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Curing Technology of Ultra-high Performance Concrete (UHPC)

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Abstract: The paper has studied the effects of different curing methods, curing temperature and curing time on the mechanical properties and microstructure of UHPC, and optimized the curing technology. The results showed that the optimal curing technology was that the UHPC was cured in hot water at 90 ℃ for 48h and then maintained in standard curing. The super high performance concrete with large dimensional stability, strong freeze-thaw resistance and durability was produced.

1. Introduction

Ultra-high performance concrete (UHPC) is a new type of ultra-high strength cement-based material with high strength, high toughness and excellent durability [1]. Its preparation mechanism is to achieve the uniformity and compactness of the material by removing coarse aggregates, reducing the water-binder ratio, increasing the activity of components and achieving the densest packing. At the same time, different curing methods are used to stimulate its hydration progress and change the structural morphology and distribution of hydration products [2]. The curing technology has a great relationship with the performance of concrete, A higher curing temperature will accelerate the hydration process of cement, improve the microstructure and improve the mechanical properties of concrete [3-5]. However, sometimes curing at too high a temperature will also have an adverse effect on concrete [6]. As of now, a scientific curing system has not been systematically established for UHPC. Therefore, based on the company's UHPC mix design, this paper discusses the differences in the physical and mechanical properties of UHPC caused by curing methods, temperatures and times, and optimizes to obtain the best curing technology under this mix ratio.

2. Raw Materials and Test Methods

2.1. Raw Materials

(1) Cement: Huaxin P.O 52.5 cement, with a specific surface area of 402 m^2/kg, a water requirement for normal consistency of 27.5%, an initial setting time of 103 minutes, a final setting time of 177 minutes, and a 28-day compressive strength of 60 MPa. The chemical composition is shown in Table 1 below.

(2) Microspheres: White fly ash microspheres produced by Shenzhen Tongcheng New Material Technology Co., Ltd., with a spherical density of 2.53 g/cm^3 and an apparent density of 0.66 g/cm^3. The chemical composition is shown in Table 1.

(3) Silica fume: Grayish-white silica fume provided by Hubei Wuda Jucheng, with a specific surface area of 224,000 cm^2/g and a water requirement of not more than 114%. The chemical composition is shown in Table 1.

(4) Sand: Quartz sand with a particle size of ≤0.6 mm.

(5) Water reducer: SK polycarboxylate superplasticizer, with a solid content of 30% and a water reduction efficiency of about 30%.

(6) Steel fiber: Copper-plated steel fiber provided by Jiangsu Bote New Materials Co., Ltd., with a diameter of 0.22 mm, an aspect ratio of 55-65, a tensile strength of not less than 2800 MPa, an elastic modulus of not less than 190 GPa, and a density of 7.7g/cm^3.

Table 1: Chemical composition analysis of raw materials

Name	Content（%）								
	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Na_2O	K_2O	SO_3	Loss
Cement	20.2	4.28	62.94	2.29	3.26	0.08	0.74	2.75	2.67
Microspheres	56.82	16.20	5.34	1.71	3.88	0.15	2.45	0.19	8.04
Silica fume	93.74	0.1	0.07	0.27	1.29	0.18	0.45	1.36	3.75

2.2. Specimen Preparation and Curing Methods

(1) Molding:

First, pour the weighed cementitious materials according to the company's UHPC mix ratio formula into a compulsory mixer and stir for 3 minutes. Then, slowly pour the uniformly mixed water and polycarboxylate superplasticizer into the mixer and continue to stir for 3 minutes. After that, pour the aggregate into the mixer and stir for 5 minutes. Finally, pour out the UHPC and place it in 100mm×100mm×100mm and 100mm×100mm×400mm molds for molding. The temperature of the molding room should be maintained at 20 ℃±2 ℃, and the relative humidity should be not less than 50%. Demold after one day.

(2) Curing:

The demolded specimens are cured according to the three curing methods in Table 2 below. The curing technology of UHPC specimens is numbered according to three aspects: curing method (normal temperature curing, steam curing and hot water curing), curing temperature (50 ℃, 80 ℃ and 90 ℃) and curing time (6h, 12h, 24h, 48h, 72h).

Table 2: Specimen numbers correspond to curing methods.

Curing method	Numbering	Curing process
Standard curing	B	After 24 hours of specimen molding, demold and directly conduct standard water curing
Steam curing	Z	After 24 hours of specimen molding, demold and conduct steam curing for a certain period of time, then conduct standard water curing
Hot water curing	R	After 24 hours of specimen molding, demold and conduct hot water curing for a certain period of time, then conduct standard water curing

Note: R90-24 — 24 hours of curing in 90 ℃ hot water.

(3) Test methods:

Perform mechanical property tests on the cured specimens according to GB/T 50081-2019 "Standard for test methods of mechanical properties on ordinary concrete".

Perform durability tests on the specimens according to GB/T 50082-2009 "Standard for test methods of long-term performance and durability of ordinary concrete".

Use the JSM-5610LV scanning electron microscope of JEOL Ltd. of Japan to analyze the microscopic morphology of hydration products.

3. Test Results and Discussion

3.1. Influence of Curing Methods on UHPC Performance

The specimens are cured in three curing methods. The temperatures of steam curing and hot water curing are both 90 ℃, and the time is 24 hours. The strength, hydration degree test analysis and microscopic morphology analysis of the specimens in three curing methods at ages of 7 days, 28 days and 90 days are carried out respectively.

Figure 1 shows the influence of three curing methods on the strength of UHPC. The comparison results show that under the same curing age, the strength of the test block under standard curing is the lowest, followed by the test block under steam curing, and the strength of the test block under hot water curing is the highest. When cured at 90 ℃ for 24 hours, the 28-day compressive strength of UHPC under steam curing is increased by 21 MPa compared with that under standard curing, about 15.3%, and the flexural strength is increased by 4.75 MPa, about 14.8%; the compressive strength of UHPC under hot water curing is increased by 28.8 MPa compared with that under standard curing, about 21.2%, and the flexural strength is increased by 5.85 MPa, about 21.7%. This is because in hot water curing, the test piece can be heated more evenly. Heating curing accelerates the hydration rate. And under the water environment condition, moisture will enter the test piece through the capillary pores of the test piece, increase the hydration amount of cementitious materials, and improve the strength of UHPC specimens.

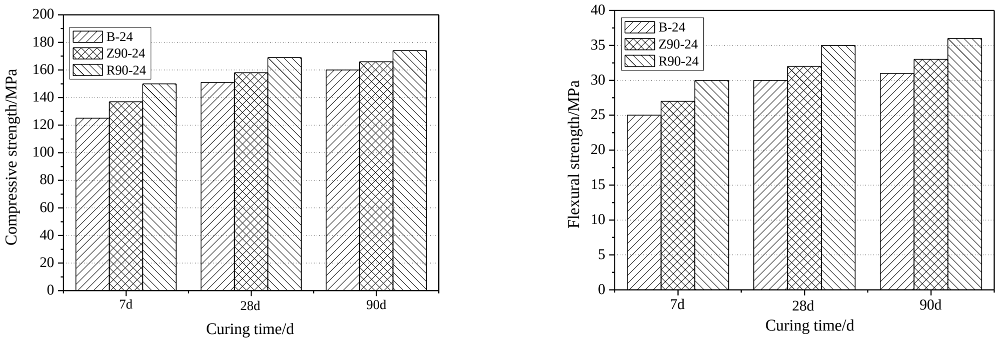
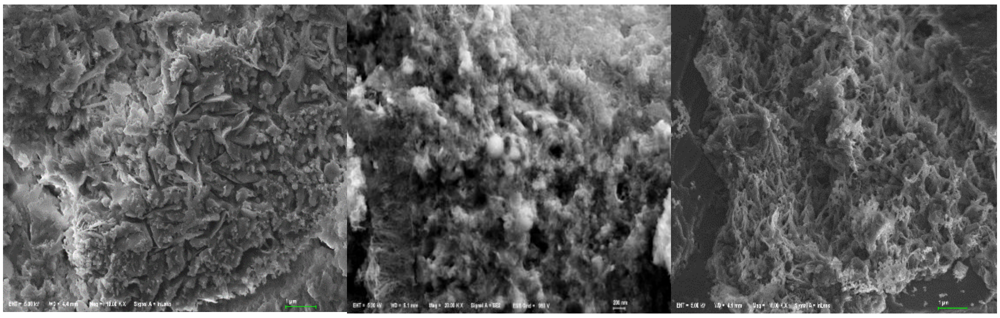


Figure 1: Influence of curing methods on UHPC strength



B-24 Z90-24 R90-24

Figure 2: SEM images of three curing methods

Figure 2 shows the SEM images of the three curing methods. It can be seen from the images that the internal structure of UHPC concrete is relatively dense, there are very few pore structures and they belong to micropores. Flocculent C-S-H gels are all formed. Only the aggregation degree of the gels is different. The internal C-S-H gel of the specimen under standard curing is relatively less. The content of C-S-H gel under steam curing is second. The C-S-H gel under hot water curing is the most, and most of them are distributed in a flocculent and acicular manner, intersecting with each other to form a tight spatial structure. Macroscopically, the structure is denser and the mechanical strength is greater.

In conclusion, hot water curing is the best curing method. High-temperature curing can stimulate the activity of cementitious materials earlier, accelerate the reaction speed and improve the strength of UHPC. In addition, the hot water environment can better maintain temperature stability, ensure that there is more moisture around the cementitious materials, increase the hydration amount of cementitious materials and improve the strength of UHPC. Since hot water curing is the best way, the following tests all use hot water curing for specimens.

3.2. Influence of Curing Temperature on the Mechanical Properties of UHPC

Figure 3 shows the strength of UHPC specimens at various ages when cured in hot water at 50 ℃, 80 ℃ and 90 ℃ for 24 hours. When cured in hot water for 24 hours, the 28-day compressive strength of UHPC cured at 80 ℃ is increased by 12.5 MPa compared with that cured at 50 ℃, about 8.47%, and the flexural strength is increased by 1.5 MPa, about 4.91%; the compressive strength of

UHPC cured at 90 ℃ is increased by 18.5 MPa compared with that cured at 50 ℃, about 12.54%, and the flexural strength is increased by 2.3 MPa, about 7.54%. From the comparison results of several groups of figures, it can be seen that when the curing method and curing time are the same, the higher the curing temperature, the higher the compressive strength and flexural strength in these three time periods. It can be seen that the increase in temperature can accelerate the rate of hydration reaction and improve the early strength of UHPC test blocks. This is because the high-temperature environment can better stimulate the pozzolanic activity of microspheres and silica fume. Silica fume and microsphere powder will quickly undergo secondary hydration reaction with cement hydration products [7]. The volume of C-S-H gel increases, the porosity decreases, and the pore structure is improved. At the same time, the bonding ability between steel fiber and matrix is also enhanced. Through comparative tests, it can be known that among several curing temperatures, demolding and hot water curing at 90 ℃ has the best effect. The curing temperature is set at 90 ℃ .

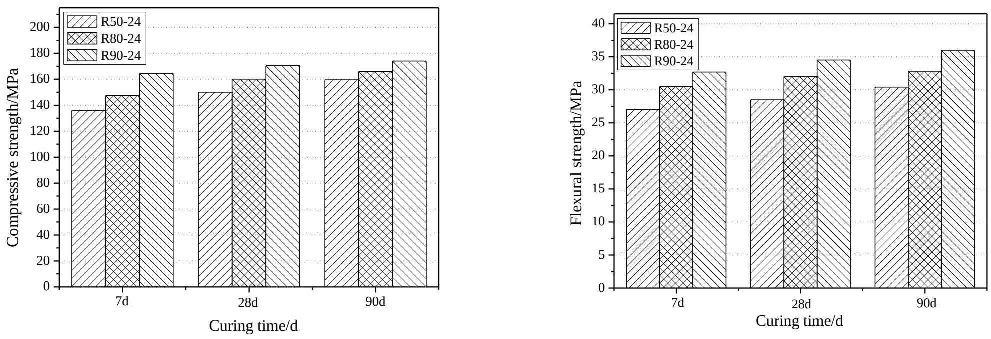


Figure 3: Influence of curing temperature on UHPC strength.

3.3. Influence of Curing Time on the Mechanical Properties of UHPC

Figure 4 shows the influence of curing time on the strength of UHPC. The compressive strength and flexural strength of UHPC test blocks at various ages when cured in hot water at 90 ℃ for 6h, 12h, 24h, 48h, and 72h. For the 28-day test block compressive strength cured in hot water at 90 ℃, the strength of the test block cured for 12 hours is 7.5 MPa higher than that cured for 6 hours, about 5.07%; the strength of the test block cured for 24 hours is 10 MPa higher than that cured for 12 hours, about 6.43%; the strength of the test block cured for 48 hours is 9.5 MPa higher than that cured for 24 hours, about 5.74%; the strength of the test block cured for 72 hours is 4.5 MPa higher than that cured for 48 hours, about 2.57%. For the 28-day test block flexural strength cured in hot water at 90 ℃, the strength of the test block cured for 12 hours is 1.8 MPa higher than that cured for 6 hours, about 6.04%; the strength of the test block cured for 24 hours is 1.2 MPa higher than that cured for 12 hours, about 3.80%; the strength of the test block cured for 48 hours is 2.6 MPa higher than that cured for 24 hours, about 7.93%; the strength of the test block cured for 72 hours is 0.7 MPa higher than that cured for 48 hours, about 1.98%.

The results show that when the curing method and curing temperature are the same, as the hot water curing time is extended, the compressive strength and flexural strength of UHPC specimens both show an upward trend. When the hot curing time is extended from 6 hours to 48 hours, the strength shows obvious growth. However, when the time is extended from 48 hours to 72 hours, although the strength is increased, it is not obvious. It can also be seen that when the hot curing time is longer, the smaller the distance between the curves representing the strengths of 7 days, 28 days and 90 days of UHPC specimens, indicating that the strength growth is smaller. The extension of hot curing time will also accelerate the hydration rate of hydrates. Therefore, the extension of curing time can improve the strength of UHPC test blocks. The curing time of 48 hours is the best, ensuring economy while meeting performance.

In conclusion, the curing technology of this UHPC is set as curing in hot water at 90 ℃ for 48 hours after demolding.

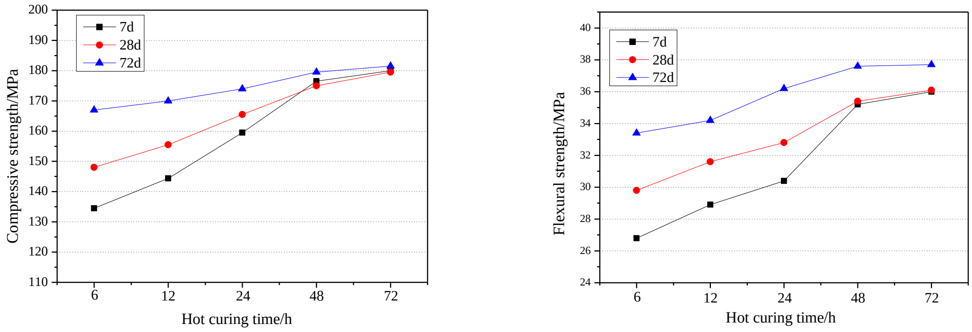


Figure 4: Influence of curing time on UHPC strength

3.4. Performance Evaluation of UHPC under Curing Technology

The performance of UHPC test blocks was tested under the technical conditions of curing in hot water at 90 ℃ for 48 hours. Figure 5 shows the size shrinkage rate of UHPC. As can be seen from the figure, as time increases, the size shrinkage becomes larger and larger, but the curve shows a gradually flattening trend. After 28 days, the size shrinkage of UHPC gradually tends to be stable. This shows that the size shrinkage of UHPC is mainly completed within 28 days, and the total shrinkage is also within 300×10-6 after 120 days, verifying the high dimensional stability of UHPC.

Figure 6 shows the relative dynamic modulus and mass change curve of UHPC test blocks under the coupling effect of seawater dry-wet and freeze-thaw. The upper curve is the change curve of elastic modulus under the cyclic action, and the lower curve is the mass change curve. Judging from the change of relative dynamic modulus under the coupling effect of seawater dry-wet and freeze-thaw, after 10 coupling cycle tests, the relative dynamic modulus of UHPC test blocks shows an increasing trend rather than a decreasing trend. This is because the sulfuric acid solution enters the interior of the concrete and reacts with some materials of the cement-based material to form insoluble salts and fills the interior of the concrete, mainly the capillary pore structure. To a certain extent, it even further densifies the internal structure, so that its change trend shows an increase. The change of dynamic modulus is all less than 5%, and even after ten cycles, its fluctuation range is very small; Judging from the mass change under the coupling effect of seawater dry-wet and freeze-thaw, after 10 coupling cycle tests, the mass of the two UHPC test blocks also shows an increasing trend. The reason is the same as above, and the increase range of mass is within 0.3%.

Table 3 shows the test and evaluation results of the durability of two different UHPCs in accordance with JGJT 193-2009 "Standard for Inspection and Evaluation of Concrete Durability". The test results of its freeze-thaw resistance, carbonation resistance, sulfate attack resistance, and impermeability are all the highest grades in the standard. The DRCM value of the chloride ion penetration resistance tested by the rapid method is 0.051×10-12m2/s, which also belongs to the highest grade RCM-V (DRCM<1.5×10-12m2/s).

In conclusion, under the optimized curing technology, UHPC materials have excellent dimensional stability, strong resistance to dry-wet freeze-thaw, and excellent comprehensive durability.

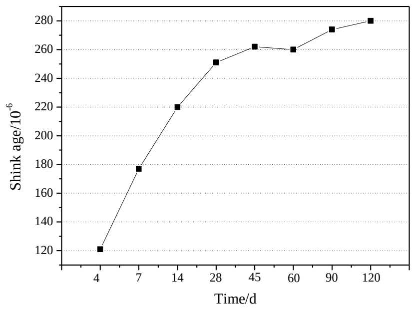


Figure 5: Shrinkage rate of UHPC

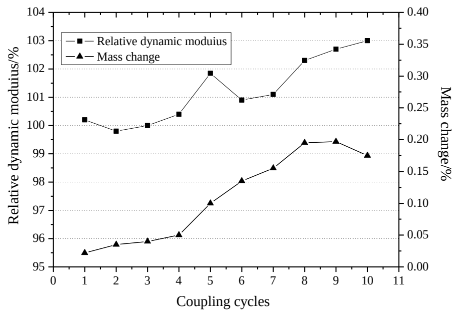


Figure 6: UHPC artificial seawater dry-wet-freeze-thaw cycle

Table 3: Evaluation of UHPC durability

Name	Frost resistance grade	Carbonation depth	D_{RCM} ($10^{-12}m^2/s$)	Sulfate attack resistance grade	Impermeability grade
QC-1	F>500	0	0.051	>KS150	>P12

4. Conclusions

(1) The best curing technology is to cure the UHPC test block in hot water at 90 ℃ for 48 hours after demolding, and then take it out for standard curing.

(2) Hot water curing can maintain uniform and stable temperature and increase the hydration amount of cementitious materials. The high-temperature environment can better stimulate the pozzolanic activity of microspheres and silica fume. Silica fume and microsphere powder will quickly undergo secondary hydration reaction with cement hydration products, improving the compactness and strength of UHPC.

(3) With the extension of hot water curing time, the compressive strength and flexural strength of UHPC specimens both show an upward trend, but the growth tends to be slow after 48 hours.

(4) Under the optimized curing technology conditions, UHPC materials have excellent dimensional stability, strong resistance to dry-wet freeze-thaw, and excellent comprehensive durability.

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