

Review

Low-Carbon Self-Healing Concrete: State-of-the-Art, Challenges and Opportunities

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Abstract: The sustainability of the construction industry is a priority in innovations made towards mitigating its notoriously high carbon emissions. Developments in low-carbon concrete technology are of peak interest today under the scrutiny of emerging policy pressures. Concrete is the external part of most structures vulnerable to permanent degradation and weathering, the possibility of an intrinsic restoration of its engineering properties promises unprecedented advancements towards structural resilience. Existing research in self-healing concrete (SHC) has often concerned the scope of material development and evaluation with inconclusive field testing, hindering its progress towards structural feasibility. This paper presents an overview of recent progress in SHC, and possible opportunities and challenges of popular healing systems are discussed. Moreover, trends are observed to investigate SHC's influence on the engineering properties of concrete, and future projections of SHC are suggested with identification of potential research needs.

Keywords: low-carbon concrete; sustainability; structural resilience; self-healing concrete application



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1. Introduction

As a primary engineering material, concrete contributes greatly to the impact of the construction industry on the global environment emitting approximately 8% of the global carbon dioxide emissions [1,2], a poor trend that may rise with growing populations. However, the urgency for green concrete is globally expanding as legal regulations intervene, placing a new challenge on existing means of concrete manufacturing and application. The United Nations Sustainable Development Goals [3] and independent regulations of individual countries have placed the industry under unprecedented scrutiny to control its carbon footprint.

In addressing some of the main influencing factors contributing to unsustainable practices such as the phenomenon of concrete cracking, the construction industry can expect promising lifecycles of various structures. Cracking creates an open path for the ingress of harmful substances into concrete structures, exposing steel reinforcement to the risk of corrosion and overall degradation of structural integrity. Similarly, the anticipated atmospheric deterioration due to climate change effects may also threaten the lifecycle and resilience of existing concrete structures. Consequently, increased concrete production becomes a requirement with maintenance and demolition of deteriorated structures, hence directly influencing the industry's carbon footprint. Within this context, costly maintenance is in demand; however, in addition to being uneconomical, some cracks and defects are hard to detect and reach in certain structures and/or ageing infrastructure. Current practices geared towards controlling concrete cracking and improving durability mainly constitute the use of supplementary cementitious materials (SCMs) and various admixtures, as well as the traditional approach of steel reinforcement. The SCMs adopted are often low-carbon industrial by-products or landfill waste such as ground granulated blast-furnace slag (GGBS), pulverised fuel ash (PFA), coal bottom ash (CBA), glass, ceramics, etc., where their use in concrete contributes to a circular economy. Most SCMs can enhance the Ordinary

Portland Cement (OPC) concrete properties such as reduced porosity, heat generation, and subsequent improved hydration, hence enhancing durability, quality, and overall practicality in versatile environments. A relatively novel approach to improving structural resilience is the enhancement of the concrete itself in preference to reinforcement reliance. This is achieved through enhancing the intrinsically regenerative nature of concrete with complimentary admixtures or through the inclusion of self-healing agents (SHA) and microorganisms capable of producing self-healing concrete (SHC).

The advantages of using SHC in structural engineering are represented by its evaluation methods involving the reset of mechanical properties, and degree of durability improvement following environmental exposure. Moreover, the sustainability of SHC is evident in its utilisation of abundantly available microorganisms or chemical agents, whereas, conventional treatments, such as applying chemicals, have several environmental and practical limitations. In reference to the advantages of using SHC shown in Figure 1, this paper presents a state-of-the-art review transcending the existing literature in its narrower scope of material development. Alternatively, recent progress in SHC is refined to inform of current and projected opportunities and challenges in relevance to specific structural applications in construction.

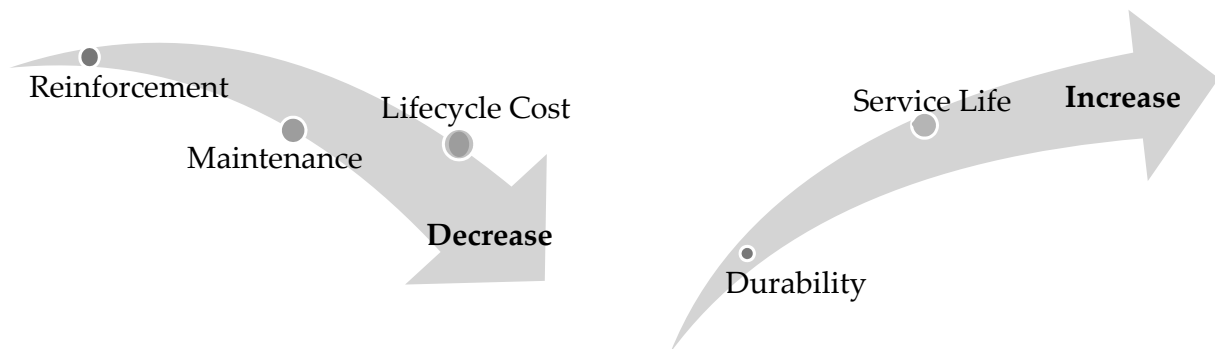


Figure 1. Advantages of self-healing concrete in construction.

2. Approaches of Self-Healing

Self-healing approaches may be categorised as either autogenous or autonomous, with prominent autonomous systems being the vascular network system and the encapsulation system [4]. The main distinction between autogenous and autonomous healing systems lies in the relationship to environmental conditions such that autogenous healing is limited to the triggering of the environmental exposure and hence poorly predictable, whereas autonomous healing has the potential of independent activation from within the concrete due to the autonomy of the embedded system.

2.1. Autogenous Self-Healing

Intrinsic or autogenous healing is a process where partial crack repair is achieved through the natural chemical processes associated with ageing concrete. For example, healing is mainly caused by further hydration of majorly unhydrated components in young concrete which reduce in content as concrete hardens and matures. Autogenous self-healing can occur in diverse infrastructures with versatile environmental conditions including underwater, underground, and cyclic wet–dry environments. However, the current literature agrees on autogenous healing limitation being governed by the width of the crack to be healed [5–7]. In practical applications of traditional concrete structures, it is unrealistic to have a controlled crack width; therefore, three prominent recommendations have been made towards improving autogenous self-healing functionality: incorporating mineral or expansive admixtures, using engineered cementitious composites (ECC), and by the modification of the following factors:

1. *Curing conditions:* Water curing is recommended to facilitate precipitation of healing products.

2. *Crack width*: Healable width mostly limited to 200 μm .
3. *Water–cement ratio*: Higher cement to water ratio has more unhydrated cement particles available for further hydration.
4. *Concrete age*: Where possible, it is better to induce cracking at early ages.
5. *Internal stress*: Prestressing at an early age to increase recovery of mechanical properties.

In precracked concrete beams, flexural strength recovery was seen in samples exposed to early compressive load [8]. In another study of concrete prisms, samples exposed to early compressive stress showed improved healing and mechanical properties recovery [9].

Ordinary concrete generally has a higher heat evolution, producing thermal expansion which triggers autogenous shrinkage and cracking [10]. This issue is typically addressed by using SCMs with low heat evolution, easing the application of mass pouring of concrete due to the controlled cracking. Some of the main durability parameters controlling concrete durability such as porosity and permeability are somewhat controlled with SCMs. In addition, long-term strength development is often found in employing SCMs due to a retarded hydration rate; however, the early-age strength may be compromised. Moreover, the sustainability of using mineral admixtures is well established; Tait and Cheung (2016) have demonstrated this in a study with three mixes utilising 100% cement, 65% PFA, and 70% of GGBS replacement where the SCM samples have shown the least environmental impact [11].

One of the most used expansive minerals in SHC is crystalline admixture (CA), defined by The European Standard 934-2 as water-resistant and by the ACI 212.3R-16 as a permeability reducer in concrete [12]. This disparity in definition hints at the issue of CA in research where a large variability exists due to nonunified and commercialised compositions. However, its suitability in SHC is made clear due to the admixture's ability to remain inactive until it has been triggered by moisture or water ingress. The controlled crack width requirement has been found to be achievable with the use of fibers or polymers producing an engineered cementitious composite (ECC) with improved durability and long-term ductility. This is accomplished as hydrophilic fibers can restrict crack width and serve as sites for healing product formation. The use of ECCs offsets the issues of concrete brittleness due to the ductility of the fibers or polymers which restrict fatigue cracking and concrete spalling, therefore reducing the risk of reinforcement corrosion. ECC concrete has specifically been a breakthrough for bridge construction, where shrinkable polymers with high ductility (bendability) can extend a deck's service life. Moreover, in using different autogenous healing systems, Table 1 summarises prominent reported recommendations and limitations consistently established in literature.

Table 1. Autogenous self-healing concrete recommendations and limitations.

Method	Recommendation	Limitation
Intrinsic	High cement content to increase amount of unhydrated cement for further hydration.	Healing mostly limited to early-age crack formation and hydration phases. Healing mostly limited to crack widths up to 200 μm [13].
Mineral admixture	Moderate SCM replacement by cement binder for sufficient availability of carbon hydroxide. Wet exposure.	Continued water exposure is required due to low permeability. Not repeatable to exhaustive mineral and cement supply and reactivity. Poor early-age mechanical properties due to delayed hydration.
Crystalline admixture	High cement content. Up to 4.5% by weight of cement. Wet exposure [14,15].	Slow healing pace [16]. Healing mostly limited to crack widths up to 300 μm [17].

2.2. Autonomous Self-Healing

Healing agents of various chemical compositions and various types of microorganisms can be used to compensate for the limitations of autogenous crack healing in concrete. In the autonomic self-healing system, these innovations are added into the concrete through encapsulation or the utilisation of an embedded vascular flow network. The direct addition of healing agents and bacteria is generally not recommended as the functionality is drastically compromised due to mixing agitation, hydration processes reducing calcium source and pore volume, which lowers the reactivity for healing product formation and damages the integrity of chemical agents or bacteria. In using encapsulation techniques or vascular networks, the healing agents are alternatively shielded against the highly aggressive environment of concrete and therefore secured against premature activation. The vascular network method is practically suitable for use in precast concrete elements [5]; however, novel 3D-printed mini-vascular networks are being explored for the increased flexibility of conveniently placing the printed mini-vascular network into concrete molds before casting [18]. This can address the specific area in which cracking is anticipated and ensure minimum spontaneity of healing action. Other promising technologies include the development of biomimetic concrete inspired by the natural defenses where vegetation and natural habitats can be hosted within a noninvasive unreinforced/reinforced concrete structure applicable to existing and new infrastructure with minimal energy consumption and resource quantum [18–24].

The efficiency of autonomous healing functionality remains dependent on adequate modification of concrete existing factors; therefore, a recommendation for biological healing systems is to incorporate a secondary component (i.e., bacteria food source, nutrients, etc.) which acts as a “controlled” trigger for the healing agents to activate without full reliance on external environment or human intervention. In biotechnological SHC, the most commonly used microorganism tends to be the genus of bacillus due to its ability of withstanding the harsh concrete environment [25]. Moreover, studies have found that a bacteria concentration of 10^5 colony-forming unit (cfu)/mL is recommended for improving concrete properties reporting enhanced mechanical properties and durability as well as strength recovery [26–30]. Another potentially viable yet less explored alternative to bacteria is fungi showing healing mechanisms comparable to the former microorganism [19–21]. In chemical systems of SHC, widely used healing agents involve silica-containing minerals [31]. The relevance of silica-containing minerals is also found in their use as alkali activators of cementitious materials in some alkali-activated concretes, potentially explaining their use in SHC through the precipitation of binding products alternatively filling cracks. Most reported recommendations and limitations of employing different autonomous healing systems are further detailed in Table 2.

Table 2. Autonomous self-healing concrete recommendations and limitations.

Method	Recommendation	Limitation
Encapsulation	Low microcapsule content and size to mimic aggregate bonding. Customable brittleness capsule (elastic when hydrated and brittle dried). Uniform dispersion of capsules for distributed healing. Placing capsules in molds during casting to avoid rupture during mixing [32].	Difficulty establishing upscaling techniques for industrial use.
Vascular flow	Homogenous distribution of vessels.	Impractical due to manual and strategic installation.

3. SHC Structural Engineering Performance

In evaluating the self-healing performance of concrete, mechanical strength recovery, durability improvement and microstructural analysis are of main interest following exposure to deterioration and cracking. In specific, the influence of different healing systems

on the engineering properties is substantial to support understanding the role of invoked healing processes in the development of mechanical and durability properties paramount to the structural engineering performance.

3.1. Mechanical Properties

A non-exhaustive summary of existing research is shown in Table 3, where figures are limited to the highest engineering performance of the respective study selected for conforming to Eurocodes, Canadian, American and Indian Standards. The selected studies are therefore repeatable and allow confirmatory corroboration for further reliability and mitigation of testing disparity in SHC. Generally, a trend is observed where the mechanical properties of concrete are improved in utilising healing systems.

Table 3. The influence of various SHC systems on engineering mechanical properties.

Healing System	Concrete	Nutrient	Curing	Mechanical Properties			Ref.
				7 Days	28 Days	56 Days	
				Compressive Strength	Split Tensile Strength	Flexural Strength	
Crystalline admixture (0.8% wt. cement)	CEM II 32.5N	-	Water	↑ 18%	-	-	[33]
Crystalline admixture (0.8% wt. cement)	CEM II 42.5 R	-	Water	↑ 12%	-	-	[34]
1% wt. cement 500 µm Arabic shell of liquid sodium silicate	OPC	-	Water	-	-	-	[35]
1% wt. cement 130 µm poly-urea of solid sodium silicate				↓ 4%			
				↓ 9%			
B. Subtilis (10 ⁵ cells/mL wt.)	OPC-43	Veg broth	Water	↑ 32%	↑ 14%	↑ 29%	[28]
B. Subtilis (10 ⁵ µBC)	OPC	0.5% calcium lactate	Water	↑ 19%	-	-	[29]
				↑ 24%	↑ 25%	-	
				↑ 32%	↑ 26%	-	
B. Subtilis (10 ⁵ µBC)	OPC and basalt fiber	0.5% calcium lactate	Water	↑ 18%	-	-	[30]
				↑ 17%	↑ 16%	-	
				↑ 15%	↑ 17%	-	
Sporosarcina pasteurii (10 ⁷ µBC)	OPC	calcium nitrate-urea	Water	↑ 44%	↑ 36%	-	[36]

Note: Denoted ↑—increase, and ↓—decrease. A single figure is representative of the 28 days result.

In using crystalline admixtures, the sealing functionality is stimulated at an accelerated rate in comparison to ordinary concrete such that a study has found sealing efficiency of SHC between 1 and 3 months to be comparable to ordinary concrete's capacity after 3–6 months [37]. An agreeing experiment testing the self-healing functionality of crystalline admixtures in concrete has shown poor compressive strength development in contrast with ordinary concrete [38]; however, the SHC rate of strength recovery was superior. It is recommended that cracking is induced during early ages to attain the advantages of autogenous healing prominent at younger ages. In some cases, it was found that the precracking induced at 7 days has resulted in 10% higher strength recovery and crack closure in contrast to 28 days cracking; however, the former has had larger crack widths which accumulated chloride ions. This recommendation may be explained by the premature flexural properties' development of younger concrete, and therefore minimal control of crack, whereas mature concrete possesses greater control of cracking width and extent.

In using chemical SHC systems, Giannaros et al. [35] have reported superior 28 days compressive strengths of the SHC samples in comparison to the control; however, at 56 days, the control samples had comparatively improved. A possible explanation for this may be that there was capsule rupture causing an accelerated early hydration which enhanced strength development up to 28 days; this is also seen in field case studies [39]. The flexural strength of the smaller capsules exceeded the values of the larger capsules; this may be due to microstructural integrity. However, from a structural view, this may be compared to standard steel reinforcement where reduced reinforcement (reduced capsule size) contributes to the favourable ductile failure, and increased reinforcement (larger capsule size) may compromise flexural properties. Moreover, there was no correlation between the crack widths reported and the mechanical performance such that the smaller capsule SHC had smaller crack widths with low compressive strength values, whereas the larger capsules had larger cracks and showed higher compressive strength values.

The typically autogenous approach of using basalt fibres has proven to be an efficient healing system with enhanced compressive strength and flexural strength when combined with bacteria [30]. Moreover, engineering properties have been reported to have been recovered to a high degree following the application of 60% of load-bearing capacity at 28 days. The combined action of fibres restricting crack width and bacteria filling the cracks may sufficiently address unwarranted healing activation.

In a study of bacterial RC beams incorporating a microbial-induced carbonate precipitation healing system [36], the deflection of the SHC beams was reported to increase progressively with increasing crack widths; however, higher loads were sustained. Moreover, assessed recovery of the flexural strength of the SHC was found to be 73%, whereas OPC concrete has shown a decrease of 41%. Hence, the study has concluded that improved flexural stiffness and load-bearing capacity may be achieved with bacterial RC beams. This may be attributed to the general increase of compressive strength reported in bacterial concrete, which has improved ductility. The latter response characteristic can be useful for the application of SHC in structures exposed to extreme natural and/or man-made hazards, e.g., earthquakes, floods, strong winds, explosions, and impacts. The study recommends for bacterial SHC to include the incorporation of a nutrient source and the introduction of cracking at an early age of 7 days for optimal tensile strength recovery; this is also applicable in using autogenous SHC incorporating crystalline admixtures [33].

3.2. Durability Properties

The durability of SHC is mainly assessed by the improvement of durability following exposure to degradation. Improvements in transport properties (i.e., permeability, sorptivity, and diffusivity), resistance to corrosion and chemical attacks, etc., are of interest when investigating durability properties in SHC.

In investigating the corrosion resistance of bacterial RC beams and cylinders [36], a 90% reduction in corrosion probability is reported; this is possibly linked to the increased watertightness. The decreased water absorption rate in bacterial SHC has been relatively consistent in research compared to OPC concrete [40–45], hence lower porosity is often found in microstructural analysis [28]. In using crystalline admixtures, its nature as water-resistant and permeability-reducing [12] hints at an ability to sustain a lower water absorption rate; this has been established in various experiments with different components of the admixture [18,19,33–35]. However, in the use of crystalline admixtures, there is a lack of comparability in research [16,17] due to nonlinearity in admixture composition and testing methods [12,16], this hinders understanding its feasibility in relation to comparably well-documented performance of bacterial SHC.

In practical applications, SHC may be an attractive technology for seismically risky locations where the smallest of impact loads present a risk of cracking in concrete; this is especially true due to the shared parametric interests regarding repeatability of self-healing under cyclic loading (i.e., earthquake dynamic loads). In a study testing the dynamic behaviour of SHC utilising microencapsulated epoxy-resin subjected to impact

loading [46], the SHC was shown to have an enhanced energy absorption capacity and a dynamic strength increase parallel to the increasing strain rate. The ability of SHC to have an improved self-healing functionality in exposure to water also suggests that it may be appropriate for humid, rainy, seaside, breakwater, and underground foundation applications. This is especially useful in the face of rising sea levels, where the current and upcoming approaches of employing sea defenses or managed realignment strategies may benefit from SHC for its tendency to thrive in such conditions.

Conclusively, two factors are identified to interfere with crack healing in SHC: increase in hydration that decreases porosity and subsequently restricted the healing system's transportation, and the likely subsequent increase in crack age, likely due to a decreased number of viable bacteria remaining after consequent pore filling. Hence, it may be feasible to employ mineral admixtures (SCMs) for their contribution to delayed hydration to counteract the high initial hydration interference. The six robustness criteria established to predict self-healing functionality may be explored further to aid in the selection of an appropriate concrete approach for specific structural applications [47]. Preliminary aspects must be addressed to achieve maximum compatibility of SHC with a specific structural application such as: width and dynamic of anticipated cracking, probability and extent of water exposure, and most importantly to tailor the mix for the specified application, it may be useful to detail the desired SHC properties and possibly categorise targets by priority according to subjected environment (i.e., recovery of mechanical properties, liquid tightness, limiting crack width, etc.).

4. SHC Market Feasibility

The experimental progress of self-healing concrete is an emergent domain that lacks in field applications where practical testing illustrates realistic structural feasibility. Government support for development of SHC was seen in major European projects such as RM4L [48] and HEALCON [49]. However, the lack of industrial collaboration in the theoretical progress of SHC research may reduce SHC prospects and the pace of adoption in real-life applications. Another barrier to the market adoption and upscale of SHC lies in the short duration of experimental testing. The current approach towards commercialisation and long-term performance prediction makes use of computer modelling to carry out lifecycle assessments and material optimisation based on simulated output, as depicted in Figure 2. This approach conforms to the standard of design by testing and reduces the high costs associated with producing and testing SHC in field applications given its currently limited understanding.

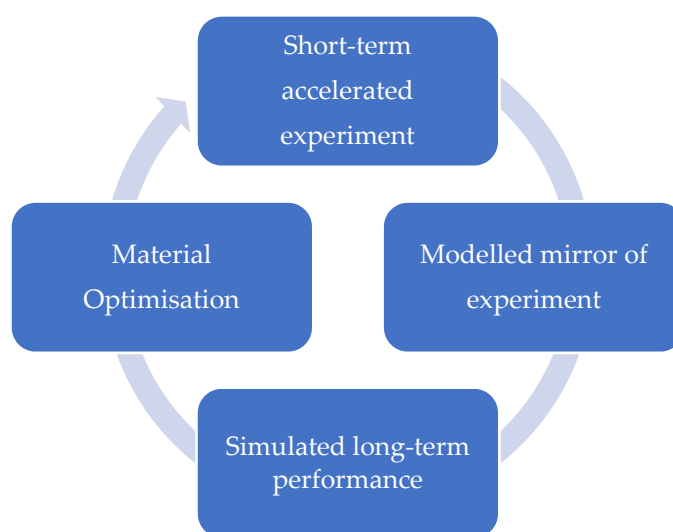


Figure 2. Current self-healing concrete testing and development process.

It may be deduced that a shortcoming in SHC progress towards commercialisation lies in the restrictions associated with short- to medium-term experimental testing compensated with accelerated tests. In addition, the persuasion of industry interest may also be hindered due to a lack of consistent testing methods and inconclusive field tests that poorly correlate with laboratory results, as shown in Table 4.

Table 4. Autonomous self-healing concrete in field applications.

SHC	Test	Laboratory Specimen	Field Application	Findings Laboratory Field	Ref.
Direct addition of Mixed Ureolytic Culture and anaerobic granular bacteria in CEM III/B 42.5 N	Capillary water absorption Water permeability	RC prism	RC roof slab	Wet–dry cycles ideal for visual crack closure. Negligible water absorption. Regain of liquid tightness. Roof slab developed condensation drops deemed favourable for self-healing activity. No cracking was observed; hence not tested. Direct addition not recommended due to further mixing requirement producing increased air content.	[50]
Lightweight aggregate containing alkali-resistant bacterial healing agent and natural fibers	Flexural strength testing Compressive strength	-	Linings for irrigation canals	15.4% compressive strength increase in SHC sample. Crack sealing after 6 months of cracking and curing. No cracking observed; hence not tested.	[51]
Microcapsule-based epoxy resin with OPC, GGBS, FA, and expansive agent	Laboratory: Compressive strength Rapid chloride migration test Field: Strain monitoring sensor	Cube	Precast concrete slab embedded structure for tunnel application	Microcapsules reduced density and uniformity of concrete, reducing compressive strength. Loss of 20% in compressive strength after crack healing. Improved impermeability. No significant fluctuations in monitored strain.	[52]
FA, GGBS, CEM I 42.5 Laboratory: Powder-based healing agent Field: Capsule-based microbial concrete	Laboratory: Workability Compressive strength Field Strain and temperature monitoring Ultrasonic testing	-	Underground metro structure	Negligible workability influence Decreased density in microbial concrete. Slightly lower compressive strength than normal concrete at 28 d. Improved impermeability after crack repair. Equivalent self-healing of cracks was observed in both normal and microbial SHC. Large strain measured on one wall caused 2 vertical cracks. The cracks were sealed after 41 d and 60 d; however, large amounts of healing product seemed to leak externally. Increased temperature monitored in early ages, likely indicating accelerated hydration, possibly due to capsule rupture. Waveform distorted with cracking and regained uniformity upon healing. Three cracks appeared and the best healing methods reported in order included: (1) Wet burlap with nutrients (2) Wet burlap with water (3) Water spraying	[39]
RC with epoxy-coated 10% wt. microencapsulated tung oil	Accelerated corrosion test Pullout test Compressive strength	Reinforced mortar cylinder Mortar cylinder Mortar cube	-	83% of SHC samples were free of corrosion. Bond stress comparable to conventional concrete with sustained integrity of interfacial bonding. SHC compressive strength was higher than standard concrete.	[53]

Field studies where SHC was used on a newly built structure have all shown no signs of cracking, which has disallowed the evaluation of self-healing performance on a real-life scale. However, valuable output can be observed regarding the feasibility of mass production of SHC for newly built structural applications. In contrast with self-healing application in new structures, mostly successful applications are reported in using SHC as a repair agent on existing structures and infrastructure with crack width closure and permeability reduction. This presents an opportunity for the use of SHC to non-invasively regenerate historical structures. The application of the SHC roof slab [50] was reported to have imposed a requirement for extending the mixing time on site, which presented the issue of an increased air content, concluding with a suggestion to avoid the direct addition of healing systems into an industrial concrete mixer.

In another application for an underground structure [39], noticeable crack formation was found within 7 days after pouring the SHC, the cracks were healed by continued wetting; however, the healing product formed was seen leaking externally, a possible indication of inadequate control of the extent of warranted healing response. This issue is especially crucial for structural applications such that self-healing system incorporation costs more than traditional concrete and, therefore, wasted product has serious economic and durability implications. Arguably, leaking product may be due to a nonuniform or inconsistent dispersion of capsules within the concrete matrix. This occurrence perhaps reveals the relevance of studying the efficiency of the extent of response of self-healing upon stimulation. Conclusively, the rapid crack formation seen in this project is concerning and may indicate that the fresh properties of SHC require further scrutiny. This is supported by the appearance of fluctuations at the early-age temperature and strain monitoring, which was translated as accelerated hydration, possibly due to potential breakage of microcapsules. Early microcapsule breakage is a common phenomenon; however, the researchers have used capsules protected with low-alkali cement. Therefore, it is worth noting that the standard procedures of concrete mixing and pouring may have contributed to the inefficient self-healing functionality.

An irrevocable appeal of SHC is the noted reduction in carbon emissions. This is portrayed by the use of SCMs in most SHC systems where utilised cement and reinforcement are simultaneously reduced. However, it is challenging to quantify the estimated emission reduction in SHC due to the wide range of composition, production and testing variability. Nonetheless, several lifecycle assessments (LCA) have been conducted on varying SHC systems, and Figure 3 shows a comparative illustration of environmental impact improvements found in using SHC in respect to traditional OPC concrete. The LCA studies shown depict the ideal minimum percentage contribution reported for a given SHC system to the environmental impact in relevance to traditional concrete in the majority of categories. For simplification of analysis, Figure 3 is limited to the reportedly optimal SHC system and notes the traditional concrete system as OPC with no reiteration of its concrete composition and tested environmental condition.

It is worth noting that the initial environmental and economical impacts of using SHC systems may be higher due to associated cradle-to-gate processes; therefore, some assessments conclude with urging that the repair costs may be relatively diminished in efficient SHC structures, offsetting initial costs with an overall improved lifecycle. Noticeably, a shortcoming was found in LCA studies of SHC regarding bacterial concrete, where most literature scopes have involved the self-healing ECC systems.

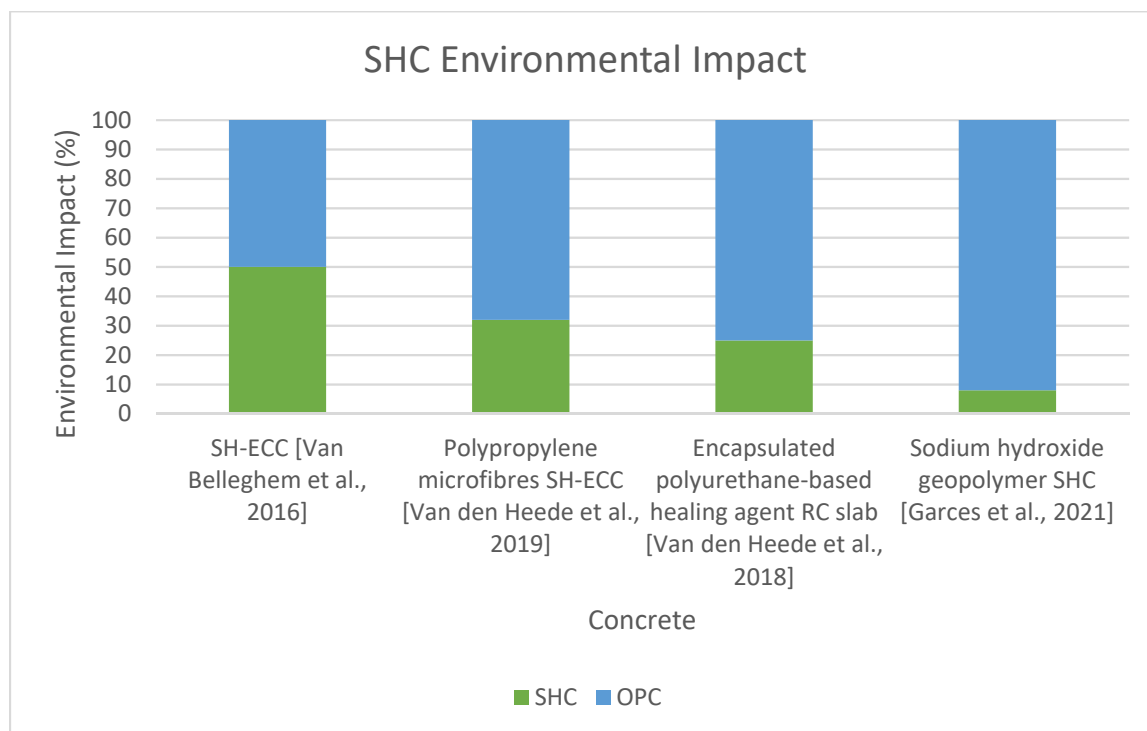


Figure 3. Lifecycle assessment studies of various SHC systems. (Adapted from Refs. [54–57]).

5. Future Perspective

The outlook of SHC is likely to witness an upward trend in field experimentation and industry collaboration such that self-healing concrete acknowledges the UN Sustainable Development Goals, namely: Goal 9 of Industry Innovation, and Infrastructure, 11 of Sustainable Cities and Communities, 12 of Responsible Consumption and Production, and 13 of Climate Action. Initiatives such as The Higher Education Sustainability Initiative (HESI) commends the important role of universities in driving the change towards sustainable development, and several universities have implemented individually scheduled targets of SDGs.

In comparing the two approaches, autogenous self-healing mechanisms seem more practical due to minimal practical requirements, whereas the autonomous mechanisms of encapsulation or vascular networks require strategic approaching. In autogenous healing, the commercialised state of various crystalline admixtures has presented literature disparity and experimental nonlinearity affecting its practicality and research reliability with respect to other healing systems. Aside from the long-term hydration seen in some SCMs, autogenous healing tends to be finite in comparison to the means of protection of chemical healing agents and long-lasting bacteria found in autonomous healing. However, in autonomous biotechnology, the embedding of the healing system within capsules or vascular networks is not sufficient to control the risk of spontaneous triggering of self-healing and possible requirement of water exposure and/or manmade intervention. Counteractive to this challenge, a secondary component may be added in the concrete to act as a systematic trigger in activating healing upon cracking. The flexibility implied by this possibility transcends the limitations of autogenous approaches where there is a restricted healable crack width and no degree of control towards healing activation save the influence of the external environment. However, increased costs are associated with employing nutrients; therefore, this technique must be evaluated against the alternative SHC reliant on external conditions to evaluate practical and economic feasibility. Arguably, it may be more practical to designate the use of secondary components in SHC to specific applications where exists a lack of ideal environmental conditions (i.e., dry locations with no water/humidity) to trigger healing with no external reliance. Alternative and perhaps less costly approaches towards

controlled healing may be through the use of a combination of crack-limiting ECCs typically employed in autogenous systems with healing agents or bacteria due to proven promising engineering properties. Moreover, for increased optionality of self-healing systems, the use of fungus has displayed promising performance that warrants further exploration.

In advancing the commercialisation of SHC, future research must aim to address reported shortcomings and exploit opportunities. Practically, field studies have proven poor survivability of encapsulated systems in standard concrete mixers; hence, it may be useful to study the feasibility of using standard concrete transport and production practices on encapsulated SHC structural components. The vascular network technique promises increased resilience in practical use through underway research involving 3D printing; however, high expenses may be associated with such sophisticated technology. As a deducible from research regarding structural application of SHC, it is necessary for the anticipated damage mechanism to be prespecified in order to design an appropriate self-healing system warranting the desired structural resilience. Similarly, relevant cost analysis studies must be undertaken to understand the economical aspect of integrating different SHC technologies in relation to the intended structural application. Relevant LCA of bacterial concrete are scarce in existing literature and require further attention, such that the focus was seen mostly on chemical healing agents. An appropriate direction for research in SHC may regard the behaviour of structural components exposed to natural environments with emphasis on non-destructive testing methods that may address the gap of inconclusive field case studies to be a reliable prototype for industrial adoption. Overall, future investigations of SHC must aim to utilise less variability in testing methods to work towards standardising SHC production and testing procedures discernible to the industry. Ultimately, SHC is a multidisciplinary endeavour ranging from microbiology to structural engineering; hence, standardising SHC procedures for real-life practices will require widescale technological convergence and profound cooperation.

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