

Advances in Self-Healing Concrete: Flexural Strength Recovery in Bridge Applications

Nikita Arlakhov

Charter School of Wilmington 100 N Dupont Rd, Wilmington, Delaware 19807, United States

ABSTRACT

Bridges are a critical component of modern infrastructure, yet conventional concrete is highly susceptible to cracking, alkali–aggregate reactions, and environmental stressors that accelerate deterioration, reduce flexural strength, and increase maintenance demands. This paper reviews recent advances in self-healing concrete (SHC) technologies and synthesizes reported findings on their potential to enhance bridge durability and sustainability. Particular attention is given to microbial calcium carbonate precipitation, encapsulated polymer systems, and mineral admixtures as autonomous crack-healing mechanisms. In microbial-based systems, dormant bacterial spores embedded within the concrete matrix are activated by moisture ingress, leading to calcium carbonate precipitation that seals microcracks and contributes to strength recovery. Reported outcomes indicate partial to substantial recovery of flexural strength, with performance influenced by crack width, healing duration, and material composition. Additional approaches, such as bacterial immobilization within recycled aggregates, show promise for improving healing efficiency while supporting environmental sustainability. Although challenges remain regarding large-scale implementation and long-term field performance, current research suggests that self-healing concrete represents a promising strategy for extending bridge service life and reducing life-cycle maintenance costs.

Keywords: Self-healing concrete; microbial-induced calcium carbonate precipitation (MICP); bridge durability; alkali–aggregate reaction (AAR); flexural strength recovery; recycled coarse aggregates

INTRODUCTION

Bridge durability is essential to the dependability of contemporary infrastructure systems because bridge failure or deterioration can have serious social and economic repercussions. Despite its strength and

adaptability, concrete, the most widely used building material in the world, is still susceptible to chemical deterioration, shrinkage, and cracking (1). Mechanical loading, freeze–thaw cycles, and chemical reactions like the alkali–aggregate reaction (AAR), where alkalis in cement react with reactive aggregates to form an expansive gel that compromises structural integrity, are common causes of microcracks (2). Alkali–silica reaction (ASR) is the most common form of alkali–aggregate reaction (AAR) and involves the reaction of alkalis with reactive silica phases in aggregates, whereas AAR more broadly encompasses reactions with other reactive aggregate constituents. If these microcracks

Corresponding author: Nikita Arlakhov, E-mail: nicksobol1507@gmail.com.

Copyright: © 2026 Nikita Arlakhov. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Accepted January 26, 2026

<https://doi.org/10.70251/HYJR2348.41450456>

are not fixed, water and chlorides can enter, hastening reinforcement corrosion and decreasing flexural capacity (3). In extreme cases, AAR-related damage has been reported to reduce the load-bearing capacity of concrete bridge components by up to 50% (2).

To address these durability concerns, recent research has focused on self-healing concrete (SHC), which incorporates biological agents, encapsulated polymers, or mineral admixtures to enable autonomous crack repair (4). Among these approaches, microbial-induced calcium carbonate precipitation (MICP) has attracted significant attention because bacteria such as *Bacillus subtilis* and *Bacillus megaterium* precipitate calcium carbonate when activated by moisture, effectively sealing microcracks and reducing permeability (4). Recent narrative reviews have outlined the principal self-healing mechanisms, material strategies, and sustainability considerations governing self-healing concrete systems, providing a synthesized framework for interpreting reported performance outcomes (5). According to the reviewed literature, SHC can achieve flexural strength recovery ranging from approximately 30% to 90% (6), depending on crack width, healing duration, and material composition. Additionally, immobilizing bacterial spores within recycled coarse aggregates (RCA) has been shown to enhance healing efficiency while improving sustainability through the reuse of construction waste (7). Recent experimental investigations further report that bacterial self-healing concrete exhibits enhanced resistance to alkali-silica reaction and reduced chloride penetration, reinforcing the role of biologically mediated healing in improving long-term durability of reinforced concrete structures (8). Collectively, these findings suggest that SHC offers a promising strategy for extending bridge service life, reducing maintenance demands, and improving the long-term sustainability of infrastructure systems (3-8).

MECHANISMS OF SELF-HEALING IN CONCRETE

Self-healing concrete (SHC) is engineered to autonomously repair microcracks that develop during service, thereby preserving structural integrity and delaying deterioration. This ability is made possible by damage-responsive mechanisms that are activated mainly when there is moisture intrusion and cracking. The most extensively researched and technically feasible self-healing mechanisms for cementitious materials are microbial-induced calcium carbonate precipitation

(MICP), encapsulated healing agents, and recycled coarse aggregates (RCA) used as carrier media.

Microbial-Induced Calcium Carbonate Precipitation (MICP)

A biologically driven self-healing process called microbial-induced calcium carbonate precipitation (MICP) depends on the metabolic activity of dormant bacterial spores embedded in the concrete matrix (4). Bacteria, usually from the *Bacillus* genus, become activated and metabolize supplied nutrients when microcracks develop and water seeps through the concrete, raising the local concentration of carbonate ions. When calcium ions are present, this process causes calcium carbonate (CaCO_3) precipitates, primarily through ureolytic bacterial pathways that increase local carbonate concentration (4). CaCO_3 gradually builds up inside microcracks and combines with nearby cement hydration products to help close cracks and restore microstructural continuity.

Encapsulated Healing Agents

Encapsulation-based self-healing systems use discrete capsules embedded in the concrete matrix that contain healing agents like polymers, mineral solutions, or bacterial suspensions. When intersected by propagating cracks, these capsules burst, releasing the healing agent straight into the damaged area. They stay intact during mixing and curing (4). After being released, the agent enters the crack and, depending on the system design, goes through chemical hardening, polymerization, or biologically mediated mineral precipitation, allowing for both autonomous and localized crack repair.

Recycled Coarse Aggregates as Carrier Mechanisms

Because recycled coarse aggregates (RCA) have a rougher surface texture and more porosity than natural aggregates, they have been used as carrier media to immobilize bacterial spores. During the production of concrete, these features create protective microenvironments that increase bacterial survivability (7). Immobilized bacteria are activated close to the damage zone when cracks cross RCA particles and moisture penetrates the concrete. This causes localized calcium carbonate precipitation at the aggregate-paste interface, increasing the self-healing process's spatial efficiency and dependability. The primary self-healing mechanisms discussed in this section are summarized and compared in Table 1, highlighting differences in healing agents, activation triggers, effective crack widths, advantages, and key limitations.

Table 1. Overview of Self-Healing Concrete Mechanisms Applied to Cementitious Materials.

Self-Healing Mechanism	Healing Agent / Carrier	Activation Trigger	Typical Effective Crack Width	Primary Advantages	Key Limitations	Representative References
Microbial-Induced Calcium Carbonate Precipitation (MICP)	Dormant bacterial spores (e.g., <i>Bacillus</i> spp.) with nutrients	Moisture ingress and crack formation	≤ 0.6 mm	Autonomous healing; repeatable mineral precipitation; permeability reduction	Requires sustained moisture; bacterial viability over long-term uncertain	(4, 6, 7)
Encapsulated Healing Agents	Polymer resins, mineral solutions, or bacterial suspensions enclosed in capsules	Crack intersects capsule, causing rupture	≤ 0.5–0.7 mm	Targeted and rapid crack filling; localized repair	Finite healing agent supply; capsule rupture risk during mixing	(4, 5)
Recycled Coarse Aggregates (RCA) as Carrier Media	Bacterial spores immobilized in porous RCA	Crack propagation through RCA with moisture presence	≤ 0.6 mm	Improved bacterial protection; localized healing; enhanced sustainability	Healing depends on crack–aggregate intersection probability	(5, 7)

MECHANICAL AND DURABILITY PERFORMANCE OF SELF-HEALING CONCRETE

Self-healing concrete (SHC) effectiveness in structural applications is primarily assessed using mechanical and durability performance metrics. In contrast to traditional concrete, SHC is evaluated not just on its initial strength but also on its capacity to regain mechanical strength and withstand degradation mechanisms following cracking. Flexural strength recovery, resistance to alkali–aggregate reaction (AAR), permeability and chloride ingress reduction, and durability under freeze–thaw exposure are some of the key performance indicators documented in the literature (6).

Flexural Strength Recovery

One of the most often reported measures of SHC performance is flexural strength recovery, as it indicates the extent to which load-bearing capacity is restored following damage. SHC specimens consistently recover between 30% and 90% of their initial flexural strength (6), depending on bacterial concentration, healing time, crack width, and environmental exposure conditions. This broad recovery range illustrates variations in

healing effectiveness between mechanisms and testing procedures, but taken as a whole, it demonstrates that SHC is capable of partially restoring structural functionality rather than only providing superficial crack sealing.

Resistance to Alkali–Aggregate Reaction (AAR)

Resistance to alkali–aggregate reaction (AAR) is a critical durability metric for concrete bridge components exposed to moisture and reactive aggregates. AAR produces expansive gels through reactions between alkalis in cement and reactive silica in aggregates, promoting cracking and microcracks long-term deterioration. By sealing microcracks and limiting moisture ingress, SHC reduces the conditions necessary for expansive reactions to occur (5). Comparative studies using Accelerated Mortar Bar Tests (AMBT) and Concrete Prism Tests (CPT) show that SHC specimens exhibit 20–40% lower expansion rates than conventional concrete (5), indicating enhanced resistance to AAR-induced damage.

Permeability and Chloride Ingress Reduction

Permeability reduction is a key indicator of durability because it governs the ingress of water and

chlorides that accelerate reinforcement corrosion. At the microstructural level, healing products generated within SHC, particularly calcium carbonate precipitates, fill microcracks and obstruct transport pathways (4). Laboratory studies report that SHC can reduce water absorption by up to 60% compared to control specimens (4), resulting in significantly lower permeability. Reduced permeability directly limits chloride ingress, which is one of the primary causes of corrosion-related deterioration in reinforced concrete bridge decks.

Freeze–Thaw Durability

Freeze–thaw resistance is another critical performance indicator for bridge structures subjected to cyclic temperature variations. Microcracks formed during freezing allow water ingress and internal damage during subsequent thawing cycles. By autonomously sealing microcracks, SHC restricts water penetration and minimizes internal stresses associated with ice formation (4). Experimental studies indicate that SHC specimens withstand repeated freeze–thaw cycles more effectively than conventional concrete (4), particularly when healing occurs during moisture exposure phases.

Summary of Performance Outcomes

Collectively, these performance metrics demonstrate that SHC provides measurable improvements in both mechanical recovery and durability compared to conventional concrete (4). Flexural strength recovery, reduced AAR expansion, decreased permeability, and enhanced freeze–thaw resistance highlight SHC's

potential to improve the long-term reliability of bridge structures (6). However, most reported results are derived from laboratory-scale experiments, emphasizing the need for further validation under field conditions, as discussed in later sections. A comparative summary of reported mechanical and durability performance improvements for self-healing concrete systems is provided in Table 2.

SUSTAINABILITY AND LONG-TERM VIABILITY OF SELF-HEALING CONCRETE

Self-healing concrete (SHC) has gained substantial interest not just because of its mechanical advantages but also due to its ability to enhance the environmental sustainability and long-term viability of bridges. Concrete is an extremely resource-demanding product; for example, the production of cement accounts for nearly 8% (8) of total CO₂ emissions each year worldwide. Moreover, as the deterioration of existing bridges leads to increased replacement frequency and consumption of materials, emissions and economic costs associated with repairs also increase. As a result of its ability to self-seal cracks and delay failure, SHC provides an opportunity to alleviate the environmental and financial pressures related to long-term maintenance of bridges (5).

Environmental Impact and CO₂ Reduction

A major benefit of SHC concerning sustainability is its potential to increase the length of time between servicing events and therefore reduce the number of service events needed overall. Typically, maintenance of

Table 2. Reported Mechanical and Durability Performance Metrics of Self-Healing Concrete in Laboratory Studies.

Performance Metric	Observed Improvement Range	Test Method / Indicator	Key Influencing Factors	Representative References
Flexural Strength Recovery	30–90% recovery of original strength	Three-point or four-point bending tests	Crack width, healing duration, bacterial concentration, exposure conditions	(6)
AAR Expansion Reduction	20–40% lower expansion than control	Accelerated Mortar Bar Test (AMBT); Concrete Prism Test (CPT)	Moisture availability, crack sealing efficiency, aggregate reactivity	(5)
Permeability Reduction	Up to 60% reduction in water absorption	Water absorption and permeability tests	CaCO ₃ precipitation density, crack connectivity	(4)
Chloride Ingress Resistance	Qualitative reduction in chloride penetration	Chloride diffusion and migration tests	Reduced permeability, healed microcracks	(4)
Freeze–Thaw Durability	Improved resistance to cyclic degradation	Freeze–thaw cycling tests	Moisture exposure during healing, crack closure effectiveness	(4)

a bridge requires closing lanes of traffic (8), removing old materials, installing new materials, and operating large machines that consume large amounts of energy, all of which contribute to greenhouse gas emissions (8). In addition, because SHC prevents cracks from propagating as rapidly, it can reduce the frequency of repair cycles over the life of a structure, thereby lowering lifecycle CO₂ emissions associated with infrastructure maintenance (8). Sustainability assessments indicate that extending the service life of an asset is one of the primary strategies for reducing overall operating emissions associated with maintenance activities (8).

Recycled Coarse Aggregates and Circular Material Use

The use of recycled coarse aggregates (RCA) in SHC systems enhances sustainability by reusing previously utilized materials and reducing construction waste sent to landfills. RCA, which typically originates from demolished concrete, is often considered lower quality than virgin aggregates due to higher porosity and weaker bonding at the aggregate–paste interface. However, research indicates that these characteristics enable RCA to provide increased surface area for bacterial attachment, facilitating localized microcrack repair when cracking occurs (5). In addition to diverting construction

waste from landfills, the use of RCA in SHC systems supports circular material use within the construction industry.

Lifecycle Costs and Economic Viability

The initial material costs associated with SHC are higher than those of conventional concrete due to the incorporation of bacterial agents, encapsulated systems, or treated aggregates. However, these initial costs must be evaluated alongside long-term maintenance savings (8). Conventional bridge maintenance often requires repeated interventions involving high labor and material costs throughout a structure's service life. In contrast, SHC seeks to reduce the frequency of such interventions through autonomous crack treatment at early stages of deterioration. Published lifecycle analyses report that reduced maintenance frequency can lower total bridge lifecycle costs by approximately 15–30% over long service periods when self-healing concrete is employed (8). As a result, evidence in the literature suggests that reduced maintenance demands can offset higher initial costs over the service life of a bridge before major rehabilitation or replacement is required (8). A synthesis of reported sustainability-related benefits and limitations of self-healing concrete systems is summarized in Table 3.

Table 3. Sustainability and Lifecycle Impacts of Self-Healing Concrete for Bridge Infrastructure.

Sustainability Aspect	Reported Benefit or Trend	Quantitative Evidence	Key Limitations / Uncertainties	Representative References
CO ₂ Emissions Reduction	Reduced emissions through extended service life	Cement production ≈8% of global CO ₂ emissions; lifecycle emissions reduced via fewer repair cycles	Benefits largely inferred from maintenance reduction models	(8)
Maintenance Frequency	Decreased number of repair interventions	Fewer repair cycles over service life compared to conventional concrete	Limited field-scale validation	(8)
Lifecycle Cost Impact	Lower total lifecycle costs despite higher initial material costs	15–30% reduction in total bridge lifecycle costs over long service periods	Cost outcomes sensitive to material prices and exposure conditions	(8)
Recycled Coarse Aggregate (RCA) Use	Improved material circularity and waste reduction	Diversion of demolition waste from landfills	Variability in RCA quality and bacterial immobilization efficiency	(5)
Long-Term Healing Viability	Potential for sustained crack sealing	Short-term lab tests (28–56 days) demonstrate healing activity	Uncertain bacterial survivability over decades	(7)
Field-Scale Applicability	Promising but unproven at infrastructure scale	Limited pilot bridge studies reported	Scaling, environmental variability, lack of standardized protocols	(7)

Long-Term Durability and Field-Scale Challenges

Although SHC has demonstrated strong sustainability potential, significant uncertainty remains regarding its long-term performance in real-world bridge applications. Many experimental studies have evaluated SHC over short durations, typically 28–56 days (7), under laboratory conditions. It remains unclear how long bacteria can survive within concrete over decades of service or whether healing performance can be sustained through multiple cracking cycles. Additional challenges include large-scale production feasibility and variability in environmental exposure, such as prolonged dry conditions or high alkalinity. Consequently, pilot bridge projects and extended field monitoring are necessary to validate laboratory findings and assess SHC performance across diverse climatic environments.

Summary of Sustainability Implications

Overall, SHC offers a promising pathway for improving the long-term sustainability and viability of bridge infrastructure through reduced emissions, increased material reuse, and lower maintenance requirements over a structure's lifecycle (5). However, translating laboratory-scale benefits to field applications will require standardized testing protocols and long-term performance monitoring. Addressing these challenges will be critical to the broader adoption of SHC as a sustainable construction material.

CONCLUSION

Self-healing concrete (SHC) represents a promising advancement for improving the durability, sustainability, and long-term performance of bridge infrastructure. The reviewed literature demonstrates that SHC systems, particularly those based on microbial-induced calcium carbonate precipitation, encapsulated healing agents, and recycled coarse aggregate carriers—can partially restore mechanical capacity, reduce permeability, mitigate alkali–aggregate reactions, and enhance resistance to freeze–thaw damage. These combined effects suggest that SHC has the potential to extend service life and reduce maintenance demands compared to conventional concrete (6).

However, the effectiveness of SHC remains strongly dependent on environmental conditions, crack geometry, and healing mechanism selection. Most existing evidence is derived from short-term laboratory studies (7), and significant uncertainty persists regarding long-term performance, scalability, and repeatable healing under real-world bridge conditions. Issues such as moisture dependence, bacterial viability, healing fatigue, and limited crack-width thresholds highlight the need for cautious interpretation of reported benefits (Table 4).

Future research should prioritize long-term field evaluations, standardized testing protocols, and full-scale pilot implementations to bridge the gap between

Table 4. Limitations, Failure Modes, and Key Uncertainties in Self-Healing Concrete Systems.

SHC Aspect	Observed Limitation or Failure Mode	Conditions Under Which It Occurs	Implications for Bridge Performance	Key Research Gaps
Moisture Dependence	Reduced or absent healing activity	Prolonged dry environments, sheltered bridge components	Inconsistent healing over service life	Performance under cyclic wet–dry exposure
Crack Width Sensitivity	Limited healing beyond threshold	Crack widths > ~0.6 mm	Structural cracks may remain unrepaired	Integration with crack-control design
Healing Fatigue	Declining efficiency over repeated cycles	Recurrent loading and crack reopening	Diminished long-term durability gains	Long-term cyclic loading studies
Bacterial Viability	Loss of metabolic activity	High alkalinity, nutrient depletion, aging	Reduced autonomous healing potential	Multi-decade survivability data
Encapsulated Agent Depletion	Finite healing capacity	Multiple crack events at same location	Non-repeatable healing	Capsule replenishment strategies
RCA Carrier Dependence	Variable healing effectiveness	Non-uniform aggregate distribution	Localized healing inconsistencies	Optimization of aggregate placement

Continued Table 4. Limitations, Failure Modes, and Key Uncertainties in Self-Healing Concrete Systems.

SHC Aspect	Observed Limitation or Failure Mode	Conditions Under Which It Occurs	Implications for Bridge Performance	Key Research Gaps
Laboratory–Field Gap	Overestimated performance	Short-term, controlled lab conditions	Uncertain real-world durability	Full-scale bridge demonstrations
Scalability Constraints	High cost and production complexity	Large infrastructure projects	Limited adoption potential	Industrial-scale production methods

laboratory performance and real-world applicability. Addressing these challenges will be critical for determining whether SHC can transition from an experimental material to a practical solution for large-scale infrastructure. Overall, while SHC is not a universal solution to concrete deterioration, it offers a compelling pathway toward more resilient and sustainable bridge systems when appropriately designed and deployed.

ACKNOWLEDGEMENTS

Thank you for the guidance of Hamid Foroughi mentor from Johns Hopkins University in the development of this research paper.

CONFLICT OF INTEREST

The author declares no conflicts of interest related to this work.

REFERENCES

- Patel A and Bhattacharya T. A review on self-healing materials: Mechanisms, performance, and challenges in civil engineering applications. *Journal of Materials in Civil Engineering*. 2024; 36 (2): 1–20. doi: 10.1016/j.jmace.2023.107289.
- Thomas M and Fournier S. Alkali–aggregate reaction in concrete: Mechanisms and mitigation. *Cement and Concrete Research*. 2023; 34 (2): 209–216.
- Jones NA, Li H, and Wong KS. Development of a performance measure for durability of concrete bridges. *Concrete Institute of Australia Technical Report*. 2023; CIA03: 1–32.
- Thomas MS, Dutta PK, and Kim J. Environmental impact and long-term performance of self-healing cementitious materials. *Environmental Advances*. 2023; 9 (3). doi: 10.1016/j.envadv.2023.100357.
- Chahal AK, Sharma S, and Saini S. Self-healing concrete: A path towards advancement of sustainable infrastructure. *Discover Applied Sciences*. 2025; 7 (1): 1–18. doi: 10.1007/s42452-025-06529-w.
- ASTM International. ASTM C1260 – Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). *ASTM International Standards*, West Conshohocken, PA, 2023.
- Alam R, Dutta RK, and Mishra PR. Effects of bacterial consortium enhanced recycled coarse aggregates on self-healing concrete immobilized with *Bacillus megaterium* MTCC 1684 and *Bacillus subtilis* NCIM 2193. *Scientific Reports*. 2024; 14 (1): 1–16. doi: 10.1038/s41598-024-58666-8.
- Verma A, Mehta A, and Singh G. Durability enhancement of bacterial concrete against alkali–silica reaction and chloride attack. *CivilEng*. 2025; 5 (1): 1–17. doi: 10.3390/civileng05000029.