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Methodologies and Behaviour of Self-Healing Phenomena in Cementitious Composites: A Review

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Abstract

Despite the extended lifespan of concrete structures under ideal circumstances, the service life is significantly reduced due to the cracks created by various loads. Unwanted crack treatments are effective only on the exterior side of the accessible concrete constructions. Therefore, there is a great need to incorporate a self-healing (S-H) mechanism within the concrete matrix. This review discusses a general trend in developing S-H concrete in the construction industry. It consists of two parts: Part I introduces an overview of S-H concrete by describing the basic concepts and available S-H techniques (agents/materials) and analyzing their applications, critiques, and performance in various published studies. Part II critically discusses the conceptual life cycle cost, the maturity level of S-H concrete, the commercial situation, potential applications, field behavior, and challenges to be addressed in future years. The most important outcome of this review is a deeper understanding of the self-healing phenomenon and its potential applications. It is shown that self-healing technologies can give concrete power to heal and prepare itself, which reduces the need for regular maintenance, substantial cost savings, and environmental protection.

Keywords: Crack Formation; Concrete Durability; Healing Agents; Maintenance; Self-Healing

1. Introduction

Concrete is an essential building material used extensively to build roads, buildings, and other types of infrastructure. The use of concrete in construction has several advantages. It is more flexible, less expensive, and resistant to fire and water damage, and it can be employed in various applications [1]. Concrete typically consists of water, binder, and gravel (coarse and fine aggregate). The cement and water will begin to react (under the hydration process) when all the elements are combined, joining together to form the hardened rock-like mass known as concrete [2],[3]. While concrete is extensively utilized in construction due to its cost-effectiveness and widespread availability, it is prone to developing cracks. When cracks emerge in concrete, its durability is compromised as chloride and water penetration occur, resulting in the corrosion of the reinforcement bars. In the typical composition of conventional concrete, the volume occupied by cement stone ranges from 10% to 30% [4],[5]. Within this cement stone is an un-hydrated component known as clinker stock, constituting 20-30% of the volume [6]. The quantity of clinker stock in concrete is influenced by the level of dispersion of Portland cement and the water-to-cement (w/c) ratio [7],[8]. Due to natural cracks in structures constructed with this type of concrete, water can infiltrate the material, initiating the hydration of Portland cement (clinker stock)[9]. The reaction produces products that can fill cracks and other defects, forming an S-H structure [10]. Concrete exhibiting self-healing properties can be termed as self-regenerating. Self-regeneration denotes the material's ability to repair cracks autonomously [11]. This is the same process in some natural materials, such as bones or trees [12]. The primary difficulty in utilizing technology based on the hydration potential of cement grains lies in accurately forecasting when the required quantity of water will be accessible to initiate the hydration process, generating reaction products adequate to halt the formation of defects such as cracks [13],[14].

The existing strategy for improving the durability of a structure predominantly centers on incorporating supplementary cementitious materials to establish a more effective barrier between the environment and the steel reinforcement [15]. The M4L (Materials for Life) research team suggests considering cementitious materials as an alternative to S-H technologies. However, there is insufficient evidence regarding the applications of these materials in the construction industry and their most effective use [16]. According to a market research study, highways and water retaining structures would benefit from S-H cementitious materials with reduced maintenance costs, which justify a premium on the material's cost over the lifetime of a structure. With fewer repairs and maintenance interventions, whole-life costs will be reduced. The economic, environmental, and social implications of repairs and maintenance events will be reduced. Concrete cracking can hurt the durability, but S-H properties can mitigate this potential loss of durability [17],[18]. So, the most direct consequence of S-H is the filling or closing of cracks to:

Making concrete structures more durable: Water is the most important fluid that can enter concrete and affect its durability because it carries aggressive ions and gases like oxygen and carbon dioxide [19]. Several approaches to S-Hare are intended to make concrete watertight. S-H agents create a better barrier between the environment and the steel reinforcement and make the material more durable [20]. Therefore, one must quantify precisely the extent of the recovery of properties and determine the effects on the performance and service life of those properties in the long term. Control the formation and propagation of cracks: When these cracks reach the reinforcement level, corrosion of the reinforcement will accelerate. So, the rate of the healing process becomes of utmost importance. Restore mechanical properties of materials: Mechanical properties may play a significant role in the crack opening control.

2. Overview of the Retrieved Data For S-H

Several articles have been published to evaluate the S-H capacities of different cement-based materials, and several reviews have been published since 1973. Alzard et al. [21] summarised and analyzed the S-H concrete papers from 1974 to 2021 to indicate the important study areas, development trends, and most productive research areas. Using bibliometric analysis software, 450 sources from Scopus were utilized to examine 1433 documents written by 2961 authors and published in the Scopus database. The findings indicate that only 46 documents were published between 1974 and 2006 and that from 2007 to 2021, there was a gradual increase in the number of publications, with an annual growth rate of 20.4%. This suggests that the field of S-H concrete is expanding and important for further study and development. Fig.1 shows the yearly scientific production between 1991 and 2021 in S-H concrete, depending on the database used in this review paper.

Numerous academic publications discuss self-healing (S-H) concrete, emphasizing engineering and material science courses. The research also spans several other fields, including physics, astronomy, environmental science, chemistry, and chemical engineering. Approximately 60.6% of the published materials are journal articles from these various fields, highlighting the interdisciplinary nature of S-H concrete research. This broad coverage underscores the need for expertise from multiple domains to fully understand and advance self-healing concrete's behavior, production, and performance. Fig. 2 shows the publications on various topical areas.

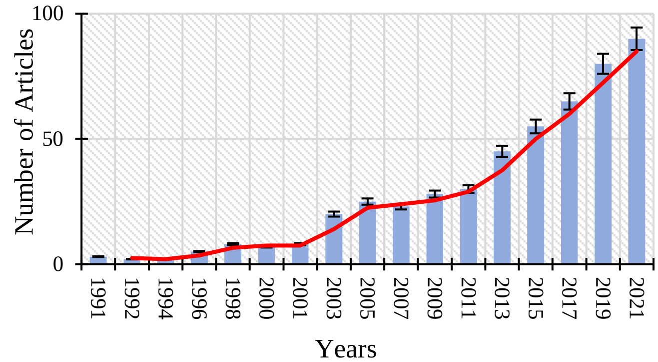

Figure 1. Published articles per year relating to concrete self-healing.

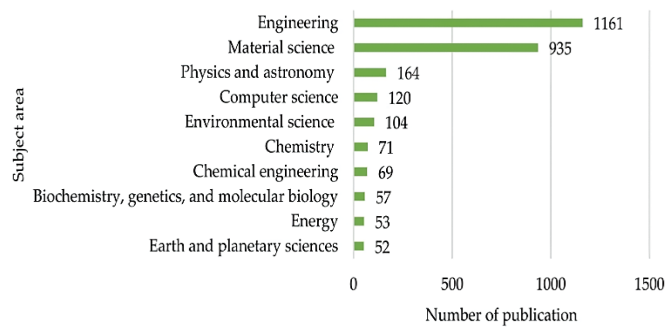

Figure 1. Trends in self-healing concrete research from 1974 to 2021, adapted from Alzard et al. [21] CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Due to the challenges and high costs associated with the routine inspection, repair, and maintenance of large-scale concrete structures, self-healing (S-H) methods are the most economically efficient approach for crack reduction (This will be explained in section 6.1). In identifying areas of development in the field, the main concern was locating and bringing together the most significant published research and determining prospects for future growth.

3. Review Papers Published in this Field

Various valuable review articles were published regarding this topic, which are mentioned in Table 1 below.

Numerous academic publications discuss self-healing (S-H) concrete, emphasizing engineering and material science courses. The research also spans several other fields, including physics, astronomy, environmental science, chemistry, and chemical engineering. Approximately 60.6% of the published materials are journal articles from these various fields, highlighting the interdisciplinary nature of S-H concrete research.

Table 1. The most important outcomes of articles were published between 2009 and 2023 in S-H concrete.

Topic	Autogenous healing	Autonomous healing				
		SAP	**CA**	**MgO**	**SiO_2**	**Cp., Bacteria and tubes**
Research outcomes (Gaps)	Limited healing: effective within the crack width up to 50–150 µm	Decrease compressive strength and workability of concrete due to a generation of voids.	No restoration for mechanical properties of concrete	Undesired expansions and stresses	Decrease compressive strength	• Protection of the healing agents within the concrete. • Activation time: the required moment for self-healing. • Decrease compressive strength • The damage can be repaired only once • In the case of vascular networks, they will be in predictable cracks and may be broken during casting.
Range of years	2009-2013	2014-2022				
Reference	Atay [22] Dinarvand and Rashno [23]	Snoeck et al. [24], Hong et al. [25], Sahmaran et al. [26], Dong et al. [27], Gruyaert et al. [28], Byoungsun and Young [29], Zhang et al. [30], Hossain [31], O. Speck and T. Speck [32], Cappellesso et al. [13], Althoey et al. [14]				
Citations	2511	794				

Note. *SAP= superabsorbent polymers, CA= Crystalline admixtures, MgO= Magnesium oxide, SiO2= silicon dioxide, Cp.= Microencapsulated (Sodium silicate), tubes= Vascular networks.*

This broad coverage underscores the need for expertise from multiple domains to fully understand and advance self-healing concrete's behavior, production, and performance. Fig. 2 shows the publications on various topical areas. Numerous academic publications discuss self-healing (S-H) concrete, emphasizing engineering and material science courses. The research also spans several other fields, including physics, astronomy, environmental science, chemistry, and chemical engineering. Approximately 60.6% of the published materials are journal articles from these various fields, highlighting the interdisciplinary nature of S-H concrete research. This broad coverage underscores the need for expertise from multiple domains to fully understand and advance self-healing concrete's behavior, production, and performance. Fig. 2 shows the publications on various topical areas.

This factor should be considered because the varied contents of these S-H materials will create varying degrees of S-H and varying losses in compressive strength. As a result, a compromise that is appropriate for each situation must be found. For bio-healing agents, the researchers in self-healing techniques claim that for conservators to accept and effectively apply biotechnological applications, they must be aware of the risks involved, particularly the long-term impacts of the bacteria being used and the medium supporting them. Extensive research has shown the significance of investigating the influence of medium composition on autochthonous bacterial development to avert any adverse secondary consequences. Studies should also focus on how nutrients and metabolic products are retained in the stone because these factors influence the microbes' ability to survive, proliferate, and build biofilms within the concrete. The challenge for the near future is to turn some of the encouraging findings in the bioremediation of building materials into wide practical applications. Table 1 shows the most critical outcomes of articles with top citations published between 2009 and 2022 in S-H concrete.

Consequently, this review critically evaluates the recent advancements in S-H concrete to provide the reader with a general framework for understanding autogenous and autonomous agents. It includes two parts: Part I briefly describes the main processes involved in these agents and the methods used in their evaluation. In addition, large-scale experiments were reviewed, which are necessary to understand whether the S-H systems can be viable. Part 2, a critical analysis of the reached levels of efficiency, follows, pointing out some weaknesses, doubts, and challenges to be addressed in the upcoming years. Fig. 3 shows the approach adopted by the current study to summarise the basic concept of various concrete healing techniques.

4. Basic Concept: Techniques of S-H Classification

The S-Hof concrete indicates a material's ability to regenerate by repairing inner and outer cracks through natural (autogenous) or external (autonomous) processes. The following sections review the processes involved in the S-H phenomenon.

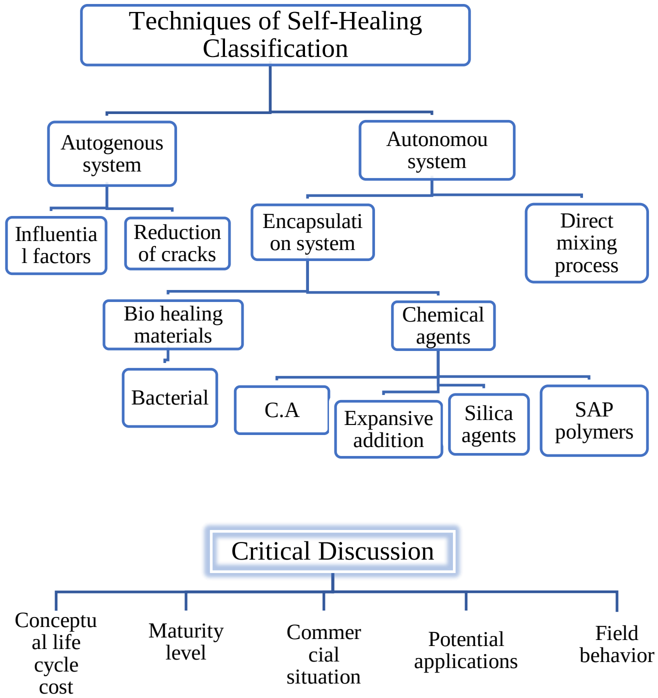

Figure 2. Outline of the current study (theoretical and analytical)

4.1. Autogenous Healing (Natural Phenomenon).

Concrete can seal fractures on its own through a process known as autogenous S-H, in which unhydrated particles react with moisture in the air to produce crystalline solids. The proportion of un-hydraunhydratedes in the concrete matrix determines the quantity of S-H products produced by the continuous hydration of cement. If the amount of these particles is usually small, this will reduce the reaction's effectiveness and the number of S-H materials that can be produced to completely seal the created cracks.

4.1.1. Mechanism of Autogenous Healing (Hydration Process).

In typical concrete, roughly 20–30% of the cement is still unhydrated. In cracking concrete, un-hydrated cement particles react with water. A hydration process is started again, producing hydration products to fill the fractures. In 2002, Dinarvand and Rashno [23] found that hydration of un-hydrated cement particles occurs mostly in early-age concrete. Calcium carbonate forms early on throughout the crack opening, preceding the fracture's healing and filling. S-H inherited processes are known as autogenous(natural) healing. The mechanism of autogenous healing is the production of calcium carbonate ($CaCO_3$) or calcium hydroxide Ca $(OH)_2$ through hydration of un-hydrated cementitious particles and Calcium-silicate hydrate (CSH) gel swelling or expansion. This process does not require any addition of specific agents to the matrix. (Fig. 4) shows a sketch of the mechanism of autogenous healing in cementation materials, and the chemical reaction process could be described as follows:

$$H_2O+CO_2 \Longleftrightarrow H_2CO_3 \Longleftrightarrow H^{+}+HCO_3^{-} \Longleftrightarrow 2H^{+}+CO_3^{-2} \quad ..(1)$$

$$Ca^{+2}+CO_3^{-2} \Longleftrightarrow CaCO_3 \quad ....(2)$$

$$Ca^{+2}+ HCO_3^{-} \Longleftrightarrow CaCO_3+ H^{+} \quad ....(3)$$

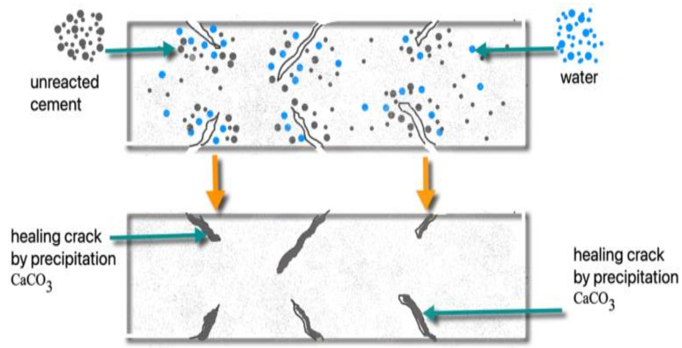

Figure 3. Mechanism of autogenous healing

Numerous studies have investigated the effectiveness of autogenous healing and the factors that affect it. Studies have shown that autogenous healing techniques are effective for small fractures (up to 0.06 mm) or, within one year, the healing of fractures up to 0.20 mm or 0.30 mm [24]. Under the autogenous technique, Hong et al. [25] were able to heal 200 µm-cracks in 1998. Also, an autogenous healing process can cure cracks up to 0.45 mm under CO2-water immersion for 90 days[26]

4.1.2. Improving Autogenous Healing (Reduction of Crack Width).

Crack width can be restricted to improve the S-H properties of concrete. Engineered Cementitious Composite (ECC) was first used by Dong et al. [27] to control fracture width. Polyvinyl alcohol (PVA) was subsequently used in a study by the same authors to obtain a 60 µm fracture healing width due to the high tensile strain capacity of the PVA, which ranges from 3 to 5% compared to concrete [28]. Polyethene (PE) was used as the matrix's mechanical reinforcement. With this additive, the average crack width was reduced by 50 µm. Accordingly, the following methods are analyzed to improve the autogenous healing process:

1. Use of the fibers: Overall, fibers reduce the crack size, maximum fracture width, and the number of cracks in a structure. Fiber type also affects the formation of precipitates inside cracks and crack control.

2. Supplementary cementitious materials (SCM_s) such as silica fume, fly ash, metakaolin, and blast furnace slag can promote autogenous healing in the later concrete stage. These materials are characterized by their high ductility and unique fracture pattern. ECC matrix has multiple cracks instead of a single crack with a large width, and the maximum crack width is less than 60 µm. They can enhance autogenous healing by taking advantage of un-hydrated

binders that have slower pozzolanic reactions (delayed hydration), dependent upon the remaining reaction capacity of the material upon cracking [29]-[31]. So, the autogenous healing process will be enhanced with cement mixes containing a higher proportion of cement and self-consolidating concrete (SCC).

Speck and Speck [32] mentioned that those fracture widths are not limited at the moment fractures develop but are unloaded at the moment. Researchers assessed the feasibility of shrinkable polymer tendons to post-tension cementitious materials at low levels. In this state, the cracks in these specimens were closed by heating them in an oven due to shrinkage of the embedded polyethylene terephthalate (PET) tendons.

4.2 Autonomic Healing (Artificial)

The autonomous concrete healing technique is an artificial process with external aid [33]. It's done when appropriate healing agents are added to concrete directly or in an encapsulated system that protects them until they are released to heal/block the fractures [34]. This section is divided into two parts: the first part illustrates the process of incorporating the agents in concrete, and the second part shows effective autonomic healing agents used in this technique.

4.2.1. The Approaches of Incorporating Agents

4.2.1.1. Direct Mixing Process

This system uses therapeutic (engineering) agents mixed directly into the cement matrix. Activation of the agent can occur through exposure to water or air within the fracture, the introduction of additional agents into the matrix, or even as a response to the cracking process. The agent's efficacy should remain inactive until its incorporation into a mixture without protective measures, ensuring its effectiveness is preserved. These materials act as water pockets like nano clays, superabsorbent polymers, and vegetal fibers [35]. In the event of a fracture forming in concrete, these substances absorb a significant quantity of water during the mixing phase and subsequently release it. This released water then reacts with unhydrated cement particles, precipitating calcium carbonate [36]. This system increases the speed of S-H when compared with the autogenous healing technique[37]. However, this method is impractical for some healing agents like bacteria because their life spans decrease if embedded directly in the cementitious matrix [38].

4.2.1.2. Encapsulation System

The most common method of delivering healing agents into the cementitious matrix is encapsulation. Various materials are accessible for manufacturing capsules and healing agents, resulting in different S-H efficiency levels. For the first time, the concept of a built-in capsule was introduced in 1994 by Dry [39], [40]. This author inserted methylmethacrylate into a hollow porous polypropylene fiber capsule as a healing agent; as a result, a higher degree of flexural strength was achieved by using this method. Van Tittelboom and De Belie [41] embedded short capsules in the concrete and attached extended capsules to the steel reinforcements. So, an essential requirement for an encapsulation system is enough mechanical resistance to hold out the internal forces in cementitious mixtures or concrete [42]. To be efficiently released inside the fracture, the capsule's healing agent must have low viscosity.

Additionally, the shell's size, diameter, thickness, and surface texture of the capsule influence the encapsulation healing process. Hong and Choi [43] manufactured microcapsules with three different shell thicknesses and an average size of 415.3 mm, and a simulated concrete solution was used to test the shell's resistance; it was found that with a lower shell thickness and a higher PH level, the release of the healing material increased. Two types of encapsulation systems are distinguished in Table 2. Typically, S-H caused by encapsulation can be classified into two broad categories: chemical agents and bacterial precipitation.

Table 1. Comparative between dispersed and predictable encapsulation systems

Sr. No.	Dispersed encapsulation	Predictable encapsulation (vascular system)
1.	Most will be micro-capsules with a diameter between 20-800 μm.	For located capsules, porous vessels with a diameter of up to 8 mm will be used, most of them made from ceramic or glass tubes with lengths of 10-100 mm.
2.	This method is suitable for dealing with unpredictable or dispersed cracking, as it adds to the concrete matrix.	Similar to the reinforcement bars, they should be placed in specific places in molds (before pouring the concrete) to allow predictable crack formation.
3.	Both methods require a physical breakage or an increase in porosity to be activated. In this case, the wall of the microcapsule must be strong enough to resist mechanical effects, weak enough to break when a fracture occurs, and also have a good bond with the concrete matrix.	
4.	For two groups, various types of healing agents can be filled.	

4.2.2 Comparative Analysis of S-H approaches

Table 3 compares the most important self-healing approaches, focusing on their efficacy, durability, and cost.

Table 2. Comparative Summary

S-H approaches
1. Microencapsulation
Efficacy: The cost is moderate. While the production process is relatively simple, incorporating microcapsules adds to the material's overall expense. **Durability**: The durability of the material hinges on the number of microcapsules embedded in it. Once these are exhausted, the material loses its self-healing capability. **Cost**: The cost is moderate. While the production process is relatively simple, incorporating microcapsules adds to the material's overall expense.
2. Vascular Networks
Efficacy: Extremely high, as these networks can continually supply healing agents to damaged areas, allowing for multiple healing events. **Durability**: The network's ability to repeatedly deliver healing agents means the material can withstand numerous damages as long as the network itself remains intact. **Cost**: The cost is high due to the complexity of designing and fabricating these intricate networks, requiring advanced manufacturing techniques.

4.3 Effective Autonomic Healing Agents

4.3.1 Chemical Additives Agents

This section has proposed a variety of healing agents. Some agents can be added without encapsulation. Similarly, certain agents require encapsulation for protection until they are needed to take action [44]. Therefore, the S-H phenomena in cement matrices have been developed using various encapsulating materials, such as polymers, lightweight aggregates, glass, ceramic tubes, etc. A polymeric capsule is a widely used encapsulating material that disperses polymeric material with oil in water in a solution [45]. Capsules can have a rougher surface using the prepolymer formed by the above reaction in the liquid phase. Thus, bonding with the cement matrix can be enhanced using the technique explained. Capsules can also be manufactured/processed (shell materials) using polyurethane/urea formaldehyde melamine-based materials, glass tubes, acrylic tubes (Perspex cast), etc[46]. These capsules contain various healing agents, such as sodium silicate and epoxy [47]; the S-H agents included in this category are crystalline admixtures, expansive, and silica-based agents.

Crystalline Admixtures (CA) are commercially available additives; crystalline admixtures (CA) produce non-soluble crystals promoting S-Hof fractures in concrete and cement products. Studies have demonstrated that CA may promote fracture closure and water tightness[48]. Moisture is important for adding chemical agents (crystalline additives) to concrete to encourage deposition and fill gaps. As a result, tricalcium silicate (C3S) interacts in the presence of moisture in the crack, forming calcium silicate hydrate (CSH) on the fracture walls to fill the fracture[49]. Occasionally, stiffness and bearing capacity recover as well. Studies found that mechanical properties were not recovered in some cases. These compounds are effective only when in direct contact with water and for cracks less than 0.30 mm wide.

Expansive Addition: Due to the expansive nature of some chemical compounds, several proposed expansive additives are in the literature, including calcium sulphoaluminate (CSA), magnesium oxide (MgO), calcium oxide (CaO), and calcium sulfate ($CaSO_4$). According to some researchers, CSA 10% by weight of binder obtained better visual closure for cracks of up to 0.3 mm in water permeation and S-H. Only minor improvements were detected in the mechanical properties [50].

Silica agents: CSH gels are generally formed by silicon-based agents, similar to the pozzolanic reaction. Sodium silicate (Na_2SiO_3) is the most commonly used S-H microencapsulated system, but colloidal silica ($mSiO_2.nH_2O$) has also been suggested. CSH or CASH are formed by complex reactions of sodium silicate with hydrated cement pastes and calcium hydroxide ($Ca(OH)_2$), calcium aluminate ($CaAl_2O_4$), followed by non-hydrated phases C_3S and C_2S. Most studies in which sodium silicate is used as an S-H agent use encapsulated products, so they react upon release from a microcapsule. It has demonstrated a beneficial influence on healing fractures measuring up to 0.20 mm, enhancing water impermeability, and improving mechanical recovery.

4.3.2 Bio-Healing Materials

Microorganisms aid in biologically healing S-H concrete when designing S-H concrete. Microorganisms are the best choice since they can grow in various environments, such as soil, acidic springs, and oil reservoirs. Four main types of microorganisms can be used to make self-healing concrete:

a. **Bacteria**: Certain bacteria, like *Bacillus* species, are the most commonly used microorganisms in self-healing concrete. These bacteria can survive in harsh conditions and remain dormant for long periods. When cracks form in the concrete and water seeps in, the bacteria wake up and start producing calcium carbonate, which fills in the cracks, effectively sealing them.

b. **Fungi**: Some fungi have also been explored for self-healing concrete. Fungi can grow in various environments and produce calcium carbonate as they grow. When used in concrete, they can help close up cracks over time. Although less studied than bacteria, fungi have potential due to their resilience and ability to spread through the material.

c. **Algae**: Algae can be used in self-healing concrete by producing calcium carbonate through photosynthesis. While algae are less common in this application, they could provide an environmentally friendly option since they use sunlight to produce the healing material. This method could benefit exposed concrete structures where sunlight is readily available.

d. Yeasts are another group of microorganisms that could be used in self-healing concrete. Similar to bacteria, certain yeast strains can produce minerals that help repair cracks. Although yeasts are not as widely used or researched as bacteria, they offer a promising alternative due to their ability to thrive in different conditions and their potential to be genetically modified to enhance their self-healing properties.

Bacteria with special strains are the most useful because they can precipitate a variety of chemicals essential to designing S-H concrete. It can be achieved in several ways, for instance, by incorporating microbial broth into freshly formed concrete, spore form, immovable form on silica gel, encapsulation, and using a vascular network. Because microorganisms cannot grow well in the concrete environment (PH level, moisture concentration, and temperature), spores are used instead of microbial broth. Although encapsulation is an effective method for rough concrete environments, this process is quite complex and costly. As another method of protection against inappropriate concrete conditions, the vascular network method expands microbial broth over cement matrix, but this method is complicated and constructible with today’s technology.

Table 4 summarizes the potential range of healing agent techniques used in concrete structures.

Table 4. Expected action of S-H agents in concrete

Healing approach	**Autogenous**	**Autonomous**					
						Bacteria	
Agents	Un-hydrate cement and supplementary cementation materials (SCMs)	SAP	CA	MgO	CSA	Urea. B.	Non-urea. B.
Potential extent of healing (mm)	Up to ≈0.15	Up to ≈0.2	Lower than ≈ 0.3	Up ≈0.5	≈ 0.3 to 0.4	Up ≈0.85to 0.97	Up to 0.45
Cracks Filling Methodology	Delayed hydration of these materials	Reacting with un-hydrated cement particles to produce CSH gel +CH + precipitation CaCO3	Produces non-soluble crystals after it reacts with humidity	Formation of CSH gels	S-H will enhance due to expansive properties	Utilize carbon source to produce: Co_2+Co_3^{-2} reacts with Ca^2 precipitate $CaCo_3$	Formation of $CaCO_3$ occurs in the presence of oxygen
Percentage of cement replacement (%)	10-25	0.3-0.6	1-1.5	1-0.8	5-10	$30*10^5$ cell/ml	$2.8*10^8$ cell/ml
References	[27], [41]	[42],[44]	[45],[47]	[48], [49]	[50], [51]	[38], [52]	

Note: SAP= superabsorbent polymers, CA= Crystalline admixtures, MgO= Magnesium oxide, CSA = calcium sulphoaluminate, Urea. B.=Ureolytic bacteria, Non-urea. B.= Non-ureolytic bacteria, SCMs= fly ash, silica fume, metakaolin.

4.4 Healing Agent Technology

4.4.1 Bacteria

The use of bacteria to repair concrete cracks and restore the strength and mechanical characteristics of the material has grown in popularity [51], [52]. The first investigation was by Jonkers et al. [53] in 2001; bacteria aided in concrete S-Hand increased compressive strength by 12% after 28 days. In contrast, Gosh et al. [54] found that the same method increased concrete mortar compressive strength by 25%. Several researchers found that if the concrete mix contains less than 1 mm of bacteria microspores, this reduces the life expectancy of the bacteria. As a result, scientists have developed different methods for delivering bacteria into the cementitious matrix before activating it. The Levasil sol-gel method (adding bacteria to silica sol in a salt solution) has been employed by Van Tittelboom et al. [55] for bacteria conservation; after this biological treatment, silica sol transformed into a silica gel to block the cracks. Also, the polyurethane technique was used by Wang et al. and Bang et al. [56], [57] to freeze (immobilize) bacteria. The same author, Wang et al. [58], utilized the microencapsulation technique to protect bacteria in one more experiment, and this method clarified the width of the fracture decreased over time (from 0 days to 21 days. Researchers have used a variety of bacteria to increase the strength and effectiveness of fracture healing. As identified by different studies, Table 5 shows the efficacy of various types of bacteria to improve healing strength.

4.4.2 Sodium Silicate ($Na_2\,SiO_3$)

The initial applications of sodium silicate involved using it as an alkaline activator to improve the strength and durability of cementitious materials. CSH or CASH gel is formed by complex reactions of sodium silicate with hydrated cement pastes (Eqs. (4) and (5)), capable of filling microcracks and ameliorating healing capacity [59].

$$Na_2O.SiO_2 + Ca(OH)_2 \Longleftrightarrow x(CaO.SiO_2).\,H_2O + Na_2O \quad ....(4)$$

$$x(CaO.SiO_2).\,H_2O + Na_2O + CO_2 \Longleftrightarrow CaCO_3 + SiO_2 + 2NaOH \quad ....(5)$$

Table 5. Improvement of the healing cracks strength in concrete through various types of bacteria

Name of the bacteria		Test Method	Strength Recovery	References
Ureolytic bacteria	Bacillus megaterium	C.S	24% recover	[59],[60]
	Bacillus Sphaericus		14.3% recover	[56],[57]
	Sprosarcina Pasteurii		22% recover	[53]
Non-ureolytic bacteria	Bacillus subtilis		12% recover	[52]
	Bacillus cohnii		10% recover	[55],[56]
	Bacillus Pseudofirmus		Decreases in CS	[54]
	Diaphorobacter Nitroreducens		Decreases in CS	[58]

Note: *Ureolytic bacteria survive in a highly alkaline medium such as concrete. *Non-ureolytic bacteria is a gram-positive bacterium that does not produce urease and can absorb Ca2+. * C.S =Compression Strength Test

Kanellopoulos et al. [60] recovered 17% of the load capacity, and fractures completely healed by placing sodium silicate in glass tube capsules in concrete beams. Huang et al. [61] injected sodium silicate materials into small sponges sealed with wax and mixed with engineered cementitious composites (ECCs); the capsules made up 5% of the sample volume, resulting in a 30% increase in load and stiffness. Gilford et al. [62] utilized a visual examination of fractured concrete made of concrete mixed with 1.0 % sodium silicate (pH=3.1) before and after a week of healing to evaluate the S-H mechanism of concrete. Also, there is considerable evidence that sodium silicate significantly improves healing and mechanical properties, as shown in Table 6.

Table 6. Improvement of the healing cracks strength in concrete through the use of Na2SiO3

	Method of use in concrete mixes	Examination Method	Efficacy in healing	References
Sodium Silicate (Na2SiO3)	Encapsulated	Three-point bending test (flexural strength)	17% Load recovery	[63]
	Micro-encapsulation		26% Flexural recovery	[59]
	Injected in small sponge and wax		30% Stiffness recovery	[61]

4.4.3. Magnesium oxide (MgO)

The volumetric alterations brought about by the carbonation and hydration of magnesium oxide inside the cementitious matrix (Eqs (6) and (7)) cause the cracks to mend and maybe narrow the gaps [63].

$$MgO+H_2O \longleftrightarrow Mg(OH)_2 \quad \text{.............................(6)}$$

$$Mg(OH)_2+CO_2+2H_2O \longleftrightarrow MgCO_3.3H_2O \quad \text{...............(7)}$$

Thus, MgO was incorporated into the concrete using different methods suggested by researchers. Quereshi and Al-Tabba [64] combined magnesium oxide powder with Portland cement and used bentonite clay (an absorbent clay) to use the clay's swelling properties. As a part of another experiment by the same author [65], different components of MgO (M92-N50) were mixed directly into concrete mixes in various ratios. In both MgO components, higher strength was noted with the low ratio of MgO due to the increased permeability. Cao and Al-Tabbaa [66] found that the percentage of crack closure increased with a higher ratio of MgO. Another incorporation method was developed by Qureshi et al. [67], the dual-walled capsule with magnesium oxide powder, which includes an inner and an outer tube of aspecific diameter. A high-humidity environment, as well as water immersion, were employed to cure the samples. Table 7 shows the efficiency of magnesium as a healing agent in concrete and its ability to improve compressive strength.

Table 7. Improvement of the healing fractures strength in concrete through the use of Magnesium Oxide (MgO)

	Method of use in concrete mixes	Examination Method	Efficacy in healing	Reference
MgO	Mixed with concrete	Three-point bending test (flexural strength)	5% improvement in compressive strength	[65]
	Encapsulated		12%load recovery	[63]
	Mixed with a kind of absorbent clay		6%load recovery	[64]

5. Essential Factors Influencing the S-H process

5.1 Age of the Concrete

For young concrete, the primary mechanism is the hydration of un_ hydrated cement particles in the presence of high moisture as it forms more CSH gel because it contains more unhydrated bonding particles. Atay [68] studied the potential for early-age cracks in cement-based materials to self-heal by introducing bacteria that can create carbonic anhydrase. To explore how cracking time affects healing ability, cement-based material specimens that were pre-cracked at ages 7, 14, 28, and 60 days were created. According to the experimental findings, bacteria had an exceptional ability to repair microscopic cracks created as early as 7 days, but S-H agents lost their power to mend cracks after 60 days. Additionally, because of the highly alkaline environment in cement-based materials, the survival rates of bacteria in the matrix decreased as the cracking age increased. $CaCO_3$ precipitation could not initiate when the number of active bacteria was very low. As specimens' cracking ages increased, the ratio of specimens that healed from cracks decreased noticeably. According to Li et al. [69], the effectiveness of the healing process changes over time. The sample's age affects how well it heals. For older concrete, the exposure to carbon dioxide (CO_2) generates a transformation of calcium hydroxide ($Ca(OH)_2$) into calcium carbonate ($CaCO_3$)[70].

5.2 Composition of the Concrete

a. Incorporating silicate: Concrete mixes containing silicate can influence pozzolanic reactions, the duration of the healing mechanism, and the consumption of Ca $(OH)_2$.

b. This factor affects the class of aggregate, the pattern of cracking, and the reaction to initiate healing.

c. The class of concrete is determined by the w/c ratio and the ease of the binder in forming a good amount of hydration-sensitive (CSH) gel based on the binder type and quantity used.

5.3 Size of the Crack

The effectiveness of self-healing is often dependent on the size of the crack, with natural or autogenous healing being more successful in the case of smaller cracks. According to Sahmaran et al. [71], a crack with a width of 5 to 300 m can be healed naturally. Regarding the magnitude of the crack in terms of either biological or microorganisms,¸ Tomczak et al. [72] discovered that when the average crack width was increased, the ability of microbial healing agents to patch up the fracture became more and more limited for specimens with crack widths up to 0.8 mm. Regarding crack widths between 0.1 and 1.0 mm, Huang and Ye [73] studied the ability of cracks in cement-based materials to integrate the bacteria to self-heal. The findings demonstrated that bacteria had a remarkable ability to mend microscopic cracks. Cracks smaller than 0.4 mm were virtually entirely sealed. Smaller cracks have a better chance of healing because less filling volume is needed to fill a smaller crack, and it will be simpler to grow from both sides of the crack's surfaces and links. It is generally true that cracks are more likely to heal completely the narrower they are [74].

5.4 The Presence of Water

A scanning electron microscope (SEM) analysis shows that when cracks in concrete are submerged in water, they regain strength due to the CSH formation.

5.5 Characteristics of Capsules (Dosage, Dimensions, and Dispersion)

Encapsulation, a component of the chemical S-H process, can produce greater quality S-H in terms of the wider range of crack width that can be mended and the quick reaction to the matrix cracking. Capsules are added to the concrete mix to improve the ability of broken concrete to mend on its own. To ensure optimal distribution of the capsules inside the concrete mix, it is crucial to add the appropriate amount. Therefore, choosing the proper dosage of S-H capsules is one of the most difficult aspects of designing the concrete mix. A higher dosage than necessary might harm the concrete's initial strength. On the other hand, providing less medication than necessary reduces the likelihood that a capsule may fracture and open. Van Breugel [75] investigated how the dosage of various-sized capsules related to the effectiveness of self-healing. The study has shown when the number of capsules grows, the S-H effectiveness also increases. The S-H effectiveness increases by 15% when the capsule dosage is 3.0% and is highest when the capsule size is 6.5 mm. Finally, it was determined that when the dosage of capsules is increased, the increase of good effects (the ability to induce self-healing) is more significant than that of negative effects (declining mechanical properties).

5.6 The Viscosity of the Healing Agent

The viscosity of the healing agent is a crucial factor. To ensure proper flow from the capsules and effective crack filling, avoiding excessively high viscosity is important. On the other hand, if the viscosity is too low, there's a risk of the agent escaping through the crack or being absorbed by the surrounding matrix and disappearing.

6. Critical Discussion on the Present Situation

The topic of S-H concrete is an area of continuous improvement. Numerous efforts have been made to recognize and improve concrete's autogenous properties and design new approaches to attain this quality through autonomous healing agents. Based on previous studies, an analysis would be essential to assess the suitability of the additional initial cost or accept future maintenance. In the following sections, the authors explain a critical discussion regarding the cost and performance of standard concrete (without ahealing agent) and S-H concrete; what is the maturity level of the S-H techniques in concrete? And the commercial status of S-H agents and their potential applications of them.

6.1 Theoretical life cycle cost of Self-healing concrete

More than 4.8 million kilometers of roads run through India, making it second of its largest road networks. Since all roads are subject to traffic load and weather conditions, these factors have caused road deterioration during the life span. Therefore, maintenance is fundamental to get the best performance out of a road structure during its design life. The government in India is increasingly focused on long-term road maintenance, where Rs 199,300 million has been spent on routine maintenance over the last financial years. The US spends approximately $5.2 billion annually on bridge maintenance.

Moreover, the American Society of Civil Engineers (ASCE) estimates that the nation's infrastructure needs to be repaired and maintained at $3.6 trillion over seven years under the specification of quality standards for 1998. Generally, around 50% of Europe's annual construction budget goes toward maintenance and repair. In China, it is estimated that the maintenance costs associated with the corrosion of reinforced concrete are approximately 250 billion Chinese yuan/per year. A crack healing technology could reduce maintenance and repair costs of concrete infrastructures by obtaining durable concrete and increasing its mechanical properties. Zhu et al. [77] evaluated concrete mixes with and without S-H properties to develop a conceptual analysis of the life cycle of concrete. In Fig. 5, solid line A shows that standard concrete requires regular repairs to maintain structural solidity until it demands reconstruction. In contrast, S-H concrete can make the structure more durable (dotted line B). Despite still being in a 'proof of concept phase, S-H concrete has been used in limited trials on actual structures, making an accurate life-cycle cost estimate difficult to calculate.

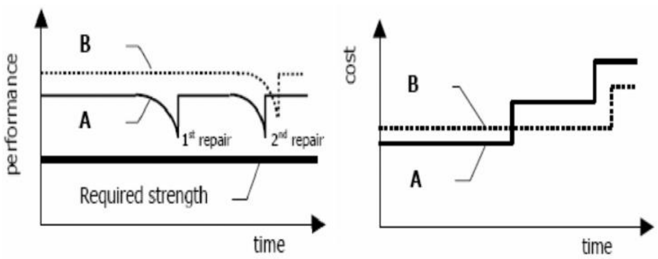

Figure 5. A comparative diagram of standard concrete is represented by line A, and S-H concrete is represented by line B [75].

6.2 Commercial constraints

Several factors affect the price of S-H agents, largely because the topic is still relatively new. Bacteria is one of the important S-H agents; based on the production process, the price of bacteria used to produce S-H concrete can range from (715 to 5760) € per cubic meter of concrete. Crystalline Admixture (CA): one of the commercially available additives, the price is between (50 to 100) € per cubic meter of concrete in the recommended dosage in the experimental work. Microcapsules made from self-synthesized urea-formaldehyde and epoxy resin cost about $15/kg in dry form. These numbers are anticipated to alter significantly over the next few years due to discoveries and advancements in the procedures used to produce S-H agents. Despite its effectiveness, S-H concrete mixtures still cost more than standard concrete, limiting their application in civil construction. According to Wang et al. [78], the construction costs increase from (7–28)% to (5–21)% when bacteria are deployed in polyurethane and silica gel. But, using S-H techniques, maintenance would be less frequent and less costly, and fewer structures would have to be inspected and repaired. Table 8 shows the estimated cost for some types of S-H agents.

Table 8. Estimated cost for some types of S-H agents

Healing agents	Estimated cost	Reference
Microcapsules (urea-formaldehyde as the shell and epoxy resin as the core.	$15/kg	[78]
Bacteria (According to the production process)	between (714 – 5760) € per m3 of concrete	[4]
Crystalline admixtures	varies between (50-100) € per m3 of concrete	[24]

6.3. Potential Applications

Several types of S-H techniques apply to various locations and structures' environments. Bio-healing materials, admixture, and autogenous S-H require water for healing, so they are best suited to underwater structures. S-H caused by an adhesive agent is not recommended for submerged structures because water prevents adhesive agents from entering cracks and causing them to harden. Additionally, all healing techniques can be used for underground structures; however, an adhesive agent will not be recommended if the water table is high. A wet/dry cycle is also present in underground structures, facilitating CO_2 precipitation into fractures and creating conditions that allow bacteria and autogenous S-H to be affected. In most cases, structures are built in the open air. Very little or no water is present in cracks; therefore, bacterial, admixture, and autogenous S-Hare are highly unlikely.

Considering the current state of development and cost analysis, S-H concrete can only be justified in high-demand applications (where safety is a significant concern) like underwater structures such as tunnels, hydroelectric dams, and nautical structures, underground structures with limited access to repair and maintenance such as raft foundations, other open-air structure that need ahigh level of strict safety, for example, bridges and retaining walls. Moreover, S-H can also benefit prefabricated elements by healing cracks produced during accelerated production and repairing cracks at identified locations. On the other hand, S-H concrete structures prefabricated in low humidity environments and small elements structures may not be justified. Table 9 shows if S-H can be justified or not for various elements of structural concrete.

Table 9. S-H can be justified √ or not *X for* various elements of structures

No	Structure environment	Justified or not for S-H	Type of S-H agents	Reference
1	Underwater structure: tunnels, hydroelectric dams, and nautical structures	√	Adhesive agent Bacteria Autogenous healing Admixture/except SAP (Decreasing in susceptibility of swelling)	[29],[40],[63]
2	Underground structures: foundations	√	Bacteria Autogenous healing Admixture	[5],[75]
3	Open-air structure: bridges and retaining walls	√	Adhesive agent Bacteria Autogenous healing Admixture	[70]
4	Low humidity environments	X	X	[30]

6.4 The need for more significant challenges (field behavior of self-healing concrete)

The Laboratory level is insufficient for the construction industry technology to prove the S-H concrete concept. Most of the data collected in the literature review related to performing S-H agents in amortar (cement/sand), not concrete mixtures. This difference is significant because the proportion of cementitious materials/S-H agents is higher in mortars than in concrete mixes. Therefore, the performance of S-H techniques in concrete should be studied at alarge-scale test (real field) to introduce it in the construction market. In Brazil, an S-H agent (CA) was used to build a football stadium's anti-floating slab (1200 m^3 of concrete). Based on the observation report of this case, there are no cracks in the hardened concrete of this slab, but no paper has been published about the effectiveness of S-H until now. In Ecuador, one of the first S-H concrete structures (a small water channel) was built in 2015 using lightweight aggregates that contained a biological healing agent as an integral part of the concrete. The dimensions of the channel were 1×1 mm with a thickness of 10 cm. There were no signs of cracking during the first five months after the casting. In 2016, bacterial S-H concrete was used in two projects: the construction of prefabricated parts for a wastewater purification tank and two walls for a water storage tank. Monitoring indicated that the repairs had been effective in the following two years. It is evident from these cases that most S-H systems are demonstrated by the absence of cracks, highlighting how difficult it may be for us to evaluate the performance of S-H systems in real constructions. The most significant reason for this difficulty is that a crack must be developed before evaluating S-H. Even though these pilot activities have shown promising results in adding information about the field behavior of S-H concrete, further research is required.

7. Conclusions

This paper provides a comprehensive overview of concrete self-healing (S-H) mechanisms, emphasizing both natural and enhanced healing processes. Ordinary concrete has a limited, inherent ability to heal due to unreacted cement particles that form limestone and calcium silicate hydrates when exposed to water and carbon dioxide. Incorporating additional materials can enhance durability and repair efficiency to accelerate this process. However, encapsulating healing agents presents challenges in balancing strength and flexibility, as capsules must remain inert and withstand mixing yet rupture upon cracking. Biological agents like bacteria show promise due to their ability to precipitate calcium carbonate. At the same time, polymers, including polyurethane, are effective in dynamic environments but face practical issues with shelf life and compatibility. Choosing the optimal S-H method requires consideration of damage type, environmental conditions, and budget. For instance, vascular networks offer repeated, long-term healing, making them ideal for high-durability applications. In contrast, microencapsulation is a more cost-effective option for less frequent damage.8. Recommendations for future work.

Several studies should be conducted to enhance the confidence of clients and manufacturers about S-H concrete instead of undergoing costly repair procedures. This technology's potential applications will likely expand in the coming years. But there are still some challenges to overcome. The main challenge is finding standardized assessment methods. There is a lack of consistency in the methods used to evaluate the S-H ability of concrete in the literature. The literature on self-healing (S-H) concrete identifies several key sections, each associated with specific challenges. In evaluating S-H ability, a significant challenge is the lack of quantitative data regarding the durability of crack healing across different concrete ages and insufficient information on the adhesive strength between the concrete and the material deposited in the cracks.

Additionally, the depth, speed, volume, and length of healed cracks need further investigation. When using bacteria as a healing agent, there is concern over potential harmful effects on both the environment and human health, which requires a thorough evaluation before implementation. Using S-H concrete in large-scale structures poses challenges in ensuring its durability across various environmental conditions, especially under operational circumstances.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Rasha Jasim Mohammed: Conceptualization, Idea, Investigation, Data curation, Formal analysis, Methodology, Visualization, Writing - original draft, Writing – review & editing.

Merool Vakil: Conceptualization, Supervision, Validation, Writing – review & editing.

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All the authors have read and agreed to the published version of the manuscript.

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