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CONCRETE'S DOCTOR: A REVIEW ON SELF-HEALING CONCRETE TECHNOLOGIES

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ABSTRACT

Cracking is one of the main reasons for the failure of reinforced concrete. Cracks allow water and other types of materials into the concrete, which directly impacts durability, strength, and also weakens the reinforcement. For overcoming the problem, Self Healing Concrete technology can be a blessing cause Conventional repair techniques are often costly and temporary, which has driven interest in self-healing concrete (SHC)—a material capable of repairing cracks either autogenously or autonomously. Self healing Concrete technology can be classified into three main types: Bacteria-Based Self-Healing Concrete, Chemical Capsule-Based Self-Healing Concrete, and Mineral Additive-Based Self-Healing Concrete. This review identifies the most current advancements in SHC relative to autogenous healing; microcapsules, microorganisms, and their techniques; chemical healing agents—sodium silicate, calcium nitrate, superabsorbent polymer, and calcium sulfoaluminate. For example, microbials and chemicals in microcapsules can heal cracks with an efficiency of 90% while superabsorbent polymers and calcium-based healing agents mixed together can consistently heal cracks greater than 750 µm; some scholars argue that recovery of mechanical strength is achieved. Yet much experimental evidence fails to surpass the laboratory stage into practical application. Concerns exist for capital costs, no universal testing metric, and indeterminate field tenure. Therefore, despite the ability for SHC to increase infrastructure lifespan, reduce repair costs, and promote sustainable construction practices, ongoing studies, approvals, and small-scale pilot tests must be assessed before implementation.

Keywords: *Self-healing concrete, autogenous healing, autonomous healing, durability*

1. INTRODUCTION

Concrete is one of the most widely popular building materials. Concrete is generally a mixture of coarse cement, sand, granular aggregate, and water. The difference of concrete from other construction materials, such as stone and bricks are the compressive strength of concrete is higher than that of others(Unnikrishna & Devdas, 2003). Though cement production alone contribute 7% global anthropogenic CO_2 emissions, which is due to limestone and clay(Jonkers et al., 2010), it is appreciated because of its strength, durability, versatility, and longevity. The biggest problem with concrete is that it cracks, and almost 80% of concrete failures are connected to it (Neville, 2011). This crack works as a door for water and harmful chemicals. These substances attack the steel structure and cause rust. They slowly eat away concretes durability and strength from inside. This resulted in a need for maintenance and repair for billions in global annual expenditure, only united state alone costing annually for maintenance and repair of concrete highway bridges due to reinforcement corrosion is nearly 4 billion dollars (Jonkers et al., 2010).

Conventional repair methodologies depend on manual repair, which is often costly, time-consuming, and provides only temporary restoration. These weaknesses of concrete have created a growing interest in new materials which, if free from these problems. Self-healing concrete thus represents an innovative method that, due to its inherent capabilities for autonomous crack repair, could offer promising benefits regarding enhancement in structural longevity and reduction in environmental impact, and usage of this material can be extended. So, CO_2 emissions due to cement production can be minimized.

This paper offers an overview of the most current advancement of self-healing concrete technologies. This study explores the mechanism of autogenous self-healing, microcapsules, chemical self-healing agents, and bio self-healing. The objective of this work is to furnish the research community with a basic conceptual framework and an informative framework of self-healing concrete technology, including an explanation of the working process of each methodology.

2. SELF-HEALING CONCRETE

2.1 Autogenous Self-healing

Autogenous healing refers to the natural ability of concrete to seal and heal small cracks without any external agents or additives. The chemical processes of autogenous healing are the two most crucial mechanisms: 1) The unhydrated cement grains continue to hydrate and 2) Calcium carbonate crystals ($CaCO_3$) precipitate on the crack faces as a direct result of chemical reactions between the calcium ions Ca^{2+} (found in the concrete matrix) and the carbonate ions CO_3^{2-} available in the water or CO_2 available in the air entering the crack (De Belie et al., 2018).

Autogenous healing in concrete mainly results from continued hydration and subsequent carbonation reactions. Initially, unhydrated cement compounds such as tricalcium silicate (C_3S) and dicalcium silicate (C_2S) react with water as shown in Fig. 1(B) to produce calcium–silicate–hydrate (C–S–H) and calcium hydroxide [$Ca(OH)_2$](Yuan et al., 2019).

$$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2 \quad (1)$$

The $Ca(OH)_2$, which formed in Eqn. (1) dissolves slightly in water and releases Ca^{2+} ions as shown in Eqn. (2). These ions react with carbonate species produced when carbon dioxide dissolves in water, as shown in Eqn. (3), forming carbonic acid and carbonate ions, which subsequently combine with Ca^{2+} ions to form $CaCO_3$ as shown in Eqn. (4) and Fig 1(A).

$$Ca(OH)_2 \leftrightarrow Ca^{2+} + 2OH^- \quad (2)$$

$$H_2O + CO_2 \rightarrow H_2CO_3 \rightarrow 2H^+ + CO_3^{2-} \quad (3)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad (4)$$

The precipitation of calcium carbonate ($CaCO_3$) crystals seals cracks, restoring water tightness and enhancing durability as shown in Fig. 1(C) (Li et al., 2023). Continuous hydration of unhydrated cement particles contributes to natural self-healing in young concrete, while calcium carbonate formation becomes the main healing mechanism in older concrete. This process mainly works for fine cracks below 0.2 mm in width (Li et al., 2023).

Figure 1: Possible mechanisms for autogenous self-healing in cementitious materials.
Note. Adapted from Talaiekhozan et al. (2014).

2.1.1 Factors Influencing Autogenous Healing

The autogenous healing of concrete strongly depends on its age. Because there are still a significant number of unhydrated cement particles in younger concrete that can continue to hydrate when exposed to moisture. The healing rate in younger concrete is high, and it gradually decreases with the passage of time, as shown in Fig.2. However, because of a denser microstructure and less reactive compound availability, older concrete has a lower capacity to heal (Neville, 2002).

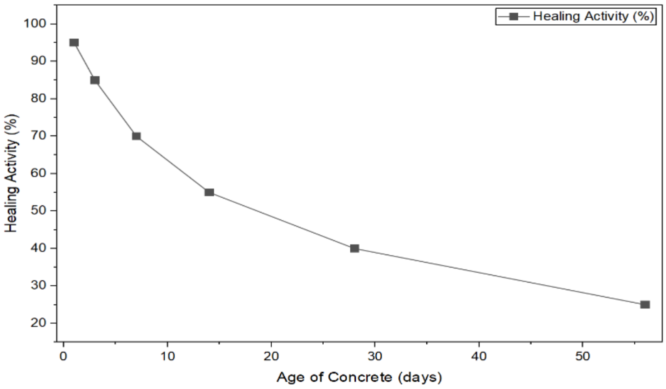

Figure 2: Conceptual relationship between the age of concrete and autogenous healing activity.
Note. Based on general trends reported in the literature (e.g., Neville, 2002; Van Breugel, 2007).

Water plays a vital role in autogenous healing by enabling chemical reactions and particle transport. Immersion provides the most effective results, while alternating wet–dry cycles may also enhance $CaCO_3$ formation due to CO_2 exposure and high alkalinity conditions. (De belie et al., 2018) The self-healing capacity of concrete depends largely on its composition. Factors such as clinker content, mineral additives, aggregate type, and concrete strength influence calcium carbonate formation, hydration activity, and crack behaviour (Sisomphon & Copuroglu, 2010).

2.1.2 Barriers and Possible Improvements in Autogenous Healing

Because of cement production, a lot of CO_2 is released to the atmosphere, which accounts for nearly 7–8% of global emissions (Scrivener et al., 2018). Using mineral additives such as fly ash, slag, or silica fume can lower this environmental impact while enhancing autogenous healing (Van Tittelboom & De Belie, 2013). Blast furnace slag (BFS) exhibits stronger self-healing potential than fly ash due to its higher calcium content and inner hydraulic reactivity, which helps continuous formation of calcium silicate hydrate (C–S–H) and calcium carbonate even at later ages. Fly ash helps in reducing CO_2 emissions and refining pore structure, but it reacts more slowly and may be less effective in promoting early-age healing, whereas BFS works better in this case (Yang et al., 2019). Crystalline admixtures can improve autogenous healing by producing insoluble crystals that can block pores and seal microcracks when moisture is present. These admixtures promote ongoing hydration and calcium silicate formation and self-sealing capacity in concrete (Qureshi et al., 2018).

Autogenous healing is generally limited to fine cracks up to 0.2 mm in width. In this case use of superabsorbent polymers (SAPs**)** has played a vital role as they can absorb and retain water within the concrete matrix, promoting continuous hydration and calcium carbonate precipitation even in larger cracks (Snoeck & De Belie, 2015).

2.2 Microcapsules

Concrete cracks can be successfully repaired using microcapsule-based self-healing, which involves encasing tiny capsules containing reactive healing agents inside the concrete matrix. Unlike autogenous healing, which depends on residual cement hydration or environmental moisture, microcapsules provide a controlled and immediate healing response directly at the site of damage (De Belie et al., 2018). The microcapsules burst due to the stress caused by concrete cracks, releasing their core contents into the damaged area. Epoxy resins, polyurethane, or mineral-based solutions such as calcium carbonate precursors, which are denoted as the healing agents, react with the matrix or the moisture to seal the cracks (Gruyaert et al., 2017).

Microcapsules vary in size, shell composition, and core composition, all of which affect how well they work. The common shell materials that help to maintain chemical stability and durability are polymethyl methacrylate (PMMA), silica, and urea-formaldehyde. Capsule size mainly ranges from micrometres to a few millimetres. Especially smaller capsules offering better penetration into fine cracks, although excessive incorporation can slightly reduce the compressive strength of the concrete. (Gruyaert et al., 2017; De Belie et al., 2018).

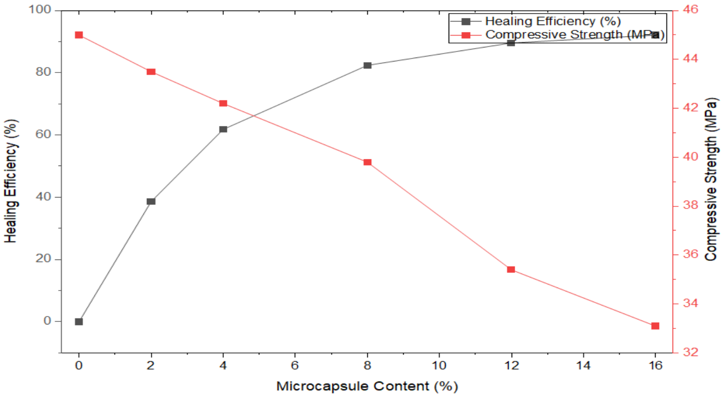

Figure 3: Relationship between microcapsule content, healing efficiency, and compressive strength of self-healing concrete. Note. Adapted from Kanellopoulos et al. (2015); Lv et al. (2020)

The advantages of microcapsule-based self-healing concrete mainly include localized repair, rapid response to cracking, and the ability to tailor the healing agent according to crack type and size, as shown in Figure 3, the healing efficiency curve. The healing efficiency is rising with the increase of microcapsule content due to more available healing agents. However, excessive microcapsule content may reduce overall mechanical strength, as shown in Figure 3 compressive strength curve also increases production costs and leads to uneven distribution during mixing, which can result in incomplete healing. Compressive strength tends to decrease beyond an optimal dosage, and so an optimal dosage is required for maximizing self-healing while minimizing adverse effects on structural performance. (De Belie et al., 2018).

Optimizing microcapsule design, including the use of nano-sized capsules and hybrid systems containing mineral precursors, can be a solution for this decrease in compressive strength. This helps to enhance healing efficiency while limiting reductions in mechanical properties. Besides, a combination of microcapsule-based healing with autogenous mechanisms can further improve durability and crack closure reliability in concrete structures (De Belie et al., 2018; Gruyaert et al., 2017).

2.3 Chemical Self-healing

Chemical self-healing is a process in which chemical agents react and help to seal cracks automatically. Some common chemical self-healing agents are Sodium silicate, Dicyclopentadiene, Calcium nitrate, Superabsorbent polymers (SAPs), Calcium sulfoaluminate (CSA), and Silica particles. Using these agents makes concrete stronger, more durable, and able to repair itself without external help.

2.3.1 Sodium Silicate (Na_2SiO_3)

When cracks create in the concrete, sodium silicate can be released from microcapsules and react with cementitious material in cement, like calcium hydroxide ($Ca(OH)_2$), to produce extra C-S-H gel incrack zone to restore its strength and improve mechanical durability. (Mokhtar & Hassan, 2021). Here is the reaction mechanism:
$2Na^{+} + SiO_2^{3-} +Ca_2+ +2OH- XH_2O \rightarrow CaOSiO_2XH_2O +2NaOH.$
Previous research shows that sodium silicate, as a healing agent, can recover a huge portion of the strength that was lost(Mokhtar & Hassan, 2021) and reduce water absorption in cracked concrete (Adhikary et al., 2024). Healing efficiency depends on crack width, dose of sodium silicate, curing condition, and how pure the agent is delivered. (Adhikary et al., 2024). Sodium silicate completely seals less than 120μm and wider than 120μm, and the crack mouth healing reaches up to 70% of it. But containing different specimens can lead to higher mouth crack sealing. (Cao et al., 2019)

2.3.2 Calcium Nitrate ($Ca(NO_3)_2$)

Calcium nitrate reacts as a source of calcium ions (Ca^{2+}) that support healing when cracks allow water, thereby helping to fill the cracks. The formed hydration products on the cracked surface result in the restoration of cracks and mechanical performance. (Adhikary et al., 2024)
$Ca(NO_3)_2 + 2Ca(OH)_2 \rightarrow 2Ca(NO_2)_2 + 2H_2O$
If we use encapsulated calcium nitrate to seal the crack opening in concrete, in 21 days, it can be fully sealed to a depth of 290μm. (Adhikary et al., 2024)

2.3.3 Superabsorbent Polymer (SAP)

SAPs are a type of material that absorbs water and slowly releases it to provide internal curing and moisture availability inside the crack. Superabsorbent polymers are a group of polymeric materials that can absorb a large quantity of liquid (about 100–500 times their own weight) and become watertight, impermeable gels. When a crack appears in the SAP-added cementitious system, and SAP comes into contact with water, it expands, seals the cracks, and restores the permeability of the cementitious system. (Adhikary et al., 2024). Research shows that CSA-based gealing products produce recognizable periods within cracks, which improve crack sealing (Park & Choi, 2021). Specimens containing 5% SAP by weight achieve significant crack sealing. (Lee et al., 2010)

2.3.4 Calcium Sulfoaluminate (CSA):

CSA is an expansive material and admixtures, when added to the concrete forms hydration products and can expand into cracks and fill them. When it comes into contact with water, CSA expands and gains durability, sealing the crack mouth. When ordinary Portland cement (OPC) was replaced with 10% CSA and 1.5% CAs, 400μm cracks could be healed within 28 days. (Park & Choi, 2021). Concrete is a highly strong material, and it can bear huge loads in different circumstances. Its compressive strength is usually varying from aggregates and admixtures. (Ding et al., 2016).

Table 1: List of chemical healing agents, doses, their fabrication method, and the before and after situation of the crack using healing agents

Self-healing concrete agent	**Fabrication Method**	**Doses**	**Mechanical performance recovery**	**Crack width (Before)**	**Crack width (After)**	**Reference**
Sodium silicate (Na_2SiO_3)	Microcapsule	16%	45% Flexural strength	22μm	15.5μm	Alghamri et al., 2016 Adhikary et al., 2024
Calcium nitrate ($Ca(NO_3)_2$)	Microcapsule	1%	6% stiffness recovered without steel reinforcement, 38% with steel reinforcement	-	-	Bonilla et al., 2018 Al-Ansari et al., 2017
SAP	SAP particle is directly mixed with the cementitious material	1.8%	103% Compressive Strength	740μm	0μm	Adhikary et al., 2024
CSA	Powder CSA replacement of an OPC	10%	150% deflection capacity	380μm	80μm	Adhikary et al., 2024

2.4 Biological Self-Healing Process

Biological Self-healing is a process of self-healing of concrete where living organisms, mostly bacteria is used to repair the cracks of concrete. Because of its self-sustaining, eco-friendly, and repeatability makes it more beneficial than "Natural Self-healing Process" and "Chemical Self-healing process". Microorganisms can be divided into three important categories: bacteria, fungi, and viruses. The pH of fresh concrete is usually around 12 to 13, which provides an alkaline environment, and the temperature of fresh concrete can go up to 70°C. After the concrete dies, there is not enough water. For this reason, the selected microorganisms must exhibit high resistance against high Temperature, High alkaline environment, and limitations of water (Talaiekhozan et al., 2014). Biological self-healing is basically focused on bacteria-based self-healing because of their ability to precipitate calcium carbonate ($CaCO_3$). Fungi are a promising option for their ability to promote biomineralization, and virus-based self-healing concrete is still largely theoretical and experimental.

2.4.1 Bacterial Self-healing in concrete :

Microbially Induced Calcium Carbonate Precipitation (MICP) is the most attractive method of bacteria-based self-healing concrete, where bacteria are introduced to $CaCO_3$ precipitation to seal cracks in concrete (Xu et al., 2018). The most effective pathway for MICP is "urea hydrolysis" (Xu et al, 2018). The bacteria used in urea hydrolysis are called ureolytic bacteria. Ureolytic bacteria produce urease, which triggers the hydrolysis of urea ($CO(NH_2)_2$) into ammonium ion (NH_4^+) and carbonate ion (CO_3^{2-}). A series of reactions takes in then process are shown in Eqn. (5) to (11) (Van Tittelboom et al., 2010).

Urea is hydrolyzed to carbamate and ammonia in the presence of urease.

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3 \quad (5)$$

The produced carbamate is hydrolyzed to produce ammonia and carbonic acid.

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3 \quad (6)$$

Carbonic acid dissociates into the bicarbonate ion and the hydrogen ion

$$H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \quad (7)$$

Ammonia is hydrolyzed to produce ammonium ion and hydroxide ion

$NH_3 + H_2O \rightarrow 2NH_4^+ + 2OH^-$ (8)

The product of eqn. (3) and (4) go towards the formation of carbonate ions for the continuous production of hydroxide ion which increases pH (Talaiekhozan et al., 2014).

$HCO_3^- + H^+ + 2.NH_4^+ + 2OH^- \rightarrow CO^{2-} + 2NH_4^+ + 2H_2O$ (9)

A bacterial cell is negatively charged. SO it draws cations from the environment, including calcium ion (Ca^+), to deposit on its cell surface. This calcium ion reacts with the carbonate ion and causes precipitation of $CaCO_3$ (Talaiekhozan et al., 2014).

$Ca^{2+} + Cell \rightarrow Cell - Ca^{2+}$ (10)

$Cell - Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 + Cell \downarrow$ (11)

Genus Bacillus is focused on the study of bacteria-based self-healing because they are commonly found in soil and are able to form spores under unfavorable conditions, they can remain dormant for over 50 years in a high alkaline environment, and they can produce enough amount of calcium carbonate through urea hydrolysis (Nguyen et al., 2019). Urea hydrolysis has numerous benefits compared to other carbonate generate approach, because it can generate larger quantities of carbonate in a short period (Ghazy et al., 2024).

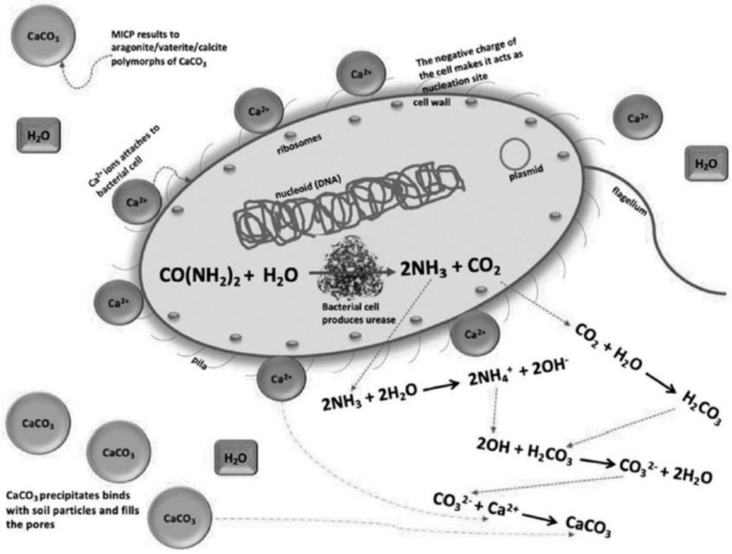

Figure 4: Ureolytic pathway of $CaCO_3$ by bacterial self-healing concrete. Note. Adapted from (Rehman et el., 2022)

Ureolytic bacteria enhance durability with their ability to repair cracks faster than other bacterial methods, and this process reduces permeability (Achal & Mukherjee, 2015). Though this process has some advantages, it has some issues; it produces ammonia, and this ammonia produces ammonium and causes a pH increase (Dhami et al., 2013). In order to avoid these things, alternative metabolic mineral-producing pathways by bacteria are introduced (Jonkers et al., 2010). This process is called a non-ureolytic process where precipitation occurs via metabolic pathways such as Denitrification (Ghazy et al., 2024), Carbonic Anhydrase activity (Jain et al., 2021), Photosynthesis, or Heterotrophic Oxidation (Lee et al., 2017). The CA-mediated mechanism bypasses urea and converts dissolved CO_2 into carbonate ions by following the reaction $CO_2 + H_2O \rightleftharpoons HCO_3^- \rightleftharpoons CO_3^{2-}$ (Jain et al., 2021). In the denitrification process, hydrogen ions are consumed, which causes pH to rise and promotes carbonate formation, which reacts with calcium to produce $CaCO_3$. These processes are shown in reactions 12 to 14 (Ghazy et al., 2024).

$NO_3^- + H^+ \text{ (Denitrification)} \rightarrow CO_2 + N_2 + H_2O$ (12)

$CO_2 + 2OH^+ \rightarrow CO_3^{2-} + H_2O$ (13)

$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$ (14)

2.4.2 Factors affecting Biological healing in concrete

2.4.2.1 Selection of bacteria

The choice of bacteria directly influenced the self-healing capabilities of concrete. *Bacillus subtilis*, *Sporosarcina pasteurii*, *Bacillus sphaericus*, and *Bacillus megaterium* are commonly used because of their high resistance, spore-forming ability, and potential to induce $CaCO_3$. Because of *Bacillus subtilis's* moving nature and shape, it is easy to classify is a group of wide varieties. It has adaptability to rough environmental conditions (Yatish Reddy et al., 2020). It increases compressive, split tensile and flexure strength up to 22%,16% and 11% after 28 days if concrete mixed with a cell concentration of 10^8% cells/ml in liquid form and water cement ratio of 0.41% (Durga et al., 2020). It can produce highly resistant spores and can heal fractures up to 0.81mm (Elgendy et al., 2025). *Sporosarcina pasteurii* is a soil-borne bacterium and non-pathogenic (Talaiekhozan et al., 2014). After 28 days, it can enhance properties like compressive strength, flexural strength, and split tensile strength up to 10.8%, 5.1% and 29.37% if M20 concrete mix is used with water cement ratio is 0.46 and fly ash us added with 10%, 20% and 30% to the weight of the cement (Yatish reddy et al., 2020). It can survive in high pH environments, it has high urease activity, and it can heal cracks up to 0.4mm (Elgendy et al., 2025). *Bacillus sphaericus* is a gram-positive, spore-forming, aerobic bacterium. (Yehia et al., 2025). It has high tolerance in alkaline environments, high temperature, and ultraviolet light, and it can heal cracks up to 0.907mm. Selecting bacteria in bio self-healing concrete requires some consideration which is vital for developing effective and reliable bacterial self-healing concrete, for example (a) the ability of forming endospores is essential because it allows bacteria to remain dormant is unfavorable condition, (b) High rate of precipitation of $CaCO_3$ is essential for efficiency, (c) alkaliphilic properties are also important for bacteria to survive in high pH levels of concrete, (d) bacteria should require minimum requirements of nutrients to sustain themselves over the long term (Elgendy et al., 2025).

Table2. Summary of bacteria used in self-healing concrete with healed crack widths.

Bacterium	Type of bacterium	Healed Crack width	CaCO3 formation pathway	Reference
Bacillus subtilis	Ureolytic	0.81mm	Ureolyisis	(Elgendy et al., 2025)
Sporosacina pasteurii	Ureolytic	0.4mm	Ureolyisis	(Elgendy et al., 2025)
Bacillus sphaericus	Ureolytic	0.907mm	Ureolyisis	(Yatish Reddy et al., 2020)
Bacillus megaterium	Non- ureolytic	0.3mm	Carbonic anhydrase	(Ahmad et al., 2025)
Bacillus pseudofirmus	Non- ureolytic	0.15mm	Denitrification	(Ivaškė et al., 2023)
Bacillus cohnii	Non- ureolytic	0.135mm	Carbonic anhydrase	(Ivaškė et al., 2023)
Bacillus cereus	Ureolytic	0.2-0.35mm	Ureolyisis	(Jain et al., 2021).
Bacillus halodurans	Non- ureolytic	0.10mm	Carbonic anhydrase	(Ivaškė et al., 2023)
Escherichia coli	Non- ureolytic	0.2mm (varies)	Iron reduction	(Ansari & Joshi, 2019)

2.4.2.2 Bacteria introduction techniques

Different methods have been used to introduce bacteria into concrete. They can be generally divided into two methods: direct and indirect. In the direct method, bacteria are used in the vegetative state and in the spore form directly on the concrete (Khan et al., 2023). Adding bacterial spores directly in concrete decreases spores significantly; it decreased 1.8x10^6 spores/cm^3 to 0.5x10^3 spores/cm^3 in 135 days of curing (Jonkers et al., 2010). There are also some limitations in this process: a) harsh concrete environment, 2) uneven distribution 3) limited nutrient supply, 4) uncontrolled biomineralization, and so on. To overcome these issues encapsulate bacteria method is introduced. In this case, bacteria are not directly introduced to the concrete matrix but are used by carriers. These carriers are different based on their size, how well they hold the bacteria, and so on. During the concrete mix process, the ability of these carriers to retain bacteria and prevent them from leaching is very important. Future studies also need to look into the cost of the material of these carriers (Khan et al., 2023).

2.4.2.3 pH

The pH of fresh concrete is usually between 10 and 13 (Talaiekhozan et al., 2014). Urease activity got stronger at pH levels 6-10. More specifically, the pH range is 7.5 to 8 for the urease enzyme (Elgendy et al., 2025). pH value prevents bacteria (12-13) from inhibiting the growth and lowering the efficiency of urea hydrolysis by 75-85% (Elgendy et al., 2025). So, the research focuses on alkaliphilic or spore-forming bacteria, generally from the *Bacillus* genus (like *Bacillus pasteurii* or *Bacillus subtilis*), which can survive harsh conditions as a dormant spore state for a long time, and some spores can be viable for up to 200 years (Jonkers et al., 2010). When water and nutrients enter a crack from the environment, and pH decreases, causing them to germinate into active vegetative cells (Elgendy et al., 2025).

2.4.2.4 Temperature

The temperature of fresh concrete goes up to 70°C (Talaiekhozan et al., 2014). Because of thermal stresses on the cells, bacteria were less successful for temperature for 40°C or higher. A temperature between 30°C to 35°C is optimal for bio self-healing (Zhang et al., 2015). At low temperature urease activity significantly decreased, and it became difficult for the bacteria to carry out regular metabolism, which makes the bacteria dormant and results in a slower rate of healing (Elgendy et al., 2025). To maximize the self-healing process efficiency, maintaining an ideal temperature is essential (Jonkers et al., 2010).

2.4.3 Fungi-mediated self-healing concrete

Bacteria do not have sufficient resistance to survive against unfavorable environment like high pH, dry conditions of concrete (Luo et al., 2018). At the same time, cation binding by fungi ia metabolism-independent process. Fungal cell walls naturally attract and bind metal ions like calcium (Ca^{2+}); this ion reacts with soluble carbonate ions and forms calcium carbonate ($CaCO_3$) (Luo et al., 2018). Fungi have a superior ability for self-healing as compared to bacteria based self-healing, because of (a) their capability of forming vast network, (b) their high biomass creates plenty of nucleation sites for CaCO3 precipitation both directly and indirectly, (c) their ability to use various nutrients, (d) their capability of growing in harsh environments relevant for concrete like high pH, high alkaline environment, varying temperature (v) superior wall-binding and metal-uptake ability due to presence of chitin in their cell walls, and (vi) the fungal cells have inherent hydrophobicity (Van Wylick et al., 2021).

3. CHALLENGES AND LIMITATIONS

Though autogenous self-healing is a beneficial property of concrete, it has significant limitations such as it is only effective on very narrow cracks, typically under 0.3mm in width. Chemical-based self-healing concrete faces some challenges before used in real-life construction. Studies show that positive results in laboratory conditions, but in large-scale and real-life applications are rare and not feasible in large-scale and real-life applications because of the unpredictable environment and market availability of these chemicals. Another problem is the lack of a standard testing procedure to evaluate healing performance, strength recovery, and crack sealing efficiency. The performance of these chemicals heavily depends on moisture, crack width, and temperature (Adhikary et al., 2024). Bio-self-healing concrete is comparatively new to chemical-based-self-healing concrete and autogenous self-healing. So, studies on bacteria on bio-self-healing are quite limited, and cost can be a significant factor for large scale of projects. Also, there is no guarantee that bacteria will heal the crack completely, especially for larger and more complex cracks. Studies indicate that it causes partial healing and leaves some areas vulnerable to further damage (Elgendy et al., 2025). Studies on fungi-based self-healing concrete are very limited, and the mechanism and efficiency of fungi in repairing cracks are not yet well understood.

4. FUTURE PROSPECTIVE

For the future, work is going on to make self-healing concrete cheaper and more reliable. New technologies, like their performance, may be improved by nanomaterials and smart additives.

Simultaneously, cooperation between scientists and engineers and it requires more industries to come up with test standards to introduce this material into mainstream construction. In other words, self-healing concrete could revolutionize the way we build things. Instead of continuous repairs, we could have self-maintaining structures, just like all living organisms (Kureshi et al., 2025). The future of bio-self-healing concrete is bright. Genetic engineering could lead to the development of bacteria that will enhance their ability to survive in harsh conditions. Future research may focus on thermotolerant and genetically modified bacteria (Elgendy et al., 2025), and fungi represent a promising area. Research should be carried out to explore their potential in this field.

5. CONCLUSION

This paper reviews the methods of self-healing concrete. Self-healing concrete has the potential to change how we build. Instead of relying on constant repairs, we could have structures that take care of themselves. The concept of self-healing is inspired by biological systems, such as the human body, which heals after injury. So, this advancement reduces maintenance frequency, extends the lifespan of structures, and lowers the lifecycle cost. Self-healing concrete contributed to sustainability by reducing cement consumption, which causes CO_2 emissions. Self-healing concrete technology is shifting toward smarter and more sustainable solutions by integrating biological, chemical, and capsule-based self-healing systems. While there are still hurdles to overcome, this technology could make construction more sustainable, cost-effective, and resilient, helping us build stronger and smarter infrastructure for the future.

6. DECLARATION OF USE OF AI

AI-assisted tools were being used to facilitate a comprehensive literature search and to identify previous relevant research titles, specially field like fungi-based self-healing concrete, where research work is so limited. Tools like ChatGPT and Gemini were only used to ensure the inclusion of the latest available data in the field. All identified sources were manually verified, and the collections of data and manuscripts were entirely prepared by the authors.

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