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# Experimental Research on Ultra-High Performance Concrete (UHPC)

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**Abstract.** Ultra-high performance concrete (UHPC) is a new type of concrete with higher strength and durability developed on the basis of the research of high performance concrete. In order to improve the toughness and flexural performance of concrete, steel fibers are added to make it have broader engineering application advantages.

## 1. Introduction

UHPC, which combines high-strength concrete and steel fiber reinforced concrete, is not simply to pull high-performance concrete to high-strength direction. It is based on the study of cementing effect of cement, coagulation of various coarse and fine aggregates, admixtures, admixtures and other hydraulic cementitious materials. Due to the high self-weight and brittleness and low strength of ordinary concrete, especially the low tensile strength, it can't meet the application requirements of super-large structure and assembly structure. Some foreign experts call the removal of coarse aggregate UHPC with fibers as UHPC. In fact, UHPC is a kind of fiber reinforced UHPC mortar. It has super-high, low brittleness and excellent durability, which can't reach the effect of ordinary concrete. In order to improve the performance of UHPC and promote its practical application, this paper studies the influence of UHPC composition material selection, mix design and maintenance mode selection on concrete performance, combining with the actual situation of relevant raw materials in China.

## 2. Preparation of Super High Performance Concrete

### *2.1. Preparation Principle*

Constantly improving construction technology requires that concrete materials not only meet the requirements of ultra-high strength, but also meet the requirements of workability and durability. UHPC performance advantages meet this demand: high compressive strength, good impact and fatigue resistance, steel fiber reinforced concrete significantly improved its tensile performance and toughness; UHPC good workability structure compact to ensure the durability requirements. Due to the high viscosity of ultra-high performance concrete with low water-binder ratio, the shear force of pipe wall increases when pumping. According to the analysis of research data, when W/C=0.385, the adhesion force is 0.01MPa, while when W/C=0.28, the adhesion force of high performance concrete is 0.04 MPa, and the adhesion force is increased three times. Therefore, the requirement of ultra-high position pumping point is the only way for commercial use of UHPC. First, the contradiction between low water-binder ratio, high viscosity and large flow should be solved; the contradiction between ultra-high pressure pumping and segregation stratification and anti-bleeding should be overcome; and

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the technical difficulties such as long distance transportation, high temperature operation, ultra-high pumping and long-time maintenance and ease requirements should be handled, which are all necessary for the popularization of UHPC engineering practice. To solve practical problems, the following are the research results at home and abroad.

*2.2. Composition Material, Mix Ratio and Preparation Technology*

UHPC is prepared with ultra-fine cement. Although the price of ultra-fine cement is high, the performance of UHPC is remarkable, and the amount of UHPC cement is large. It is necessary to overcome the defects of large shrinkage deformation during curing. Components such as non-closed section can be used to design components so as to make the stress distribution uniform when concrete shrinks. Ultrafine reactive powder can fill the voids between slightly coarse cementitious materials, improve the rheological properties of concrete mixtures, reduce water consumption, and effectively improve the strength of UHPC after hydration. Some studies have shown that cement grinding to ultra-fine cement has the characteristics of ultra-fine reactive powder, and silicon powder is rarely used. Admixture with appropriate amount of admixture can reduce the amount of cement and material cost, which is conducive to improving the performance of UHPC. The mechanical properties of concrete products with partially replaced cementitious materials in UHPC by granulated blast furnace slag and fly ash were tested. The effect of granulated blast furnace slag replacing cementitious materials was the best, and the amount of silica powder could be reduced. The low water consumption of water reducing agent UHPC must depend on the high performance water reducing agent with fine dosage to ensure the working performance of concrete. Polycarboxylic acid water reducing agent is widely used in engineering. Fibers use micro-steel fibers less than 13 mm in length to improve the ductility and tensile properties of concrete, overcome the problems of easy overlap of long fibers and low fluidity, too short steel fibers, insufficient bonding force and insufficient flexural delay of concrete. The flexural properties of UHPC can be improved obviously by appropriate fiber length-diameter ratio. To develop UHPC with mixed water, the minimum water consumption should be confirmed first, and then the actual water consumption and high-efficiency water reduction dosage should be fine-tuned through the workability test of concrete. The rheological properties and strength of concrete are affected by the type, particle shape, particle size and quantity of aggregate. Quartz sand with particle size ranging from 0.15mm to 0.6mm was selected in the initial stage of UHPC research, and the particle size range of aggregate was relaxed in the follow-up study.

According to the research data, UHPC meets the working performance of concrete mixtures under low water consumption. The ratio of mortar to cement is generally about 1.1, the ratio of silica fume to cementitious material is 5%-20%, and the ratio of silica fume to cementitious material is less than 40%. A small amount of quartz powder can reduce the water consumption of concrete and improve the compactness and strength of concrete. It is necessary to ensure the toughness and economy of UHPC. It is found that the volume content of steel fibers is between 1.5% and 3%.

## 3. Examples of Mix Proportion Design

*3.1. Mix Ratio Optimization*

According to the above scheme, C110 mix proportion is preliminarily designed, and the initial mix proportion is determined by actual test and adjustment. The 28-day compressive strength value is 118 MPa and the flexural strength is 15.3 MPa. The concrete mix ratio is shown in Table 1.

**Table 1.** Initial base mix ratio of UHPC kg/m$^3$

| Cement | Fly Ash | Silica Ash | Water | Quartz Sand | Water Reducing Agent | Steel Fiber |
|---|---|---|---|---|---|---|
| 620 | 105 | 121 | 175 | 1230 | 9 | 113 |

*3.2. Maintenance Technology*

After forming, 100 cubic millimeter concrete specimens are put into the static curing room under the following conditions: temperature (77±3°F) and relative humidity above 60%. The specimens with

mound are maintained for 24 hours, and then maintained in the following three different ways: Maintenance mode A: The specimens were maintained by steam for 3 days in an accelerated curing box with temperature of (158±5°F), then in a standard curing room (68±2°F) for 3 days, and then naturally maintained for 28 days. Maintenance mode B: Maintenance for 3 days in standard curing room (68±2°F), then steam curing for 3 days in accelerated curing box with temperature of (158±5°F) and natural curing for 28 days. Maintenance mode C: After 7 days of sprinkler curing under natural conditions, the specimens will be cured naturally until the testing age.

## 4. Test Results and Discussion

### *4.1. Effect of Water-binder Ratio on UHPC Performance*

On the basis of the initial mix ratio, the effects of water-binder ratio of 0.19, 0.20, 0.21, 0.22 and 0.23 on the fluidity and strength of UHPC were studied experimentally and comparatively. The curing method adopted category A. The results are shown in Table 2.

**Table 2.** Effect of Water-binder Ratio on UHPC Performance

| No. | Water-binder Ratio | Mortar-binder Ratio | Slump Expansion mm | Volume Density $kg/m^3$ | 28-day Compressive Strength MPa |
|---|---|---|---|---|---|
| 1 | 0.19 | 1.37 | 352 | 2390 | 117.2 |
| 2 | 0.20 | 1.37 | 468 | 2414 | 123.4 |
| 3 | 0.21 | 1.37 | 524 | 2391 | 134.1 |
| 4 | 0.22 | 1.37 | 569 | 2360 | 111.8 |
| 5 | 0.23 | 1.37 | 620 | 2345 | 96.1 |

From the data in Table 2, it can be seen that when the water-binder ratio is equal, the fluidity increases obviously, less than 0.19 water-binder ratio, the mixture is sandy; when the water-binder ratio reaches 0.23, the concrete mixture is in slurry state, the slump expansion can reach 620 mm, and the increase of water-binder ratio promotes the fluidity of UHPC obviously. The test results in Table 2 show that the decrease of water-binder ratio, the inverse increase of UHPC strength, the less water content of concrete mixtures with low water-binder ratio, the dense hydration film formed on the surface of cementitious particles after hydration reaction and the hindrance of further hydration reaction are beneficial to the homogeneity of UHPC by bonding cementitious materials and fine aggregates; in addition, the inner part of concrete mixtures with low water-binder ratio is beneficial to the homogeneity of UHPC. The porosity is also low, which is beneficial to improve the compressive strength of concrete; but when the water-binder ratio is less than 0.20, the strength decreases slightly. This is because the low water-binder ratio results in the higher viscosity of the mixture, and the slurry can't be vibrated and compacted during production. The result of volume density in Table 2 is also reflected. When the water-binder ratio is 0.20, the volume density of hardened slurry decreases by about 1.36%, that is, the compactness decreases, resulting in UHPC. The strength does not increase with the decrease of water-binder ratio.

### *4.2. Effect of Mortar-Rubber Ratio on UHPC*

When mixing UHPC, the amount of cementitious material is more, volume shrinkage is unavoidable, and the mechanical properties of concrete will also be affected. Therefore, the mix ratio tests of concrete with sand-binder ratios of 0.96, 1.16, 1.36, 1.56 and 1.76 are set up to test the fluidity and compressive strength respectively. Table 3 shows that with the increase of sand-binder ratio, the fluidity of the mixture decreases, because the increased slurry content has sufficient capacity to wrap the aggregate surface and reduce the cohesive performance of the mixture.

From Table 3, it can be seen that the compressive strength of concrete increases gradually with the increase of sand-binder ratio, but when the ratio exceeds 1.57, the segregation of concrete mixtures results in the decrease of strength; too little cement paste can't fill the gap between aggregates, nor can

it wrap the aggregate surface, which increases the void of concrete hardening material and reduces the overall performance of concrete. Therefore, it is appropriate to control the sand-binder ratio of UHPC mixtures at about 1.57.

**Table 3.** Effect of Mortar-Rubber Ratio on UHPC Performance

| No. | Water-binder Ratio | Mortar-binder Ratio | Slump Expansion mm | Volume Density kg/m$^3$ | 28-day Compressive Strength MPa |
|---|---|---|---|---|---|
| 1 | 0.21 | 0.97 | 582 | 2343 | 106.3 |
| 2 | 0.21 | 1.17 | 573 | 2361 | 123.1 |
| 3 | 0.21 | 1.37 | 527 | 2389 | 125.9 |
| 4 | 0.21 | 1.57 | 478 | 2392 | 116.2 |
| 5 | 0.21 | 1.77 | 321 | 2384 | 107.5 |

*4.3. Effect of Steel Fiber Ratio on UHPC Performance*

The toughness of concrete is shown in flexural and tensile strength. Steel fiber improves the toughness of UHPC obviously. The following tests are based on the flexural and compressive strength tests of concrete with five different steel fiber contents. The concrete results are shown in Table 4.

**Table 4.** Effect of steel fiber content on UHPC performance

| No. | Steel Fiber Content % | Slump Extension mm | Volume Density kg/m$^3$ | Flexural Strength 28d(MPa) | Compressive Strength 28d(MPa) |
|---|---|---|---|---|---|
| 1 | 0.0 | 632 | 2341 | 10.8 | 85.7 |
| 2 | 1.0 | 557 | 2378 | 14.7 | 111.5 |
| 3 | 1.5 | 513 | 2394 | 17.9 | 123.6 |
| 4 | 2.0 | 495 | 2427 | 19.7 | 124.7 |
| 5 | 2.5 | 416 | 2421 | 18.4 | 121.2 |

The experimental results show that the compressive strength and flexural strength of UHPC increase by 45.5% and 82.4% respectively when steel fibers are mixed in the ratio of 0% to 2%. The mechanical properties of UHPC are improved by steel fibers and the flexural strength is improved more effectively. Steel fiber restrains the crack propagation in the defective parts of concrete, which can further play the role of steel fiber toughness in cement paste after the concrete specimen reaches the ultimate compressive strength. But when the content of steel fiber is 2.5%, the compressive strength decreases by 2.9% and the flexural strength decreases by 7.1%. The reason is that too many steel fibers are added, the fluidity of concrete mixtures decreases and it is difficult to form, and the strength decreases because of the voids in concrete.

*4.4. Effect of Maintenance on Mechanical Properties of UHPC*

Maintenance is the key to the increase of concrete strength. Choosing reasonable curing methods to promote hydration reaction is beneficial to the improvement of concrete strength. In the test scheme, the base mix ratio is set up to maintain in three different ways, and the compressive strength values of three ages are tested respectively. The concrete test results are shown in Table 5.

The 28-day strength of the cured specimens in group A is 11.7% higher than that in group C, while that in group B is 19.6% higher than that in group C. The strength of the specimens cured at high temperature ceases to increase in the later stage, and the curing at high temperature promotes the active reaction of admixtures, which is conducive to the formation of dense structure of the cementitious body. From the curing method of group A and B, the compressive strength of the specimens cured at high temperature after high temperature is 6.98% higher than that cured at When powder is mixed with UHPC, the peak value of exothermic reaction of concrete hydration lags behind.

Thereafter, high temperature curing just reduces the temperature difference between inside and outside of the specimen, which is beneficial to the generation of stress difference between inside and outside of the specimen, and avoids cracking inside the concrete.

**Table 5.** Effects of different curing methods on compressive strength growth of UHPC

| No. | Maintenance Method | Compressive Strength(MPa) | | |
|---|---|---|---|---|
| | | 7d | 14d | 28d |
| 1 | A | 110.1 | 115.4 | 117.5 |
| 2 | B | 123.4 | 126.2 | 125.8 |
| 3 | C | 81.7 | 92.7 | 105.2 |

*4.5. Durability Test*

The impermeability of concrete directly reflects the durability of concrete. The direct way to improve the durability is to make the internal structure of concrete compact, and to add ultra-fine reactive powder to improve the impermeability of concrete. Experiments on the impermeability of UHPC show that the impermeability of UHPC can reach above P28. The compactness is very effective to the impermeability of concrete. It can inhibit the diffusion and permeation of $CO_2$ and $Cl^-$ and improve the durability of concrete structures.

## 5. Conclusion

From the above test results, it can be seen that the optimum water-binder ratio of UHPC is 0.20, the optimum sand-binder ratio is about 1.57, and the optimum content of steel fiber is about 2%. It is beneficial for concrete reinforcement to adopt relatively delayed high temperature curing start time.

To study the technical direction of super high performance concrete and the fusion of high strength and high durability of high performance concrete and concrete. In order to obtain the optimal UHPC product, the impermeability of concrete was studied and the impermeability of the product was tested.

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