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Introduction

1.1 Overview

Concrete is the most widely used man-made material and a primary building material in the world today, playing an irreplaceable role. Compared to other common building materials such as metals and organic materials, concrete has low production energy consumption, wide availability of raw materials, simple preparation processes, and consequently low production costs. At the same time, it possesses characteristics such as durability, fire resistance, strong adaptability to engineering and the environment, and convenient application [1, 2].

Concrete technology has evolved from the early use of primitive natural cementing materials to the contemporary use of artificially produced cementing materials. The material composition has progressed from a simple triad of cementitious materials, aggregates (ranging from coarse to fine), and water to a diverse system with various additives and functional admixtures. The material performance design has advanced from basic single mechanical strength to a combination of ultra-high strength, high durability and functionality. The preparation technology has developed from the simplest hand mixing to the application of various advanced technologies and intelligent methods. In short, today's concrete has comprehensively entered a new stage known as high-tech concrete [3–6].

High-tech concrete refers to concrete prepared based on ordinary concrete technology using advanced material science theories and innovative manufacturing technologies. This ensures the prepared concrete exhibits superior material properties, excellent functionality, and unique, environmentally friendly characteristics. It effectively expands the application scope of traditional concrete, giving it a stronger vitality. The categorization of high-tech concrete includes high-strength concrete (HSC), high-performance concrete (HPC), ultra-high-strength concrete (UHSC), and ultra-high-performance concrete (UHPC), as well as special composite concrete.

The development of high-tech concrete began in the mid-20th century, accompanying the progress of modern society, large-scale infrastructure construction, and the expansion of human living spaces, leading to new and higher requirements for building materials. It also relies on the rapid development of science and

technology in other fields, possessing a strong logical connection to the era. During this period, concrete experts worldwide actively participated in the technological innovation wave, seizing opportunities, actively exploring, and making continuous breakthroughs in various aspects of concrete, from strength and various performance metrics to raw materials and preparation methods, as well as the application of concrete materials, products, and engineering. This has continuously elevated the foundational and critical role of concrete in social development to a new and higher level. Today, we can see various iconic modern concrete projects everywhere: super-long, super-deep, and super-large underwater tunnels; various types of large-span bridges; massive underground structures; towering skyscrapers; transportation networks crossing mountains and rivers; ocean engineering in swift waves and harsh extreme environments; and special major projects. All of these contributions are attributed to high-tech concrete.

Undoubtedly, this is a proud era in the history of concrete development. However, it is also precisely because of the unprecedented activity in technological thinking and the freedom and breadth of research work that concrete has never experienced such a flourishing of technological achievements. This often leads to disputes over technical concepts and evaluation systems, affecting the overall efficiency of research work. The reasons for this are, on the one hand, the broader and more independent thinking of contemporary scientists, who are more innovative. On the other hand, this is influenced by the widespread introduction of advanced theories and technologies from other disciplines, resulting in more research methods and technical approaches. Additionally, due to the development of information technology, people are increasingly accustomed to rapid learning through online information, lacking the important research atmosphere of conferences, effective deliberation, and consensus formation. We should view this rationally and dialectically. It is a sign of social progress, broadening our horizons, quickly borrowing from advanced theories and methods, helping researchers effectively break free from traditional constraints, improving research efficiency and level, and promoting greater progress in the scientific and technological aspects of this discipline. Of course, at the same time, we should also pay attention to new problems, strengthen academic exchanges and collaborative research on common issues, share achievements, avoid detours, and advance the overall research level and scientific and technological achievements in this discipline.

1.2 Brief History of High-tech Concrete Development

1.2.1 Ordinary Concrete

The technical characteristics of ordinary concrete are a relatively simple material composition, a higher water–cement ratio (W/C), and the use of a relatively straightforward mixing and preparation technique. The compressive strength of concrete is generally less than 50 MPa. Ordinary concrete includes plain concrete and ordinary reinforced concrete.

1.2.1.1 Plain Concrete

Plain concrete refers to concrete that does not add any other supplementary components in addition to the three basic components of concrete: cement, aggregate and water. Modern Portland (silicate) cement, the world's first patented cement invented by British construction worker Joseph Aspdin in 1824, marked the beginning of modern cement, and the cost was low, especially with lower energy consumption. The advent of this hydraulic cementitious material endowed concrete with the needed strength and durability. Its raw materials were easily available. Consequently, it significantly expanded the application scope of concrete, establishing its indispensable position in construction materials. The technical characteristics of plain concrete involve using only the three basic ingredients and simple mixing and forming processes, resulting in a compressive strength generally ranging from 20 to 30 MPa after hardening.

For over a century, concrete technology has undergone continuous development and exploration. However, there have been no fundamental breakthroughs in the main performance strength during this time. In 1896, French scientist Feret first proposed a strength formula based on pore content. In 1919, American scientist Duff Abrams found through numerous experiments that there was a correlation between the water–cement ratio (W/C) and concrete strength, indicating an inverse relationship between concrete strength and W/C. In 1930, Swiss scientist Belomey studied and proposed the famous relationship formula between concrete strength, actual cement strength, and W/C under certain conditions, demonstrating that reducing the amount of water could enhance concrete strength. In the 1960s, American researcher T. C. Powers conducted more in-depth research, considering the main hydration product of cement (gel) and establishing the well-known T. C. Powers model. He proposed the relationship formula between strength and gel-to-void ratio, indicating the impact of capillary pore volume on strength. The basic conclusion of these research results is that a lower W/C can reduce the volume of voids (pores) in concrete materials, leading to a higher strength. However, for ordinary concrete, to meet the preparation process and ensure the workability of fresh concrete mixtures, it is necessary to add water significantly higher than the complete hydration of cement. Therefore, it is challenging to significantly improve the strength of concrete, and a higher W/C also makes the material structure relatively loose, affecting other properties of concrete [7].

1.2.1.2 Ordinary Reinforced Concrete

To improve the strength and enhance the performance of concrete, researchers began to experiment with introducing additional raw materials or improving the concrete preparation methods based on plain concrete. The goal was to achieve concrete with better strength and performance. These efforts paved the way for the development of modern concrete technology. A milestone achievement in this journey occurred in 1849 when French landscape architect Joseph Monier invented the original reinforced concrete, thereby enhancing the stability and durability of concrete structures. In 1879, Austrian Hatschek produced asbestos fiber concrete, marking the era of fiber-reinforced concrete and achieving breakthroughs in

the crack resistance of concrete products. In 1910, H. F. Porter from the United States obtained a patent for steel fiber-reinforced concrete, improving the strength and overall performance of concrete. In 1928, Freyssinet from France created prestressed reinforced concrete. In 1934, the United States invented the concrete vibrator, effectively compacting and uniformizing concrete during the forming process, thereby enhancing its strength and impermeability. In 1937, E. W. Scipitrit from the United States researched and patented the world's first water reducer, Pozzolitn, providing a technological approach to improving concrete strength by reducing the water-cement ratio (W/C). At the end of the 19th century and the beginning of the 20th century, polymers appeared in concrete, and it was discovered that the brittleness of concrete could be improved by adding organic materials. In the 1960s, the United States invented polymer-impregnated concrete. In the 1970s, China developed glass fiber-reinforced concrete. By employing these methods, the strength of concrete has been increased to varying degrees, reaching a basic level of approximately 40 MPa, with some approaching 50 MPa.

1.2.2 High-strength Concrete

Modern civil engineering construction demands concrete with higher strength, and the century-long exploration of ordinary concrete technology has laid the foundation. The development of the modern chemical industry and materials science and technology has made HSC a reality. In the late 1950s to the early 1960s, the advent of highly efficient water reducers with a water-reducing rate exceeding 20% marked the beginning of the development of HSC technology [8]. During this period, Germany invented melamine-based superplasticizers, and Japan developed naphthalene-based superplasticizers. These superplasticizers overcame significant technical challenges, such as the difficulty of working with dry and hard concrete mixtures due to reduced water content. They allowed concrete to be compacted under lower water-cement ratio conditions, resulting in denser material and, consequently, higher strength. The definition of HSC evolves with the progress of scientific and technological advancements over time. From a comprehensive perspective of technical classification, HSC, as defined here, has a strength greater than 50 MPa.

The main characteristics of HSC components include the incorporation of highly efficient water reducers and mineral admixtures. The significant breakthrough in concrete technology comes from the use of highly efficient water reducers. From the perspective of material structure, the reduction in water content significantly reduces voids and internal defects in hardened concrete. The reduction in defects not only enhances concrete strength but also increases material density. This, in turn, effectively hinders harmful external substances from entering the concrete through pores, thereby improving the durability of the concrete. HSC with added superplasticizers maintains good fresh concrete flowability and can be conveniently applied in on-site construction. This is one of the reasons why various large-scale concrete projects opt for HSC.

1.2.3 High-performance Concrete

HPC is a type of concrete characterized by high strength, durability, and workability. Unlike HSC, which emphasizes only mechanical properties, HPC must meet high-performance requirements in terms of workability, mechanical performance, and durability simultaneously [9]. HPC demands not only high workability and strength but also important properties such as resistance to chemical corrosion. These include high volume stability, high elastic modulus, low drying shrinkage, low creep, low-temperature deformation, and high impermeability. The technical characteristics of HPC involve the use of new-generation superplasticizers and ultra-fine materials based on HSC. Ultra-fine materials, with particle sizes $<10\ \mu\text{m}$ and specific surface areas equivalent to $600\ \text{m}^2/\text{kg}$ or more, are commonly used in high-performance cement-based composite materials. Common varieties include fly ash, finely ground water-quenched slag powder, silica fume, finely ground zeolite powder, kaolin, diatomaceous earth, calcined shale, and expanded slag.

Ultra-fine powder is a key component in preparing HPC. Its mechanisms of action include: first, filling the voids of the cementitious material, reducing porosity, and refining pore size; second, enhancing the inducing activity of the mixed material, participating in the hydration reaction of the cementitious material, improving the density of the concrete, and reducing hydration heat [10]. The reduction in porosity is a direct factor in improving concrete strength and durability, while the increased activity of the mixed material further enhances the interface structure of the concrete. The reduction in porosity, refinement of pore size, and improvement of the interface structure can enhance the concrete's resistance to permeability, thereby improving its durability. Due to its superior comprehensive performance, HPC quickly found application and promotion in practical engineering. Currently, HPC with a strength of C60 is widely used in projects such as bridges, high-rise buildings, and airport construction. Concrete with strengths exceeding 80 and 100 MPa has also been applied in various engineering projects.

1.2.4 Ultra-high-strength Concrete

UHSC, defined as concrete with compressive strength exceeding 100 MPa, emerged as a research trend worldwide from the early 1980s to the early 21st century. The theoretical basis for the design of UHSC is the maximum packing density theory. According to this theory, the constituent materials, comprising particles of different sizes, form the tightest possible packing in optimal proportions. In other words, the interstices between millimeter-sized particles are filled with micrometer-sized particles, and the interstices between micrometer-sized particles are filled with sub-micrometer-sized particles, achieving the maximum packing density. To attain this state of maximum packing density, UHSC concrete is molded using special preparation techniques. The following types are representative and influential.

1.2.4.1 Macro-defect-free Cement

In 1981, Birchall and colleagues in the United Kingdom invented a cement–polymer composite material with unique properties [11, 12]. This composite material, named macro-defect-free (MDF) cement, is characterized by the absence of large pores and coarse crystals in the hardened body, attributed to specialized production techniques and an extremely low water–cement ratio (0.12–0.16). The primary components of MDF material include cement, water-soluble polymers, superplasticizers, and water, with the cement being either Portland cement or aluminate cement. Key points in the preparation process of MDF materials include the following: first, mixing various components to form a homogeneous slurry through specialized mixing equipment; second, shaping the mixture through processes such as hot pressing, extrusion, rolling, or injection.

The mechanical properties of MDF significantly surpass those of ordinary concrete. Its compressive strength ranges from 200 to 300 MPa, tensile strength from 50 to 120 MPa, flexural strength from 150 to 200 MPa, elastic modulus from 25 to 50 GPa, and fracture toughness up to $3 \text{ MPa}\cdot\text{m}^{1/2}$. The hardened body of the MDF also exhibits excellent sound absorption, antistatic properties, and crack resistance at low temperatures. Its main drawback lies in poor water stability, with a noticeable strength decrease after absorbing moisture, especially when alumina cement is used primarily due to the water absorption and swelling of the polymers in MDF.

Since the mid-1980s, the author has conducted in-depth and systematic research on the reinforcement mechanism of MDF materials, as well as the practicality of material design and preparation technology. This research has revealed the polymer–cement interface enhancement mechanism and the multiple roles of polymers in MDF materials [13–19]. The formation of a characteristic multi-phase interpenetrating network structure in the material has been identified and confirmed [20], leading to the proposal of criteria for polymer selection and optimization methods for material structure design. An accurate calculation and control method for polymer dosage has been introduced, effectively improving water resistance and enhancing volume stability by minimizing excess usage through polymer interface chemical reactions. Furthermore, breakthroughs have been achieved in improving the overall durability of MDF materials by reinforcing them with fibers [21–24].

1.2.4.2 Densified System Containing Homogeneously Arranged Ultra-fine Particles

In 1982, Danish researchers, led by Bache, developed a densified system containing homogeneously arranged ultra-fine particles (DSP) [25]. The formulation involves two key aspects: first, the uniform mixing of cement with an average particle size of approximately $10 \mu\text{m}$ and highly reactive ultra-fine volcanic ash with an average particle size of approximately $0.1 \mu\text{m}$ in appropriate proportions, forming the tightest packing. This results in extremely small pore sizes, very low porosities, and disconnected pores. Second, the addition of high-efficiency water-reducing agents to achieve an extremely low water–cement ratio (0.16 or lower) further reduces

porosity, prevents the agglomeration of cement particles and ultra-fine powders, and strives for their uniform distribution.

DSP primarily utilizes the principle of dense filling or filling effects to reduce porosity and enhance compactness. According to theoretical models of particle packing, coarse particles have a significant impact on packing density, while merely changing the size and quantity of fine particles has a minimal effect on the overall material packing density. Therefore, it is possible to consider substituting a significant portion of unhydrated cement in DSP with other supplementary materials to reduce cement consumption. Studies have shown that using fly ash, slag powder, and other particles to replace or partially replace silica fume in DSP can achieve cost reduction without compromising performance.

The compressive strength of typical DSP made with Portland cement and silica fume can exceed 120 MPa, and when high-strength aggregates are added, the compressive strength of DSP can reach over 250 MPa. One drawback of DSP is that the increase in the modulus of elasticity and fracture energy is limited, resulting in high brittleness and the likelihood of generating numerous microcracks during the hardening and drying shrinkage processes. Introducing a certain amount of fibers into DSP can enhance ductility and toughness while can also providing low shrinkage, low permeability, and high corrosion resistance.

1.2.4.3 Compact Reinforced Composite

In 1986, Bache and others developed a composite material containing a significant amount of fibers and closely spaced steel reinforcement, known as compact reinforced composite (CRC) [26]. The base material of CRC is composed of high-strength DSP, with its main reinforcement being similar to that of steel reinforcement in conventional reinforced concrete but with a much larger quantity (volume ratio ranging from 10% to 20%). Aggregates, such as quartz particles or particles with a high Al_2O_3 content, along with appropriate fibers (with a volume ratio of 5–10%, fine diameter, and high-strength steel fibers), are used to create a base material that is tightly bonded to the steel reinforcement, providing high tensile strength, stiffness, and ductility.

CRC typically achieves a compressive strength of up to 200 MPa, with some formulations exceeding 300 MPa. Its tensile strength is comparable to structural steel reinforcement and exhibits considerable ductility. In comparison to DSP, CRC not only boasts higher strength but also has significant deformation capacity. CRC exhibits exceptional durability, surpassing that of conventional HPC, primarily due to the extremely dense nature of its base material. It demonstrates high resistance to projectile penetration, making it suitable for military engineering facilities. CRC is well suited for the production of lightweight, slender precast components or components cast on-site. It has been applied in various scenarios, including the construction of tunnel lining blocks, the bottom plate of cantilevered balconies, supporting beams for stairs, manhole covers, and joints in on-site cast connections for precast slab-column systems.

1.2.4.4 Reactive Powder Concrete

In 1993, French scholars Richard and Cheyrezy developed reactive powder concrete (RPC) using the DSP model [27–29]. The main processes of RPC include the following: first, following the principle of maximum packing density by eliminating coarse aggregates and using fine aggregates with a maximum particle size of 400–600 μm , such as quartz sand, and adding high-activity mineral admixture silica fume to form a particle system with high uniformity and density; second, employing a large amount of high-efficiency water-reducing agent to significantly reduce the water content and decrease porosity; third, adding steel fibers to reduce material brittleness and improve toughness; fourth, applying pressure and deaeration before and during hardening to further enhance density; and finally, post-curing through hot pressing to improve the chemical reactivity and internal structure density.

RPC materials exhibit ultra-high strength, exceptional durability, and high toughness. It also possesses good volumetric stability, with compressive strength exceeding 150 MPa, flexural strength up to 50 MPa, elastic modulus exceeding 50 GPa, and fracture energy ranging from 20,000 to 40,000 J/mm². These performance indicators indicate that RPC materials have reached a new level in mechanical properties, surpassing previous concrete materials. RPC has seen significant progress in mix design methods, raw material composition, and preparation technology.

Despite its remarkable mechanical strength and excellent performance, RPC faces some challenges. First, due to the large amounts of cement and silica fume in the material composition, as well as the elimination of coarse aggregates, RPC experiences significant shrinkage. Second, the forming process requires compression and high-temperature curing, making it suitable only for factory prefabrication and not applicable to on-site concrete engineering. Third, the high cost, high-energy consumption, and complex preparation process seriously constrain the practical application of RPC.

1.2.5 Ultra-high-performance Concrete

To promote the practical application of UHSC, researchers have proposed the concept of UHPC based on UHSC [30, 31]. “Ultra-high performance” encompasses two aspects: exceptionally high durability and mechanical performance, with a crucial emphasis on practical applicability. When in a freshly mixed state, the material should exhibit good flowability for ease of preparation and application. Therefore, the key focus of UHPC technology development lies in simplifying the preparation process and reducing material costs. Although a unified definition has not yet been established, it is clear that the material needs to possess outstanding physical and mechanical properties, with compressive strength generally reaching or exceeding 150 MPa.

The technical characteristics of UHPC include the following: first, the utilization of a multicomponent binder system, incorporating industrial waste superfine powder to achieve energy savings and cost reduction without compromising performance. Second, the incorporation of coarse aggregates with a size of 10–20 mm enhances the material’s volume stability and durability while effectively lowering

costs. Third, the use of superplasticizers imparts flowability to the concrete, facilitating on-site construction for engineering projects. Fourth, the preparation of UHPC involves conventional techniques, eliminating the need for pressure molding and high-temperature curing. The research conducted by the author's team primarily focuses on optimizing material composition and understanding the formation of material structures [32–36]. UHPC can be considered the most durable engineering material, with mechanical properties approaching those of steel structures when appropriately reinforced. Additionally, it exhibits excellent wear resistance and blast resistance. Therefore, UHPC is particularly suitable for use in large-span bridges, blast-resistant structures, thin-walled structures, and environments with high abrasion and corrosion.

1.2.6 High-performance Composite Structural Concrete and Innovative Functional Concrete

High-performance composite structural concrete and innovative functional concrete are based on ordinary concrete, introducing components that significantly enhance and improve concrete properties or confer special functions. These utilize composite technology methods in material design, employing advanced manufacturing processes to optimize the material's structure, resulting in superior performance and unique functionalities. Based on their application characteristics, they can be classified into structural and functional types, with the former commonly used in various structural engineering projects. The authors and their team have dedicated years to the research of high-performance composite structural concrete and innovative functional concrete technology, achieving the following outcomes.

- 1) Utilizing various fibers, particles, and additives to enhance the strength, impact resistance, and crack resistance of concrete materials, such as high-strength, high-penetration resistance, blast-resistant concrete, and grout fiber concrete [37–43].
- 2) Using various special aggregates to give concrete specific functions, such as radiation-resistant concrete, lightweight aggregate concrete, abrasion-resistant concrete, and heat storage concrete [44–49].
- 3) Employing supplementary cementitious materials or composite cementitious material systems to improve the properties of the concrete matrix, such as UHSC and HPC, shrinkage-compensating concrete, high-permeability crack-resistant concrete, and large-volume low-heat and highly durable concrete, and so on [50–55].
- 4) Material composite and structural composite technology can be applied to enhance the structural performance of concrete, including concrete-filled steel tube composite materials, bridge deck pavement concrete, ultra-high structures with large spans, tunnel structural concrete, and highly durable concrete [35, 56–60].
- 5) Using various organic components to improve the toughness of concrete materials, such as high-ductility concrete, polymer-modified concrete, cement asphalt mortar, and so on [61–66].

- 6) Employing additional components to alter the material structure and confer new uses to concrete, such as resin aggregate concrete, CO₂ driven 3D printing concrete, and other innovative concrete technologies [67–72].

1.3 Challenges and Opportunities for Concrete Materials

Concrete, steel, and polymer materials are the most important representatives of the three main materials: inorganic non-metallic, metallic, and organic. These three major types of materials have their own properties. Table 1.1 shows their performance characteristics [6, 72].

As shown in Table 1.1, there are significant differences in the engineering performance of the three materials. Steel exhibits high strength, with elevated tensile, flexural, and shear strengths. It possesses good ductility, allowing for substantial plastic deformation and various cold-working processes such as bending, stretching, drawing, and stamping at room temperature. Additionally, steel is characterized by uniform quality and reliable performance. However, its primary drawback lies in susceptibility to corrosion, leading to poor durability. Polymer materials feature characteristics such as light weight, high elasticity, low elastic modulus, high insulation, and low thermal conductivity. Nevertheless, their disadvantages include lower strength compared to steel, poor rigidity, high thermal expansion, low heat resistance, and susceptibility to aging.

Table 1.1 Comparison of properties of concrete, steel, and polymer materials.

Performance	Steel	Polymers	Ordinary concrete	High-tech concrete
Compressive strength (MPa)	235–1600	105–400	10–50	100–300
Flexural strength (MPa)	~500	60–150	3–6	50–200
Tensile strength (MPa)	400–1900	46–200	1.27–3.11	4.5–24
Flexural/compression ratio	0.23–2.13	0.25–1.10	0.15–0.31	0.20–0.50
Elastic modulus (GPa)	190–210	0.10–2.00	22–38	37–55
Toughness	Excellent	Excellent	Poor	250 times for ordinary concrete
Poisson's ratio	0.25–0.30	0.30–0.50	0.20	0.19–0.24
Density (kg/m ³)	~7800	900–1500	1900–2500	~2500
Coefficient of thermal expansion (10 ⁻⁶ /°C)	10–15	72–150	~10	~10
Thermal conductivity [W/(m·K)]	48–52	0.08–0.50	~3	1–30
Bulk resistivity (Ω·cm)	10–15	10 ¹⁶ –10 ¹⁸	10 ⁸ –10 ¹⁵	10 ⁹ –10 ¹¹
Fracture energy (J/m ²)	10 ⁵ –10 ⁶	600–1500	110–160	10 ⁴ ~4×10 ⁴

Note: The data presented in Table 1.1 for high-tech concrete are representative indicators and are not taken from a specific material.

Ordinary concrete materials have the lowest strength, but within a certain range, their strength can be designed and controlled from low to high to meet the varied strength performance requirements of different projects. Concrete mixtures exhibit plasticity, allowing for simple and convenient forming processes. They can be cast into various shapes and sizes of integral structures or prefabricated components as per engineering requirements, making their processing much easier than that of other materials. However, due to its low tensile strength and brittleness, concrete typically cannot withstand tensile stress and has low impact resistance and a relatively low strength-to-mass ratio. Moreover, the volume instability of concrete is a significant drawback.

From the above comparative analysis, as the most widely used artificially prepared material globally, concrete has made significant contributions to societal civilization and technological progress. However, with societal development and technological advancements, there is an increasing demand for higher performance in various concrete products. Modern engineering construction is evolving toward larger-scale, longer-span structures, deeper underground spaces, and more complex and harsh environments. These major construction projects pose challenges with high difficulty, requiring high strength and durability. The material properties of ordinary concrete and its inherent limitations are no longer able to meet the demands of this progressive era. Concurrently, rapid advancements in other material technologies pose additional competition in traditional application areas for concrete.

Nevertheless, it is heartening to observe, from the innovative development and achievements in concrete technology (as indicated in Table 1.1), that high-tech concrete materials produced using advanced techniques have made significant progress in many aspects. Some properties and functionalities have even experienced substantial breakthroughs, indicating substantial development potential in concrete materials. On the other hand, the ongoing progress in science and technology, coupled with developments in relevant disciplines and interdisciplinary fields, provides a broader perspective and valuable experiences for breakthroughs in concrete material technology. Importantly, the foreseeable future promises unprecedented opportunities for concrete materials due to China's rapid and high-quality economic development, extensive infrastructure construction, and urbanization. Therefore, building upon existing work, carefully summarizing past experiences, analyzing and clarifying development strategies, selecting and establishing research objectives, following scientifically effective research methods, and further improving research and development efficiency to achieve new breakthroughs in concrete technology are not only crucial tasks for scientists and technologists in this field but also significant opportunities for the innovative development of concrete materials.

1.4 Technical Characteristics and Research Content of High-tech Concrete

The concept of high-tech concrete (ATC) proposed by the author differs from previous definitions based on concrete performance indicators or compositional

features. Instead, it is defined based on the advanced nature of concrete preparation technology and material performance, utilizing a comprehensive evaluation method. The concept of high-tech concrete is introduced from the perspective of the technical characteristics of concrete. Its purpose is to establish a more scientific and consensus-forming concrete technology system and evaluation standards. This approach aims to avoid disputes arising from different definitions of certain concrete technologies, facilitating consensus formation and enhancing the efficiency and level of innovation in concrete technology. The categorization system of high-tech concrete materials includes HSC, HPC, UHSC, UHPC, and special composite concrete. The technical characteristics and research content of high-tech concrete encompass aspects such as high performance, multifunctionality, full ecological integration, and the incorporation of new technologies.

- 1) High Performance: Researchers can adopt the comprehensive technological innovation to enhance various chemical, physicochemical, and mechanical properties of concrete, making it more conducive to production, structural construction, and possessing superior material and engineering performance. This further enhances the safety and durability of concrete engineering, extending its service life.
- 2) Multifunctionality: Researchers can adopt the material design innovation to adjust the composition of concrete materials and forming corresponding performance structures, the characteristic functions of concrete can be expanded to meet the needs of various special purposes. In addition, they can adopt the innovative composite technologies, exploring and developing composite structures of concrete with other materials, creating material composite effects, overcoming inherent shortcomings, and achieving new breakthroughs in expanding application areas.
- 3) Full Ecologization: Researchers can adopt the material chemistry innovation, developing and utilizing various industrial and domestic waste as substitutes for the components of ordinary concrete, achieving the goals of resource conservation, energy efficiency, and environmental friendliness in concrete production. Through innovative design concepts, developing concrete from material selection to manufacturing, use, and recycling, incorporating materials into a fully life-cycle recyclable design and preparation technology.
- 4) Adoption of new technologies: Researchers can adopt the interdisciplinary innovation, learning from and applying technological methods and experiences from other fields, developing new designs, new raw materials, and new manufacturing methods, seeking revolutionary leaps in the properties and functions of concrete materials. In addition, they can adopt the intelligent innovation, developing smart concrete with self-diagnostic, self-repair, self-organization, and self-adjustment functions. Ultimately, they will integrate information technology innovation, developing big data, digitalization, and networking technologies, endowing concrete with new qualities for the modern era.

References

- 1 Mindess, S., Young, J.F., and Darwin, D. (2005). *Cement*. Beijing: Chemical Industry Press.
- 2 Mehta, P. and Monteiro, P. (2005). *Concrete: Microstructure, Properties, and Materials*. New York: The McGraw Hill Companies Inc.
- 3 Jahren, P. and Sui, T. (2013). *Concrete and Sustainability*. Beijing: Chemical Industry Press.
- 4 Zhongjin, L. (2011). *Advanced Concrete Technology*. Hoboken: Wiley.
- 5 Hu, S. and Yang, D. (1995). Optimizing design of high-tech concrete composites. *New Development in Concrete Science & Technology*. Southeast University Press, Nanjing, (in Chinese).
- 6 Hu, S. (2009). *Advanced Cement-Based Composite Materials*. Beijing: Science Press.
- 7 Li, F.M. (1984). *Cement and Concrete Chemistry*. Beijing: China Architecture Publishing House (in Chinese).
- 8 Miao, C.W. (2008). *High Performance Admixture for Concrete*. Beijing: Chemical Industry Press (in Chinese).
- 9 Wu, Z. and Lian, H. (1999). *High Performance Concrete*. Beijing: China Railway Publishing House (in Chinese).
- 10 Steven, H.K., Beatrix, K., and William, C.P. (2009). *Design and Control of Concrete Mixtures*. Beijing: Science Press.
- 11 Birchall, J.D., Howard, A.J., and Kendall, K. (1981). Flexural strength and porosity of cements. *Nature* 289 (5796): 388–390.
- 12 Birchall, J., Kendall, K., and Howard Anthony, J. (1981, January 07). Cementitious product. EP 0021682.
- 13 Hu, S., Guan, X., and Ding, Q. (2002). Research on optimizing components of microfine high-performance composite cementitious materials. *Cement and Concrete Research* 32 (12): 1871–1875. (in Chinese).
- 14 Peng, Y., Hu, S., and Ding, Q. (2009). Dense packing properties of mineral admixtures in cementitious material. *Particuology* 7 (5): 399–402. (in Chinese).
- 15 Ding, Q., Ye, Q., and Hu, S. (2018, April 10). An ultra-high performance concrete prepared by wet granite powder. CN 201711192782. (in Chinese).
- 16 Hu, S. (1994). XPS nondestructive depth analysis method and its application in cement based composite materials. *Cement and Concrete Research* 24 (8): 1509–1514. (in Chinese).
- 17 Hu, S. (1993). An investigation of bonding behavior on the interface of polyacrylamide-aluminous composites. *Journal of Wuhan University of Technology (Materials Science Edition)* 8 (2): 19–25. (in Chinese).
- 18 Hu, S. (1993). Structure analysis of polymer-cement interface bonding layer. *Journal of Wuhan University of Technology* (04): 12–17. (in Chinese).
- 19 Hu, S. (1994). Kinetic analysis of the hydration of $3\text{CaO}\cdot 3\text{Al}_2\text{O}_3\text{-CaSO}_4$ and the effect of adding NaNO_3 . *Thermochemica Acta* 246: 129–140. (in Chinese).

- 20 Hu, S. and Yang, D. (1995). IPCN structure and its formation condition in MDF cement. *New Development in Concrete Science & Technology*. Southeast University Press, Nanjing, (in Chinese).
- 21 Ding, Q., Hu, S., and Li, Y. (1997). Research on fiber reinforced MDF cement Materials. *Concrete and Cement Products* 1997 (3): 14–17. (in Chinese).
- 22 Hu, S. (1996). Studies of MDF cement reinforced with glass fiber. MAETA Workshop on High Flexural Polymer-Cement Composite. Sakata, Japan, (in Chinese).
- 23 Ding, Q., Li, Y., and Hu, S. (1998). Research on carbon fiber reinforcement of MDF cement. *Journal of Wuhan University of Technology* 20 (3): 14–17. (in Chinese).
- 24 Li, B. (1998). *Research on Moisture Sensitivity and Modification of Cementitious Composite Materials Without Macroscopic Defects*. Wuhan: Wuhan University of Technology (in Chinese).
- 25 Bache, H. (1981). Densified cement ultra-fine particle-based materials.
- 26 Bache, H. (1989). Fracture mechanics in integrated design of new, ultra-strong materials and structures. *Fracture Mechanics of Concrete Structures: From Theory to Applications*. Chapman & Hall, London.
- 27 Richard, P. and Cheyrezy, M. (1995). Composition of reactive powder concretes. *Cement and Concrete Research* 25 (7): 1501–1511.
- 28 Richard, P. and Cheyrezy, M. (1989). Reactive powder concretes with high ductility and 200-800 MPa compressive strength. *ACI Symposium Publication* 144: 507–518.
- 29 Cheyrezy, M., Maret, V., and Frouin, L. (1995). Microstructural analysis of RPC (reactive powder concrete). *Cement and Concrete Research* 25 (7): 1491–1500.
- 30 Zhang, Y., Zhang, W., and Liu, J. (2005). *Ultra-High Performance Cementitious Composites*. Beijing: Chemical Industry Press (in Chinese).
- 31 Guan, X., Hu, S., and Ding, Q. (2022). Research on ultrafine high performance cement. The 5th International Symposium on Cement and Concrete. Tongji University Press, Shanghai, (in Chinese).
- 32 Hu, S. and Li, Y. (1999). Research on the hydration, hardening mechanism, and microstructure of high performance expansive concrete. *Cement and Concrete Research* 29 (7): 1013–1017. (in Chinese).
- 33 Ding, Q., Liu, X., and Liu, Y. (2016). Effect of curing regimes on microstructure of ultra high performance concrete cement pastes. First International Conference on UHPC Materials and Structures. RILEM Publications S.A.R.L., Paris, (in Chinese).
- 34 Zhang, X., Liu, Z., and Wang, F. (2019). Autogenous shrinkage behavior of ultra-high performance concrete. *Construction and Building Materials* 226: 459–468. (in Chinese).
- 35 Hu, S., Wu, J., Yang, W. et al. (2010). Relationship between autogenous deformation and internal relative humidity of high-strength expansive concrete. *Journal of Wuhan University of Technology (Materials Science Edition)* 25 (3): 504–508. (in Chinese).
- 36 Ding, Q., Yan, P., and Hu, S. (2018, April 20). A lightweight low shrinkage ultra-high performance concrete and its preparation method. CN 201711233051. (in Chinese).

- 37 Alford, N.M. and Birchall, J.D. (1985). Fibre toughening of MDF cement. *Journal of Materials Science* 20 (1): 37–45.
- 38 Wu, S., Hu, S., and Ding, Q. (1999). The effect of polymer in steel fiber reinforced cement composites. *Journal of Wuhan University of Technology* 14 (3): 23–27. (in Chinese).
- 39 Zhang, F., Ding, Q., and Lin, Q. (2005). Research on steel fibre reinforcement lightweight aggregate concrete for deck pavement of steebox bridge. *Concrete* (11): 47–49+60. (in Chinese).
- 40 Li, Y., Hu, S., and Ding, Q. (2001). Properties of ettringite type expansive agent. *Journal of Wuhan University of Technology* 16 (4): 53–56. (in Chinese).
- 41 Hu, S., Ding, Q., and Wang, H. (2007, May 09). A high-energy delayed expansion agent for enclosed concrete and its preparation method. CN 200510019477. (in Chinese).
- 42 Hu, J. and Hu, S. (2004). Effect on anti-shrinkage property of concrete with multiple anti-cracking additive. *Concrete* 171 (1): 22–23+40. (in Chinese).
- 43 Ma, B., Wang, X., and Hu, S. (2006, June 21). Shield tunnel lining segments and their preparation methods. CN 200510120533. (in Chinese).
- 44 Hu, S., Ding, Q., and Wang, F. (2004, April 28). Preparation method of high-strength lightweight aggregate concrete. CN 03125310. (in Chinese).
- 45 Hu, S., Yang, T., and Wang, F. (2010). Influence of mineralogical composition on the properties of lightweight aggregate. *Cement and Concrete Composites* 32 (1): 15–18. (in Chinese).
- 46 Ding, Q., Hu, S., and Tian, Y. (2010, February 24). Preparation method of high-strength and high toughness lightweight aggregate concrete. CN 200710053634. (in Chinese).
- 47 Hu, S. and Wang, F. (2006). *Lightweight Aggregate Concrete*. Beijing: Chemical Industry Press (in Chinese).
- 48 Nie, S., Hu, S., Wang, F. et al. (2017). Pozzolanic reaction of lightweight fine aggregate and its influence on the hydration of cement. *Construction and Building Materials* 153: 165–173. (in Chinese).
- 49 Shen, P., Lu, L., Wang, F. et al. (2020). Water desorption characteristics of saturated lightweight fine aggregate in ultra-high performance concrete. *Cement and Concrete Composites* 106: 103456. (in Chinese).
- 50 Hu, S, He, Y., and Lu, L. (2006, November 29). A composite cementitious material and its preparation method. CN 200610018820. (in Chinese).
- 51 Hu, S, Ding, Q., and Wang, H. (2007, February 14). High activity compensating shrinkage mineral admixture and its preparation method. CN 200510018820. (in Chinese).
- 52 Peng, Y., Hu, S., and Ding, Q. (2010). Preparation of reactive powder concrete using fly ash and steel slag powder. *Journal of Wuhan University of Technology (Materials Science Edition)* 25 (2): 349–354. (in Chinese).
- 53 Hu, S., Wang, H., and Ding, Q. (2006). The preparation of a high activated and slight expansive admixture base on steel slag and the study on its performance. *Concrete* 202 (8): 47–49. (in Chinese).
- 54 Huang, X., Hu, S., Wang, F. et al. (2019). The effect of supplementary cementitious materials on the permeability of chloride in steam cured high-ferrite

- Portland cement concrete. *Construction and Building Materials* 197: 99–106. (in Chinese).
- 55 Hu, S. (2010). *Special Cement*. Wuhan: Wuhan University of Technology Press (in Chinese).
- 56 Hu, S., Ding, Q., and Lu, L. (2007, May 23). A method for finely controlling the expansion of steel tube concrete. CN 200510019476. (in Chinese).
- 57 Hu, S., Lin, H., and Ding, Q. (2007, May 23). A paving method for steel bridge deck composite layer. CN 200410061407. (in Chinese).
- 58 Wang, X., Ding, Q., and Hu, S. (2009). Research on the performance of lightweight aggregate concrete for steel box girder bridge deck. *Highway* (4): 60–65. (in Chinese).
- 59 Li, Y. and Hu, S. (2001). The microstructure of the interfacial transition zone between steel and cement paste. *Cement and Concrete Research* 31 (3): 385–388. (in Chinese).
- 60 Wang, F., Liu, Y., and Hu, S. (2013). Effect of early cement hydration on the chemical stability of asphalt emulsion. *Construction and Building Materials* 42: 146–151. (in Chinese).
- 61 Wang, T., Hu, S., and Wang, F. (2008). Research on the main influencing factors of CA mortar strength. *Railway Engineering* (2): 109–111. (in Chinese).
- 62 Hu, S., Zhang, Y., and Wang, F. (2012). Effect of temperature and pressure on the degradation of cement asphalt mortar exposed to water. *Construction and Building Materials* 34: 570–574. (in Chinese).
- 63 Wang, T. (2008). *Research and Application of CA Mortar for High-Speed Railway Slab Ballastless Track*. Wuhan: Wuhan University of Technology (in Chinese).
- 64 Wang, F., Liu, Y., and Hu, S. (2013). Interaction mechanism between portland cement and cationic asphalt emulsion droplets. *Journal of Materials Science & Engineering* 31 (2): 186–190. (in Chinese).
- 65 Hu, S., Wang, T., and Wang, F. (2006, August 23). A high early strength self expanding CA mortar material. Wuhan CN 200610018439. (in Chinese).
- 66 Ding, Q., Hu, S., and Sun, Z. (2008, November 19). Preparation method of interface modified injectable organic-inorganic composite pavement materials. Wuhan CN 200910272815. (in Chinese).
- 67 Tian, K. (2010). Study of new cementitious microwave absorbing materials. *Journal of Building Materials* 13 (3): 295–299.
- 68 Ding, Q., Hu, S., and Huang, X. (2014, May 14). A type of absorbing lightweight aggregate and its preparation method. Wuhan CN 201410202947. (in Chinese).
- 69 Hu, S., Wu, J., Yang, W. et al. (2009). Preparation and properties of geopolymer-lightweight aggregate refractory concrete. *Journal of Central South University of Technology* 16 (6): 914–918. (in Chinese).
- 70 Tian, Y., Hu, S., and Wang, F. (2009). Analysis of fatigue properties of damping and high strength concrete. *Journal of Building Materials* 12 (3): 328–331. (in Chinese).
- 71 Hu, S., Ding, Q., and Tian, Y. (2008, May 07). Preparation method of high-strength and high damping concrete. Wuhan CN 200710053633. (in Chinese).
- 72 Wang, C. (2001). *Building Engineering Materials*. Beijing: Earthquake Publishing House (in Chinese).