The Characteristics of Ultra-High Performance Concrete and Its Application in Structures

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Abstract. This paper mainly introduces a new engineering material-Ultra-High performance concrete (UHPC). By adding different aggregates to the mix, UHPC has a smaller packing density and higher durability, as well as higher compressive and tensile strength and other mechanical properties. The content of silica fume and the shape of steel fiber also affect the performance of UHPC. UHPC with hooked steel fiber has higher bond strength, which improves compressive strength. Due to its enhanced durability and mechanical properties, UHPC is used in a variety of architectural and structural applications, including building structures, finishes and cladding. Based on the project background of a children's playground platform in Chongming, Shanghai and Dongguan Binhai Bridge, this paper focuses on the application of UHPC in practical projects. The results show that the combination of steel and UHPC can provide high overall stiffness and safety. In the future, the different properties of UHPC when combined with different materials should be explored, so that UHPC can be more widely used.

Keywords: Ultra-High Performance Concrete; mechanical; durability; building structure.

1. Introduction

The initial invention of Ultra-High Performance Concrete (UHPC) can be traced back to the patent application by Hans Henrik Bache from Denmark in 1979 [1]. However, UHPC materials gained more prominence in France during the 1990s. With rapid economic growth, engineering structures became longer, taller, and deeper, increasing the demand for high-performance construction materials. As a result, there was a search for ultra-high-performance civil engineering materials [2]. The term UHPC was coined by French scholars in 1994, and in the same year, Richard from France reported Reactive Powder Concrete (RPC), which is the most representative type of concrete, marking the beginning of the UHPC era [2]. Since then, countries worldwide have been researching and utilizing UHPC materials. Currently, UHPC finds widespread applications in engineering. Ordinary concrete often lacks durability, leading to cracking and damage in building structures. Consequently, the lifespan of many structures is only 50-100 years, and some structures require repairs after just 10-20 years of use. However, the use of UHPC materials improves the durability, workability, practicality, and strength of structures. This paper primarily discusses the preparation methods of UHPC, including the utilization of the Maximum Packing Density theory, different aggregates, and control of the mix proportion to enhance the mechanical and durability properties of UHPC. Additionally, it introduces the current application status and case studies of UHPC in residential and bridge structures.

2. The Configuration Principle and Mechanical Properties of UHPC

2.1. Configuration Principle

The researches on UHPC nowadays are mainly based on the Maximum Packing Density theory [3]. In this approach, cement serves as the gel material, coarse aggregates are removed, and various fillers such as quartz sand, glass powder, river sand, limestone powder, and active admixtures, as well as a small amount of nano-materials, are added [4]. Compared to ordinary concrete and high-performance concrete, UHPC has a lower water-cement ratio, typically ranging from 0.14 to 0.27, and a reduced maximum aggregate size of 0.4mm to 0.6mm, resulting in a decreased porosity of 2% to 6%. These changes lead to a smaller packing density, significantly improved durability, and enhanced mechanical properties of UHPC, thereby increasing the service life of structures and reducing maintenance costs. However, there are many other factors that can influence the performance of UHPC, such as the mix proportion of different materials. Therefore, experimental testing is necessary to evaluate the effects of different mix proportions on the performance of UHPC.

2.2. Compressive Performance

Ordinary concrete structures have a high self-weight and compressive strength ranging from 20-40 MPa. In contrast, UHPC has significantly improved compressive strength, typically ranging from 120-180 MPa. This improvement is achieved through the addition of different types of steel fibers and the inclusion of silica fume in the mixture. Fig.1 shows that the compressive strength of UHPC significantly increases at 28 days compared to 1 day, with varying amounts of silica fume [5]. The small particle size and large specific surface area of silica fume allow it to fill the pores in the matrix, thereby increasing the density of the UHPC. When used in conjunction with high-efficiency water-reducing agents, the performance of UHPC is further enhanced.

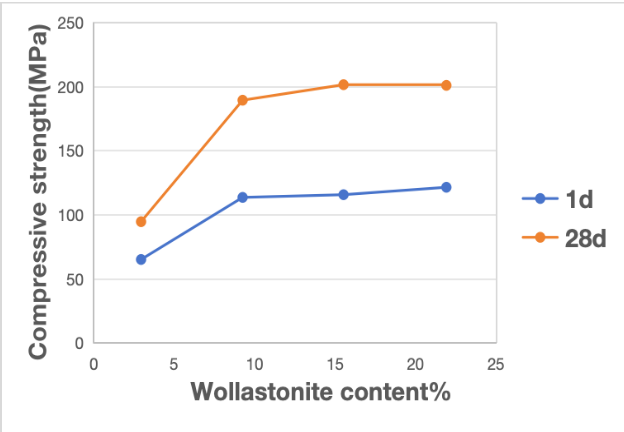

Fig. 1 Compressive strength diagram of UPHC [5]

The shape of steel fibers also affects the compressive strength of UHPC. Fig. 2 shows that straight steel fibers intersecting with hooked-end fibers have better flowability [5]. The hooked-end steel fibers have higher bond strength and better mechanical properties due to their improved flowability.

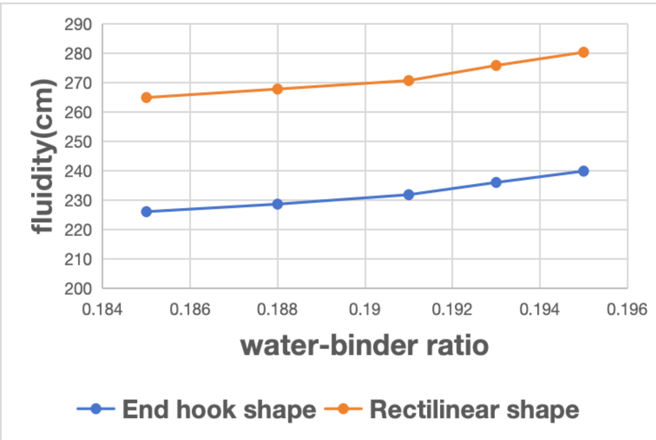

Fig. 2 Compressive strength diagram of UPHC [5]

2.3. Tensile Properties

Because ordinary concrete is heavy and often cracks in the tensile zone, UHPC, with the addition of steel fibers, allows the structure to bear certain tensile forces before cracking. Studying the axial stress-strain curve of UHPC is also an important prerequisite for studying its tensile properties. Fig. 3 shows that it can be divided into three stages [6]. In the first stage, when the load is small, the axial stress-strain curve of UHPC is close to a straight line. In this stage, UHPC is in the elastic deformation phase, without crack development inside. The second stage is the stage of unstable development, where cracks develop in UHPC as the load increases, until the strain reaches its peak at the ultimate strength. The third stage is the strain softening stage, where the load-bearing capacity decreases with increasing strain, and critical cracks appear. However, the addition of steel fibers can improve the mechanical properties of UHPC to some extent.

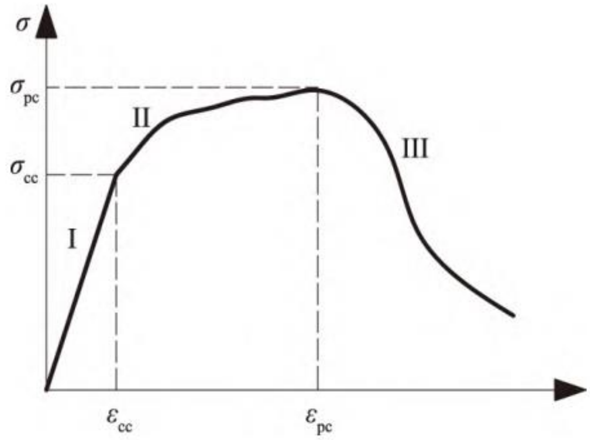

Fig. 3 Stress-strain curve of UPHC [6]

2.4. Other Performance

The durability of UHPC is closely related to its impermeability, and lower impermeability can increase the total porosity of the concrete, allowing ingress of aggressive substances, which leads to erosion and damage of the concrete, thereby reducing its durability [7]. Compared to ordinary concrete and high-performance concrete, UHPC has a lower water-to-cement ratio and good pore distribution, which improves its durability by reducing its permeability. A higher water-to-cement ratio in concrete leads to a higher creep ratio. UHPC has a lower water-to-cement ratio compared to ordinary concrete, resulting in lower creep. Creep affects the long-term deformation of concrete under sustained loading, so the lower creep of UHPC also enhances its load-bearing capacity. In terms of flexural strength, UHPC has a flexural strength ranging from 18MPa to 35 MPa, which is higher than that of ordinary concrete and comparable to high-performance concrete. In experiments on UHPC-reinforced beam structures, UHPC contributes to the flexural load-bearing capacity. Moreover, a higher amount of longitudinal reinforcement in UHPC increases the load-bearing capacity of the tensile zone, so the use of reinforcement in UHPC layers improves the flexural performance of the structure [8].

3. The Application of Ultra High Performance Concrete in Building Structures

3.1. Application Status

The application progress of UHPC varies significantly among different countries. In Denmark, UHPC is mainly used in the construction sector. In France, UHPC finds extensive applications in the design field, and the scale of its usage is the largest. South Korea has shown innovation in the application of UHPC in both bridge and building projects. Malaysia, the United States, and Canada focus their UHPC applications and research primarily on bridge structures. In China, UHPC is predominantly used in steel bridge deck paving and steel-UHPC composite bridge structures. However, UHPC has also been applied in other buildings. For example, the Yuelai Exhibition Center in Shenzhen and the Yuhang Cultural and Art Center in Hangzhou, as well as the Shanghai Conservatory of Music Opera House in Shanghai, adopted UHPC materials [1]. Due to the improved durability and mechanical properties of UHPC, it is widely used in various building structures to enhance their mechanical performance, durability, reduce self-weight, and minimize maintenance costs. Compared to bridge structures, the design requirements for building structures are relatively lower, and the cost of UHPC materials is higher. Therefore, UHPC is primarily applied in bridge structures, while in building structures, it is mainly used for decoration, shaping, and enclosure structures of public buildings. UHPC is also utilized in ancillary facilities such as pedestrian deck panels in bridge structures. Some structures in the marine field have also explored the application of UHPC [9].

3.2. Application Case

The children's playground platform at the 10th China Flower Expo held in Chongming, Shanghai, China, was constructed using UHPC as the main material. UHPC is lighter in weight compared to ordinary concrete and has strong compressive, tensile, flexural, and durability properties. Considering that the platform needs to reduce its own weight while supporting people and various play facilities, UHPC precast elements were used for assembly. The platform is a temporary structure with a lifespan of 5 years. It has a flower-like shape with eight petals, with the inner side of the petals touching the ground and the outer side suspended. The outer diameter is approximately 11.2m,the inner diameter is approximately 6m, and the highest point of the platform is about 2.35m. Please refer to the specific structural diagram in Fig. 4 [10].

Fig. 4 Three-dimensional model diagram of the amusement platform [10]

In the structural design, the selected material is UHPC reinforced with stainless steel fibers. The overall structure consists of 14 prefabricated UHPC components, with 26 nodes at the bottom of the components connected to the foundation using high-strength bolts [10]. Stress analysis was conducted on the structure, and under the ultimate limit state load combinations, the stress level of UHPC is relatively low due to its high compressive strength, which is not fully utilized in ordinary bending members. Pull-out tests were performed on the embedded elements, and due to the excellent anchoring capability of UHPC compared to ordinary concrete, the anchorage depth can be reduced accordingly.

4. Application of UHPC in Bridge Structures

4.1. Application Status

Due to its excellent durability and significantly improved tensile and compressive properties compared to ordinary concrete, UHPC is widely used as the main structural material in many high-demand bridges. Orthotropic steel bridge decks are widely used in bridge structures due to their light weight, high load-bearing capacity, and good overall integrity. However, orthotropic steel decks have complex construction and are prone to fatigue cracking under railway loads [11]. To address these issues, UHPC has been applied to the bridge deck panels of highway steel bridges, specifically in the form of a steel-UHPC composite deck structure, to enhance the stiffness of the bridge deck. The application of steel-UHPC composite deck structures is now widespread. In the Netherlands, early constructed bridges such as Caland Bridge and Moerdijk Bridge, as well as in Japan, bridges like

Yokohama Bay Bridge and Shonan Ohashi Bridge, experienced fatigue cracks and severe damage to the bridge decks. Subsequent repair plans involved replacing the original cast asphalt concrete with UHPC [12]. In China, according to incomplete statistics, over 292,000 steel-UHPC composite beams or composite bridge decks have been constructed as of 2022 [13].

4.2. Application Cases

The Binhai Bay Bridge in Dongyun City, China, adopts a steel-UHPC composite deck. Longitudinally movable and transversely limited seismic spherical steel bearings and transverse steel dampers are installed on the auxiliary piers and transition piers on the east and west sides. Under normal service loads, the vertical forces on the auxiliary piers and transition piers are dominant, while under seismic loads, they share the lateral seismic effects, ensuring the stability and safety of the bridge structure. The main span of the bridge is (60+200+200+60) meters, and the total width of the main girder is 60 meters. The bridge deck of this cable-stayed bridge is paved with UHPC of grade 160 MPa, with a thickness of 60 mm. By using the steel-UHPC composite deck, the self-weight of the main girder is reduced, and compared to conventional concrete deck paving bridges, the stress on the steel panels is reduced by 25%-74%. The peak stress of the longitudinal stiffening ribs is reduced by 30%-50%, and the peak stress of the transverse diaphragms is reduced by 10%-16% [13]. The subsequent construction process is also efficient due to the high assembly efficiency of the composite deck. The reduced self-weight of the bridge deck leads to a relatively lower cost. The deck panels can withstand reduced stress, making maintenance easier and relatively less expensive in the future.

5. Conclusion

In this paper, the properties of UHPC and its application in building structures are systematically studied, and the following conclusions are drawn:

(1) Most UHPC materials are based on the maximum packing density theory, where the addition of cementitious materials and fine aggregates, as well as the removal of coarse aggregates, reduces the water-to-binder ratio, particle size, and porosity, resulting in significant improvements in the properties of UHPC compared to ordinary concrete. Experimental results show that the addition of silica fume significantly enhances the compressive strength of UHPC after 28 days. The shape of steel fibers also affects the compressive strength of UHPC, with hooked-end fibers performing better than straight fibers. The study of UHPC's tensile properties relies on the axial stress-strain relationship and its variations during loading. The increased total porosity of UHPC affects its durability and permeability, leading to improved durability. UHPC also exhibits reduced creep compared to ordinary concrete, and its mechanical properties, such as flexural and bending strength, are also improved.

(2) The children's play platform at the 10th Shanghai Chongming Flower Expo is taken as an engineering case study. The structure of the platform requires the suspension of amusement facilities and the ability to withstand significant crowd loads. UHPC, with its superior properties compared to conventional asphalt concrete, is used as the primary material for constructing the final structure.

(3). The application of steel-UHPC composite bridges is discussed based on the Binhai Bay Bridge in Dongyun, China. The deck of Binhai Bay Bridge is assembled with steel-UHPC composite material, which ensures the overall stability and safety while reducing the weight of the bridge. This method also reduces the construction and maintenance costs of the bridge deck.

(4) UHPC has been widely applied in various countries, particularly in bridge engineering and construction projects. However, the full potential of UHPC has not been fully realized, and it has not been extensively used in large-scale projects with significant deformations or high seismic requirements. Future research should focus on exploring the different performance aspects of UHPC when combined with different materials and optimizing their proportions.

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