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Review

Self-Healing Concrete Techniques and Technologies and Applications

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Abstract

The main weakest point of concrete is its exposure to cracks, and concrete structure repair is expensive, especially for infrastructure maintenance, which is difficult to access. The ability of self-healing concrete (SHC) to successfully heal fractures without the assistance of humans has received much attention since it increases operational life and lowers maintenance expenses. This paper reviews various techniques and technologies of autogenous and autonomous self-healing concrete. Much more attention is given to the autonomous SHC, including the encapsulation materials, capsule geometries, and healing agents. This is due to its accuracy for healing locations and better healing capabilities compared to the uniform hydration of autogenous SHC. Polymeric materials have shown great potential in both capsules and healing agents. Because they can meet the unusual demands of capsules, which include being flexible when mixing concrete and becoming brittle when cracks develop, the healing agent's viscosity must be low enough to allow it to flow out of the capsules and fill tiny cracks. In contrast, if the viscosity is too low, the healing agent will either seep out of the fracture or be absorbed by the pores of the concrete matrix.

Additionally, some projects have been cited to demonstrate the feasibility of self-healing concrete in the construction industry.

Keywords

Self-healing concrete; autogenous healing; autonomous healing; healing agent; encapsulation technique; capsules

1. Introduction

Concrete is the most-used building material in the world, with about 2.5 tons per person per year, and is made especially attractive due to its cheap price. Builders have been constructing concrete structures since the discovery of Portland cement in the mid-nineteenth century. It is a quasi-brittle material that is strong in compression but weak in tension. That is why reinforcement is usually used with it for construction [1]. However, its weakest point is that it is subject to cracking and deterioration with time, and the renovation of concrete buildings is costly, especially for infrastructure maintenance, which is not easily accessible. Recently, biological systems have become the inspiration for material scientists. This fundamental change in material design philosophy has resulted in the creation of 'smart' materials, including self-healing materials. Different ways classify various strategies and techniques for self-healing concrete. As the concept of sustainable materials has become increasingly popular in recent years, self-healing concrete has emerged as an appealing topic as a potential solution to the sustainability challenge.

Dry [2] explored the idea of self-healing functionality in civil engineering, specifically for cementitious materials, despite the majority of studies on self-healing materials being focused on polymers and polymer composites for high-tech applications in space and airplane areas. Also, various techniques and healing agents, such as polymer, bacteria, and mineral admixtures, have been used to improve the healing capability. However, encapsulation-based self-healing concrete has lately received much interest because of its capacity to heal fractures effectively without human intervention, extending the operational life and lowering maintenance costs. Once the propagating cracks hit the capsule shell, the healing agents are released to heal the cracks near the damaged part. Because of this, SHC has excellent perspectives for infrastructures exposed to water and corrosion, such as tunnels and bridges. Several experimental studies have been carried out in the literature to investigate the fracture of the capsules and their healing capability. These studies have revealed that the bond between the capsule shell and the cement matrix is imperfect. The healing efficiency depends on the fracture of microcapsules and the release of the healing agent to heal the cracks. Computational modeling of encapsulation-based self-healing concrete has shown its privilege to study the physical phenomena that are challenging to investigate experimentally. Such as capsular clustering effects, interfacial fracture properties between the capsules and the concrete matrix, and effects of healed crack length and interfacial cohesive properties between the solidified healing agent and the cracked surfaces [3-5]. This paper comprehensively reviews the development, definitions, concepts, and techniques of self-healing concrete. The encapsulation techniques, including the types of capsules and healing agents, are outlined and classified. In addition, applications of self-healing concrete in practical projects are discussed. Figure 1 illustrates the flow chart detailing the methodology employed in this review study.

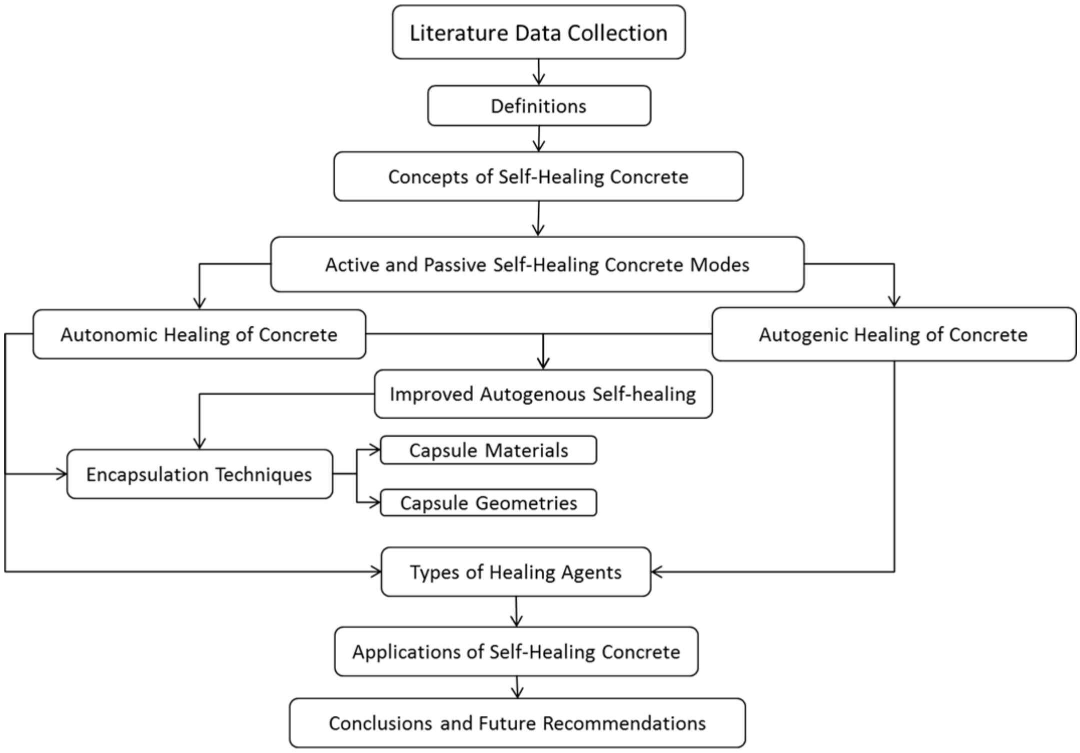

Figure 1 Flow chart representing the present methodology of the review study.

1.1 Definitions

The ability of concrete to naturally and autonomously heal or repair its cracks without any intervention from outside is commonly referred to as self-healing concrete [1]. Several terms have been used in the literature related to this new area of self-healing materials, including intelligent materials, smart materials, smart structures, and sensory structures. The definitions of these terms in the literature can be confusing. The following are simplified explanations of these definitions:

1.1.1 Intelligent Materials

Intelligent materials "incorporate both the concept of information and physical characteristics such as strength and durability" [6]. The systematic combination of numerous individual functions results in this higher level function, or "intelligence." To respond to numerous circumstances in a controlled way, intelligent materials must also possess the ability to maintain self-control. This behavior resembles many natural materials, including skin, bone, and tendons [1].

1.1.2 Smart Materials

Smart materials refer to specially designed materials that exhibit unique and efficient responses to changes in their immediate environment [7]. Piezoelectric materials, magnetostrictive materials, shape-memory materials, temperature-responsive polymers that can change color with temperature, and smart gels that can contract or expand by a factor of up to 1000 in response to chemical or physical stimulation are examples of smart materials. As a result, the degree to which a material can gather information, process it, and respond appropriately distinguishes it from an intelligent material [1].

1.1.3 Smart Structures

In contrast to smart materials, smart structures are manufactured composites of conventional materials that have sensing and control properties as a result of the characteristics of the constituent components. Many self-healing materials fall under the umbrella of smart structures because they have encapsulated healing agents released when fracture develops, ''healing'' the ''injury'' and prolonging the materials' functional life. Researchers have conducted self-healing experiments on polymers, coatings, composites, and concrete. However, these "structures" depend on pre-existing knowledge of the damage mechanisms they may encounter, categorizing them as smart rather than intelligent [1]. Further details of Self-healing concrete will be discussed in section 2.

1.1.4 Sensory Structures

Sensory structures can detect things, but they cannot act on them. Smart bricks are one type of sensory structure that can track temperature, vibration, and movement within a structure. Smart optical fibers can detect harmful chemicals, moisture, and strain. Smart paints contain silicon-microsphere sensors that track their condition and degree of protection [1].

2. Concepts of Self-Healing Concrete

Concrete that can repair itself employs various methods and processes categorized in various ways. Two exciting studies comparing different healing techniques were conducted at TU Delft [8] and Ghent University [9]. Also, recently, many review studies have been done to summarize the different strategies and techniques of self-healing concrete, such as [10, 11]. However, only two main concepts of self-healing, namely autogenous and autonomous self-healing, form the basis for all of them.

2.1 Autogenic Healing of Concrete

The healing process is known as autogenic healing if a material's healing abilities are specific to that material, and the material is, therefore, potentially classified as a smart material. Rehydrating a concrete specimen in water can start the hydration process by reacting with pockets of dehydrated cement in the matrix. It may also occur naturally without needing extra healing agents since cementitious materials have an inherent autogenic potential to self-repair. Cementitious materials can naturally self-heal, a phenomenon that has been understood for a long time. The ability of many historic buildings and structures to survive for an extended period with minimal service and maintenance is generally recognized as one of the causes of this phenomenon. This phenomenon helps explain the unanticipated lifespan of several historic bridges in Amsterdam [12]. The high quantities of chalk or calcium in the surrounding cement are thought to contribute to this lifespan. It is believed that calcium breaks down in the presence of water, deposits in cracks, and partially repair the cracks while preventing further growth. Recently, researchers have proposed that the autogenic healing of microcracks causes a gradual decrease in the diffusion coefficient of concrete marine structures. Microcracks' self-healing, which provides a durability advantage, is limited for concrete constructions that are not submerged. This scenario might be improved by regularly wetting the structures, but doing so is costly and typically not feasible [1]. Chemical, physical, and mechanical processes are thought to be the primary factors of autogenic self-healing. The primary processes are (i) cement pastes swelling and hydrating, (ii) calcium carbonate crystals precipitating, and (iii) flow channels becoming blocked by the deposition of water impurities or the movement of concrete fragments that separate during the cracking process [13], see Figure 2. Several researchers have studied this phenomenon. Examining the impact of damage severity on the self-healing capacity of normal strength and high strength concrete [14].

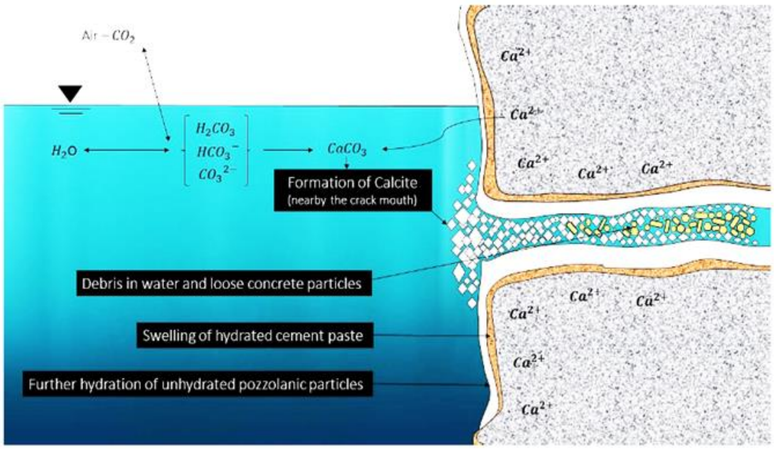

Figure 2 Schematic mechanism of autogenous self-healing concrete [15].

Concrete can also repair itself after being exposed to high temperatures, such as fire. The effectiveness of this self-repair process depends on several factors, including the maximum temperature endured, the composition of the concrete mixture, and the application of cooling and curing techniques after the fire. When subjected to fire, concrete undergoes both physical and chemical changes, resulting in phenomena such as induced thermal stresses and the evaporation of free water, which lead to significant cracking. Consequently, efficient post-fire self-healing properties would be advantageous, as it would enhance the chances of reusing the concrete in the event of a fire [16]. Therefore, the literature has explored the examination of temperature's influence on cracked concrete's permeability and self-healing capabilities [17]. Recently, machine learning modeling has been employed to predict the recovery of compressive strength in high-temperature damaged concrete due to self-healing [16]. Engineered cementitious composites (ECCs) have been given some consideration about the impact of autogenous healing [18]. In [19], the study examined the effectiveness of autogenic healing on the strength recovery of fully cured concrete beams exposed to quick freeze/thaw cycles. The research concluded that autogenous healing could achieve only a 4-5% recovery of compressive strength. It has been found that early-age concrete has the highest potential for autogenous repair [20].

According to research, autogenous healing is only effective for tiny fractures, requires water to function, and is challenging to manage [21]. The maximum healable crack width through autogenous healing was discovered to be 200 µm and 300 µm. Several investigations into autogenous healing in concrete were conducted to address the issue of the width restriction of healable cracks. They recommended the use of compressive forces as a solution [22]. To limit fracture width, other people suggested employing engineered cementitious composites (ECC) made of synthetic fibers such as polyvinyl alcohol (PVA) and polypropylene (PP) [22]. Superabsorbent polymers (SAP), which can store and supply moisture over a longer time, were suggested as alternate methods for restoring water and activating hydration in concrete. However, pores or voids in concrete become weak points in the matrix when water is released from SAP, making concrete. Cracks could even spread through the structure's service life [1]. In other research, the use of additional cementitious materials to promote autogenous healing, such as fly ash and blast furnace slag, has been investigated. Because materials like fly ash and slag hydrate more slowly than cement, unhydrated particles of these minerals encourage autogenous repair when concrete is more advanced. The drawback of this strategy is that the healing material is used up during the procedure and might not be available for additional hydration later [1]. Jonkers [23] suggested using bacteria spores to facilitate the formation of calcium carbonate, a crucial component of the healing process. Even though the bacteria started the precipitation and deposition of calcium carbonate at the crack faces, when they were added to the freshly mixed concrete, they did not survive for very long because of two factors: the strongly alkaline environment of the concrete mixture and the shrinkage of pores due to the hydration of the cement. In recent literature, various bacterial carriers have been employed to extend the viability of bacteria in concrete, thereby enhancing its shelf life [24]. It is important to note that the improvements above to autogenous self-healing are also known as improved autogenous self-healing [15]. In conclusion, the autogenous healing mechanism has several shortcomings, such as dependence on concrete age, requirement for a long-lasting internal water source, survival of bacteria for carbonate precipitation, and requirement for restriction on the width of the crack that can be healed [1].

2.2 Autonomic Healing of Concrete

In autonomic healing concrete, the healing capability is achieved by inserting self-healing units of a container, such as a capsule or tube containing the healing agent, into the concrete matrix. The healing agent is triggered by cracking. Therefore, the healing process is known as autonomic healing since it occurs near the cracked region. The concept of autonomic healing in concrete was proposed initially for cementitious materials by Dry [25] using hollow glass tubes as containers and methyl methacrylate as a healing agent. Recent intense research has been drawn to an autonomous self-healing method using microcapsules for more accurate healing location and better healing capabilities [26]. Discrete microcapsules embedded in the substrate material contain the healing agents. Approaching cracks break the capsule shell to release the healing agent; hence, the healing occurs near the damaged part, see Figure 3. The healing is more localized than the uniform hydration of autogenous healing. Numerous healing agents, including polymer, bacteria, sodium silicate, and different capsule shell materials, including gelatin, silicon, and glass, were manufactured and examined to extend the life of the healing agent, accelerate the reaction after cracking, and enhance the healing capability [27, 28].

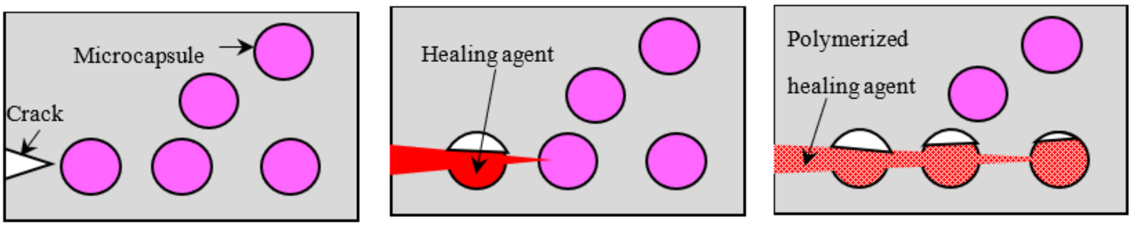

Figure 3 Schematic mechanism of autonomous self-healing concrete.

While autogenous healing relies on the presence of water, and bacteria-based autogenous healing has problems with bacteria survival and low recovered strength of the repaired concrete, the microcapsule self-healing technique using polymer healing agents appears to be the most promising due to improved high healing capability [9, 29]. Another technique based on the autonomic healing concept is vascular self-healing, which imitates the human body's vascular network system. In order to provide a healing chemical to the cracked/damaged areas, a network of tubes can be constructed in concrete. In this procedure, an external source delivers healing substances via hollow tubes or a network of tubes. Two approaches to vascular self-healing exist: the single-channel and multiple-channel systems. The single-channel vascular approach uses only one healing agent, while the multiple-channel system employs two healing agents for the healing response. Furthermore, although feasible at the laboratory scale, casting concrete with a network of pipes for vascular self-healing on actual construction sites is problematic. The issues identified by these two techniques can be solved differently by encapsulation-based self-healing [10].

It is important to note that several factors influence the autonomous healing mechanism's performance, including the healing agent's strength, size and percentage of microcapsules, shell thickness, and encapsulation technique [9]. Laboratory testing is currently the primary focus of present developments. In most experiments, researchers test the healing efficiency for pre-notched specimens where the direction of crack propagation can be well controlled. However, the crack location in engineering applications will not be known in advance. Moreover, specific physical phenomena are difficult to detect experimentally. It is worth mentioning that defining the healing mechanism has become more complex by introducing the advantages of the autonomic mechanism to the autogenic to decrease its disadvantages, as is well known by Improved Autogenous Self-healing. A simple diagram is presented in [15] to illustrate the interaction between the self-healing mechanisms, see Figure 4.

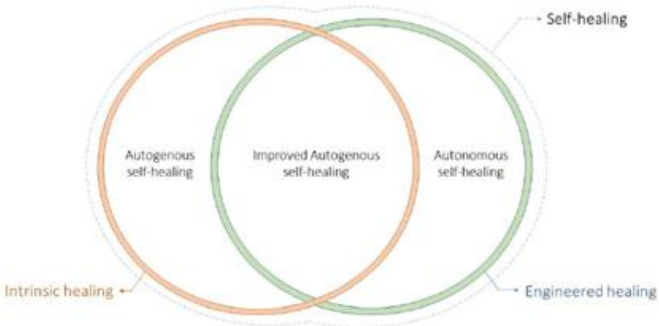

Figure 4 Concepts of self-healing concrete [15].

Engineering the self-healing concrete involves designing and optimizing the concrete where the microcapsules are driven to burst and discharge their entire payload at a damaged region, thereby delivering a high concentration of healing agents to a small area. Fluidity is necessary to transport the agents to a damaged site or to spread the healing agents throughout the affected region. For an efficient SHC design, introducing fluidic components into concrete without sacrificing the mechanical properties of the concrete structure is of utmost importance. Therefore, it is essential to understand the capsules' rupture behavior and the encapsulated healing agent release [30]. Experimentally studying such behavior is challenging because some interface parameters between the concrete matrix and the capsule surface are difficult to determine. Therefore, computational modeling of the interaction between the concrete matrix and the capsule surface can provide helpful information about the fracture probability or debonding of the capsule when it counters the crack [3, 4]. The interface strength between the capsule and the concrete should be high enough to avoid interface failure, so studying the cracking process is very important to guarantee that the capsules will break to release the healing agent; hence, the transportation and solidification process can begin properly.

3. Active and Passive Self-Healing Concrete Modes

Self-healing mechanisms can also be classified based on whether they are passive or active in their healing abilities. A passive mode self-healing structure can respond to exterior effects without human interaction, whereas an active mode smart structure requires human intervention to complete the healing process. Dry [2] investigated both mechanisms concerning concrete. They are shown in Figure 5 for active release mode by melting a wax coating on porous fibers containing methylmethacrylate healing agent and Figure 6 for passive release mode by only the physical cracking of the brittle fiber under loading. The fundamental advantage of an entirely passive release mechanism is that no human inspection, repair, or maintenance is required.

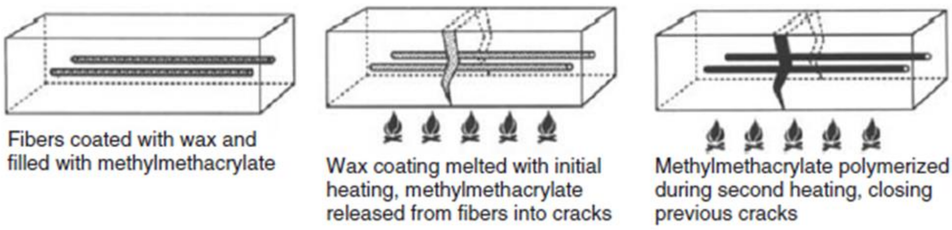

Figure 5 Active mode of self-healing concrete (Dry [2]).

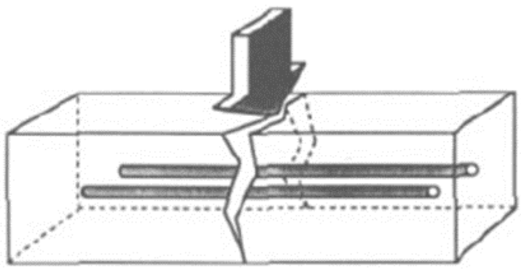

Figure 6 Passive mode of self-healing concrete by cracking under loading (Dry [2]).

4. Encapsulation Techniques

Numerous encapsulating strategies have been presented in the literature. Appropriate encapsulation techniques and materials should be able to endure the concrete mixing process, requiring the capsules to possess flexibility and strength throughout this process. Minimizing the impact of capsules on the workability of fresh concrete is essential. When the concrete hardens, the capsules must be able to release the healing agent when a crack forms. If the self-healing process activates upon crack creation, the capsules must become brittle enough to rupture as soon as a crack develops after the concrete has hardened. Furthermore, the capsules' impact on hardened concrete's mechanical and physical characteristics must be restricted. The shape and dimensions of the capsules must be optimized to allow cracks to pass through the capsules and efficiently release the healing agent. Although there are many requirements for the encapsulation material, it is also important to note that capsules must withstand the harsh conditions inside the concrete matrix and are appropriate with the healing agent used [31].

4.1 Capsule Materials

Developing the self-healing mechanism in concrete has used various encasing materials, including glass, ceramic, gelatin, silicon, expanded clay, cementitious, and polymers. Polymeric microcapsules, made using an oil-in-water dispersion mechanism based mainly on miniemulsion polymerization, are widespread [32]. The urea-formaldehyde (UF) capsule shell wall is created by the liquid phase reaction of urea and formaldehyde, which finally becomes cross-linked. The prepolymer resulting from the reaction in the aqueous phase can be deposited to give the microcapsules a rough texture, increasing their bonding with the cementitious matrix. Researchers utilized healing agent-containing capsules in [33-37]. Polyurethane (PU) capsules have also been utilized in self-healing technologies [38]. Melamineurea-formaldehyde (MUF) microcapsules have been shown to possess qualities superior to those formed from UF, and their production is more straightforward [39]. A helpful summary of the comparison of capsule materials has been presented in the literature [9, 10]. Once the capsules have made it through the mixing and casting of the concrete, it is crucial that they remain stable within the extremely alkaline cementitious matrix and that the enclosed contents do not harm the shell. Hence, using inert encapsulation materials, like glass, may be advantageous. Although glass is widely used as an encapsulating material, it should be noted that a significant amount of alkalis in the cementitious matrix may cause an alkali-silica reaction. Utilizing inert ceramic capsules, as suggested by [40], avoids this problem. [41] has compared the effectiveness of cylindrical capsules composed of glass and perspex (PMMA). Perspex is stronger and more ductile than glass. However, this study has shown that it was unsuitable because it reacted with the healing agent. Other organic materials such as gelatin, PP, PU, UF, and EVA had positive outcomes when utilized as an encapsulation material. Since silica capsules are more likely to be chemically compatible with the cementitious matrix and may produce a superior interface than their polymeric equivalents, they have been employed instead of those products [9].

Cement-based tubes are gaining popularity as a substitute, and this has only recently been discussed in the literature [42] due to their excellent interfacial bonding characteristics with concrete. Additionally, a recent study examined the use of additive manufacturing techniques as a potential method for creating novel kinds of macro-capsules that are suitable for filling with various healing agents and then embedded in cementitious materials to introduce self-healing properties and address the sensitivity of these materials to crack formation. Regarding this, researchers generated 3D-printed tubular macro-capsules and filled them with either a liquid sodium silicate or an expanding polyurethane resin [43]. Polymeric capsules can change their properties, enabling them to satisfy the conflicting demands of being flexible during the mixing of concrete and being more brittle during the fracture mechanism [31].

4.2 Capsule Geometries

It is crucial to take into account the inserted capsule's shape. A spherically shaped capsule, when broken, will deliver the healing agent in a more regulated and increased manner, reducing stress concentrations near the breakage area. Although the tubular capsule has a higher surface area than the volume ratio, it has the same volume of healing agent. Localized and repeated cracks will restrict the effective distribution of the healing agent, reducing the amount of healing agent that might be released upon cracking [1].

4.2.1 Continuous Supply Pipes/Vascular Tubes

Self-healing systems that use vascular technology closely resemble the vascular network system in the human body [10]. Dry [2] proposed an active supply of a healing agent using a vacuum pressure system, as demonstrated in Figure 7. Continuous glass supply pipelines, with or without vacuum pumps, allow the kind of healing agent to be varied and additional supply to be delivered. Without a vacuum pressure system, gravity and capillary forces will force the healing agent from the tank into the fracture. In Figure 8(A), the utilization of a one-channel vascular system is demonstrated when this strategy is combined with a one-component healing agent.

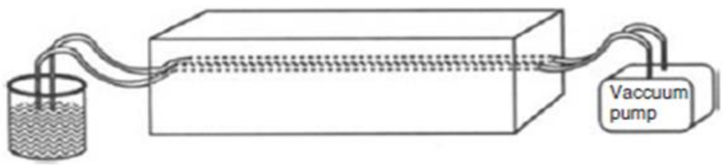

Figure 7 Continuous supply pipes with a vacuum pump to supply healing agent (Dry [2]).

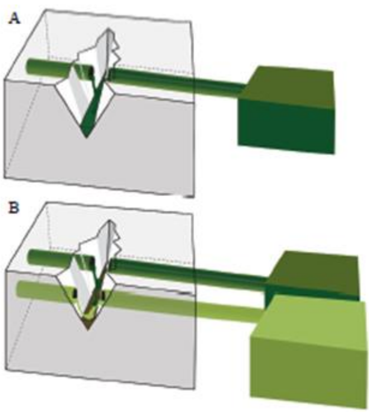

Figure 8 Vascular tubes with the tank to supply healing agent (without vacuum pump) [9].

In contrast, Figure 8(B) illustrates using a multiple channel system when combined with a multi-component healing agent [9]. As opposed to previous encapsulation techniques, this enables the healing of wider cracks. The method's primary drawback is the caution required during casting to prevent tube breakages. Therefore, this process is not appropriate for casting concrete on site. For the idea of self-healing in cementitious materials, it does offer an intriguing feasibility test [1]. Other experimental studies have utilized an air-curing cyanoacrylate healing material supplied in glass tubes [9]. Even though the vascular-based approach allows for the repair of even wider cracks, the healing agent may seep out of the gaps if they become too broad. Therefore, some research paired this strategy with narrowing the crack. Continuous adhesive-filled glass tubes and shape-memory alloy (SMA) wires were introduced to enable glass tubes to crack when damaged. Due to the superelasticity of the SMA wire, the structural member immediately regains its deflection after unloading. The healing agent pours out of the cracked fibers, and at that exact moment, the repairing vessel's switch is turned on to fill and repair the fractures [9].

4.2.2 Capillary Tubes

Researchers utilize capillary tubes developed for blood testing in the medical industry as encapsulating containers for an ethyl cyanoacrylate healing agent. They initially conducted tests to confirm the sensing and actuation mechanisms of engineered cementitious composites (ECC) by forcing the cracking of single hollow capillary tubes under the eye of an environmental scanning electron microscope (ESEM) [44]. Custom-made hollow capillary tubes, 500 µm in diameter and 60 µm wall thickness, embedded inside ECC specimens with dimensions 10mm × 10mm × 1.5 mm, were used, as illustrated in Figure 9 [1].

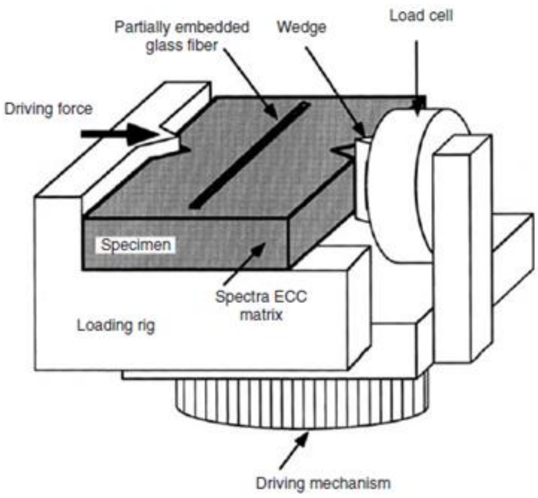

Figure 9 Capillary tube specimen loading configuration [1].

4.2.3 Tabular Capsules/Cylindrical Tubes (Macro-capsules)

Recent experimental studies on macro-capsules constructed of thin glass, thick glass, and cementitious materials were carried out by a research team at the University of Ghent, as shown in Figure 10. They evaluated the impact of the capsules on fracture processes using acoustic emission. The localization of events showed a 40% extension of the fracture process zone. They demonstrated that the capsules act as local reinforcements by altering the crack's path and forming many microcracks. It was confirmed by digital picture correlation [45], which provides further evidence. Although this technology can increase the likelihood that a fracture would impact the tubes, the tubular encapsulation technique can only be used on precast concrete elements because it requires manually inserting the tubular capsules [9].

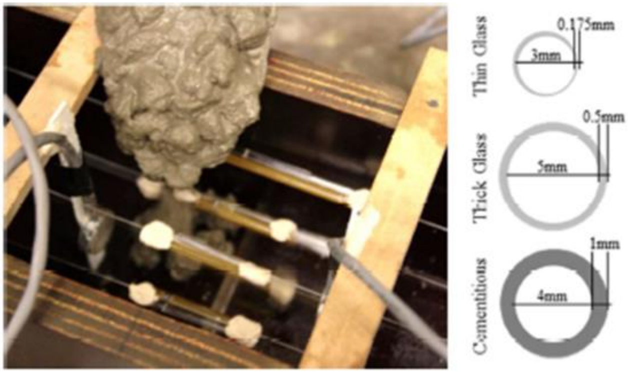

Figure 10 Tabular capsules from different materials [45].

4.2.4 Microcapsules

The system based on microcapsules can employ capsules of different shapes, like spherical, cylindrical, and so on. The benefit of scattered microcapsule inclusion is that the concrete can respond to diffuse cracking at numerous points and leakage of a healing agent from the capsules into the fracture due to gravitational and capillary pressures. The drawback is that no additional repairing agent can be provided once the first one runs out [1]. When a damage or crack grows large enough to rupture the capsule's shell and release the healing agent, microcapsule based self-healing is activated. There are numerous ways to trigger a healing agent reaction. Contact with moisture or air, heating (Figure 11 A & B), or contact with the cementitious matrix (Figure 11 C & D) can trigger the reaction. The reaction can also be initiated by contact with a second component already in the matrix (Figure 11 E & F) or by additional capsules (Figure 11 G & H). The capsules in the microcapsule-based system might be spherical (Figure 11 A, C, E & G) or cylindrical (Figure 11 B, D, F & H) [9].

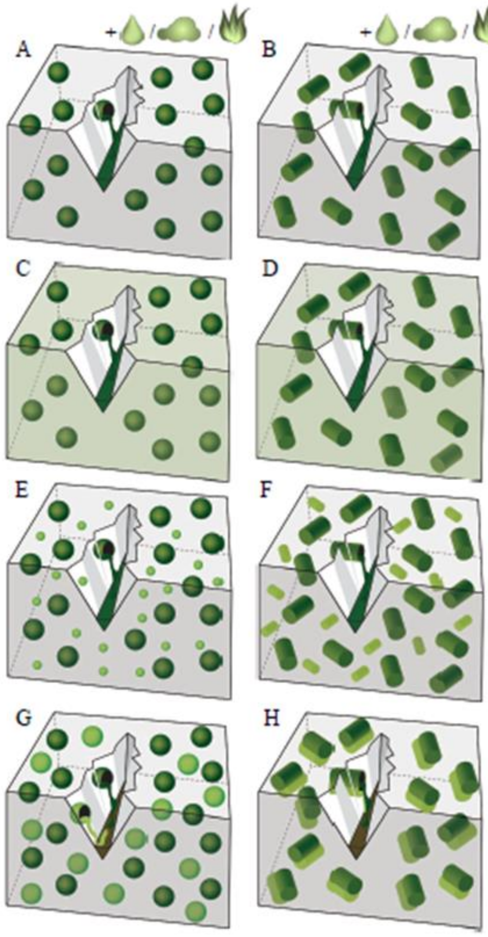

Figure 11 Microcapsule based self-healing concrete techniques. Reaction of encapsulated healing agent due to different contact with (A & B) moisture or air or heating (C & D) concrete matrix (E & F) second component present in the concrete matrix (G, H) second component provided by additional microcapsules [9].

In preliminary studies, researchers conducted compression and splitting tests using urea-formaldehyde microcapsules (diameter 20-70 µm) filled with epoxy resin and gelatin microcapsules (diameter 125-297 µm) filled with acrylic resin. Additionally, researchers concluded that, along with the challenges of blending two-agent epoxies, the amount of healing agent delivered by microencapsulation is small and restricted, and the bond strength between the microcapsule and the matrix must be stronger than the microcapsule's strength [6]. The insertion of hollow capsules containing a healing agent may affect the concrete's tensile and compressive strength. Furthermore, spherical, cylindrical, or tubular capsules leave holes in the concrete matrix after releasing the healing agent. As a result, capsule dimensions must be modest enough to avoid significantly affecting the structure's characteristics [9]. A study used UF spherical microcapsules with a diameter of 120 µm and concluded that these capsules did not affect the compressive strength of concrete [35]. Another investigation found that embedding spherical PU microcapsules did not affect compressive strength [38]. Spherical capsules, in general, have less influence on mechanical properties because their shape minimizes stress concentrations adjacent to the gap left by empty ones [46].

5. Types of Healing Agents

Healing agents play a vital role in self-healing, especially in autonomic self-healing. The investigations conducted on the self-healing of concrete have introduced a variety of healing agents. The capillary forces, controlled by the crack width, are not the only factors that affect the healing process. However, a healing agent must meet several conditions to be suitable for self-healing concrete [1]. The healing agent will be included in the concrete matrix during the casting time, but it should not lose its reactivity until cracks develop. Also, the viscosity of the healing agent is a critical issue during the breaking time of capsules. The healing agent should have a low enough viscosity to flow out of the capsules and fill tiny cracks. However, if the viscosity is too low, the healing agent will either be absorbed by the pores of the cementitious matrix or will seep out of the fracture and not remain inside it. The polymerization reaction should ideally occur without the need for human involvement. Furthermore, one crucial factor is how quickly the healing agent reacts. Inadequate time is given to the healing agent to fill the crack when it reacts too quickly. However, the reaction time should be minimal to stabilize the crack and stop it from widening. The released healing agent must accomplish this task to fill the cracks and prevent the entry of aggressive substances. As a result, expansion of the healing agent upon response is a desired attribute since it allows for the filling of wider cracks [31].

5.1 Bacteria

Researchers are investigating the potential of bacteria to function as a self-healing agent in concrete. Bacteria are found naturally almost everywhere on Earth, not just on the surface but also deep within, for example, in rock at depths of more than 1 km. Various species of extremophilic bacteria, or bacteria that survive in severe conditions, can be discovered in very dry environments such as deserts, inside rocks, and even ultrabasic environments ideal for the interior concrete environment. Previously published studies documented the use of bacteria to clean concrete surfaces and improve the strength of cement-sand mortar. Other investigations also investigated and reported the crack-healing capacity of mineral-precipitating bacteria on surfaces of cracked limestone and concrete [1]. This method utilizes bacteria to induce the precipitation of calcium carbonate ($CaCO_3$) produced by bacterial metabolism in an environment with high calcium levels. It should be possible for bacteria to find nutrients in the concrete environment. For the bacteria to survive the highly alkaline environment of cement and internal compressive pressure, the right bacteria type must be selected [47].

Using bacteria as a healing agent in concrete is known as Microbial concrete, Bioconcrete, or bio-mineralized concrete. In this particular technique, the utilization of a bacterial metabolic process, commonly referred to as Microbial Induced Calcium Carbonate Precipitation (MICP), has emerged as an alternative approach for crack healing and mitigating environmental impact. Although this technique has proven effective in reducing CO_2 emissions from the cement industry, the bacteria, specifically microorganisms Bacillus subtilis and Bacillus pasteurii, have a significant and productive role in healing concrete fractures. The $CaCO_3$ layer they produce can withstand a certain level of acid rain and effectively prevent corrosion of steel reinforcement, particularly in marine environments. However, it is essential to acknowledge several limitations, such as selecting suitable bacteria, which may require additional protective measures to accommodate specific environmental conditions, must be considered. Additionally, the survival time of bacteria within the cement matrix is restricted due to the presence of smaller pore diameters. Furthermore, an adverse effect on compressive strength has been observed in some trials. Moreover, the healing process in microbial concrete results in the release of ammonia and ammonium ions, thereby increasing nitrogen load and significant environmental concerns. It is also worth noting that increased pores within the matrix contribute to a decrease in the fluidity and strength of cement composites. Another consideration is the cost of Bioconcrete. The primary sources of expense are nourishment, bacterial preparation, and immobilizing chemicals. Consequently, extensive research is required to validate the positive outcomes of microbial concrete in an environmentally friendly and safe manner. In addition, it is necessary to examine the calcium carbonate adhesion deposited on the fracture surface, which is the most crucial factor in determining the efficiency of that technique [24, 48].

It is worth mentioning that the encapsulation technique is applied to bacteria as well. This technique encapsulates the spores of Bacillus pseudofirmus and Bacillus cohnii, calcium lactate, and yeast extract in porous expanded clay [49]. Visual observation of self-healing was made through the presence of calcium carbonate precipitates on the cracked surface [47]. Porous clay aggregates, or lightweight aggregates (LWA), serve as an internal moisture supply essential to enable bacterial precipitation action. However, various factors affect efficiency, including water content, aggregate spacing, and aggregate pore structure. The application of expanded clay encapsulation has a restriction. Using clay LWA instead of natural aggregates significantly decreases the mechanical strength of concrete. Most concrete contains aggregates, and its toughness significantly influences its compressive strength. After 28 days, a strength drop of up to 50% was observed, which is not ideal for structural applications. The bacterium spores came into touch with the air when the clay particles broke, which led to calcium precipitation through microbial action. After 100 days of submersion in tap water, the most comprehensive crack that could be fully healed was approximately 0.46 mm, and up to six months of activity had been noted [10]. Researchers have also explored polymeric microcapsules based on melamine to encapsulate Bacillus sphaericus spores. Calcium nitrate was used as a mineral precursor and added to the concrete as it was combined with other nutrients such as urea and yeast extract [24].

5.2 Super Absorbent Polymers (SAP)

Super absorbent polymers (SAP), commonly called hydrogels, have been studied in various research studies as a potential way to add more water to cementitious materials. Cross-linked polymers such as SAP can swell significantly after absorbing much liquid and build into an insoluble gel. When combined with fresh concrete, SAP particles show less swelling because their ability to swell enormously relies on the solution's ionic content and alkalinity. Once the cement has hydrated, the SAP releases the water it has absorbed, contracts, and leaves behind tiny pores. Cracks that form are likely to spread through the pores, allowing moisture to enter through the crack and causing the SAP to expand once more. If the external fluid has a low ionic content, the SAP will inflate more than it does in the concrete pore solution, spreading outside the pore into the crack and having a direct physical blocking effect. The release of SAP's water content during dry seasons encourages autogenous repair. Researchers have identified that the initial swelling of SAP particles during concrete mixing leads to the formation of pores and a subsequent reduction in strength. Subsequent studies have been conducted to address this limitation [9].

5.3 Mineral Admixtures (Alkali-Silica Solution)

Researchers have investigated mineral admixtures, such as alkali-silica solution, as potential healing agents for self-healing concrete. The study [6] tested diluted and undiluted alkali-silica solutions for this purpose. In the presence of oxygen, the alkali-silica solution induces hydration, which bonds the initial fracture faces together. Although the bond's strength is lower than that of glue, this is insignificant as long as it exceeds the tensile strength of the concrete matrix [1]. Another experiment used a sodium silicate solution encapsulated in polyurethane microcapsules embedded in the concrete matrix. The results have shown that it is a promising material for construction because of the recovery of flexural strength, enhanced toughness, and decreased corrosion [38]. Notably, researchers have encapsulated sodium silicate solution in 5 mm wax capsules for self-healing in a cementitious composite. This encapsulation demonstrated the recovery of mechanical properties, including flexural stiffness and strength, after damage induced by three-point bending tests [50].

5.4 Polymeric (Epoxy, Cyanoacrylate, Polyurethane, MMA)

As polymeric materials are commonly used for conventional manual crack injection, various polymeric healing agents have already been encapsulated and embedded in the concrete matrix to achieve self-healing capabilities. Most polymeric healing agents come in single-component or multicomponent systems comprising one or two parts. The single-component healing agent that polymerizes when in contact with moisture is more appropriate than the one that polymerizes by heat application. Multicomponent agents that harden upon contact with a second component can be used, but both components should be embedded in separate capsules. On the other hand, the reaction and the polymerized healing agent's properties need to be unaffected by the mix ratio and not thoroughly mixed together [31].

Encapsulated methyl methacrylate (MMA), a multicomponent healing agent, created self-healing concrete [2, 28, 29, 51]. As a single-component agent, silicone has also been used as a healing agent in self-healing concrete [52]. Cyanoacrylate (CA), or super glue, is a single-component agent in self-healing concrete. The primary restorative agent for concrete floors, bridge decks, and similar structures is low-viscosity epoxy resin. Epoxy resins are considered strong materials because of their exceptional resistance to heat, moisture, and light, which come in one- and two-part systems. While the heat activates a one-part epoxy to cure the substance, a hardener and resin component in a two-part system cures the material component [1]. Single- or multicomponent epoxy is already used as a healing agent inside self-healing concrete [31]. The chance of presenting both components simultaneously at a fracture location is too low, which is the fundamental issue with using two-part epoxy resins for the autonomic healing of concrete. The two components can be manually placed in adjacent capsules to get around this. Poor mechanical behavior was observed despite both capsules splitting and releasing their respective agents because the fluid blend was not well mixed [6]. Researchers have reported single- and multicomponent polyurethane encapsulation as a promising healing agent for the following reasons. The fundamental objective of self-healing concrete is to increase the durability of concrete structures, which necessitates effective crack filling and expansion of the encapsulated healing agent upon polymerization. Polyurethane is the only polymeric healing agent indicated above that expands following polymerization. Both single- and multicomponent polyurethane react when they come into touch with moisture, but the multicomponent polyurethane's response speeds up when it comes into contact with the second component. To facilitate the flow of the healing agent inside the crack, researchers utilized polyurethanes with a very low viscosity [31]. [9, 10] provides an exciting summary comparison of the healing agent materials commonly used in the literature.

6. Applications of Self-Healing Concrete

The World's first self-healing concrete building was constructed in the Netherlands using self-healing concrete with bacteria acting as self-healing agents (organic concrete). This pilot project is a lifeguard station by a lake developed by Delft University of Technology [53]. As reported, the same Delft research group recently executed two full-scale demonstrator projects with bacteria-based self-healing concrete. The first one concerned the construction of a wastewater purification tank consisting of precast concrete elements. The second full-scale, self-healing concrete demonstrator project included cast-in-situ rectangular concrete water reservoir. In addition, they reported the developed bacteria-based self-healing repair mortar, which was applied in two full-scale projects to demonstrate structural repair applicability and delivery of water tightness of cracked concrete basement walls, respectively [54]. In Belgium, bacterial self-healing concrete was recently used for the first time on a large scale in constructing a roof slab for an inspection pit that is currently functioning normally [55].

In the UK, the first site trial of self-healing concrete was a research project, Materials for Life (M4L), a collaboration between the Universities of Cardiff, Bath, and Cambridge to investigate the development of self-healing cementitious construction materials. The research project involved building five concrete panels in-situ, utilizing various self-healing techniques on the A465 Heads of the Valleys Highway upgrade project's construction site. Four self-healing strategies were applied, both singly and in combination. First, use microcapsules developed by the University of Cambridge in partnership with industry and contain mineral healing agents. Secondly, Bath University developed the use of bacteria as a healing method. Thirdly, Cardiff University developed the utilization of a shape memory polymer (SMP) for controlling crack closure. Fourthly, Cardiff University developed a vascular flow network to deliver the mineral healing agent [56]. In China, microbial self-healing concrete is utilized at the junction of the side wall and bottom plate of the sluice chamber in the Beijing-Hangzhou canal [57]. It is worth mentioning that self-healing concrete is not only limited to buildings, structures, and pavements, as some studies have explored the application of the self-healing concept in asphalt materials [58].

7. Conclusions and Future Recommendations

This paper reviews various techniques and technologies of autogenous and autonomous self-healing concrete. The autonomous self-healing concrete with encapsulation technique has recently attracted more attention for better healing locations and capabilities than autogenous self-healing concrete's uniform hydration. Also, such encapsulation techniques provide a suitable environment for healing agents during concrete mixing. Polymeric materials have shown great potential for use in both capsules and healing agents, although various materials have been utilized for encapsulation and healing agents. Regarding capsules, they can satisfy the conflicting demands of being flexible while mixing concrete and hardening into brittleness during the development of cracks. The viscosity of the healing agent should be sufficiently low to permit the flow out of the capsules and the filling of tiny cracks. However, if the viscosity is too low, the healing agent will either be absorbed by the pores of the concrete matrix or will seep out of the fracture and not remain inside it. Additionally, a few real projects have been mentioned to demonstrate the applications of self-healing concrete in the construction industry.

In order to facilitate the application of self-healing concrete in the construction industry, some future research works need to be explored. Concerning microbial concrete, the mechanical efficiency of that healing technique should undergo validation by examining the adhesion between the deposited calcium carbonate and the crack surface. The mix design should be optimized by determining the optimal bacterial concentration and nutrient medium. Concerning encapsulation techniques, design methods for manufacturing capsules and mixing them with other concrete ingredients still need to be developed. Cost analysis should be performed for all different healing techniques and compared with the traditional repairing techniques of concrete structures. Although, in general, much experimental research is conducted in the literature, there is a need for more development and execution of numerical and computational modeling to reduce computational costs without sacrificing accuracy.

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

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