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Mechanisms of Self Healing in Concrete: A Review

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Abstract: Concrete is the one of the most vital and prevalent material in the construction industry, given importance mainly for its affordability and accessibility, despite being susceptible to crack formation. Subsequently, there has been a consistently growing interest in different kinds of self-healing materials, especially green and sustainable concrete, with a number of researchers across the globe exploring numerous techniques over the last two decades. However, selecting the most efficient and effective method has its own challenges, as different research organizations utilize different protocols and procedures to evaluate the healing efficacy. Self-healing concrete is an innovative development in the construction industry that has the potential to revolutionize the way we construct and maintain infrastructure. This concrete is designed to repair itself when damage and cracks occur, without human intervention. Conventional concrete structures are susceptible to cracking and deterioration over a period, which subsequently leads to expensive repairs and potential safety hazards. Self-healing concrete or SHC possesses the ability to autonomously repair itself, thereby considerably decreasing the need for any external intervention to identify and overcome any detoriations and damage, such as cracks. This ability eventually mitigates concerns related to reinforcement corrosion and concrete degradation, ultimately reducing the maintenance expenses and enhancing durability. The importance of self-healing extends beyond just reducing maintenance costs. It can significantly extend the lifespan of structures, making them more sustainable and reducing the need for frequent replacements. This is particularly crucial for infrastructure in harsh environments or areas prone to natural disasters. Self-healing concrete also has the potential to improve safety in construction. By automatically repairing minor damage, it can prevent small cracks from developing into larger, more dangerous structural issues. In terms of environmental impact, self-healing concrete can contribute to reduced carbon emissions. The production of cement, a key component of concrete, is a major source of CO_2 emissions. By extending the life of concrete structures and reducing the need for repairs and replacements, self-healing concrete can help decrease the overall demand for cement production. To further enhance the effectiveness of self-healing concrete, researchers are exploring ways to combine multiple self-healing mechanisms. This could involve using both bacteria and polymer capsules in the same mixture, creating a more robust and versatile self-healing capability. Considering the advantages offered by SHCs, this article provides a comprehensive review of the topic, examining the strategies, influencing factors, mechanisms, and effectiveness of self-healing. The literature review also includes critical summaries of the properties, performance, and assessments of the self-healing efficiency of SHC composites. Additionally, we explore the developmental trends in research aimed at fostering a deeper under standings of SHC's potential as a superior concrete alternative and a pivotal advancement in the creation of sustainable and durable concrete for contemporary construction. It is envisioned that SHC will empower builders to erect structures with reduced concerns regarding damage and extensive maintenance. This extensive review underscores that SHC represents a significant interdisciplinary research area, integrating fields such as chemistry, microbiology, civil engineering, and materials science.

Keywords: Self-healing concrete, Water-cement ratio, Engineered cementitious composites (ECC), Autogenous self-healing, Autonomous self-healing, Ultra high-performance fiber-reinforced concrete (UHPFRC), Cryogenic cooling.

1. Introduction

Self-healing concrete in recent years has emerged as a promising solution to enhance the durability and longevity of concrete structures. Researchers have shown its degree of effectiveness in repairing cracks and enhancing mechanical properties [1]. Studies have concluded that cracks of 0.15mm can be successfully and efficiently self-healed within three days of re-curing, with larger ones of 0.22mm decreasing to 0.16mm after seven days [2]. This phenomenon of self healing in concrete is attributed to different mechanisms, these include; autogenous healing through carbonation and continuing hydration, and autonomous healing using specific types of agents like, crystalline admixtures, superabsorbent polymers and bacteria. Interestingly, self-healing concrete has shown great potential, there are conflicts, contradictions and challenges. The effect of bacteria on mechanical properties can be subjective, and have a potential to influence them positively or negatively[1]. Additionally, the implementation of sustainable concrete construction practices faceseconomic, technical, as well as social barriers[3]. Self-healing concrete represents a vital advancement as far as sustainable construction is concerned, ensuring considerable improvement in durability as well as reduction in maintenance expenditure. At the same time, further research is required to be executed to address existing research gaps, such as developing a generalized self-healing performance index that incorporates both mechanical and self-healing efficiency[1]. Future researches and developments should focus to overcome the implementation challenges, exploring opportunities of new innovative healing mechanisms, and investigating the long-term performance of self-healing concrete in real-world applications [4]

Self-healing agents used in concrete applications vary in their effectiveness as well as in the cost, with each type offering unique advantages and limitations as well. Both capsule-based and vascular network systems have given promising outcomes in prospects of healing efficiency. For instance, in vascular network systems, sealing efficiencies above 100% were achieved for most healing agents tested, with epoxy resin and polyurethanes demonstrating high strength regain [5] Bacteria-based self-healing concrete has given outcomes of degree of efficiency for healing cracks up to 0.8 mm wide under laboratory conditions, depending on the dosage of the healing agent [6], [7]. This approach could potentially decrease the consumption steel reinforcement in watertight constructions, which leads to cost savings and considerable improvement in terms of environmental performance. However, full-scale demonstrator projects have shown mixed results, with limited evidence of increased crack-healing performance in real-world applications [6]. However, the overall cost-effectiveness of different self-healing agents is not extensively compared in the provided papers. Different self-healing agents show promise in laboratory settings, their effectiveness in real-world applications and cost-efficiency require further investigation. Standardized testing methods and full-scale demonstrations are crucial for accurately comparing different self-healing agents and determining their practical viability in concrete applications [8].

Self-healing in case of bio-concrete is greatly influenced by several key factors: The ureolytic activity of bacterial strains and their survival in cementitious composites are much crucial factors affecting self-healing efficiency[9]. The method of incorporating bacteria (for self-healing) into the concrete matrix, so that immobilization on carrier materials, affects their survival and healing performance[9] . Self-healing in concrete is facilitated through different mechanisms, primarily classified into **autogenous healing** and **autonomous healing**. **Autogenous healing** on one hand, is an intrinsic process that occurs in concrete without external intervention, primarily governed by continuing hydration process and carbonation [10]. In continuing hydration process, unhydrated cement particles react with water that infiltrate cracks, resulting into new hydration products that can fill small fissures. Carbonation involves the reaction of calcium hydroxide in concrete with atmospheric carbon dioxide, resulting in calcium carbonate crystals that can seal cracks. The process is generally limited to heal the crack widths of range of approximately 100-150 μm[11]. Conversely, autonomous healing involves the deliberate incorporation of specific agents to induce self-healing. These agents can be integrated directly into the concrete matrix, encapsulated, or introduced through vascular networks [12]. Notably, recent research has suggested that fungi may offer advantages over bacteria as self-healing agents in concrete, though this area has remained unexplored to a large extent [13]. Recent advancements have facilitated the development of different self-healing techniques [10],[14],[15]. These techniques encompass capsule-based self-healing, vascular self-healing, electrode position self-healing [16], microbiological self-healing, and the utilization of shape memory alloys (SMA) for self-healing applications[10],[14],[15]. To enhance self-healing in concrete subjected to stress as well as cracking, urea-formaldehyde microcapsules containing epoxy resin, and gelatin microcapsules (ranging from 125 to 297 μm in diameter) filled with acrylic resin, are employed[17]. The system consists of an air-curing agent released through glass tubes, that are open to the atmosphere at one end and curved at the other end in order to dispense the healing agent [18]. When the contents in these tubes are depleted because of cracking in the concrete, additionally some specific chemicals can be introduced through the exposed end so as to repair larger cracks [10]. The electrode position method has been proposed as a medium for restoration of the damaged concrete structures, and its impacts on different properties of concrete have been investigated [16]. Furthermore, the efficiency of bacteria as a self-healing agent in concrete has been explored, particularly their potential to repair the existing cracks. Research indicates that utilizing bacterial spores as a self-healing mechanism may offer a viable solution [19]. Additionally, the incorporation of SMA wire as a reinforcing component has been shown to aid in sealing cracks and facilitating urgent repairs in concrete structures, due to the highly elastic properties of the integrated SMAs, which effectively close the fissures[20].

Abbreviations: SHC ; Self Healing Concrete; w/c ; Water-Cement Ratio ECC; Engineered Cement Composites, SCM; Supplementary Cementatious Materials, GGBS; Ground Granulated Blast-Furnace Slag, UHPFRC; Ultra-High Performance Fiber-Reinforced Concrete, CSA; Calcium Sulfoaluminate, OPC; Ordinary Portland Cement, BFS; Blast Furnace Slag, SAP ;Super Absorbent Polymer, SMA; Shape Memory Alloy, UHPC; Ultra-High Performance Concrete.

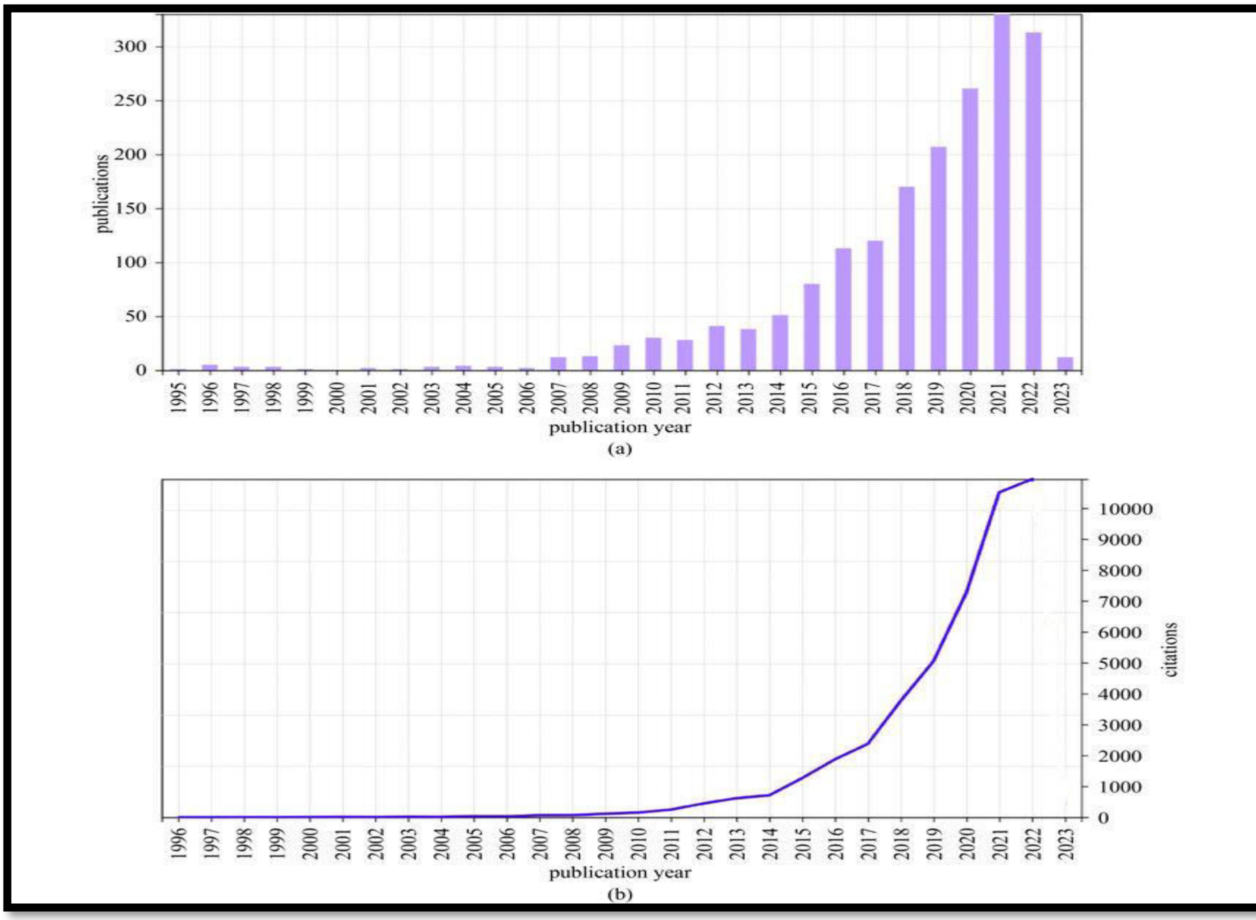

Fig.1. Distribution of published papers and citations of the self-healing concrete: (a) Number of papers published on the self-healing concrete; (b) citation frequency of the self-healing concrete research.[21]

S. Zhou, Z. et.al. "Microcapsule-enabled self-healing concrete: A bibliometric analysis (2023)

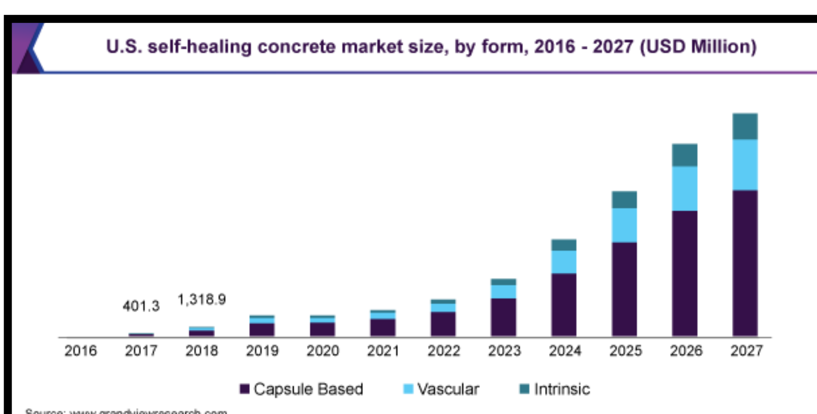

Fig.2. US Self-Healing market size (Future Anticipations) [22]Self-healing Concrete Market Size, Share & Trends Analysis Report By Form (Intrinsic, Capsule Based Report Overview.”

2. Previous Researches on Self Healing Concrete

Self-healing concrete has been an area of significant research and development over the past three decades, with numerous studies exploring different approaches to enhance concrete's ability to repair itself. The above bar charts and graph in **figure 1** shows the constantly increasing interest of researchers for innovations in self healing concrete over the past three decades. Similar is the case with the citation frequency, which can be considered a vital parameter of statistical analysis of studies done in the field of self healing concrete,
Represented by **figure 2** is consumption of self-healing concrete in past few years at the same time, on the basis of past consumptions, some future anticipations are done regarding the consumption of self healing concrete in next couple of years.

Key Takeaways

- The past 30 years have seen increasing interest in self-healing concrete.
- Research on different concrete self-repair methods has grown, with rising studies and citations.
- Self-healing concrete usage has increased recently, and experts anticipate this trend to continue.

3. Effect Water–Cement Ratio on Self Healing Concrete

Researches have indicated that employing a comparatively higher proportion of cement content, at the same time, a low water-to-cement (w/c) ratio increases, to a considerable extent, the autogenous self-healing capacity of engineered cementitious composites (ECC)[23]. Previous researches have suggested that a reduction in w/c ratio results in a greater quantity of un-reacted cement particles, which can be subsequently used for process of hydration, consequently, augmenting the production of calcium carbonate. Additionally, the timing of formation of cracks is also very crucial. Concrete that cracks earlier contains more un-reacted cement particles around the developed crack, thereby offering a higher self-healing potential by promoting continued hydration [23]. The substantial proportion of unhydrated cement at an early age contributes to a greater autogenous self-healing capacity, while other factors such as compressive pressure to limit propagation of cracks as well as wet–dry cycles can further increase this capacity [24]. It has been concluded that by replacing cement with calcium sulphoaluminate pellets, up to 10 % weightof cement, with a 1:3 cement-to-sand ratio and water-cement ratio w/c = 0.5, results in the complete sealing of cracks between 0.1 and 0.2 mm within 14 days, whereas cracks larger than 0.2 mm require 16 days for full sealing. Figure 5 illustrates different self-healing groups, including autogenous and autonomous[25], along with information on the material type, whether paste, mortar, or concrete [26], [27]. This could facilitate the assessment of whether researchers have considered the impact of mixture components, such as aggregates. The percentages indicate the number of studies citing the material type. The influence of coarse particles on the fracture pattern has been overlooked, as demonstrated. This oversight is primarily due to the fact that aggregates may compromise the survival of capsules during mixing and transportation processes[28].

4. The Efficiency of Self-Healing Mechanisms

Self-healing phenomenon of concrete is considered promising for improving the longevity and functionality of cement-based structures, with water being a key element for the self-healing process to take place [29]. Bacillus pasteurii has been demonstrated to help the cracked concrete to recover up to 90% of its initial strength.

In recent years, researches have highlighted the self-healing properties of ultra-high-performance fiber-reinforced concrete (UHPFRC), which shows properties for self-repair because of the influence of micro steel fibers that mitigate cracking effect after being exposed to cryogenic cooling [30],[31] . A straightforward method for enabling self-healing in existing UHPFRC structures involves applying cryogenic cooling, that allows the beams to absorb water from melting frost that forms on their surfaces. However, only a small number of researchers [32] have examined the self-healing characteristics of UHPFRC. Granger et al. [32] conducted flexural and acoustic emission tests to determine the self-healing efficiency of pre-cracked ultra-high-performance concrete (UHPC) that lacks steel fibers. They also investigated how different re-curing methods affect self-healing. Their findings indicated that pre-cracked beams maintain their original stiffness, with formation of new crystals occurring only after being re-cured in water. In contrast, re-curing in air showed no signs of recovery or development of any kind of crystals [32].

Key Takeaways

- Researches indicate that high cement content, a low water-to-cement ratio, and early crack formation enhance the autogenous self-healing capacity of engineered cementitious composites (ECC).
- Factors such as wet-dry cycles, compressive pressure, fiber incorporation, and the use age of super-plasticizers can further improve the potential of **autogenous healing.**
- Studies have concluded that substituting cement with calcium sulphoaluminate pellets can result in the complete sealing of cracks within 14-16 days.
- Water has a vital role in the process of self-healing of concrete, and **Bacillus pasteurii** has shown its potential to facilitate the recovery of cracked concrete structures up to 90% of its initial strength. Ultra-high-performance fiber-reinforced concrete (UHPFRC) exhibits self-healing properties due to the influence of micro steel fibers.

- Cryogenic cooling is a method for enabling and enhancing self-healing property in existing UHPFRC structures. Studies have concluded that pre-cracked UHPC beams maintain their original stiffness, with formation of new crystals occurring only after re-curing in water, whereas re-curing in air shows no signs of recovery or crystal development.

5. Various Mechanisms of Self-Healing

5.1. Autogenic Self-Healing

Autogenic self-healing refers to potential of concrete to mitigate or close the cracks in presence of moisture and absence of tensile stresses[33]. The preliminary role in the processes of self healing of concrete is to seal the cracks in concrete structures, eventually prolonging their life and serviceability as well. This also improves the durability and hence the sustainability of the structures [34]. The phenomenon of autogenic self-healing began to draw researchers' attention at the start of the nineteenth century when the first water-retaining structures, likepipes and culverts, were observed to self-repair [35]. Generally, the processes of autogenous self-healing can be classified into three categories: **physical, chemical, and mechanical**. Physical factors involve the expansion of the cement matrix around the crack-opening because of water absorption process by the hydrated cement matrix, which eventually results in mitigation of crack width. The process of autogenous self healing is also influenced by marine environment to a considerable extent. [36], [37] In a laboratory test simulating saltwater immersion, Ordinary Portland Cement (OPC) mortar specimens outperformed blast-furnace slag (BFS) mortar specimens [36], [37]. On the contrary, in freshwater, the results were found to bereversed. In another study [37], to understand further, the degree of potential of autogenous self-healing phenomenon in marine conditions, the efficiency of OPC and BFS mortar samples in chloride and a mixture of chloride and sulfate solutions to simulate a marine environment was examined [37]. The results indicated that while a chloride solution did not affect the self- healing process, solutions with additional magnesium sulfate enhanced the effect of crack sealing due to formation of brucite layers at the crack planes. Hence, it can be concluded that the composition of the cement matrix, including certain supplementary cementitious materials, and the healing environment significantly influence the autogenous healing process [38].

Key Takeaways

- Autogenic self-healing is the process which refers to the potential of concrete to mitigate or close the cracks in presence of moisture and absence of tensile stresses.
- This process is influenced by a variety of physical, chemical, and mechanical factors, and the composition of the cement matrix and the surrounding healing environment. On the contrary, autonomic bacteria-based self-healing employs additives such as bacterial spores and organic mineral precursors to facilitate the deposition of healing materials. The bacteria responsible for converting organic acids or urea into calcium carbonate, effectively sealing cracks and mitigating the risk of corrosion in steel reinforcement.

- To prolong the activity of microorganisms in low-temperature marine environments, protective strategies such as encapsulation indiatomaceous earth, expanded clay, or alginates have been implemented.
- Autonomic capsule-based self-healing, on the other hand, depends on microcapsules containing healing agents that are released upon the formation of cracks.
- A variety of encapsulation materials and healing agents have been investigated, and the design cycle encompasses encapsulation, integration, mechanical characterization, triggering, and evaluation of the healing agent.

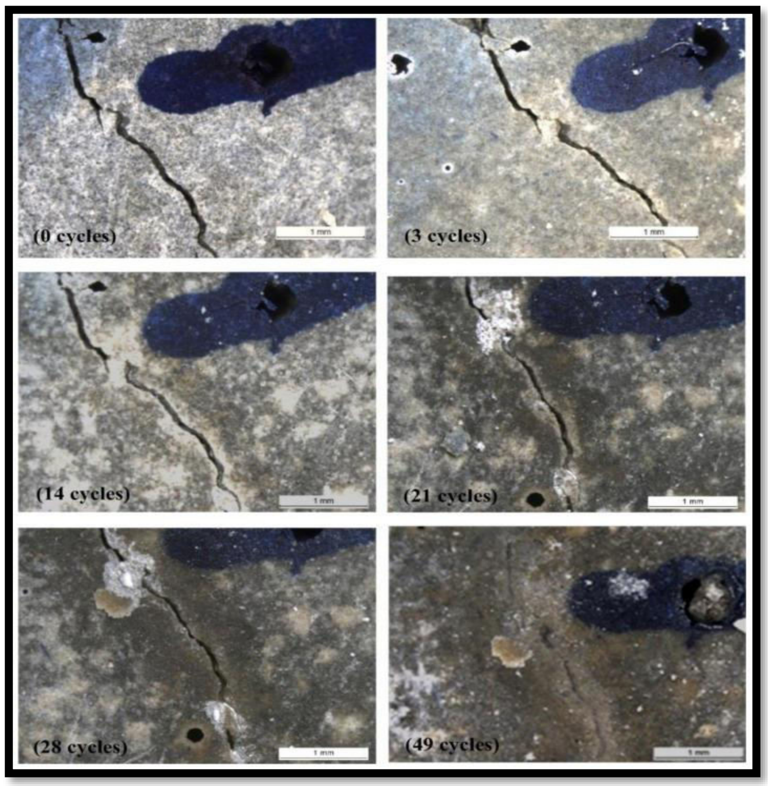

Fig.3. Closure of a 100 μm crack in an OPC M (0.45) sample cyclically exposed to 33 g/L NaCl [35] W. Zhong and W. Yao, "Influence of damage degree on self-healing of concrete (2008).

5.2 Autonomic Bacteria-Based Self-Healing

The mechanism of autonomic self-healing utilizes additives such as microcapsules consisting of healing agents filled with bacterial spores, which are responsible for deposition of healing materials [38]. Autonomic bacteria-based self-healing represents an alternate approach which frequently deploys bacteria in the form of thick-walled, sphericalcells, such as alkaliphilic endospore-forming bacteria [39] were among the pioneers in introduction of a bacteria-based self-healing concrete (SHC) agent consisting of bacterial spores along with an organic mineral precursor [40]. In these types of systems, the mechanism of self-healing mainly relies on the process known as synthesis of calcium carbonate through bacterial metabolic conversion of organic acids or enzymatic ureolysis. However, this mechanism requires the presence of an organic substrate that provides nutrients and water to stimulate bacterial activity [41]. Crack-induced water ingress activates bacterial spores, that mature into active organic cells having a potential of converting mineral precursor chemicals into calcium carbonate. The precipitation of calcium carbonate in steel-reinforced concrete cracks can prevent water infiltration andmitigate or minimize susceptibility to chloride intrusion, eventually reducing the possibility of corrosion in steel reinforcement of concrete structures.. Despite the fact that the majority of the world's marine infrastructure is situated in mild climate zones (annual average temperature of 10 °C, and average summer temperature of 20 °C) [7], [42], bacteria-based SHC has been shown to perform better in freshwater and room-temperature conditions [7], [42]. For bacteria-based SHC to be more effective in low-temperature marine environments, the bacteria-based agents employed must also function in such conditions. Furthermore, it has been demonstrated that effective microorganisms injected directly into concrete after mixing have limited functionality over time due to a lack of nitrates[19]. Consequently, to protect bacteria-based agents in such conditions, bacterial spores have been encapsulated in expanded clay capsules [39], [42], and bacteria in diatomaceous earth and melamine-based microcapsules [40], [43], prior to their incorporation into cementations composites. Although these strategies extend the duration of microorganism activity to achieve healing, they do not significantly enhance repair capability. Alginates have recently been proposed as a protective transporter of bacterial spores [44] and to produce a bacteria-based bead [45]. According to the latter study, the bacteria-based bead, composed of bacterial spores encapsulated in calcium alginate containing a bacterial nutrient source (yeast extract) and a mineral precursor compound (magnesium acetate), swelled when submerged in a low-temperature (8 °C) simulative marine concrete crack solution, forming a bacteria-activated calcite ($CaCO_3$)–alginate composite material [41], [45]. It is anticipated that incorporating this bacteria-based bead technology into a cementitious material would confer superior crack-healing activity. Figure 8 provides a schematic of the proposed Healing mechanism for a cementitious composite integrated with the bacteria-based bead technology [45].

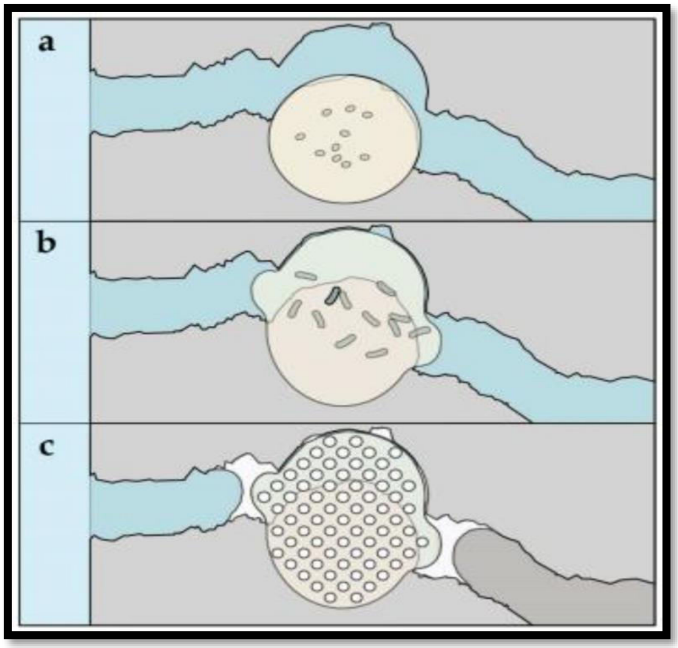

Fig.4.Schematic diagram illustrating the proposed healing mechanism[9]
J. Fronczyk et.al. "Immobilization of (bio-)healing agents for self-healing concrete technology (2023).

5.3 Autonomic Capsule-Based Self-Healing

The autonomic self-healing mechanism depends on additives like microcapsules in combination with healing agents [38]. A vital strategy explored in recent years includes encapsulation of a healing substance. This process activates as soon as a crack develops in the binder matrix, resulting into disintegration of capsule followed by release the healing agent. The substance so released mitigates and eventually seals the crack, preventing its further propagation. Genrally, capsules are made of urea–formaldehyde, glass, and silica, while calcium nitrate, epoxy resin, polyurethane, and superabsorbent polymers (SAP) are commomly used as healing agents [26], [46]. Nishiwaki et al.[29]highlighted that encapsulating healing agents is highly effective for achieving entire crack sealing with chemical agents, preventing penetration by aggressive substances, and sometimes partially restoring mechanical properties, which is crucial for maintaining performance over the service life (succession of crack formation). The design cycle for capsule-based self-healing materials includes:

- Encapsulating the capsule;
- Integrating the capsule into the matrix;
- Mechanical characterization;
- Triggeringand releasing the healing agent to the damaged area; and
- Assessing the healing agent [47].

In a single-capsule system, at least one healing agent is encapsulated, which could be a solvent, reactive chemical, or a low-melting-point metal. The capsule or dispersed catalyst healing mechanism involves encapsulating a self-healing agent in brittle capsules and dispersing the catalyst/hardener within the matrix. In case of damage propagating as a crack, the capsules disintegrate, releasing the monomer[28], [48], [49]. The third approach involves phase separation in droplets or capsule systems, where at least one healing component undergoes phase separation, and the other component is encapsulated. When released, these substances react with each other. The double-capsule system includes one or more reactive liquid healing agents or polymerizes, whereas the all-in-one microcapsule system is entirely self-contained [47]. Glass capsules are commonly used to contain the healing agent [50], [51], [52], [53]. These capsules break effectively when cracks appear, but they struggle to withstand well as the concrete mixing process without special protection [28]. Therefore, researchers have proposed bundling the capsules with a water-soluble solution in order to protect them during the truck mixing process [54].

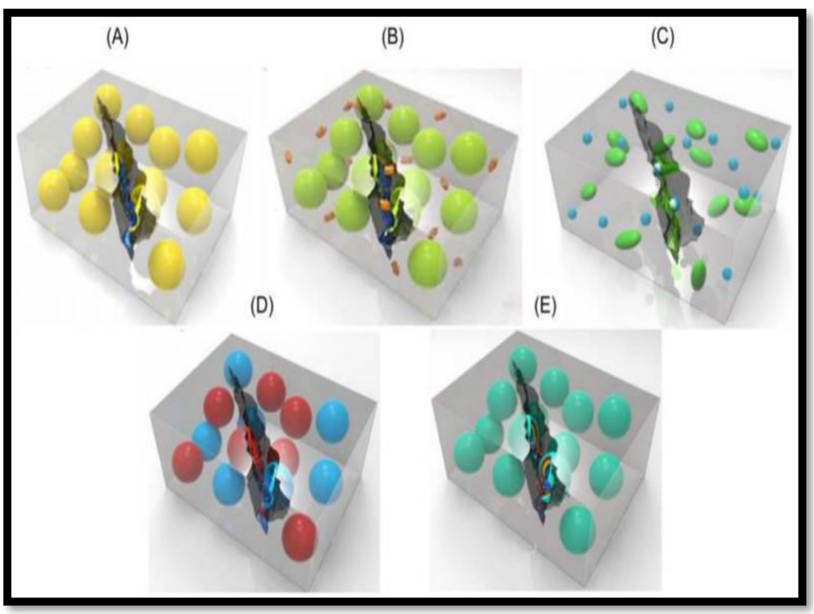

Fig.5. Capsule-based self-healing systems:(A) single capsules, **(B)** capsule (green)/dispersed catalyst (orange), **(C)** phase-separated droplet/capsules (green), **(D)** double-capsule (blue capsules with hardener, red capsules with healing agent) and**(E)** all-in-one microcapsules (multiple shell walls depicted with different colors.[48].D. Y. Zhu, M. Z. Rong, and M. Q. Zhang, “Self-healing polymeric materials based on microencapsulated healing agents: From design to preparation (2015)

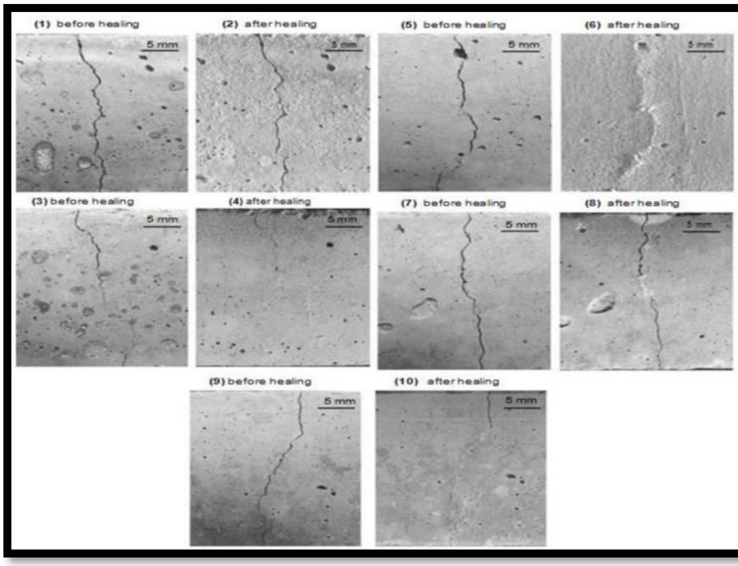

Fig.6. Images of crack healing process [61]A. Kanellopoulos, P. Giannaros, and A. Al-Tabbaa, "The effect of varying volume fraction of microcapsules on fresh, mechanical and self-healing properties of mortars.(2016)

Key Takeaways

- The autonomic self-healing mechanism in concrete involves the encapsulation of healing agents within capsules composed of materials such as urea-formaldehyde, glass, as well as silica.
- When formation of cracks occurs, the capsule ruptures, resulting into release of the healing agent, which consequently seals the crack and inhibits further propagation.
- The design cycle for capsule-based self-healing materials encompasses encapsulation, integration, mechanical characterization, triggering, and assessment.
- Different methodologies are employed, including single-capsule, double-capsule, and all-in-one microcapsule systems. Glass capsules are effective in breaking upon the appearance of cracks; however, they necessitate protection during the concrete mixing process, which can be achieved by bundling them with a water-soluble solution.

6. Conclusions

The process of self-healing in concrete is complex, which includes a combination of chemical, physical, and mechanical interactions. Concrete's inherent tendency of low tensile strength renders it susceptible to development of cracks, which reduces its durability by allowing the infiltration of liquids and gases that carry deleterious matter. In case these micro-cracks propagate to an extent to reach the reinforcement, both the reinforcement and the concrete may suffer damage. Subsequently, it becomes imperative to control crack width and focus on the repairs promptly. This study focuses on the developmental aspect of self-healing concrete (SHC) due to considerable costs associated with the maintenance and repair of structures. By providing the autonomous healing to cracks, the lifespan of concrete could be increased

considerably, thereby enhancing both efficiency and resilience. SHC represents an approach for creating smart advanced materials along with substential adaptability. Different types of self-healing concretes with technological advancements can be deployed depending on the specific uses or applications. Different primary concerns confronting almost all self-healing technological advancements in concrete industry include, managing increased costs,
achieving widespread adoption, and ensuring long-term effectiveness as far as durability is concerned.

Ensuring the increament in the autogenous self-healing capacity of concrete can be done by following the strategies which includeutilizing wet–dry cycles, minimizing crack formation and incorporating supplementary cementitious materials (SCMs) like, silica fume, ground granulated blast furnace slag (GGBS)and fly ash. In addition to these, the usage of expansive minerals, including, magnesium oxide (MgO), bentonite clay calcium sulfoaluminate (CSA), quicklime, and crystallizing mineral agents are some of the important matericals which can contribute further to this enhancement. However, the efficiency of autogenous self-healing depends upon the quantity of unhydrated cement and minerals present in the concrete to a large extent, which has thus been limited to lesser crack widths, prolonged healing time, and only a partial strength recovery. On the contarary, autonomic healing of concrete requires the release of self-healing agents from encapsulated sources or a continuous and constant supply system to surpass the self-healing efficiency of autogenous type of methods. Prominent autonomic systems of self-healing systems include microvascular, microencapsulation, networks, and pellets containing different agents such asmethyl methacrylate, microorganisms epoxies, cyanoacrylates, , minerals, and alkali–silica solutions. Encapsulating biological healing agents within concrete is a much more effective option, as the interaction of healing agents along with unhydrated cement particles that gives beneficial outcomes. The successful self-healing process depends upon the interaction between the matrix and the healing agent, size, shape of the crack. For example, process of repair of cracks of uniform width differs from those with varying widths. The self-healing capacity (SHC) decreases the requirement of external intervention to identify and repair internally damaged structures, such as cracks, leading to concrete degradation and corrosion in reinforcements, at the same time, decreasing the costs and increased durability. This study minutely focuses on the strategies, influential factors, mechanisms, and effectiveness of self-healing. At the same time it also provides critical summaries of the characteristics, performance, and evaluation of SHC composites' self-healing efficiency. Moreover, research is increasingly focusing on understanding the potential applications of SHC as an advanced concrete material, marking a pivotal moment for promoting sustainable and functional concrete nano-composites in modern construction. Encapsulating biological healing agents within concrete is a more effective option because the interaction between un-reacted cement particles and healing agents yields beneficial results. The success of a healing process, based on existing techniques, depends on the interaction between the matrix and the healing agent. Additionally, the crack's size and shape influences the effectiveness of concrete healing. For example, repair of cracks of constant and consistent width differ from addressing those with variable widths. The self-healing capability (SHC) decreases the requirement of external efforts to identify and fix any kind of internal damage, such as cracks. This results into reduced levels of concrete deterioration, decreased intensity of corrosion in concrete reinforcements, lesser costs, and increased durability. This study thoroughly examined the strategies, influential factors, mechanisms, and effectiveness of self-healing. It also provides essential summaries of the characteristics, performance, and assessment of SHC composites' self-healing efficiency. Moreover, research is increasingly focusing on a comprehensive understanding of SHC's potential as an advanced concrete material, marking a pivotal moment for promoting sustainable and functional concrete nano-composites in modern techniques used in construction.

The comprehensive literature review results in a conclusion that the continuous development of self-healing high-performance concretes constitutes ainnovative, pioneering, accessible, and environmentally sustainable concrete technology, aimed at constructing resilient and sustainable structures for generations to come in future. It has been found that the recovery of initial strength characteristics remains incomplete. In conventional concrete, restoration of strength properties takes place partially and is achievable following fracture healing, also, this challenge is exacerbated in high-strength concrete because of its much superior initial mechanical properties. Furthermore, addressing the healing for larger cracks is crucial, particularly in highly aggressive environments or when concrete structures are subjected to much more severe conditions. Achieving these objectives essentially requires the effective implementation of self-healing procedures and systems that are compatible for the concrete matrix. It is evident that the nano-technology is going to play a pivotal role, as self-healing systems utilizing nano-particles are anticipated to have a minimal adverse impact on initial strength properties when compared to those which depend on microcapsules. Moreover, self-healing concrete or (SHC) will enable builders to construct concrete structures with considerably reduced concerns for damage and costly maintenance.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used AI TOOL in order to [Enhance the language and readability]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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