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Advancements in Self-Healing Concrete: Sustainable Solutions for Enhanced Durability and Structural Resilience

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ABSTRACT

Self-healing concrete has emerged as a transformative innovation in sustainable structural engineering, addressing the challenges of durability degradation, cracking, and high maintenance costs in conventional cement-based materials. It utilizes advanced cementitious composites incorporating industrial by-products, chemical additives, and bio-based systems, such as bacteria-induced calcium carbonate precipitation, to autonomously repair cracks. Recent developments in multifunctional and intelligent concrete systems, integrating self-healing with sensing capabilities, have further enhanced structural resilience. Despite the promising benefits in reducing environmental impact and maintenance costs, challenges remain in large-scale implementation, microbial stability, and long-term performance validation.

Keywords: *Self-Healing Concrete, Sustainability, Bio-Based Systems, Structural Resilience.*

I. INTRODUCTION

Self-healing concrete had emerged as a transformative innovation in sustainable structural engineering, primarily aimed at addressing the persistent challenges of cracking, durability degradation, and high maintenance costs associated with conventional cement-based materials. The construction industry had been recognized as one of the largest contributors to global carbon emissions and resource depletion, largely due to extensive cement production and continuous infrastructure repair requirements (Kalantari, 2020). In response to these environmental concerns, researchers had increasingly focused on developing advanced cementitious composites capable of autonomous crack repair and extended service life. Early studies had indicated that the incorporation of industrial by-products and supplementary cementitious materials, such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS), had significantly improved both mechanical performance and sustainability outcomes (Cao et al., 2026). These materials had not only reduced cement consumption but had also enhanced hydration processes and microstructural densification, thereby contributing to improved durability and reduced permeability. Furthermore, the integration of chemical additives such as sodium silicate and calcium nitrate had been shown to promote internal crack sealing and water absorption recovery, thereby strengthening the self-healing potential of cementitious systems (Cao et al., 2026). Parallel research had also highlighted that self-healing concrete had been conceptually aligned with the broader objectives of sustainable architecture, where material longevity, resource efficiency, and reduced lifecycle environmental impact had been considered essential design parameters (Kalantari, 2020). Consequently, self-healing concrete had been positioned as a key material innovation supporting next-generation resilient and eco-friendly infrastructure development.

The development of self-healing concrete had been significantly advanced through both biological and autonomic healing mechanisms, which had expanded the scope of material functionality beyond traditional passive durability. Bio-based self-healing concrete systems, particularly bacteria-induced calcium carbonate precipitation techniques, had been widely investigated due to their ability to autonomously seal microcracks under favorable environmental conditions. Pooja and Tarannum (2025) had reported that bacteria-based systems had demonstrated improvements in compressive strength, water resistance, and chloride penetration resistance, provided that adequate moisture and crack width conditions had been maintained. Similarly, Mitikie and Elsaigh (2024) had explained that bacterial activity, activated through urea hydrolysis, had facilitated calcite formation within cracks, thereby restoring structural integrity and extending service life. However, these studies had also emphasized that the efficiency of bacterial self-healing had depended heavily on microbial viability, nutrient compatibility, and environmental stability within the concrete matrix. Schreiberová et al. (2019) had further demonstrated that while certain nutrient additives such as calcium nitrate and calcium lactate had enhanced early-age strength development, other components such as yeast extract had adversely affected mechanical properties, thereby highlighting the necessity for optimized chemical formulations. In addition to biological approaches, capsule-based and mineral-based self-healing systems had also been explored to improve reliability and scalability. Cao et al. (2026) had demonstrated that optimized combinations of mineral admixtures had enabled synergistic interactions that improved both strength recovery and crack sealing efficiency. Moreover, Irico et al. (2017) had shown that sodium silicate-based healing agents had chemically interacted with hydration products such as calcium hydroxide and calcium aluminate phases, forming secondary cementitious gels that had contributed to crack closure and mechanical restoration. These findings had collectively indicated that self-healing mechanisms in concrete had evolved into a multidisciplinary domain integrating microbiology, chemistry, and materials engineering.

In recent years, research had further expanded toward multifunctional and intelligent concrete systems that had integrated self-healing capability with sensing, environmental adaptability, and lifecycle optimization. Sharma et al. (2024) had reported that self-healing concrete incorporating recycled materials had exhibited porous, water-retentive characteristics suitable for sustainable applications such as green infrastructure systems, while self-sensing concrete had been developed using conductive fillers like carbon nanotubes, steel fibers, and nickel particles to enable real-time structural monitoring. De Jong et al. (2021) had emphasized that advancements in smart materials, including shape memory alloys and engineered cementitious composites, had enabled structures to autonomously respond to stress, damage, and environmental changes, thereby improving resilience and safety. Additionally, digital engineering tools such as Building Information Modeling (BIM) and computational simulation had been reported to enhance material optimization, predictive maintenance, and lifecycle management efficiency. From an economic and environmental perspective, Panza Uguzzoni et al. (2023) had demonstrated through life-cycle costing analysis that self-healing concrete had significantly reduced maintenance frequency, operational costs, and environmental impacts compared to traditional concrete systems. Similarly, Onyelowe et al. (2022) had shown that bacterial self-healing concrete had achieved lower global warming potential and improved eco-toxicity performance while maintaining satisfactory mechanical strength, as validated through artificial intelligence-based predictive modeling techniques. Gardner et al. (2018) had further identified cracking as the most prevalent form of deterioration in concrete infrastructure and had emphasized that self-healing materials had the potential to substantially reduce long-term repair requirements in critical infrastructure such as bridges and highways. Overall, the literature had consistently demonstrated that self-healing concrete had evolved into a highly promising sustainable construction material; however, challenges related to large-scale implementation, long-term durability validation, microbial stability, and standardized performance evaluation had remained key areas for future research and development.

II. RESEARCH BACKGROUND

Cao et al. (2026) had examined the urgent need to reduce the construction sector's carbon footprint by promoting the resource-efficient use of industrial by-products in cementitious composites. The study had systematically investigated the individual and combined effects of six mineral and chemical admixtures, namely fly ash, silica fume, ground granulated blast furnace slag (GGBS), sodium silicate, sodium bicarbonate, and calcium nitrate, on compressive strength and self-healing performance. A unified testing protocol, Taguchi L27 orthogonal array, and an improved response surface methodology (RSM) had been employed to optimize mix proportions while minimizing experimental cost. The findings had shown that replacing 30% of cement with GGBS had maximized compressive strength, whereas 60% GGBS had optimized crack healing and strength recovery. Sodium silicate and calcium nitrate had significantly enhanced internal crack healing and water absorption recovery, with limited influence on strength. The study had concluded that the synergistic interaction of admixtures provided an effective basis for developing sustainable, high-performance self-healing concrete.

Pooja and Tarannum (2025) had presented a comprehensive review of self-healing concrete (SHC) as a promising approach for improving the durability and service life of concrete structures while reducing the dependence on external repair interventions. The authors had examined various self-healing techniques, including autogenic and autonomic methods, with particular emphasis on bacteria-based and capsule-based systems. They had discussed the essential conditions required for effective healing, such as moisture availability, crack width, and hydration time, and had explained their influence on the healing process. The review had further evaluated the quality and effectiveness of different SHC strategies, especially the selection, growth conditions, and implementation of bacteria as healing agents. It had been reported that bacteria-based SHC positively influenced compressive strength, water absorption, and chloride permeability resistance. The study had also highlighted existing limitations and had suggested future research directions for advancing SHC in sustainable construction and infrastructure development.

Sharma et al. (2024) had reviewed recent advancements in biotechnology and material science that had contributed to the development of smart and innovative construction materials, particularly self-healing and self-sensing concrete. The authors had reported that self-healing concrete, composed of nearly 90% recycled materials, had exhibited hyper-porous characteristics, enabling water retention similar to a sponge and supporting eco-friendly applications such as green walls and green roofs. They had further noted that self-sensing concrete, also known as piezoresistive concrete, had been developed through the incorporation of functional fillers such as carbon fibres, carbon nanotubes, nickel powder, and steel fibres, which had enhanced its ability to detect stress, strain, cracking, and damage while also improving mechanical performance. The study had employed a systematic literature review to examine recent developments, comparative applicability, manufacturing processes, costs, setting time, and environmental and economic benefits. The findings had suggested that these materials held significant promise for future construction practices and policy formulation.

Mitikie and Elsaigh (2024) had emphasized the significant role of bacteria in self-healing concrete for promoting sustainable construction practices. They had observed that concrete was continuously exposed to environmental interactions, which had led to increased maintenance costs and sustainability concerns. The review had highlighted that the bacterial-induced calcite precipitation process, activated through the enzymatic hydrolysis of urea, had facilitated the formation of calcium carbonate crystals within concrete. This process had improved the mechanical strength and durability characteristics of concrete, thereby extending its service life. The authors had further noted that ensuring bacterial compatibility within concrete was essential and could be affected by admixtures such as superplasticizers, accelerators, and the viability of bacterial spores. They had suggested that collaborative efforts among researchers and stakeholders were necessary to overcome challenges related to scalability, durability, and standardization. Additionally, they had proposed future directions including optimization of bacterial concrete, use of genetically modified bacteria, sustainable manufacturing practices, and smart damage-detection technologies.

Panza Uguzzoni et al. (2023) examined the growing importance of concrete as one of the most widely used construction materials and highlighted recent research efforts directed toward extending the service life of reinforced concrete structures through self-healing properties. The study was aimed at reducing maintenance interventions and minimizing associated environmental impacts while also addressing issues of cost and financial feasibility. To support the selection of preferable material alternatives during the early design stages, the authors proposed a methodology based on a life-cycle perspective using the Life-Cycle Costing (LCC) approach. Three material solutions, namely traditional concrete and two types of self-healing concrete, were compared for a wall component case study in Turin, Northern Italy, through Global Cost calculations. The study further combined LCC with the Factor Method (FM) to account for service life performance. The findings indicated that self-healing concrete offered significant benefits through reduced maintenance costs, improved durability, enhanced residual value, and lower environmental impacts.

Onyelowe et al. (2022) had examined the environmental and mechanical performance of Bacillus subtilis-based self-healing concrete (SHC) as a sustainable alternative to conventional concrete, considering the high annual CO_2 emissions associated with concrete production. The study had evaluated the life cycle assessment (LCA) of SHC using indicators such as global warming potential, terrestrial acidification, eco-toxicity, and human toxicity. It had been reported that the SHC-350 mix exhibited 18% lower global warming potential than self-healing geopolymer concrete cited in earlier literature, although the most impactful mix showed about 6% higher CO_2 emissions. The study had further indicated a 69–75% reduction in terrestrial acidification compared to previous findings. In addition, artificial intelligence models had been applied to predict compressive, splitting tensile, and flexural strengths, along with slump. Among the models, ANN had outperformed GEP and EPR by providing more accurate predictions with minimal error and superior overall performance.

De Jong et al., (2021) examined the ongoing transformations in the field of structural engineering, which were reportedly driven by innovations in materials science and novel engineering methods. They presented a comprehensive analysis of these innovative practices in advanced materials and structural engineering, emphasizing their influence on constructing safer, more efficient, and sustainable structures. The study highlighted that advancements in materials, including ultra-high-performance concrete, self-healing materials, and smart sensors, had altered approaches to infrastructure construction and monitoring. For example, the integration of shape memory alloys and engineered cementitious composites was reported to enable structures to adapt to stress and heal autonomously, thereby enhancing longevity and resilience against environmental threats. The authors also noted that the development of lightweight, high-strength materials facilitated more intricate architectural designs without compromising structural integrity. Furthermore, they observed that digital tools such as Building Information Modeling (BIM), 3D printing, and computational simulation had improved fabrication precision, material optimization, and risk reduction, collectively advancing eco-friendly and disaster-resilient construction practices.

Kalantari (2020) emphasized that sustainable architecture was a critical factor for fostering sustainable societies and ensuring overall environmental sustainability. The study argued that human life and the survival of other creatures could be jeopardized if environmental sustainability were compromised, highlighting the urgent need to consider sustainable architectural factors. It was noted that the construction sector contributed significantly to global material consumption and energy use, necessitating strategies that could enhance building sustainability. Kalantari suggested that continuing conventional construction practices would negatively impact both current and future generations. The research highlighted the decisive role of building materials, particularly intelligent and self-healing materials, in mitigating the harmful effects of construction by improving building quality and longevity. The study investigated principles and practical rules for implementing such materials and explored their potential applications for achieving structural stability. Ultimately, it was concluded that the use of self-healing materials could advance sustainable architecture and improve the overall sustainability of buildings.

Schreiberová et al., (2019) investigated the composition of biological self-healing agents and their effects on concrete material characteristics. The study noted that the direct addition of mixtures containing bacterial spores and nutrients into the concrete matrix had been widely examined in prior research. Under specific conditions, the microorganisms were reported to produce $CaCO_3$, which enabled autonomous sealing of microcracks and suggested potential for more durable and cost-effective structures. However, it was observed that the self-healing agents, particularly the nutrients, could either positively or negatively affect material properties. The authors directly incorporated commonly proposed nutrients, including calcium lactate, calcium nitrate, calcium formate, urea, and yeast extract, into cement mortar during mixing, and assessed their influence on compressive strength, flexural strength, and rheology. Findings indicated that calcium nitrate, calcium formate, calcium lactate, and urea generally enhanced early-age compressive strength, whereas yeast extract caused a significant decrease, highlighting the need for dose optimization. Flexural strength was found to be minimally impacted.

Gardner et al., (2018) examined the substantial annual costs associated with repair, maintenance, and replacement of civil engineering infrastructure in the UK, noting that these expenditures attracted significant attention. They observed that both existing and newly constructed concrete structures frequently experienced repair and maintenance issues, yet objective, industry-supported data on the prevalence and nature of these problems had been limited. To address this gap, the Materials for Life (M4L) EPSRC-funded research project commissioned a market research exercise, which revealed that cracking in concrete structures was the most commonly reported form of damage by clients, design team members, and contractors. Structures subjected to dynamic loads, such as bridges, were found to be particularly vulnerable, with damage predominantly occurring at joints, bearings, and decks. Gardner et al. highlighted that current longevity-enhancing approaches relied on additional cementitious material, while the M4L team proposed self-healing cementitious materials, identifying highways, general infrastructure, and water-retaining structures as the most promising applications for reducing whole-life costs and maintenance interventions.

Irico et al., (2017) investigated the identification of cost-effective healing agents for cement-based materials that could promote autonomous crack healing, addressing the challenge of enhancing the durability of building structures. They carried out a detailed examination of the chemical reactivity between hydrated Portland cement and sodium silicate solutions, employed as healing agents, aiming to quantitatively assess both the reactivity and the actual binding capacity of sodium silicate. Mechanical recovery was evaluated through strength tests conducted on hydrated cement treated with sodium silicate. Furthermore, XRPD and solid-state NMR analyses were utilized to determine reaction times, the species involved, and the nature and stability of the resulting products. The study highlighted that sodium silicate interacted not only with $Ca(OH)_2$ (portlandite) but also with calcium aluminate phases (AFt, AFm, TAH), facilitating the extraction of calcium and/or aluminum ions and leading to the formation of crystalline or semi-crystalline C–S–H/C–A–S–H tobermorite phases, thereby contributing to the self-healing process.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective	Methodology	Key Findings	Contribution to Self-Healing Concrete Development
Cao et al. (2026)	To optimize sustainable self-healing concrete using industrial by-products and admixtures	Taguchi L27 orthogonal array and Response Surface Methodology (RSM)	GGBS (30%) improved compressive strength; 60% enhanced healing; sodium silicate and calcium nitrate improved crack healing	Provided optimized mix design for sustainable high-performance self-healing concrete
Pooja & Tarannum (2025)	To review self-healing techniques in concrete	Systematic literature review	Bacteria-based SHC improved strength, durability, and permeability resistance	Highlighted autogenic and autonomic healing mechanisms for sustainable infrastructure
Sharma et al. (2024)	To analyze smart construction materials including self-healing and self-sensing concrete	Comparative literature review	Recycled-material SHC showed eco-benefits; self-sensing concrete enabled damage detection	Introduced multifunctional smart concrete systems for future construction
Mitikie & Elsaigh (2024)	To study bacterial concrete for sustainability	Review-based analysis	$CaCO_3$ precipitation improved strength and crack sealing	Emphasized microbial healing and sustainability benefits in concrete
Panza Uguzzoni et al. (2023)	To evaluate economic feasibility of self-healing concrete	Life-Cycle Costing (LCC) and Factor Method	SHC reduced maintenance cost and improved durability	Provided economic justification for SHC adoption in infrastructure
Onyelowe et al. (2022)	To assess environmental and mechanical performance of SHC	Life Cycle Assessment (LCA) and AI models	Reduced global warming potential; ANN showed best prediction accuracy	Linked environmental sustainability with AI-based performance prediction
De Jong et al. (2021)	To analyze innovative structural engineering materials	Review of advanced materials and digital tools	Smart materials improved adaptability and resilience	Integrated SHC with smart infrastructure and digital engineering
Kalantari	To explore	Conceptual and	SH materials	Linked SHC with

(2020)	sustainability role of self-healing materials in architecture	literature-based study	improved building longevity and reduced environmental impact	sustainable architectural development
Schreiberová et al. (2019)	To evaluate effect of bacterial nutrients on concrete properties	Experimental testing of additives	Calcium compounds improved strength; yeast extract reduced performance	Identified importance of nutrient optimization in bacterial SHC
Gardner et al. (2018)	To identify construction defects and benefits of SH materials	Industry survey and case analysis	Cracking was most common damage; SHC reduced maintenance needs	Established real-world necessity of self-healing materials
Irico et al. (2017)	To study sodium silicate-based self-healing mechanism	NMR and XRD analysis	Formation of C-S-H and C-A-S-H improved crack sealing	Explained chemical mechanism of autonomic healing in cement

IV. CONCLUSION

The reviewed literature had collectively established that self-healing concrete had emerged as a highly promising advancement in sustainable structural engineering, addressing critical limitations of conventional cement-based materials such as cracking, durability loss, and high maintenance demand. Studies had consistently demonstrated that the incorporation of industrial by-products like fly ash and GGBS, along with chemical and microbial agents, had significantly enhanced both mechanical performance and autonomous crack-healing capability (Cao et al., 2026; Pooja & Tarannum, 2025). The findings had indicated that self-healing mechanisms, whether autogenic, capsule-based, or bacteria-induced, had contributed to improved compressive strength, reduced permeability, and extended service life of concrete structures. Furthermore, life-cycle assessments had confirmed that self-healing concrete had offered substantial environmental benefits by reducing carbon emissions, lowering maintenance frequency, and improving overall resource efficiency (Onyelowe et al., 2022; Panza Uguzzoni et al., 2023). In addition, the integration of smart materials and sensing technologies had expanded the functional capabilities of concrete, enabling structural health monitoring alongside self-repair mechanisms (Sharma et al., 2024; De Jong et al., 2021). Overall, the literature had strongly suggested that self-healing concrete had the potential to transform traditional construction practices into more durable, cost-effective, and environmentally sustainable systems.

V. FUTURE SCOPE

The future development of self-healing concrete is expected to focus on improving scalability, long-term performance, and real-world applicability. One major direction involves the optimization of bacterial and chemical healing agents to enhance compatibility with cementitious environments while ensuring consistent healing efficiency under varying climatic conditions. Advanced genetic engineering of bacteria and nano-encapsulation techniques may further improve the survival and activation of healing agents in concrete matrices. Another important area includes the integration of artificial intelligence and machine learning models to predict healing efficiency, structural damage progression, and lifecycle performance under different loading conditions. Moreover, the combination of self-healing mechanisms with smart sensing technologies is likely to enable real-time monitoring and adaptive repair systems in infrastructure. Future research may also focus on reducing production costs and improving standardization protocols to support large-scale industrial adoption. Additionally, sustainability assessments using life-cycle approaches will remain crucial to quantify environmental benefits and guide policy development. Ultimately, the evolution of self-healing concrete is expected to contribute significantly to the development of intelligent, resilient, and sustainable infrastructure systems worldwide.

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