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A Review of Ultra-High Performance Concrete (UHPC)

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ABSTRACT

Ultra-high performance concrete (UHPC), as a new generation of cement-based composite, features ultra-high strength, excellent toughness, and outstanding durability, demonstrating tremendous application potential in civil engineering. This paper systematically reviews the development history, preparation technologies, performance mechanisms, engineering applications, and future trends of UHPC. By analyzing recent research achievements at home and abroad, it summarizes significant progress in material composition optimization, process improvement, performance enhancement, and engineering applications. Results indicate that UHPC technology is becoming increasingly mature, with expanding applications in bridges, buildings, and marine engineering. Nevertheless, further research is needed in cost control, standardization, and long-term performance evaluation. With the deepening concepts of green construction and sustainable development, UHPC is expected to play an increasingly important role in infrastructure construction.

KEYWORDS

Ultra-high performance concrete; mechanical properties; durability; engineering applications.

1. INTRODUCTION

Concrete, as the most widely used building material in the world today, plays an irreplaceable role in human social development [1, 2]. Since the advent of modern concrete in the mid-19th century, concrete technology has evolved from normal-strength concrete to high-strength concrete and high-performance concrete. However, conventional concrete suffers from relatively low strength, high brittleness, and insufficient durability, making it difficult to meet the increasingly stringent performance requirements of modern engineering. Especially under extreme conditions such as long-span bridges, super high-rise buildings, and marine engineering, higher demands are placed on the strength, toughness, and durability of concrete materials.

Ultra-high performance concrete (UHPC), as a significant milestone in the development of concrete technology, is currently the most innovative and promising cement-based material [3]. Its origins can be traced back to the 1970s. In 1972-1973, Brunauer and others published a series of papers on low-porosity hardened cement paste in Cement and Concrete Research, reporting cement-based materials with a compressive strength of 240 MPa, laying the theoretical foundation for UHPC [4]. Subsequently, Bache, using the densified systems containing homogeneously arranged ultra-fine particles (DSP) approach, prepared concretes with strengths of 150-200MPa via the combined use of silica fume and high-range water reducers [5]. In 1994, French scholars Larrard et al. formally proposed the concept of UHPC [6], marking the establishment of this new material.

Entering the 21st century, with the rapid development of global infrastructure and rising requirements for structural safety and durability, UHPC technology has received extensive attention worldwide. UHPC is a novel cement-based composite composed of cement, mineral admixtures, fine aggregate, fibers, chemical admixtures, and water, exhibiting extremely high strength, excellent toughness,

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outstanding structural reliability, and durability, with remarkable mechanical performance [7]. By incorporating steel fibers to improve the brittleness of conventional concrete, ductility and energy dissipation capacity can be significantly enhanced [8], effectively improving seismic performance in infrastructure. Meanwhile, UHPC exhibits extremely low permeability during service, nearly no carbonation, and excellent resistance to chloride and sulfate attacks [9]. These characteristics help improve resource and energy efficiency, aligning with sustainability goals.

Currently, UHPC technology is in a rapid development phase, flourishing in both theoretical research and engineering applications. Nevertheless, widespread adoption still faces challenges such as high cost, complex preparation processes, and incomplete standards and specifications. This paper aims to systematically review the current state of UHPC research, analyze technological development trends, and provide references for further promoting the development and application of UHPC technology.

2. RESEARCH ON UHPC PREPARATION TECHNOLOGY

2.1. Raw Materials Composition and Optimization

UHPC preparation requires careful selection and optimization of constituents, generally including binder materials, fine aggregates, fibers, and chemical admixtures. The binder is the core component, typically using high-quality Portland cement as the primary binder. Cement selection should consider chemical composition, mineral phases, and physical properties, generally requiring high C3S content, low alkalis, and high specific surface area.

Silica fume, as an important reactive admixture, is typically dosed at 15–25% of the total binder. Its ultra-fine particles (average size ~0.1μm) and high activity (SiO2≥85%) help fill voids between cement particles and increase density. Its pozzolanic reaction with Ca(OH)2 from cement hydration generates additional C-S-H gel, further improving strength. In recent years, to reduce cost and enhance sustainability, researchers have explored alternatives. Fly ash, as an industrial by-product with good pozzolanic activity, can partially replace silica fume. Ultrafine slag with latent hydraulicity can improve later-age strength. Natural pozzolans such as metakaolin and rice husk ash have also been used. These alternatives not only reduce cost but also benefit environmental protection and resource recycling.

The selection of fine aggregates significantly affects UHPC performance. Traditional UHPC uses high-quality quartz sand with particle size less than 1.25 mm, requiring good gradation, low impurities, and high strength. The high hardness and chemical stability of quartz sand contribute to UHPC strength and durability. However, natural quartz sand is limited and costly, prompting studies on replacing it with manufactured sand. Manufactured sand has good angularity and controllable gradation; through gradation optimization and surface treatment, properties comparable to natural sand can be achieved.

Fibers are key to achieving UHPC is superior toughness. Currently, high-strength steel fibers with diameters of 0.15–0.25 mm and lengths of 10–20 mm are mainly used, with typical volume fractions of 1–3%. Aspect ratios are generally 50–100 and tensile strength exceeds 2000 MPa. To prevent corrosion, steel fibers are often copper-coated or otherwise protected. In recent years, carbon fibers, glass fibers, and polypropylene fibers have also been used. Carbon fibers feature high strength, low weight, and corrosion resistance but are expensive; polypropylene fibers are low-cost and alkali-resistant, but have relatively lower strength and modulus.

Chemical admixtures significantly influence both workability and mechanical properties. High-range water reducers (HRWR) are crucial, typically using polycarboxylate superplasticizers at 1–3% of binder mass. They offer high water-reduction rates, good slump retention, and strong adaptability, enabling very low water-to-binder ratios while maintaining workability. Defoamers remove entrapped air during mixing to increase density. Shrinkage-compensating agents can effectively control shrinkage cracking.

2.2. Mix Proportion Design: Theory and Methods

UHPC mix design is a complex multi-objective optimization problem, requiring an integrated consideration of strength, workability, durability, and economy. Currently, the maximum packing density principle is central to mix design. By optimizing particle size distribution to achieve mutual filling among particles, the maximum packing density is realized, thus reducing porosity and improving strength and durability. The Andreasen particle packing model is the most widely used, expressed as:

$$\mathrm{P(D)} = \left(\frac{D}{D_{max}}\right)^q \tag{1}$$

where P(D) is the cumulative fraction smaller than particle size D, Dmax is the maximum particle size, and q is the distribution modulus. The water-to-binder ratio (w/b) is critical. UHPC typically uses w/b of 0.15-0.25, far lower than ordinary concrete. While low w/b benefits strength and durability, it reduces workability, necessitating HRWR to balance requirements. Determining w/b should consider cement demand for water, HRWR effectiveness, and construction process needs.

Fiber optimization must consider fiber type, geometry, and dosage. Aspect ratio influences reinforcement efficacy: too small causes poor anchorage; too large leads to balling. There is an optimal volume fraction: insufficient content limits benefits, while excessive content harms workability and may reduce strength. Uniform distribution is essential and depends on optimized mixing procedures.

Common design methods include empirical methods, theoretical calculations, experimental optimization, and AI-based methods. Empirical methods rely on extensive testing and engineering experience—simple and practical but lacking theoretical rigor. Theoretical methods use particle packing and hydration theories—scientific but parameter-intensive. Experimental optimization uses orthogonal and single-factor tests—reliable but laborious. AI methods (neural networks, genetic algorithms) can handle complex nonlinear relations and are a key future direction.

2.3. Processing and Production Techniques

UHPC properties are directly influenced by processing, including mixing, forming, and curing. Mixing is a key link. Due to complex composition and high viscosity, traditional mixing methods are insufficient. A recommended sequence: dry-mix cement, silica fume, and fine aggregates; add water and HRWR for wet mixing; finally add fibers and continue mixing. Total mixing time is usually 8–15 minutes, 3–5 times longer than for normal concrete.

Forming should suit component characteristics and construction conditions. With good flowability, UHPC can be placed by casting or pumping. For precast elements, vibration tables or pressure forming may be used. Control casting speed to avoid segregation and air entrapment; for complex shapes, layered casting is advisable. Fiber orientation impacts performance and can be optimized by controlling casting direction and vibration.

Curing is crucial. Standard curing (20°C, RH≥95%) yields good baseline properties and suits in-situ work. Steam curing (90°C, 48-72h) accelerates hydration, increases early strength, and shortens production cycles-suitable for precast. Autoclave curing (250-400°C,20-50MPa) can attain the highest performance but with complex equipment and high cost, mainly for special components.

Humidity control during curing is important to prevent cracking. UHPC's low w/b leads to pronounced self-desiccation and risk of autogenous shrinkage cracking. Maintain sufficient humidity at early ages with wet coverings or mist curing. For steam curing, control heating and cooling rates to 20–30°C/h to avoid thermal gradients that cause cracking.

3. MECHANISMS UNDERPINNING UHPC PERFORMANCE

3.1. Microstructural Characteristics

UHPC's excellent properties fundamentally derive from its dense microstructure. Compared to ordinary concrete, UHPC's optimized pore structure is foundational to its high performance. The porosity of ordinary concrete is typically 10–15%, whereas that of UHPC is usually less than 5%, even as low as 2–3%. Using a low w/b to reduce capillary pores and ultra-fine admixtures to fill voids enhances packing density, concentrating pore sizes mainly within the nanoscale (<100nm) and minimizing large pores (>1μm), thereby greatly improving strength and durability.

Improved interfacial structure is also key. In ordinary concrete, the interfacial transition zone (ITZ) between aggregate and cement paste is a weak link with high porosity and low strength. UHPC, by eliminating coarse aggregate and adding ultra-fine admixtures, significantly improves the interfacial structure. Silica fume and other ultra-fine materials fill gaps between cement and aggregate particles to form a denser interface, while pozzolanic C-S-H further enhances bonding. Studies indicate that the ITZ thickness in UHPC is only 1/3-1/2 that of ordinary concrete, with over 50% reduction in porosity.

Optimization of hydration products is another important reason for UHPC's high strength. Under standard curing, primary hydration products resemble those of ordinary concrete, including C-S-H, Ca(OH)2, and ettringite. However, due to low w/b and highly reactive admixtures, UHPC contains more C-S-H with a denser structure. Under high-temperature curing, C-S-H may transform into crystalline products such as tobermorite, further enhancing strength. When curing temperature exceeds 250°C, hard silica-calcium minerals may form.

Crystalline structure evolution also affects performance. XRD shows that with elevated curing temperatures, Ca(OH)2 content decreases, while crystalline phases like tobermorite and hard silica-calcium increase. These crystalline phases are stronger and more stable, crucial for achieving ultra-high strength. NMR indicates that the polymerization degree of silicate tetrahedra in C-S-H increases under high-temperature curing, forming longer Si-O chains and enhancing gel structural stability.

3.2. Fiber Reinforcement and Toughening Mechanisms

Fibers are critical to UHPC's excellent toughness [10]. The effect is not governed by a single process but by a sequence of interacting mechanisms evolving with loading and crack development: early-stage crack initiation and propagation suppression, post-cracking bridging, pullout energy dissipation, orientation-induced anisotropy and statistical utilization, all strongly modulated by fiber-matrix interfacial bonding and anchorage. Their multi-stage coupling governs cracking strength, strain-hardening behavior, and fracture energy.

Fibers form a 3D network in the dense matrix, providing geometric obstruction and stress redistribution during microcrack initiation and early propagation. When local tensile stress exceeds matrix tensile strength and microcracks form at defects, fibers reduce the strain energy release rate of a single crack, causing bifurcation and deflection, transforming a dominant crack into multiple fine cracks. Thus, primary crack formation and penetration are delayed, enhancing nominal cracking strength and promoting uniform crack distribution-preparing favorable conditions for subsequent stable multiple cracking. This early control underpins the transition from high strength to high toughness.

Fibers bridging across cracks transmit tensile forces and generate bridging stresses, allowing the material to maintain or even increase load-bearing capacity after cracking. Bridging stress depends on interface bond strength, fiber aspect ratio and surface morphology, intrinsic fiber strength and stiffness, and the projected embedded length normal to the crack. UHPC's strong, dense matrix affords excellent interfacial anchorage, enabling steel fibers to mobilize a high fraction of their tensile capacity, often achieving 60-80% of fiber tensile strength. Consequently, UHPC may not soften immediately upon first cracking but rather exhibits strain hardening with stepwise stable crack growth, delivering significant ductility and a residual strength plateau.

Crack propagation involves debonding and pullout of fibers, overcoming interfacial friction and mechanical interlock and possibly incurring local plastic deformation, continuously dissipating energy. Fiber pullout work typically dominates UHPC fracture toughness, increasing fracture energy by one to several orders of magnitude relative to normal concrete, commonly by 10-50 times. Key parameters influencing pullout energy include aspect ratio, surface roughening and end-anchorage features, and volume fraction. Research and practice indicate an aspect ratio window (often 60-80) that maximizes pullout work.

Overall, fiber toughening in UHPC is a cross-stage, multi-scale synergistic process. Material design and engineering application should systematically optimize fiber volume fraction, aspect ratio and surface features, orientation control, matrix toughness, and interface tailoring to achieve uniform multiple cracking, pronounced strain-hardening, and high fracture energy, thereby delivering high ductility and reliability at component and structural scales.

3.3. Strength Formation Mechanisms

UHPC's ultra-high strength arises from multiple synergistic mechanisms. Densification strengthening is fundamental. According to Griffith's theory, strength is closely related to defect (pores, cracks) size and quantity. UHPC significantly increases density and reduces defect size and number by optimizing particle packing, lowering w/b, and incorporating ultra-fine admixtures, thereby markedly improving strength. Studies show an exponential relationship between compressive strength and porosity.

Hydration product strengthening is the main chemical mechanism. Extensive reactive admixtures participate in pozzolanic reactions to generate additional C-S-H, increasing binder volume and improving gel structure. Under high-temperature curing, C-S-H transforms into crystalline phases such as tobermorite, providing higher strength and stability. Meanwhile, adding silica fume and others lowers Ca(OH)2 content and reduces weak links.

Interface strengthening enhances composite performance. UHPC improves interparticle interfaces and increases interfacial bond strength. Filling and reactions of ultra-fine admixtures in interfacial regions bring ITZ performance close to or even exceeding the matrix, eliminating weak links-a key contributor to improved tensile strength and toughness.

Size-effect mitigation is embodied in eliminating coarse aggregate. Coarse aggregate induces stress concentrations around particles, serving as crack initiation sites. UHPC removes coarse aggregate, reducing stress concentrators and improving homogeneity. Fine aggregates better match the matrix modulus, reducing stress concentrations from modulus mismatch.

4. MECHANICAL PROPERTIES AND DURABILITY OF UHPC

4.1. Mechanical Properties

As shown in Table 1, UHPC exhibits superior mechanical properties far exceeding those of ordinary concrete [11].

Table 1 Comparison of main mechanical and durability properties between UHPC and ordinary concrete

Project	UHPC	Ordinary concrete
Compressive strength (MPa)	150~300	20~50
Tensile strength (MPa)	10~20	2~4
Flexural strength (MPa)	25~60	2~5
Elastic modulus(GPa)	40~60	30~40
Creep coefficient	0.2~0.3 (after high-temperature steam curing)	1.4~2.5
Chloride diffusion coefficient (m2/s)	<0.01×10-11	>1×10-11
Resistivity (kΩ·cm)	1133	96（C80）
Carbonation depth at 91 d (mm)	1	15

Compressive strength is UHPC's most prominent feature. Typical compressive strength ranges from 150-300MPa, with maxima up to 800MPa—3-16 times that of ordinary concrete. Key influencing factors include w/b, silica fume content, and curing regime. Studies show that reducing w/b from 0.25 to 0.15 can increase compressive strength by 30-50%; increasing silica fume from 0 to 25% can increase strength by 50-80%; steam curing can improve strength by 20-40% compared to standard curing. The ascending branch of the UHPC compressive stress-strain curve is approximately linear, with peak strain about 3-5‰, slightly higher than ordinary concrete (2-3‰).

Tensile performance is another notable advantage. UHPC tensile strength can reach 10-20MPa, and the material can sustain significant tensile stress after cracking, exhibiting strain-hardening behavior. This yields better crack resistance and safety reserves for structures. Fiber content is critical; increasing fiber volume from 1% to 3% can raise tensile strength by 50-100%.

Flexural performance reflects integrated mechanical behavior. UHPC flexural strength is typically 15-20% of compressive strength. In flexural tests, UHPC shows good bending toughness, with multi-peak load–deflection curves indicative of progressive fiber pullout.

Elastic modulus is an important design parameter, typically 40-60GPa for UHPC, comparable to high-strength concrete. While a correlation exists between modulus and compressive strength, it is less pronounced than in ordinary concrete due to fiber presence and high-strength matrix influencing deformation characteristics. Poisson's ratio for UHPC is generally 0.18-0.25, close to ordinary concrete (0.15-0.22), and increases with stress level under compression, reflecting damage accumulation.

4.2. Long-Term Properties

Shrinkage merits special attention. Due to low w/b and high binder content, UHPC shrinkage is relatively large, comprising autogenous and drying shrinkage. Autogenous shrinkage, driven by internal water consumption during hydration, typically reaches 60-80% within 24h after casting. Drying shrinkage is governed by moisture migration due to ambient humidity and develops more slowly. Total shrinkage is typically 600-1000×10-6, 20-50% higher than ordinary concrete. Rapid early shrinkage favors precast production efficiency but increases cracking risk.

Creep is relatively small due to high strength and modulus. Under standard loading, UHPC creep coefficients are usually 0.5-1.0, significantly lower than ordinary concrete. Its development law is similar—rapid early development followed by stabilization. Curing regime significantly influences creep; steam curing markedly reduces it.

Fatigue performance is critical under cyclic loads. Benefiting from fiber reinforcement, UHPC exhibits excellent fatigue resistance. In bending fatigue tests, UHPC can withstand 2 million cycles without fatigue failure, with fatigue strength about 60-70% of static strength. Fatigue life relates to stress level following a clear S-N relation consistent with the Wöhler equation. Fibers effectively inhibit fatigue crack growth, extending life.

4.3. Durability Assessment

Impermeability is a foundational durability indicator. UHPC has an extremely low permeability coefficient, usually below 10-18 m2, 3-4 orders of magnitude lower than ordinary concrete, mainly due to its dense pore structure and low porosity. This effectively prevents ingress of water and deleterious agents.

Resistance to chloride ingress is critical in marine and deicing salt environments. UHPC chloride diffusion coefficients are typically below 10-12m2/s, 1-2 orders lower than ordinary concrete. Rapid chloride permeability test (RCPT) charges are usually below 100 Coulombs, considered negligible. This exceptional resistance prolongs service life in marine environments.

Freeze-thaw resistance is important in cold regions. After 300 cycles, UHPC often shows less than 5% strength loss, less than 1% mass loss, and retains over 95% of relative dynamic modulus, mainly due to low porosity and optimized pore structure. Fibers further improve resistance by preventing cracking from freeze-thaw damage.

Carbonation resistance governs rebar corrosion risk. Due to extremely low porosity, UHPC exhibits minimal carbonation—after 5 years of natural exposure, depth is typically less than 1 mm. Even under accelerated conditions (CO2 potency—20%, 20°C, RH 70%), carbonation is much slower than ordinary concrete.

Chemical attack resistance matters in special environments. UHPC shows good resistance to sulfates and acids. After 1 year in sodium sulfate solution, strength loss is typically below 10%. Even in strong acid (pH=1), corrosion depth is significantly less than that of ordinary concrete. This is attributed to dense microstructure and optimized pore solution chemistry.

4.4. Performance in Special Environments

High-temperature performance is vital for fire safety and special processes. UHPC retains properties with relatively small degradation at elevated temperatures, remaining essentially stable below 300°C. Above 300°C, strength begins to decline due to evaporation of free and bound water, but to a lesser extent than ordinary concrete. After exposure to 600°C, UHPC can retain 60-70% of its initial strength. Fibers can further mitigate high-temperature damage and prevent spalling and excessive cracking.

Impact resistance is important for protective and transportation engineering. Due to fiber reinforcement, UHPC has excellent impact and blast resistance. In drop-weight impact tests, toughness is 5-10 times that of ordinary concrete. Under blast loading, UHPC structures exhibit significantly less damage, providing better protection.

Abrasion resistance is crucial in pavements and hydraulic engineering. UHPC demonstrates superior wear resistance, with wear depth typically one-third to one-half of ordinary concrete, mainly due to high strength and dense structure. Steel fibers further improve wear resistance, especially under high-stress abrasion.

5. ENGINEERING APPLICATIONS AND DEVELOPMENT OF UHPC

5.1. Bridge Engineering

Bridges are the most extensive and successful application field of UHPC [12]. Deck panels are among the earliest and most successful UHPC applications. UHPC bridge decks feature small thickness, light self-weight, and good durability. Since 2006, the United States has widely applied UHPC deck panels in Iowa, New York, and other states; hundreds of bridges have adopted this technology. Typical deck systems comprise precast panels and cast-in-place overlays. Precast panels are 30-50 mm thick, and overlays 20-25 mm. Panels connect to steel girders via shear studs, and overlays achieve composite action through surface roughening of interfaces.

Precast girder bridge applications showcase UHPC's structural advantages. Its high strength and excellent toughness enable longer spans and lighter self-weight. In France, multiple UHPC precast girder bridges with spans of 40-60 m and girder depths of only L/25-L/30 have been built, much smaller than ordinary RC girder bridges. Japan developed UHPC precast girders using prestressing, achieving spans over 80 m. In China's Beijing-Shanghai High-Speed Railway, many UHPC precast girders were used; for 32 m simply supported spans, self-weight was reduced by 20-30% compared to ordinary concrete girders.

Cast-in-place girder applications benefit from construction convenience. UHPC's high flowability and self-compacting nature suit in-situ casting. Several UHPC cast-in-place girder bridges in France achieved good construction quality and aesthetics. This approach accommodates complex forms but demands higher construction expertise.

Arch bridges leverage UHPC's high compressive strength. Being 3-8 times that of normal concrete, UHPC is well-suited for arch bridges. France and South Korea have built multiple UHPC arch bridges with spans of 100-200 m, featuring large spans, graceful forms, and excellent durability, promising in signature bridges.

Bridge strengthening is an emerging application. Existing bridges often require retrofitting due to increased loads and material aging. UHPC's high strength and good bond make it ideal for strengthening via section enlargement, bonded overlays, or prestressed retrofits.

5.2. Building Engineering

Although starting later, UHPC applications in building engineering are developing rapidly with continuous innovation.

High-rise buildings primarily adopt UHPC in critical load-bearing components. Its high strength is ideal for cores, mega-columns, and connection nodes with huge loads and complex stress states. Using UHPC reduces member sizes, increases usable space, and improves safety. Dubai's Burj Khalifa adopted UHPC technologies in certain critical nodes with favorable results.

Precast components are the main application form in buildings. UHPC precast elements feature high strength, dimensional accuracy, excellent surface finish, and outstanding durability, suitable for factory production. Components include exterior wall panels, slabs, beams, columns, and stairs. France and Japan have extensively used UHPC elements, promoting industrialized building. Connection technologies—bolting, welding, and adhesive bonding—are key for precast UHPC systems.

Architectural features exploit UHPC's aesthetic value. Its formability and surface quality allow crafting complex shapes and textures via molds. UHPC feature elements offer high strength, durability, and low maintenance, widely used in high-end projects. Notable examples include the Jean Bouin Stadium in Paris and the Dongdaemun Design Plaza in Seoul.

Protective structures leverage UHPC's safety functions. Its high strength and toughness suit blast and impact-resistant structures. In military facilities, nuclear plants, and critical government buildings, UHPC can effectively resist extreme loads. The U.S. military has adopted UHPC in multiple projects, validating its protective performance.

5.3. Infrastructure

In pavements, UHPC is used in special zones and demanding locations, such as road surfacings, bridge expansion joints, toll plazas, and service areas. UHPC pavements offer high strength, wear resistance, and long service life, particularly suitable for heavy traffic and harsh environments. France applied UHPC pavements at highway toll stations with good results. UHPC expansion joints provide large deformability, good durability, and low maintenance, used in long-span bridges.

In underground works, UHPC shows environmental adaptability. Faced with complex geology and corrosive conditions, UHPC's high strength and durability suit applications in metro stations, utility tunnels, and tunnel linings. Singapore has adopted UHPC in several metro stations with good results.

In hydraulic engineering, UHPC capitalizes on durability under water exposure, scour, freeze–thaw, and chemical attacks. Applications include dam facings, gates, channel linings, and seawalls. The U.S. has applied UHPC in multiple hydraulic projects with favorable performance.

In marine engineering, UHPC is a significant direction. Marine environments with high salinity, humidity, and temperature fluctuations are severe durability challenges. UHPC's excellent chloride resistance and durability make it ideal for platforms, piers, breakwaters, and subsea tunnels. Norway and the Netherlands have used UHPC in many marine projects.

6. OUTLOOK

With the application of cutting-edge technologies such as nanotechnology and bionics, UHPC's strength, toughness, and durability will be further enhanced. New nano-admixtures will optimize microstructure; bio-inspired fibers will strengthen fiber reinforcement; multifunctional additives will impart special functionalities.

Advances in automated and intelligent production will make UHPC manufacturing more efficient and stable while reducing costs. AI will enable automatic mix optimization and smart process control, effectively utilizing industrial by-products to reduce material costs. Advanced equipment will improve efficiency and quality, simplifying processes and lowering production costs. Establishing standardized production systems will ensure quality consistency and economies of scale.

As application domains expand, technical standards and specifications will be refined. A comprehensive national standard system for UHPC and detailed industry guidelines will support broader adoption in traditional fields such as bridges and buildings, as well as rapid development in emerging fields like new energy infrastructure, smart infrastructure, and extreme environment engineering. Special functional applications—EM shielding, vibration damping/noise reduction, and environmental remediation—will gradually emerge.

Green development is a key direction. With rising environmental awareness and sustainability imperatives, and under the "carbon peak and carbon neutrality" goals, green high-performance UHPC materials will be emphasized. Developing low-carbon binders will reduce CO2 emissions; recyclable fibers (e.g. natural fibers, biodegradable synthetics) will reduce environmental burdens; promoting green processing will lower energy consumption, leading to substantially reduced life-cycle carbon emissions for UHPC.

7. SUMMARY

(1) UHPC preparation technology is becoming mature, forming a relatively complete technical system. By optimizing raw material selection, mix design, and processing, UHPC with stable, superior performance can be consistently produced. In material composition optimization, a mix design theory centered on maximum packing density has been established; in processing, complete

procedures including mixing, forming, and curing have been developed; in quality control, full-process control from raw materials to finished products has been instituted.

(2) The mechanisms underpinning UHPC's superior performance have been deeply elucidated. Microstructural analyses indicate that UHPC's ultra-high performance mainly arises from its dense pore structure, optimized interfaces, and improved hydration products. Fiber mechanism studies show significant toughness enhancement through crack control, bridging, and energy dissipation. Strength formation analyses indicate that densification, hydration product strengthening, and interface strengthening synergistically produce ultra-high strength.

(3) UHPC's mechanical and durability performance comprehensively surpass those of ordinary concrete. Mechanically, UHPC not only has ultra-high compressive and tensile strengths but also exhibits good toughness and fatigue performance. In durability, UHPC has extremely low permeability, excellent chloride resistance, good freeze-thaw resistance, and strong chemical resistance, ensuring long-term service in harsh environments.

(4) Significant progress has been made in engineering applications, with expanding fields. Bridges are the most successful domain, from deck panels to precast girders, cast-in-place structures to strengthening; UHPC technology is relatively mature. In building engineering, applications in high-rises, precast components, and architectural features are increasing. In infrastructure and special works, UHPC has successful cases in roads, underground works, hydraulic engineering, marine engineering, and nuclear power.

(5) UHPC development trends include green, functional, and intelligent directions. In materials, trends include greening, functionalization, and cost optimization; in processing, intelligent production, standardized manufacturing, and special processes; in performance research, multi-scale, long-term, and extreme-environment studies; in applications, improved design theories, construction techniques, and expanded domains.

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