

A review of the mechanics and pumping properties of UHPC

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Abstract

Ultra-High Performance Concrete (UHPC), as a high-end product in the field of concrete materials, exhibits extraordinarily high strength, excellent durability, and favorable workability, making it highly suitable for major engineering projects such as super-tall buildings and long-span bridges. High strength and pumpability are the two key factors that enable the practical application of UHPC in engineering: the former determines its structural load-bearing capacity, while the latter ensures the feasibility of its construction methods. This article, based on relevant research findings, provides a comprehensive review of the current state of research regarding UHPC's high strength and pumpability. It analyzes the key factors that affect these properties, the methods available for their control, and existing challenges, offering insights that can contribute to advancement in UHPC research and its practical application in engineering.

Keywords

UHPC; High strength; Pumping performance; Research progress.

1. Introduction

With the development of the construction industry towards high-rise and large-span structures, traditional concrete has been difficult to meet the needs of engineering for material strength, durability and construction efficiency. Ultra-high performance concrete (UHPC) is a new type of high-performance cementitious composite material, the concept of which was first proposed by Larrard and Sedran in 1994, and then the French company Bouygues developed Reactive Powder Concrete (RPC), which is considered a variant of UHPC[8]. As a new high-performance material, it is usually based on a low water-cement ratio (≤ 0.25), and achieves the combination of compressive strength ≥ 100 MPa, excellent durability and favorable pumping performance by optimizing particle gradation, incorporating active admixtures and high-strength fibers. Among them, high strength is the core prerequisite for UHPC to replace traditional concrete, reduce structural weight, and increase the span, while pumping performance is the key guarantee for UHPC to achieve efficient construction in large-scale projects such as super-high-rise buildings. In recent years, scholars at home and abroad have carried out a large number of experimental studies and theoretical analyses around the high strength and pumping performance of UHPC, forming substantial research findings, but there are still problems such as high viscosity, pumping difficulty, and high heat of hydration, which limit its large-scale engineering application. This paper focuses on the two core properties of UHPC, high strength and pumpability, integrates relevant research progress, clarifies the research sources of each conclusion, sorts out the control strategy, and provides reference for subsequent research and engineering practice.

2. Research progress on UHPC high strength performance

The high strength of UHPC is mainly reflected in ultra-high compressive strength, high tensile and flexural strength, and its strength formation mechanism is closely related to factors such as raw material composition, mix design, curing method and fiber dosage. Through

experimental research and theoretical analysis, researchers worldwide have clarified the influence of various factors on the high strength of UHPC, and established strength prediction models, which provide theoretical support for the optimization of UHPC mix proportions.

2.1. Core influencing factors for high strength

2.1.1. Raw materials and mix ratio factors

The type, dosage and mix parameters of raw materials are the basis for determining the high strength of UHPC, among which the water-cement ratio, cementitious material composition, and aggregate gradation are the core influencing factors.

The water-cement ratio is the key parameter affecting the strength of UHPC, and a low water-cement ratio is the prerequisite for achieving high strength of UHPC. The results show that the compressive strength of UHPC increases significantly with the decrease of the water-cement ratio, but too low a water-cement ratio will lead to a decrease in the fluidity of the slurry and affect constructability. Deng et al.[1] found that when the water-cement ratio increases from 0.15 to 0.18, the compressive strength of UHPC mortar remains relatively stable, and when it continues to increase to 0.20, the compressive strength decreases rapidly, suggesting that the water-cement ratio should not exceed 0.18. Zheng et al.[2] showed that when the water-cement ratio varied within the range of 0.16 to 0.25, the compressive strength of UHPC reached its maximum at a water-cement ratio of 0.2.

The composition and dosage of cementitious materials are crucial for the strength formation of UHPC. Commonly used cementitious materials for UHPC include cement, silica fume, fly ash, ultrafine slag, etc., among which the incorporation of silica fume is the key to improving the strength of UHPC. With its ultra-high specific surface area (13,000–30,000 m²/kg) and high activity, silica fume can react with cement hydration products to form calcium silicate hydrate (C-S-H) gel, fill the internal pores of the slurry, improve the microstructure, and thus increase the strength. Liu Hongbin et al.[3] found that silica fume can significantly improve the splitting tensile strength of UHPC, but there is an optimal dosage, and it is recommended to use 12% by weight of cement. Wu et al.[5] showed that the optimal content of silica fume is 10%–15%, and the viscosity of UHPC decreases and the strength increases within this range. Wang et al.[9] also found that with the increase of mineral admixture content, the chloride permeability and carbonation resistance of UHPC first increased and then decreased, which indirectly affected its long-term strength stability.

The aggregate gradation has a significant impact on the packing density of UHPC, which in turn determines its strength. UHPC usually uses fine aggregate (fine quartz sand with a particle size ≤ 0.6 mm), which can increase the packing density of solid particles, reduce internal porosity, and improve strength by optimizing aggregate gradation[6]. Based on the densest packing model derived from the Dinger-Funk equation, Cui et al.[7] found that when cement: silica fume: ultrafine mineral powder: quartz sand: water = 1:0.27:0.19:1.08:0.23, the mixture can reach the maximum packing density and the corresponding compressive strength reaches 186.6 MPa. Long et al.[10] found that the addition of ultrafine slag and fly ash can increase the packing density of solid particles in cement slurry, and improve the fluidity and strength of cement slurry with a low water-cement ratio.

2.1.2. The influence of additives

Fibers are the key components for improving the tensile strength, flexural strength and toughness of UHPC. The dosage, aspect ratio and type of fibers have a significant impact on the high strength of UHPC. Zhang Qianqian et al.[11] found that when the fiber content was increased to 1% and 3% (compared to 0), the yield stress of UHPC increased by 48.5% and 133.0%, and the plastic viscosity increased by 39.4% and 82.3%, respectively. The compressive strength also increased. Taking steel fiber as an example, Ju Yanzhong et al.[12]-[13] showed

that when the volume content of steel fiber is 1.0%–3.5%, it can bridge cracks and significantly improve the compressive strength of UHPC. When the content exceeds 3.5%, it will reduce the compactness of the mixture and lead to a decrease in strength. It is recommended that the reasonable volume content of steel fiber ranges from 2.0% to 3.5%.

The aspect ratio and type of steel fibers also affect the strength of UHPC. Hoang et al. [14] found that UHPC had the highest axial tensile strength when the steel fiber aspect ratio was 13/0.175 (length 13 mm, diameter 0.175 mm), reaching 10.66 MPa and 13.29 MPa at volume contents of 1.5% and 3%, respectively. Wu et al. [15] showed that, at a steel fiber volume content of 2%, the flexural strength of UHPC with hooked-end steel fibers was 34.4 MPa, higher than that with corrugated (31.8 MPa) and straight (27.8 MPa) fibers. Mixing long and short fibers not only improves the strength and toughness of UHPC, but also avoids the problem of excessive pumping resistance caused by using only long fibers.

2.1.3. The influence of maintenance methods

The curing method influences the strength development of UHPC by affecting the hydration degree and microstructure of the cement. Commonly used curing methods include standard curing, steam curing, and autoclave curing [16]. Xu Haibin et al. [17] found that, compared with natural curing, using steam curing at 60°C and 90°C for 2h increased the compressive strength of UHPC cubes by 12.3% and 31.6%, respectively, and the axial compressive strength by 11.2% and 27.7%, respectively. Zdeb [18] showed that steam curing (preheating for 6 h, maximum temperature of 90°C, and cooling for 12h) and high-pressure steam curing (preheating for 6h, maximum temperature of 250°C, and cooling for 6h) could achieve high compressive strength of UHPC, reaching 244-265 MPa under high-pressure steam curing.

2.2. Evaluation and prediction of high strength performance

Based on extensive experimental data, researchers worldwide have established prediction models for UHPC strength, which mainly include prediction formulas for compressive strength, elastic modulus, peak strain, and other mechanical properties.

In terms of compressive strength, different researchers have obtained different predictive relationships based on the fitting of experimental data. Graybeal [19][21] studied various mechanical properties of UHPFRC and found that the relationship between elastic modulus and axial compressive strength was as follows:

$$E = 3840\sqrt{f_c} \quad (1)$$

Based on 15 sets of experimental data, Jin Lingzhi et al. [22] fitted the relationships among the cube compressive strength, axial compressive strength, and elastic modulus of UHPC, from which they derived the specific relationship between the elastic modulus and axial compressive strength.

$$E = 10^4(0.307\sqrt{f_c} - 1.35 + 1.169) \quad (2)$$

2.3. Summary of Research on High-Strength Properties

At present, research on the high strength of UHPC is relatively mature. UHPC with a compressive strength of 100-265 MPa can be prepared by optimizing the mix proportion (low water-cement ratio, reasonable aggregate gradation), adding active admixtures (silica fume, ultrafine slag, etc.), incorporating steel fibers, and adopting appropriate curing methods. However, several problems remain: the use of highly active admixtures (e.g., silica fume) increases material cost; an excessively high amount of steel fiber affects the fluidity of the slurry; and the high-pressure steam curing process is complex, which limits the large-scale application of UHPC.

3. Research progress on UHPC pumping performance

The pumping performance of UHPC is key to achieving efficient construction in large-scale projects such as super-high-rise buildings and long-span bridges, and mainly depends on the rheological properties (yield stress, plastic viscosity) of freshly mixed UHPC. Its core requirements are good fluidity, cohesiveness, and water retention while ensuring high strength, so as to avoid problems such as pipe blockage, segregation, and bleeding during pumping. Researchers worldwide have carried out extensive research on the influencing factors, control strategies, and pumping process of UHPC pumping performance, and have clarified the intrinsic relationship between pumping performance and rheological properties.

3.1. The core evaluation index of pumping performance

The pumping performance of UHPC is mainly evaluated by the rheological parameters and workability indicators of the freshly mixed slurry, among which the rheological parameters (yield stress, plastic viscosity) are the core indicators reflecting the difficulty of pumping, and the workability indicators (slump flow and slump) are the common indicators for directly evaluating the fluidity.

Yield stress determines the minimum pressure required for the UHPC slurry to start pumping, and plastic viscosity determines the resistance of the slurry when flowing in the pipeline, both of which together affect the pumping efficiency and pumping safety. The results show that the yield stress of UHPC should be controlled within a reasonable range, and if it is too high, it will lead to excessive pumping pressure and easily cause pipe blockage. If it is too low, it will lead to slurry segregation and bleeding, affecting the construction quality. Jiadi[26] found that increasing the water-cement ratio of UHPC from 0.21 to 0.27 reduced its plastic viscosity by 62%, and the yield stress decreased from 182.78 Pa to 1.68 Pa, significantly improving the fluidity and making it easier to pump.

Slump flow and slump are direct indicators for evaluating UHPC fluidity, usually requiring a slump flow of ≥ 500 mm and a slump of ≥ 200 mm to meet pumping requirements. Wang et al. [27] found that when the UHPC mix proportion is optimized, the slump can reach 268 mm, and the mixture exhibits good pumping performance. The UHPC mixture prepared by Liu et al. [28] had a slump flow of 162 mm, which needed to be further optimized to meet the pumping requirements.

3.2. Factors affecting pumping performance

3.2.1. Water-binder ratio and high-efficiency water reducer

The water-to-binder ratio is the core parameter affecting the pumping performance of UHPC, as it directly determines the fluidity and cohesion of the slurry. The water-to-binder ratio of UHPC is usually low (≤ 0.25). When it is too low, the slurry has high viscosity and poor fluidity, making it difficult to pump. When it is too high, the slurry is prone to segregation and bleeding, which affects the pumping performance and strength. Huang et al. [29] found that an increase in the water-to-binder ratio decreased the viscosity of UHPC slurry and increased fluidity, which was conducive to pumping; however, a high water-to-binder ratio could easily lead to bleeding and segregation.

Superplasticizer is a key admixture for improving the pumping performance of UHPC. It generates electrostatic repulsion and steric hindrance on the surface of cement particles, disperses the flocculated structure, releases entrapped free water, and increases the water film thickness, thereby reducing the yield stress and plastic viscosity of the slurry and improving fluidity. At present, polycarboxylate superplasticizers (PCEs) have become the preferred admixtures for UHPC preparation. Their dispersion effect, slump retention, and viscosity-reducing capability are superior to other types of superplasticizers, such as naphthalene-based

ones[30]. Liu Shasha[31]found that UHPC slurry with polycarboxylate superplasticizers exhibited a slump flow that had a small loss over time, and the initial yield stress was low, which was more conducive to pumping.

When the superplasticizer dosage exceeds the critical value, the molecules are no longer effectively adsorbed on the surface of the cementitious particles; instead, they cause bleeding and adversely affect pumping performance[32]. Jiadi[26]found that when the superplasticizer content was increased from 2.5% to 4.5%, the plastic viscosity of UHPC decreased by 20% and the yield stress decreased by 88%; however, when the content exceeded 4.5%, the slurry became prone to bleeding. Huang et al.[33] showed that when the superplasticizer content ranged from 2.5% to 4.0%, the yield stress and plastic viscosity of UHPC decreased by 88.9% and 20.6%, respectively, as the dosage increased, achieving the best dispersion effect. By adjusting the superplasticizer dosage, incorporating a defoamer, and optimizing the mixing process, the air content in UHPC is controlled, which not only ensures strength but also improves pumping performance.

3.2.2. Solid particle bulk density and specific surface area

Research has shown that the rheological properties of UHPC mixtures are closely related to the thickness of the water film on particle surfaces. Increasing this water film thickness can effectively reduce internal friction between particles, thereby improving the rheological characteristics of fresh UHPC mixtures. The packing density and specific surface area of solid particles affect the rheological properties of UHPC by influencing the water film thickness on their surfaces [26,29,34]. According to the water film thickness formula, higher packing densities of solid particles lead to thicker water films, resulting in better fluidity of the mixture and facilitating pumping. Conversely, higher specific surface areas reduce the water film thickness, increasing the viscosity of the mixture and making pumping more difficult [11].

$$WFT = u'w / A_s \quad (3)$$

The addition of mineral admixtures such as fly ash and ultrafine slag can increase the packing density of solid particles and improve the pumpability of the mixture. Studies by Zhang Qianqian et al. [11] have shown that incorporating 15%, 30%, or 45% fly ash increased the water film thickness by 11.0%, 19.2%, and 22.2%, respectively, while reducing the yield stress and viscosity of the mixture and enhancing its fluidity. On the other hand, adding 4%, 8%, or 12% silica fume resulted in a decrease in water film thickness by 69.8%, 81.1%, and 86.2%, respectively, leading to increased viscosity and greater pumping difficulty. Cao Runzhuo et al. [35] found that when ultrafine fly ash is used to replace conventional fly ash and the replacement ratio is less than 50%, the fluidity of the UHPC slurry increases with increasing ultrafine fly ash content. At the same time, the yield stress and plastic viscosity decrease significantly, making the slurry easier to pump.

3.2.3. Viscosity modulates admixtures and fiber properties

In addition to superplasticizers, viscosity-modifying admixtures (viscosity reducers, viscosity enhancers) can further optimize the pumping performance of UHPC. Viscosity reducers lower slurry viscosity and improve fluidity by reducing the yield stress and plastic viscosity of the slurry. Commonly used viscosity reducers include ethers and esters [36]. Shen Rui [37] added a viscosity reducer and a defoamer to UHPC, and the viscosity reduction effect was significant, achieving a viscosity reduction rate of up to 42.9%, which effectively improved the pumping performance. Xu Bin et al. [38] showed that after the addition of a viscosity reducer, the yield stress of UHPC was close to 100 Pa and the plastic viscosity was about 70 Pa·s, which could effectively improve pumping performance without affecting mechanical performance.

Fiber content and aspect ratio have a significant impact on the pumping performance of UHPC. With increasing fiber content, the yield stress and plastic viscosity of the slurry increase, leading to higher pumping resistance and greater pumping difficulty. Zhang Qianqian et al. [11]

found that when the fiber content increased from 0 to 3%, the plastic viscosity of UHPC increased by 82.3%, the yield stress increased by 133.0%, and the pumping resistance increased significantly. In addition, a high fiber aspect ratio increases the flow resistance of the slurry, which is detrimental to pumping. It is generally recommended that the aspect ratio of steel fibers be controlled within the range of 50–100 [14].

3.2.4. Pumping process parameters

Pumping parameters, such as pumping pressure, pumping speed, and pipe diameter, also affect the pumping performance of Ultra-High Performance Concrete (UHPC). The pumping pressure must be determined based on the yield stress of the concrete mixture and the resistance of the piping system; too high a pressure can lead to pipe rupture, while too low a pressure will prevent the mixture from flowing. In typical projects in China, for example, the Guangzhou West Tower project, C100 UHPC was successfully pumped vertically to a height of 411 meters. The pumping pressure was properly controlled, and no issues such as pipe blockage or rupture occurred. In the Guangzhou East Tower project, C120 UHPC was pumped vertically to a record height of 417 meters, setting a new world record for vertical pumping of UHPC. The pipe diameter and pumping speed must also be carefully matched: too small a pipe diameter increases flow resistance, while too fast a pumping speed can cause the mixture to segregate. It is generally recommended that the pipe diameter be at least 150 mm and that the pumping speed be controlled between 1 and 3 m³/h. Additionally, the mixing process also affects the pumping performance of UHPC. Optimizing mixing conditions (mixing time and speed) can improve the uniformity of the mixture, reduce flocculation, and enhance its pumpability.

3.3. Summary of research on pumping performance

Based on the aforementioned influencing factors, researchers worldwide have proposed various techniques for regulating the pumping performance of UHPC. These approaches focus on optimizing the mix proportion, judicious selection of admixtures, improving fiber characteristics, and optimizing the pumping process, thereby achieving a balance between high strength and excellent pumpability.

The first approach is to optimize the mix proportion. By adjusting the water-to-binder ratio, aggregate gradation, and the amount of mineral admixtures, the packing density of solid particles can be increased, the water film thickness can be increased, and the slurry viscosity can be reduced [27]. For example, incorporating an appropriate amount of fly ash or ultrafine slag to replace a portion of cement can increase the packing density and improve workability; controlling the silica fume content between 10% and 15% helps achieve a balance between strength and pumping performance [10,39,40].

The second approach involves judicious selection of admixtures. The use of polycarboxylate-based superplasticizers, combined with appropriate amounts of viscosity reducers and defoamers, can effectively improve the rheological properties of the slurry.

The third approach is to optimize fiber characteristics. By controlling the steel fiber content (2.0%-3.5% by volume) and aspect ratio (50-100), or by mixing fibers of different lengths, the adverse effects of fibers on pumping performance can be mitigated.

The fourth approach focuses on optimizing the pumping process. This includes selecting appropriate pumping pressure, pumping speed, and pipe diameter, as well as ensuring adequate pipe lubrication and uniform mixing of the slurry to prevent issues such as blockages and segregation during transport.

At present, significant progress has been made in research on the pumping properties of ultra-high performance concrete (UHPC). However, several issues remain: a low water-to-binder ratio results in higher viscosity of the UHPC slurry, thereby increasing pumping resistance; the addition of steel fibers further complicates the pumping process; when transporting UHPC over

long distances to great heights, the rheological properties of the slurry are susceptible to temperature and pressure, leading to reduced stability. In addition, there is a trade-off between the pumpability of UHPC and its high strength. How to achieve an optimal balance between these two aspects remains a key focus of current research.

4. Synergistic optimization of UHPC strength and pumpability

The high strength of UHPC and its pumping performance are mutually restrictive: the pursuit of high strength requires reducing the water-to-binder ratio and increasing the amounts of active mineral admixtures and steel fibers, which leads to increased slurry viscosity and reduced pumpability. The pursuit of favorable pumping performance requires increasing the water-to-binder ratio and reducing the steel fiber content, which adversely affects strength development. Therefore, achieving synergistic optimization of these two properties is key to the large-scale engineering application of UHPC.

Through experimental research, researchers worldwide have proposed several synergistic optimization methods. First, based on the densest packing theory, optimize the gradation of aggregates and cementitious materials to increase packing density and water film thickness, thereby improving pumpability while ensuring strength[41]. Second, use a high-performance admixture re-dosing technology that combines a polycarboxylate superplasticizer with a viscosity reducer and a slump retaining agent. This reduces water demand while maintaining dispersion effectiveness and improving pumpability. Third, optimize the steel fiber content and type. Using high-efficiency steel fibers, such as hooked-end or corrugated fibers, can improve strength and toughness at a lower dosage while reducing adverse effects on pumping performance [42]. Fourth, a segmented curing process is adopted: standard curing is carried out first after pouring to ensure the fluidity and pumpability of the slurry, followed by steam curing to enhance strength.

5. Conclusions and Prospects

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5.1. Conclusion

The high strength and pumping performance of ultra-high performance concrete (UHPC) are the two core factors for its engineering application. Researchers worldwide have carried out extensive research on these two properties and achieved substantial findings:

(1) The high strength of UHPC mainly depends on the water-to-binder ratio, cementitious material composition, aggregate gradation, steel fiber content, and curing method. By optimizing the mix proportion, incorporating active admixtures and steel fibers, and adopting appropriate curing methods, a compressive strength of 100–265 MPa can be achieved, along with high tensile strength, flexural strength, and toughness.

(2) The pumping performance of UHPC mainly depends on the rheological properties of the slurry, which are affected by factors such as water-to-binder ratio, superplasticizer, packing density of solid particles, fiber characteristics, and pumping process.

(3) The high strength and pumping performance of UHPC are mutually restrictive. Synergistic optimization of the two can be achieved by optimizing particle gradation based on the densest packing theory, using admixture re-dosing technology, and optimizing fiber characteristics and curing methods.

Future research should focus on the development of low-cost alternative materials, the correlation between rheological properties and pumping performance, the improvement of synergistic optimization theory, and the advancement of engineering applications. This will

promote the large-scale application of UHPC in the construction industry and provide high-performance material support for major projects such as super-high-rise buildings and long-span bridges.

5.2. Prospects

Although significant progress has been made in research on the high strength and pumping performance of UHPC, the following problems still exist in theoretical research and engineering applications:

(1) High strength performance: The high cost of highly active admixtures (silica fume, ultrafine slag) limits their large-scale application. An excessively high steel fiber content affects the fluidity and pumpability of the slurry and easily leads to fiber agglomeration. The high-pressure steam curing process is complex and energy-intensive, making it difficult to promote in ordinary projects.

(2) Pumping performance: A low water-to-binder ratio leads to high viscosity of the UHPC slurry, high resistance during ultra-high pumping, and a tendency for pipe blockage. The rheological stability of the slurry is poor and is significantly affected by factors such as temperature, humidity, and mixing time. The loss of slurry during pumping and the difficulty of pipeline cleaning are considerable, which increases construction costs.

(3) Synergistic optimization: The synergistic mechanism between the high strength and pumping performance of UHPC is not yet fully understood, and there is a lack of unified mix proportion design methods and performance evaluation standards. Research on the compatibility between different raw materials (cement, mineral admixtures, chemical admixtures) is insufficient, which affects performance stability.

In view of the above problems and considering the current research status, future research directions for UHPC high strength and pumping performance mainly include:

(1) Develop low-cost, high-performance alternative materials to reduce the preparation cost of UHPC. For example, use industrial waste residues (fly ash, slag, rice husk ash, etc.) to replace part of the silica fume, optimize particle gradation, and reduce cost while ensuring strength. Develop new high-efficiency steel fibers or novel fiber materials (carbon fiber, basalt fiber) to achieve improved strength and toughness at lower dosages and reduce adverse effects on pumping performance.

(2) Deepen the understanding of the intrinsic relationship between the rheological properties of UHPC and its pumping performance, and establish more accurate prediction models for pumpability. Using numerical simulation technology, simulate the flow behavior of UHPC in pipelines, optimize pumping process parameters, reduce pumping resistance, and improve pumping safety and efficiency.

(3) Improve the synergistic optimization theory for UHPC high strength and pumping performance, and establish unified mix proportion design methods and performance evaluation standards. Strengthen research on the compatibility between different raw materials and develop specialized admixtures to achieve an optimal balance between high strength and pumping performance.

(4) Promote green and energy-efficient curing technologies to replace high-pressure steam curing. For example, develop new curing agents and utilize solar energy for curing to reduce energy consumption and construction costs while ensuring strength development.

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