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Review on the Innovation of Ultra-High-Performance Concrete Materials and the Frontier of Engineering Applications

Yuanpeng Huang *

Aulin College, Northeast Forestry University, Harbin, China

* Corresponding Author Email: hyp2004@nefu.edu.cn

Abstract. With the aging of infrastructure worldwide and people's increased demand for green and smart construction, Ordinary concrete is facing a series of problems such as poor durability, environmental adaptability, and short service life. In many cases, frequent maintenance and premature replacement of ordinary concrete structures not only increase costs but also cause resource waste and environmental burden. Ultra-high performance concrete (UHPC) has good strength, impermeability, and durability and plays an important role in leading the innovation of civil engineering. Compared with traditional concrete, UHPC provides a denser microstructure, superior crack resistance, and longer service life, which makes it highly suitable for bridges, high-rise buildings, and harsh environmental conditions. In this paper, we summarize some new results on UHPC materials, design methods, processing techniques, functions, and engineering applications from five aspects, including its existing predictions about performances, preparation schemes, pre-processing solution schemes, and practical applications; moreover, special attention is given to the integration of advanced characterization technologies and computational simulation in predicting UHPC performance, which provides more accurate guidance for material optimization. At the same time, we also discuss issues that require more urgent solutions concerning UHPC, such as cost, structural adaptability, and standardized practice exploration as well as the need for recycling strategies and sustainable raw material utilization for the development and application of UHPC to promote intelligent, low-carbon, and modular construction, which are conducive to advancing UHPC engineering and standardization.

Keywords: UHPC; Material Design; Fiber Reinforcement; SSUHPC; Engineering Applications.

1. Introduction

With the increasing frequency of global infrastructure aging and people's urgent need for more digital, intelligent, and sustainable solutions, UHPC has gradually become one of the main materials in the civil engineering field. Due to its superb strength and durability, it is known as "super material." As a new type of composite building material, UHPC has extraordinary strength, density, and impermeability; therefore, it becomes the focus of concern of many engineers and researchers. The purpose of this review is to help readers understand UHPC better by focusing on its development and advantages, and thus promote its exploration and utilization by the industry.

As human beings continue to strive to improve existing material properties from NSC → HPC → UHPC at present, structure design will be expanded to new boundaries continuously [1,2]. Compared with other types of concrete, the compressive strength of UHPC can reach up to 150 MPa, which is three times that of HPC; furthermore, its excellent resistance to permeability and fatigue makes it indispensable in future construction. At present, there are only a few research results about the basic theory and some test methods of UHPC; however, the number of actual projects using UHPC is very small compared to the amount of such information. Recently, statistics showed that more than 500 bridges in North America began to adopt UHPC in the construction process, which is approximately twice the number in 2016. However, the quantity of these 500 bridges accounted for less than 0.08% of the total, meaning that their usage rate was still quite low [3], mainly due to the high price, unadapted construction techniques, and unclear designs of UHPC. To enable more applications of UHPC, much work must still be done regarding the design, construction technology, and standards in the coming years [4].

This paper mainly focuses on the optimization of composition and preparation technique, extension of function, and engineering application of UHPC, especially paying attention to the mechanism of fiber reinforcement, low-carbon formulation, and forming technology, including 3D printing and dry prefabrication.

2. Material Design and Preparation Technology of UHPC

UHPC is a new type of material with high strength, high permeability and high fatigue resistance. The excellent performance of UHPC not only relies on the dense matrix but also depends on the raw materials mix ratio design and the preparation process. Therefore we summarize some effective methods to improve the UHPC properties from three aspects: raw materials,mix ratio creation and process creation.

2.1. Composition and Function of Raw Materials

The excellent performance of UHPC is closely related to its raw material composition and composite optimization. The cement-based material consists of high content cement, silica fume, fly ash and other fine admixtures with very low content water-to-binder ratio (0.2-0.3) so as to be dense cementing [5]. As shown in **Fig. 1**, we list the raw materials of cement which can meet the design strength grade and durability requirements. Silica fume is partially replaced by slag powder, thereby improving the flowability and strength [6].

Fig 1. Cement Raw Materials

To improve mechanical properties and durability, fibers are often added in amounts of 1–3%. **Fig. 2** illustrates the role of polypropylene (PP) fibers, which help control crack propagation and improve the overall material toughness. Steel fibers, as shown in **Fig. 3**, enhance toughness and impact resistance. Studies have shown that adding 2–3% steel fibers significantly enhances compressive strength and crack resistance [7]. A mixed mechanism of steel and PP fibers can increase the 28-day compressive strength by 2.5–6%, with significant improvements in both compressive and crack resistance [8].

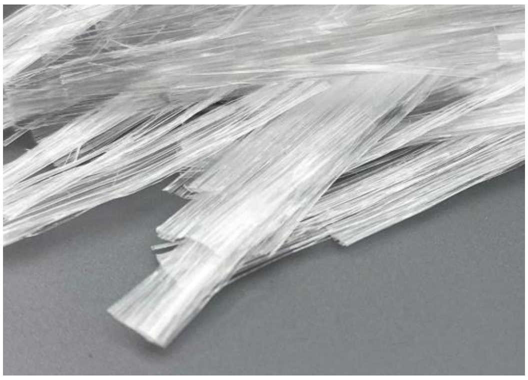

Fig 2. PP Fiber Materials

Fig 3. Steel Fiber Materials

2.2. Mix Ratio Design Optimization

In addition to selecting the most optimized raw materials, optimizing the mix ratio is a key step in improving performance. UHPC typically does not contain coarse aggregates, and fine aggregates are optimized using grading and particle packing theory to reduce porosity and enhance mechanical properties [5]. A low water-to-binder ratio is critical for ensuring early strength while maintaining durability in the long term [5,9,10].

Additionally, green and low-carbon designs are becoming a trend. By partially replacing silica fume with fly ash or slag powder, both mechanical properties are maintained while reducing CO2 emissions [11]. Machine learning predictive models help optimize mix ratios, improving engineering feasibility and stability [12].

2.3. Process Innovation in Preparation

Thermal curing and room temperature curing were also considered. Curing at 90°C for 48h is beneficial to transform the C-S-H structure into the snow calcite structure, optimize the microstructure, and improve the long-term mechanical performance [4], so that steel fiber has better stability and toughness under thermal curing.

In addition, 3D printing and intelligent manufacturing promote personalized production of UHPC [13]. The combination of particle shape optimization and AI algorithm can greatly increase the compressive strength and tensile strength of 3D printing, which is very important in the preparation direction of UHPC [14].

3. Functional Expansion and Engineering Applications of UHPC

3.1. Advanced Functional Technological Expansions

3.1.1. SSUHPC Technology

SSUHPC is obtained by adding conductive filler such as carbon black (CB), carbon nanotube fibers (CNTF), graphene (G), etc., forming a continuous network of conductive filler with good conductivity, detecting stress, crack and damage through resistance and capacitance signal [15-17]. When CB and CNTF are mixed together, the conductivity threshold was reduced; its piezoresistive sensitivity was improved, but its Mechanical property declined slightly [16]; using 3D printer to improve the directional uniformity of filler has improved the Sensing stability [18], and it has been applied to smart bridge and smart precast components, but there are still some problems in environment sensitive, material homogeneous and standard engineeringized applications [15,17].

SSUHPC is achieved by incorporating conductive fillers such as carbon black, carbon nanotube fibers, and graphene into UHPC, forming a conductive network that allows for the detection of stress, cracking, and damage via resistivity or capacitance signals [15-17]. Studies have shown that mixing carbon black and carbon nanotube fibers reduces the conductivity threshold, while improving piezoresistive sensitivity and mechanical properties [16]. The application of 3D printing technology further enhances the uniform distribution of conductive fillers along the print direction, improving sensing stability [18]. Currently, this technology has been trialed in smart bridges and smart precast components, though challenges remain, such as environmental sensitivity, material homogeneity, and standardization for engineering applications [15,17].

3.1.2. Particle Packing Factor (PPF) as a Performance Indicator for UHPC

PPF is an important parameter used to quantify the packing density of the cementitious system, which can be used to predict the flowability, compressive strength, and porosity of UHPC [19-21]. For example, increasing the PPF from 52 to 68 can lead to a 39% increase in 28-day compressive strength, while also reducing porosity and enhancing the effectiveness of superplasticizers [19]. Integrating PPF into machine learning models, along with other parameters like water-to-binder ratio and specific surface area, helps optimize mix ratios and predict performance with high accuracy [22]. While PPF is currently used mainly in experimental settings, its application in sustainable design materials has garnered significant attention [20,22].

3.2. Structural Engineering Innovations

The Bricker Road Bridge, located in St. Clair County, Michigan, completed in 2022, is the first fully UHPC superstructure bridge in the U.S. It uses an open-recipe UHPC, mixed on-site using conventional ready-mix trucks, and consists of six prefabricated ribbed panels. The bridge was constructed without specialized equipment or training [23-25]. The bridge spans 7.25 m with a width of 11 m and a rib thickness of approximately 7.5 cm, resulting in a structure that is about two-thirds lighter than a traditional 16-inch concrete bridge. This reduces both construction time and transportation costs, cutting short-term expenses from \$560,000 to \$379,000, a 32% savings [24]. The high-density microstructure of the UHPC, along with its excellent freeze-thaw resistance and chloride ion corrosion resistance, gives the bridge a projected lifespan of 150–200 years [23,25]. This project won the First Prize in the Small Bridge Category at the 2023 International UHPC Interactive Symposium and is regarded as a "small bridge with big implications," showcasing the feasibility and cost-effectiveness of UHPC in lightweight, long-lasting bridge construction [25].

4. Challenges and Future Prospects

4.1. Challenges in Promoting UHPC Materials

While UHPC surpasses ordinary concrete in strength, impermeability, and fatigue resistance, its application in large-scale structures faces multiple challenges, including cost and construction issues:

(1) UHPC is relatively expensive, mainly due to the large amounts of binder materials and fibers used, as well as the increased energy consumption and costs during production [26,27].

(2) UHPC requires specific construction methods, especially because its high viscosity makes pumping and mixing challenging during the pouring process [26,28].

(3) UHPC exhibits significant autogenous shrinkage and drying shrinkage, leading to plastic cracking in the early stages and microcrack control issues that affect its durability [26,29].

(4) Under extreme conditions, the high strength of UHPC can lead to explosive failure, and further research is needed to understand its fire response [26,30].

(5) The use of UHPC in large-scale structures is still in the stage of gradually developing technical standards, with construction and design standards yet to be unified, limiting its widespread application [27,31].

4.2. Prospects for the Development of UHPC Materials

In the future, UHPC will evolve toward intelligent, low-carbon, and integrated solutions. By using industrial waste materials such as fly ash and slag as substitutes for silica fume, low-carbon and cost-effective UHPC can be achieved [27,28]. Artificial intelligence and machine learning will play a critical role in optimizing UHPC designs by simulating mix ratios, fiber distribution, and construction parameters to improve performance, promoting data-driven design approaches [32,33]. The addition of nano-materials and hybrid fibers can enhance fire resistance, making UHPC suitable for high-temperature environments [29,30]. Additionally, integrating 3D printing and modular prefabrication techniques will accelerate the use of UHPC in complex structures and rapid construction [32,33]. Several international organizations are working on developing guidelines for the design, acceptance, and evaluation of UHPC to provide institutional support for its engineering applications [31].

5. Conclusion

UHPC, a product of the intersection of material science and civil engineering, is gradually leading structural materials toward higher performance and intelligence with its high strength, density, and design flexibility. By optimizing binder systems, fine aggregate grading, and multi-scale fiber reinforcement, the synergy between mechanical properties and workability can be enhanced. The integration of heat treatment, 3D printing, and prefabrication processes has driven the industrialization and personalized production of UHPC. Self-sensing technologies, intelligent monitoring, and low-carbon mix designs lay the foundation for transforming UHPC into smart engineering materials. Main conclusions are as follows:

(1) UHPC has expanded from small applications, such as bridge deck repairs, to bridge deck

paving, beam integration, and full superstructure bridges, with projects like the Bricker Road Bridge demonstrating the technical and economic advantages of rapid assembly and long service life.

(2) PPF provides a theoretical basis for performance prediction and mix ratio optimization;

SSUHPC has established a health monitoring system that detects material behavior through signal response.

(3) There is insufficient research on cost-saving mechanisms, limited exploration of performance

under high temperatures and fire conditions, inadequate construction equipment and protocols, and the need for further research into multi-physics coupling and intelligent integration.

(4) Future efforts should focus on integrated material and structural design, life-cycle prediction,

and low-carbon research, along with coordinated efforts in research, industry, and standardization to promote the widespread application of UHPC in engineering.

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