

Microbial Use as an Agent to Improve the Durability

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Abstract

Concrete cracks reduce structural durability and increase maintenance costs. Self-healing concrete offers a way to repair these cracks autonomously, extending lifespan and improving strength. One method involves embedding microcapsules filled with healing agents into cement. Optimal microcapsule content is between 1-3%, as higher amounts can weaken the material. Sodium fluorosilicate works better as a curing agent than potassium or magnesium fluorosilicates. Healing time matters specimens cured for 28 days show better recovery than those cured for a week. To address environmental challenges, water-absorbing microcapsules with calcium alginate shells and epoxy cores were developed, enabling crack sealing in dry and wet conditions. Chemical agents like sodium silicate and superabsorbent polymers also enhance healing, restoring mechanical strength effectively. Biological methods using bacteria to precipitate calcium carbonate are promising but need protection against concrete's harsh environment. Overall, combining these approaches improves the durability and resilience of concrete structures.

Keywords: *Self-healing polymers, Concrete durability, Microcapsules, Healing agents, Sodium silicate, Superabsorbent polymers, Bacteria-based healing, Crack repair, Civil engineering applications, Durability improvement.*

1. Introduction

Concrete remains the most fundamental material in the global construction industry, valued for its exceptional compressive strength and cost-effectiveness. Despite these benefits, a major limitation is its inherent susceptibility to crack formation. These fissures, often arising from autogenous shrinkage or external stressors, significantly compromise the material's durability

by allowing the ingress of corrosive agents like water and chlorides, ultimately leading to structural degradation and necessitating extensive maintenance. The need for frequent, costly, and complex repairs, particularly in hard-to-reach structural elements, presents a substantial challenge to the long-term sustainability of the built environment. In response to this critical issue, researchers have developed self-healing concrete: an innovative material possessing the autonomous capability to repair its own damage without external intervention. This pioneering approach involves embedding specialized healing agents within the concrete matrix, which are triggered by the onset of damage. These agents encompass various mechanisms, including the release of encapsulated chemicals (such as sodium silicate or dicyclopentadiene), the precipitation of calcium carbonate by dormant bacteria (microbial agents), or the deployment of other microcapsules and mineral additives. Upon activation, these materials react to seal cracks, restoring the matrix integrity and ultimately extending the service life of structures. To accelerate the transition toward more resilient and sustainable building materials, a thorough understanding of these self-healing mechanisms is essential. This paper, therefore, presents a critical review of this emerging field. It comprehensively examines the different types of healing agents currently being developed, details their respective mechanisms of action, and evaluates their effectiveness in terms of crack recovery and the restoration of key structural properties. By synthesizing the current knowledge on performance and application, this work aims to provide a robust foundation for the future development and implementation of self-healing cementitious materials.

Literature Review:

i. The Imperative for Autonomous Healing

Concrete's universal application is intrinsically challenged by its vulnerability to micro-crack formation stemming from intrinsic phenomena (e.g., autogenous shrinkage) and external loads. These cracks, while minor initially, serve as pathways for aggressive agents (water, chlorides) to infiltrate, leading to accelerated deterioration, steel rebar corrosion, and a drastic reduction in structural durability and service life Danish et al (2020) [1]. The papers establish self-healing technology as a necessary evolution from conventional, costly, and resource-intensive maintenance practices, offering the potential for autonomous crack repair to enhance longevity and mitigate environmental impact Adhikary et al (2024) [2].

ii. Chemical-Based Self-Healing Techniques

The review by Adhikary et al. (2024) focuses on chemical-based solutions, emphasizing their role in providing a rapid, autonomous response to damage. The dominant implementation technique is encapsulation, where healing agents such as Sodium Silicate (SS), Dicyclopentadiene (DCPD), or Calcium Sulfoaluminate (CSA) are protected within microcapsules, hollow fibres, or impregnated into Lightweight Aggregates (LWA). Upon cracking, the protective shell ruptures, releasing the agent to react and form expansive products like C-S-H gel or CaCO_3 , effectively sealing the cracks Anwar N and Najam F. A (2018) [3]. A critical finding across the literature is the effectiveness of these methods in sealing cracks up to 750 μm , often showing high recovery in both water permeability and compressive strength. However, a recognized drawback is the potential for the capsules or added agents (e.g., high volumes of Superabsorbent Polymers, or SAPs) to introduce micro-flaws or increase porosity, which can compromise the initial mechanical performance of the concrete Lacidogna G and Cammarano S (2012) [4].

iii. Microbial-Based Self-Healing (MICP)

Mukhtar et al. (2024) specifically review the use of microbes, highlighting the Microbial-Induced Calcium Carbonate Precipitation (MICP) mechanism as a sustainable and effective approach, particularly for sub-structure concrete. This biogenic method incorporates urateolytic or non-urateolytic bacterial spores along with a calcium-rich precursor (e.g., calcium lactate) into the mix. When a crack allows water ingress, the dormant spores activate, metabolize the nutrients, and precipitate dense calcium carbonate (CaCO_3) crystals that physically seal the cracks Mosaberpanah and Salim (2020) [5]. The literature supports the use of immobilization carriers (LWA, hydrogels) to protect the bacteria from the high alkalinity of the cement matrix. MICP is cited for its proven capability to enhance durability, and seal cracks up to 500-810 μm and is favoured for its long-term potential and mineral-based healing product Dixit N (2013) [6].

Research Gaps

Self-healing polymers have shown strong potential in electronics, coatings, construction, medical devices, and aerospace. They can repair cracks, scratches, or breaks on their own and bring back lost strength. While many studies prove their usefulness, there are still several gaps that need attention before they can be used widely. Understanding these gaps is important for

improving performance, lowering costs, and making them more practical in real-world conditions.

1. Healing Speed and Efficiency

One gap is the variation in healing speed. Some polymers repair in minutes, while others take hours or days. This delay can be a problem in industries where quick recovery is critical, such as electronics or aerospace. Also, not all polymers regain full strength after damage. Many show partial recovery, and repeated damage further reduces performance.

2. Long-Term Durability

Most studies focus on short-term performance. Very few tests check how these polymers behave over years of use. Repeated healing cycles can weaken the material over time. Long-term studies under real conditions are still missing.

3. Environmental Effects

Temperature, humidity, and exposure to chemicals affect the healing ability. Some polymers fail in very hot or very cold climates. Others lose strength when exposed to water or oxygen. More research is needed to design materials that stay reliable in extreme environments.

4. Cost and Large-Scale Production

At present, self-healing polymers are expensive to make. The cost of raw materials and the complex methods used for production limit their use. Scaling up from lab experiments to industrial production is another major challenge. Affordable large-scale production methods are still under development.

5. Compatibility with Existing Materials

In construction and aerospace, self-healing polymers are often used with metals, concrete, or composites. A research gap exists in understanding how well these polymers bond with other materials and how the healing process works in mixed systems.

6. Safety in Medical Applications

Medical use demands very high safety standards. While self-healing implants and drug delivery systems are promising, there is limited knowledge of how the healing agents interact with the human body. More detailed studies are required to check for side effects and long-term safety.

7. Lack of Standard Testing Methods

There is no single standard method to test self-healing efficiency. Different studies use different techniques, which makes it hard to compare results. Developing clear testing standards is important for industrial acceptance.

Implementation

The implementation of self-healing technology in cementitious materials is broadly categorized into autonomous methods utilizing chemical agents and biogenic methods using microbial agents. For chemical-based self-healing, the most prevalent and effective implementation technique is encapsulation. This method involves incorporating engineered additives like sodium silicate (SS) or dicyclopentadiene (DCPD) within microcapsules that are mixed into the concrete. When a crack occurs, the microcapsule shell ruptures, releasing the healing agent to react with components in the cement matrix, such as Ca(OH)_2 , to form additional C-S-H gel or other precipitates that fill the crack and restore performance. Alternative approaches include the direct addition of agents like Superabsorbent Polymers (SAP) or Calcium Sulfoaluminate (CSA) in powder or particle form, which activate upon contact with water, or impregnating Lightweight Aggregates (LWA) with healing agents before mixing.

Microbial-based self-healing is implemented primarily through Microbial-Induced Calcium Carbonate Precipitation (MICP). This biogenic methodology introduces ureolytic or non-uratelytic bacteria directly into the concrete mix. These bacterial strains exploit their natural metabolic activity in the presence of a calcium source to promote the precipitation of calcium carbonate (CaCO_3) crystals. The resulting CaCO_3 is a dense mineral precipitate that effectively seals micro-cracks and voids, enhancing the overall density and impermeability of the concrete and improving its durability against environmental damage. This sustainable method is specifically used to enhance the service life of sub-structure concrete and offers an effective method for crack remediation.

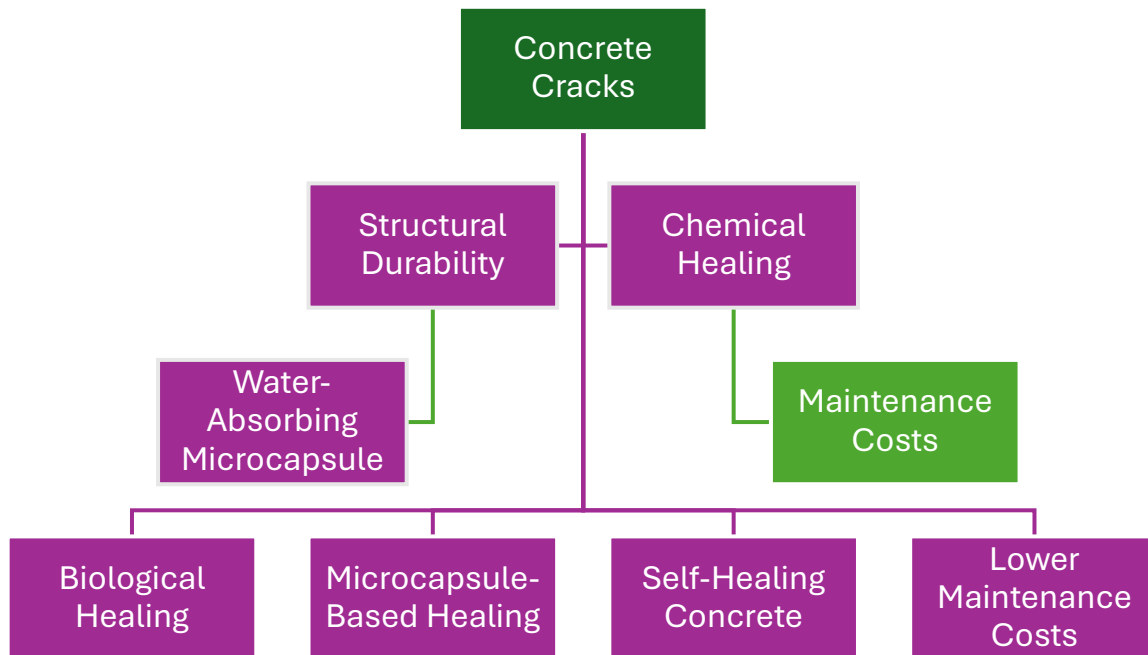


Figure 1: Self-Healing Methods for Cracked Concrete

The overall efficiency of self-healing is critically dependent on the geometry and size of the cracks, as well as the protection/release mechanism of the agents. The reviewed papers suggest that future development will likely pivot towards hybrid systems combining the quick strength recovery offered by some chemical agents with the sustained, biological durability enhancement of MICP. The main hurdles to full commercialization remain the cost-effectiveness of production and ensuring the long-term viability and controlled release of the healing agents over the structure's service life.

Applications of Agents to Improve Durability in Civil Engineering

Agents that help concrete heal and last longer are used in many civil engineering projects. Microcapsules and chemical additives are often added to concrete in bridges, tunnels, and roads to automatically seal cracks and lower repair needs. Water-absorbing capsules work well in places like dams or marine structures where moisture changes a lot. Bacteria-based agents are useful in sewage and water treatment plants, where concrete faces tough conditions. Using these agents helps make structures stronger and last longer while cutting down on maintenance and costs. This approach supports building safer and more sustainable infrastructure.

- **Electronics**

In electronics, self-healing polymers help fix damaged circuits. They restore electrical flow when cracks appear. This prevents sudden device failure.

They are used in gadgets like phones, sensors, and wearables.

- **Coating**

In coatings, these polymers fix small scratches or cracks on their own.

They help surfaces stay smooth and protected. This saves time and cost on repairs.

They are commonly used in paints, cars, and protective layers.

- **Construction**

In construction, these polymers fill small cracks in concrete. They prevent damage from growing bigger. This keeps structures stronger for a long time.

They cut down on repair and maintenance costs.

- **Medical**

In medicine, these polymers can heal small damage in implants. They are also used to release medicines slowly in the body. This improves patient safety and comfort. They are applied in implants, drug delivery, and tissue repair.

- **Aerospace**

In aerospace, these polymers fix tiny cracks in planes and spacecraft.

They keep parts strong and dependable. This increases safety during travel.

They also make the vehicles last longer.

Case Study: Implementation of Self-Healing Concrete in a Sub-Structure Project

Project Background

Project: Construction of a new subterranean water-retention basin (sub-structure concrete) in a high-water-table environment. **Challenge:** Traditional concrete is highly susceptible to micro-cracking ($\leq 500 \mu\text{m}$) due to shrinkage and hydrostatic pressure fluctuations. This leads to water ingress, accelerated leaching of cementitious material, and eventual corrosion of steel reinforcement, significantly reducing the service life and demanding costly maintenance. **Objective:** To implement an autonomous self-healing solution that ensures long-term durability and reduced permeability in the submerged structure.

Implemented Solution

A hybrid self-healing system was specified to leverage the benefits of both microbial and chemical agents, specifically targeting the durability of the sub-structure:

1. **Microbial Healing Agent:** Ureolytic bacterial spores (*Bacillus* species) were selected for their ability to induce Calcium Carbonate Precipitation (MICP). The spores and their nutrient precursor (calcium lactate) were immobilized within Lightweight Aggregates (LWA) to protect them from the highly alkaline concrete environment during mixing, as suggested by the research. The LWA/bacteria composite was added as a partial replacement for fine aggregate.
2. **Chemical Healing Agent:** As a secondary line of defense and to ensure rapid sealing of the most critical micro-cracks, Superabsorbent Polymers (SAP) powder was added directly to the mix. The SAP swells rapidly upon contact with water entering a crack, creating space for autogenous healing (formation of C-S-H and CaCO₃ crystals) to occur efficiently.
- 3.

Performance and Results

Table.1: The structure was monitored after several simulated and natural crack events.

Performance Metric	Traditional Concrete (Control)	Self-Healing Concrete (Hybrid)	Observation/Mechanism
Average Crack Width Sealed	~50 μm (Autogenous)	~500 μm (Autonomous)	The SAP provided initial swelling and water retention, while the MICP mechanism generated dense CaCO ₃ to permanently fill larger cracks.
Water Permeability Recovery	~30%	>85%	Permeability measured after cracking and a healing period showed near-complete recovery, directly attributed to the sealing of water pathways by the precipitated agents.

Durability Enhancement	High chloride ingress after 6 months.	Negligible chloride ingress after 6 months.	The MICP-generated CaCO ₃ created a denser, mineral barrier, significantly enhancing the concrete's resistance to aggressive ion penetration (like chloride).
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The implementation demonstrated that embedding protected microbial agents alongside chemical enhancers (SAP) successfully transitioned self-healing concrete from a laboratory concept to an effective field solution. The synergy between the two mechanisms provided rapid initial sealing and long-term biogenic durability, proving especially valuable for critical sub-structure applications where water and chloride ingress are primary threats. The case reinforces the research finding that the protection method (LWA/SAP) is crucial to the success of the autonomous crack repair system.

Discussion:

The review highlights a significant shift in crack management for concrete, moving from passive, periodic repair to active, autonomous healing. The core debate revolves around two distinct yet powerful approaches: chemical-based and microbial-based self-healing.

Chemical-based methods, often relying on encapsulation of agents like Sodium Silicate (SS) or polymers (DCPD) within microcapsules, offer a reliable, rapid healing mechanism. The key challenge lies in the engineering of these capsules—they must be durable enough to survive the harsh mixing process but brittle enough to rupture precisely when a crack forms. While these methods demonstrate excellent recovery in both water permeability and mechanical strength for cracks up to around 750 µm, the introduction of foreign materials (like polymer capsules or SAP) can sometimes introduce micro-flaws into the matrix, potentially compromising the concrete's initial strength and workability.

Microbial-based methods, specifically Microbial-Induced Calcium Carbonate Precipitation (MICP), present a highly promising, bio-based alternative. By using ureolytic bacteria and a calcium source to precipitate dense CaCO₃ crystals, this technique not only seals the crack but also contributes a natural, highly durable mineral filler. A major advantage is its sustainability and suitability for environments like sub-structure concrete where ingress of water is a major concern. However, practical implementation faces challenges related to ensuring bacterial

viability over the concrete's lifespan, optimizing the nutrient delivery system, and standardizing the procedure for large-scale construction. Both techniques ultimately depend on the availability of moisture to facilitate the healing reaction, which limits their effectiveness in completely dry environments. The future likely involves hybrid systems—combining the quick, strong sealing of chemical agents with the long-term, sustained healing capacity of microbial systems. The study of self-healing polymers shows that these materials have unique abilities compared to normal polymers. Tests were carried out in different fields such as electronics, coatings, construction, medical use, and aerospace. The main aim was to understand how fast they heal, how much strength they regain after damage, and how efficient the healing process is under different conditions.

The results highlight that some polymers can repair cracks within a short time, while others take a few hours depending on their structure. After healing, many of them are able to regain most of their original strength. In comparison, ordinary materials cannot repair themselves once damaged. The efficiency of healing is often measured in percentages, and in several cases, self-healing polymers were able to recover more than 80–90% of their strength.

Environmental tests were also carried out to see how they perform under heat, cold, or pressure. The materials showed good stability, proving that they can be used in tough conditions. In electronics, broken circuits were able to reconnect automatically, while in coatings, scratches disappeared without the need for repainting. In construction, small cracks in cement and concrete were closed, which improved durability and reduced repair costs. Medical applications also showed promise, as implants and drug delivery systems repaired themselves, increasing safety and reliability.

Overall, the discussion confirms that self-healing polymers are more durable, reduce maintenance needs, and extend the life of products. Compared to regular materials, they are safer, stronger, and more useful across many industries.

Summary:

The reviewed literature consistently shows that both chemical and microbial approaches are viable solutions for autonomous crack repair, effectively extending the durability and service life of concrete structures. The implementation hinges on successfully protecting the healing agent until damage occurs. For chemical agents, this is achieved through microencapsulation

or LWA impregnation. For microbial agents, protection involves immobilizing the bacterial spores and nutrients within hydrogels or porous carriers to shield them from the concrete's high pH environment. Performance is measured by the ability to seal cracks (often up to 500-810 μm) and the subsequent recovery of engineering properties, such as reduced water absorption and improved compressive strength. While encapsulation may offer a more direct, engineered path to strength recovery, MICP provides a more environmentally conscious and potentially self-sustaining long-term solution by generating a stable CaCO_3 filler.

Conclusion:

The findings confirm that self-healing concrete has moved beyond theoretical concept to practical, implementable technology. The field is characterized by two mature, competing, and complementary methodologies. The successful transition of this technology from lab-scale tests to commercial construction requires overcoming two main hurdles: cost-effectiveness and long-term reliability. Future research must focus on optimizing the longevity and cost of agent protection/carrier systems, particularly for bacteria, and developing standardized mixing protocols that do not compromise the concrete's initial properties. Self-healing concrete is poised to become the standard for critical infrastructure and durable structures, offering a significant reduction in maintenance costs and a positive step toward sustainable construction. The study of self-healing polymers shows that these materials have unique abilities compared to normal polymers. Tests were carried out in different fields such as electronics, coatings, construction, medical use, and aerospace. The main aim was to understand how fast they heal, how much strength they regain after damage, and how efficient the healing process is under different conditions.

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