

Smart Self-Healing Concrete for Sustainable and Intelligent Infrastructure Systems

Abstract

Concrete is the most commonly used construction material in the world, but it is prone to cracking from mechanical loading, thermal changes, shrinkage, and chemical exposure, which has a major impact on a structure's service life and durability. Many traditional repair and maintenance methods are labor-intensive, costly, and not effective in challenging environments or inaccessible areas. To address these challenges, a new concrete material that can self-heal cracks without intervention has been developed and is known as smart self-healing concrete (SHC). The major self-healing mechanisms in concrete have been comprehensively reviewed in this chapter, namely autogenous healing, bacterial-based healing, microencapsulation, vascular networks, and superabsorbent polymer (SAP)-based systems. The mechanism of crack remediation, healing efficiency, mechanical strength recovery, and durability enhancement are discussed critically in this regard. The chapter assesses the sustainability advantages, life-cycle performance, and infrastructure applications of SHC in extreme environmental exposure scenarios. There are also various issues of large-scale implementation, such as high production costs, absence of standard testing procedures, long-term durability, and climatic adaptability that are discussed. Further, novel research trends related to artificial intelligence, structural health monitoring systems, Internet of Things (IoT)-enabled sensing, and 3D concrete printing are emphasized as breakthrough research initiatives for the future evolution of autonomous and resilient infrastructure materials. The study opens a new perspective of smart self-healing concrete for a durable, low-maintenance, and environmentally friendly civil infrastructure system.

Keywords: Self-healing concrete; Smart construction materials; Bacterial self-healing concrete; Sustainable infrastructure; Crack remediation; Structural durability; Autonomous repair systems; Microencapsulation; Life-cycle assessment; Resilient infrastructure.

1. Introduction

Concrete is the basic material of modern civil infrastructure and is widely used in the construction of buildings, bridges, highways, tunnels, dams, marine structures, and transportation systems. As the world's most commonly used construction material, global consumption of concrete is more than 4.4 billion tonnes a year, due to its high compressive strength, low cost, and high availability. While concrete offers many engineering benefits, it has a high degree of brittleness and is prone to cracking due to influences such as shrinkage, thermal stresses, cyclic loading, chemical attack, and environmental exposure. The aging process of cracking, which results from a variety of aggressive agents (chlorides, sulfates, humidity, and carbon dioxide) entering the structure, leads to reinforcement corrosion, loss of durability, and premature deterioration of the structure.

The need for resilient and sustainable construction materials with minimal maintenance requirements and long-term durability has been growing in recent years, driven by the increasing demand for such products due to the rapid pace of urbanization, the aging of infrastructure, and the impact of climate change (Agbamu et al., 2024; Pooja & Tarannum, 2025). Global anthropogenic CO₂ emissions from the cement industry are almost 8% of the total (Huseien et al., 2022). Repair methods that are currently used (e.g., epoxy injection, crack sealing, and surface patching) can be labor-intensive and expensive and are often not feasible for other structures that are inaccessible, such as tunnels, offshore platforms, marine substructures, and deep foundations, and are only temporary solutions.

In this context, smart self-healing concrete (SHC) has become a revolutionary development in the field of sustainable construction materials and intelligent infrastructure engineering. The design of SHC is inspired by the self-repair mechanism observed in biological systems, which means that it can autonomously seal and repair cracks in the structure without relying on external intervention (Uddin et al., 2023; Ibrahim et al., 2025). There are several physical, chemical, and biological methods for self-healing, such as autogenous healing, bacterial mineral precipitation, microencapsulation, vascular healing systems, and superabsorbent polymer (SAP)-based technologies. The mechanisms impact greatly the crack closure, impermeability, durability, and long-term structural performance.

The intelligent SHC technologies have been accelerated with the recent technological developments of biotechnology, nanotechnology, artificial intelligence (AI), additive manufacturing, and smart sensing systems, which have enabled the integration of SHC

technologies with structural health monitoring (SHM), Internet of Things (IoT) sensing, and predictive maintenance. Advancements like this bring several disciplines together, opening up the potential for autonomous infrastructure systems that can detect damage, self-diagnose, and perform repairs on the fly. SHC is closely compatible with the global effort to achieve sustainability in built infrastructure through extending the service life of infrastructure, reducing its maintenance frequency, minimizing its embodied carbon emissions, and facilitating low-carbon construction practices using supplementary cementitious materials (SCM) and sustainable concrete technologies (SCT) (McMillan, 2023; Nguyen et al., 2023).

The development of such a new generation of civil engineering application systems that are resilient, sustainable, low-maintenance, and climate-adaptive is therefore the perfect opportunity to develop and apply self-healing concrete.

2. Objectives of the Chapter

The main objectives of this chapter are:

1. To review the fundamental mechanisms of smart self-healing concrete systems.
2. To evaluate the crack-healing efficiency and durability performance of SHC technologies.
3. To analyse the sustainability and lifecycle benefits of SHC in civil infrastructure.
4. To examine the integration of SHC with AI, IoT-enabled sensing, and smart monitoring systems.
5. To identify the major challenges, research gaps, and future research directions in SHC technologies.

3. Historical Development of Self-Healing Concrete

3.1 Early Understanding of Autogenous Healing

Early studies on autogenous healing showed that cement can partially close microcracks by ongoing hydration during the cementation process and by calcium carbonate precipitation in moist environment conditions (Barbu & Stoian, 2021). The efficacy of the natural healing was restricted

to very small crack widths and favorable environmental conditions, which limited its use in a large-scale infrastructure system.

The knowledge of autogenous healing has also been improved by recent research using supplementary cementitious materials, nano-additives, and innovative internal curing technologies, which are able to enhance the crack-sealing performance and durability under aggressive environmental conditions.

3.2 Emergence of Engineered Self-Healing Systems

Natural autogenous healing systems had drawbacks, and researchers turned to engineered self-healing systems that could autonomously heal cracks. Early research was on capsule technologies containing healing materials, such as epoxy resins, polymers, and mineral-based materials, embedded in the concrete matrix (Nguyen et al., 2023). As cracks appeared, these capsules burst open, allowing healing substances to flow into damaged areas and restore impermeability and durability.

These engineered methods were the first steps toward the modern field of research into self-healing concrete and a great leap forward for the field of smart construction materials. Studies have been conducted recently to enhance the stability, mechanical compatibility, and large-scale application of engineered SHC systems. New materials for healing, such as nanocomposites, bio-based polymers, and multifunctional encapsulation technologies, have shown enhanced healing efficiency and recovery of durability.

3.3 Development of Bacterial Self-Healing Concrete

A major progress in SHC technology was the development of bacterial self-healing concrete, which was mainly developed at Delft University of Technology. In this method, bacteria were employed that can precipitate calcium carbonate in the process of microbial metabolic activities, thus sealing cracks in the concrete matrix by itself (Huseien et al., 2022). Bacterial SHC garnered worldwide recognition for its eco-friendly healing process and ability to effectively seal cracks in concrete structures.

Recent improvements are directed towards enhancing the survivability of bacteria, techniques of nutrient entrapment, and healing potential under different climatic conditions over time. Research with silica-based systems of encapsulation, optimization of the bio-mineralization, and use of strains of bacteria genetically modified for crack healing has shown significant improvement in adaptability to the environment and efficiency in crack healing.

3.4 Evolution of Advanced Healing Technologies

Further developments in SHC research have resulted in vascular healing systems, superabsorbent polymers (SAPs), and hybrid self-healing systems with repeated healing capabilities.

The hybrid SHC systems that combine the functionality of bacterial healing, vascular networks, nanomaterials, and polymer technology have received growing interest in recent years due to their increased reliability of healing and their multifunctional properties. Combined with 3D concrete printing, smart sensing technology, and intelligent monitoring technology, SHC has boosted the progress of autonomous infrastructure materials suitable for future smart city applications.

3.5 Current Research Trends and Global Perspective

Nowadays, the study of self-healing concrete has become a multidisciplinary area that combines materials science, biotechnology, nanotechnology, structural engineering, and artificial intelligence. Currently, the research emphasis is on making HEAs more reliable with respect to healing, more cost-effective, more adaptable to the environment, and more sustainable in terms of low carbon, suitable for use in large-scale infrastructure projects (Asgharpour & Hosseini, 2024; Xing et al., 2025).

Important progress has also been made in the field of crack monitoring with AI, sensor networks with IoT devices, digital twins, and predictive maintenance systems combined with SHC technologies. Although significant laboratory-scale advances have been made, widespread field use is hindered by economic concerns, variability in test methods and protocols, and uncertainty about the long-term durability performance. However, SHC is still regarded as one of the most promising technologies for the resilient, sustainable, and intelligent infrastructure development of the 21st century.

Table 1. Evolution of Self-Healing Concrete Technologies

Period	Major Development	Key Contribution
Before 2000	Autogenous healing	Natural crack sealing capability
2001–2010	Capsule & bacterial SHC	Autonomous crack remediation
2011–2020	Vascular & SAP systems	Repeated healing functionality
2021–2025	AI-integrated smart SHC	Intelligent infrastructure applications

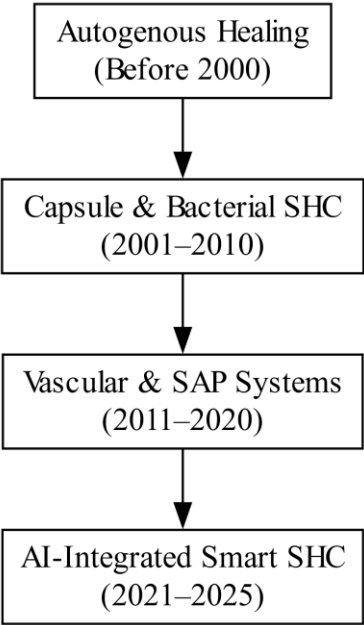


Figure 1. Evolution of SHC Technologies

4. Mechanisms of Self-Healing in Concrete

4.1 Autogenous Healing Mechanism

This is the natural phenomenon where concrete can close any cracks that may be present without the need for any intervention. The process is mainly achieved by ongoing hydration of unconsumed cement particles and precipitation of calcium carbonate in regions of cracks under optimal moisture conditions. Generally, only very narrow cracks will autogenously heal, and the healing process is highly dependent on environment, quantity of water, and cement composition.

Ongoing developments have enhanced the efficiency of the autogenous healing process by the addition of supplementary cementitious materials, crystalline additives, and internal curing agents that are capable of improving the ability to close the cracks and recover the durability. Although

being simple but with the desired sustainability benefits, autogenous healing is less efficient for areas of larger crack size and for damage by repeated cycles (Nguyen et al., 2023).

4.2 Bacterial Self-Healing Mechanism

The microbial self-healing concrete technology is developed by using microorganisms that can precipitate calcium carbonate by the metabolic activity of bacteria. In this mechanism, the spores of bacteria and nutrients are added to the concrete matrix with a protective encapsulation method. If cracks occur in the concrete and water permeates the cracks, then the bacteria are activated, and calcium carbonate precipitation seals the crack automatically.

Bacterial SHC has shown good potential due to its eco-friendly healing process, high crack-sealing ability, and enhanced durability properties. In recent years, researchers have concentrated on improving the survivability, stability of nutrients, and healing ability of the bacteria in different environments. However, the commercialization of these products is still hindered by several challenges such as high materials cost, long storage periods of bacterial viability, and large-scale field implementation (Huseien et al., 2022; Uddin et al., 2023).

4.3 Capsule-Based Self-Healing Mechanism

In capsule-based SHC systems, microcapsules/hollow fibers filled with healing material like epoxy resins, polyurethane, sodium silicate, or mineral-based materials are embedded in the concrete matrix. When cracks occur, the capsules burst, and the healing agents go into damaged portions of the crack, filling the crack and making it impermeable.

Rapid healing capability and relatively good crack sealing for smaller crack widths are achieved in this mechanism. Capsule geometry, the kind of encapsulation material, and compatibility of the healing agent with the capsule material are important factors that affect healing performance. Mechanical compatibility and environmental sustainability have been improved due to the recent advances in nanocomposite capsules and bio-based healing agents. However, most systems using capsules do not have the capability of reactivating the capsule after it has been broken, which means they are only allowed to heal once. (Asgharpour & Hosseini, 2024)

4.4 Vascular Self-Healing Systems

Vascular self-healing systems are based on biological circulatory networks and contain channels that are embedded in the concrete matrix, which can carry healing agents back and forth to the damage area many times. If cracks occur, they are spontaneously closed by the healing agents passing through the vascular network.

One of the most significant benefits of vascular SHC systems is the ability to heal multiple times and their use for widespread infrastructure where long-term durability is important. The study of advanced geometries of vascular networks, intelligent delivery systems, and multi-functional healing agents has been explored recently to gain reliability in healing and structural compatibility. The fabrication complexity, high production costs, and mechanical strength reduction are still significant challenges (Nguyen et al., 2023).

4.5 Superabsorbent Polymer (SAP)-Based Healing

Superabsorbent polymers (SAPs) are materials that will absorb and hold a significant amount of water in the concrete matrix. The SAP particles will absorb moisture infiltrating the crack and slowly release it, allowing ongoing cement hydration and crack sealing (Anbazhagan & Arunachalam, 2025).

The use of SAP-based SHC systems can greatly enhance internal curing, moisture retention, and autogenous healing properties and mitigate cracking caused by shrinkage. The recent development has been on the hybrid SAP systems combined with the nanomaterials and bacterial healing technology to enhance the multifunctional performance of SAP. Too high a dosage of SAP can have a negative impact on the mechanical strength and porosity properties of concrete.

4.6 Hybrid Self-Healing Mechanisms

The hybrid SHC systems are used to provide a combination of healing mechanisms, like bacterial healing, microencapsulation, vascular networks, and SAP technologies, which can provide superior healing efficiency and multifunctional performance. The aim of these systems is to overcome some of the disadvantages of individual healing systems and give a more reliable sealing of cracks with different environmental conditions.

Some recent advances in hybrid SHC technologies have shown excellent healing capacity after multiple cycles, high durability recovery, and better integration with intelligence-infused

infrastructure systems with artificial intelligence, structural health monitoring, and IoT-sensing technologies. The development of resilient and sustainable infrastructure in the future is becoming one of the most promising solutions with hybrid systems (Nguyen et al., 2023; Vignesh et al., 2025).

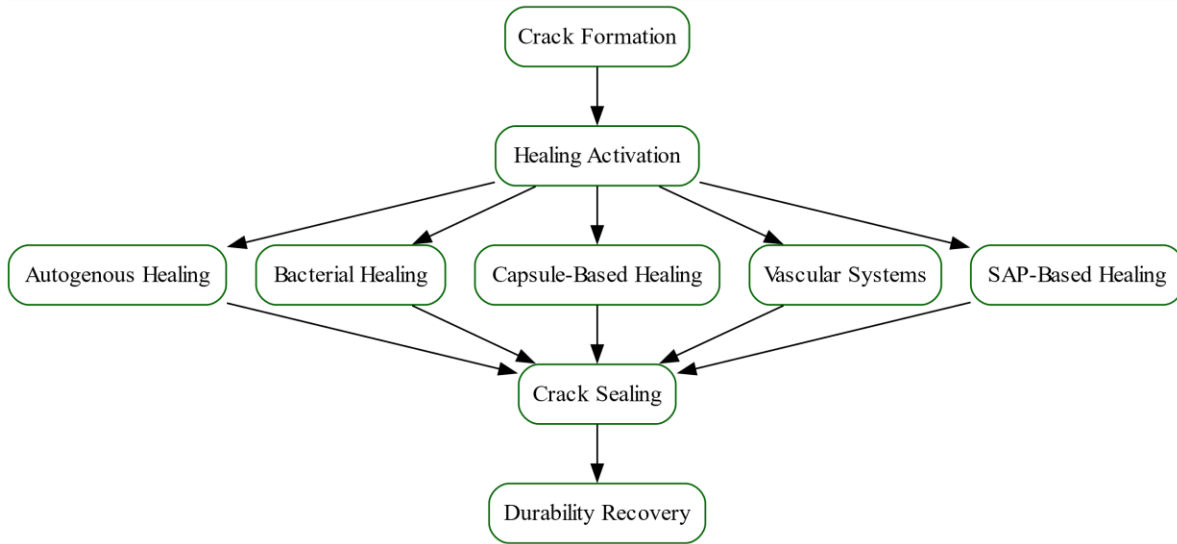


Figure 2 Mechanisms of Self-Healing in Concrete

Table 2. Comparison of Self-Healing Mechanisms

SHC Mechanism	Healing Principle	Advantages	Limitations
Autogenous Healing	Continued cement hydration	Simple and sustainable	Limited crack width
Bacterial SHC	Calcium carbonate precipitation	Eco-friendly and durable	High cost
Capsule-Based SHC	Release of healing agents	Rapid crack sealing	One-time healing
Vascular SHC	Network-based healing-agent delivery	Repeated healing capability	Complex fabrication
SAP-Based SHC	Moisture absorption and release	Improved internal curing	Strength reduction at high dosage

Hybrid SHC	Combination of multiple mechanisms	Enhanced multifunctionality	Higher system complexity
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5. Comparative Performance Evaluation of Self-Healing Concrete

5.1 Mechanical Performance Recovery

Most frequently, the self-healing concrete is considered to be successful when the mechanical properties like compressive strength, flexural strength, and flexural stiffness can be recovered after cracking. The mechanical recovery of various SHC mechanisms ranges from very low to very high, depending on the width of the crack, environmental exposure, healing time, and the composition of the material.

The bacterial and capsule-based SHC systems have been shown to significantly enhance the compressive strength recovery and crack sealing capacity, especially in microcracks and in moderate structural damage conditions. The combined use of different healing mechanisms has been observed to produce better results in the hybrid SHC systems due to their better healing reliability and multifunctionality. The initial strength of concrete may be compromised by the overuse of healing agents and/or encapsulation materials.

5.2 Durability and Permeability Performance

One of the key benefits of SHC is its capability of lowering permeability and enhancing long-term durability performance. Crack sealing has the effect of greatly limiting the ingress of aggressive materials that cause reinforcement corrosion and durability issues, including chlorides, sulfates, moisture, and carbon dioxide.

Significant decreases in water permeation, chloride penetration, and freeze–thaw damage have been reported for the SHC systems compared with conventional concrete. Both the bacterial and SAP-based SHC systems have proven to have a very good moisture control property and improved resistance under the most aggressive environmental exposure conditions. However, performance aspects of durability under actual field conditions are still under research (Xing et al., 2025).

5.3 Healing Efficiency Assessment

An important parameter to assess the crack-remediation performance of the SHC systems is the healing efficiency. It is normally evaluated by crack closure measurements, permeability decrease, mechanical recovery, and microscopic examination of healing products.

More recent studies have indicated that the crack-healing efficiency is >80-90% (Nguyen et al., 2023). The capability of healing repeatedly and with greater consistency has also been successfully proven for hybrid SHC technologies compared to conventional healing techniques. Environmental conditions, crack geometry, moisture availability, and concrete matrix healing-agent distribution play a key role in healing efficiency (Nguyen et al., 2023).

5.4 Economic Feasibility and Cost Performance

While more expensive at the outset in terms of materials and production, SHC technologies provide long-term economic advantages in terms of a reduced frequency of maintenance, lower maintenance costs, and an increased service life of the infrastructure.

Cost studies of SHC systems show that these systems can significantly reduce maintenance costs of critical infrastructure systems like bridges, tunnels, marine structures, underground facilities, etc. These are limited for commercial applications at large scale due to high production costs, lack of industrial standardization, and uncertainty of long-term performance under field conditions (Pooja & Tarannum, 2025)

5.5 Infrastructure Suitability and Practical Applications

Each of the SHC mechanisms is suitable for particular infrastructure applications with respect to the structural requirements, environmental conditions, and maintenance accessibility. Not only their excellent durability performance but also their moisture-dependent healing ability makes bacterial SHC systems suited for water-retaining structures, marine infrastructure, and underground tunnels.

Capsule-based systems work well for buildings that need to be sealed rapidly when a crack occurs, while vascular systems would be more suitable for massive infrastructure with multiple healing requirements. In the future, smart infrastructure systems are increasingly being considered by hybrid SHC technologies due to their multifunctional characteristics and their compatibility with intelligent monitoring technologies.

Table 3. Comparative Performance of Self-Healing Concrete Systems

SHC Type	Crack Width Capacity	Healing Efficiency	Major Advantages	Limitations
Autogenous Healing	< 0.2 mm	Moderate	Simple and sustainable	Limited healing capacity
Bacterial SHC	0.2–0.8 mm	High	Eco-friendly and durable	High material cost
Capsule-Based SHC	0.3–1.0 mm	High	Rapid crack sealing	One-time healing
Vascular SHC	> 1.0 mm	Very High	Repeated healing capability	Complex fabrication
SAP-Based SHC	< 0.5 mm	Moderate–High	Moisture retention	Strength reduction risk
Hybrid SHC	Variable	Very High	Multifunctional performance	High system complexity

6. Sustainability and Life-Cycle Assessment of Self-Healing Concrete

6.1 Environmental Sustainability

Due to its ability to decrease the need for repairs, limit material consumption, and extend the service life of infrastructure, self-healing concrete has become a promising sustainable building material. Maintenance and rehabilitation activities are needed regularly on conventional concrete structures to consume a significant amount of raw materials, energy, and finances during their operational life (Pooja & Tarannum, 2025).

SHC systems have the ability to seal cracks on their own and prevent early deterioration, which greatly decreases the amount of repair materials and reconstruction projects. This helps to reduce the environmental impact, waste generation, and efficiency of resources in infrastructure development. The use of supplementary cementitious materials, recycled aggregates, and bio-based healing agents further improves the potential sustainability of SHC technologies.

6.2 Reduction of Carbon Emissions

Due to the energy-intensive clinker production process, the cement industry is one of the leading sources of carbon dioxide emissions all across the world. SHC technologies are important in reducing carbon mainly through infrastructure life extension and minimizing maintenance-related activities.

The operation of repair and reconstruction can be reduced by employing SHC systems, which results in a decrease of the embodied carbon emissions from the production, transportation, construction equipment, and reconstruction processes of cement. The use of low carbon binders, geopolymer materials and carbon sequestering bacterial systems in SHC technologies has also been investigated recently to further improve the environmental sustainability (Pooja & Tarannum 2025). The sustainability interactions related to SHC are shown in Figure 3.

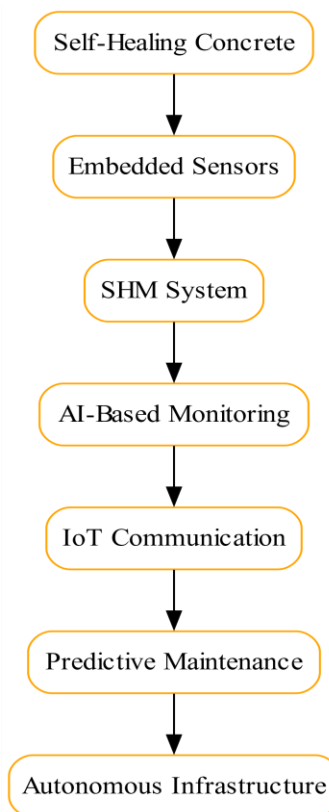


Figure 3. Sustainability Framework of SHC

6.3 Service-Life Extension and Infrastructure Resilience

The most important benefit of SHC systems is their capacity to prolong the life of infrastructure in severe environmental conditions. Crack remediation helps to make structures more durable and

to prevent the entry of harmful substances, leading to corrosion of the reinforcements and degradation of the materials.

SHC technologies have shown significant promise for enhancing the resilience of bridges, tunnels, marine structures, underground facilities, and transportation infrastructure under extreme climatic and chemical conditions. Not only does extended service life increase the reliability of the structure, but it also decreases maintenance spending along the structure's lifespan and any environmental impact from the replacement of the infrastructure.

6.4 Life-Cycle Cost Assessment

Typical disadvantages of SHC systems are greater up-front construction costs compared to conventional concrete systems, but lifecycle cost analysis has shown that the systems provide substantial long-term economic benefits. The overall cost of structures can be reduced over their service life due to a combination of reduced frequency of maintenance, reduced repair costs, minimized service interruptions, and increased durability of infrastructure.

Some research has revealed that SHC technologies are especially cost-effective for critical infrastructure systems with limited access to maintenance and for systems that have economically costly repair operations, including offshore platforms, underground tunnels, marine systems, and nuclear containment facilities. There remain uncertainties around scale-up in the field and durability performance over the long term that continue to have an impact on commercial uptake.

6.5 Sustainable Infrastructure Development

The progress towards SHC is closely aligned with global SDGs and climate-resilient infrastructure efforts. Infrastructure systems are increasingly becoming more complex, and demand for construction materials that can deliver durability, resilience, environmental sustainability, and a lower reliance on maintenance in the face of a changing climate is growing.

More recently, its capabilities have been further extended to enable intelligent and sustainable infrastructure applications through synergies with smart sensing, AI, digital twins, and predictive maintenance systems. As a result, SHC has become a promising technology for the future with regard to sustainable and climate-resilient civil engineering systems (Vaduganathan, 2025).

7. Emerging Applications and Smart Infrastructure Integration

7.1 Structural Health Monitoring Integration

In recent years, self-healing concrete has been developed and combined with structural health monitoring (SHM) systems that can detect, assess, and predict the damage. Stress, moisture, crack propagation, and durability parameters can be monitored continuously with sensors integrated into the SHC structures.

The combination of SHC with SHM technologies significantly enhances the safety and maintenance planning of infrastructures, and their reliability in operation. Smart monitoring systems can also aid in identifying damage at an early stage and automatically trigger the healing process, thus lowering the cost of maintenance and avoiding major structural deterioration (McMillan, 2023)

7.2 Artificial Intelligence and IoT-Enabled Infrastructure

Artificial intelligence (AI) and Internet of Things (IoT) sensing technologies are becoming more and more popular as tools to be included in SHC systems to manage the infrastructure intelligently. These algorithms can use the data collected by the sensors to predict how cracks will grow, schedule maintenance tasks, and assess the effectiveness of the repair. The algorithms can analyze the data collected by the sensors to predict the growth of cracks, optimize maintenance timings, and evaluate the effectiveness of the repair under different environmental conditions.

The IoT-based SHC systems enable autonomous management of infrastructure, allowing the sensors, monitoring platforms, and maintenance networks always to communicate with each other. These technologies are especially useful in large-scale transportation networks, smart cities, marine applications, and underground infrastructure systems that have to monitor the performance continuously (Yahia et al., 2025; Zebua et al., 2025).

7.3 Applications in Marine and Underground Structures

Marine structures, offshore platforms, underground tunnels, and water-retaining systems are extremely susceptible to the aggressive environment, to chloride attack, and to moisture-related deterioration. SHC technologies have been proven to increase durability and decrease maintenance needs in such demanding conditions.

The moisture-assisted healing ability of bacterial and SAP-based SHC systems and their resistance to moisture-related deterioration due to permeability make them especially suitable for marine and underground applications. SHC's autonomous crack sealing capability also extends the service life of inaccessible structures that are difficult and costly to repair.

7.4 3D Concrete Printing and Additive Manufacturing

The advances in both additive manufacturing and 3D concrete printing technologies have led to new opportunities to include SHC mechanisms in the digitally manufactured infrastructure systems. Printable concrete mixtures can be produced that are compatible with SHC, which can repair the microcracks created during printing and service conditions on their own, thus enhancing the structural integrity and durability (Vignesh et al., 2025).

Recent research has focused on embedding encapsulated healing agents, nanotechnology, and bacterial spores in printable concrete composites to improve the self-healing ability of concrete. SHC and 3D printing technologies are expected to have a great impact on future sustainable and automated construction practices.

7.5 Smart Cities and Sustainable Urban Infrastructure

The Smart Cities concept is becoming more about resilient, low-maintenance, sustainable infrastructure systems to support rapid urbanization and adaptation to climate change. SHC technologies are well suited to these goals due to their ability to autonomously repair, enhance durability, and provide benefits in terms of lifespan sustainability.

Enabling SHC to be combined with the digitization of urban infrastructure and management tools, renewable energy infrastructure, and intelligent transport systems is expected to further speed up the development of next-generation smart urban infrastructure. Hence, the SHC technology is becoming a significant enabling technology for the future intelligent and sustainable civil engineering systems (Ebrahimi & Gholamzadeh, 2024).

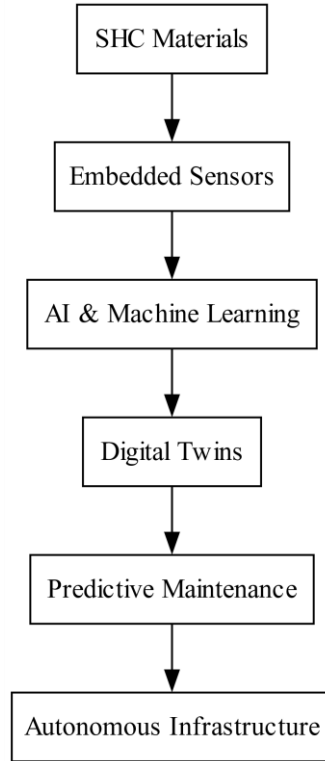


Figure 4. Smart Infrastructure Integration of SHC

8. Challenges and Limitations of Self-Healing Concrete

8.1 High Initial Material and Production Costs

The high material and production costs are one of the most important factors that hinder the utilization of the self-healing concrete technologies at large scale when compared with the conventional concrete systems. The use of special healing materials like bacterial spores, encapsulated polymers, vascular networks, nanomaterials, and superabsorbent polymers significantly raises the complexity of manufacturing and total construction costs. Further, further improved technologies for production, protective encapsulation, and quality control have further led to an economic investment increase during material preparation and infrastructure construction (Asgharpour & Hosseini, 2024).

Many construction industries are still not using SHC systems due to their comparatively high initial cost, although there are significant economic advantages in the long term of less maintenance, fewer repairs, and longer service life. This is especially important in the developing world or for low-cost infrastructure projects where budget constraints have a significant impact on material

choice and construction techniques. One of the most critical challenges to commercializing the SHC technologies on a large scale is to optimize the production cost while ensuring healing efficiency.

8.2 Limited Large-Scale Field Applications

The use of SHC systems in large-scale projects of infrastructure is still relatively limited. The majority of the studies that have been performed have been done under controlled environmental conditions where moisture availability, crack geometry, curing temperature, and loading conditions, amongst others, can be precisely controlled. Operating and environmental conditions in real infrastructure systems can be very complex, potentially affecting the healing performance and long-term structural behavior.

In field applications, factors like cyclic loading, temperature changes, chemical corrosion, freeze-thaw cycles, heavy traffic, and moisture changes can negatively impact the healing ability of SHC systems. Lack of adequate long-term monitoring data in full-scale infrastructure projects reduces confidence in the reliability and durability of these technologies. It is thus necessary to conduct large-scale pilot projects and long-term field investigations to validate the structural performance and durability recovery of SHC systems in realistic service conditions and to demonstrate the economic viability of SHC systems.

8.3 Durability and Long-Term Reliability Concerns

Self-healing concrete is still in the early stages of development and has many technical challenges that persist and require considerable research. Laboratory studies have shown that SHC systems have yielded good results in crack sealing efficiency and improvement in durability; however, some doubts remain as to their performance over long-term use. There are many key factors to consider when evaluating the healing ability of many of the SHC mechanisms, such as moisture availability, bacterial survivability, encapsulation stability, and compatibility of the healing agents with the cementitious matrix (Huseien et al., 2022).

Over time, elevated temperature, exposure to chlorides, sulfate attack, UV radiation, and repeated freeze–thaw cycles may cause degradation of the healing effect and contribute to long-term structural instability. One of the biggest challenges in bacterial SHC systems is keeping the bacteria alive for extended periods of time in the high-pH concrete environment. Likewise, degradation of

encapsulation material, over time, and the reduction of healing agent effectiveness can reduce the ability to heal more than once. For this reason, enhancing the long-term reliability of SHC technologies when applied to harsh environmental conditions is crucial for the practical sustainability and structural safety of SHC technologies.

8.4 Standardisation and Regulatory Limitations

Another important issue that has to be addressed in the industrial use of SHC systems is the absence of generally accepted testing standards, design methods, and performance evaluation procedures. Currently, various researchers and organizations use different experimental methods and criteria to evaluate the efficiency of healing, crack closure, permeability reduction, and recovery of durability. This lack of consistency may be challenging in determining the effectiveness of different SHC technologies and will limit their adoption in the construction industry (Azanaw, 2025).

The absence of standardised regulatory guidelines also creates uncertainty among engineers, contractors, and infrastructure authorities regarding the practical application and structural reliability of SHC materials. Current building codes and construction standards are primarily developed for conventional concrete systems and do not adequately address the unique characteristics of SHC technologies. Consequently, the development of internationally recognised standards, testing protocols, and design specifications is essential for promoting industrial confidence, commercial implementation, and large-scale infrastructure adoption of self-healing concrete systems.

8.5 Mechanical Compatibility and Structural Performance

The incorporation of healing agents and specialised self-healing components within the concrete matrix can significantly influence the fresh and hardened properties of concrete. Parameters such as workability, setting time, porosity, compressive strength, flexural performance, and bonding behaviour may be affected depending on the type and dosage of healing materials incorporated into the mixture.

For example, excessive use of superabsorbent polymers may increase internal porosity and reduce compressive strength, whereas large vascular channels or high capsule concentrations may negatively influence structural integrity and crack resistance. Similarly, improper compatibility

between healing agents and cementitious materials may adversely affect hydration behaviour and durability performance. Achieving an optimal balance between healing capability and mechanical performance therefore remains a major engineering challenge. Future research should focus on developing multifunctional SHC systems capable of providing efficient crack remediation without compromising structural reliability and mechanical strength.

8.6 Scalability and Commercialisation Challenges

Although SHC technologies have shown remarkable scientific and technological progress over the past two decades, their transition from laboratory research to commercial infrastructure applications remains relatively slow. Large-scale production of specialised healing materials often requires sophisticated manufacturing processes, advanced encapsulation technologies, and controlled material handling systems that are not yet widely available within the construction industry (Agbamu et al., 2024).

In addition, the integration of SHC systems with advanced technologies such as artificial intelligence, digital twins, structural health monitoring, and IoT-enabled sensing platforms requires interdisciplinary expertise and substantial technological investment. Limited industrial awareness, insufficient market readiness, and uncertainties regarding long-term economic benefits further restrict widespread adoption. Overcoming these scalability and commercialisation barriers will therefore require strong collaboration among researchers, construction industries, infrastructure authorities, and policymakers to facilitate technology transfer, industrial standardisation, and practical field implementation of SHC systems.

Table 4. Major Challenges in Self-Healing Concrete Implementation

Challenge	Description	Impact
High Cost	Expensive healing materials, encapsulation technologies, and smart sensing systems increase overall production expenditure	Limits large-scale commercial adoption
Lack of Standardisation	Absence of universally accepted testing methods and design guidelines	Restricts industrial implementation and regulatory approval

Long-Term Reliability	Uncertainty regarding durability and healing performance under real environmental conditions	Reduces confidence in practical infrastructure applications
Mechanical Compatibility	Healing agents may influence workability, porosity, and compressive strength of concrete	Potential reduction in structural performance
Scalability Issues	Complex manufacturing and material-processing requirements	Limited industrial-scale production
Environmental Variability	Climatic conditions affect healing efficiency and crack-remediation performance	Inconsistent field performance

Research Gaps and Emerging Challenges

9.1 Limited Understanding of Long-Term Field Performance

Although self-healing concrete technologies have demonstrated significant potential under laboratory conditions, one of the most critical research gaps remains the limited understanding of long-term field performance under realistic infrastructure environments. Most currently available studies are conducted under controlled laboratory conditions where environmental variables such as temperature, humidity, crack geometry, and loading conditions can be carefully regulated. Actual infrastructure systems are continuously exposed to highly complex operational and environmental conditions that may significantly influence healing efficiency and structural durability over extended service periods (Nguyen et al., 2023).

Factors including cyclic traffic loading, chloride exposure, freeze–thaw cycles, moisture fluctuations, chemical attack, and thermal variation can affect crack-healing behaviour and long-term material stability. The absence of sufficient large-scale field demonstration projects and long-duration monitoring studies limits the practical understanding of how SHC systems perform throughout the lifecycle of infrastructure systems. Future research should therefore prioritise real-time field investigations and long-term performance monitoring to establish the practical reliability and durability of SHC technologies under diverse climatic and operational conditions.

9.2 Insufficient Standardisation and Performance Evaluation Methods

Another major research gap involves the lack of universally accepted testing methodologies and standardised performance evaluation frameworks for SHC systems. At present, different researchers employ varying experimental techniques, crack-healing assessment procedures, and durability evaluation methods, making direct comparison among different SHC technologies highly difficult.

Healing efficiency is often evaluated using diverse parameters such as crack closure percentage, permeability reduction, compressive strength recovery, ultrasonic pulse velocity, and microscopic analysis of healing products. No globally standardised procedure currently exists to uniformly assess these parameters across different healing mechanisms and environmental conditions. The absence of standardisation creates uncertainty regarding practical design implementation and industrial acceptance. Consequently, future research must focus on the development of internationally recognised testing standards, durability assessment protocols, and lifecycle evaluation methodologies for reliable comparison and commercial application of SHC systems.

9.3 Limited Research on Multifunctional Hybrid SHC Systems

Although several individual SHC mechanisms such as bacterial healing, microencapsulation, vascular networks, and SAP technologies have been extensively investigated, comparatively limited research has focused on multifunctional hybrid SHC systems capable of combining multiple healing approaches within a single infrastructure material.

Hybrid systems possess significant potential because they can overcome the limitations associated with individual healing mechanisms and provide improved crack remediation, repeated healing functionality, enhanced durability recovery, and intelligent monitoring capability (Vignesh et al., 2025). The interaction between multiple healing agents, compatibility within the cementitious matrix, and optimisation of multifunctional performance remain insufficiently understood. Further research is therefore necessary to develop highly efficient hybrid SHC systems capable of simultaneously providing structural reliability, environmental sustainability, repeated healing capability, and smart infrastructure integration.

9.4 Integration with Artificial Intelligence and Smart Infrastructure

The integration of SHC technologies with artificial intelligence, Internet of Things (IoT)-enabled sensing systems, digital twins, and predictive maintenance frameworks remains at an early stage

of development. Although recent studies have explored AI-assisted crack detection and smart monitoring systems, limited research has investigated fully autonomous infrastructure systems capable of real-time self-diagnosis, healing activation, and predictive structural management.

Future smart infrastructure systems are expected to combine SHC materials with embedded sensors, wireless communication technologies, machine-learning algorithms, and digital monitoring platforms for continuous infrastructure assessment and autonomous maintenance decision-making. Challenges related to data integration, sensor durability, real-time analytics, and system interoperability remain largely unresolved (McMillan, 2023; Yahia et al., 2025). Addressing these interdisciplinary challenges will be essential for the development of intelligent and self-sustaining infrastructure systems in future civil engineering applications.

9.5 Economic and Commercialisation Research Gaps

Limited research has focused on comprehensive economic feasibility assessment and large-scale commercialisation strategies. Most existing investigations primarily emphasise laboratory healing efficiency and material performance, while comparatively less attention has been devoted to lifecycle economic analysis, industrial scalability, market readiness, and practical implementation strategies.

The high production cost of specialised healing agents, encapsulation technologies, and smart sensing systems remains a major barrier to widespread industrial adoption. Uncertainties associated with long-term maintenance savings and infrastructure lifecycle performance restrict commercial confidence among construction industries and infrastructure authorities (Azanaw, 2025). Future research should therefore emphasise cost optimisation, industrial manufacturing strategies, and large-scale implementation frameworks to facilitate the transition of SHC technologies from experimental research to commercial infrastructure applications.

10 Future Research Directions and Technological Outlook

10.1 Development of Intelligent Autonomous Infrastructure Systems

The future development of self-healing concrete is expected to move beyond conventional crack remediation toward fully autonomous and intelligent infrastructure systems capable of self-diagnosis, real-time monitoring, predictive maintenance, and adaptive structural response. Future

SHC technologies are likely to integrate advanced sensing systems, artificial intelligence, digital twins, and wireless communication networks to create infrastructure capable of continuously assessing its structural condition and initiating autonomous healing actions without human intervention (McMillan, 2023).

The incorporation of machine-learning algorithms and data-driven monitoring platforms will significantly improve the prediction of crack propagation, structural deterioration, and maintenance requirements under varying environmental and loading conditions. Such intelligent systems will play a vital role in the development of next-generation smart cities, resilient transportation networks, and climate-adaptive infrastructure capable of operating efficiently under increasingly complex urban and environmental challenges.

10.2 Advanced Hybrid Self-Healing Technologies

Future research is expected to focus extensively on the development of multifunctional hybrid SHC systems that combine multiple healing mechanisms within a single material platform. Hybrid systems integrating bacterial healing, vascular networks, microencapsulation, nanomaterials, and superabsorbent polymers possess substantial potential for improving healing reliability, repeated crack remediation, and long-term structural performance (Vignesh et al., 2025).

The combination of different healing technologies can overcome the limitations associated with individual systems while simultaneously enhancing mechanical compatibility, environmental adaptability, and durability recovery. In addition, future hybrid SHC materials may incorporate self-sensing functionality capable of detecting crack initiation and activating targeted healing responses automatically. Such multifunctional materials are expected to significantly improve infrastructure resilience and reduce long-term maintenance dependency in critical civil engineering applications.

10.3 Integration with Artificial Intelligence and Digital Twins

Artificial intelligence and digital twin technologies are expected to become integral components of future SHC infrastructure systems. Digital twins can provide virtual replicas of physical structures capable of continuously receiving real-time data from embedded sensors and monitoring systems. This integration will enable predictive structural assessment, simulation of crack

propagation behaviour, optimisation of maintenance schedules, and evaluation of healing efficiency under different environmental conditions (Yahia et al., 2025).

AI-assisted infrastructure systems may also facilitate automated decision-making for maintenance prioritisation and infrastructure management. By integrating SHC materials with AI-driven predictive analytics and digital twin platforms, future infrastructure systems can achieve enhanced operational efficiency, improved durability management, and reduced lifecycle costs. Such advancements are expected to revolutionise infrastructure maintenance strategies and significantly contribute to sustainable urban development.

10.4 Sustainable and Low-Carbon SHC Materials

Sustainability considerations are expected to strongly influence future SHC research and material development. Future investigations will likely focus on the incorporation of low-carbon binders, recycled construction materials, geopolymer systems, and bio-based healing agents capable of reducing environmental impact while maintaining efficient crack-healing performance (Vaduganathan, 2025).

Researchers are also exploring carbon-sequestering bacterial systems and environmentally friendly encapsulation materials capable of contributing to carbon neutrality objectives within the construction industry. The development of sustainable SHC technologies will therefore support global climate-resilience initiatives, circular-economy strategies, and low-carbon infrastructure development programmes aimed at reducing greenhouse gas emissions associated with conventional construction practices.

10.5 Large-Scale Commercialisation and Industrial Adoption

Although SHC technologies have demonstrated substantial scientific progress, future research must increasingly emphasise practical implementation and industrial scalability. Large-scale manufacturing methods, cost-effective healing materials, industrial standardisation, and field demonstration projects will be essential for facilitating widespread commercial adoption.

Future collaborations among researchers, construction industries, infrastructure agencies, and policymakers will play a crucial role in developing practical implementation frameworks and regulatory guidelines for SHC applications (Agbamu et al., 2024). In addition, the incorporation of

SHC systems into smart-city infrastructure, transportation networks, marine facilities, and climate-resilient construction projects is expected to accelerate industrial acceptance and global market expansion over the coming decades.

Table 5. Future Directions in Self-Healing Concrete Research

Future Direction	Expected Advancement	Potential Impact
Intelligent Infrastructure	AI-integrated autonomous monitoring and healing systems	Predictive maintenance and reduced infrastructure failure
Hybrid SHC Systems	Combination of bacterial, vascular, SAP, and encapsulation technologies	Enhanced healing reliability and multifunctionality
Digital Twin Integration	Real-time structural simulation and monitoring	Smart infrastructure management
Sustainable Materials	Development of low-carbon and bio-based SHC materials	Reduced environmental impact
Industrial Scalability	Cost-effective manufacturing and standardisation strategies	Large-scale commercial implementation

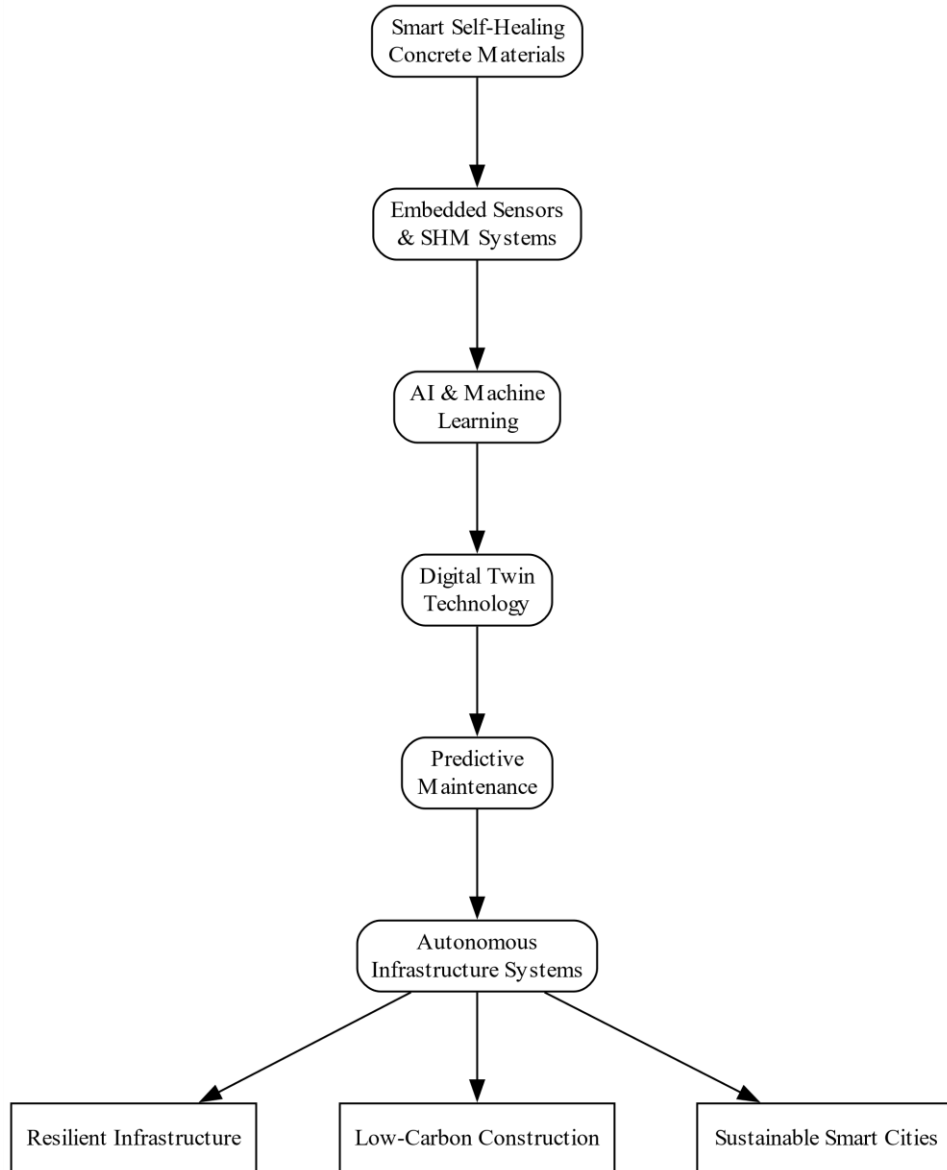


Figure 5 Future Vision of Autonomous SHC Infrastructure

11. Conclusion

Self-healing concrete is one of the most promising developments in the field of construction materials and sustainable infrastructure engineering. Self-sensing, self-sealing, and self-repairing of cracks are some of the most promising features of SHC systems, which can lead to better durability, safety, and service life in the area of civil infrastructure. Typical concrete structures are very susceptible to cracking due to exposure to the environment, shrinkage, thermal stress, chemical attack, and mechanical load, often leading to failure of the concrete's durability, corrosion

of its reinforcement, and expensive maintenance activities. SHC technologies offer an innovative solution that, in this context, can contribute to reducing the deterioration of the infrastructure while improving its long-term performance.

The chapter covers in detail the historical evolution, healing mechanism, comparison of performances, sustainability benefits, emerging applications, challenges, research gaps, and future directions of SHC systems. The autogenous healing, bacterial mineral precipitation, microencapsulation, vascular healing systems, and superabsorbent polymer-based technologies for healing were critically analyzed based on their healing efficiency, durability, recovery, environmental sustainability, and practical applicability. Of these strategies, hybrid SHC systems with multiple healing mechanisms have proven to have significant potential in enhancing the reliability of crack remediation and multifunctional infrastructure performance.

Additionally, the study identified the pivotal role of sustainable and climate-resilient infrastructure development with the use of SHC technologies. SHC systems can significantly reduce the amount of materials used, repair costs, and embodied carbon emissions, as well as decrease the frequency of maintenance, by extending the service life. The combination of SHC with other CIMs, low-carbon binders, and smart infrastructure technologies is an excellent contribution toward the global sustainability initiatives and the low-carbon construction strategies.

With recent developments in AI, IoT (Sensing) systems, SHM, Digital Twins, and Additive Manufacturing, SHC has turned into an intelligent infrastructure technology, able to monitor, predict, and self-repair autonomously. The interdisciplinary developments are anticipated to have significant influence in the future development of smart cities, resilient transportation systems, marine infrastructure, and sustainable urban development.

There are still some problems that hinder the use of SHC systems on a large scale in commercial applications. The high production costs, field validation of production in a few small-scale trials, non-standardized evaluation procedures, questions regarding the long-term durability, and the limited scale are still key constraints that need to be addressed. Thus, there is a need for future research to focus on cost optimization, industrial standardization, hybrid healing technologies, long-term field monitoring, and incorporation with smart infrastructure management systems.

In conclusion, self-healing concrete is a groundbreaking and promising technology for the future, offering a sustainable solution for enhancing the durability and performance of civil engineering structures. Further interdisciplinary research and collaboration between academia, industry, and infrastructure agencies are necessary to enable the successful large-scale deployment of SHC systems in the development of resilient and sustainable infrastructure of the future (Nguyen et al., 2023; Yahia et al., 2025)

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