

Original Article

Emerging Self-Healing Concrete Systems: Improving the Durability and Damage Resistance of Reinforced Concrete through Self-Healing Systems

Firda Herlina^{1*}, Yuli Panca Asmara², Kushendarsyah Saptaji³, Jainal Arifin¹, Robiatul Adawiyah¹, Sugiman⁴

¹Universitas Islam Kalimantan Muhammad Arsyad Al Banjari Banjarmasin.

²INTI International University, Faculty of Engineering and Quantity Surveying, 71800 Negeri Sembilan, Malaysia.

³Department of Mechanical Engineering, Faculty of Engineering and Technology, Sampoerna University, Indonesia.

⁴Department of Mechanical Engineering, Engineering Faculty, Mataram University, Indonesia.

*Corresponding Author : tanyafirda@gmail.com

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Abstract - Self-healing concrete is a sophisticated material that can repair fissures during service life in modern infrastructure more sustainably and durably, with the effect of auto-repairing faults. Conventional concrete has suffered from micro-cracks, which, when not properly managed, proliferate and attract water (especially chloride ions and other aggressive agents), leading to loss of structural strength. Self-healing alternatives, including autogenous healing, encapsulated healing agents, bacterial activity, and mineral admixtures, have been proposed with the goal of overcoming these challenges. These techniques allow for crack sealing and mechanical and durability attributes to be regained using such methods on the site without the need for external assistance and rehabilitation. Self-healing methods save on maintenance, repair costs, and the cost of concrete structure, and they may increase the lifetime of the concrete structure, making it a key construction method towards sustainable building. This paper addresses its mechanisms, materials, and its application: it looks at how concrete self-healing might improve construction resiliency and environmental performance, to name just a couple, and how it may well transform construction altogether. Despite rapid advances in self-healing concrete, key challenges remain: most studies are limited to laboratories, focus on crack closure rather than structural recovery, and overlook interactions with steel reinforcement. Single-use mechanisms, high costs, and limited environmental assessments further limit practical application. This study addresses these gaps by exploring an approach that combines multi-cycle self-healing, corrosion-resistant reinforcement, and data-driven monitoring to enhance durability, performance, and sustainability in real structures.

Keywords - Self-healing concrete, Crack repair, Durability enhancement, Sustainable building, Reinforced concrete.

1. Introduction

Concrete is an adaptable material suitable for the construction of many construction products, such as offshore structures, roads, dams, ports, and buildings. Concrete is formed by the scattering of cement, sand, gravel, crushed stone, and water. It is solidified material at least tenacious when hardened due to the mixed concrete; therefore, it is the building's solidification [1-5]. It has good chemical resistance and strength. So its raw materials are virtually a universal product. But its biggest shortcoming is cracking, making it susceptible to long-term harm. Cracks occur at one of three phases, either during curing periods or immediately after concrete solidifies in a solution phase [6]. Cracking is often due to such factors as premature-age concrete freezing, stress due to shrinkage, or structural alteration upon the removal of formwork [7].

Cracking can be caused by other factors, including Alkali-Aggregate Reactions (AAR), Temperature Differences, Steel Corrosion, Mechanical overloading,

matrix fatigue, material shrinkage, and creep factor [8-10]. Frequent loading, such as traffic on bridges, vibration in buildings, leads to these cracks and increases their susceptibility to breaking and damage. This allows CO₂ and chloride ions (Cl⁻) and other hazardous materials to pass into the concrete, which in turn leads to the corrosion of embedded steel reinforcement materials. With time, this corrosion leads to an inferior strength of reinforcing bars, weakens the strength bond between the steel and concrete, and decreases the structural load-bearing capacity, which in turn decreases the stress capacity of the steel reinforcement and thus generalizes to increasing the failure risk for the steel in the reinforced concrete. This issue demands regular maintenance and inspection. However, due to the labor required to repair concrete cracks, as well as the indirect cost of delays or inactivity on the project, such repair of concrete cracks may ultimately face a high cost. Danish et al. [13] stated that the construction maintenance costs have multiplied as much as 2 1/2 times the cost to produce concrete. Of all costs, maintenance expenses account for



over half [14]. If cracks grow bigger and the material becomes increasingly complex, so, too, is the cost of repairs, which adds to both cost and effort. SHC is the most hopeful developed for curing concrete damage [15-18]. This new material has all the means where its cracks can self-heal, be it through calcite build-up by bacterial cells, or embedding healing agents. Self-healing is based on the addition of hydrated cement particles, calcium swelling, silicate hydrate, and carbonation of calcium hydroxide in Engineered Cementitious Composites (ECC).

Research reveals that crack widths of between 10 µm-300 µm are completely closed under these conditions [19-21]. Self-healing concrete also leads to lower capillary water absorption; some slabs remain crackless at casting even after

1 year. As some found in a case report for the underground engineering field, this case report showed that a crack would be well healed by 28 days post-curing [22]. Self-healing concrete has numerous benefits, such as reduced repair costs, reduced damage to the life cycle of materials, greater durability, and enhanced environmental effects [23-27]. It obviates the requirement of several costly strategies and is a rather time and cost-effective solution [23, 28]. Self-healing concrete may be manufactured in various forms deliberately to automatically heal cracks and prolong the life of the concrete. Ancillary approaches to induce self-healing phenomena in concrete that dramatically improve durability and correct the damage arising from cracks and defects by autonomic and autogenic repair mechanisms have recently been described, illustrated in Figure 1.

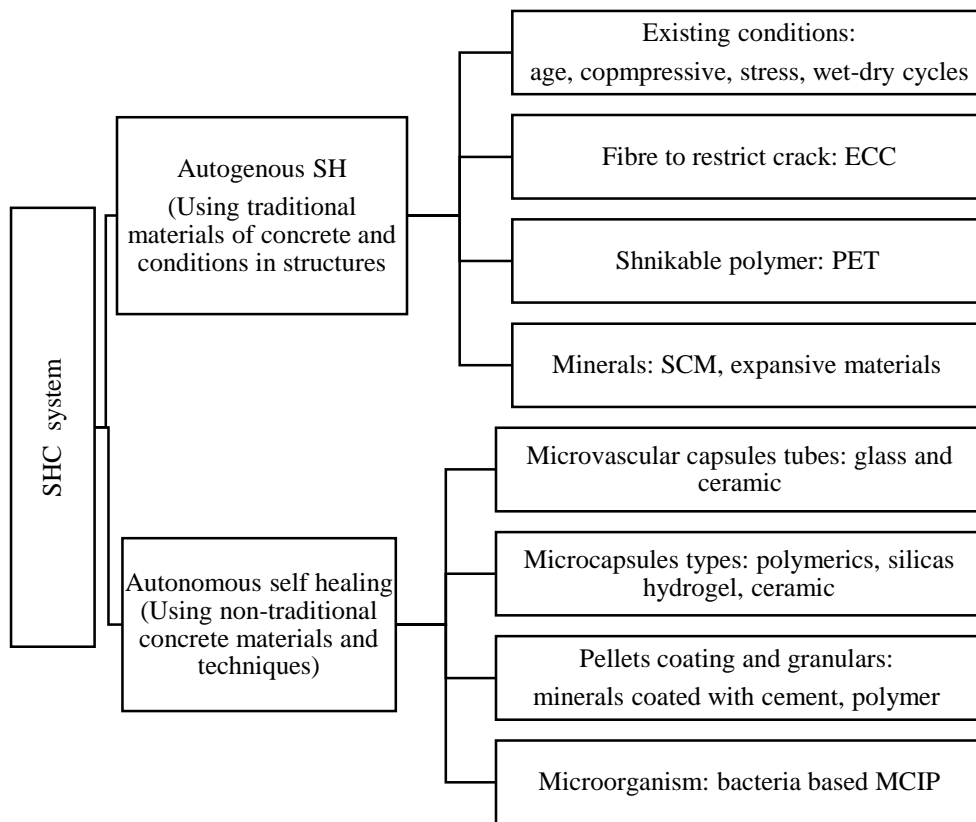


Fig. 1 Various ways of inducing self-healing in concrete and diverse procedures [30]

Over the years, as the damage recovery mechanism has gradually improved, the literature for self-healing concrete has considerably grown. Before 2010, the published works had few experimental results and concentrated on conceptual and autogenous healing systems, so that the crack-healing potential was limited and the applications of the method were only slightly limited. By that time, between 2011 and 2015, there was a steady proliferation of publications, the development of bacterial-based self-healing systems and encapsulation approaches was introduced, and an increasing interest in those areas, indicating the shift from theory to application through research. The fssield has reached maturity stage since 2016, when, due to a sudden surge in publication numbers and more interest in durability enhancement, strength restoration, and sustainability performance. Such evolution seems to be reflected in citation

trends: prior to 2010, research was cited sparsely, a sign of a lack of scientific visibility and impact, but self-healing concepts gained traction from 2011 to 2014 as they became more mainstream and accepted, as well as verified. The period following 2015 was a time of massive citations confirming the self-healing concrete studies' scope for impact, breadth, scientific acceptance, and high scientific value in the context of high-quality Q1 journal articles. Table 1 is a chronology of Stages in Research for the Development of Self-Healing Concrete [32].

Although self-healing concrete has developed rapidly, several important gaps remain. Most studies are conducted only in laboratory settings, leaving the performance of self-healing concrete in real structures uncertain. Research has primarily focused on crack closure, while the recovery of

strength and overall structural performance has been less studied. Additionally, the interactions between self-healing systems and steel reinforcement-particularly regarding corrosion and bonding-remain unclear. Many self-healing methods are single-use, which limits their long-term effectiveness. High costs and challenges in large-scale applications also persist. Furthermore, research on

environmental benefits using life cycle analysis is still limited. Building on these gaps, this study proposes a novel approach that integrates multi-cycle self-healing mechanisms with corrosion-resistant reinforcement and data-driven monitoring to enhance durability, structural performance, and sustainability in real-world applications, addressing limitations identified in recent research.

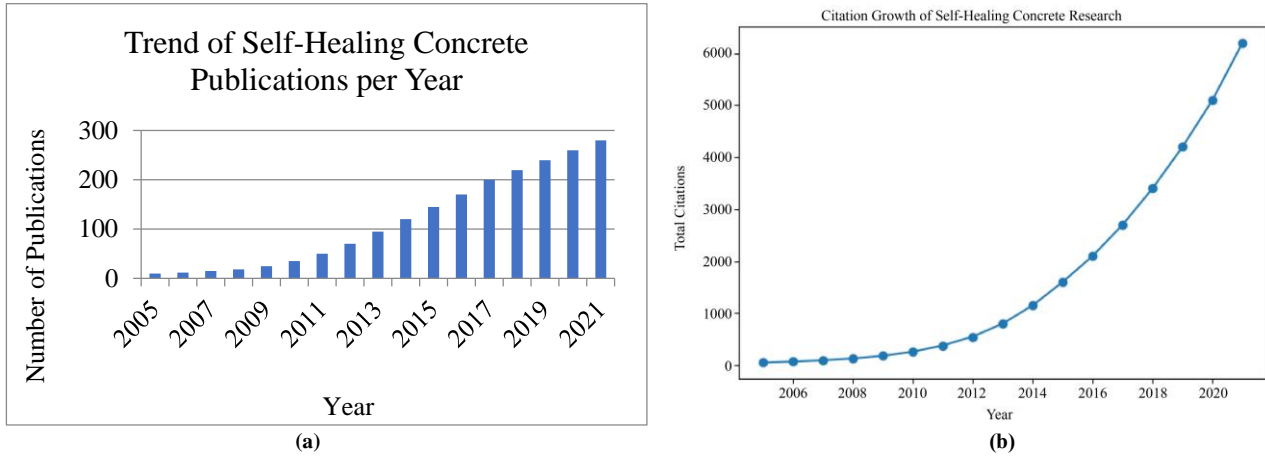


Fig. 2 Annual number of publications (a) and growth of cumulative citations (b) on self-healing concrete research from 2005 to 2021 [32].

Table 1. Stages of Research Development on Self-Healing Concrete

Period	Research Stage	Main Focus	Key Characteristics	Representative Outcomes and Impacts
Before 2010	Conceptual & Autogenous Healing Stage	Natural crack-healing mechanisms	• Continued hydration of unreacted cement	<ul style="list-style-type: none"> • Crack closure efficiency up to 70–100% under wet curing • Limited structural strength recovery • Low publication output and minimal citation impact [33]
			• Carbonation-induced CaCO ₃ precipitation	
			• Effective mainly for microcracks (≤0.2 mm)	
			• Strong dependence on water availability	
2011–2015	Innovation & Autonomous Healing Stage	Development of engineered healing systems	• Introduction of bacteria-based self-healing (MICP)	<ul style="list-style-type: none"> • Healing of wider cracks (≤0.6–0.8 mm)• Improved crack sealing and durability • Steady growth in publications and citations as concepts gained recognition [34, 35]
			• Capsule-based systems (epoxy, sodium silicate, polyurethane)	
			• Use of mineral admixtures for enhanced healing	
2016–2020	Performance & Durability Optimization Stage	Mechanical recovery and transport properties	• Quantification of strength recovery (compressive and flexural)	<ul style="list-style-type: none"> • Strength recovery reaching 80–95% of original values • Permeability reduction up to 90–95% • Rapid increase in citation rates, indicating high scientific impact [36, 37]
			• Reduction of water and chloride permeability	
			• Evaluation of repeated cracking behavior	
2021–Present	Sustainability, Scalability & Field Application Stage	Long-term performance and environmental impact	• Lifecycle assessment (LCA) and CO ₂ reduction potential	<ul style="list-style-type: none"> • Shift toward sustainable and resilient infrastructure • High visibility in Q1 journals • Exponential growth in citations reflecting maturity and industrial relevance
			• Integration with low-carbon binders and green concrete	
			• Pilot-scale and real-structure applications	

2. The Effects of Factors on Self-Healing in Concrete

Several reasons contribute to the efficacy of concrete self-healing. For this condition to take place, the hydrated cement particles must be stimulated through the medium of a moist medium for precipitation of calcium carbonate or C-S-H to take place to heal cracks, but excessive consumption of the process or insufficient availability of water can hinder the treatment process. The thickness of the cracks is a significant factor for cracking recovery, which can be enhanced with smaller ones ($\leq 100 \mu\text{m}$) due to higher contact environments, allowing better hydration and a lesser formation of deeper, wider cracks. The time until water is consumed allows cement to react and form carbonate, forming compounds that fill more cracks, usually with the help of fine particles or by material such as silica fume or biochar. These pressurized and external forces drive healing agents into cracks and enhance compressive strengthening, which improves sealing; the decreased water-cement ratio drives unreacted cement, improving autogenous repair. Improving these factors in this way inevitably results in long-lasting, strong, self-healing concrete with closed cracking that actively recovers, because successful repair can result. In concrete, the self-healing concrete damage recovery mechanism can be understood in terms of two main mechanisms: autogenous and autonomous.

Natural autogenous healing is enabled by the hydration of unreacted cements, and cracks are gradually filled with hydrous products as time goes by [38]. When carbonation forms of Calcium Carbonate (CaCO_3) also narrow the cracking to an extent of $200 \mu\text{m}$ with CO_2 reacts with $\text{Ca}(\text{OH})_2$ to form CaCO_3 , this causes cracking crack to be stiffer and more impervious to water attack [39]. Crystalline compounds, precipitation of soluble minerals or admixtures (e.g., xypex, kryton, and penetron) can enhance the cracking closure by capillary, crystallization, condensation, and hydration reactions. Mechanical loading can help with self-healing, as debris is generated among the cracks that water and unhydrated cement or calcite take over for extra C-S-H or CaCO_3 to support the concrete structures [41]. The self-healing mechanism relies on external agents activated by crack initiation, such as encapsulated chemicals, bacteria, fibre reinforcement material, and mineral content of silica fume, rice husk ash, metakaolin, and reactive MgO, that in turn reacts with calcium hydroxide to form more cementitious material [42]. They integrate with fly ash, carbonated steel slag, blast furnace slag, superplasticizers, PVA fibers, and limestone powder to enhance the sealing, mechanical strength, durability, and long-term maintenance of cracks. Concrete self-healing mechanisms, therefore, make concrete self-healing, extending the service life, and avoiding an external role, implying self-healing concrete is a material, resilient, and environmentally friendly infrastructure [43].

Mechanical properties of self-healing concrete. A significant aspect of concrete durability and longevity deteriorates due to its brittle characteristics and crack susceptibility. Self-healing concrete heals small microcracks

by constant hydration or bacteria-linked mineralization, as well as by adding various healing agents. It can give much higher mechanical properties when compared to traditional concrete. Following cracking, it is known that self-healing concrete can recover 80–90% of its compressive strength with adequate filling of cracks by calcium carbonate or other healing agents [44]. Compared to non-healed conventional concrete, fracture-sealing and micro-defect bridging enhance flexural strength by about 15–25% [45]. Self-healing concrete strengthens the functionality of solid concrete with good structural integrity. It would help them have a good performance after cracking, and they can obtain the toughness of fracture, and the cyclic load-induced microcrack sealing could prolong the fatigue life [46, 47]. Thus, less permeability and internal microcracking could enhance longer-term macrostructure resistance, that is to say, improved longevity of the structure [48]. Due to their working process, the fracture is not cured with Ordinary Portland Cement (OPC) concrete, which can be prone to microcracks that lead to longer-lasting structural failure.

In comparison, self-healing concrete possesses either an autogenous or autonomous nature, improving the mechanical and service life of concrete due to its nature developed to withstand and overcome damage. Conventional OPC concrete showed only natural autogenous healing capable of small-scale cracking, as described in the literature. In the wet cement cure, 70–100% water-tight cracks (smaller ones of $\leq 0.2 \text{ mm}$ in width) are shown to be at most one- to two- fold less permeable by 28 days [33]. Even if the compensation value of compressive strength recovery can only be up to 10%–30% of the starting post-cracked strength, loss of greater cracking size $> 0.3 \text{ mm}$ does not recover under wet curing in a moist medium [49]. However, there are also some benefits of the use of self-healing concrete in bacteria-based applications. Cracks of 0.5–0.8 mm can be completely closed, and a 90–95% reduction in water penetration, compared to conventional concrete, as well as a 10–20% improvement in compressive strength, is recorded after repair. In addition, the structure's life span is predicted to be lengthened by 20–30 years [35], while the cost of 2 to 4 times that of OPC concrete has been reported. For the self-healing concrete, capsules will also be a material (epoxy, sodium silicate, polyurethane) used in the process of healing.

Cracking takes place, and the capsules rupture, letting the restorative substance of the capsule crack through, breaking; hence sealing the crack. The crack closure efficiency of this approach is 80–100% for a crack width $\leq 0.6 \text{ mm}$, and the strength recovery for flexural strength recovery is 75–90% of its original values after 24–72 h [34]. In addition, the chloride penetration (40–60%) and Chloride Diffusion Coefficient (ChCl) fall from 10^{-12} to $10^{-13} \text{ m}^2/\text{s}$ [37]. A limitation for these methods is their one-time cure. Though self-healing is necessary, autogenous healing can cure a crack width $\leq 0.2 \text{ mm}$ with 50–100% efficiencies, and is cost-effective, while bacterial-based healing is more expensive, to the extent of curing a crack width of 0.8 mm with 90–100% efficiencies. Capsule-based systems are

moderately–highly effective (80–100%) but at a high price. Systems use only 0.4 mm cracks of mineral admixtures at 60–80 % efficiency or at moderate cost. If the compressive strength of OPC concrete is diminished when cracked, it is to be expected. The failure rate and reduction of compression are 60–75%. In contrast, self-healing concrete retains 75–95% strength depending on the cure mode. The maximum recovery of bacteria-based self-healing concrete (85–95%) is followed by capsule-based and mineral admixture forms (80–92%). According to White et al. (2001; Wang et al., 2014), the flexural strength recovery ratio of OPC concrete is about 55%, and the fracture recovery of bacterial and capsule-based self-healing concrete is 80–95%, so they can be used for bending structural members, beams, and slabs in concrete. In terms of elastic modulus, loss of elasticity increases by 20–30%, while in self-healing concrete, loss of

elasticity is less than 10%, this shows that the stabilization of stiffness and crack control is much better [37].

Decreased permeability decreases the likelihood of chloride ingress and reinforcement corrosion, which results in improved long-term mechanical characteristics [33, 37]. Table 2 provides an overview of the self-healing concrete interventions, including autogenous healing, bacterial healing systems, capsule healing, mineral admixture methods, and so on. According to the evidence in tables 3–6, the self-healing concrete has significantly better properties in comparison to the conventional concrete material and the remaining body of the concrete, including the compressive, flexural, elastic modulus, and permeability, among other characteristics.

Table 2. Comparison of Healing Effectiveness (Summary) [33, 37, 38]

Method	Maximum Crack Width	Healing Efficiency	Cost
Autogenous	≤0.2 mm	50–100%	Low
Bacterial	≤0.8 mm	90–100%	High
Capsules	≤0.6 mm	80–100%	Medium–High
Mineral admixture	≤0.4 mm	60–80%	Medium

Table 3. Comparison of Compressive Strength

Concrete Type	Initial Compressive Strength (MPa)	After Crack & Healing (MPa)	Strength Recovery
Ordinary concrete	35–40	25–30	60–75%
Self-healing (autogenous)	35–40	30–34	75–90%
Self-healing (bacterial)	35–40	32–38	85–95%
Self-healing (capsule/mineral)	35–40	30–36	80–92%

Table 4. Comparison of Flexural Strength

Concrete Type	Initial Flexural Strength (MPa)	After Cracking (MPa)	Recovery
Ordinary concrete	4.5–5.5	2.5–3.0	≈55%
Self-healing (bacterial)	4.5–5.5	4.0–4.8	80–90%
Self-healing (capsule)	4.5–5.5	4.2–5.0	85–95%

Table 5. Comparison of Elastic Modulus

Concrete Type	Initial Flexural Strength (MPa)	After Cracking (MPa)	Recovery
Ordinary concrete	4.5–5.5	2.5–3.0	≈55%
Self-healing (bacterial)	4.5–5.5	4.0–4.8	80–90%
Self-healing (capsule)	4.5–5.5	4.2–5.0	85–95%

Table 6. Comparison of Permeability & Strength Impact

Parameter	Ordinary Concrete	Self-Healing Concrete
Permeability coefficient	$10^{-10} - 10^{-11}$ m/s	$10^{-12} - 10^{-13}$ m/s
Long-term compressive strength loss	High	Low
Chloride resistance	Low	High

2.1. Investigated Cases

Self-healing concrete has well outperformed ordinary concrete in terms of strength, lifetime, and maintenance time in numerous lab and field applications. Bacterial-mediated self-healing concrete has been used in water-retaining structures and canal lining in the Netherlands, where cracks 0.5–0.8 mm wide have been entirely closed with microbiologically induced calcium carbonate precipitation, which led to a 90–95% water permeability reduction, 20–30 years of extended service life in corrosion retardation [35, 36]. Self-healing capsule systems with epoxy or sodium silicate-loaded polymeric microcapsules have been applied to bridge decking and beam components in the USA that achieve crack closure efficiencies of more than 80–100% for cracks up to 0.6 mm, healing time of 24–72 h, 75–90% flexural strength recovery, and sharp chloride penetration reduction [34, 37], or long-term resilience in harsh environments.

Self-healing concrete, supported by crystalline admixture technology, has found effective use in development works, such as underground structures (tunnels, basements, or water reservoirs), at the continuous moisture entry point, where capillary-driven crystallization mechanisms can close openings of up to 0.3–0.4 mm, with reduced permeability by one to two orders of magnitude as well as mechanical stability due to long service times [33, 37]. In addition, long-lasting crack closing in long-term UK laboratory test results in a cycled wet-dry and high chloride environment reduced chloride diffusion coefficient by

approximately 50% and freeze–thaw fracture resistance, further proving that self-healing systems with satisfactory performance can endure over the long run in an environment of physical service [50]. Especially in research, more than in practical application studies, self-healed concrete achieved much more effective crack, permeability, and durability control, which leads to making it more and more viable for the use of this material in critical facilities, including bridges, tunnels, marine infrastructures, and water-retaining systems, over time, and is also affordable and sustainable.

3. The Damage Recovery Mechanism of Self-Healing Concrete

Autogenous and autonomous approaches are the basic mechanisms for self-healing concrete. In addition, autogenous healing is an organic phenomenon in the material and is commonly attributed to the action of the hydration of unreacted cement particles. Conventional concrete employs the self-healing mode that may naturally result in cracks (formation from small holes) or lead to these in its casting [52].

Some mechanisms for autogenous self-healing in concrete have also been created to stop the propagation of cracks. Autogenous self-healing mechanisms in concrete work are natural processes that are developed by nature without any added stresses or intervention (e.g., with the aid of water supply, crystal growth developing in cracks in concrete—Figure 3) [29].

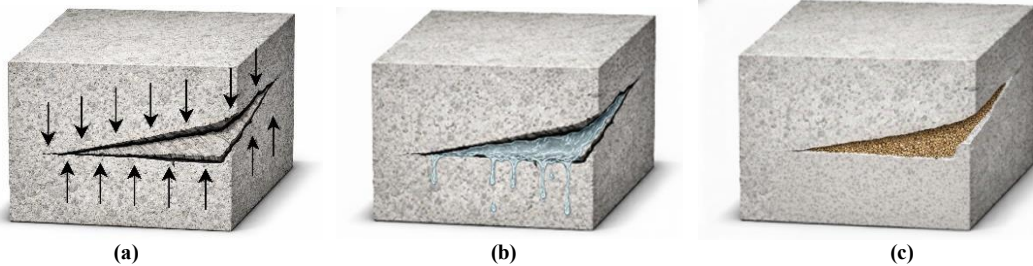


Fig. 3 Typical mechanism of self-repairing of cracked concrete (a), application of stress (b), hydration, and (c) crystallization.

3.1. Unreacted Cement Hydration

Hydration of unreacted cement is one of the predominant autogenous self-healing mechanisms in concrete, leading to the reaction of residual cement particles with water to produce hydration products for filling the crack over a period of time. About 50% of the cement in conventional concrete remains unhydrated after curing. Healing activity is especially pronounced in the first seven days, especially in newly cast concrete [38]. The sealing of cracks can be improved by precipitation of calcium

carbonate ($CaCO_3$), formed from carbonation reaction with CO_2 and $Ca(OH)_2$, and can serve to close fractures as wide as 200 μm [53].

3.1.1. Calcium Carbonate Formation

Formation of Calcium Carbonate. Carbonation is a consequence. Carbonation of cracked hardened concrete is facilitated by the reaction between atmospheric CO_2 and calcium hydroxide within cracked concrete, producing $CaCO_3$, which eventually fills and seals cracks [39]. This

mechanism works best for small cracks to serve as a built-in fill, which increases strength and water resistance. It is slower and constrained as compared to engineered systems, but it substantially slows deterioration and maintains structural integrity [80].

3.1.2. *Precipitation of Crystalline Compounds*

Crystalline Compounds Precipitation. Crystalline self-healing is achieved by transporting dissolved minerals or crystalline admixtures (e.g., Xypex, Kryton, Penetron), which are carried into cracks and sealed by recrystallization [41]. These admixtures are usually introduced at 0.3–2% by cement weight and are considered PRA (permeability-reducing admixtures) in EN 934-2 and under ACI 212.3R-16 and can work in hydrostatic and non-hydrostatic conditions [54]. The healing process comprises precipitation, crystallization, hydration, and capillary-mediated processes for decreasing permeability and increasing longevity [55].

3.1.3. *Mechanical Loading Effects*

Mechanical loading promotes self-healing as debris is created as a result of fractured aggregates or partially

hydrated cement, which is entrained in the cracks and limits the width of the cracks [84]. The addition of C-S-H or CaCO₃ enhanced crack sealing and durability of the cracked concrete, which occurs after the contact of water and residual cement, such as during the period of repeated loading [41].

3.2. *Autonomous Self-Healing and Mineral Additives*

Autonomous self-healing is based on external materials like encapsulated chemicals, bacteria, fibers, and mineral additives that act upon cracking and recover the damage. Mineral admixtures like silica fume, rice husk ash, metakaolin, and reactive MgO also promote self-healing as a result of the reaction with calcium hydroxide, which has an additive effect on cementitious materials. Additional compounds such as fly ash, blast furnace slag, carbonated steel slag, PVA fibers, superplasticizers, and limestone powder are effective in improving crack sealing, strengthening recovery, and long-lasting performance [56, 57]. Specifically, metakaolin improves microstructural density and self-repair efficiency with the enhancement of denser hydration products [58]. As depicted in Figure 4, certain additives heavily influence concrete properties such as strength, durability, and workability.

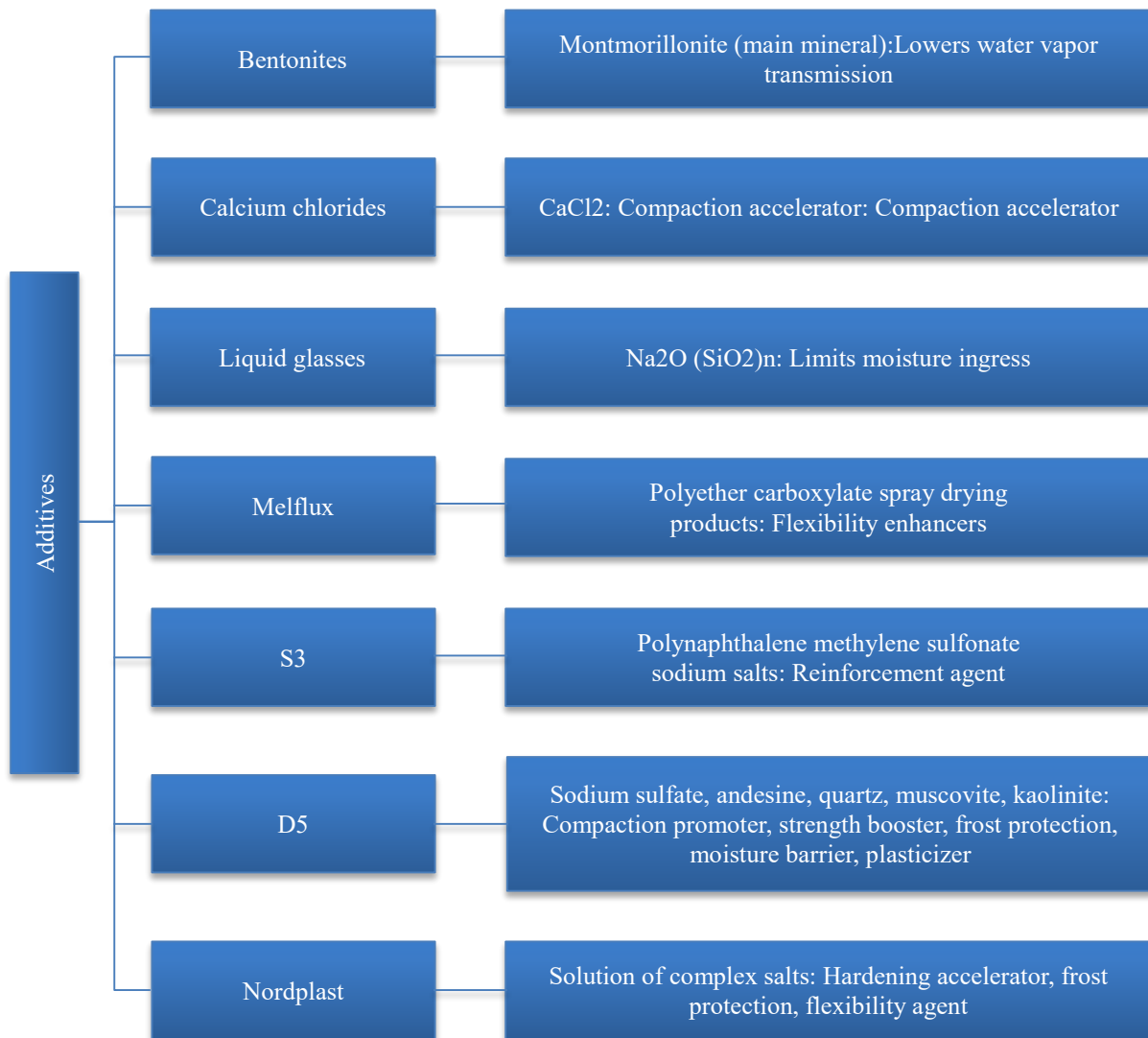


Fig. 4 Different additives dramatically affect concrete properties such as strength, durability, and workability [58]

4. Application of Self-Healing Concrete for Corrosion Prevention of Steel Reinforcement

Self-healing concrete is essential for protecting steel reinforcements from corrosion, helping to improve the durability of reinforced concrete structures. This has been performed by injecting chemical inhibitors into the rebar concrete in order to prevent corrosion. These chemical solutions are the actives that protect the reinforced concrete surface and, by that, can adjust the chemical environment of the concrete on which it is based, thus promoting corrosion resistance [59].

Inhibitors inhibit wear and corrosion by decreasing the anodic or cathodic polarization, attenuating the ion diffusion of the soil-metal interface, and increasing the resistance of the solution to the metal surface [60]. They are divided into various classes according to their protective mechanisms and include passivating (anodic) inhibitors, cathodic inhibitors, precipitation inhibitors, and volatile corrosion inhibitors. Passive anodic inhibitors reduce corrosion at the anode by moving potential values closer to a positive value. Such inhibitors include oxidizing anions, e.g., chromate and nitrite, which passivate steel without oxygen, and non-oxidizing ions, e.g., phosphate and molybdate, that utilize oxygen for passivation. The cathodic inhibitors, however, decrease the potential of cathodic reactions like dissolved oxygen reduction or lay down a protection layer on the cathode. Examples are arsenic and antimony or calcium and magnesium ions that form protective oxide layers. Organic inhibitors usually apply a hydrophobic film covering the metal surface to protect it from corrosion. Their effectiveness depends on their composition, the molecular composition, and environmental factors such as temperature and pressure. When film formation is an adsorption process, the conditions in the environment, where the system operates for a performance, are thus vital. A number of natural and synthetic inhibitors are most commonly used in order to protect metals in aggressive environments, providing a good boost to their corrosion resistance [61]. Poly(methyl

methacrylate-co-N-vinyl-2-pyrrolidone), for example, has been employed for potentio-dynamic polarization approaches for 95% corrosion protection of J55 steel at 1000 ppm. In another example, Chitosan And Carboxymethyl Cellulose (CMC) were employed to safeguard metal pipeline steel, providing 54% with 55% efficacy with 100 ppm inhibitors. • Strengthening by fiber

One approach is the addition of fibers. For example, steel fibers can be mixed with mineral substances like fly ash, superplasticizers, and silica fume to improve the self-healing process [29]. Steel macro fibers and crystalline admixtures are also incorporated with respect to healing without additives [62]. Some uses where carbon fibers are added along with high-range water reducers, Polyvinyl Alcohol (PVA) Fibers, and Fly ash are effective in enhancing the healing process of SHC [63]. PVA fibers with superplasticizers, along with silica fume, exhibit significant self-healing ability [64]. Steel cord and Polyethylene (PE) fibers may be used either as single or hybrid fibers and may also be enhanced with superplasticizers and silica fume [65]. Polypropylene (PP) fibers may work in combination with superplasticizers in the self-healing process [66].

The reinforcement of concrete with fibres is considered to depend on several key mechanisms [49]. To begin with, the fibers are designed to act as a form of mechanical reinforcement, which is dispersed throughout the mix of concrete to resist and distribute loads and inhibit cracking if a strain is exerted. Second, they are useful because, to avoid additional cracking, they have to be used as a barrier to stop the already existing cracks from expanding and to keep the concrete structurally sound.

Finally, they help with automatic repair by acting as a mesh that holds fractured concrete together and helps repair it, further strengthening where they are damaged. Figure 5 shows the mechanism of self-healing concrete incorporated into reinforced fibre.

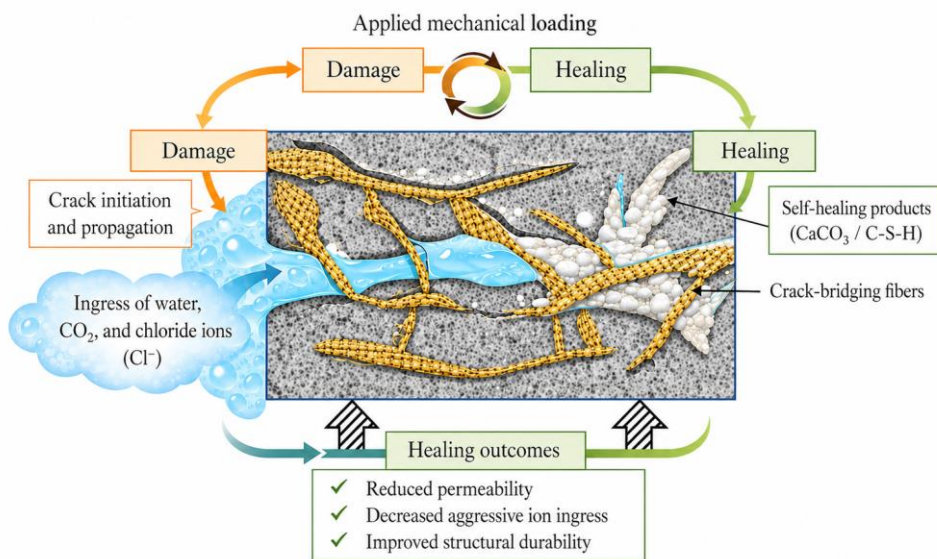


Fig. 5 Illustration of self-healing concrete reinforced with fibers, showing how the fibers control crack propagation and facilitate the self-healing process in the concrete

4.1. Microorganism

Some concrete types are capable of healing themselves with specific bacteria or microorganisms. When cracks occur in the concrete, they can become activated by water or moisture to "wake up" some of these microorganisms. They start producing calcium carbonate. Such a method enables the concrete to close microcracks and macrocracks and might be used to immobilise concrete as well as cement elements, such as sand, gravel, or aggregates [69].

4.2. Encapsulation

Encapsulation is a successful type of membrane, as it converts solids into capsules with healing agents. Instead, these agents are released into the concrete once cracks occur, creating a self-healing mechanism. The encapsulation success is determined by shell thickness, diameter, capsule viscosity, and surface area in the concrete mixture; all of which need to be optimized to resist internal forces [70]. These encapsulations should have mechanical resistance to prevent premature rupture and release of healing agents in a controlled manner over long periods. From various materials, different results are obtained in the encapsulation process. For example, epoxy-containing urea formaldehyde (C₂H₆N₂O₂) capsules increase flexural strength in a replacement fraction of 1–4% cement weight [31]. Poly-urea

capsules with Na₂SiO₃ added (0.8% replacement) inhibit capillary absorption, and divinylbenzene (C₁₀H₁₀) boosts fracture strength at a replacement of 0–2% [71]. Melamine with epoxy (1–4% replacement) capsules were also found to improve flexural strength [72]. Such encapsulation methods can enhance structural applications, where concrete may have limited durability over a long period of time, but the ability of concrete to self-heal can ultimately improve and be beneficial for structures. Microcapsules in self-healing concrete are made of a core, which may be solid or liquid, and/or a solid suspended in a liquid, and have a shell containing polymer, wax, or ceramic materials that surrounds them [67]. The microcapsules with a diameter between 1 and 1000 micrometers can be single-nucleated (one core), multi-core (multiple cores), or double-shell (multiple shells around the core).

Certain varieties, such as microspheres, have a uniformly distributed core inside a shellless material. Activation of such an element releases the core material, helps with the repair of the cracks, and promotes self-healing in concrete. The technique of microencapsulation—where active agents inside a protective shell are released when they become active—further enhances the self-healing effect with concrete and illustrates this in Figure 6.

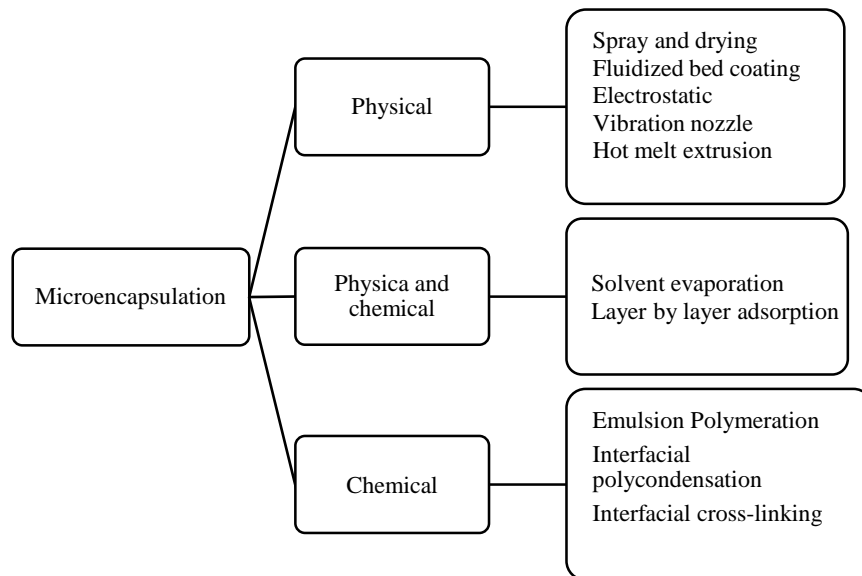


Fig. 6 Different approaches to utilize self-healing agent within capsules [67]

Self-healing of concrete cracks and their mechanisms by the encapsulation method are shown in Figure 7. When the material fractures or undergoes damage, a healing agent is released into the damaged region. The healing agent polymerizes upon exposure to air, heat, or a catalyst, which fills the crack and restores the integrity of the material.

Typical mechanisms for repairing cracks [73] are:

- Encapsulation: A healing agent (possibly liquid monomer) is encapsulated in small microcapsules and distributed throughout the host material (e.g., polymer, composite).

- Formation of Cracks: Cracks develop and spread through the matrix since the material experiences damage.
- Release of healing agent: if cracks develop, they burst microcapsules and release agents into the damaged area.
- Polymerization: the agent, then, enters the crack and hits a catalyst or hardener in the matrix. This produces a chemical reaction, usually known as polymerization, to condense the healing agent and bond the cracks and their surfaces.
- Restoration of material: after polymerization, the crack is sealed, and the material regains its mechanical properties, restoring strength and functionality.

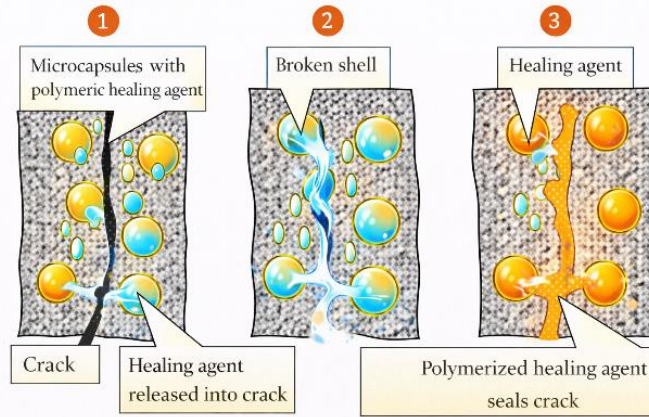


Fig. 7 Mechanism of self-healing concrete cracks using the encapsulation method. Polymerization (a) occurs due to contact between the recovering agent in the broken capsules, and (b) the catalyst in the concrete [73]

Microencapsulation is suited to small localised cracks, whereas encapsulation systems are only suitable for moderate-scale damage, and vascular systems are most suitable for repeated or extensive damage of structures. Vascular systems, on the other hand, add a system of hollow channels to the concrete to supply healing agents as crack sites develop. This method provides multiple rounds of repair and is effective for larger cracks, but may be complex design-wise and contribute to the structural weaknesses in some cases.

The future work will be developed to further improve these systems and include them in the improvement steps of the self-healing concrete process to enhance the performance, toughness, and sustainability. Encapsulation-based Self-Healing Concrete (SHC) offers great possibilities to improve durability, while it experiences a high cost of production at scale, as it is also an expensive technology to design and implement. Compatibility with the concrete matrix is critical to avoid starting weakness, while the triggering mechanism must function to release healing agents after cracking has occurred. Capsules need to cope with durability to not break or crack, as well as how stable they are against mixing stresses and cracking rupture. The healing ability, especially for the cure of the larger defects, is one of the problems of difficulty, and the long-term performance under these harsh conditions has to be confirmed. Environmental issues with synthetic materials imply sustainable bio-based alternatives can also become essential, along with problems of uneven crack coverage and, in the absence of a standard testing protocol, which are a hindrance that will require new engineering and standardization. In the face of these challenges, an interdisciplinary cooperation may be needed to maximize the encapsulation technologies and create an efficient application of SHC with an environmentally sound and efficient approach in a practical environmental encapsulation technology. The article explores future directions of research into these methods that will aid the improvement of performance of these methods, as per technology, the addition of high-performance materials, hybrid schemes, and optimized designs and systems to achieve self-healing concrete in one or more ideal ways, in an environmentally sustainable manner.

Autogenous self-healing uses unreacted cement particles, while minerals that dissolve in solution by means of crystalline admixtures, however, will also react with water and produce some substances, such as calcium carbonate, that might act as crack sealants. By contrast, autonomous self-healing utilizes external agents (i.e., encapsulated chemicals; corrosion inhibitors; fibers and microorganisms) which, as the product cracks, are activated as a repairing agent. These microcapsules are containers that hold a core (healing agent) in a shell or membrane that will hold onto the agent until it is needed for self-healing.

Autogenous self-healing concrete and autonomous self-healing concrete both have advantages and disadvantages in their own right. Autogenous self-healing relies on the concrete's natural chemical processes and energy requirements (calcium carbonate precipitation, for example) to repair small cracks. Although an inexpensive and practical way to heal small cracks resistant to autogenous healing, it is limited in its application.

Autonomous self-healing systems, by contrast, utilize external agents such as microcapsules or bacteria to actively seek repair of more complex or sophisticated damage, offering further healing capabilities and flexibility at a significant price. They may also fail or be harsh with durable materials, and making large numbers of such systems is difficult. The research should mainly concentrate on enhancing healing efficiency and production of durable healing agents as well as hybrid systems of healing that are adapted to local environmental conditions, and cutting costs to ensure wide access to these technologies. Moreover, nanotechnology and smart materials can allow more accurate and cost-effective solutions for self-healing.

Table 7 provides a comparative analysis of established and emerging self-healing concrete systems, highlighting their underlying mechanisms, effectiveness in crack closure, repeatability of healing cycles, cost and implementation complexity, and key literature references. This comparative framework not only contextualizes traditional approaches such as autogenous, microcapsule-based, vascular, and bacterial systems but also emphasizes the advantages of emerging hybrid and smart systems, which integrate multi-

cycle healing and data-driven monitoring. By presenting these distinctions, the table serves as a concise reference for evaluating performance, guiding the selection of appropriate

self-healing strategies, and identifying research gaps for future development in durable and sustainable reinforced concrete applications.

Table 7. Comparison of permeability & strength impact

Self-Healing System	Mechanism	Crack Healing Performance	Repeatability / Cycle	Cost & Complexity	Ref.
Autogenous (Intrinsic)	Continued hydration of unhydrated cement particles and calcium carbonate formation that fills cracks naturally.	Heals primarily <i>small cracks</i> (limited by material chemistry).	Single instance, limited by residual unhydrated phases.	Low; no added healing agents.	74
Microcapsule-based	Healing agents encapsulated in polymer/other shells release when cracks occur.	Effective for <i>small to moderate cracks</i> , depending on agent type.	Typically, a <i>single healing event</i> per capsule.	Moderate to high; capsule fabrication increases cost.	75
Vascular Networks	Embedded hollow channels deliver healing agents when cracks form.	It can be effective for <i>larger cracks</i> analyzed in composite design.	<i>Multi-cycle</i> healing is possible through refillable networks.	High, complex production and integration challenges.	76
Bacterial / Microbial	Microorganisms precipitate calcium carbonate in cracks upon activation.	A <i>wide range</i> of crack closure is reported as bio-mediated precipitation.	Potential for multiple cycles if nutrients and viability are maintained.	Higher microbial viability and nutrient delivery are challenges.	77
Emerging Hybrid / Smart Systems	Combines multi-cycle mechanisms with smart monitoring (e.g., sensors, data-driven feedback).	Designed to achieve both <i>crack closure and structural recovery</i> .	Designed for <i>multi-cycle</i> healing.	Potentially high initially, tailored for long-term ROI.	

5. Future and Challenge of Self Heal-Concrete

5.1. Economic and Environmental Impacts

Another promising trend within this sector is the growing application of Self-Healing Concrete (SHC) materials in construction as an alternative to standard concrete. With each SHC comes a multitude of benefits in terms of environment, economy, and society. From the perspective of the environment, SHC has significantly reduced the production of cement, identified as a material with substantial waste as it tends to emit air CO₂ [78, 79]. By enhancing durability and autonomously repairing cracks, SHC also reduces the frequency and extent of repair and maintenance work, thereby lowering the consumption of raw materials, energy, and associated emissions over the lifecycle of infrastructure.

This not only mitigates environmental impacts but also decreases overall maintenance costs, extending the service life of structures and supporting more sustainable and cost-effective construction practices. Furthermore, widespread adoption of SHC could contribute to circular economy principles, minimizing material waste and promoting the efficient use of resources in urban and civil infrastructure projects.

At a low cost, the SHC process is one way of extending the life of buildings and infrastructure and minimizing maintenance, leading to cost savings. Socially, human occupation of SHC reduces safety and noise. Thus, the SHC can play a huge role in sustainability and innovation in construction [80]. In this framework, cost-effectiveness is one of the key aspects of construction. The average U.S. market price of conventional concrete in 2023 was approximately \$125 to \$165 per cubic yard. When measuring these figures for use with self-healing bacteria in concrete, it costs roughly US\$6,876 a cubic meter. Despite its potential long-term prospects [79], the sharp price differential between existing concrete and self-healing concrete demonstrates both the possible financial value as well as the constraints towards its profitability. The main challenges include the reliability of self-healing as well as the good use of additional healing agents according to the environment. Furthermore, complete scale application of SHC also requires controlled development of new, optimized healing processes - i.e., the width of cracks and the recovery response in terms of time.

A second challenge is the price effect of concrete; integrations and cost-effectiveness of the addition of healing

agents will have to be balanced with the benefits of increased longevity. Similarly, understanding the long-term performance and behavior of SHC across different environments will guide the way forward for its application. It will require continual ingenuity, investigation, and collaboration between academia, industry, and decision makers to address these challenges. Another method (or two) could be applied to show the advantages and disadvantages of this self-healing method in order to provide a comparison to the optimal utilization of self-healing concrete.

5.2. Standardisation Issues

To implement this technology effectively, however, the management of its implementation should be closely scrutinized and overseen in terms of reliability, safety, and quality. Hence, guidelines and standards on the utilization of self-healing concrete for the purposes of worldwide construction projects are fundamental. Application of self-healing concrete in the construction industry, present in a scarce number of occasions, is still embryonic. The rules and standards for this technology are just emerging in some countries and institutions. Leading prominent international organizations include ASTM and ISO standards. They have likewise begun analyzing and establishing criteria for self-healing concrete in construction. Whereas no universally accepted standard is currently being developed, there have been current studies and field tests that provide a good indication as to what the criteria for SHC use should be for future studies. At present, changing regulations are based on certain critical quality parameters, including Material Qualification, Safety and Performance, Sustainability, and Environmental Impact, to ensure that the material meets the standards for its use in construction, so that the self-healing concrete is both safe and durable. Figure 8 presents the environmental and physical challenges of infrastructure elements, and the contribution of self-healing concrete to

enhancing structural strength, durability, and long-term viability is noted.

5.3. Field Application, Monitoring, and Smart Sensing Integration

Although laboratory investigations have deepened understanding of self-healing mechanisms, field application of self-healing concrete remains limited, and translating lab-scale performance to real structures poses significant challenges. Implementing self-healing systems in the field must address issues of uniform distribution of healing agents, integration with reinforcement, and environmental variability such as temperature changes, moisture cycles, and aggressive exposure conditions, which can all influence healing efficiency and durability [81-83]. Long-term monitoring is critical to validate real-world performance over the lifecycle of structures, yet only a few studies have incorporated real-time monitoring systems, sensor networks, or embedded indicators that can track crack formation and healing progression [84]. Integration with smart sensing and digital technologies, such as self-sensing cementitious composites and IoT-enabled monitoring solutions, offers promising avenues for continuous health assessment and data-driven maintenance strategies; these systems can measure strain, stress, or environmental changes within the concrete, supporting early detection of damage and facilitating predictive maintenance [82, 84]. However, challenges such as sensor calibration, environmental effects on sensor behaviour, and disparities between laboratory calibration and field conditions must be addressed to achieve reliable large-scale deployment [83, 84]. Combining self-healing mechanisms with embedded smart sensing technology not only enhances structural health monitoring but also contributes to durability, performance optimization, and cost savings over the structure's service life, demonstrating a key direction for future research and practical implementation.

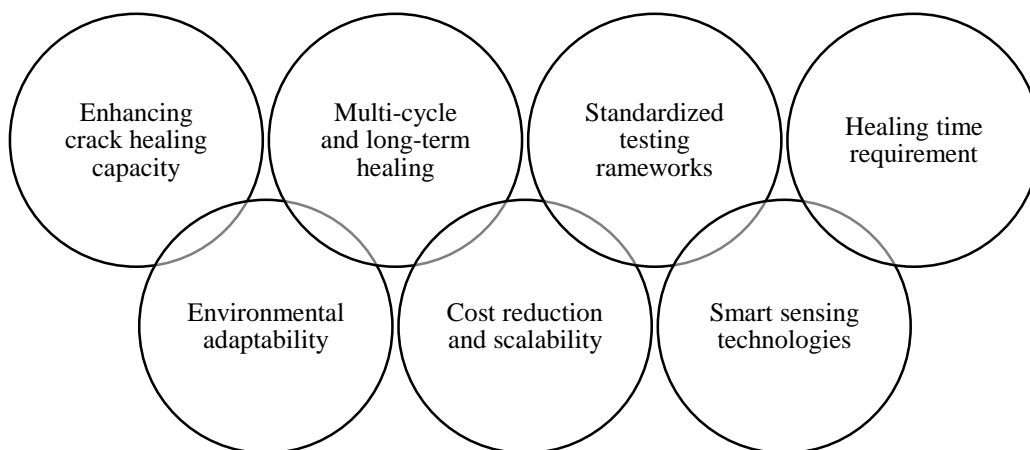


Fig. 8 Possible advancements towards self-healing concrete

6. Conclusion

Self-healing concrete (SHC) represents a significant advancement in reinforced concrete technology, offering enhanced durability, damage resistance, and structural

resilience. By autonomously sealing microcracks, SHC limits the ingress of aggressive agents such as chlorides, carbon dioxide, and moisture, thereby reducing corrosion risk and extending service life. Beyond technical

performance, SHC provides environmental benefits through lower cement consumption and reduced CO₂ emissions, economic advantages via decreased maintenance and rehabilitation costs, and social benefits by minimizing disruption and improving infrastructure safety.

Despite its promise, widespread adoption of SHC faces challenges, including high initial costs, variability in healing efficiency under diverse environmental conditions, limited long-term field data, and the lack of standardized regulatory frameworks. Addressing these barriers through continued research, large-scale validation, cost optimization, and development of industry standards will be critical to enable practical, performance-based implementation. SHC offers a transformative, adaptive, and sustainable solution for next-generation infrastructure, shifting concrete design from a passive protection approach toward an active, self-

recovering material system capable of improving service life, resilience, and long-term performance

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Conflicts of Interest

The authors acknowledge the non-conflicting role of their parties in this manuscript's publication. The research was performed individually without any financial or personal connections to the data that could have impacted the results or conclusions provided.

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