RECENT ADVANCES IN SELF-HEALING CONCRETE FOR SUSTAINABLE CONSTRUCTION SECTOR

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Abstract: Innovations designed to reduce the construction sector's infamously large carbon emissions prioritise the sustainability of the sector. Low-carbon concrete technology advancements are currently of utmost importance due to mounting political pressure. The majority of structures' exteriors are made of concrete, which makes it susceptible to weathering and persistent deterioration. If its engineering features could be restored intrinsically, structural resilience would see extraordinary breakthroughs. The advancement of self-healing concrete (SHC) research towards structural viability has frequently been hampered by the breadth of material development and assessment with contradictory field testing. This essay provides a summary of current developments in SHC and discusses the potential and drawbacks of well-known therapeutic approaches. Additionally, patterns are seen to look at how SHC affects engineering qualities.

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

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.

With over 8% of the world's carbon dioxide emissions coming from concrete, a key engineering material, the building sector has a negative effect on the environment that may get worse as population increases. The need for green concrete is growing, nevertheless, as legislative restrictions impose increasing restrictions on the ways that concrete is currently produced and used. The sector is now subject to unprecedented scrutiny to reduce its carbon impact as a result of the United Nations Sustainable Development Goals [3] and separate legislation of various nations. The building industry may anticipate potential lifecycles of various structures by addressing some of the major influencing variables contributing to unsustainable practises, such as the occurrence of concrete cracking. By opening up a pathway for dangerous chemicals to enter concrete buildings, cracking exposes steel reinforcement to the risk of corrosion and a general loss of structural integrity. Similar to this, the lifetime and durability of existing concrete structures may be threatened by the projected atmospheric degradation brought on by climate change impacts. Therefore, with repair and removal of deteriorating structures, greater concrete production becomes necessary, thereby affecting the carbon footprint of the sector. In this situation, expensive maintenance is required; However, some fractures and faults in some structures and/or outdated infrastructure are difficult to find and access in addition to being uneconomical. Use of supplemental cementitious materials (SCMs), different admixtures, and the time-honored method of steel reinforcing are the key practises being used to reduce concrete cracking and increase durability. When SCMs are used, they are frequently low-carbon industrial waste byproducts or landfill debris, such as ground granulated blast-furnace slag (GGBS), pulverised fuel ash (PFA), coal bottom ash (CBA), glass, and ceramics, whose usage in concrete promotes a circular economy. The majority of SCMs may improve the qualities of Ordinary Portland Cement (OPC) concrete, such as reduced porosity, heat production, and subsequently enhanced hydration, increasing durability, quality, and general usefulness in a variety of situations.

The assessment techniques used by SHC in structural engineering, which involve the reset of mechanical properties and degree of durability improvement after environmental exposure, illustrate the benefits of adopting SHC. Furthermore, the sustainability of SHC is demonstrated by the use of chemical or microbes that are widely accessible, as opposed to conventional therapies such applying chemicals that have a number of practical and environmental drawbacks. This work offers a state-of-the-art review that transcends the previous literature in its more constrained scope of material development with relation to the benefits of adopting SHC illustrated in Figure 1. As an alternative, recent SHC advancements are improved to inform about existing and anticipated opportunities and obstacles in relation to certain structural applications in building.

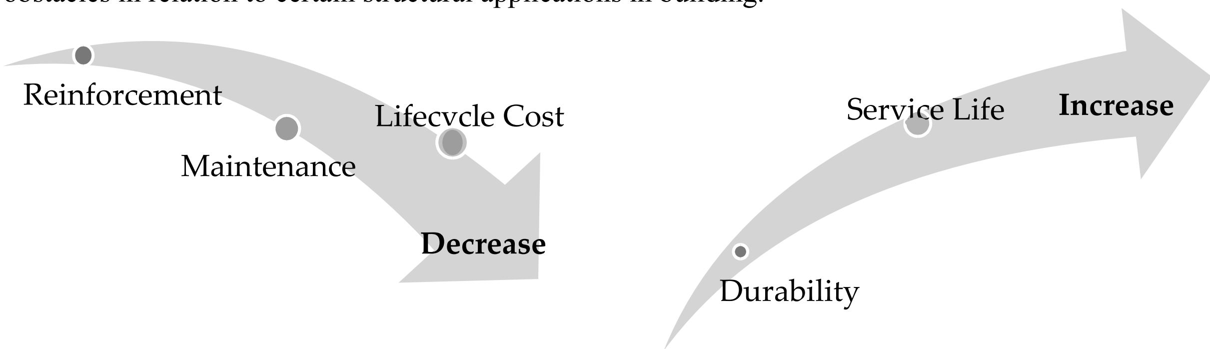

Figure 1. Advantages of self-healing concrete in construction.

2. Approaches of Self-Healing

Autonomous systems like the vascular network system and the encapsulation system are examples of well-known autonomous systems. Self-healing techniques may be classified as either autogenous or autonomous [4]. The main difference between autogenous and autonomous healing systems is their relationship to environmental conditions, with autonomous healing having the potential for independent activation from within the concrete due to the embedded system's autonomy while autogenous healing is limited to the triggering of environmental exposure and is therefore less predictable.

2.1. Autogenous Self-Healing

Partial fracture restoration is accomplished by the intrinsic or autogenous healing process by the normal chemical ageing of concrete. For instance, increased hydration of early concrete's mostly unhydrated components, which are reduced in content as concrete hardens and develops, is the fundamental cause of healing. Underwater, subterranean, and cyclic wet-dry settings are only a few examples of the various infrastructures with a variety of environmental variables that might experience autogenous self-healing. The diameter of the fracture to be mended, according to the present research, is what limits autogenous healing [5-7]. Three important suggestions have been made to enhance the performance of autogenous self-healing since it is implausible to have a regulated fracture width in actual applications of conventional concrete structures: Using engineered cementitious composites (ECC), adding mineral or expanding admixtures.

1. Curing conditions: To aid in the precipitation of therapeutic agents, water curing is advised.
2. Crack width: Healable width is typically 200 millimetres or less.
3. Water-cement ratio: More unhydrated cement particles are available for further hydration when the cement-to-water ratio is higher.
4. Concrete age: It is preferable to cause cracking at a young age whenever it is feasible.
5. Internal stress: Early prestressing to speed mechanical property recovery.

Flexural strength recovery was seen in samples of precracked concrete beams that had been subjected to an early compressive load [8]. Samples exposed to early compressive stress in a study of concrete prisms demonstrated enhanced healing and mechanical property recovery [9].

The heat development of ordinary concrete is often greater, resulting in thermal expansion that causes autogenous shrinkage and cracking [10]. SCMs with low heat evolution are frequently used to overcome this problem, making it easier to apply bulk concrete pours thanks to the controlled cracking. SCMs can manage some of the key durability factors affecting concrete durability, including permeability and porosity. Additionally, using SCMs frequently results in long-term strength growth because to a slower rate of hydration; nevertheless, early-age strength may be affected. Crystalline admixture (CA), which is described as water-resistant by The European Standard 934-2 and as a permeability reduction in concrete by ACI 212.3R-16, is one of the most often utilised expanding minerals in SHC [12]. The issue of CA in research, where there is significant variability because to non-uniform and commercialised compositions, is hinted at by this variance in classification. The admixture's capacity to remain inactive until it has been activated by moisture or water infiltration, however, makes its usefulness in SHC obvious. It has been discovered that using fibres or polymers can produce an engineered cementitious composite (ECC) with better durability and long-term ductility while still meeting the controlled fracture width criterion. This is made possible by the fact that hydrophilic fibres can limit fracture breadth and act as creation sites for healing substances. Due to the flexibility of the fibres or polymers, which prevent fatigue cracking and concrete spalling and lessen the danger of reinforcement corrosion, the use of ECCs balances off the problems of concrete brittleness. The development of ECC concrete has been particularly significant for the building of bridges, because shrinkable polymers with high ductility (bendability) can increase the service life of a deck. Additionally, Table 1 highlights important documented suggestions and restrictions that have been repeatedly established in the literature when applying various autogenous healing methods.

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

The limits of autogenous fracture healing in concrete can be overcome by using healing treatments with a variety of chemical compositions and microorganisms. These improvements are included into the concrete in the autonomic self-healing system either through encapsulation or the use of an integrated vascular flow network. Since mixing agitation, hydration processes that reduce calcium source and pore volume, which lower the reactivity for healing product formation and harm the integrity of chemical agents or bacteria, make it generally unwise to add healing agents and bacteria directly. The healing agents are alternatively protected from the very hostile environment of concrete and hence safeguarded against premature activation by applying encapsulation methods or vascular networks. However, new 3D-printed mini-vascular networks are being investigated for the enhanced flexibility of comfortably inserting the printed mini-vascular network into concrete moulds before casting [18]. The vascular network technology is practically appropriate for application in precast concrete parts [5]. This can target the precise place where cracking is predicted and guarantee the least amount of spontaneity in the healing process. Other promising technologies include the creation of biomimetic concrete that is inspired by natural defences and allows for the hosting of vegetation and natural habitats inside a non-invasive, reinforced or unreinforced concrete structure that can be applied to both new and existing infrastructure with the least amount of energy and resources needed [18–24].

A suggestion for biological healing systems is to include a secondary component (such as bacteria food source, nutrients, etc.) that acts as a "controlled" trigger for the healing agents to activate without total reliance on external environment or human intervention. This is because the effectiveness of autonomous healing functionality remains dependent on adequate modification of concrete existing factors. Due of its capacity to endure the severe concrete environment, the genus of bacillus is typically the bacterium utilised most frequently in biotechnological SHC [25]. Furthermore, research has shown that a bacterium content of 105 colony-forming units (cfu)/mL is advised for enhancing the mechanical characteristics, durability, and strength recovery of concrete [26–30]. Fungi, which exhibit healing processes resembling those of the earlier microorganism, are a second potentially effective but less researched alternative to bacteria [19–21]. Commonly utilised healing agents in SHC chemical systems comprise minerals that contain silica [31]. The usage of silica-containing minerals in SHC may be explained by the precipitation of binding products that alternately fill fissures. Silica-containing minerals are also used as alkali activators of cementitious materials in some alkali-activated concretes. Table 2 provides more information on the majority of stated suggestions and limits of using various autonomous healing systems.

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

Following exposure to deterioration and cracking, mechanical strength recovery, durability enhancement, and microstructural characterization are of primary importance in assessing the self-healing capabilities of concrete. To help comprehend the part that healing mechanisms play in the development of mechanical and durability attributes crucial to the performance of structural engineering, there is a significant effect of various healing systems on engineering properties.

3.1. Mechanical Properties

It provides a non-exhaustive overview of the literature, with data only representing the top engineering performance of each study chosen for compliance with Eurocodes, Canadian, American, and Indian Standards. The chosen studies may be replicated, which enables confirmatory corroboration for increased reliability and reduces testing discrepancy in SHC. In general, there is a tendency towards using healing systems to enhance the mechanical qualities of concrete.

When crystalline admixtures are used, the sealing functionality is stimulated more quickly than with regular concrete; as a result, a study revealed that the sealing effectiveness of SHC between 1 and

3 months was equivalent to the capacity of conventional concrete after 3-6 months [37]. According to an experiment examining the self-healing capabilities of crystalline admixtures in concrete, compressive strength growth was subpar compared to that of regular concrete [38], but the SHC rate of strength recovery was greater. To take advantage of the benefits of autogenous healing, which are more pronounced at younger ages, it is advised that cracking be induced at early ages. According to certain studies, precracking that is induced at 7 days has a 10% larger impact on strength recovery and crack closure than precracking that is induced at 28 days.

Giannaros et al. [35] observed greater compressive strengths for the SHC samples at 28 days compared to the control, but after 56 days, the control samples had significantly improved. This has also been seen in field case investigations [39]. One reason for this would be that there was a capsule rupture, which expedited early hydration and increased strength development up to 28 days. The microstructural integrity of the smaller capsules may be the reason why their flexural strength was greater than that of the larger capsules. However, this may be compared structurally to ordinary steel reinforcement, where less reinforcement (smaller capsule size) contributes to the more advantageous ductile failure and more reinforcement (bigger capsule size) may degrade flexural characteristics.

When paired with bacteria, the conventional autogenous method of employing basalt fibres has been shown to be a successful healing system with improved compressive strength and flexural strength [30]. Furthermore, it has been claimed that engineering characteristics recovered to a good degree after applying 60% of the load-bearing capacity at 28 days. Unwanted healing activation may be effectively stopped by the combined action of bacteria filling the fractures and fibres limiting the breadth of the fissures.

The deflection of the SHC beams was found to grow gradually with increasing fracture widths in a study using bacterial RC beams including a microbial-induced carbonate precipitation healing mechanism [36], although larger loads were maintained. Furthermore, the measured recovery of the SHC's flexural strength was determined to be 73%, compared to a decline of 41% in the OPC concrete. Therefore, the study has come to the conclusion that bacterial RC beams may be used to produce better flexural stiffness and load-bearing capability. This might be explained by the overall rise in compressive strength observed in bacterial concrete, which has enhanced ductility. For the use of SHC in structures subject to severe natural and/or man-made risks, such as earthquakes, floods, high winds, explosions, etc

3.2. Durability Properties

The improvement in durability after exposure to deterioration is the primary metric used to determine SHC's durability. When examining the durability characteristics of SHC, improvements in the transport properties (such as permeability, sorptivity, and diffusivity), resistance to corrosion and chemical assaults, etc., are of interest.

A 90% reduction in corrosion likelihood is observed in studies on the corrosion resistance of bacterial RC beams and cylinders [36], which may be related to the improved watertightness. Lower porosity is frequently discovered in microstructural investigation [28] because the reduced water absorption rate in bacterial SHC has been somewhat consistently reported in studies compared to OPC concrete [40]. The potential to sustain a reduced water absorption rate is suggested by the use of crystalline admixtures because of their nature as water-resistant and permeability-reducing materials [12]. This has been shown in several studies with various admixture components [18,19,33-35]. However, due to nonlinearity in admixture composition and testing techniques [12,16], there is a lack of comparability in studies [16,17] regarding the usage of crystalline admixtures, which makes it difficult to evaluate its viability in comparison to the similarly well-documented performance of bacterial SHC.

Due to the shared parametric interests regarding the repeatability of self-healing under cyclic loading (i.e., earthquake dynamic loads), SHC may be a desirable technology in real-world applications for seismically risky locations where even the smallest impact loads can cause cracks in concrete. The dynamic behaviour of SHC using microencapsulated epoxy-resin exposed to impact loading was tested in a research and it was discovered that the SHC had improved energy absorption capabilities and a rise in dynamic strength parallel to the increasing strain rate. The greater self-healing capabilities of SHC in the presence of water also hints that it would be suitable for applications such as subterranean foundations and breakwaters in humid, rainy, coastal environments.

In conclusion, two factors are found to prevent crack healing in SHC: an increase in hydration that reduces porosity and subsequently restricts the transportation of the healing system, and a probable subsequent increase in crack age that is probably caused by a decline in the number of viable bacteria after subsequent pore filling. In order to mitigate the significant initial hydration interference, it may be possible to use mineral admixtures (SCMs) for their contribution to delayed hydration. To help in the selection of a suitable concrete strategy for certain structural applications, it may be helpful to further study the six robustness criteria proposed to forecast self-healing functioning. 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 the subjected environment. These preliminary aspects include: width and dynamic of anticipated cracking, probability and extent of water exposure, and most importantly, to achieve maximum compatibility of SHC with a specific structural application.

4. SHC Market Feasibility

Self-healing concrete research is an emerging area that requires field applications where actual testing would demonstrate true structural viability. The development of SHC was supported by the government in significant European programmes like RM4L and HEALCON. The theoretical advancement of SHC research, however, may suffer from a lack of industrial collaboration, which might slow the implementation of SHC in practical applications. The short length of experimental testing is another obstacle to the market adoption and upgrading of SHC. As shown in Figure 2, the present strategy for commercialization and long-term performance prediction uses computer modelling to undertake lifecycle analyses and material optimisation based on simulated output. This strategy complies with the design by testing criterion.

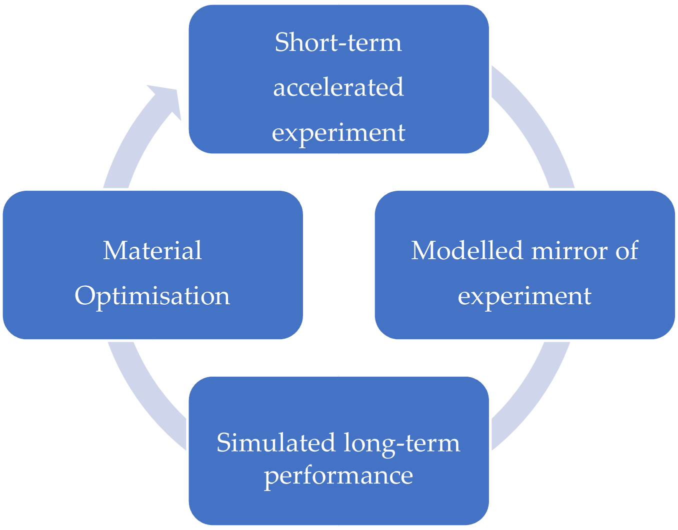

Figure 2. Current self-healing concrete testing and development process.

The limitations of short- to medium-term experimental testing offset by expedited tests are inferred to be a weakness in SHC development towards commercialization. Additionally, as demonstrated, the absence of uniform testing procedures and inconclusive field tests that have weak correlations with laboratory data may make it difficult to persuade corporate interest.

The application of SHC on freshly constructed structures in field tests has never resulted in any evidence of cracking, making it impossible to assess the effectiveness of self-healing on a practical level. However, significant results regarding the viability of SHC mass manufacturing for applications in freshly constructed structures may be shown. SHC has been used as a repair agent for existing structures and infrastructure with fracture width closure and permeability decrease, in contrast to self-healing uses in new structures, with largely effective applications documented. This offers a chance for the non-invasive regeneration of old structures using SHC. According to reports, the application of the

SHC roof slab necessitated lengthening the mixing time on site, which brought the issue of an increased air.

In a different application for an underground structure [39], visible crack formation was discovered seven days after pouring the SHC. The cracks were repaired by continuing to wet the material, but the healing product formed was observed leaking externally, which may be an indication of insufficient control of the extent of the warranted healing response. Since self-healing systems are more expensive to incorporate into structural applications than regular concrete, wasted material has major consequences for both durability and the economy. It is possible that an uneven or irregular distribution of capsules inside the concrete matrix is the cause of product leakage. This incidence may highlight the value of researching the efficacy of the degree of self-healing response to stimulus. In conclusion, the project's quick fracture creation is alarming and could be a sign that SHC's novel features need to be investigated further. This is corroborated by changes seen in early-age temperature and strain monitoring, which were interpreted as rapid hydration, potentially as a result of probable microcapsule breaking. Early microcapsule breaking is a typical occurrence, however the researchers employed capsules shielded by low-alkali cement. It is important to note that the ineffective self-healing capability may have been a result of the conventional methods of mixing and pouring concrete.

The noticeable decrease in carbon emissions is an unquestionable benefit of SHC. The usage of SCMs in the majority of SHC systems, where cement and reinforcement are simultaneously lowered, illustrates this. The vast range of composition, manufacturing, and testing variations makes it difficult to put a number on the expected emission decrease in SHC. However, a number of lifecycle analyses (LCA) have been performed on various SHC systems, and Figure 3 provides a comparison of the environmental effect improvements discovered when employing SHC in comparison to conventional OPC concrete. The LCA analyses presented illustrate the optimal minimal percentage contribution to the environmental effect recorded for a certain SHC system in comparison to traditional concrete in the majority of categories. For the sake of clarity, Figure 3 only shows the purportedly ideal SHC system and refers to the conventional concrete system as OPC without repeating the details of the concrete's composition or the tested environmental conditions.

Due to the associated cradle-to-gate processes, it is important to keep in mind that the initial environmental and financial effects of using SHC systems may be greater. As a result, some assessments recommend that efficient SHC structures have relatively lower repair costs, which would offset the initial costs with an overall improved lifecycle. A notable flaw was discovered in LCA studies of SHC relating bacterial concrete, where the self-healing ECC systems have been the focus of most literature surveys.

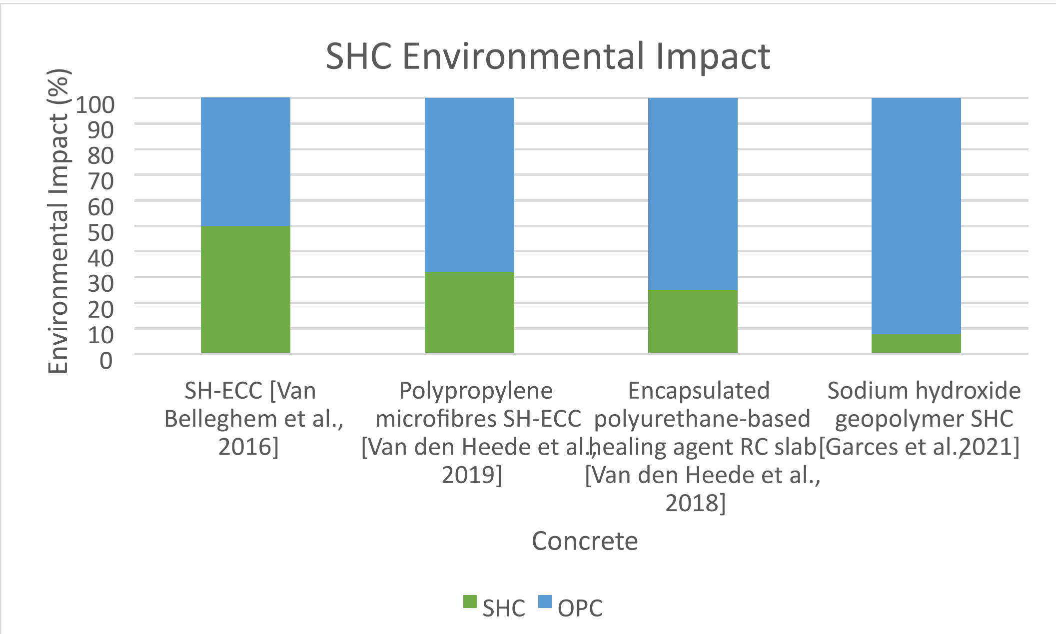

Figure 3. Lifecycle assessment studies of various SHC systems.

5. Conclusion

In order for self-healing concrete to recognise the UN Sustainable Development Goals, specifically Goals 9 of industry innovation and infrastructure, Goals 11 of sustainable cities and communities, Goal 12 of responsible consumption and production, and Goal 13 of climate action, the outlook for SHC is likely to see an upward trend in field experimentation and industry collaboration. Universities play a significant role in advancing sustainable development, according to initiatives like The Higher Education Sustainability Initiative (HESI), and several universities have implemented the SDGs' particular planned objectives.

In contrast to the autonomous processes of encapsulation or vascular networks, which need a strategic approach, autogenous self-healing mechanisms appear to be more feasible due to their modest practical requirements. The commercialised form of numerous crystalline admixtures in autogenous healing has created literature gaps and experimental nonlinearity that have impacted its applicability and research dependability in comparison to other healing systems. Autogenous healing appears to be limited in contrast to the mechanisms of protection provided by chemical healing agents and long-lasting microorganisms seen in autonomous healing, with the exception of the long-term hydration seen in some SCMs. The implantation of the healing system within capsules or circulatory networks is insufficient in autonomous biotechnology, however, to regulate the danger of spontaneous self-healing activation and potential need for exposure to water and/or artificial materials. In order to overcome this difficulty, a secondary element may be included into the concrete in order to function as a methodical trigger for the activation of healing after breaking. The flexibility offered by this potential goes beyond the constraints of autogenous techniques, where the breadth of the healable fracture is constrained and there is no degree of control over the activation of the healing process aside from the effects of the external environment. However, using nutrients comes at a higher cost; as a result, the practicality and economic viability of this approach must be compared to the alternative SHC dependent on external circumstances. It could be more practicable, in certain cases, to limit the usage of secondary SHC components to specialised applications where there aren't the right environmental circumstances to naturally initiate healing. Due to their proven promising engineering features, crack-limiting ECCs often used in autogenous systems might be combined with healing agents or microorganisms to create alternative and perhaps less expensive methods of controlled healing. Furthermore, the application of fungus has demonstrated potential performance for improved optionality of self-healing systems, which justifies further investigation.

Future research must focus on addressing issues and seizing opportunities in order to further the commercialization of SHC. Field experiments have demonstrated the low survival of enclosed systems in conventional concrete mixers, hence it could be worthwhile to investigate if encapsulated SHC structural components can be transported and produced using conventional concrete production methods. Through ongoing research using 3D printing, the vascular network approach offers enhanced robustness in real-world applications; yet, significant costs may be connected to such complex technology. In order to build an adequate self-healing system that will ensure the needed structural resilience, it is important to prespecify the predicted damage mechanism, according to research on the structural application of SHC. To comprehend the economic benefits of integrating various SHC technologies in connection to the planned structural application, pertinent cost analysis studies must also be conducted. Since there is little current research on relevant LCA of bacterial concrete, the emphasis has been mostly on chemical therapeutics. The behaviour of structural elements exposed to natural settings with a focus on non-destructive testing techniques may fill the gap left by field case studies that are insufficiently decisive to serve as a trustworthy prototype for industrial adoption. In order to standardise SHC manufacturing and testing techniques that are obvious to the industry, future research into SHC must attempt to use less variety in testing methodologies. In the end, SHC is a multidisciplinary project.

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