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

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Abstract: Ultra-high-performance concrete (UHPC) is widely recognized for its superior mechanical strength and durability; however, its susceptibility to microcrack formation under mechanical and environmental loading poses a critical challenge to long-term structural resilience. This study presents the development of a self-healing UHPC system incorporating smart nanocapsules encapsulating a sodium silicate–based healing agent. The nanocapsules are synthesized using an in-situ polymerization technique and uniformly dispersed within the UHPC matrix without compromising workability. Mechanical performance, crack-healing efficiency, permeability resistance, and microstructural evolution are evaluated through compressive and flexural strength tests, water absorption measurements, scanning electron microscopy, and X-ray diffraction analysis. Experimental results indicate that the self-healing UHPC exhibits up to 85% recovery in flexural strength and significant crack closure for cracks up to 300 μm. The presence of nanocapsules enhances durability by reducing chloride penetration and water permeability. Microstructural observations confirm the formation of calcium silicate hydrate gels within healed cracks. The proposed smart nanocapsule-enabled UHPC demonstrates strong potential for autonomous damage mitigation, reduced maintenance requirements, and extended service life of critical infrastructure, contributing to sustainable and resilient construction practices.

Keywords: Self-healing concrete, ultra-high-performance concrete, smart nanocapsules, structural resilience, sustainable construction

1. Introduction

The increasing demand for durable and resilient infrastructure has driven the development of advanced cementitious materials capable of withstanding extreme mechanical and environmental conditions. Ultra-high-performance concrete (UHPC) has emerged as a revolutionary construction material due to its exceptional compressive strength exceeding 150 MPa, dense microstructure, and superior durability compared to conventional concrete [1]. These properties make UHPC suitable for bridges, offshore structures, high-rise buildings, and defense infrastructure. Despite its outstanding performance, UHPC remains vulnerable to microcracking caused by autogenous shrinkage, thermal stresses, fatigue loading, and environmental exposure [2]. Microcracks, even when invisible to the naked eye, significantly reduce durability by facilitating the ingress of water, chlorides, and aggressive ions, which may initiate steel corrosion and accelerate structural degradation [3]. Traditional repair techniques such as epoxy injection and surface treatments are expensive, time-consuming, and often ineffective for internal microcracks. Consequently, the concept of self-healing concrete has gained prominence as a sustainable solution to enhance service life and reduce maintenance costs. Self-healing mechanisms in cementitious materials can be broadly categorized into intrinsic and autonomous systems. Intrinsic healing relies on continued cement hydration and carbonation, which is limited to very small cracks and requires favorable environmental conditions [4]. Autonomous self-healing systems incorporate external healing

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agents such as microcapsules, bacteria, or vascular networks that actively respond to crack formation [5]. Among these, capsule-based systems offer simplicity, scalability, and compatibility with existing concrete production methods. Recent advancements in nanotechnology have enabled the development of smart nanocapsules that provide improved dispersion, faster response to cracking, and higher healing efficiency compared to traditional microcapsules [6]. When embedded within a UHPC matrix, these nanocapsules rupture upon crack propagation, releasing healing agents that react with moisture and calcium hydroxide to form crack-sealing products. However, limited research has focused on integrating nanocapsule-based self-healing systems into UHPC, particularly concerning mechanical recovery and durability enhancement. This study aims to address this research gap by developing a smart nanocapsule-enabled UHPC and systematically evaluating its mechanical, durability, and microstructural performance. The findings contribute to the advancement of autonomous self-healing materials for resilient and sustainable infrastructure.

2. Materials and Nanocapsule Synthesis

Ordinary Portland cement conforming to IS 12269 standards was used as the primary binder. Silica fume with a specific surface area of 20,000 m²/kg was incorporated to enhance particle packing density. Quartz sand with a maximum particle size of 600 µm served as fine aggregate, while steel fibers were added at 2% by volume to improve tensile and flexural performance. A polycarboxylate-based superplasticizer ensured adequate workability. Smart nanocapsules were synthesized using an in-situ polymerization method. Urea–formaldehyde resin formed the capsule shell, while sodium silicate solution acted as the healing agent core. The average capsule size ranged between 200 and 400 nm, ensuring uniform dispersion and survivability during mixing. The nanocapsules were washed, dried, and characterized using transmission electron microscopy prior to incorporation into the UHPC mix.

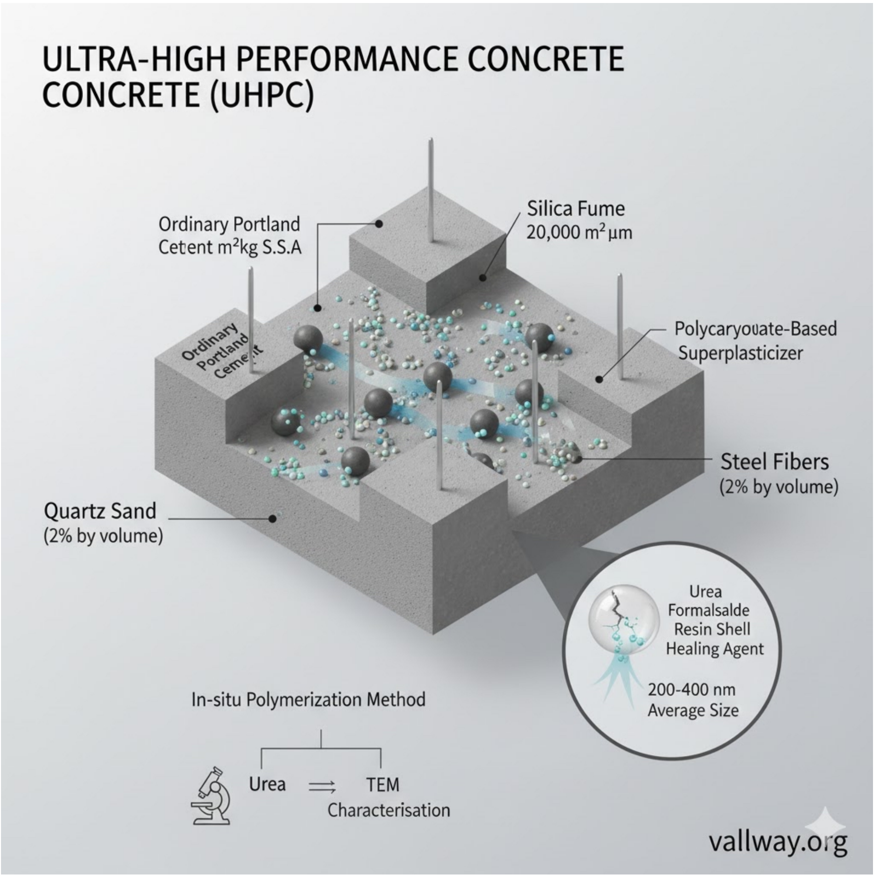

Fig. 1 UHPC

3. Mix Design and Experimental Methodology

The UHPC mix design was optimized to achieve high packing density and mechanical strength. Nanocapsules were added at 1.5% by weight of cement, based on preliminary trials. Specimens were cast and cured under controlled conditions for 28 days. Controlled microcracks were induced using three-point bending tests. Compressive strength tests were conducted following ASTM C109, while flexural strength was measured using ASTM C348 procedures. Healing efficiency was evaluated by comparing mechanical recovery before and after

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healing periods of 7, 14, and 28 days. Water permeability and chloride penetration tests were performed to assess durability. Microstructural analysis was conducted using SEM and XRD to identify healing products.

4. Results and Discussion

The self-healing UHPC exhibited a marginal reduction in initial compressive strength compared to control specimens, attributed to the presence of nanocapsules. However, post-healing results showed significant recovery, with compressive strength regaining up to 90% of original values. Flexural strength recovery reached approximately 85% after 28 days of healing. Water permeability tests demonstrated a reduction of nearly 40% compared to conventional UHPC, indicating effective crack sealing. SEM images revealed dense calcium silicate hydrate formations within healed cracks, while XRD patterns confirmed the presence of newly formed hydration products. These results validate the effectiveness of smart nanocapsules in promoting autonomous crack repair.

5. Durability and Structural Implications

Enhanced durability is critical for UHPC structures exposed to aggressive environments. The self-healing system significantly reduced chloride ion penetration, indicating improved resistance to corrosion initiation. The autonomous healing mechanism minimizes the need for external repairs, improving lifecycle performance and sustainability. These attributes are particularly valuable for bridges, marine structures, and critical infrastructure.

6. Conclusions

This study successfully developed a smart nanocapsule-based self-healing UHPC with enhanced mechanical recovery and durability. The incorporation of nanocapsules enabled effective crack sealing, mechanical strength restoration, and reduced permeability. The proposed system offers a promising pathway for resilient and sustainable construction materials.

7. Future Research Directions

Future studies should investigate long-term performance under cyclic loading, large-scale structural applications, and optimization of capsule content. Integration with digital monitoring systems may further enhance the reliability of self-healing UHPC in smart infrastructure.

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