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A Review of Research on Self-Healing Properties of Ultra-High Performance Concrete

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Abstract: As a novel cement-based composite, Ultra-High Performance Concrete (UHPC) is increasingly recognized as an essential material in modern construction and infrastructure projects, owing to its superior mechanical characteristics and long-lasting durability. This paper systematically introduces the basic properties, development background, and mechanical properties of UHPC, focusing on its self-healing mechanism and its application in special environments. The self-repairing capabilities of UHPC can be achieved through both autogenous and autonomous healing mechanisms, in which autogenous healing repairs the cracks by further hydration or chemical reaction of the cementitious materials, whereas autonomous healing realizes cracks repair through the addition of specific healing agents, such as bacteria or microcapsules) to achieve crack repair. This paper also includes a literature review on self-healing behavior of UHPC and its loss mechanism under different harsh environments such as high temperatures, dry and wet cycles, freeze-thaw cycles, and so on. It is shown that UHPC still maintains a strong self-healing ability in these environments, but may face a decline in self-healing effect in extreme environments. Therefore, future research should focus on optimizing self-healing techniques and improving their adaptability in specific environments. The innovation of this paper systematically summarizes the research results on the self-healing performance of UHPC in diverse settings in the existing literature, and analyzes the specific influence of various types of environments on the self-healing effect, offering a theoretical foundation for the future use of UHPC in engineering applications and advancing the development of self-healing technologies in UHPC.

1. Introduction

As China's infrastructure development expands and urbanization progresses, concrete materials are increasingly utilized across a wide range of engineering applications. Concrete, being the most commonly used building material, is favored for its wide range of raw materials, simple production process, and excellent durability and adaptability. However, conventional concrete often suffers from problems such as high weight and brittleness, which limit its wide application in certain projects. Today's modern engineering structures are moving towards higher, longer, and deeper structures, which place higher demands on the performance of the material. The durability and strength of conventional concrete are severely affected when dealing with harsh environments, especially special ionic environments, such as marine environments or industrially polluted areas. In these environments, the action of corrosive ions, such as chloride and sulfate, accelerates the deterioration of concrete, reducing structural safety and service life. The emergence of UHPC overcomes the performance limitations of conventional concrete.

Existing literature shows that UHPC outperforms conventional concrete in dealing with harsh environments. Ji C [1]found experimentally that chloride ions in the marine environment have significantly lower corrosion effects on UHPC than on conventional concrete, UHPC has fewer cracks than ordinary concrete when it receives damage and has higher flexural strength. In addition, for freeze-thaw cycles with extreme temperature changes, Zhong R et al [2] found that UHPC exhibits significantly better frost resistance compared to traditional concrete. Additionally, after undergoing freeze-thaw cycles, UHPC maintains superior compressive and tensile strength, leading to an extended service life in cold climates. These experimental findings have led researchers to recognize that UHPC not only outperforms conventional concrete in terms of mechanical properties but also offers substantial advantages in durability and resistance to environmental stresses.

2. UHPC material properties and development

2.1 Background of UHPC development

UHPC, which usually has a high cement dosage and a low water-cement proportion, and the incorporation of specific mineral admixtures and fibers, is a novel kind of cementitious composite material with high strength, ductility, and durability. Due to its ultra-high compressive and tensile flexural strengths, superior durability, and ultra-high toughness, it has a broad spectrum of applications in structures requiring long life and high performance. At present, both domestic and international researchers have conducted extensive studies on the properties of UHPC. The concept of UHPC was first introduced in 1994. In 1998, the first international conference with UHPC as the theme marked the wide application potential of UHPC in many fields. Hunan University took the lead in conducting research on UHPC materials in China, followed by Tsinghua University and East China. Tsinghua University conducted uniaxial compression tests under different loading amplitudes to study the stress characteristics of UHPC under uniaxial cyclic loading. Wuhan University investigated the mechanical characteristics of UHPC with coarse aggregate under uniaxial tensile conditions. According to the study, the current compressive strength of UHPC is as high as 150~810 MPa, and the tensile strength can be more than 10 MPa.

2.2 UHPC Mechanical and Operational Properties

UHPC has significant advantages in terms of mechanical and serviceability properties compared to ordinary concrete.

(1) Excellent Mechanical Properties.

UHPC exhibits much higher properties than ordinary concrete in terms of tensile resistance and flexural strength. According to Amran M et al [3], the tensile strength of UHPC is approximately two to four times greater than that of conventional concrete, while its elasticity modulus is roughly twice as high.

(2) Strong durability.

UHPC is a construction material with excellent durability, and studies have shown that the durability of UHPC can be more than 200 years. After proper reinforcement treatment, due to fewer microcracks and discontinuous pore structure within UHPC, this effectively decreases the permeability of the material and brings its mechanical characteristics close to the level of steel, thus significantly improving the durability of the structure. UHPC also enhanced its resistance to permeability and chemical erosion by optimizing the maximum packing density of the material and improving the densification of the microstructure, especially in the resistance to freezing and sulfate erosion, and has a level of self-healing ability. The study of Xi B et al [4]showed that UHPC has outstanding resistance to sulfate attack, and the cracks in microcracked UHPC can still be partially healed after prolonged exposure to geothermal water, and the continuous self-healing process effectively counteracts the effects from chloride and sulfate ion attack. UHPC contains a significant quantity of unreacted cement particles, which have the ability to self-heal and exhibit superior durability in harsh environments.

UHPC exhibits different geometrical characteristics for crack formation compared to ordinary concrete due to its dense matrix structure and fiber toughening. The more dense microstructure of UHPC, the use of finely powdered mineral materials and the optimized water-cement ratio greatly reduce the porosity within the material, which effectively improves its resistance to cracking and abrasion. According to MCS-EPFL [5], the tensile properties of fiber concretes can be classified as strain-softening type (ultimate tensile hardening strain <0.15%) and strain-hardening type (ultimate tensile hardening strain >0.15%) as shown in Figure 1[5]. Due to the high fiber content in the UHPC composite ratio and the close proximity to the theoretical maximum densification, its tensile properties usually exhibit strain-hardening behavior. Therefore, the strain-hardening material UHPC has excellent strength、good toughness and post-cracking tensile properties that promote its self-healing after cracking. Meanwhile, high strain-hardening UHPC typically has a crack width of 20-30 μm, which does not exceed 50 μm even in the strain-hardening phase. This is much less than that of PVA fiber-reinforced Engineered Cementitious Composites at the same stage, indicating superior crack-width control in UHPC.

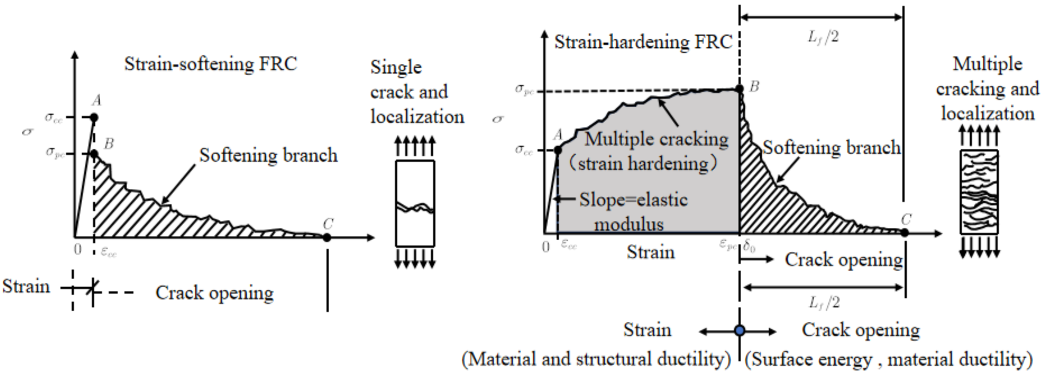


Figure 1. UHPC full tensile stress-strain curve [5]

2.3 UHPC self-healing mechanism

At present, methods for self-healing in concrete are typically divided into two primary categories: autonomous healing and autogenous healing.

Autogenous healing is the process of crack repair by inducing continued hydration or active reaction of the cementitious components within the cementitious material, as shown in Figure 2[6].

The primary mechanisms of autogenous healing are attributed to chemical, physical, and mechanical processes [7], which are achieved through the following four pathways (Figure 3 [7]): (1) Additional hydration of unreacted cement particles or other cement-based materials; (2)The interaction between calcium hydroxide in concrete and carbon dioxide either in the air or dissolved in water results in the creation of new calcium carbonate or calcium hydroxide within the fissures; (3)Particles and impurities suspended in water are displaced by the action of water, thus blocking the cracks; (4)Concrete undergoes expansion owing to the creation of calcium silicate hydrate on both sides of the cracks. During the early stages of hydration, the primary self-healing mechanism is the ongoing hydration of unreacted cement particles. As the concrete matures over time, the predominant self-healing process shifts to the precipitation and formation of calcium carbonate.

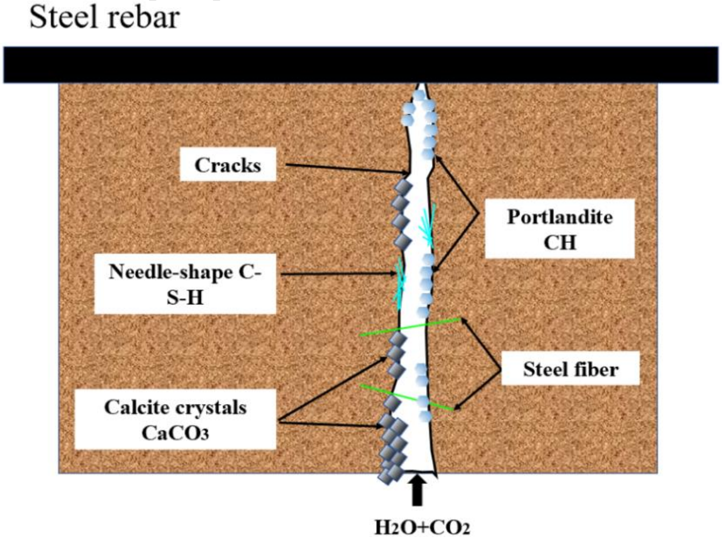


Figure 2. UHPC crack autogenous healing mechanism diagram [6]

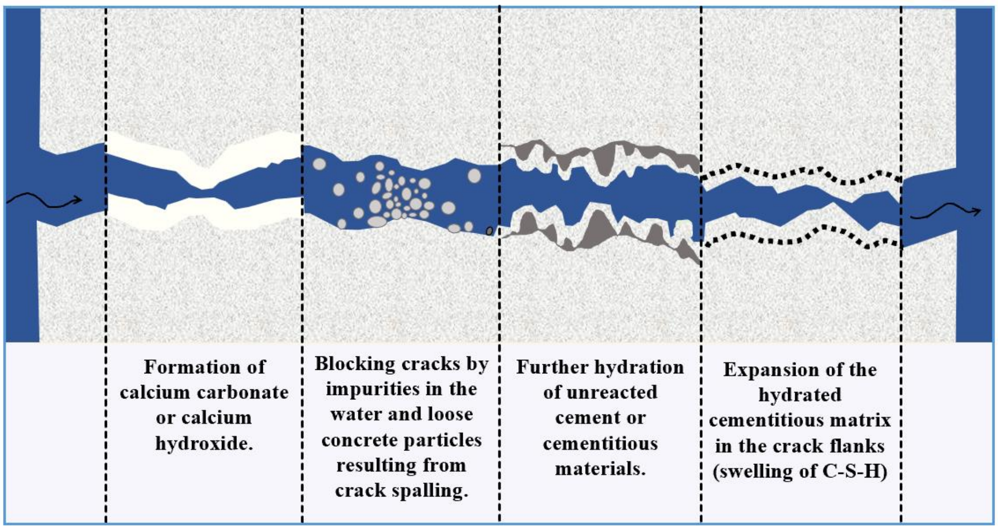


Figure 3. Major pathways for self-healing of concrete cracks [7]

Autonomous healing promotes the autonomous repair of cracks by adding specific healing agents to the matrix, and there are two main ways of applying healing agents in concrete: direct bacterial application and microencapsulation. The direct bacterial application method is a self-healing technique that utilizes bacteria to precipitate CaCO3 to repair concrete cracks. The method works by admixing dormant and active bacteria and nutrients into concrete, and when cracks are formed, the moisture in the cracks activates the metabolic activities of the bacteria, prompting them to precipitate CaCO3 through mechanisms such as urea hydrolysis, thus sealing the cracks and repairing the concrete structure to enhance the durability of the concrete. As demonstrated in Figure 4 [8].

Microcapsule self-healing technology involves encapsulating healing agents within microcapsules, and by embedding microcapsules, it can effectively reduce water infiltration into concrete after cracks appear and significantly improve its crack resistance, restoring the strength and durability of concrete. White et al [9] proposed the application mechanism of using the microcapsule method to incorporate healing agents in the self-repair of materials (Figure 5 [9]): when a crack occurs in a material, the microcapsule embedded in it is triggered by the expansion or rupture of the crack, and the internal healing agent is discharged into the crack surface by capillarity effect, promoting self-healing within the material, and it comes into contact with the pre-embedded catalysts in the material, triggering a chemical reaction (such aspolymerization or cross-linking), causing the healing agent to cure rapidly, thus achieving crack repair and closure. However, compared with autogenous healing, the poor compatibility of most mainstream repair media with the UHPC matrix leads to a more limited healing effect of the autogenous healing technology in UHPC cracks, and it is difficult to ensure the stability of the matrix properties.

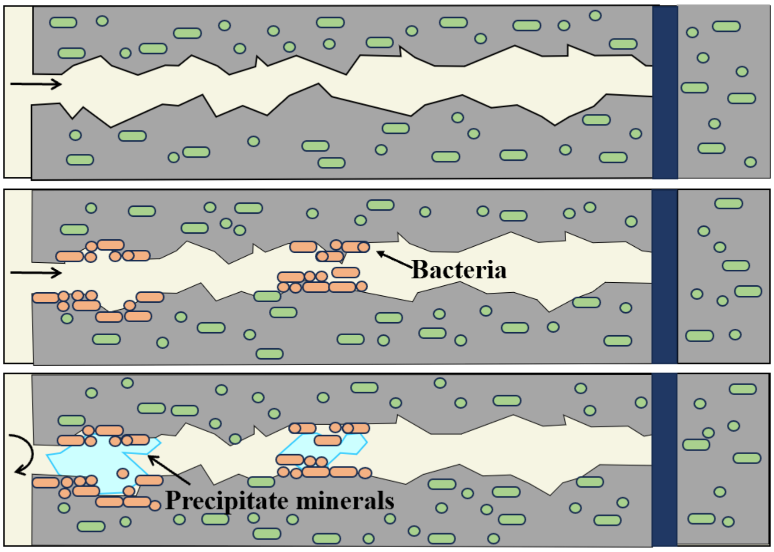
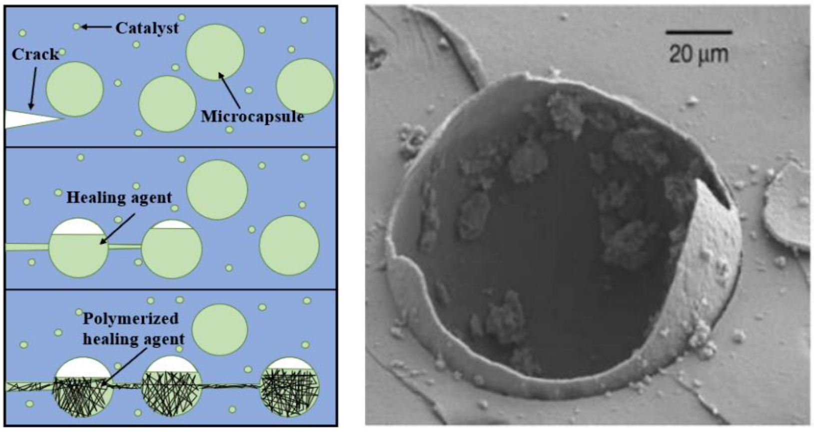


Figure 4. Diagrammatic representation of crack healing by immobilized bacteria in concrete [8]



（a） Self-healing mechanism diagram under microencapsulation technology

（b） Broken microcapsules

Figure 5. Diagram of self-healing mechanism under microencapsulation technology and ruptured microcapsules under ESEM [9]

3. Self-healing properties and applications of UHPC in special environments

The UHPC's self-repair capabilities enable it to autonomously mend cracks through specific mechanisms when damaged or when microcracks form. This ability reduces maintenance costs and prolongs the lifespan of structures, making it a preferred material in modern construction and infrastructure projects. For example, in bridge construction, UHPC self-healing properties can effectively repair microcracks, avoid moisture and corrosive substances from entering the structure, and improving the durability and service life of bridges; in high-rise buildings, especially landmark buildings with high requirements for appearance and structural safety, UHPC self-healing properties can automatically repair microcracks when they occur in the concrete to ensure the integrity of the facade and the safety of the building. Safety. However, in the service process of UHPC, it is frequently subjected to various harsh environmental conditions, resulting in a significant weakening of its repair effect, or even complete failure. For example, in the marine environment, UHPC will be exposed to high humidity and salt spray for extended periods. With the accumulation of salt and the intrusion of chloride ions, the cementitious materials in the self-healing system cannot be effectively activated, inhibiting the repair reaction and even causing the gradual expansion of microcracks, which may ultimately lead to the decay of the structure and its failure.

Currently, many scholars have performed substantial research on the self-healing performance of UHPC, as shown in Table. 1. Researchers have studied the self-healing ability of UHPC in special environments such as low and high temperature, freeze-thaw cycle, dry-wet cycle, vapor, persistent loading and analyzed the influencing factors. Therefore, this table summarizes some of the current studies.

Table. 1. Study of self-healing properties of UHPC in various environments

hostile environment	Author	methodologies	Results
High-temperature	Liu Z[10]	1. Characterization of self-healing capacity 2. Fracture toughness test	The mechanism of loss of self-healing traits of UHPC after high temperature exposure was investigated.
	Y Qian[8]	1. Dry and wet cycle test 2. Microanalytical techniques	The influence of high temperature damage above 800 ℃ on the performance of UHPC was evaluated under various wet-dry cycles and exposure to salt solutions.
dry and wet cycle	Ji C[11]	1. Chloride ion dry and wet cycle treatment 2. ABAQUS numerical simulation	The mechanism behind the loss of self-healing ability of UHPC under chloride ion wet and dry cycling conditions was examined.
	Niu L[12]	1. Dry and wet cycle test 2. Flexural strength test	The study focused on the self-healing abilities and mechanisms of the loss of flexural strength in pre-cracked UHPC subjected to dry-wet cycles in a NaCl solution.
freeze-thaw cycle	Kan L[13]	1. Uniaxial tensile test 2. ImageJ technology	The impact of freeze-thaw cycles on the tensile properties of cracked UHPC was examined.
	Wen L L[14]	1. Pre-strain damage and freeze-thaw cycle test 2.Uniaxial tensile properties and microstructure analysis	The mechanism behind the loss of self-healing abilities in UHPC subjected to freeze-thaw cycles was elucidated.
	Zhong R[15]	1. Freeze-thaw cycle test 2. Thermogravimetric analysis and scanning electron microscope test	The self-healing ability and durability of UHPC under freeze-thaw and chloride salt conditions were assessed.
vapor	Tan Y[16]	1. Tensile deformation and steam environment conservation 2. Gas permeation and acoustic emission analysis	The mechanism of loss of self-healing properties of UHPC in vapor settings is revealed.
	Guo J Y[17]	1. Sound wave emission analysis 2. Gas permeability measurement	The self-healing effect of high-strain hard UHPC under the action of steam was investigated.
low temperature	Kim S[18]	1. Thermal deformation constraint test 2. Four-point bending test	The mechanism of loss of self-healing properties of UHPC in low-temperature environment was revealed.
persistent loading	Alameri M[19]	1. Bending fatigue test 2. Tensile fatigue test	The mechanism behind the loss of self-healing in UHPC under cyclic bending and tensile stress was examined.
	Davolio M[20]	1. Continuous loading experiment 2. Environmental exposure test	The self-repairing characteristics of UHPC under prolonged loading and harsh environmental conditions were examined.

4. Conclusions

This paper comprehensively discusses the properties, development background, mechanical properties and its self-healing characteristics of UHPC under special conditions.

(1) UHPC has a substantially greater compressive, tensile and flexural strengths compared to traditional concrete, which can meet the needs of high-strength structures and is suitable for projects requiring high load-bearing capacity.

(2) UHPC's dense microstructure significantly improves its resistance to permeability and chemical erosion, especially in frost protection, anti-sulphate erosion and other aspects of outstanding performance, with a service life of up to 200 years or more.

(3) UHPC exhibits remarkable self-healing capabilities, enabling it to repair microcracks and restore structural integrity, thereby prolonging the lifespan of the structure under normal environmental conditions. Although the effect is different in some extreme environments, the overall performance can still guarantee the long-term stability of the structure. Wide range of applications Based on its excellent overall performance, UHPC shows strong potential for use in bridges, high-rise buildings and other projects requiring long life and high durability.

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