

A Review on Study of Self-Healing Concrete in Architectural Applications

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Abstract:

Concrete has continued to be a significant component of contemporary construction, but its ability to crack compromises structural integrity and increases maintenance needs. The development of self-healing concrete offer solutions to these problems by extending its lifespan and repairing damage on its own (autonomous healing). The mechanisms of various self-healing systems including autogenous, microbial, capsule-based, vascular and polymeric approaches are investigated in this study. To restore strength and stability and to stop cracks from spreading, each mechanism makes use of different healing agents and techniques. Tests on water tightness and permeability, SEM (Scanning Electron Microscopy), mechanical, tensile and flexural strength recovery and microstructure are used to evaluate performance, and the results show positive results in watertightness, durability and resistance to environmental degradation. The study also covers the practical and economic factors that affect the extensive use of SHC in addition to its structural and functional advantages, stating that it can lower maintenance costs, carbon emissions and material loss. The start of developments in bio-based and hybrid systems suggests future applications to sustainable architecture and infrastructure, also pointing out the disadvantages and limitations of the same. In summary, self-healing concrete is a notable advancement in construction techniques.

1. Introduction

From the earliest lime and volcanic ash mixtures to the most advanced composites of today, concrete has been the foundation of modern civilization for many centuries. Despite being widely used and robust, concrete is prone to cracking, a flaw that compromises durability and shortens the building's lifespan. Early in the twenty-first century, the concept of self-healing concrete was presented as a solution to all of these prevalent issues. Due to global demand, self-healing concrete is required. Common concrete preservation methods are expensive and require a lot of energy and materials. One of the materials in this study that can fix cracks without direct human assistance is self-healing concrete. The structure's integrity is restored and crack-related deterioration is avoided through a number of methods. One creative method that blends creativity and materiality is self-healing concrete. It is anticipated to revolutionize building construction in the years to come.

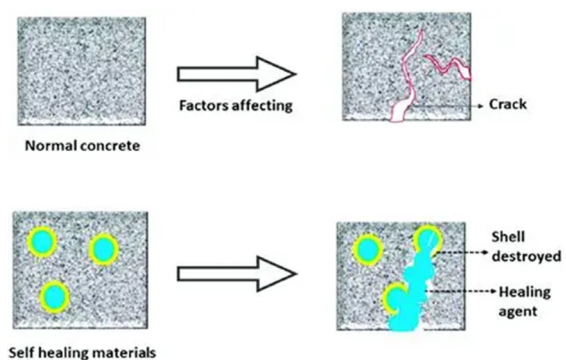


Fig. 1:

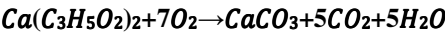
Differentiation between normal concrete and self-healing concrete

Source: Raghav Muralidharan et al. (2021)

2. Mechanisms of Self-healing Concrete

2.1. Autogenous healing: Concrete has the inherent ability to mend minor cracks on its own without the need for an outside agent. This phenomenon is caused by carbonation of calcium hydroxide method, which depends on various factors like temperature, water availability, cement type and crack size. This mechanism of healing is usually effective for cracks that are between 0.2 and 0.3 mm wide.

2.2. Microbial or Bacterial self-healing: The use of biological ways to repair cracks is one of the leading and most successful concept in material science. This is adapted from natural systems, where specific bacterial strains, such as *Bacillus subtilis*, *Bacillus sphaericus*, or *Bacillus pasteurii*, are added to the concrete mixture, along with calcium lactate. The bacteria are embedded within the concrete and remain dormant as spores until water seeps through the cracks formed in the surface of concrete. The precipitation of calcium carbonate (CaCO_3) begins when the bacteria are activated and begin to metabolize the calcium-based nutrients. This inorganic compound restores the density and impermeability of the concrete by filling in through the cracks. The overall reaction can be shown as:



2.3. Capsule-based self-healing: In this type of healing, the concrete mixture is supplemented with special capsules containing healing agents. The capsules burst and the healing agent begins to spread, right as the cracks begin to form and spread through the concrete. The concrete's structural integrity is restored when the released agent responds to an outside stimulus and seals the cracks together.

2.4. Vascular self-healing: This advanced healing technique is based on biological circulatory systems. A network of interconnected tubes or artificial capillaries embedded in concrete are examples of such systems. The healing agent automatically seeps into the damaged area after passing through the network when a crack opens up these tubes. Vascular networks are multi-cycle systems because they continuously supply healing agents. The healing medium, which is typically epoxy resin, sodium silicate, or polymeric material, is maintained in an external reservoir that is connected to the internal

network and can be replenished continuously or as needed.

2.5. Polymeric healing: Polymers, such as epoxy resins, polyurethane, cyanoacrylates, or methyl methacrylate (MMA), are the main agents used in polymeric healing to fix cracks. These systems can be applied alone or in conjunction with vascular or capsule-type techniques. The polymer is released into the crack as it forms, where it undergoes polymerization or curing, which is typically brought on by exposure to air, moisture or a catalyst. The polymer preserves the strength and longevity of the concrete structure by curing to form a flexible, long-lasting seal that is impermeable to chemicals and water.

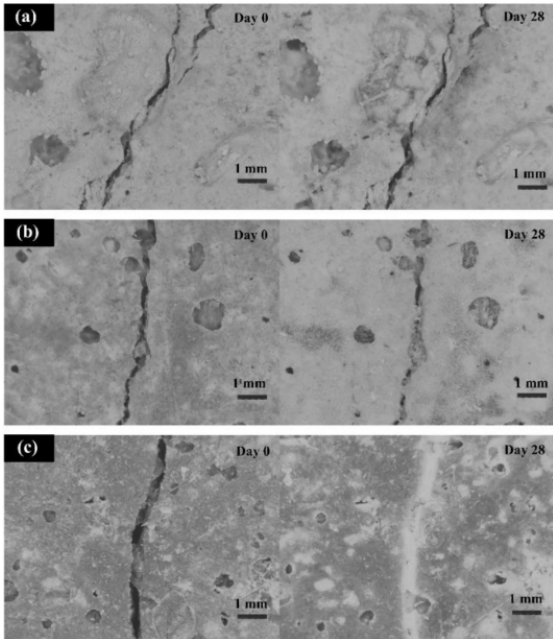


Fig. 2: Evolution of crack healing via microbial process: (a) reference; (b) abiotic control; (c) microbial
Source: [Mugahed Amran et al. \(2022\)](#)

3. Material Composition

Table 1: Healing mechanisms, primary materials and healing agents – a comparison

Healing Mechanism	Key Materials Used	Healing Agent / Additives
Autogenous Healing	Ordinary Portland Cement (OPC), Supplementary Cementitious Materials (SCMs) like fly ash, silica fume, slag	Un-hydrated cement particles, water, CO_2 from air
Microbial (Bacterial) Healing	Cement matrix, bacterial spores (e.g., <i>Bacillus subtilis</i> , <i>Bacillus pasteurii</i>), calcium source	Calcium lactate, yeast extract, urea
Capsule-Based Healing	Cement matrix embedded with polymeric or glass micro/macro capsules	Epoxy resin, polyurethane, sodium silicate, or dual-component resin + hardener
Vascular Network System	Concrete matrix with embedded hollow glass tubes, polymeric pipes, or capillary channels	Epoxy, sodium silicate, cyanoacrylate, or polymeric adhesives
Polymeric Healing	Cementitious matrix with dispersed polymeric phase or capsules	Epoxy, polyurethane, methyl methacrylate (MMA), cyanoacrylate

Source: Joseph et al. (2010)

4. Tests and Performance

Table 2: Healing mechanisms, tests, performance and sources

Healing Mechanism	Tests	Performance	Sources
Autogenous Healing	Water permeability test, Crack sealing observation (microscopy), Compressive & flexural strength recovery	Reduction in water permeability up to 60–80%, Visible crack closure (≤ 0.3 mm), Partial recovery of strength (10–40%)	Snoeck & De Belie (2015); Van Tittelboom & De Belie (2012); Li & Herbert (2012)
Microbial Healing	Water absorption and permeability, Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) for CaCO_3 formation, Strength recovery test	Crack closure up to 0.8 mm, CaCO_3 precipitation confirmed by XRD, Strength regains up to 80–90%	Jonkers (2007); Wiktor & Jonkers (2011); Seifan et al. (2016)
Capsule-Based Healing	Split tensile & flexural test before/after healing, Microscopy for capsule rupture, Ultrasonic pulse velocity test	Restoration of tensile strength up to 70%, Crack sealing efficiency dependent on capsule distribution	Joseph et al. (2010); Yang et al. (2011); Van Tittelboom & De Belie (2010)
Vascular Network Healing	Flow test, Crack width monitoring over time, Repeated healing cycle analysis	Multiple healing cycles possible, Self-repair of cracks up to 0.5–1 mm width	Van Tittelboom et al. (2010); Joseph et al. (2010)
Polymeric Healing	Mechanical strength recovery, Scanning Electron Microscopy, Water tightness & permeability	Sealing efficiency up to 90%, Improved durability and reduced permeability	Wang et al. (2012); Yang et al. (2011)

5. Discussions

5.1. Sustainability Implications

Self-healing concrete is a revolutionary advancement in construction materials, particularly with regard to durability and sustainability. Its ability to extend the lifespan of buildings lead to fewer replacements and repairs, which immediately reduce waste production and prevent the depletion of essential raw materials that are becoming scarcer. The environmental benefit is even greater because self-healing concrete lowers the overall cement consumption, since cement manufacturing is a major global source of carbon dioxide emissions. Self-healing concrete can also improve energy and cost efficiency. Self-healing concrete is a better choice for sustainable development in both public and private sectors since it requires less maintenance, which lowers labour, material and energy costs over the course of a structure's lifetime. To add on, infrastructure resilience is important as climate change causes more severe and frequent weather occurrences. The ability of structures to withstand weather stresses is highly increased in terms of self-healing concrete, which is a highly desirable property in regions vulnerable to severe weather or environmental degradation.

5.2. Architectural Applications

5.2.1. Roads and Bridges: Heavy vehicles contribute to the continuously shifting forces that affect roads, bridges and roadways, in terms of weather-related factors like temperature fluctuations, the effects of rain and extremely hot weather. All of these factors have the potential to develop tiny cracks over time, which, if left untreated, could grow larger in size. Cracks allow water and other harmful to concrete substances to seep inside, accelerating the deterioration of the steel inside and weakening the structure as a whole. Self-healing concrete makes roads and bridges

stronger for longer periods of time, making the transportation system safer and more reliable.

5.2.2. Tunnels and Underground Structures: Tunnels and underground structures are enclosed, subject to high pressure from the ground below and constantly come into contact with subterranean water. Water can enter these structures through even tiny cracks, speeding up the rusting of the steel within the concrete. Common repair techniques like adding additional layers or injecting grout, are costly and time-consuming. In fact, using self-healing concrete when building tunnels would increase the structure's resilience to stress. Self-healing concrete would be especially useful for underground structures that are challenging to reach for repair.

5.2.3. Marine and Coastal Structures: Harbors, offshore platforms, and seashore bridges are examples of construction projects that are subject to difficult environmental conditions along the sea and coastline. Due to seawater, waves, high humidity, and high levels of chlorides from the seawater, the concrete and the steel inside are exposed to harsh corrosive conditions. Chloride ions can enter through these internal cracks in the structure, which drastically reduces how long the structure will last and the chance that it will collapse. Since early crack sealing can stop chlorides from seeping into the concrete, delay steel rust, and keep the structure secure, self-healing concrete is incredibly helpful. As previously stated, the concrete can self-heal minor cracks as soon as they appear using a variety of techniques. Because fewer costly underwater inspections and repairs are required, stronger ocean structures that can withstand unfavourable conditions for years can be built.

5.2.4. Water Retaining Structures: To prevent water losses and guarantee proper operation, water should not leak out of dams, canals, reservoirs, water tanks, or water

treatment facilities. These structures have leaks that allow water to escape, which not only renders them ineffective but also deteriorates the soil, erodes the structure, and eventually leads to failure if left unfixed. These structures must be regularly inspected and any leaks must be sealed, which can be expensive, time-consuming, and challenging to do in remote areas. Self-healing concrete offers a long-lasting and reasonably priced solution by enabling these structures to automatically patch minor cracks as they appear. In places where water scarcity is common, this technology serves helpful.

5.3. *Economical and Practical Considerations*

5.3.1. *Initial Expense vs. Long-Term Advantage:*

The initial cost of installing self-healing devices is a major drawback. According to research (Van Tittelboom & De Belie, 2013), the initial costs of producing SHC can be 30–50% higher than those of producing regular concrete. However, when comparing lifetime costs, it becomes clear that the higher prices are justified because there is less need for future maintenance and repairs. According to Li & Herbert (2012) and Jonkers (2007), for example, buildings built using SHC can be extended by 20–40%, greatly lowering the long-term costs of inspection, repair, and lost time.

5.3.2. *Material Scalability and Availability:* The availability of materials locally actually determines how well SHC can be produced at high levels. Some self-healing and bacteria-based systems use regular cement components, but capsule and vein-like systems usually need materials that are imported or specially made for them (Yang et al., 2011). In less developed areas or on smaller construction projects, where it is better to use inexpensive, locally accessible materials, this becomes more challenging to use. In order to make things more cost-effective and ecologically friendly, the most recent research focuses on healing agents made of waste or living things, such as locally grown bacteria or recycled plastics.

5.3.3. *Construction and Implementation Compatibility:* It must be compatible with the way we currently build things in building applications. Self-healing concretes that use bacteria and natural processes can be mixed and poured using standard methods and are more useful for field construction. Vein-like and capsule-based systems, on the other hand, are best suited to items that are pre-prepared or crucial structural components because they require extremely careful control when pouring and mixing to avoid breaking or losing things (Joseph et al., 2010). These systems work best in controlled settings, like sturdy building components or factory-made wall sections.

5.3.4. *Durability and Reliability:* The functionality of self-healing concrete is determined by its healing procedure and its endurance against different loads and weather conditions. Bacterial systems, for example, is not preferable in extremely dry or freezing conditions because they need certain specific humidity and temperature levels to function and began the healing process (Wiktor & Jonkers, 2011). In order to make self-healing concrete more efficient across a wider range of conditions, scientists are creating hybrid approaches, like combining two or more

healing mechanisms together to form a more resilient healing mechanism. (Wang et al., 2012).

5.3.5. *Sustainability and Environmental Impact:*

Self-healing concrete improves sustainability by lowering the need for maintenance and repairs, waste production and energy consumption over the lifetime of a building. This is because self-healing concrete lasts longer and fewer CO₂ emissions are released, making it a good choice for green building certifications like LEED and GRIHA. Since bacterial healing uses natural calcium carbonate, it is especially environmentally friendly and coordinates with sustainable building methods.

5.3.6. *Current Market Feasibility:* Self-healing concrete is still new to building design and constantly under process in the research and development sector. There are currently problems with the cost of using special healing agents. However, concrete variants that are bacteria-based and self-healing are slowly brought into the picture in some building markets.

Conclusion

Self-healing concrete is a need-for-the-moment development in building materials that could give structures higher strength, reduced repair costs and longer lifespans. This technology prevents cracks from spreading and structural damage by helping concrete to heal autonomously using special external agents. It is becoming more cost-effective and ecologically friendly, according to ongoing research in biological technology and intelligent devices. Self-healing concrete may play a key role in resilient and low maintenance structures in the near future.

Limitations

Self-healing concrete has several drawbacks that prevent its use in real-world construction projects despite its advantages. The primary problem is the high initial cost of healing materials to the concrete mixture. The use of very expensive materials and procedures raises production costs considerably. The secondary problem is self-healing systems being in use today can only repair small cracks. Larger structural cracks cannot be repaired by current techniques. Another issue is the stability of the healing agents in concrete, when environmental conditions change. It is necessary to use materials that can act with resilience to changes in temperature, chemicals and moisture, as some healing mechanisms use chemical healing agents (like bacteria) that must stay active for decades with the same initial efficiency.

Future scope

Self-healing concrete could completely transform the way we build and maintain structures, if sustainable building techniques and the need for enduring infrastructure are given more attention. Self-healing concrete is a significant advancement in construction technology that has the potential to completely transform the construction sector. This innovative material provides a long-lasting, environmentally friendly and permanent solution for construction projects. Self-healing concrete could contribute to the development of a robust built environment in the future by repairing cracks, reducing maintenance expenses, reducing carbon emissions and making structures safer. Self-healing concrete is expected to become an important subject

of study, as research and development advances, bringing us one step closer to a more robust and long-lasting building future.

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