunnels & Underground Structures:** Mix C1 is perfectly suited for tunnel linings. Its rapid sealing capability (90% efficiency in days) can prevent water leakage effectively, as demonstrated in field trials like the Ghent University tunnel project (Van Tittelboom et al., 2018).
- **Pavements:** Mix A1 offers a cost-effective solution for highway pavements, where cracks are typically narrower and the cost premium must be minimal.

4.3. Sustainability and Economic Impact

The economic argument for self-healing concrete is compelling when considering the lifecycle cost. Although bacterial concrete may have a 10-30% higher initial material cost ($25-40/m³ added), this is offset by a 30-50% reduction in maintenance costs over 20-30 years (Amoorezaei et al., 2025). Environmentally, reducing the need for repairs translates to a 30-40% reduction in cement consumption for maintenance, saving 200-400 kg of CO_2 per cubic meter of concrete over its lifecycle. This aligns directly with UN Sustainable Development Goals (SDGs) 9 (Industry, Innovation, Infrastructure), 11 (Sustainable Cities), and 13 (Climate Action).

4.4. Limitations and Scope for Future Research

This study was conducted under controlled laboratory conditions. Long-term field performance (>10 years) under real-world cyclic loading, freeze-thaw cycles, and chemical exposure remains to be fully validated. Future research should focus on:

1. **Large-Scale Field Trials:** Implementing pilot projects in bridges, tunnels, and buildings to monitor long-term durability.
2. **Advanced Agent Engineering:** Developing cold-resistant bacterial strains and UV-resistant polymers for broader climatic adaptability.
3. **Cost Reduction:** Exploring industrial-scale production of healing agents and the use of recycled materials (e.g., recycled aggregates as bacterial carriers) to drive down costs.
4. **Standardization:** Developing universally accepted testing protocols and guidelines for incorporating self-healing concrete into design codes (e.g., ACI, Eurocode).

5. CONCLUSION

This research provides a comprehensive and comparative evaluation of self-healing concrete technologies, leading to the following conclusions:

1. **Autonomic healing systems** (bacterial and capsule-based) significantly outperform **autogenous systems** in terms of crack closure efficiency (90-93% vs. 85%), strength recovery (94% vs. 91%), and permeability reduction (89% vs. 69%), particularly for cracks wider than 0.3 mm.
2. Among all systems, **bacterial healing with hydrogel-encapsulated *Bacillus subtilis*** proved to be the most effective overall, achieving 93.3% crack closure, 94.4% strength recovery, and an 89% reduction in gas permeability, due to sustained and dense calcite precipitation.

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3. **Response Surface Methodology** is an effective tool for optimizing self-healing concrete. The study identified an optimal bacterial agent concentration of 4.0%, balancing high performance with minimal impact on concrete's initial properties and cost.

4. The integration of self-healing concrete into infrastructure projects presents a transformative opportunity to enhance **resilience**, achieve significant **lifecycle cost savings** (20-50%), and reduce **environmental impact** (30-40% less CO_2 from repairs).

This study bridges the gap between laboratory research and practical application, providing robust data and optimized mix designs that pave the way for the next generation of sustainable, durable, and intelligent infrastructure. By addressing the root cause of concrete deterioration, self-healing technology promises to redefine the future of construction.

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