Advances in Autogenous and Autonomous Self-Healing in Cementitious Composites: A Critical Review

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Abstract: The intrinsic susceptibility of traditional concrete to cracking contributes substantially towards infrastructure fragility and the need for expensive, unsustainable repair. This review thoroughly examines self-healing (S-H) cementitious composites, classified into Autogenous (Intrinsic) and Autonomous (Engineered) healing systems. Autogenous healing, depending on ongoing hydration and precipitation of calcium carbonate, is generally restricted to the sealing of microcracks less than 150 µm. Autonomous approaches bypass this limitation through encapsulated agents, vascular networks, or bio-concrete, which utilizes microbial-induced calcite precipitation (MICP) to fix larger damage (up to 1 mm). Autonomous technologies hold the promise of increased longevity and multi-year life extension, but are limited by widespread adoption due to high upfront costs, requiring standardized testing protocols, and still unsolved material compatibility problems, including a potential war between antimicrobial nanomaterials and bio-agents. Finally, self-healing technologies offer a clear plan for reducing life-cycle costs and creating the next generation of resilient and sustainable building materials.

Keywords: Self-healing; Autogenous healing; Autonomous healing

1. INTRODUCTION

Concrete is the most widely used building material worldwide, as it is affordable, easy to access, durable, and possesses high compressive strength. It has many uses, serving as the basis for infrastructure construction today, such as roads and buildings, dams and tunnels. Yet this broad application conceals a critical intrinsic weakness, i.e., its low tensile strength and limited ductility, which makes it extremely prone to cracking. This crack development, even on microscopic levels, is a common and almost unavoidable occurrence, and it is the main cause of structural deterioration.

The creation of cracks provides a pathway for the invasion of aggressive substances, i.e., water, acid rain, chlorides, and corrosive chemicals, into the concrete structure. This penetration results in a gradual loss of material durability and can lead to the corrosion of steel reinforcing bars, which are vital to a structure's tensile strength. This degradation undermines the structural integrity and remarkably reduces the service life of concrete structures. The economic cost of this deterioration is widespread, with it being estimated that billions of dollars are spent annually on the repair and restoration of concrete structures alone in the United States.

Conventionally, the sector has relied on conventional, reactive repair methods to crack repair, e.g., manual patching, epoxy injection, or cement slurry application. However, such a form of intervention is usually inefficient, resource-intensive, and costly, particularly for extensive or inaccessible infrastructure like highways, bridges, and underwater foundations. One of the serious weaknesses of these types of intervention is their inability to cope with internal microcracks, which are usually impossible to see but act as triggers for further, large-scale degradation. Also, constant repair is only temporary by nature and does not displace the original strength of the building, and further work will be required in the future. This reliance on outside, human-dependent means for repairs demonstrates a systemic inefficiency within the current paradigm of building, which justifies the need for a more preventative, in-built approach.

Self-healing materials are not a new idea; autogenous healing in cementitious composites had been explained by the French Academy of Science as early as 1836 Ojha et al., (2025). However, the field has been revolutionized, from an early observation to a growing arena of active research. The volume of scientific papers on self-healing concrete rose exponentially starting in 2007 with a 20.4% yearly growth rate, from 2007 to 2021 Karawi et al., (2025). Such growth, which is driven by growing interest in infrastructure life-cycle cost, sustainability, and safety, is an indicator of a resounding shift toward the development of intelligent, "smart" concrete that can self-heal and extend its service life with little or no external intervention.

2. SELF-HEALING CONCRETE MECHANISM CLASSIFICATION

Self-healing technology in concrete is typically categorized into two fundamental approaches: autogenous healing, based on inherent material properties, and autonomous healing, based on sophisticated, engineered systems.

2.1. Autogenous (Intrinsic) Healing

Autogenous healing is understood as the intrinsic capacity of concrete to heal cracks employing its native constituents. It is a passive process, with no addition of engineered, specialized healing substances, which has been observed in normal concrete over centuries. It relies mostly on the presence of un-hydrated cement particles as well as the presence of suitable external conditions to allow the necessary chemical reactions. While it is an economical and environmentally friendly technique, its biggest drawback is that it can only repair small cracks, typically less than 100-150 µm Yang et al., (2009). Lack of knowledge of when sufficient moisture will be present to render the healing feasible is another significant limitation of this technology.

2.2. Autonomous (Engineered) Healing

Unlike autogenous healing, autonomous healing is a process that involves the direct addition of engineered additives to the concrete matrix during the mixing or casting process. These "healing agents" are designed to react to a stimulus, i.e., the emergence of a crack, to trigger a repair process autonomously. This method overcomes the limitation of autogenous healing through the capability to heal bigger cracks, normally bigger than 300 µm and, in some cases, up to 1 mm Maes et al., (2014). The central strategies of autonomous healing include encapsulation-based systems, bio-based healing, vascular networks, electrodeposition, and shape-memory materials.

3. AUTOGENOUS HEALING: THE INTRINSIC REPAIR CAPACITY

The fundamental concept of self-healing concrete begins with its inherent ability to heal itself. This, in most cases, happens in ageing infrastructure, and is a combination of advanced chemical and physical mechanisms which are driven by the composition of the material and exposure to the environment.

3.1. Processes of Autogenous Healing

Autogenous healing is a process involving multiple steps. It depends upon the interaction among water, cement, and air gases in terms of developing new minerals and compounds that seal and occupy physically a crack.

3.1.1. Continued Hydration

Continued hydration is also identified as a major mechanism of autogenous healing, taking advantage of the natural inefficiency of concrete production. A large percentage of the cement, usually 20–30% of its volume, is left unhydrated following the initial setting stage. Upon the development of a crack and water entry into it, the sleeping cement particles are reactivated, triggering a secondary hydration reaction. This reaction forms new hydration products, mostly calcium-silicate-hydrate (C-S-H) gel and calcium hydroxide (CH), that expand physically to occupy the void and cap the crack. This process is especially useful because the healing products have a strength similar to the original C-S-H matrix, so the lost mechanical properties can be restored partially.

The analysis of the formed hydrate structures, as divided by Huang et al. (2013), indicates high sensitivity to the cement type. CEM (I) cement, for example, leads to healing products dominated by crystalline CH, with small amounts of C-S-H (17%) and $CaCO_3$ (5%). CEM (III) cement, on the other hand, produces a more balanced structure with a larger proportion of C-S-H (57%) and considerable $CaCO_3$ (20%). The composition of CH is a very important consideration, as it is the primary source of Ca^{2+} ions and implies that the type of cement has a significant and indirect effect on the extent and effectiveness of carbonation, the other principal autogenous healing mechanism.

3.1.2. Calcium Carbonate ($CaCO_3$) Precipitation

Calcium carbonate ($CaCO_3$) precipitation is commonly identified as the prevalent process responsible for efficient crack sealing in autogenous healing. Autogenous healing is a process involving multiple steps and depends upon the interaction among water, cement, and air gases in terms of developing new minerals and compounds that seal and occupy physically a crack.

Water that seeps through the crack first dissolves any present calcium hydroxide (CH) in the cement matrix, which releases calcium ions (Ca^{2+}) into the pore solution. At the same time, atmospheric carbon dioxide dissolves in the water to produce carbonic acid (H_2CO_3), which splits into carbonate ions (CO_3^{2-}). The mixing of these ions precipitates $CaCO_3$ crystals that form on the crack faces and sequentially fill the opening. The total chemical reaction is basically expressed as:

$$Ca^{2+}+CO_3^{2-}\rightleftharpoons CaCO_3$$

The formation of $CaCO_3$ deposits is the intrinsic foundation for prolonged self-healing when cracked concrete is subjected to fresh water (usually near or above the neutral pH) and a CO_2 rich atmosphere. outside surfaces of cracks. The precipitation kinetics are important, commencing with a fast, "surface-controlled crystal growth" stage, followed by a much slower "diffusion-controlled crystal growth" stage as the local concentration of Ca^{2+} ions at the crack face is depleted.

The chemical pathway is shown in detail, showing the pH-dependence of the process. The production of carbonate species is given by the equilibrium:

$$H_2O+CO_2\rightleftharpoons H_2CO_3\rightleftharpoons H^{+}+HCO^{3-}\rightleftharpoons 2H^{+}+CO_3^{2-}$$

The following $CaCO_3$ precipitation takes different courses depending on the solution pH:

$$Ca^{2+}+CO_3^{2-}\rightleftharpoons CaCO_3\ (\text{pHwater}>8)$$

$$Ca^{2+}+HCO^{3-}\rightleftharpoons CaCO_3+H^{+}\ (7.5<\text{pHwater}<8)$$

Whereas early research by Neville et al., (1995) merely explained self-repair as due to ongoing hydration of the unhydrated cement constituents, later studies have shown that this phenomenon holds only for the initial years of the life of concrete. On the contrary, the formation of calcium carbonate has been proven to be the main and general foundation of self-repairing through the following and more robust stages.

3.1.3. Physical Mechanisms (Swelling and Blocking)

In addition to the main chemical reactions, autogenous healing is assisted by two physical mechanisms: swelling and blocking. Swelling is an ongoing, partially reversible process in which water is taken into the cement stone, causing a localized expansion that physically closes the crack. Although studies indicate this effect is relatively small for wider cracks than 100 µm, sealing could reverse partly under dry conditions Lahmann et al., (2023). Cyclic exposure tests have indicated that loss of sealing decreases with repetition, which shows the process is not reversible. It is still a major area of research to quantitatively measure the independent effect of swelling because it is always in interaction with simultaneous mechanisms such as calcite precipitation and autogenous shrinkage. The second mechanism, blocking, is prompted by the mechanical action of fluid transport. This is because fine debris from the crack faces or impurities and suspended fine particles in the intruding water are physically trapped at narrow points within the crack's morphology. This mechanical block truly diminishes water flow along the crack, producing a micro-environment with increased saturation and residence time, more favorable to the following and continued chemical healing reactions. Even though this mechanism is deemed central to the self-healing process regulated by fluid motion, offering conclusive, definitive experimental evidence of the precise flow pathway blockage is a recognized challenge within the materials research community.

3.2. Factors Governing Autogenous Healing Effectiveness

Autogenous healing is not always guaranteed, but it is highly dependent on several decisive factors:

1. *Geometry and Width of the Crack:* Autogenous healing is best suited for highly narrow cracks. Perfect healing is always specified for cracks smaller than 50 μm, while the mechanism becomes less efficient as the crack width approaches or is more than 100-150 μm. For larger cracks, the quantity of healing material may not be sufficient to fully bridge and seal the gap. The size of the crack, or its depth and length, also plays a role, since smaller-width cracks would require less material to repair.

2. *The Key Role of Water and Curing Conditions:* Water is an absolute necessity for all processes of autogenous healing and serves the dual role of both a reactant for prolonged hydration as well as a vehicle for ion and particle transfer. Studies have shown that immersion in water at all times is highly successful because it delivers an unlimited supply of a critical reactant. However, other studies show that wet/dry cycling could be even more advantageous because the drying time allows atmospheric CO_2 to penetrate, which is a required element of the calcium carbonate precipitation process.

3. *Age of Concrete and Mix Proportions:* The cracking age of the concrete is a significant parameter. Early-stage cracking is more useful for healing since the concrete matrix

contains a higher percentage of unhydrated cement particles to participate in further hydration. The mix proportion of the concrete also matters, i.e., the water-to-cement (W/C) ratio; the lower the W/C ratio, the higher the available un-reacted cement residue to contribute to the healing reaction.

4. ADVANCED APPROACHES FOR STIMULATED AUTOGENOUS HEALING

In addition to the inherent characteristics of traditional concrete, various engineered supplements can be included that will deliberately activate and augment the autogenous healing process, essentially extending its potential beyond the natural limits.

4.1. Nano-fillers' Action in Autogenous Self-Healing

Nanofillers constitute a group of additives that are very efficient in increasing the strength, durability, and smart characteristics of cement-based materials and have proved to be successful in different composites such as epoxidized natural rubber and epoxy nanocomposites. Their capacity to increase the self-repair of concrete is based on three major mechanisms. In the first place, since they possess a high surface energy, compounds such as nano-ZrO_2, nano-TiO_2, and Carbon Nanotubes (CNTs) serve as nucleation (seeding) sites in the cement pore solution Jialiang et al., (2018). This significantly increases the deposition of hydration products, essentially reducing the inactive phase of cement hydration and inducing a denser matrix (Fig. 4). Second, nanofillers improve the three-dimensional network of the cement matrix. Such improvement guarantees that upon the occurrence of damage, it appears in the form of finer, scattered microcracks instead of extensive, critical fractures. For example, CNTs in ECC were found to minimize maximum crack width to 50 μm and facilitate successful crack bridging, along with the recovery of mechanical properties. Lastly, active nanofillers like nano-SiO_2 and coated nano-TiO_2 engage in pozzolanic reactions with calcium hydroxide ($Ca(OH)_2$) Wang et al., (2018). The reaction generates more Calcium-Silicate-Hydrate (C-S-H) gel, which further densifies and chemically seals cracks in the material. This physical and chemical process enables researchers to produce composites with highly controllable healing capacity and fracture toughness.

4.2. Role of Mineral Admixtures and SCMs

The use of Mineral Admixtures and Supplementary Cementitious Materials (SCMs) is one of the main methods of enhancing the autogenous self-healing ability of concrete. Minerals such as fly ash (FA), ground granulated blast-furnace slag (GGBFS), and silica fume (SF) are incorporated into the mix, where they are partially un-hydrated. When a crack develops and water enters the matrix, these concrete materials exhibit a retardation pozzolanic reaction. This reaction absorbs the available calcium hydroxide (CH) to produce more Calcium-Silicate-Hydrate (C-S-H) gels, which seal the crack physically and increase the long-term strength and durability of the concrete. The process's effectiveness relies on the presence of adequate amounts of CH to initiate the reaction and can be improved by means of alkaline solution or higher curing temperatures. Besides SCMs, expansive minerals are also utilized, either being left unhydrated to react in the future or creating expansive hydrated products for immediate crack healing.

Autogenous healing can be significantly enhanced by adding various materials such as expansive minerals and Crystalline Admixtures (CAs). One traditional mode utilizes additives such as Calcium Sulphoaluminate (CSA) or multi-mineral mixtures (e.g., bentonite clay, quartz, and carbonates). These mixes are formulated to trigger swelling, expansion, and subsequent re-crystallization to seal gaps.

While chemical expansive additives give a speedier volume expansion than silica-based CAs' slow process of crystallization, the best solution is generally to use silica-based, swelling, and crystalline materials to best achieve speed and duration balance. Steel fiber-reinforced concrete study with CAs set up crack sealing to 0.3 mm in water, although healing was limited without a constant supply of water Cuenca et al., (2018). Other expansive admixtures that are efficient include mixtures of bentonite clay, magnesium oxide (MgO), and quicklime, which substitute Portland cement (PC) best by 12.5–15% Ahn et al., (2010). This strategy increases healing even in old PC mixes and has been found to seal drying shrinkage cracks up to 400–500 μm in expansive mineral mixtures, significantly surpassing the capacity of plain PC mixes (∼160 μm). Importantly, in fiber-reinforced MgO-cement composites, seawater-exposed $Mg(OH)_2$ precipitation was found to effectively prevent chloride permeation. Certain SCMs employed in the concrete matrix for autogenous healing are as follows:

1. *Ground Granulated Blast-Furnace Slag (GGBFS):* GGBFS, which is an industrial waste, significantly enhances autogenous repair, particularly in the long term, owing to its pozzolanic and cementitious properties. Concretes with the addition of slag (to 50%) have very high potential for autogenous healing, and hydration products are more complex in

nature than usual PC, i.e., calcite, ettringite, portlandite, and hydrotalcite. Tests have established that GGBFS tends to excel over FA in inducing self-healing due to its higher pH and CaO composition, which will enhance the generation of calcite. For instance, 45% slag-blended samples recovered tensile strength by as much as 59% in re-cured tap water, and cracks up to 100 µm were successfully healed in slag-blended ECC Sun et al.,(2022). The decreased rate and extent of hydration in GGBFS blends compared to normal PC indicates a greater reservoir of un-hydrated material available for near and remote crack filling.

2. *Fly Ash (FA):* FA, a coal combustion by-product, is mainly composed of silicates and aluminates. Substituting 15–20% OPC with FA improves repairing qualities by improving the pore structure and enhancing the development of C-S-H gel during subsequent ages Termkhajornki et al., (2009). While FA provides a lot of non-reacted binder, studies show conflicting evidence about its impact on early-age cracking. When concrete is prematurely pre-cracked (at 3 days), FA-blended specimens typically exhibit poorer healing due to the insufficient availability of CH needed to initiate the pozzolanic reaction. However, FA significantly enhances the self-healing capability of matured concrete, with complete crack sealing and high compressive strength regain after long curing durations with 40% dosages Luan et al., (2023).

3. *Silica Fume (SF) and Nanosilica (NS):* SF has extensive early-stage reactivity and is inclined to limit its long-term capability for autogenous healing as opposed to FA. Nevertheless, incorporation of 20% or higher SF enhances secondary hydration within cracks, aiding in closure through silicon-containing healing phases and stimulating regeneration of the fiber-matrix interface Zheng et al., (2023). Incorporation of nanosilica (NS) is a very effective refinement approach. NS improves matrix density and enhances fiber-matrix bond strength. Research on ECC demonstrates that an optimized dosage of 1 wt% NS significantly enhances autogenous self-healing by decreasing the mean crack width (≈59%) and improving mechanical performance as well as durability parameters such as chloride migration resistance Offei et al., (2023).

4.3. Action of Curing Agents

The use of specific additives as internal curing agents is a remarkable method to increase the self-healing capability of cement materials, predominantly through the creation of internal water reservoirs. This method resolves problems such as autogenous shrinkage that occur due to self-desiccation in low W/B ratio mixes (such as high-performance concrete), enhancing both durability and potential for healing. Internal curing agents trap and hold mixed-up water that is slowly released back into the surrounding matrix as cement paste cures and humidity drops. This extended internal moisture promotes constant hydration of un-hydrated cement particles and Supplementary Cementitious Materials (SCMs), promoting the formation of more C-S-H gel and $CaCO_3$ precipitates to fill cracks. Main curing agents are:

1. *Superabsorbent Polymers (SAPs):* This hydrogel is very effective, capable of absorbing 500 times its weight in water. SAPs first swell by osmotic pressure, retaining mixing water Dang et al., (2017). When a crack forms and water penetrates, the SAPs further swell, providing a quick physical barrier effect, preventing the invasion of fluid and sealing the aperture. Studies validate the fact that SAPs aid healing in even 10-year-old concrete, resulting in recovery of mechanical strength and freeze-thaw resistance through the formation of protective voids like entrained air Snoeck et al., (2022).

2. *Lightweight Aggregates (LWA):* Porous materials like expanded clay (LECA), expanded shale, or pumice act as internal reservoirs upon pre-wetting Akhnoukh et al., (2018). Water is lost from the larger pore voids of the LWA to the smaller capillary pores in the cement paste by the action of vapor pressure gradients. Fine LWA is typically employed in place of coarse LWA due to its greater surface area, and ensures a more uniform distribution of curing water Wang et al., (2021).

3. *Natural Fibers (NF):* Wood-based fibers (e.g., cellulose, kenaf) are hygroscopic with two kinds of pores that allow water to pass through by diffusion and osmotic pressure. The fibers transport moisture in the matrix efficiently, allowing delayed hydration as well as carbonation reaction, enhancing the mechanical recovery of the material and reinforcing the fiber-matrix interface Snoeck et al., (2015).

4. *Porous Superfine Powders (PSPs):* Such as rice husk ash (RHA) Rößler et al., (2014) and cenosphere Liu et al., (2017), whose pore diameters are on the order of nanometers, also supply internal humidity. While RHA's pozzolanic nature absorbs CH (material for $CaCO_3$

healing), the synergy of RHA with SAPs has been found to greatly improve self-repair capability.

5. AUTONOMOUS HEALING: ADVANCED ENGINEERED SYSTEMS

Autonomous healing refers to the most highly developed area of self-healing concrete, using advanced, specialized systems to provide repair that is more reliable, efficient, and able to treat greater-scale damage than its autogenous equivalent.

5.1. Encapsulation-Based Systems

The fundamental principle of autonomous self-healing is encapsulating a reactive healing agent and delivering it to the damaged site accurately. Here, the healing material is encapsulated in a protective shell and cast into the concrete matrix. When a crack travels through the material, it breaks the shell and releases the agent immediately into the void to react and heal the damage White et al., (2001). This technique gives a specific, single fix and can seal wider cracks than native autogenous techniques.

1. *Capsule Classification:* Encapsulated systems are generally classified by size:
    a. *Microcapsules:* These are extremely small, commonly less than 1 mm in diameter, and are intended to be dispersed evenly throughout the matrix to treat a broad range of microcracks Ma et al., (2023).
    b. *Macrocapsules:* They are larger, usually cylindrical capsules, measuring a few millimeters to several centimeters in size. They are inserted in areas that are more prone to cracking and can give a larger volume of healing agent to seal wider cracks Mullem et al., (2020).

2. *Healing Agents and Shell Materials:* There are numerous materials that can be used for the capsule shell and the healing agent, depending on the intended effect.
    a. *Healing Agents:* Common healing agents include polymers, for example, epoxy resin, which can cross-link and thicken upon interaction with the calcium hydroxide in the concrete matrix. Another useful agent is sodium silicate, which, on reacting with calcium hydroxide, produces C-S-H gels, a normal by-product of cement hydration, which successfully seals cracks Ma et al. (2023).
    b. *Shell Materials:* The capsule shell is the main component and must be tough enough

to withstand the harsh conditions of concrete mixing and, at the same time, brittle enough to fracture when a crack is formed. Materials used are glass, ceramics, and other polymers Xue et al., (2019)

5.2. Microbial Autonomous Self-Healing: The Biomineralization Approach

Use of some microorganisms to induce precipitation of minerals—a biotechnological method known as Microbially Induced Calcium Carbonate Precipitation (MICP)—is one of the major techniques in autonomous self-healing concrete. It applies nature's mechanisms to heal cracks autonomously, with an environmentally friendly repair process in comparison to traditional repair, and reduces buildings' total carbon footprint Yu et al., (2023).

5.2.1. The Biomineralization Process

The biomineralization process starts from the addition of specialized bacterial species, generally dormant spores (e.g., Bacillus subtilis or Sporosarcina pasteurii), into the concrete matrix. The spores may survive for decades. As a crack occurs, water and oxygen ingress cause the spores to germinate into metabolically active vegetative cells. The negatively charged bacterial cell wall is an important nucleation site by virtue of its ability to bind positively charged calcium ions (Ca^{2+}) released from the matrix. These cells subsequently metabolize a provided organic nutrient source, releasing carbonate ions (CO_3^{2-}), which precipitate with the Ca^{2+} ions, to form $CaCO_3$ crystals onto the cell surface Amjad et al., (2023). Calcite is the preferred polymorph because it has better thermodynamic stability, and these crystals grow to physically fill and seal the fracture. Once sealed and water contact is removed, the bacteria enter a dormant state, allowing the system to function as a long-term, multi-cycle healing process. The effectiveness of bio-based healing is strongly influenced by its metabolic pathway and microbial agent:

Ureolytic Pathway (MICP): This is the most studied and effective approach. Urease-producing microbes (for example, Bacillus sphaericus or Bacillus subtilis) break down urea, an easily accessible nutrient, to form carbonate and ammonium ions. This enzymatic reaction increases the local pH and carbonate concentration, leading to the subsequent precipitation of $CaCO_3$ Van Tittelboom et al., (2010).

$$CO(NH_2)_2+H_2O \rightarrow NH_2COOH+NH_3$$

$$NH_2COOH+H_2O \rightarrow NH_3+H_2CO_3$$

$$H_2CO_3 \leftrightarrow HCO^{3-} + H^+$$

$$2NH_3 + 2H_2O \leftrightarrow 2NH^{4+} + 2OH^-$$

$$HCO^{3-} + H^+ + 2NH^{4+} + 2OH^- \leftrightarrow CO_3^{2-} + 2NH^{4+} + 2H_2O$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

Although extremely effective, the process is associated with the inconvenience of ammonium byproducts.

5.2.2. Controlling Factors for Performance

Performance of bacteria-based self-healing is controlled by several variables associated with the concrete's built-in harsh environment:

1. *Bacteria Type and Concentration:* Spore-producing, Gram-positive alkaliphiles (such as Bacillus strains) are the first choice because they outlast the high pH (up to 11) of concrete best Ramachandran et al., (2001). Yet, research indicates that an increased concentration of bacteria does not always enhance healing, indicating a peak density (e.g., 10^5, 10^7 cells/ml range) is required to balance nutrient supply and structural stability Dinarvand et al. (2022).

2. *Nutrients and Precursors:* Organic nutrient source selection and quantity (e.g., urea, calcium lactate, calcium acetate) have a significant effect on healing, as calcium-based nutrients are commonly used because they are a direct source of Ca^{2+} ions Schreiberova et al., (2019).

3. *Environmental Conditions:* Temperature and pH both have direct impacts on bacterial viability and metabolic rate. Although extremely high pH (pH>13) and temperatures (≥55°C) are inimical, utilization of protective carrier materials (e.g., encapsulated lightweight aggregates with styrene-acrylic emulsion coatings) and the observation that cracks decrease local pH can increase bacterial survival. Sustained availability of water (often achieved by water immersion or wet/dry cycles) is essential for initiating spore germination and for conducting nutrient transport Luo et al., (2015).

5.3. Other Autonomous Technologies

1. *Vascular Systems***:** This is similar to infusing the concrete with a small, internal circulatory system of blood vessels. A network of empty tubes or capillaries is embedded permanently in the concrete matrix and is filled with a liquid healing compound. When a crack crosses these channels, the agent is delivered directly into the gap. The special benefit of this method is the possibility of repeated healing; the agent can be re-supplied from an outside reservoir, so that the structure can self-heal several times during its working lifetime. This technology is difficult and expensive to deploy on a large scale and suffers from technical problems, such as clogging within the fine network Davies et al., (2021)

2. *Electrodeposition:* This process uses the application of a gentle electric current to force the movement of ions, namely Ca^{2+} and CO_3^{2-}, to the crack faces. This resultant forced movement causes the rapid, selective deposition of minerals (calcite) that effectively seal and fill the damage Ryou et al., (2005). This method is especially suited for buildings in water-saturated or aquatic conditions (such as underwater tunnels) where there is a continuous supply of electrolyte. Its greatest challenge is the high energy requirement of applying and sustaining the required electric current over extended surfaces Rotta et al., (2023).

   (Fig. 18 in the document Kasra Amoorezaei.pdf demonstrates the process).

3. *Shape-Memory Materials:* SM alloys or polymers are incorporated into the concrete and are trained to restore a pre-programmed original shape upon the application of an external stimulus, in most cases, heat Sakai et al., (2003).This shape recovery produces a strong restorative force that strongly pulls the crack faces together, physically closing the gap and aiding in mechanical property recovery. The main disadvantages are the expense of the SM materials and the logistics difficulty of applying the required external heat source safely and economically to initiate activation of a large or embedded structural member Song et al., (2006).

6. ECONOMIC FEASIBILITY AND MARKET CHALLENGES

The market environment of self-healing concrete is one of large potential offset by immense technical and economic challenges. The most suitable measure for rationalizing the additional upfront investment is said to be a life-cycle cost analysis, taking into consideration lower maintenance and a longer service life. It is of special relevance in the situation of large-scale infrastructure where maintenance is logistically inconvenient and expensive, for example, highways and water-retaining structures.

1. *Cost vs. Benefit:* The cost of initial autonomous healing agents is still a significant hurdle to mass adoption. Bacteria-based systems cost thousands of dollars per cubic meter of concrete, whereas self-synthesized microcapsules have been estimated at $15 per kilogram. These prices contrast sharply with traditional concrete materials. Yet, the self-healing concrete market is expected to expand considerably, from an estimated USD 26.32 billion in 2024 to USD 254.97 billion in 2033 and from USD 1.95 billion in 2024 to USD 8.5 billion in 2035, at a compound annual growth rate (CAGR) of 14.32% to 28.7%. Growth, especially in the infrastructure sector, mirrors the increasing industry recognition of the long-term value of a self-healing, long-lasting material Rasha et al., (2025).

2. *Obstacles to Market Adoption*: Aside from cost, several factors are inhibiting the market adoption of these technologies. The chief hindrance is the lack of a standard set of testing and characterization methods, and this undermines the consistency in comparing different healing agents' performance and end product reliability and safety. Additional extensive field testing is also urgently required to validate laboratory data and create industry confidence in long-term performance and longevity of self-healing concrete under real service conditions.

7. FUTURE DIRECTIONS: THE PURSUIT OF HYBRID AND SUSTAINABLE SOLUTIONS

The future of self-healing concrete will most likely be defined by the development of hybrid and green solutions with the most advantageous aspects of various technologies. This might include:

1. *Hybrid Systems:* Integrating low-cost, intrinsic autogenous healing approaches with high-efficiency, target-oriented autonomous methods. For example, a concrete mixture could be designed with mineral admixtures to deal with day-to-day microcracking and use encapsulated agents or bio-agents to address major, extensive damage.

2. *Sustainable Materials:* Increasing focus on the application of industrial waste products, like slag and fly ash, as SCMs to enhance healing as well as reduce the carbon footprint of cement

production. Research into bio-agents and novel biomineralization pathways may also bring in less toxic alternatives than conventional chemical healing agents.

3. *Overcoming Contradictions:* A combined effort is required to demystify the technical contradictions that arise when various "smart" materials are combined, such as the antimicrobial activity of some nanoparticles on bio-agents. This requires a better, deeper insight into their interactions so that a next generation of hybrid systems that are synergistic and powerful in nature can be developed.

7. CONCLUSION

Self-healing concrete is a breakthrough technology for the construction sector, providing an attractive alternative to the traditional durability issues of conventional concrete. The top-level review process systematically reviewed the key ideas, ranging from the intrinsic mechanisms of autogenous healing to the sophisticated, designed strategies of autonomous healing.

The review points out that autogenous healing is an inexpensive, passive process based on ongoing hydration and $CaCO_3$ precipitation; its potential is typically limited to sealing microscopic cracks, normally less than 100-150 µm. Autonomous approaches, however, like encapsulation, vascular systems, and bio-based healing, have a proactive mechanism with the potential to heal more extensive and larger cracks, typically larger than 300 µm. These systems transform concrete from a passive material to an active composite, significantly increasing its lifetime.

The rationale for mass application is strongly based on economic efficiency in the long term and environmental sustainability. Self-healing technologies are the most economically efficient approach to crack management in massive infrastructure development, including roads and water-retaining structures, since the saved maintenance and repair interventions over the lifetime of the structure pay off the initial premium price. In addition, by lengthening the lifespan of buildings, these products reduce the need for new production of cement, thus significantly reducing the construction sector's enormous contribution to worldwide CO_2 emissions.

The route ahead, however, is hampered by severe technical and commercial constraints. Research needs of key importance are the absence of field-tested standards for testing protocols that can consistently compare system performance and an urgent need for full-scale, multi-year field tests to confirm long-term durability under actual environmental conditions. In commerce, the substantial up-front cost of advanced healing agents is still the chief barrier to market penetration.

Above all, next-generation research needs to focus on the creation of hybrid systems that leverage the strengths of both autogenous and autonomous healing, while proactively overcoming major material incompatibilities, including the detrimental impact some strengthening nanomaterials can have on living bio-agents. By overcoming these sophisticated trade-offs, self-healing concrete can transform from an innovative scientific concept into a source material for a long-lasting and sustainable next-generation infrastructure.

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