Study on manufacturing method of improving the strength of UHPC under natural curing conditions

Dingtao Mao\textsuperscript{1a}, Yong Ding\textsuperscript{1b}, Xinlei Shi\textsuperscript{2c}

\textsuperscript{1}School of Civil and Environment Engineering, Ningbo University, Ningbo 315211, China
\textsuperscript{2}Ningbo Traffic Planning and Design Institute Limited, Ningbo, Zhejiang 315000, China
\textsuperscript{a}1911083044@nbu.edu.cn, \textsuperscript{b}dingyong@nbu.edu.cn, \textsuperscript{c}624102541@qq.com

Abstract—Standard or steam curing is generally used in the production of ultra-high performance concrete (UHPC), which puts forward higher hardware conditions for the production of this material. In order to promote the popularization and application of UHPC, it is necessary to explore its fabrication method under natural curing, that is, without accurate control of temperature and humidity. The research method used in this paper is experimental analysis. By adjusting the components of UHPC materials, adjusting the proportion of each component, humidifying with watering and other simple measures, the methods to improve the strength of UHPC under natural curing conditions are explored. The experimental results show that the addition of high-efficiency solid water reducer can make the UHPC blocks have higher compressive strength than liquid water reducer. When the ratio of silica fume to cement is 30\%, the compressive strength of UHPC reaches the maximum. Reducing or increasing the silica fume will reduce the strength of UHPC. Humidification by simple watering can be used to improve the compressive strength of UHPC. UHPC with strength over 100MPa can still be obtained under natural curing condition.

1. Introduction

With the increasing demand for building new special structures and repairing damaged old engineering structures, the requirements for the strength of building materials are higher and higher. Ultra high performance concrete [1], referred to as UHPC, is proposed and manufactured under this demand. Bouygues successfully developed the first generation UHPC [2] for the first time. UHPC has excellent properties such as high strength, high ductility and high durability [3,4], and its compressive strength usually exceeds 100MPa. Different from ordinary concrete, UHPC only has fine aggregate and completely eliminates coarse aggregate. The addition of fine activated silica fume and low water cement ratio greatly reduce the internal defects of the material and obtain large tensile strength and excellent durability. At the same time, the addition of micro steel fiber enhances the toughness and ductility of the material. However, UHPC usually needs to be manufactured under standard curing and steam curing conditions to improve the compressive strength, which increases the manufacturing difficulty of this material and puts forward higher requirements for hardware facilities.

In order to simplify the manufacturing conditions of UHPC materials, the manufacturing method under the natural curing conditions is explored without accurately controlling temperature and humidity. The strength of UHPC under natural curing is improved by selecting the best water reducing...
agent, adjusting the proportion of silica fume and cement, and humidifying by simple watering method. The method proposed in this paper is helpful to reduce the manufacturing conditions of UHPC materials and promote the application of UHPC materials.

2. Experiment

2.1. Selection of manufacturing method

2.1.1 Proportion of silica fume
A certain amount of silica fume can improve the compaction and slump of concrete [5,6]. However, it will also lead to excessive reaction heat and internal cracks in concrete. Wang points out that the optimum ratio of silica fume to cement under steam curing condition is 0.3 [7]. Therefore, in order to obtain the best ratio of silica fume to cement under natural curing condition, the ratios were initially selected as 20%, 30% and 40% for experimental research. While the proportion of other materials remains unchanged.

2.1.2 Proportion of steel fiber
Lee [8] found that the steel fiber can improve the strength of UHPC. Wang [7] and Xu [9] found that the optimum steel fiber content under steam curing condition is 2%. Therefore, in order to obtain the optimum proportion of steel fiber under natural curing condition, the initial proportions of steel fiber are selected as 1%, 2% and 3%. While the content of other materials remains unchanged.

2.1.3 Selection of water reducing agent
Water reducing agent can improve the strength of concrete. In order to determine the appropriate water reducing agent, a group of comparative experiments under natural curing condition were carried out. As shown in table 1, the solid polycarboxylate superplasticizer can improve the workability of slurry, and increase the compressive strength of concrete.

| Block number | Type                        | Workability | Compressive strength |
|--------------|-----------------------------|-------------|---------------------|
| 1            | Liquid water reducer        | bad         | 78MPa               |
| 2            | Solid polycarboxylate       | good        | 101MPa              |

Table.1 Comparative experiment of different water reducing agent

2.1.4 Selection of ratio of water to binder
Low ratio of water to binder is the key factor to improve the strength of UHPC. Wan [10] found that with the increasing of the ratio of water to binder from 0.12 to 0.22, the compressive strength increases initially, and decreases later, while the proportion of steel fiber is kept as is 2%. When the ratio of water to binder is 0.18, the compressive strength of UHPC reaches a maximum. Therefore, the ratio of water to binder is determined as 0.18.
2.2. Selection of curing condition
There is strong correlation between the curing condition and the compressive strength of UHPC. Manning [11] found that the compressive strength of UHPC under steam curing condition exceeds the ultimate compressive strength under normal curing condition. Because during steam curing, the concrete is in a humid environment. It produces fewer cracks. However, steam curing also increases the difficulty of UHPC manufacturing. It limits the application of UHPC.

In the current experiments, the temperature is only the atmospheric temperature, the pressure is atmospheric pressure, and test sample is moisturized simply by watering or covered by wet cloth. Therefore, the curing condition is very simple and easier to be satisfied than the standard curing or steam curing. The comparative experiments of natural curing condition with watering and the natural curing condition only were carried out. The average temperature is about 25°C.

2.3. Manufacturing of UHPC specimens
During the manufacturing process of UHPC specimens, high uniformity is required for the distribution of various materials in the slurry. Wan [10] pointed out that mixing various materials in the concrete mixer first, mixing in the dry state, and then adding water for mixing is helpful to improve the uniformity of the slurry.

Therefore, the following steps were taken: (1) Placing cement, sand, silica fume and solid polycarboxylate superplasticizer in the mixer; (2) Stirring in the dry state to mix the materials for 1 minute; (2) Adding water and stirring for 2 minutes. (3) Adding 1% steel fiber and stirring for 30 seconds; (4) Adding another 1% steel fiber and stirring for 30 seconds; (5) Pouring the slurry into the standard mold, which has been daubed isolating agent (Fig.2). (6) Vibrating the slurry evenly. In above process, the steel fiber is added twice to make it evenly distributed. Table 2 shows the mixture ratio.

| Material Group | Group number | Cement | Sand | Water | Silica fume | Water reducer | Steel fiber |
|---------------|--------------|--------|------|-------|-------------|---------------|-------------|
| Different proportion of silica fume | A | 33.1 | | | | 6.6 | |
| | B | 30.5 | 41.6 | 14.6 | | 9.3 | 2 | 2 |
| | C | 28.4 | | | | 11.4 | |
| Different proportion of steel fiber | D | 31.5 | | | | 1 | |
| | E | 30.5 | 41.6 | 14.6 | | 9.3 | 2 | 2 |
| | F | 29.5 | | | | | 3 |

As shown in Table 2, six groups of UHPC specimens were manufactured according to different conditions, and there are 8 samples in each group. The test samples are placed in different curing environments for 28 days. There are 4 standard samples in each environment, then their compressive strength will be tested (Fig.3).

![Fig.2 The slurry is poured into the mold](image-url)
2.4. Analysis of the results

The experimental groups with different proportion of silica fume were numbered as S1, S2 and S3. The experimental group with different proportion of steel fiber were numbered as F1, F2 and F3. UHPC test samples in the same group are numbered in the order of a ~ h. The a/b/c/d blocks are placed under natural curing condition with watering, and the e/f/g/h blocks are placed under natural curing condition only. The average compressive strengths of each group of samples are shown in table 3 and table 4, and the results are plotted in Fig.4 and Fig.5.

### Table 3: Experiment of different content of silica fume

| Group number | Curing condition                     | Block numbers | Average compressive strength |
|--------------|--------------------------------------|---------------|------------------------------|
| S1           | Natural condition with watering      | S1a/S1b/S1c/S1d | 103                          |
|              | Natural condition only               | S1e/S1f/S1g/S1h | 83                           |
| S2           | Natural condition with watering      | S2a/S2b/S2c/S2d | 109                          |
|              | Natural condition only               | S2e/S2f/S2g/S2h | 94                           |
| S3           | Natural condition with watering      | S3a/S3b/S3c/S3d | 101                          |
|              | Natural condition only               | S3e/S3f/S3g/S3h | 82                           |

### Table 4: Experiment of different content of steel fiber

| Group number | Curing condition                     | Block number | Average compressive strength |
|--------------|--------------------------------------|--------------|------------------------------|
| F1           | Natural condition with watering      | F1a/F1b/F1c/F1d | 105                          |
|              | Natural condition only               | F1e/F1f/F1g/F1h | 90                           |
| F2           | Natural condition with watering      | F2a/F2b/F2c/F2d | 109                          |
|              | Natural condition only               | F2e/F2f/F2g/F2h | 94                           |
| F3           | Natural condition with watering      | F3a/F3b/F3c/F3d | 112                          |
|              | Natural condition only               | F3e/F3f/F3g/F3h | 96                           |

Fig.3 Measurement of compressive strength

Fig.4 Different proportion of silica fume
As shown in Fig. 4, the compressive strength of the test sample of group 2 is higher than other two groups. The ratio of silica fume to cement in group 1, group 2 and group 3 is 20%, 30% and 40%, respectively. This phenomenon indicates that with the increase of ratio of silica fume to cement, the compressive strength of UHPC test block increases firstly, and then decreases. The reason may be that the appropriate proportion of silica fume can improve the compactness of concrete and then improve the strength of concrete, but too much silica fume will cause excessive heat generation during hydration of concrete slurry, resulting in cracks in the test block and affecting the strength of concrete. And as shown in Fig.5, with the increasing of the proportion of steel fiber, the compressive strength of UHPC samples improves slowly. It shows that a more steel fiber can improve the compressive strength of UHPC under natural curing condition. But more steel fiber means an increase in cost, and it should be controlled within an appropriate range.

As shown in the Fig.4 and Fig.5, the compressive strength of UHPC test samples can reach 109MPa under natural curing condition with watering. It meets the requirement of material strength in most civil engineering application. And the strength of watered UHPC samples is higher than that of non-watered test samples. It indicates that high humidity promotes the growth of UHPC strength.

3. Conclusion
The manufacturing method of UHPC under the natural curing condition without accurately controlling temperature and humidity is presented, the results are shown as follows.

(1) In natural curing condition, humidification by simple watering can be used to improve the compressive strength of UHPC.

(2) The addition of solid polycarboxylate superplasticizer can make the UHPC blocks have higher compressive strength than liquid water reducer.

(3) When the ratio of silica fume to cement is appropriate, the compressive strength of UHPC reaches the maximum.

(4) UHPC with strength over 100MPa can still be obtained under natural curing condition, that meets the requirement of material strength in most civil engineering application.

Acknowledgments
This work has been supported by the Natural Science Foundation of Zhejiang Province (LY19E080009), the Comprehensive Insurance for Country Road in Haishu District of Ningbo City, and Ningbo Transportation Science and Technology Project (202104).

References
[1] Zhao Yun, Lian Huizhen, Jin Jianchang. (2013) A new model of steel-concrete composite-Ultra High Performance Concrete (UHPC/UHPFRC). J. Concrete world, 10: 56-69.
[2] Ma Jian, Sun Shouzeng, Yang Qi. (2021) Summary of academic research on Bridge Engineering in China. J. Chinese Journal of highway, 34(2):97.
[3] Zhang Yunsheng, Zhang Wenhua, Chen Zhenyu. (2017) A Complete Review of Ultra-high Performance Concrete: Design and Preparation Microstructure, Mechanics and Durability, Engineering Applications. J. Materials Reports, 32(23): 1-16.

[4] Chen Baochun, Ji Tao, Huang Qingwei, Wu Huazhong, Ding Qingjun. (2014) Review of Research on Ultra-high Performance Concrete. J. Journal of Architecture and Civil Engineering, 31(03): 1-24.

[5] He Xiaofang, Lu Juntai, Li Xiaonan, Qing Peiliang, Cao Xinxin. (2013) Progress in Research of Effect of Silica Fume on the Performance of Cement Concrete. J. Bulletin of the Chinese Ceramic Society, 32(03): 423-428.

[6] Chen Baochun, Li Cong, Huang Wei, An Mingzhe, Han Song. (2018) Review of ultra-high performance concrete shrinkage. J. Journal of Traffic and Transportation Engineering, 18(01): 13-28.

[7] Wang Dehui, Shi Caijun, Wu Linmei. (2016) Research and Applications of Ultra-High Performance Concrete (UHPC) in China. J. Silicate bulletin, 35 (1): 142-149.

[8] Lee Ming-Gin, Lee Kun-Long, Tia Mang. (2013) UHPC precast product under severe freeze-thaw conditions. C. China: Chinese Society of Theoretical and Applied Mechanics.

[9] Xu Haibin. (2015) Research on the performance of HRB500 bars reinforced prestressed ultra-high performance concrete beams. D. Beijing University of technology, 1-164.

[10] Wan Chaojun. (2016) Preparation of ultra-high performance concrete. J. Silicate bulletin, 35 (1): 141-149.

[11] Manning Mark P, Giesler Andrew J, Weldon Brad D, Jauregui David V, Newtson Craig M. (2015) Early-age compressive and tensile strength gain of a locally developed UHPC. C. Geneva: International Association for Bridge and Structural Engineering.