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A Review and Prospect of the Application of New Building Materials

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Abstract: Ultra-high-performance concrete (UHPC), as a typical representative of new building materials, demonstrates unique advantages in the field of civil engineering with its ultra-high strength, high toughness, and excellent durability. This paper systematically combs the material properties and preparation processes of UHPC, deeply analyzes its application status in prefabricated buildings, bridge engineering, tunnel reinforcement, and other fields. Combined with practical cases such as the south extension project of Ningbo Airport Road and the reinforcement of expressway bridges, this paper discusses the technical paths for UHPC performance optimization, including the regulation of steel fiber content, the improvement of thermal curing systems, and composite interface treatment. The study shows that UHPC can significantly improve the bearing capacity and durability of components through material composition optimization and structural design innovation, but it still faces challenges such as cost control, specification adaptation, and construction process standardization. Future research should focus on green preparation technologies, intelligent applications, and multi-functional integration to promote the wide application of UHPC in complex engineering environments.

Keywords: Ultra-high-performance concrete; Prefabricated buildings; Bridge engineering; Performance optimization; Engineering application.

1. Introduction

1.1. Research Background and Significance

Against the backdrop of accelerated contemporary urbanization and infrastructure upgrading, the limitations of traditional concrete materials in terms of high strength, durability, and construction efficiency have become increasingly prominent. Ultra-High Performance Concrete (UHPC), boasting a compressive strength of ≥150MPa, a flexural strength of ≥20MPa, and excellent impermeability and frost resistance, has emerged as a key material for addressing challenges in long-span structures, engineering projects in complex environments, and connections in prefabricated buildings[1-3]. Its applications in fields such as bridge reinforcement, tunnel lining, and the preservation of historical buildings have provided an important direction for the development of new construction materials—not only meeting the higher requirements of modern engineering for structural performance but also driving technological innovation and sustainable development in the construction industry[4].

1.2. Current Research Status at Home and Abroad

Research on UHPC abroad began in the 1990s, and countries such as France and Japan have applied it to projects including bridges and nuclear facilities. In China, systematic research on UHPC has been carried out since the early 21st century, and remarkable progress has been achieved in recent years in areas such as prefabricated joints and composite structure reinforcement[5-7]. However, there are still many unresolved issues regarding UHPC in terms of material composition design, structural calculation theory, and engineering application specifications. For instance, there are significant differences in the quantitative calculation of the role of steel fibers between domestic and international specifications, which has restricted its promotion in complex engineering projects[8-9].

2. Material Properties and Preparation Technology of Ultra-High Performance Concrete (UHPC)

2.1. Material Composition and Microstructure

UHPC adopts a low water-binder ratio (≤0.2), a high dosage of mineral admixtures (such as silica fume and fly ash), and fine aggregates (quartz sand), with the incorporation of steel fibers at a volume dosage of 1-3%, forming a dense microstructure. Scanning electron microscopy (SEM) observations show that the UHPC matrix with an optimized mix proportion has a high content of C-S-H gel, a porosity of less than 5%, and a tight interface bond between steel fibers and the matrix[10-11]. Among these components, silica fume fills pores through a pozzolanic reaction, fly ash improves the fluidity of the paste, and steel fibers inhibit crack propagation through a bridging effect[12].

2.2. Optimization of Preparation Process

2.2.1. Thermal Curing Regime

Steam curing (90°C × 48h) can promote the early hydration of UHPC, enabling its 3-day compressive strength to reach over 140MPa, which is an increase of approximately 30% compared with standard curing[3,9]. The practical application of the South Extension Project of Jichang Road in Ningbo shows that high-temperature steam curing can reduce the drying shrinkage rate of UHPC to below 0.015%, effectively reducing the cracking of components[13].

2.2.2. Fiber Reinforcement Technology

When the steel fiber dosage is 160 kg/m³, the flexural strength of UHPC reaches 23.0 MPa, the elastic modulus is 46.2 GPa, and the drying shrinkage rate decreases with the increase of fiber dosage[5]. Compared with straight steel fibers, end-hooked steel fibers can improve the flexural toughness by 46.26%, due to their stronger mechanical interlocking effect with the matrix[14].

2.2.3. Composite Interface Treatment

In the splicing of prefabricated structures, the adoption of a V-shaped interface combined with interface chiseling can increase the bonding strength between new and old concrete by 40%[13]. After the introduction of self-healing microcapsule technology, the impermeability of UHPC is further improved, and the chloride ion diffusion coefficient can be reduced to below 1×10^{-12} m^2/s[4].

3. Mechanical Properties and Optimization Mechanism of Ultra-High Performance Concrete (UHPC)

3.1. Uniaxial Mechanical Behavior

3.1.1. Compressive Performance

The cubic compressive strength of Ultra-High Performance Concrete (UHPC) is closely related to the steel fiber dosage, showing a trend of first increasing and then decreasing with the increase of steel fiber dosage. The optimal dosage is 2.5%, at which point the compressive strength can reach 135.7 MPa[5,14]. Meanwhile, the curing regime also has a significant impact on the compressive strength of UHPC: high-temperature steam curing can increase the compressive strength of UHPC by 20-30% compared with standard curing[7]. This indicates that in engineering practice, reasonable control of steel fiber dosage and selection of an appropriate curing regime can effectively improve the compressive performance of UHPC.

3.1.2. Tensile and Flexural Performance

When the volume dosage of steel fibers is 2%, the tensile strength of UHPC can reach 9.6 MPa, and its flexural strength is 58.82% higher than that of plain UHPC[6,14]. The strain-hardening characteristic of UHPC enables it to exhibit a multi-crack cracking mode when subjected to tension. This characteristic endows UHPC with better ductility and toughness under tensile forces, which can effectively delay crack propagation and improve the safety and durability of structures.

3.2. Shear and Flexural Bearing Capacity

3.2.1. Shear Performance of Beam Members

The shear failure mode of T-section Ultra-High Performance Concrete (UHPC) beams is jointly influenced by the steel fiber dosage and shear-span ratio. Studies recommend a fiber volume fraction of 2%, under which the shear bearing capacity is 35% higher than that of UHPC without fibers[14]. By comparing the calculation results of UHPC beam shear bearing capacity from different codes, it is found that the results calculated using the European Code (EN 1992) have a high degree of agreement with the experimental values, which provides an important reference for the shear design of UHPC beams.

3.2.2. Flexural Performance of Bridge Piers

For prefabricated bridge piers using a hybrid connection of UHPC and mortise-tenon joints, their flexural bearing capacity increases with the increase of the axial compression ratio and reinforcement ratio. However, for every 10% increase in the slenderness ratio, the bearing capacity decreases by approximately 8%. The error between the calculated values of the flexural bearing capacity of such piers using Chinese codes and the experimental results is within 10%[2], indicating that Chinese codes have a certain degree of applicability in the design of such piers, but still need further improvement.

3.3. Durability Enhancement Mechanism

3.3.1. Impermeability and Frost Resistance

UHPC exhibits excellent impermeability and frost resistance. Its electric flux is less than 40 C, and the mass loss after 500 freeze-thaw cycles using the rapid freezing method is $\leq$ 6%. These indicators are significantly superior to those of ordinary concrete[9,12]. The excellent durability of UHPC is mainly attributed to its dense microstructure and the crack-inhibiting effect of steel fibers. The dense microstructure reduces the penetration channels for water and harmful substances[5,8], while the presence of steel fibers can effectively prevent the initiation and propagation of cracks, thereby enhancing the impermeability and frost resistance of UHPC.

3.3.2. Chloride Ion Penetration Resistance

After optimizing the mix proportion, the chloride ion diffusion coefficient of Ultra-High Performance Concrete (UHPC) is $\leq 1\times10^{-12}$ m^2/s, which is 2–3 orders of magnitude lower than that of C50 concrete[4,16]. This indicates that UHPC exhibits superior durability under harsh conditions such as marine environments and saline soils, which can effectively extend the service life of structures and reduce maintenance costs.

4. Current Status of Engineering Applications of Ultra-High Performance Concrete (UHPC)

4.1. Field of Prefabricated Construction

4.1.1. Joint Connection Technology

By combining concealed steel corbels with UHPC, the new prefabricated UHPC joints achieve seismic performance close to that of cast-in-place structures, with their energy dissipation capacity increased by 40%[15]. This joint connection technology addresses the issues of insufficient connection reliability and structural integrity in traditional prefabricated building joints, providing strong technical support for the promotion and application of prefabricated buildings. In the wet joints of prefabricated underground stations, UHPC meets the requirements of self-compacting property and micro-expansibility, with an interface bonding strength of $\geq$5 MPa[8], ensuring the safety and stability of underground station structures.

4.1.2. Application of Prefabricated Components

Prefabricated UHPC road slabs demonstrate excellent load-bearing capacity: their ultimate bearing capacity can reach 368 kN, and no obvious cracks are observed when loaded up to 120 kN, making them suitable for heavy-duty traffic scenarios[11]. In the South Extension Project of Jichang Road in Ningbo, UHPC was used as the wet joint material for small box girders, improving construction efficiency by 50%[13] while ensuring project quality, thus providing valuable experience for the construction of similar projects.

4.2. Application in Bridge Engineering

4.2.1. Newly Built Bridge Structures

When UHPC (with a steel fiber dosage of 160 kg/m^3) is applied in steel bridge deck pavements, the pavement surface remains smooth and crack-free, and its anti-skid performance meets code requirements[5], enhancing the safety and comfort of bridge operation. Compared with traditional concrete arch bridges, prefabricated UHPC arch bridges have a 30% reduction in self-weight and improved spanning capacity[16]. This is of great significance for the construction of long-span bridges, as it can reduce project costs and enhance the economy and applicability of bridges.

4.2.2. Bridge Strengthening and Reconstruction

After reinforcing the simply supported T-beams of an expressway in Guangdong with UHPC diaphragms, the lateral stiffness increased by 25%, and the load-bearing capacity was enhanced to 1.8 times the original design[10]. This effectively resolves structural defects of the bridge and extends its service life. In the reinforcement of historical bridges, the UHPC single-sided formwork system enables non-destructive reinforcement, and the wall surface after reinforcement shows a uniform color[9], which not only ensures the structural safety of the bridge but also preserves the original appearance of the historical building.

4.3. Tunnel and Underground Engineering

4.3.1. Tunnel Lining Strengthening

When using the UHPC-NC (Normal Concrete) composite structure to reinforce highway tunnels, the load-bearing capacity of a 150 mm-thick composite layer is equivalent to that of a 200 mm-thick ordinary concrete layer, and the requirement for construction space is reduced. This is of great significance for meeting the "no clearance occupation" requirement in tunnel reinforcement projects. The flexural stiffness of composite beams treated with keyways is 35% higher than that of beams without keyways[17], improving the overall performance of tunnel linings.

4.3.2. Connection of Underground Structures

The application of UHPC in the wet joints of the secondary structure of prefabricated underground stations can shorten the construction period by 40%, and the joint durability meets the 100-year design requirement[8]. This is of great significance for the rapid construction and long-term service of underground stations, improving the construction efficiency and quality of underground projects.

5. Future Development Trends

5.1. Green Preparation Technology

5.1.1. Resource Utilization of Solid Wastes

Replacing part of the quartz sand with recycled construction waste aggregates, fly ash, and other materials can not only reduce the cost of Ultra-High Performance Concrete (UHPC) but also realize the resource utilization of solid wastes and minimize environmental pollution caused by construction waste. Studies have shown that such replacement can lower UHPC costs by 20% while reducing carbon emissions[9,12], which aligns with the requirements of green buildings and sustainable development.

5.1.2. Low-Carbon Curing Technology

The development of UHPC cured at low temperatures (50–60 °C), combined with the use of solar heat collection systems, can reduce curing energy consumption by 50%[7,13]. This low-carbon curing technology not only cuts down on energy consumption during UHPC production but also reduces reliance on traditional energy sources, driving the development of UHPC preparation technology toward a greener and more low-carbon direction.

5.2. Intelligence and Functional Integration

5.2.1. Intelligent Monitoring System

Optical fiber sensors are pre-embedded in UHPC components to enable real-time monitoring of conditions such as the degradation of component bearing capacity and crack propagation[15,16]. Through the intelligent monitoring system, potential structural issues can be detected in a timely manner, providing a basis for structural maintenance and reinforcement and enhancing the safety and reliability of structures.

5.2.2. Multifunctional Composite

Multifunctional UHPC with properties like self-cleaning, fire resistance, and electromagnetic shielding has been developed to expand its application in special engineering projects[12]. For instance, in projects with high safety and functionality requirements—such as nuclear power plants and data centers—multifunctional UHPC can meet diverse engineering needs and play a crucial role.

5.3. Standardized and Systematic Development

5.3.1. Improvement of Design Codes

Specialized specifications for UHPC structural design should be established to clarify the constitutive relations of UHPC materials, component calculation methods, and structural detail requirements [2,14]. Comprehensive design specifications can provide scientific guidance for the engineering application of UHPC, improve the rationality and safety of UHPC structural design, and promote the widespread use of UHPC in engineering.

5.3.2. Standardization of Construction Technology

Standardized processes for UHPC preparation, pouring, and curing should be formulated, and specialized construction equipment should be developed[3,11]. Standardized construction technology and specialized equipment can improve the efficiency and quality of UHPC construction, reduce uncertainties during the construction process, ensure the stable performance of UHPC components, and advance the standardization and regularization of UHPC construction technology.

6. Conclusion

Through the optimization of material composition and innovation in preparation technology, Ultra-High Performance Concrete (UHPC) demonstrates significant advantages in terms of mechanical properties and durability, and has been successfully applied in various fields such as prefabricated buildings and bridge engineering. Its performance in enhancing structural bearing capacity, shortening construction periods, and improving durability provides an important reference for the development of new construction materials. However, the widespread application of UHPC still faces challenges such as cost control, code improvement, and construction technology optimization. Future research should focus on green preparation, intelligent monitoring, and multi-functional integration to promote the large-scale application of UHPC in complex projects, provide more powerful material support for infrastructure construction, and contribute to the technological progress and sustainable development of the construction industry.

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