

# Development of Self-Healing Ultra-High-Performance Concrete Using Smart Nanocapsules for Enhanced Structural Resilience

Rishab Singh<sup>1\*</sup>, Nita Rathore<sup>2\*</sup>, Harshit Kulkarni<sup>3\*</sup>

<sup>1</sup>Department of Civil Engineering, Yashwantrao Chavan College of Engineering, Nagpur, India

<sup>2</sup>Department of Civil Engineering, Institute of Engineering and Management, Kolkata, India

<sup>3</sup>Department of Civil Engineering, Sanjay Ghodawat University, Kolkata, India

\*Authors Email: rishab.s@ycce.ac.in, nita.r@iem.ac.in, harshit.k@sgu.ac.in

Received:  
Jan 14, 2026  
Accepted:  
Jan 16, 2026  
Published online:  
Jan 17, 2026

**Abstract:** Ultra-High-Performance Concrete (UHPC) represents a significant advancement in construction materials due to its exceptional strength, durability, and low permeability. However, its dense microstructure and low strain capacity result in microcrack formation under mechanical loading, thermal gradients, and shrinkage effects, which may compromise long-term structural performance. This study presents the development of a smart self-healing UHPC system incorporating polymer-filled nanocapsules designed to autonomously repair microcracks and enhance structural resilience. Nanocapsules with controlled size distribution were synthesized and embedded within the UHPC matrix at varying concentrations. Mechanical performance, crack-healing efficiency, microstructural evolution, and durability characteristics were systematically evaluated. Experimental results demonstrate that self-healing UHPC achieves up to 85% recovery in flexural strength after crack formation and exhibits significantly reduced permeability and chloride ion penetration compared to conventional UHPC. Microstructural analyses confirm effective crack sealing through polymerization and secondary hydration reactions. The findings indicate that nanocapsule-enabled UHPC offers a promising pathway toward sustainable, low-maintenance infrastructure capable of prolonged service life under aggressive environmental conditions.

**Keywords:** Self-Healing Concrete, Ultra-High-Performance Concrete, Nanocapsules, Structural Resilience, Smart Materials

## 1. Introduction

The rapid expansion of urban infrastructure and increasing exposure of structures to extreme environmental conditions have intensified the demand for advanced construction materials capable of delivering superior performance over extended service lives. Conventional concrete, despite its widespread use, is inherently prone to cracking due to its low tensile strength and brittle nature. These cracks act as pathways for aggressive agents such as chlorides, sulfates, and carbon dioxide, leading to steel reinforcement corrosion and premature structural deterioration. Maintenance and repair of cracked concrete infrastructure impose substantial economic and environmental burdens worldwide [1]. Ultra-High-Performance Concrete (UHPC) has emerged as a revolutionary material characterized by ultra-low porosity, compressive strengths exceeding 150 MPa, and exceptional durability. Its dense microstructure is achieved through optimized particle packing, low water-to-binder ratios, and the inclusion of supplementary cementitious materials such as silica fume. Steel fibers further enhance its tensile and flexural performance, making UHPC suitable for critical applications including long-span bridges, offshore platforms, and high-rise buildings [2]. However, the same dense microstructure that imparts high strength also restricts internal stress relaxation, resulting in microcracking under service loads and environmental actions. Traditional crack repair methods, including epoxy injection and surface sealing, are reactive, labor-intensive, and often impractical for inaccessible or submerged structures. As a result, the concept of self-healing concrete has gained prominence as a proactive approach to damage mitigation. Self-healing materials are inspired by biological systems, where damage triggers autonomous repair mechanisms without external intervention [3]. In cementitious materials, self-healing can occur through autogenous processes such as continued hydration and carbonation, though these mechanisms are limited in effectiveness and durability.

Autonomous self-healing approaches overcome these limitations by incorporating engineered healing agents within the concrete matrix. Among various strategies, nanocapsule-based systems have attracted significant attention due to their ability to protect healing agents during mixing and curing, release them upon crack formation, and ensure targeted repair. The integration of smart nanocapsules into UHPC presents a unique opportunity to combine ultra-high strength with autonomous damage repair, thereby enhancing structural resilience and sustainability. This research focuses on the development, characterization, and performance evaluation of self-healing UHPC incorporating polymer-filled nanocapsules. The study aims to investigate the influence of nanocapsule content on mechanical properties, crack-healing efficiency, durability, and microstructural evolution, providing insights into the feasibility of deploying such materials in real-world infrastructure systems.

## 2. Literature Review

Extensive research has been conducted on self-healing mechanisms in cementitious materials over the past two decades. Early studies primarily focused on autogenous healing, which relies on the hydration of unreacted cement particles and precipitation of calcium carbonate within cracks. While autogenous healing can effectively seal microcracks smaller than 50  $\mu\text{m}$ , its efficiency diminishes over time and is highly dependent on environmental conditions such as moisture availability [4]. To address these limitations, autonomous self-healing strategies have been developed, including bacterial-based healing, vascular networks, and encapsulated chemical agents. Bacterial self-healing systems utilize microorganisms capable of precipitating calcium carbonate when activated by moisture and nutrients. Although promising, concerns related to bacterial viability, cost, and long-term stability have restricted large-scale implementation [5]. Encapsulation-based self-healing systems offer greater control and reliability. Microcapsules or nanocapsules containing healing agents such as epoxy resins, polyurethane, or sodium silicate are embedded within the concrete matrix. Upon crack propagation, capsules rupture and release the healing agent, which reacts with the surrounding matrix to seal the crack [6]. Nanocapsules, in particular, provide advantages in terms of uniform dispersion, reduced impact on mechanical properties, and enhanced responsiveness to microcrack formation. Despite significant progress, limited studies have explored the integration of nanocapsule-based self-healing systems into UHPC, where the dense matrix and high fiber content pose additional challenges. This research seeks to bridge this gap by systematically evaluating the performance of nanocapsule-enabled UHPC under mechanical and environmental loading.

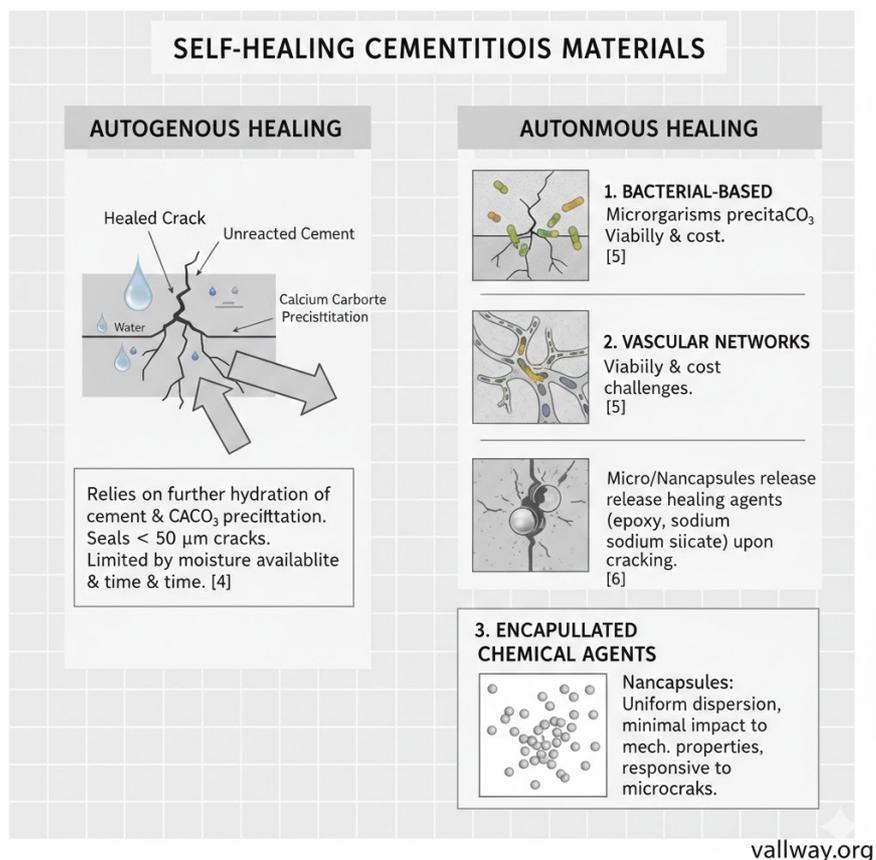


Fig. 1 SHCM

## 3. Materials and Experimental Methodology

The UHPC matrix was designed using ordinary Portland cement, silica fume, quartz powder, and fine quartz sand to achieve optimal particle packing and minimal porosity. A polycarboxylate-based superplasticizer was used to ensure adequate workability at low water-to-binder ratios. Steel fibers with a length of 13 mm and an aspect ratio of 65 were incorporated at a volume fraction of 2% to enhance tensile performance. Smart nanocapsules were synthesized through in-situ polymerization, producing capsules with a mean diameter of 300 nm and a polymeric healing agent core. The shell material was designed to rupture under tensile stress induced by crack formation while remaining stable during mixing. Nanocapsules were added to the UHPC mix at dosages of 0.5%, 1.0%, and 1.5% by weight of cement. Specimens were cast into molds for compressive, flexural, and durability testing and cured under controlled conditions. Mechanical tests were conducted in accordance with ASTM standards, while durability assessments included water permeability, chloride ion penetration, and freeze–thaw resistance tests [7].

#### **4. Mechanical Properties and Crack-Healing Efficiency**

The compressive strength of UHPC specimens decreased marginally with increasing nanocapsule content, primarily due to the introduction of non-load-bearing inclusions within the matrix. However, even at the highest nanocapsule dosage, compressive strengths exceeded 140 MPa, meeting the requirements for UHPC applications. Flexural testing revealed a pronounced improvement in post-cracking behavior for self-healing specimens. Controlled cracks were induced, and specimens were allowed to heal under moist conditions. After 14 days, UHPC containing 1.0% nanocapsules exhibited flexural strength recovery of up to 85%, compared to less than 40% for conventional UHPC. This recovery is attributed to the polymerization of the healing agent within cracks, restoring stress transfer across damaged zones [8]. Repeated loading tests demonstrated that self-healing UHPC maintained superior fatigue resistance, indicating its suitability for structures subjected to cyclic loading such as bridges and pavements.

#### **5. Microstructural Analysis and Healing Mechanism**

Scanning electron microscopy provided detailed insights into the healing mechanism. Healed cracks were observed to be filled with continuous polymeric films tightly bonded to the cement matrix. Energy-dispersive X ray spectroscopy confirmed the presence of carbon-rich phases associated with the healing agent, distinguishing them from hydration products. X-ray diffraction analysis revealed increased formation of secondary hydration products in healed regions, suggesting that the healing agent promoted additional chemical reactions within the matrix. This combined physical and chemical healing mechanism contributed to the observed improvements in mechanical and durability performance [9].

#### **6. Durability Performance and Environmental Resistance**

Durability tests demonstrated that self-healing UHPC exhibited significantly reduced water permeability and chloride ion penetration compared to control specimens. The autonomous sealing of microcracks effectively prevented the ingress of aggressive agents, enhancing resistance to corrosion-induced damage. Freeze–thaw resistance tests further confirmed the superior performance of self-healing UHPC, with minimal mass loss and surface deterioration observed after 300 cycles. These results highlight the potential of nanocapsule-based UHPC for infrastructure exposed to harsh environmental conditions [10].

#### **7. Sustainability and Lifecycle Performance Assessment**

From a sustainability perspective, self-healing UHPC offers substantial benefits by reducing maintenance frequency, extending service life, and lowering lifecycle costs. Although the initial material cost is higher due to the inclusion of nanocapsules, lifecycle analysis indicates net economic and environmental advantages over conventional repair-intensive concrete systems.

#### **8. Conclusions**

This study confirms that smart nanocapsule-enabled UHPC can autonomously repair microcracks, significantly enhancing mechanical recovery, durability, and structural resilience. The developed material represents a promising solution for sustainable infrastructure development, particularly in critical and aggressive service environments.

#### **References**

1. V. C. Li and E. H. Yang, “Self-healing in concrete materials,” *Materials Today*, vol. 11, no. 12, pp. 14–20, 2008.

2. P. Richard and M. Cheyrezy, "Composition of reactive powder concretes," *Cement and Concrete Research*, vol. 25, no. 7, pp. 1501–1511, 1995.
3. S. Van Tittelboom and N. De Belie, "Self-healing in cementitious materials—A review," *Materials*, vol. 6, no. 6, pp. 2182–2217, 2013.
4. K. Van Breugel, "Is there a market for self-healing cement-based materials?" *Proc. Int. Conf. Self-Healing Materials*, 2007.
5. H. M. Jonkers, "Bacteria-based self-healing concrete," *Heron*, vol. 56, no. 1–2, pp. 1–12, 2011.
6. A. Al-Tabbaa et al., "Self-healing concrete: A review of recent research," *Construction and Building Materials*, vol. 178, pp. 399–415, 2018.
7. ASTM C1202-22, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, ASTM International, 2022.
8. M. Alghamri and A. Al-Tabbaa, "Mechanical recovery of self-healing cementitious materials," *Materials and Structures*, vol. 51, pp. 1–15, 2018.
9. J. Yang et al., "Microstructural characterization of healed cracks in cementitious composites," *Cement and Concrete Composites*, vol. 73, pp. 126–137, 2016.
10. N. De Belie et al., "Durability of self-healing concrete," *Journal of Materials in Civil Engineering*, vol. 30, no. 3, 2018.



© 2026 by the authors. Open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>)