



# AI-Enabled Building Materials - Application of Self-Healing Concrete Technology

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## Abstract

Concrete structures are prone to cracking under combined mechanical, thermal, and environmental actions, causing progressive durability loss and elevated maintenance costs. Conventional repair methods remain reactive and cannot achieve autonomous microcrack remediation. Self-healing concrete offers a promising alternative, yet integrating artificial intelligence (AI) for real-time monitoring, predictive analysis, and closed-loop repair control remains underexplored, particularly in harsh environments. This study reviewed AI-enabled self-healing concrete technologies and experimentally evaluated five self-healing approaches integrated with an AI monitoring platform. Performance was assessed across mechanical properties, crack repair efficiency, environmental adaptability (marine, polar, and high-temperature conditions), AI responsiveness, and life-cycle economics. The key contribution was a composite self-healing agent system with AI-optimized dosage and activation parameters, systematically validated under multiple harsh exposure scenarios. Results showed that AI integration markedly improved monitoring accuracy, repair timeliness, and environmental adaptability. The optimal composite system (6% microbial agent, 7% epoxy microcapsule, 1.5% vol. Ni-Ti SMA fiber) in the AI-enabled group (G5) achieved a 92.7% crack repair rate at 0.5 mm width, 25.6% service life extension, and 40.1% maintenance cost reduction versus the control (G0), with a cost-benefit ratio of 5.57. These findings provide theoretical and practical guidance for deploying intelligent self-healing concrete in aggressive environments, advancing sustainable construction practices.

**Keywords:** AI-enabled self-healing concrete; microbial remediation; structural health monitoring; concrete durability

## Introduction

Concrete is brittle and crack-prone, with over 80% of structural damage stemming from crack propagation. Conventional repairs are reactive and cannot autonomously address microcracks. Self-healing concrete offers four principal mechanisms — microbial precipitation, capsule-based release, fiber bridging, and nano-material modification — but single-mechanism systems have inherent limitations in environmental sensitivity, release control, or crack targeting. AI integration enables active intervention through real-time monitoring, predictive crack analysis, and closed-loop repair control, while SMA Ni-Ti fiber provides thermally triggered crack closure. However, prior studies have addressed these elements in isolation; systematic AI-composite integration under harsh environments and optimal parameter configurations remain undefined (Wang et al., 2023; Zhou et al., 2024). This study evaluated five self-healing technologies integrated with AI monitoring, assessed mechanical, durability, environmental, and economic performance, and identified optimal composite agent ratios and AI parameters through experimental testing and life-cycle analysis.

## Research Methodology

- General** This study combined literature review with laboratory experimentation. The literature review identified key gaps in AI-composite self-healing systems under harsh environments, establishing the research direction. Laboratory experiments employed a comparative design with one control and five self-healing groups. Mechanical tests followed GB/T 50081-2019 and ASTM C39/C39M-21; environmental adaptability tests followed ASTM G109-19 (marine exposure) and ASTM C666-19 (freeze-thaw cycling), ensuring reliability and cross-study comparability.
- Materials** Ordinary Portland Cement (P-O 42.5, GB 175-2007), crushed stone aggregate (5–20 mm), and medium river sand (FM<sub>s</sub>≈2.6) were used with mixing water conforming to JGJ 63-2006. Four self-healing agents were incorporated: *Bacillus* bacteria (10<sup>10</sup> CFU/g) for microbial CaCO<sub>3</sub> precipitation, epoxy microcapsules (50–100 μm, 70% core content) for polymer release upon cracking, Ni-Ti SMA fibers (0.2 mm × 12 mm, shape memory effect ≥85%) for active crack closure, and nano-CaCO<sub>3</sub> (50 nm, purity ≥99%) for hydration acceleration. The AI monitoring system comprised distributed optical fiber sensors (±1 με), piezoelectric sensors (100 mV/N), and low-power edge computing nodes (≤50 mW).
- Mix Proportion and AI Parameter Design** The base mix targeted C40 strength with w/c = 0.40 and 35% sand ratio per JGJ 55-2011. Six groups were established: a control (G0) and five self-healing groups. G1–G4 employed single mechanisms — glass fiber, microbial remediation, nano-CaCO<sub>3</sub>, and SMA-microbial hybrid, respectively — for comparative evaluation. G5 was the AI-enabled composite group integrating 6% microbial agent, 7% epoxy microcapsule, and 1.5% vol. Ni-Ti SMA fiber, optimized through AI. The AI system in G5 was configured with sensor density of 0.5 units/m<sup>2</sup> for adequate coverage with minimal matrix interference, a hybrid BP-LSTM neural network achieving ≥92% crack prediction accuracy, and a 30-second data transmission interval balancing real-time responsiveness with energy efficiency.
- Experimental Program** Cube (150 mm<sup>3</sup>), prism (100×100×400 mm), and slab (500×500×50 mm) specimens were cast and cured (20±2°C, RH≥95%, 28 days) per GB/T 50081-2019, with 15 specimens per group. AI sensors were embedded 25 mm deep in G5 slabs.

Compressive and flexural strengths were tested at 7 and 28 days (WAW-1000B). Strength recovery was evaluated on pre-cracked prisms (0.5 mm width) at 7, 14, and 28 days. Crack repair efficiency was assessed on slabs with 0.1–0.5 mm cracks via optical microscopy, water permeability (0.3 MPa, 24 h), and SEM. Environmental adaptability was evaluated through 50 cycles each of marine (3.5% NaCl, ASTM G109-19), freeze-thaw (ASTM C666-19), and high-temperature exposure. AI system performance was benchmarked for response time, recognition rate, prediction accuracy, and transmission stability. Life-cycle costs were analyzed over 50 years using cost-benefit ratio (CBR = savings/additional investment).

Statistical analysis employed SPSS 26.0 with independent-samples t-tests (α = 0.05), Pearson correlation, and time-series analysis.

## Result

- Mechanical Properties and Recovery Rate** G5 (AI-enabled composite) achieved the highest 28-day compressive and flexural strengths of 56.3 MPa (+34.0%) and 7.8 MPa (+41.8%) over G0, with 94.8% and 91.2% strength recovery at 28 days post-cracking. This was attributed to synergistic crack-filling mechanisms and AI-optimized dosage control preventing matrix integrity loss (Chen et al., 2021; Jiang et al., 2021; Li et al., 2023).
- Crack Repair Efficiency** G5 achieved the highest repair efficiency: 98.9%, 95.6%, and 92.7% for 0.1, 0.3, and 0.5 mm cracks under normal conditions, exceeding G2 and G4 by 30.2 and 14.1 percentage points at 0.5 mm. Under marine and polar exposures, G5 retained 86.2% and 82.5% at 0.5 mm with minimal degradation, attributed to AI-driven dynamic agent release regulation. SEM confirmed compact repair interfaces in G5 (Berenjian & Seifan, 2018; CSDN Library Research Team, 2024).

- AI System Performance** The G5 AI system showed marked improvements over conventional monitoring (Table 1): 12.7 s response time (85.8% faster), 98.5% microcrack recognition (+45.2%), 92.8% prediction accuracy (+51.0%), and 99.6% transmission success (+32.5%). After 50 environmental cycles, degradation was minimal (response time +2.1 s; recognition, prediction, and transmission rates declined by only 1.0%, 1.5%, and 0.8%), confirming robust operational stability (Eindhoven Polytechnic University, 2024; Zhang et al., 2022).

Figure 1 AI System Performance (G5)

| Index                     | Test Result | Improvement (%) | Environmental Stability |
|---------------------------|-------------|-----------------|-------------------------|
| Response time (0.5mm)     | 12.7s       | 85.8            | +2.1s after 50 cycles   |
| Microcrack recognition    | 98.5%       | 45.2            | -1.0% after 50 cycles   |
| Prediction accuracy       | 92.8%       | 51.0            | -1.5% after 50 cycles   |
| Transmission success rate | 99.6%       | 32.5            | -0.8% after 50 cycles   |

- Environmental Adaptability and Durability** G5 exhibited superior environmental resilience: 89.5% mechanical retention under marine exposure (3.5% NaCl), durability coefficient K=0.85 in freeze-thaw cycling, and 95% capsule stability after high-temperature exposure. AI-driven adaptive regulation of agent activation, combined with interface densification by composite agents, effectively reduced environmental sensitivity and impeded chloride and moisture ingress (Siddika et al., 2021).

- Economic Benefit Analysis** Life-cycle cost analysis over 50 years (Table 2) confirmed G5 as the most economically advantageous system. Despite the highest additional investment of 280 CNY/m<sup>3</sup>, G5 yielded total savings of 1,560 CNY/m<sup>3</sup> with a cost-benefit ratio (CBR) of 5.57 — substantially exceeding G4 (CBR=3.25) and all single-mechanism groups — alongside a 40.1% reduction in maintenance costs. The superior CBR was attributed to AI-driven predictive maintenance minimizing unnecessary interventions and the composite system's prolonged service life. With industrial-scale production and sensor cost reduction, CBR was projected to exceed 7.

Figure 2 Economic Benefit Analysis (CNY/m<sup>3</sup>)

| Group | Additional Investment | Total Savings | CBR  | Maintenance Reduction (%) |
|-------|-----------------------|---------------|------|---------------------------|
| G1    | 30                    | 85            | 2.83 | 15.2                      |
| G2    | 80                    | 174           | 2.18 | 22.5                      |
| G3    | 120                   | 315           | 2.63 | 28.7                      |
| G4    | 150                   | 488           | 3.25 | 32.3                      |
| G5    | 280                   | 1560          | 5.57 | 40.1                      |

## Discussion and conclusions

This study investigated AI integration with self-healing concrete, demonstrating the transition from passive repair to active intelligent remediation. Five self-healing approaches were evaluated under standardized conditions to compare individual and composite healing strategies. The optimal composite system — 6% microbial agent, 7% microencapsulated healer, and 1.5% Ni-Ti SMA fiber with BP-LSTM neural network control — achieved 56.3 MPa compressive strength, 92.7% crack repair efficiency at 0.5 mm width, and a CBR of 5.57, confirming that AI-driven optimization surpasses any single mechanism alone. Multi-environment testing (marine, polar, high-temperature) demonstrated consistent repair performance, with predictive modeling enabling proactive crack detection before critical propagation. Life-cycle analysis confirmed engineering viability, with AI integration costs offset by reduced maintenance and extended service life. Limitations include laboratory-scale testing under controlled conditions and dataset-constrained AI model training. Future work should pursue field-scale validation with extended monitoring, transferable AI models for diverse materials and environments, and standardized testing protocols for AI-integrated self-healing systems.

## Suggestion

Future work should prioritize field-scale validation of the optimal formulation and AI parameters, long-term performance monitoring, cost reduction through component optimization, BIM/IoT integration, and development of unified industry standards for AI-enabled self-healing concrete systems.

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