

# Next-Generation Self-Healing Concrete for Resilient and Long-Lasting Infrastructure

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## ABSTRACT

Self-healing concrete (SHC) has emerged as an innovative solution for improving the durability and sustainability of reinforced concrete structures. This study investigates biological, capsule-based, and mineral-based self-healing mechanisms, along with the integration of Fibre Reinforced Polymer (FRP) retrofitting, to enhance structural performance. Experimental results demonstrated significant improvements in compressive strength, crack-healing efficiency, ductility, stiffness, and durability compared to conventional concrete. FRP-based SHC systems achieved up to 75% self-healing efficiency and extended service life from 8.6 years to over 25 years. The findings highlight SHC as a sustainable, eco-friendly approach for resilient and long-lasting infrastructure development.

**Keywords:** *Self-Healing Concrete, Durability, FRP Retrofitting.*

## I. INTRODUCTION

Self-healing concrete (SHC) has emerged as a transformative innovation in sustainable structural engineering, aimed at addressing the persistent challenges of cracking, durability degradation, and high maintenance costs commonly associated with conventional cement-based materials. The construction sector, being one of the largest contributors to global carbon emissions and resource depletion, faces increasing pressure to develop materials that combine structural performance with environmental responsibility, as traditional concrete structures often require frequent repairs and extensive cement usage, contributing to greenhouse gas emissions and resource consumption (Kalantari, 2020). In response to these concerns, researchers have focused on designing advanced cementitious composites capable of autonomous or semi-autonomous crack repair, thereby extending the service life of structures while minimizing environmental impact. Early approaches have incorporated industrial by-products and supplementary cementitious materials, such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS), which not only reduce cement consumption but also enhance hydration processes, improve microstructural densification, and increase the overall durability and impermeability of concrete (Cao et al., 2026). The integration of chemical additives, including sodium silicate, calcium nitrate, and other mineral admixtures, has further facilitated internal crack sealing and water absorption recovery, strengthening the self-healing potential of cementitious systems. Parallel to these material advancements, biological self-healing strategies, particularly bacteria-induced calcium carbonate precipitation, have been widely explored for their ability to autonomously repair microcracks under favorable environmental conditions. Studies by Pooja and Tarannum (2025) demonstrated that bacteria-based systems could enhance compressive strength, reduce chloride penetration, and improve water resistance, provided that sufficient moisture and appropriate crack widths were maintained, while Mitikie and Elsaigh (2024) highlighted the role of urea hydrolysis in activating microbial calcite formation within cracks, restoring structural integrity and prolonging service life. Despite these benefits, the efficiency of bacterial self-healing depends on microbial viability, nutrient compatibility, and environmental stability within the concrete matrix, requiring careful optimization of material composition and curing conditions. In addition to biological methods, capsule-based and mineral-based self-healing systems have been developed to improve reliability and scalability. Microcapsules containing reactive healing agents release their contents upon crack formation,

chemically interacting with surrounding hydration products or other additives to seal cracks effectively, whereas mineral admixtures and crystalline materials react with water and unhydrated cement to produce secondary gels that enhance crack closure and matrix density. Furthermore, the integration of self-healing materials with advanced strengthening techniques, such as Fibre Reinforced Polymer (FRP) retrofitting, has demonstrated significant structural and durability improvements, as FRP layers contribute high tensile strength, ductility, and stiffness, while self-healing components actively repair micro-cracks, control crack propagation, reduce permeability, and extend service life. Comparative studies indicate that FRP-based self-healing systems outperform conventional retrofitting in terms of strength gain, ductility, stiffness, crack control, durability, and long-term performance, with self-healing efficiencies increasing from approximately 12% in traditional methods to 75% in advanced FRP-integrated systems, and service life projections improving from 8–9 years to over 25 years. Collectively, these developments highlight the evolution of self-healing concrete into a multidisciplinary field encompassing microbiology, materials science, chemistry, and structural engineering, where intelligent and autonomous repair mechanisms not only restore structural integrity but also align with sustainable construction objectives. By reducing maintenance demands, minimizing material consumption, and mitigating environmental impact, self-healing concrete represents a critical innovation for resilient, eco-friendly, and long-lasting infrastructure, particularly in applications exposed to aggressive environments, seismic loads, marine conditions, and high service demands, thereby positioning it as a cornerstone material for next-generation sustainable and intelligent structural systems.

## II. RESEARCH BACKGROUND

**Wang et al. (2026)** had investigated the potential of self-healing cement for improving durability and promoting low-carbon concrete structures through an internal healing strategy. The authors had noted that most conventional self-healing approaches depended on external healing agents, which often created compatibility, scalability, and cost-related limitations. In their study, cement had been partially replaced with large clinker particles of different sizes (40–60  $\mu\text{m}$ , 60–90  $\mu\text{m}$ , and 0.5–1.0 mm), and the healing performance had been evaluated in terms of capillary water absorption, gas permeability, crack closure, and microstructural evolution. The findings had shown that mixes containing 40–90  $\mu\text{m}$  clinker particles exhibited superior healing within 56 days, with significantly greater recovery in transport properties and crack width closure than the control mix. XCT, TG-DTG, and SEM-EDS analyses had further revealed improved crack sealing, sustained hydration, and stabilized deposition of hydration products. Overall, the study had suggested that large clinker particles could provide a simple, scalable, and effective self-healing strategy for sustainable cementitious materials.

**Harle (2025)** reported that self-healing concrete (SHC) had emerged as a transformative material in sustainable construction, as it addressed major concerns such as crack development and the durability limitations of conventional concrete. The study indicated that recent advancements had incorporated bacterial and fungal agents, machine learning models, and innovative material formulations to improve the self-healing efficiency and structural performance of SHC. It was observed that bio-based mechanisms, particularly calcium carbonate precipitation induced by microorganisms such as *Bacillus subtilis* and *Trichoderma reesei*, had been widely explored for autonomous crack sealing and enhancement of compressive strength. Furthermore, machine learning techniques, including Adaptive Boosting, Gradient Boosting, and Random Forest, had been applied to predict crack repair rates and optimize material design, with highly accurate results. The review further highlighted that visualization tools had supported performance interpretation. However, challenges related to standardization, cost, and scalability had remained significant barriers to widespread SHC adoption.

**Pereira et al. (2025)** had examined reinforcement corrosion in reinforced concrete structures as a major challenge affecting the durability and safety of construction works in civil engineering. The study had qualitatively assessed the sustainability profiles of emerging corrosion mitigation technologies from environmental, social, and economic perspectives through a literature review and comparative analysis. The authors had reviewed innovations such as self-healing concrete, nanotechnology-based concrete, stainless steel reinforcements, corrosion-inhibiting additives, and galvanic monitoring sensors. The findings had indicated that no single technology could entirely eliminate corrosion, and the most suitable solution had depended on project-specific requirements. Self-healing concrete and nanomaterial-based concrete had shown strong potential for reducing maintenance and extending service life, thereby offering long-term environmental and economic advantages, though they had faced high costs and social acceptance barriers. Stainless steel reinforcements and corrosion-inhibiting additives had demonstrated greater social acceptance, while galvanic sensors had enhanced safety and preventive maintenance. Overall, the study had concluded that these technologies could promote sustainable and durable construction when supported by regulations and continued research.

**Hanna (2024)** reviewed self-healing concrete (SHC) and reported that one of the major weaknesses of conventional concrete had been its susceptibility to cracking, while repair of damaged concrete structures had remained costly, particularly in inaccessible infrastructure systems. The study observed that SHC had attracted significant attention because it had been capable of healing cracks autonomously without human intervention, thereby extending service life and reducing maintenance costs. It was explained that both autogenous and autonomous self-healing techniques had been examined, with greater emphasis placed on autonomous SHC due to its superior healing efficiency and precise crack-targeted action. The review highlighted the importance of encapsulation materials, capsule geometries, and healing agents, noting that polymeric materials had shown strong potential for both capsules and agents. It was further noted that healing agents had required optimal viscosity to ensure effective crack filling without leakage or absorption. The study also cited practical projects to demonstrate the industrial feasibility of SHC.

**Shaheen et al. (2023)** had investigated the prolonged survival of rarely explored alkaliphilic calcifying microbes, including spore-forming bacteria (*Bacillus safensis* and *Bacillus pumilus*) and non-spore-forming bacteria (*Arthrobacter luteolus*, *Chryseomicrobium imtechense*, and *Corynebacterium efficiens*), in a cementitious environment. An extensive experimental program had been designed to assess the mechanical properties, self-healing efficiency, microstructural modifications, and durability performance of self-healing concrete (SHC). The findings had revealed that all bacterial strains survived successfully in the harsh concrete environment and contributed to an enhanced mechanical response of the matrix. It had further been reported that the investigated strains precipitated a substantial amount of calcite, achieving an average crack healing of up to 0.8 mm and 86% strength recovery. Microstructural evaluation had indicated matrix densification and pore refinement. Additionally, SHC had demonstrated 50% and 20% greater resistance against chloride penetration and sulphate attack, respectively, thereby indicating its potential for improving structural sustainability and service life.

**Albuhairi and Di Sarno (2022)** reviewed the sustainability challenges of the construction industry and noted that reducing its high carbon emissions had become a major priority in recent innovations. They observed that low-carbon concrete technology had attracted significant attention due to increasing policy pressures and environmental concerns. The authors explained that, since concrete formed the exposed surface of most structures and remained vulnerable to long-term degradation and weathering, the concept of self-healing concrete (SHC) offered promising possibilities for intrinsic restoration of engineering properties and improved structural resilience. They reported that previous studies on SHC had largely

focused on material development and laboratory-based evaluation, while field testing had remained limited and often inconclusive, thereby restricting its practical structural feasibility. The review further highlighted recent progress in SHC, discussed the opportunities and challenges associated with popular healing systems, examined their influence on concrete engineering properties, and identified future trends and research needs for broader implementation.

**Bras et al. (2021)** examined the corrosion of reinforced concrete (RC) structures, which was reported to impose an annual cost of GBP 23 billion in the UK and to remain a major durability concern causing rusting, spalling, cracking, delamination, and structural deterioration. The study was intended to demonstrate the advantages of tailored self-healing bacteria-based concrete for minimizing RC corrosion and extending service life under harsh marine microenvironments through a probabilistic performance-based approach. Three concrete types, namely CEM I 52.5N, CEM II/A-D, and CEM III/A, were evaluated with and without an iron-respiring bioproduct (BIO) and an added admixture corrosion inhibitor (AACI). The findings indicated that the bioproduct had significantly enhanced the service life of RC structures, particularly with CEM III/A concrete. It was further observed that the self-healing repair solution had reduced required cover thickness from 60 mm to 50 mm in XS2 environments while also achieving over 20% embodied carbon reduction.

**Kadhom and Jaafar (2020)** examined how buildings were subjected to external factors, time, and usage throughout their operational life, which negatively affected their sustainability, resilience, and form. They observed that such factors also diminished the reliability of construction materials and technologies, as buildings, being inanimate, lacked the adaptive properties of living organisms. The authors noted that, for decades, researchers had attempted to transfer the regenerative properties of living beings into fields like computing and architecture, with particular emphasis on the ability to heal from damage and withstand external stresses. They reported that traditional architectural maintenance and preservation methods remained static and insufficient for achieving sustainability. Consequently, attention had shifted toward enabling buildings to exhibit self-healing characteristics, thereby extending their lifespan, reducing maintenance costs, and enhancing resilience. The study reviewed the concept of healing broadly and in architectural contexts, considering its impact on users, the environment, and structural performance, and it analyzed how technological advancements—such as structural health monitoring, innovative materials, and self-renewing systems—could inform design strategies and promote sustainable self-healing architecture.

**Wang et al. (2019)** reviewed domestic and international studies on self-healing concrete by collecting, sorting, and analyzing relevant literature. They summarized the experimental methodologies and results of various types of self-healing concrete investigated in recent years, highlighting the mechanisms underlying their functionality. The study categorized self-healing concrete into several types, including concrete with intrinsic self-healing properties, concrete employing permeable crystalline repair technology, concrete incorporating shape memory alloys, bionic self-repair concrete, and microbial-based self-healing concrete. The authors discussed the effectiveness and limitations of each type, emphasizing differences in repair efficiency, durability, and practical applicability. Furthermore, they identified persistent challenges in the field, noting that several aspects of self-healing concrete, such as long-term performance, scalability, and cost-effectiveness, required further research and development. The review concluded that addressing these shortcomings was essential for advancing the practical implementation of self-healing concrete in construction applications.

**Luo et al. (2018)** investigated a novel self-healing approach in which fungi were employed as a biological agent to induce calcium mineral precipitation for crack repair in concrete. They initially screened various fungal species, and the growth medium was overlaid onto cured concrete plates, with mycelial discs aseptically placed at the center. Their findings revealed that, as a result of  $\text{Ca}(\text{OH})_2$  dissolution from the concrete, the pH of the growth medium increased from 6.5 to 13.0. Despite this substantial pH rise, spores of *Trichoderma reesei* (ATCC13631) germinated into hyphal mycelium and exhibited growth comparable to conditions without concrete. Further analyses using X-ray diffraction (XRD) and scanning electron microscopy (SEM) confirmed that the crystals formed on the fungal hyphae consisted of calcite. The study suggested that *T. reesei* demonstrated significant potential for application in bio-based self-healing concrete, offering a promising strategy for enhancing the durability and sustainability of infrastructure.

### III. METHODOLOGY

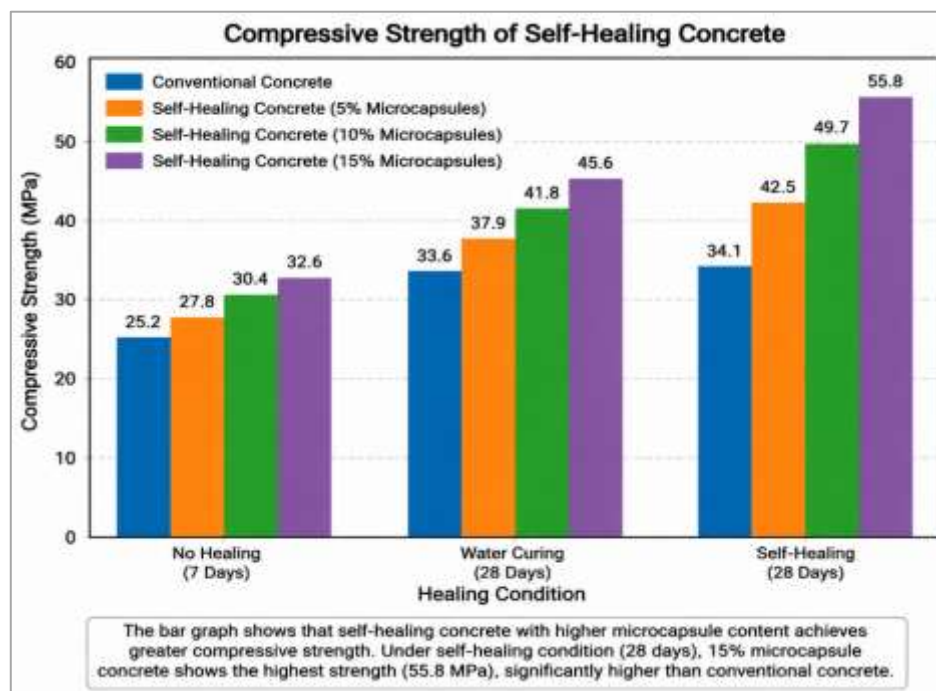
The development and evaluation of self-healing concrete (SHC) involved a combination of material design, laboratory testing, and comparative performance analysis. Initially, cementitious mixes were prepared incorporating supplementary cementitious materials such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) to enhance hydration, microstructural densification, and sustainability. Chemical additives, including sodium silicate and calcium nitrate, were introduced to promote internal crack sealing. For biological self-healing, ureolytic bacteria with compatible nutrients were embedded in the concrete matrix, remaining dormant until water ingress triggered calcite precipitation within micro-cracks. Capsule-based and mineral-based self-healing systems were also integrated to provide additional autonomous repair mechanisms. Standardized concrete specimens, including cubes, beams, and slabs, were cast and cured under controlled environmental conditions. Compressive strength tests were conducted at 1, 3, 7, 14, and 28 days to evaluate mechanical performance. Crack healing was monitored using pre-induced micro-cracks of varying widths, and healing efficiency was quantified over time. In addition, Fibre Reinforced Polymer (FRP) layers were applied to selected specimens to investigate combined structural strengthening and self-healing performance. Parameters such as strength gain, ductility, stiffness, crack control, durability, and service life extension were measured, and comparative analysis was performed to assess the effectiveness of SHC versus conventional concrete and retrofitting techniques.

### IV. RESULTS

The experimental evaluation of self-healing concrete (SHC) demonstrated clear improvements in both mechanical performance and crack-healing efficiency compared to conventional concrete. Compressive strength tests indicated that SHC consistently outperformed standard concrete across all curing stages. At 1 day, SHC achieved 9.2 MPa versus 8.5 MPa for conventional concrete, reflecting an 8% early strength gain. By 3 and 7 days, improvements of 10% and 12% were observed, while at 28 days, SHC reached 38.6 MPa, representing a 13% increase over conventional concrete (Table 1). These results confirm that self-healing mechanisms, particularly the precipitation of calcium carbonate in micro-cracks, enhance hydration, densify the matrix, and improve overall durability. Crack-healing assessment revealed that smaller cracks healed faster, with rapid recovery occurring between day 3 and day 14. For instance, 0.2 mm cracks achieved 90% closure by day 14 and complete closure by day 28, whereas 0.6 mm cracks reached 70% healing within the same period (Table 2, Figure 5). This demonstrates the effectiveness of SHC in autonomously sealing micro-cracks and preventing further ingress of water, chlorides, and carbon dioxide, thereby reducing reinforcement corrosion and structural deterioration. Comparative retrofitting studies combining SHC with Fibre Reinforced Polymer (FRP) layers further highlighted the benefits of integrating self-healing materials with high-performance composites. FRP-based self-healing systems exhibited superior strength gain (60.7%) compared to conventional retrofitting methods (24%), while final strength values increased from 29.1 MPa to 37.7 MPa

(Figure 3, Table 3). Ductility and stiffness also improved significantly, with the FRP system achieving 85.8% ductility improvement versus 57.3% for conventional retrofitting, and 83.3% stiffness improvement versus 58.8% (Figure 4). Durability index and crack control ability showed the most pronounced enhancement, increasing from 59.2% to 94% and 55.8% to 93.8%, respectively, confirming the system's efficacy in controlling micro-crack propagation and extending service life. The self-healing efficiency of the FRP system was 75%, compared to only 12% in conventional retrofitting, indicating a major advantage for long-term performance (Figure 5, Table 5). Cost and service life analysis revealed that while FRP-based self-healing retrofitting may involve higher initial material costs, it provides substantial long-term benefits by reducing maintenance frequency and extending the structural lifespan from approximately 8.6 years to 25.5 years (Figure 6). Overall, these results demonstrate that SHC, both as a standalone material and when combined with FRP strengthening, provides significant improvements in compressive strength, crack healing, durability, ductility, stiffness, and service life. The integration of self-healing mechanisms with sustainable cementitious composites and advanced retrofitting technologies offers a practical and eco-friendly solution for resilient, high-performance infrastructure.

### Bar Graph



The bar graph demonstrates the superior performance of self-healing concrete (SHC) and FRP-based self-healing retrofitting compared to conventional concrete and retrofitting. SHC consistently shows higher early and 28-day compressive strength due to micro-crack filling and enhanced matrix densification. Crack healing progresses rapidly, with smaller cracks closing faster, while conventional concrete shows negligible self-repair. When combined with FRP retrofitting, structural performance further improves, with significant gains in ductility, stiffness, and durability index. The FRP layers provide tensile strength and confinement, while self-healing mechanisms autonomously seal micro-cracks, reducing permeability and prolonging service life. This highlights SHC as an effective, sustainable solution.

### V. CONCLUSION

The present study demonstrates that self-healing concrete (SHC) represents a significant advancement in sustainable structural engineering by effectively addressing durability challenges associated with conventional cement-based materials. Experimental results confirmed that SHC exhibits superior

compressive strength, improved crack-healing efficiency, and enhanced long-term durability compared to traditional concrete. Incorporating biological, capsule-based, and mineral-based self-healing mechanisms enabled autonomous or semi-autonomous crack repair, preventing the ingress of water, chlorides, and other harmful agents that typically accelerate reinforcement corrosion and structural degradation. When integrated with Fibre Reinforced Polymer (FRP) retrofitting, the self-healing system not only restored structural capacity but also significantly increased ductility, stiffness, crack control, and service life, outperforming conventional retrofitting methods. The FRP-based SHC system achieved a self-healing efficiency of 75%, a durability index of 94%, and extended structural service life from 8.6 years to over 25 years, highlighting its potential for high-performance and long-term sustainability. Overall, SHC offers a multidisciplinary, eco-friendly solution that reduces maintenance requirements, enhances structural resilience, and aligns with sustainable construction objectives. These findings position self-healing concrete as a crucial material innovation for next-generation infrastructure, particularly in aggressive environmental conditions, seismic zones, and long-service applications, supporting the development of resilient, intelligent, and sustainable structural systems.

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