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EFFECT OF LOW PRESSURE ON THE PROPERTIES AND MICROSTRUCTURE OF ULTRA-HIGH PERFORMANCE CONCRETE

XIONG WU*, **, WEN YANG**, #YAOLING LUO**, XINYI YAN**, YUHAO XIE**

**School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, China*
***China West Construction Academy of Building Materials, Chengdu, 610015, China*

#E-mail: cqulyl@qq.com

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The properties of fresh concrete, the mechanical properties and microstructure of Ultra-High Performance Concrete (UHPC) with different admixtures were studied in Chengdu and Lhasa, for exploring the influence of low pressure on the performance of UHPC. The test results indicated that: The plateau low pressure environment can significantly reduce the dosage of the admixtures and improve the performance of fresh UHPC, but the compressive strength was significantly reduced at 28 d and 60 d. The porosity and average pore size of the UHPC under low pressure are relatively small, but the pore size of the UHPC above 10000 nm takes up a larger proportion. In addition, the low pressure environment on the plateau can also reduce the degree of hydration of the UHPC.

INTRODUCTION

The climate of the plateau area has the obvious characteristics of a low ambient temperature, low relative humidity, thin air and a low ambient air pressure. Concrete is more vulnerable to damage in the plateau environment. For example, concrete cracking is common in concrete bridge projects in the Qinghai-Tibet Plateau [1]. In the plateau area, the most significant feature is the low air pressure, which is inversely proportional to the rate of water evaporation. Low air pressure can significantly accelerate the evaporation of water [2]. In addition, a low air pressure accelerates the evaporation of water from the surface of concrete, then makes the internal water migrate to the surface, and increases the reduction rate of the internal humidity of the concrete. Therefore, the internal water loss of concrete in plateau area is faster, which has adverse effects on various properties [3]. Along with the low air pressure, the plateau also has significant low humidity characteristics. Therefore, the low air pressure and low humidity environment significantly reduce the mechanical properties, the durability of the concrete and increase the porosity of the concrete [4-6].

Ultra-high performance concrete (UHPC) has ultra-high strength, ultra-high toughness and ultra-high durability. Its compressive strength is more than 150 MPa and its flexural strength is more than 20 MPa. Its water to binder ratio is generally about 0.20, and the lowest can reach 0.13 [7-9]. UHPC has excellent durability, which can greatly improve the service life of concrete structures and reduce the maintenance cost of concrete structures. It has almost no carbonation, and the penetration of chloride ion and sulfate are almost zero [10-12]. The excellent wear resistance of UHPC extends the service life of bridges, and the anti-corrosion performance of it provides protection for concrete structures in harsh environments. In the case of cracking, due to the existence of a large number of unhydrated cement particles in the UHPC, the concrete has a self-repairing function [13].

In the plateau environment, due to the accelerated deterioration of the concrete properties, it is difficult for ordinary concrete to serve as a long-term material in such an area. UHPC is theoretically feasible to resist extreme harsh environment. Based on the advantages of UHPC, the effects of the low plateau pressure environment on the properties of fresh concrete, its mechanical properties and the microstructure of the cured UHPC were investigated, which leads to laying a theoretical basis for the long-term service of UHPC in a plateau environment.

EXPERIMENTAL

Basic materials

Ordinary Portland cement 52.5R: the 3-day compressive strength is 35.8 MPa, and the 28-day compressive strength is 59.4 MPa. Semi-encrypted grade 94 silica fume: the 28-day activity index is 109 %, and the water demand ratio is 103 %. S95 granulated blast furnace slag: The 28-day activity index is 112 %. Fly ash microbeads from Hebi, Henan: $d_{50} \leq 2.8$ µm, water demand ratio is 88 %, 2the 8-day activity index is 86 %. The main chemical compositions of the four powders are reported in Table 1.

Fine aggregate: manufactured sand from Beichuan, Sichuan, with a fineness modulus of 2.6.

Chemical admixture: An admixture for the UHPC with high water reduction, viscosity reduction and shrinkage reduction functions which was adopted.

Steel fibre: Copper plated straight, length 13 mm, diameter 0.22 mm, tensile strength ≥ 2000 MPa.

Experimental methods

The Lhasa Plateau in Tibet with a low environmental pressure was chosen as the experimental area, and then the atmospheric pressure was compared to that of the Chengdu region where the relative humidity of the laboratory environment was constant. The air pressure and relative humidity of the two places are shown in Table 2.

Table 2. Laboratory pressure and relative humidity in Chengdu and Lhasa.

Region	Atmospheric pressure (kPa)	Laboratory relative humidity
Chengdu	97.2	83 %
Lhasa	64.7	82 %

Table 1. Chemical composition of the raw materials in wt. %

Materials	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	TiO_2	SO_3	P_2O_5	MnO
Cement	21.39	5.15	61.04	2.82	0.638	0.615	3.86	0.848	3.1	0.095	-
Granulated blast furnace slag	11.7	11.15	57.23	11.74	0.682	0.536	2.62	2.18	1.6	-	0.438
Silica fume	95.61	-	1.81	1.91	0.665	-	-	-	-	-	-
Fly ash microsphere	43.949	24.351	12.381	1.927	2.418	4.904	5.161	3.064	0.165	1.207	0.103

Table 3. Mix proportions of the UHPC.

Cement	Granulated blast furnace slag	Silica	Fly ash fume	Sand microsphere	Water	Steel fibre	Admixture %
1.0	0.36	0.27	0.18	1.82	0.29	0.29	0.2
1.0	0.36	0.27	0.18	1.82	0.29	0.29	0.4
1.0	0.36	0.27	0.18	1.82	0.29	0.29	0.6

The UHPC concrete specimens with a size of 100 mm × 100 mm × 100 mm were prepared according to the mix proportion shown in Table 3. The water to binder ratio was 0.16, and the solid content of the admixture was 0.2 %, 0.4 % and 0.6 %, After 24 hours, the specimens were placed in a standard curing room for 7 days then placed outdoors. The mechanical properties and microstructure of the specimens were tested after 7 days, 28 days and 60 days.

The samples were divided into six groups, the UHPC with three kinds of additives were formed in Chengdu and Lhasa, and the relevant properties were tested. The test groups are shown in Table 4.

Table 4. Test groups.

Groups	Dosage of admixtures
Chengdu: C2	0.2 %
Chengdu: C4	0.4 %
Chengdu: C6	0.6 %
Lhasa: L2	0.2 %
Lhasa: L4	0.4 %
Lhasa: L6	0.6 %

Test methods

Performance of the fresh concrete: Test the slump flow, air content and slump time of the fresh UHPC.

Mechanical performance testing: The compressive strength of the UHPC by the China GB/T 31387-2015 standards.

Pore structure: The mercury intrusion method (MIP) was mainly used to test the pore structure. The sample was soaked in anhydrous ethanol for 48 h, and then dried and crushed in vacuum at 60 °C to make particles with a diameter of 3 ~ 5 mm. The pore structure was tested by an American Mike AutoPore V series mercury porosimeter, and the pore diameter range was 0.003 to 1100 µm.

X-Ray Diffraction (XRD): The samples were dehydrated by absolute ethyl alcohol for 48 h, then the samples were tested after vacuum drying at 60 °C. Then ground in a ceramic mortar to pass through a square-hole sieve of over 80 μm. A PANalyticalEmpyrean X-ray diffractometer was used to analyse the phase composition. The target material of the instrument was copper, the scanning range was 5 ~ 70°, and the scanning speed was 5 minutes per sample.

RESULTS AND DISCUSSION

Macroscopic performance

Performances of concrete

The slump flow, air content and slump time of the UHPC in Chengdu and Lhasa were tested with different admixtures. The results are shown in Figure 1. It can be seen from Figure 1 that when the admixture content was 0.2 % and 0.4 %, the expansion degree of the UHPC formed in Lhasa was significantly higher than that in Chengdu, and the difference between the two regions was small when the admixture content is 0.6 %; When the admixture content was 0.4 % and 0.6 %, the air content of the UHPC in Chengdu was significantly higher than that in Lhasa. When the admixture content was 0.2 %, the air content in Lhasa was higher than that in Chengdu. The results showed that the slump time in the Chengdu area was significantly higher than that in the Lhasa area under the three different admixtures, which indicates that the viscosity of the UHPC formed under the high pressure environment in Chengdu was higher.

Under the high pressure conditions in Chengdu, the workability of the UHPC gradually improved with an increase in the admixture content, the slump time gradually decreased, and the admixture content did not reach saturation. In the Lhasa low pressure area, when the admixture content reached 0.4 %, increasing the admixture content had no improvement on the workability, indicating that the 0.4 % admixture content had reached saturation in the Lhasa low pressure area. When the admixture content was 0.4 % and 0.6 %, the gas content of the UHPC in the Lhasa low pressure area was significantly lower than that in Chengdu high pressure area. The main reason is that the low pressure would have led to the continuous floating of bubbles, which reduces the overall gas content. Therefore, the air content of the UHPC was higher than that in the Chengdu high pressure area. The above results showed that the air content and viscosity of the UHPC can be reduced by forming the UHPC in a low pressure environment. Under the same workability, the low pressure could improve the fresh mixing performance of the UHPC better when the dosage of the admixture and saturated dosage were properly reduced.

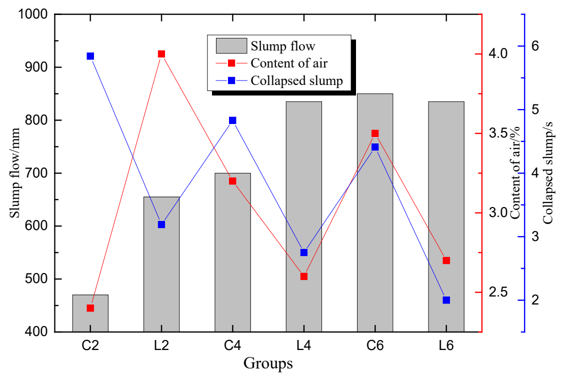


Figure 1. Properties of the fresh UHPC in Chengdu and Lhasa.

Mechanical property

The 7-days, 28-days and 60-days compressive strengths of the UHPC formed in the high pressure area of Chengdu and the low pressure area of Lhasa were tested, and the results are shown in Figure 2. At the three ages, 7 days, 28 days, and 60 days, the compressive strength of the Chengdu high pressure area was significantly higher than that of the Lhasa low pressure area. On the 60th day, both Chengdu and Lhasa had the highest compressive strength when the admixture content was 0.4 %. Surprisingly, the compressive strength of the UHPC with 0.4 % admixture was significantly higher in the low pressure area of Lhasa than in the high pressure area of Chengdu.

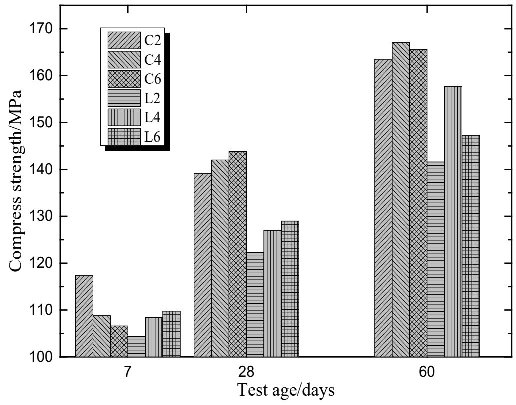


Figure 2. Compressive strength of the UHPC in Chengdu and Lhasa.

Pore structure

The pore structures of the specimens at 60 days under the different admixtures in Chengdu and Lhasa were tested. The results are shown in Table 5, Figure 3 and Figure 4. Table 5 shows that the porosity and average pore diameter in the Lhasa low pressure area were significantly lower than those in the Chengdu high pressure area when the admixture dosage was 0.4 % and 0.6 %, while the Lhasa area was higher than the Chengdu area when the admixture dosage was 0.2 %.

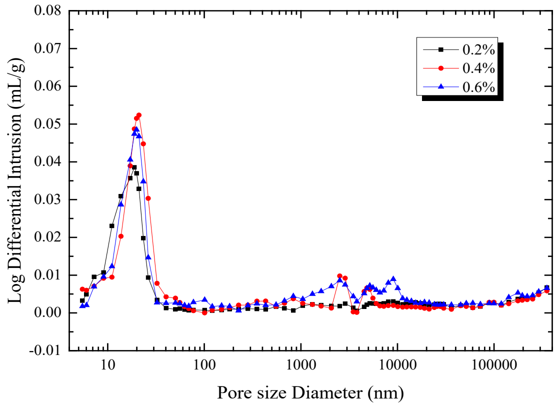
Table 5. Pore distribution of the UHPC in Chengdu and Lhasa at 60 d.

Groups	Porosity (%)	Average pore size/nm
C2	5.7316	20.90
C4	6.5804	24.86
C6	7.4011	29.15
L2	7.1773	31.76
L4	4.7875	18.85
L6	6.7831	24.96

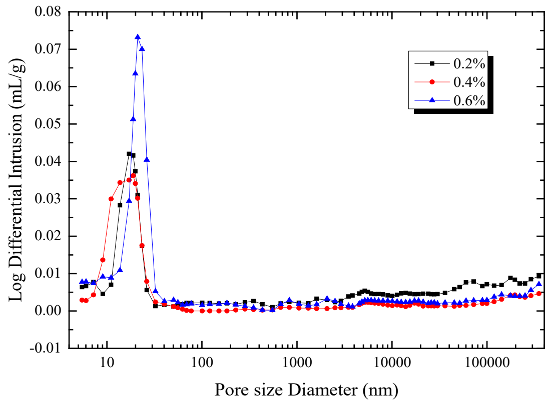
The pore structure distribution and aperture distribution of the samples at 60 days of age with the different admixtures in Chengdu and Lhasa are shown in Figure 3 and Figure 4. It can be seen from the figure that the aperture of 1000 - 10000 nm in the Chengdu high pressure area was obviously higher than that in the Lhasa area. The pore structure in the high pressure area was mainly 10 - 100 nm, followed by 1000 - 10000 nm. The pore structure in the Lhasa low pressure area was also dominated by the aperture of 10 - 100 nm, followed by the aperture of more than 10000 nm.

Mechanism analysis

Although it can be seen that the overall porosity and average porosity of the Chengdu high pressure area were higher than the Lhasa low pressure area, the distribution of the large aperture above 10000 nm in the Lhasa area was relatively high. The average compressive strength of the Chengdu high pressure area was significantly higher than that of the Lhasa low pressure area, which was mainly affected by the aperture of more than 10000 nm. The low humidity and low air pressure in the outdoor environment of Lhasa led to the rapid loss of water, especially after 28 days, which greatly affected the hydration and pore structure changes of the UHPC. Griffiths [14] pointed out that the gel pores of UHPC at an early age would absorb water, resulting in the separation of the surface of the gel pores and weakening of the van der Waals force. Therefore, a small amount of water loss of UHPC at 7 days could enhance the compressive strength to a certain extent. This effect offset the loss of compressive strength caused by the insufficient hydration to a certain extent. With the growth of the age, the water loss caused by the low humidity and low air pressure had gradually become the dominant factor in

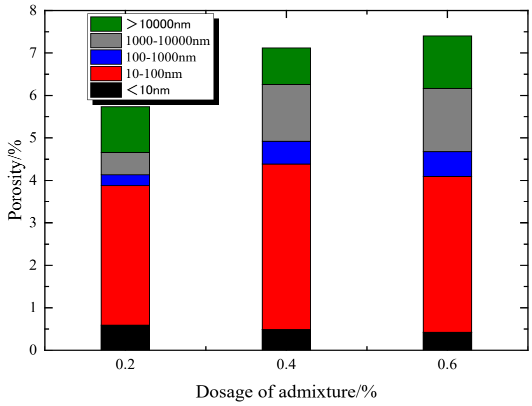


a) Chengdu high pressure area.

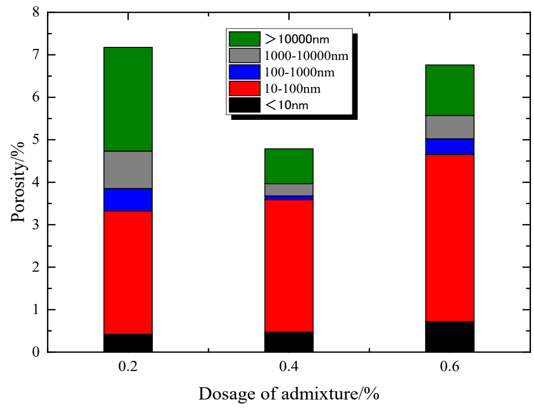


b) Lhasa low pressure area.

Figure 3. Pore distribution of the UHPC in Chengdu and Lhasa at 60 d.



a) Chengdu high pressure area.



b) Lhasa low pressure area.

Figure 4. Pore size distribution of the UHPC in Chengdu and Lhasa at 60 d.

the difference of the compressive strength, and the water loss caused by the low humidity and low air pressure took a certain time, so a regular pattern of compressive strength reduction was more obvious in the later stage. In order to further verify the influence of the air pressure on the hydration, the two groups of specimens (C2 and L2) with the most obvious difference in compressive strength at 60 days were subjected to an XRD phase analysis. The results are shown in Figure 5.

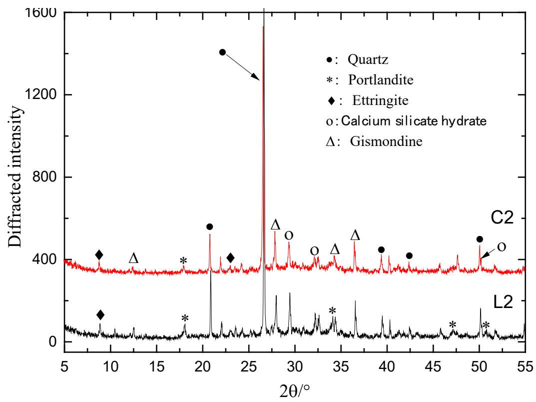


Figure. 5 XRD of the UHPC in Chengdu and Lhasa at 60 d.

It can be seen from Figure 5 that the air pressure had no effect on the types of hydration products of the UHPC that formed in Chengdu and Lhasa, but had a certain effect on the degree of hydration. The diffraction intensities of calcium hydroxide and calcium silicate hydrate in the hydration products of the UHPC formed in the Chengdu area were significantly lower than those formed in the Lhasa area. The mix proportion of the UHPC in this experiment contains three mineral admixtures (fly ash beads, blast furnace slag and silica fume). The higher the hydration degree, the greater the consumption of calcium hydroxide. Combined with the results of Figure 5, it could be considered that the hydration degree of the UHPC formed in the Chengdu high pressure area was higher than that in the Lhasa low pressure area. Therefore, the compressive strength of the UHPC formed in Chengdu and Lhasa was quite different. The compressive strength in the high pressure area of Chengdu was significantly higher than that in the low pressure area of Lhasa.

In addition, the low air pressure would not only significantly improve the fresh mixing performance of the UHPC, especially the workability, but also significantly reduce the saturated content of the UHPC admixtures. There was a good linear relationship between the air pressure and the surface tension coefficient of the liquid. The lower the air pressure, the greater the surface tension coefficient [14]. Moreover, the surface tension coefficient was positively related to the capillary phenomenon. The larger the surface tension coefficient, the higher the capillary rose in height. In the low pressure environment, the admixture could be better dispersed between the small cement particles, which was conducive to the dispersion of the cement particles and improved the working performance of the UHPC.

CONCLUSIONS

In this paper, the properties of fresh concrete, its mechanical properties and the microstructure of a UHPC with different admixtures in the Chengdu high pressure area and the Lhasa low pressure area were compared to explore the effect that the pressure has on the performance of the UHPC. The results were as follows:

(1) The performance of the UHPC was better in the plateau low pressure environment, which could significantly reduce the content of the admixture, air content and viscosity of fresh the UHPC;

(2) The compressive strength of the UHPC in the plateau low pressure environment was significantly lower than that in the high pressure area, especially at 28 days and 60 days of age, but the effect is less at 7 days of age;

(3) In the plateau low pressure environment, the overall porosity and average pore size of the UHPC were lower than those in high pressure areas, but the pore size larger than 10,000 nm accounts for a larger proportion. At the same time, because the low pressure and low humidity were beneficial to the water loss, the hydration degree of the UHPC in the plateau low pressure environment was lower than that in the high pressure area, which eventually led to the compressive strength of the UHPC in the plateau low pressure area being significantly lower than that in the high pressure area.

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