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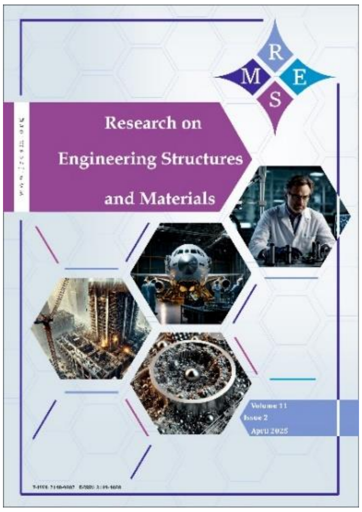

Encapsulation technologies in self-healing concrete: Advancements, challenges, and future directions

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Review Article

Encapsulation technologies in self-healing concrete: Advancements, challenges, and future directions

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Abstract

Concrete, being a widely used construction material, is vulnerable to crack formation, which significantly compromises the structural integrity of concrete and service life and requires higher maintenance costs, which prompts the development of self-healing concrete. This review systematically investigates encapsulation-based self-healing methods, focusing on microcapsules, hydrogels, and polymeric shells. This review critically analyses the advancement in healing agent materials, capsule materials, activation mechanisms, and performance with environmental conditions such as freeze-thaw cycles and chloride ingress. Key performance indicators, such as healing efficiency, durability, strength recovery, and fracture closure rates, are compared across encapsulation techniques. Additionally, this study evaluates the cost-effectiveness of these technologies and explores integration with novel technologies, such as embedded sensors for predictive maintenance. By identifying issues such as compatibility, durability, and scalability, this review highlights the research gaps. These findings provide a roadmap for optimizing encapsulation technologies for improved resilience, sustainability, and longevity in concrete infrastructure.

1. Introduction

Concrete is one of the most widely used construction materials around the globe because of its high compressive strength, versatility, availability, cost, and durability. However, one significant concrete problem is cracking [1], [2]. Cracks in concrete affect strength, structural integrity, and durability. These cracks lead to creating pathways for aggressive agents, such as chlorides, reinforcement corrosion, reduced mechanical performance, and eventually deteriorating concrete, which leads to structural collapse based on the extent, size, and connectivity of cracks [3], [4], [5]. Upon deterioration, concrete structures need to be repaired, having a production cost of 60$/m^3 to 80$/m^3, and the repair and maintenance cost rises to 147$/m^3 [6]. Traditional methods of repairing include sealing with epoxy or latex binding agents, stitching, overlaying, and grouting. The traditional methods are labor-intensive, involve high costs, affect the aesthetics of the structure, and create environmental impacts [4], [6]. Self-healing concrete with encapsulated healing agents presents a promising approach to these cracking problems [3]. This microencapsulation releases a healing agent that precipitates and polymerizes with an embedded catalyst to heal and seal the crack initiated [7].

Self-healing concrete can repair its cracks without external intervention through any of the following mechanisms. Autogenous self-healing relies on the unhydrated cement particles present in concrete, which continue to hydrate and produce hydration products that fill the cracks. However, it has a limited water requirement; it cannot proceed without water, making it more

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prominent in fresh concrete. Vascular self-healing relies on the network of tubes that delivers the healing agent to the cracked location. Even though an external source is involved, it is not technically self-healing. However, it is more suitable for laboratory-scale structures because it is not feasible on most of the actual construction sites to install a network of pipes in concrete for vascular self-healing. Encapsulation self-healing relies on micro-capsules that provide mechanical protection to self-healing agents, mixed with concrete and trigger when a crack opens and fills the crack due to capillary action and solidifies through a chemical reaction to seal and heal the concrete and restore the structural integrity [3], [6], [8]. An overview of different types of self-healing in concrete and their classification can be seen in Fig. 1.

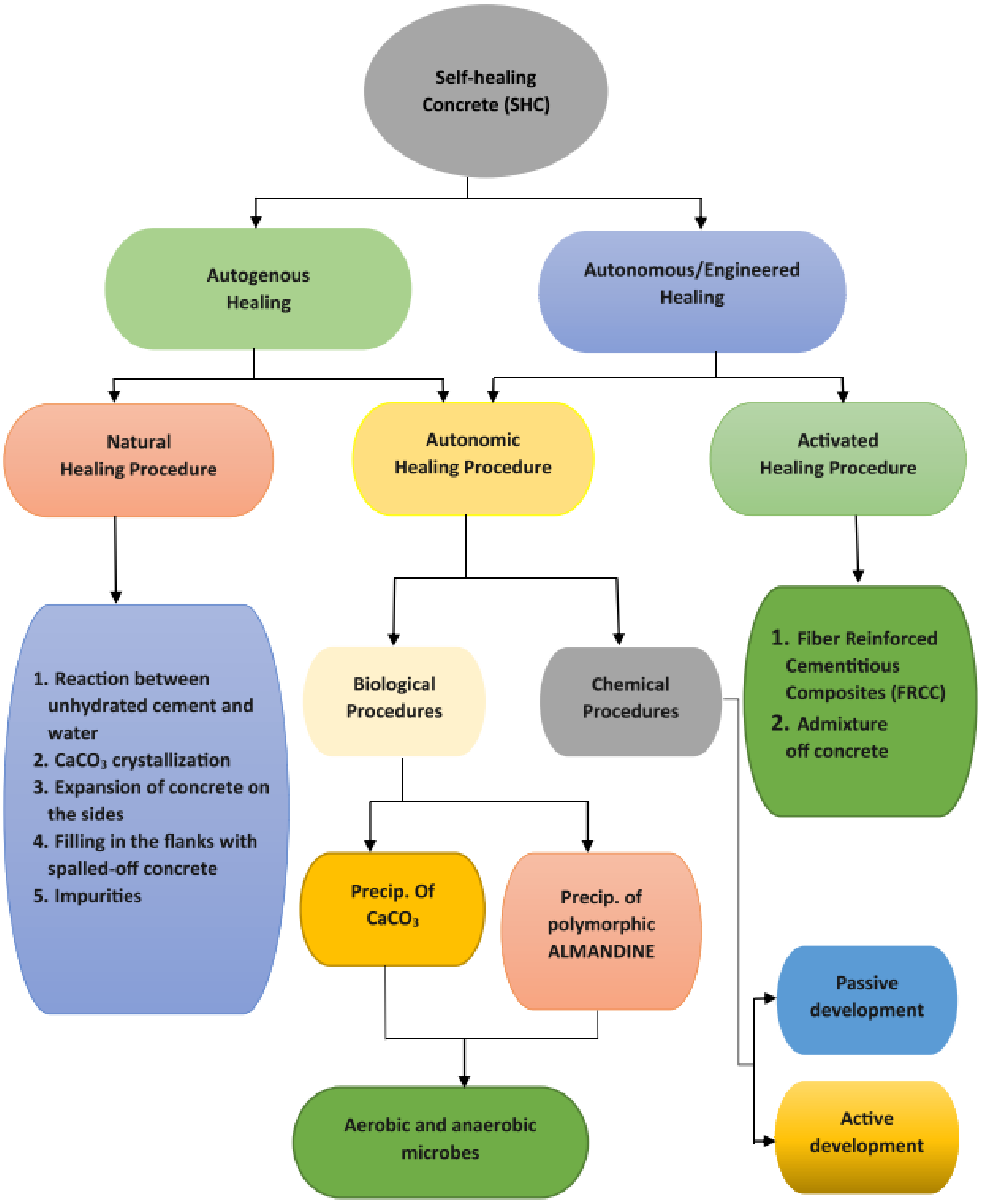


Fig. 1. Self-healing procedures are arranged hierarchically[13]

This review study aims to access and compare different encapsulation techniques for self-healing concrete, focusing on material composition, mechanical performance, activation mechanism, and durability. It analyzes the effectiveness of different self-healing strategies in concrete based on their healing efficiency, strength recovery, and durability in an exposed environment. While several reviews have explored self-healing mechanisms in general, few have comprehensively examined encapsulation-based methods under real-world environmental conditions or assessed their economic feasibility and integration with intelligent systems. There is a lack of standardization in evaluating healing performance, and long-term durability studies remain limited. This review addresses these gaps by systematically analyzing recent encapsulation advancements, comparing healing efficiencies under cyclic conditions, evaluating cost-effectiveness, and highlighting emerging smart technologies. It also underlines the key challenges pertaining to the dispersion and stability of the encapsulated agents, the mechanical survivability of the capsules during the mixing of the concrete, and the need for standardized methodologies for the assessment of performance similar to ASTM C1202 (test for chloride ingress), ASTM C1585 (for rate of absorption), ASTM C-157 (for shrinkage testing), ASTM C157 (for length change because of moisture testing) [9], [10], [11], [12]. By highlighting current research gaps and future potential improvements, this review defines the future direction taken by the optimization of encapsulation-based self-healing systems using sustainable and cost-effective materials integrated with smart monitoring technologies in order to enhance the resilience of concrete infrastructure.

2. Encapsulation Technologies in Self-Healing Concrete

When cracks occur in concrete, some healing agent is required to go and fill the affected area. A mobile liquid healing agent is required to reach cracks of varying sizes and expand to seal the crack. Therefore, a carrier is required that can carry the healing agent and can show brittle behavior and adhesion in the concrete matrix so that it can release the healing agent when the crack opens [8], [14], [15]. These encapsulations also prevent the self-healing agents from participating in concrete hydration and can be embedded in the concrete mixer during concrete preparation [16]. This section covers the various encapsulations involved in self-healing concrete, including microcapsules, hydrogels, and polymeric shells. Their rupture mechanism, composition, and comparative properties are discussed. An overview of various self-healing mechanisms in concrete is illustrated in Fig. 2 below.

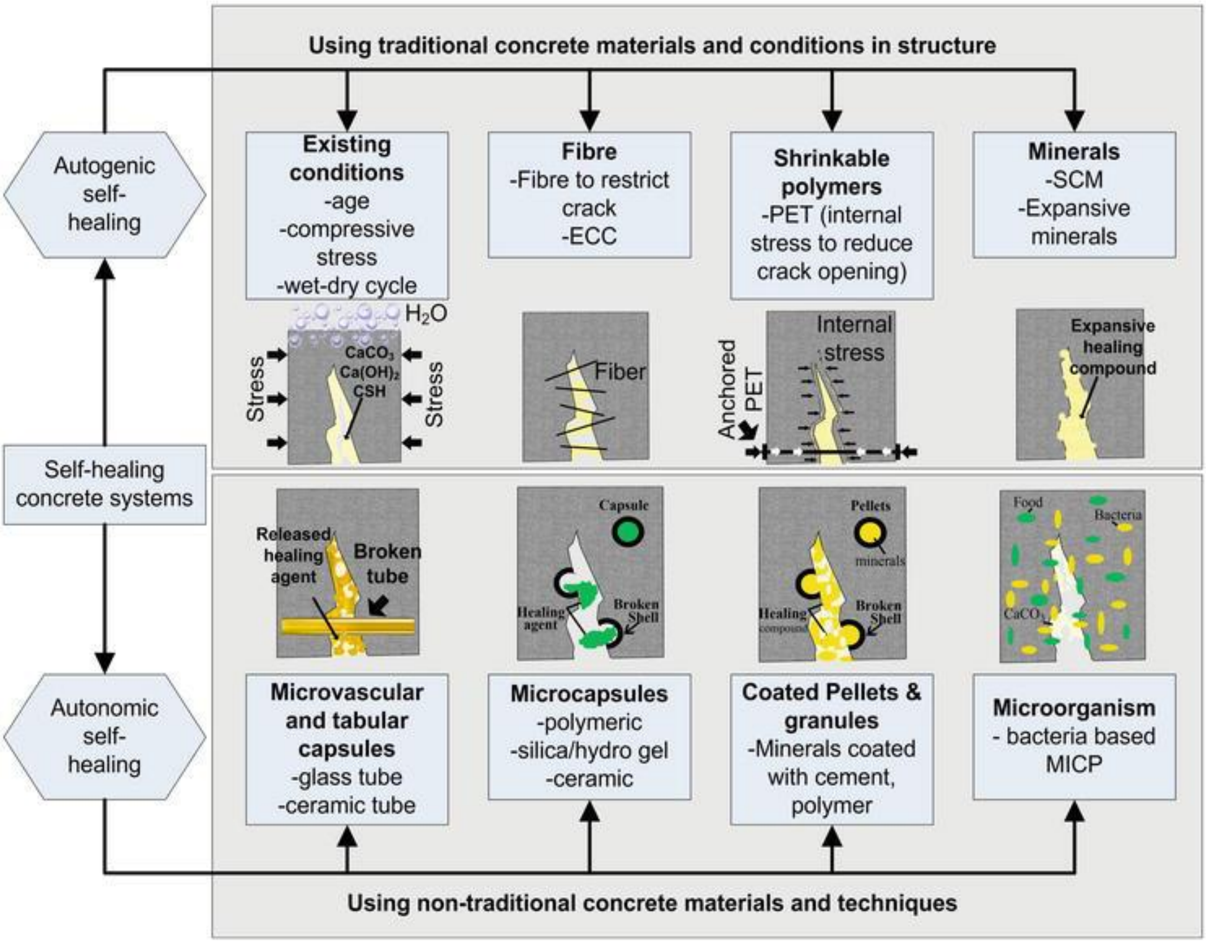


Fig. 2. Self-healing concrete systems [17]

2.1. Microcapsules

Microcapsules typically contain self-healing agents that are engineered to increase the efficiency and durability of the self-healing process. These microcapsules typically have a core-shell structure that protects the therapeutic agent until the appropriate activation mechanism has occurred. Shell materials and healing agent combinations are presented in Table 1. The primary materials utilized for microcapsule shells are:

- Epoxy Resins: The shells are made with epoxy resins characterized by high wet adhesion strength and highly resistant to chemicals. Therefore, they are suitable for microcapsules that will be subjected to a corrosive environment. The epoxy shells protect the healing agent inside, providing a delicate connection with the embedded catalysts, which form a robust network upon activation [18], [19].
- Polyurethane: Polyurethane is another material suitable for microcapsule shells in self-healing concrete. Polyurethane films provide flexibility and resilience during certain load ranges. Prevents premature rupture of microcapsules. This makes it suitable for concrete masses that experience cyclic loading and dynamic cracking [20].
- Cementitious Shells: Capsules composed of sodium silicate and Portland cement have been shown to improve the crack-sealing ability in both fresh and hardened concrete/mortar. Cementitious shells have a greater affinity for the cement matrix, lowering the interfacial stress while providing the necessary structural support [3].

2.1.1. Mechanism of Healing upon Capsule Rupture

The self-healing process is initiated when cracks propagate, causing the capsule shells to rupture and release healing agents into the damaged area [21]. Table 1 provides common combinations of healing agents and shell materials. The mechanism varies based on the agent:

- Epoxy-based agents: When the capsule ruptures in self-healing concrete containing polyurethane agents as the healing agent, it is released into the crack faces by capillary action. The healing agent contacts the catalyst, triggering polymerization, thus ensuring the closure of the nearby cracks [22].
- Polyurethane agents: Crack openings in moist surrounding trigger them, it expands and cures the crack upon activation with moisture content, filling the cracks and restoring the structural integrity [23].
- Cementitious agents: Sodium silicate (Na_2O-SiO_2) is induced in concrete through microcapsules, which release upon crack opening and react with Calcium Hydroxide $Ca(OH)_2$, already present in concrete, and moisture in surrounding to produce calcium silicate hydrate (C-S-H) gel, which fills the crack and enhance the durability of concrete [24].

Table 1. Common combinations of shells materials and healing agents.

Healing Agent	Shell Material	Reference
Epoxy resins	Perspex, glass, poly (melamine-formaldehyde), poly(urea-formaldehyde)	[25], [26], [27]
Polyurethane	Quartz glass, ceramics	[15], [28]
Cementitious agents	Polyurethane, urea formaldehyde	[24], [29]

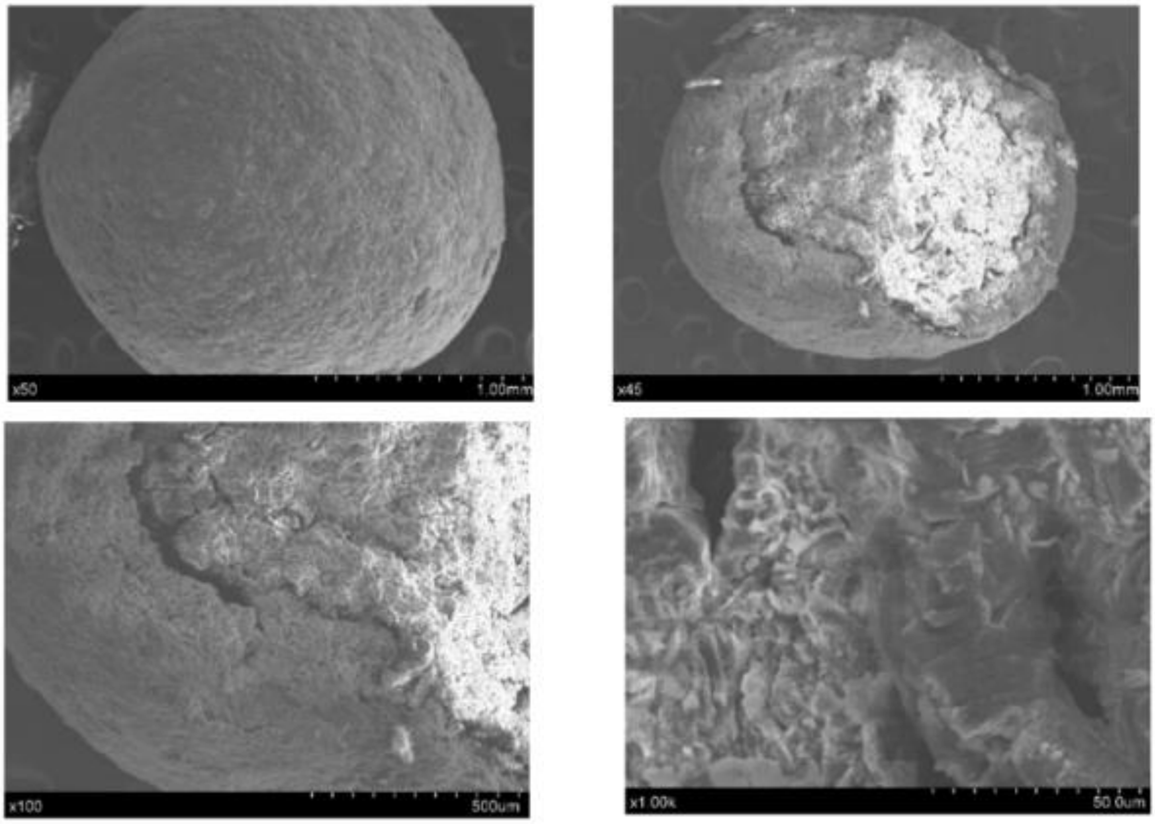


Fig. 3. SEM analysis of microcapsules (a) SEM image of a complete microcapsule, (b) microcapsules after repture, (c) enlarged SEM image of wall material and (d) enlarged Sem image of core material [30]

2.2. Hydrogels

Hydrogel-based encapsulation involves adding alkali-resistant bacteria in a cementitious matrix that can precipitate calcium carbonate ($CaCO_3$) and heal the cracks by protecting the bacteria, such as bacillus, through hydrogel around them [31]. Hydrogels are synthesized from hydrophilic polymers, are macromolecular networks composed of hydrophilic polymer chains. They are primarily super absorbents composed of acrylamide/acrylic acid copolymer and polyacrylic acid, which can absorb water up to 1000 times their weight [32]. Their primary roles in self-healing include:

2.2.1 Crack Response

When hydrogels are mixed in concrete at an early stage, they absorb water, which is later used for mitigating cracks because of autogenous and plastic shrinkage. When cracks open and water ingress into the concrete body, they swell upon that water ingress, which seals a crack from the intruding water and helps in regaining the watertightness of the concrete body. Ultimately, swelling occurs upon water absorption, which closes cracks and prevents further damage [33].

2.2.2 Internal Curing

Hydrogels can cementitious materials, healing the cracks by autogenous healing, which primarily precipitates calcium carbonate $CaCO_3$ by continuing the hydration of unhydrated cement particles in the cementitious matrix. However, this mechanism happens only when a suitable amount of moisture is present in the crack. Further hydration of cement particles occurs only when all unhydrated cement particles have been consumed. Calcium hydroxide continues to dissolve and carbonate with time. [34].

2.2.3 Crack Closure Efficiency

Performed experiments to examine the crack closure efficiency of protein-based hydrogel, achieving complete closures and regaining compressive and flexural strengths more than the original samples of concrete without cracks. This is because the protein-containing hydrogels contributed to the interfacial bond contributed by the released proteins. The proteins bind together the solid constituents of healing products and the surface of the crack, hence improving the overall strength of the samples [35].

2.2.4 Water Retention

At room temperature of 20 ◦ C with relative humidity of 60%, pure hydrogels show water retention of 30% and 70% after a day and half a day, respectively [36].

2.3. Polymeric Shells and Advanced Encapsulation Methods

Polymeric shells are vastly studied and have experienced many innovative modifications.

2.3.1. Innovations in Encapsulation

Continuous studies are being carried out on new progressive materials and methods of concrete encapsulation, which have made a remarkable breakthrough in the efficiency of self-healing concrete structures. The development of the microencapsulation approach will support longer-lasting structures. This development not only improves the durability of concrete but also minimizes the environmental impact by reducing the need for repairs and resource-intensive maintenance [37]. The following are some recent advancements in them, improving different aspects of self-healing mechanism:

2.3.1.1 Bio-based Polymers

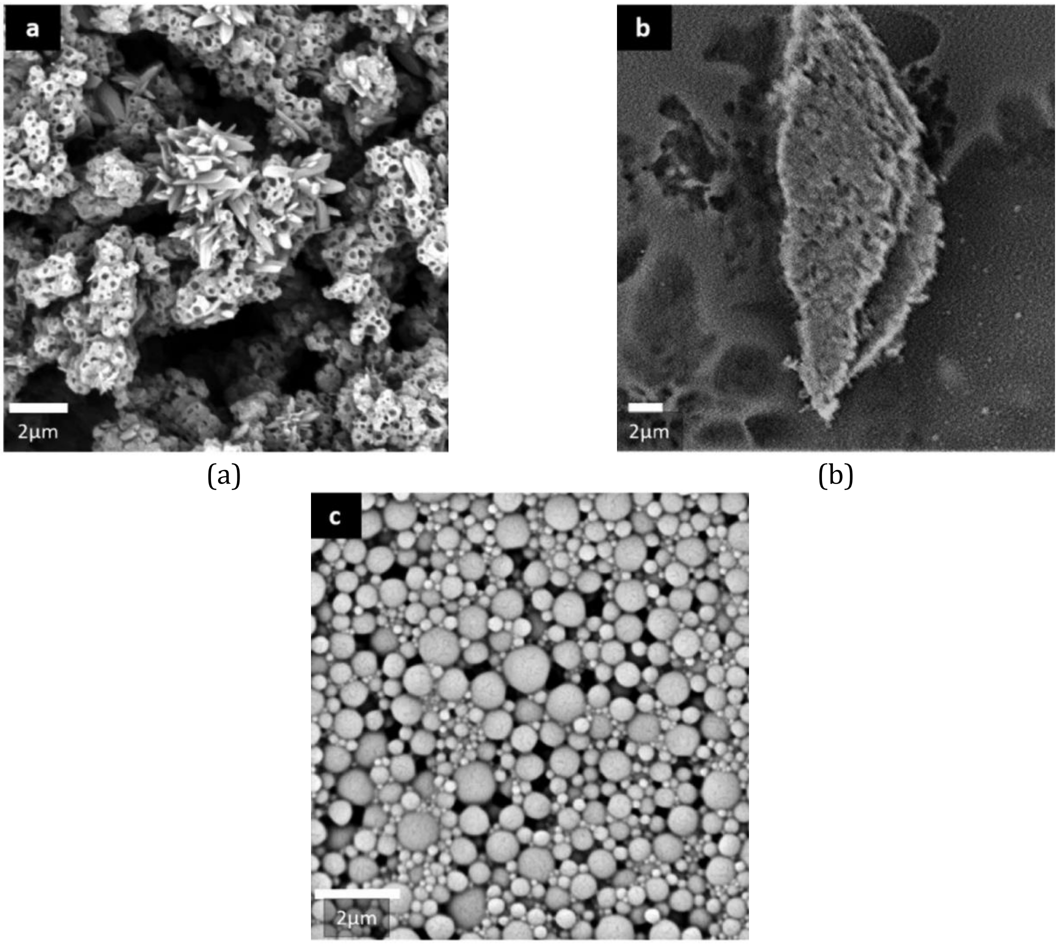
Materials like polylactic acid (PLA), composed of biodegradable polymer from natural biomass resources, are being explored for their biodegradability and compatibility with cementitious matrices, reducing the environmental footprint. Recent studies have shown that PLA has dual behavior in highly alkaline environments. Initially, PLA shows high survivability during concrete mixing with negligible degradation during the first 28 days of exposure to a concrete environment at varying temperatures (23 °C and 50 °C). However, after 90 days, PLA undergoes significant degradation due to the alkaline-induced hydrolysis of its ester bonds.

Fig. 4. Schematic diagram of self-healing concrete using biodegradable corn as starting material [16]

In 0.1 M NaOH solution (pH 13), the tensile strength of PLA decreased by 24%, while Young's modulus increased by 26%, indicating embrittlement. Thermogravimetric analysis (TGA) revealed that PLA capsules lost up to 90% of their mass after 90 days of immersion, with degradation onset temperatures decreasing by over 100 °C compared to the unaged PLA. Moreover, thermal degradation was accompanied by mineralization due to the interaction with cement hydration products, particularly portlandite. These results confirm that while PLA capsules maintain integrity during early curing stages, they progressively degrade and lose mechanical stability in the long term—making them suitable for delayed activation of healing agents. This switchable property may be advantageous for triggered release upon cracking but raises concerns about long-term encapsulation durability, necessitating future research into coatings or hybrid systems to extend PLA's functional lifespan. Fig. 4 shows the mechanism of this bio-based polymer in self-healing concrete [16].

2.3.1.2 Nano-Encapsulation

A recent study [38] assessed different nanoparticles in the cementitious matrix and found that nano capsules ensure uniform dispersion, minimizing agglomeration. This strategy can help maximize crack-sealing capability by uniform dispersion of capsules containing self-healing agents. Nano-encapsulation also opens opportunities for integrating multifunctional properties such as self-sensing and enhanced mechanical performance. However, challenges related to the scalability, cost, and long-term stability of nano capsules remain key areas for future research.



(a) (b) (c)

Fig. 5. SEM micrographs of nano capsules prepared from different shell materials and encapsulation techniques. (a) the potato starch capsules synthesized via the miniemulsion/polyaddition polymerization process. (b) the PLLA (polylactic acid) capsules synthesized via the miniemulsion/ solvent evaporation process; (c) the PMMA (polymethyl methacrylate) capsules synthesized via the miniemulsion/solvent evaporation process [39]

2.3.1.3 Elongated Shaped Encapsulation

Analyzed the probability of various encapsulation shapes hitting the cracks. They concluded that elongated-shaped encapsulations hit the cracks more easily than spherical capsules due to their increased area of interaction, thus increasing their efficiency of self-healing, but it depends on their aspect ratio [40].

2.3.2. Emerging Trends in Dual/Multi-Agent Systems

2.3.2.1 Dual-Agent Systems

Studied the dual-agent system-based self-healing in which a catalyst and microcapsules were embedded in the cementitious matrix. When a crack opens in a polymer matrix in which capsules contain dicyclopentadiene (DCPD) and Grubbs' catalysts are dispersed uniformly. The rupture of DCPD capsules initiates the rapid catalytic reaction with the dispersed catalysts, as shown in Fig. 6. Therefore, ending up with effective polymerization [41].

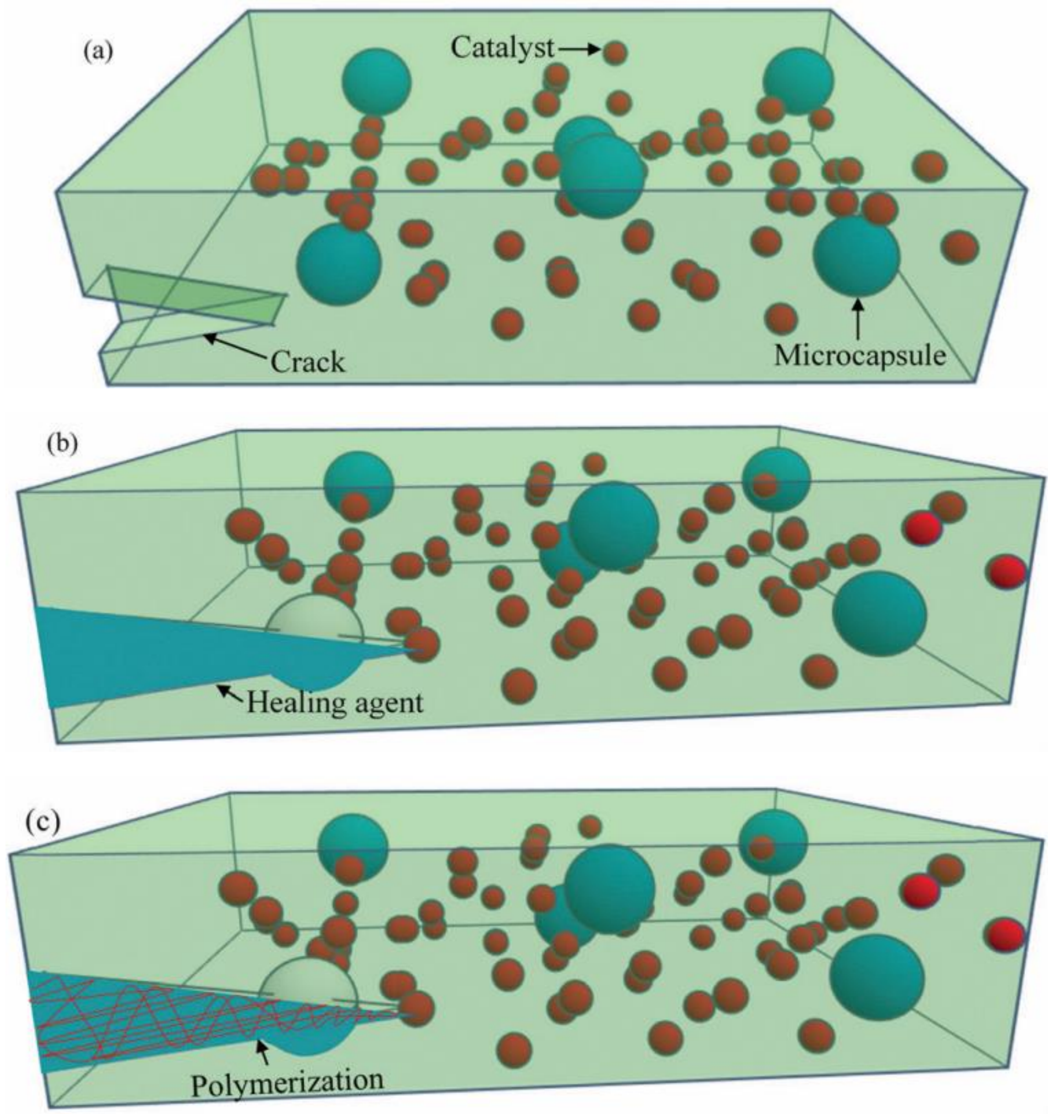


Fig. 6. Microencapsulated based self-healing process: (a) crack forms in the matrix, (b) crack ruptures the microcapsules, releasing the healing agent into the crack through capillary action, (c) healing agent contacts the catalyst, resulting in polymerization and repair of the matrix. [42]

2.3.2.2 Multi-Functional Capsules

Self-sensing composites utilize multiple materials, particularly carbon fibers, to detect strain and damage through electrical conductivity. Recently, a carbon-based nanophase has been introduced to non-conductive composites like glass fiber-reinforced plastics (GFRPs). Nanomaterials such as carbon nanotubes and graphene improve both mechanical and electrical properties. When the nanophase concentration surpasses the percolation threshold, a continuous network is formed, enabling the composite to function as a sensitive sensor for structural changes. These capsules represent an innovative approach to concrete self-healing, in which the self-healing mechanism detects and repairs the chemical or mechanical damage to restore the concrete by repairing the cracks [43].

2.4. Bacterial Strains for Self-Healing

Self-healing based on bacteria in concrete relies on the biological precipitation of calcium carbonate ($CaCO_3$) to heal and seal the cracks to restore durability and strength. Different types of bacterial strains provide varied performance based on their urease activity, environmental tolerance, and survival in concrete's alkaline conditions, as shown in Table 2.

Table 2. Common bacterial strains used in self-healing concrete and their characteristics

Bacterial Strain	Healing Mechanism	Crack Width Healed	Key Features	Reference(s)
Sporosarcina pasteurii (ATCC 11859)	Microbial-induced $CaCO_3$ precipitation	≤ 400 μm	High urease activity, good salt tolerance; ability to survive in relatively high pH (up to 11.2) environments	[44]
Bacteria with high urease activity	Ureolytic $CaCO_3$ precipitation via encapsulated RCAs	≤ 600 μm (depth ≤ 17.8 mm)	Promotes deep crack healing; effective with recycled carriers	[45]
Bacillus megaterium	Polysaccharides on the cell wall link cells together to form pairs.	100-2000 μm	Good temperature resistance and can reproduce at temperatures ranging from 3 to 45 ◦ C	[46]
Sporosarcina Koreensis and Bacillus	Fills the cracked sections by the formation and deposition of calcite via microbial activity	288.7 μm	Effective at temperatures of 38 ∘ C and alkaline conditions (pH 9.5)	[47]
Bacillus Pseudomycoides strain HASS3	Urea-based MICCP (microbially induced calcium carbonate precipitation)	400 μm	Requires 68 days to heal and seal the crack	[48]

3. Performance Metrics for Encapsulation Technologies

3.1 Healing Efficiency

Concrete cracks are often caused due to fractures or separations in the concrete matrix. It occurs when a tensile load greater than concrete strength is applied to the structure. It includes several factors, such as thermal changes, drying shrinkage, structural loads, freeze-thaw cycles, and inappropriate curing practices [49], [50]. Healing efficiency depends on the regain of different properties like strength, durability, and impermeability of concrete structures that were compromised by the cracks, leading to water ingress, corrosion of reinforcements, and certainly reduced service life [51].

Bacterial spores, polymers, or different chemical substances are used as healing agents [49]. This article presents a brief review of different encapsulated healing techniques, highlighting the effects and outcomes, as well as the efficiency of repairing concrete cracks. It also mentions the limitations of their methods in addressing different crack sizes and healing challenges.

Table 3 compares different aspects of healing efficiency for varying encapsulation methods. Additionally, [45] Investigates the use of recycled concrete aggregates (RCAs) as self-healing carriers for microbial self-healing concrete. Bacteria with high urease activity were impregnated in RCAs to promote Calcium Carbonate precipitation in the event of cracks. The study demonstrates a crack area healing ratio of up to 84% after 28 days of curing, highlighting the effectiveness of microbial action. RCAs can repair cracks up to 600 μm wide and up to 17.8 mm in depth. The compressive strength of concrete reached more than 99%, indicating the complete recovery of structural integrity. According to [52], the most frequently employed bacterial species for this purpose is Sporosarcina pasteurii. The phenomena have the tendency to heal smaller cracks of up to 200 μm, while the larger cracks exhibit partial healing depending on the type and concentration of healing agents.

Table 3. Healing efficiency parameters comparison

Encapsulation Method	Crack Closure Rate	Healed Crack Width	Strength Recovery	Additional Findings	Reference
Engineered Aggregates (PU in Glass Tubes)	Up to 70%	100–450 μm	82% split tensile strength	- Smaller cracks not effectively healed. - High water permeability reduction.	[54]
$MgO\text{-}SiO_2$ Capsules with Bacteria	97% (250–350 μm), 85% (350–600 μm)	250–600 μm	Maintained compressive strength	- 40 wet/dry cycles reduced water passing rate by 80%. - Long-term stability of bacteria.	[55]
Single Bacteria Spore LbL Encapsulation	95–100%	200–450 μm	No compromise in compressive strength	- Reduced water passing rate to 0%. - Effective even in extreme conditions.	[51]
Reactive Magnesia Cement-Based Capsules (RMC-B)	93%	Average 243 μm	Improved by 18% compared to control	- Dense calcite formation - Water permeability reduced by 80%.	[49]
Cement-Shell Encapsulation	100% (cracks ≤ 200 μm), partial (>200 μm)	≤400 μm	Dense $CaCO_3$ layer restored zero-seepage	- Achieved after 30 wet/dry cycles.	[56]
Glass Capsules with Epoxy Resin	>90%	Up to 300 μm	Significant load-bearing capacity retained	- Reduced permeability - capsule geometry critical for efficient healing.	[57]

Compressive strength of up to 90% after 28 days curing period is achieved. The crack closure rate depends upon the self-healing granules with the capacity to heal cracks of width up to 300 μm. Wider cracks in concrete can also be healed with the interaction of Mg^{2+} and CO_3^{2-} under the presence of seawater. Under chemical reaction, the resultant product will be Magnesium Hydroxide and Calcium Carbonate [53]. According to [50], using synergistic use of self-healing granules (SHGs) and polyvinyl alcohol (PVA) fibers in concrete and curing with sea water fed with CO_2 has the tendency to repair the cracks up to 500 μm with compressive strength recovering up to 92.76%. Self-healing agents released under the combination of SHGs and PVA fibers act as crack bridges, resulting in increased durability and performance of repaired material.

3.2. Durability

Small capsules filled with fluid are inserted into a matrix, which is the common method of encapsulation based on self-healing concrete. Glass capsules are often used for encapsulation-based self-healing strategies. Selection of material depends on the identical brittleness levels of both materials [57]. Bonding with the concrete along with the stiffness of the healing agent is necessary for maximum recovery of mechanical strength. Stiffer healing agents are more beneficial due to their greater impact on structure but due to their inherent brittleness, movement is restricted [58].

Complete healing of concrete occurs over time, ranging from several hours to several weeks. However, during the healing process, steel is exposed to the environment, and corrosion can occur. Very limited studies are available on the durability of self-healing concrete. In most cases, durability is linked to several external factors, such as water absorption or water permeability of cracked and healed concrete. Few studies have focused on chloride ingress and actual reinforcement corrosion [59].

[60] Performed an experiment using lightweight aggregates (LWA) impregnated with sodium silicate. Vacuum-impregnated LWAs coated with a polymer layer are used to prevent premature reaction. Pre-cracked specimens (up to 300 μm wide) were tested under water curing conditions. Results showed a flexural strength recovery of up to 80% for LWA specimens compared to 14% for control specimens. Complete crack sealing was observed in LWA specimens, whereas control specimens exhibit only partial sealing. The results demonstrate how sodium silicate-impregnated LWAs can improve concrete water resistance, durability, and self-healing effectiveness.

Expanded perlite was used to determine the sustainability of construction in cold regions. Expanded perlite was impregnated with bacteria and nutrients using encapsulation and non-encapsulation methods to evaluate the durability of repaired cracks. Experiment indicates that encapsulated self-healing agents repair cracks up to 0.757 mm under normal conditions and 0.643 mm after 100 freeze-thaw cycles, as more cycles of freeze-thaw increases the crack width and lead to deterioration which triggers the capsule rupture [61].

The longevity of encapsulation in self-healing concrete is critical to their effectiveness in maintaining durability in various conditions. Glass capsules are widely used encapsulation material due to their high mechanical resistance, making them long-term viable in extremely harsh alkaline conditions [62]. Although polymers like polyurethane provide instant healing, their lifespan is limited due to exposure to harsh environmental conditions [59]. Encapsulation systems are effective in mitigating chloride ingress, with crack sealing rates exceeding 95% under simulated wet-dry cycles [63]. Long-term monitoring reveals that encapsulation activates only upon crack formation, thus protecting premature reactions [64].

3.3. Cost and Scalability

One main factor leading to the adaptation of self-healing concrete is the rising demand for sustainable materials. The ability to combine cost savings and environmental benefits aligns with the construction industry's focus on minimizing expenses [65]. Self-healing concrete also contributes to environmental sustainability by reducing waste generation and optimizing maintenance strategies. Adopting self-healing concrete can also sequester CO_2 as a variety of bacteria consume CO_2 for food [52].

[66] proposes a methodology to evaluate the economic feasibility of self-healing concrete in replacement for traditional concrete by applying a lifecycle cost (LCC) analysis. The method included comparing traditional concrete with two self-healing systems: Virtual capsules formed by compacting active powders at high temperatures and 3D-printed capsules sealed with epoxy resin. Factors under consideration include lifetime, maintenance cost, and residual values to access the technological and economic aspects of these materials. Results indicated that self-healing concrete reduces the overall lifecycle cost by minimizing maintenance and increasing durability and residual value.

Use of advanced techniques such as microencapsulation influence economic feasibility and cost performance of self-healing concrete to repair surface cracks and prevent structural deterioration. Traditional repair methods are labor intensive and require silicates or mortar whereas encapsulation offers more efficient and cost-effective alternatives including mixing of microcapsules containing healing agent into the concrete mix [67].

The microencapsulation also enhances cost performance by protecting microorganism activity and creating a protected environment during the concrete mix. Encapsulated bacteria also induce Calcium Carbonate resulting in improvement of concrete's mechanical properties by filling available voids. Resultants offer long-term economic benefits by enhancing durability and reducing maintenance cost [67].

Market rates for conventional concrete in the USA were in the range of $125 to $165 per cubic yard in the year 2023. In comparison, the cost, including self-healing bacterial concrete, was reported to be approximately $6,876 per cubic meter based on 2015 data. The greater price of self-healing concrete makes it difficult for construction projects to widely embrace it despite its lower maintenance cost, improved durability, and resistance to chloride intrusion. The selection of materials such as cement, admixtures, and bacteria species affect how well the self-healing mechanism will work [68].

LCCA (lifecycle cost analysis) is an essential metric used to evaluate economic feasibility and compare the lifecycle cost of self-healing concrete to that of traditional concrete. LCCA includes key metrics such as (i) initial material and construction costs, (ii) cost of maintenance interventions, (iii) service life extension, and (iv) indirect costs such as traffic disruptions, productivity loss, and environmental impact. Examples include Bridge maintenance in the USA alone, which costs approximately $5.2 billion annually, and indirect costs related to traffic delays and productivity losses, which are estimated to be ten times higher. Similarly, Europe allocates 50% of construction budgets, and China loses 250 billion RMB due to corrosion-related degradation. Self-healing concrete, which increases the initial cost, enables crack closure and strength recovery, reduces the repair frequency, extends structural service life, and contributes to long-term savings. Studies have reported that bacterial self-healing concrete systems increased construction costs by 7–28% (polyurethane encapsulation) and 5–21% (silica gel). The estimated microcapsule costs $15/kg using urea-formaldehyde shells and epoxy resin cores. These insights affirm that while SHC may involve higher upfront costs, it offers significant lifecycle benefits, especially in durability-critical infrastructure. Further long-term field trials are necessary to validate and standardize these economic benefits across different environmental and loading conditions [69].

4. Technical Barriers

Damaged tissues can be self-healed as they have the necessary nutrients to produce new substitutes for the healing part. Similarly, for the self-healing of cementitious materials, the essential products are required to fill the damaged portion. During the past few decades, several experiments and studies have been conducted with the focus to endow composite materials self-healing ability and improving the effectiveness of repairing. These efforts have led to several innovative strategies, such as hollow fibers, microencapsulation, expansive agents, and bacterial strategies [22].

It is difficult to incorporate self-healing encapsulated capsules with cementitious material in a natural manner. If the encapsulated material does not react with the surrounding material, the matrix strength may be threatened. Overall stability of the structure is dependent on the chemical properties such as interaction with hydration process, and stability in alkaline environment [70].

Uniform distribution of healing agents is also a major challenge. Areas with insufficient healing agents might result in limited healing capacity. Variance in capsule size, improper mixing, or different densities can all contribute to the unequal distribution [70]. It is important for the microcapsule to be smaller than 1 mm in size. Capsules larger than 1 mm are considered microcapsules [3].

The development of encapsulated healing agents and self-healing cementitious materials are two major approaches in the field of the construction industry [3]. For effective self-healing, inserted capsules and cementitious matrix must be compatible. Capsules must be strong enough to tolerate heat of hydration and extreme alkaline conditions. Ordinary glass can react with alkali and generate alkali-silica reactions; therefore, inorganic shells such as ceramics or modified glass should be used. Organic shells show good stability under these conditions. Bond strength at the capsule-matrix interface must be greater than the strength of the capsule itself to guarantee that cracks shatter the capsule and release healing chemicals instead of spreading along the interface [71].

The bonding strength between cementitious matrix and capsules must be compatible since the healing agents must be released when the capsules break during the cracking. Bonding strength between capsules and cement mix can be improved by surface modification of capsules. Brittle materials such as glass and ceramics have lower bonding strength due to their structural resilience as compared to Polystyrene (PS) capsules [72].

The biological self-healing system has drawn the potential interest of researchers due to its ability to increase the service life of construction without external intervention [73]. Biologically healed concrete uses microorganisms such as bacteria to create an eco-friendly self-healing environment. Due to the ability of useful precipitation of chemicals, bacteria are preferred over other microorganisms. Using techniques such as microbial broth, spores, silica gel immobilization, encapsulation, or vascular networks, these bacteria are introduced into concrete. Encapsulation or spore-based techniques are preferred due to extreme conditions such as low moisture, high pH, and temperature fluctuations leading to inhibition of bacterial growth [29].

Bacterial survival is necessary to ensure cracks must be sealed for a long time during self-healing process. Applying bio-agents directly to concrete minimizes the chances of bacterial survival. Research has shown that direct addition of bacteria will limit life to only 2 months and hence, only young samples are healed effectively [74].

5. Comparison of Encapsulation Methods in Self-Healing Concrete

This part of the paper summarizes the findings from the literature review done including strengths and weaknesses of each encapsulation method covered (summarized in Table 4) and underscores the research gaps in current literature.

5.1. Key Findings from Literature

Among all the research studies and different encapsulation methods analyzed in this study, it was found that every method of encapsulation in self-healing concrete has its own strengths and weaknesses in terms of mechanical performance, environmental adaptability, and crack healing efficiency. Table 4 provides an overview of comparisons of the different strengths and weaknesses of these encapsulation methods.

Table 4. Strengths and weaknesses of encapsulation techniques

Encapsulation Method	Strengths	Weaknesses
Microcapsules	- Epoxy resin shells provide durability in corrosive environments [18], [19]. - Polyurethane shells offer flexibility under cyclic loading [20]. - Cementitious shells enhance compatibility with the cement matrix [3]. - Glass capsules have high mechanical resistance and work well in alkaline conditions [62]. - Sodium silicate-impregnated light weight aggregates achieve up to 80% strength recovery [60].	- Limited survivability during concrete mixing [21]. - Ineffective for cracks smaller than 50 μm [54]. - Encapsulation limits the number of healing agents, restricting large-scale applications [8] - Balancing stiffness and flexibility remains a challenge [58].
Hydrogels	- Excellent water absorption and swelling properties for crack sealing [32].	- Performance heavily depends on moisture availability, therefore,

	- Capable of precipitating $CaCO_3$, enhancing crack healing [31]. - Protein-based hydrogels restore both compressive and flexural strengths [35].	limited effectiveness in dry climates or extreme temperature variations [34]. - Long-term stability in varying environmental conditions is uncertain [36]
Polymeric Shells & Advanced Methods	- Bio-based polymers (PLA) offer eco-friendly encapsulation [16]. - Nano-encapsulation ensures uniform dispersion and reduces agglomeration[38]. - Elongated encapsulations improve crack interaction [40].	- High production costs may hinder widespread adoption [38]. - Polymeric resins have a limited shelf life and higher costs [63].

5.2. Research Gaps

Despite significant advancements in self-healing concrete, several critical research gaps remain:

5.2.1. Long-Term Performance and Durability

There is currently a lack of sufficient data and studies available on the long-term durability and performance of self-healing concrete under varying environmental conditions. In this respect, additional research is needed to examine the durability and performance of self-healing concrete subjected to variations in environmental conditions such as extreme temperature, humidity fluctuations, and exposure to many chemicals, all possible factors affecting the performance of self-healing concrete [1].

Further studies are needed on the interaction of self-healing factors within encapsulation, and harsh environmental factors such as chloride-rich environments, and freeze-thaw cycles provide many opportunities for the further enhancement of self-healing concrete [75].

5.2.2. Unexplored Material Combinations:

Very few studies exist to investigate the synergistic effects of integrative materials with different kinds of cementitious matrices. This issue demands more investigation on the synergistic relationship of encapsulated materials with different kinds of cementitious matrices for improving self-healing mechanism efficiency [76], [77].

The encapsulated materials would have an integrated dual-agent system consisting of polymerization catalysts and healing agents that need further research and optimization. The dual-agent system can enhance self-healing effectiveness [78].

5.2.3. Scaling and Implementation Challenges:

The current cost of self-healing is about 6000 USD per cubic meter for bacteria-infused self-healing concrete [79]. [6] found that the expense of self-healing technology is about 33-44 USD/m^2. Such expense limits the practical application of self-healing concrete. Additionally, the practical application of bacterial self-healing concrete lacks consistency because of the lack of systematic data available. Ultimately, advanced encapsulation techniques face practical challenges and large-scale production. Further research is needed to scale these methods and overcome issues related to cost and manufacturing complexities.

Nanomaterials and bio-based materials for encapsulations are some of the most promising options for self-healing concrete, although they also face a significant barrier in terms of cost for widespread production and use in construction projects [38].

All these challenges and limitations highlight the need for continued interdisciplinary research to bridge these knowledge gaps to enhance the application of self-healing concrete technologies. The future research directions can be focused on the enhancement of long-term durability, developing cost-effective and scalable solutions, and optimizing the compatibility of novel encapsulation methods with various concrete matrices.

6. Future Directions

6.1. Innovations in Materials and Techniques

The innovations can be in shell materials; we can try to synergize the advantages of multiple encapsulations, such as microcapsules work excellently for the controlled release of healing agents, and hydrogels are good in retaining moisture; we can be utilized in the healing process for enhancing its efficiency. Similarly, cementitious shells are compatible with concrete matrices, and they can also be synergized with other encapsulation methods to increase compatibility with and activation under diverse conditions. Moreover, encapsulation production techniques can be further investigated for precise manufacturing of nano-encapsulations in terms of the shape, size, and functionality of encapsulation. As per [76], there is a need to investigate the long-term durability and stability of Nano-SiO_2-modified microcapsules under varying environmental conditions. Moving towards more eco-friendly alternatives is another direction for future research, such as bio-based polymers, including polylactic acid (PLA) and recycled industrial byproducts, which can not only reduce the environmental impact but can also reduce the production cost of encapsulations [16].

6.2. Field Implementation and Testing

Before scaling from the lab scale to the field scale, comprehensive testing is required to analyze the performance of self-healing concrete under realistic environmental conditions, chloride ingress, freeze-thaw cycles, dynamic stresses, and thermal gradients. Long-term studies also needed to be carried out to validate the durability of self-healing concrete. Standardized testing methods and performance benchmarks need to be developed for examining the performance of self-healing concrete on an industrial scale, such as creating a quantifiable matrix for crack closure rates, efficiency, strength recovery, and recovery time for different encapsulation methods under identical environmental exposure. All this testing is essential to up-scale encapsulation-based self-healing concrete to the industrial level. [3] suggested that comprehensive research on self-healing concrete, from encapsulation agent production to their application, focusing on mechanical properties, is required.

6.3. Integration with Smart Technologies

Encapsulations in self-healing concrete with integrated monitoring systems, such as embedded sensors, are also a novel idea to improve the monitoring of structural health, including strain variations, temperature changes, moisture detection, and crack formation, which can then activate the self-healing mechanism of encapsulated healing agents. This monitoring data can also be utilized to create digital twins (virtual models of physical structures) to enhance real-time health monitoring and improve maintenance strategies for the prolonged service life of structures. Researchers may focus on optimizing the interface between these types of embedded monitoring systems and encapsulation to improve performance under varying conditions. [52] suggested that more research is needed to be done on integration of smart technologies, such as self-sensing concrete and biocrete, to minimize its production cost future.

All these areas can be possible research directions for the future, which can revolutionize the implementation of self-healing concrete and can contribute to its enhanced performance, durability, monitoring, and standardization.

7. Conclusion

This review evaluates the encapsulation techniques in self-healing concrete to enhance its sustainability and durability. This study compares the encapsulation methods and highlights their strengths and weaknesses, including microcapsules, hydrogels, and polymeric shells-based encapsulation. Microcapsules were found to be versatile, using a variety of shell compositions, such as epoxy resins, polyurethane, or cementitious shells, suitable for environmental conditions and self-healing performance. Hydrogels were found to be showing water-absorbing capabilities as superabsorbent with precipitation functionalities. However, they remained moisture dependent. Polymeric and advanced encapsulations such as nano capsules, which offer uniform dispersion of encapsulated materials, and bio-based encapsulations show promising enhancements in self-healing efficiency.

This review emphasizes the significance of self-healing encapsulation advancements in improving self-healing efficiency, which can offer more durable, resilient, and sustainable alternatives. The healing efficiency comparisons promote the suitability of different encapsulation techniques for various conditions, such as the extent of strength recovery and healing speed. The limitations and challenges highlighted in this review offer a view of critical concerns regarding each encapsulation method, such as the survivability of capsules in concrete mixing, chemical and mechanical adaptability with cementitious matrices, long-term durability under extreme conditions, and points to future research directions to overcome those limitations and challenges including scalability and cost concerns. Integration of current technologies with self-healing concrete, such as sensors and digital twins, is also discussed, which elevates the sensitivity of the healing mechanism and improves monitoring. To address these hurdles, coordinated interdisciplinary research, which combines the power of structural engineering, material science, and nanotechnology, is needed.

Future research results could probably combine different encapsulation techniques to develop a hybrid solution that takes the best of several existing options. This will make newer methods more sustainable and possibly even more cost-effective, besides fulfilling enhanced technical properties of uniform dispersion, structural strength, and improved durability. There should be joint efforts by different academic institutions, industries, and regulatory agencies to establish guidelines for standardized methodologies that will facilitate the fast translation of laboratory-scale research to large-scale industrial uses. Encapsulation technologies can revolutionize self-healing concrete, making it more durable, able to perform better, and sustainable.

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