

Research on the Mechanical Properties of Economical UHPC and Application in UHPC-NC Slabs

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Abstract

In this study, an economic ultra-high performance concrete (UHPC) fabrication process is proposed and the mechanical properties are investigated. In order to better promote it in engineering projects, finite element analysis is conducted on ultra-high performance concrete-normal concrete (UHPC-NC) composite slabs and a normal concrete (NC) slab. By comparing UHPC-NC composite slabs with NC slabs of the same size, the flexural properties are derived and guidance is given for the further optimization of UHPC-NC floor slabs, so that the ultra-high-performance concrete can be used reasonably and efficiently for the promotion of engineering applications.

Keywords

Ultra-high performance concrete; Mechanical properties; UHPC-NC composite slabs; Flexural properties.

1. INTRODUCTION

Ultra-high performance concrete (UHPC) exhibits superior mechanical properties compared to conventional concrete (NC). With the current fabrication technology, its compressive and tensile strengths are able to reach more than 150 MPa and 10 MPa, respectively [1-5], which means that it is able to withstand higher pressures and tensile forces. In addition, the toughness of UHPC can be further enhanced by incorporating an appropriate volume of steel fibers so that it can better absorb energy and maintain structural integrity when subjected to external forces. Despite the excellent mechanical properties of UHPC, its material cost is high, and the market price is about ten to twenty times or even higher than that of ordinary concrete [6]. Therefore, the application of UHPC in practical engineering is still limited, and how to reasonably and effectively utilize UHPC is still a hot topic. In order to reduce the cost of UHPC and promote its wide application in engineering, scholars and research institutions at home and abroad have carried out a large number of related research work, which mainly focuses on reducing the cost of raw materials used and innovative preparation process [7]. Through the use of crushed stone to replace part of the quartz sand, the use of other cementitious materials to replace part of the cement dosage and other methods can reduce the material cost of UHPC to a certain extent; at the same time, through the pre-fabricated components, assembled components and other methods can be carried out in the mechanical properties and economic aspects of research, so as to achieve the maximization of the overall benefit of construction.

The load-bearing capacity and plasticity of structures are crucial factors in structural design, and their importance is self-evident [8]. Over the years, there have been numerous serious safety accidents such as house collapses caused by insufficient load-bearing capacity, however, for the new material UHPC, there is still a relative lack of research on structural design, especially in composite components, and the structural design system of UHPC-NC composite slabs has not yet been formed. This undoubtedly brings certain challenges and limitations to the application of UHPC in actual projects. With the emphasis on green development and technological innovation in the industry, how to better utilize UHPC has become a pressing issue in the current industry. This study aims to reduce the cost of research and development materials while the combined floor slabs can also maintain better flexural performance.

2. PREPARATION PROCESS OF UHPC AND MECHANICAL PROPERTIES OF MATERIALS

2.1. Preparation of UHPC

In this paper, the raw materials for making UHPC are described as follows:

Cement: 52.5 MPa ordinary silicate cement from the building materials market is used, and the main performance indexes are shown in Table 1.

Silica fume: choose powdered silica fume, the average particle size is less than 0.2 μm , other performance parameters are shown in Table 2.

Fine aggregate: low-priced river sand is used instead of quartz sand, which greatly reduces the production cost, the maximum particle size is within 0.6 mm, and the mud content is about 0.1%. Before mixing, it is necessary to use a sieve to remove debris such as shells and soil with a pore size of 0.075 mm or less.

High-efficiency water reducing agent: domestic powdered polycarboxylic acid high-efficiency water reducing agent is selected, and its related technical parameters are shown in Table 3.

Steel fiber: choose the market price is low, simple shape of short fine smooth copper-slabd steel fiber, its main performance parameters: tensile strength of 2660 MPa, flexural strength of 203 GPa, length 13 mm, diameter 0.2 mm.

The specific mixing ratio of UHPC production is shown in Table 4.

In order to make the distribution of steel fibers more uniform during the mixing process, half of the volume content of steel fibers and other materials were first poured into the mixing drum for about 4 minutes of dry mixing, and then the remaining steel fibers were poured into the mixing drum for about 5 minutes while adding water for mixing. According to ASTM C666/C666M-1 [9], the flow test was conducted, and the flow of UHPC reached about 25 cm after 25 vibrations within 15 s. The wet material after mixing was poured into the mold and vibrated on the vibration table for about 10 s. Too long a time will lead to the deposition of fibers at the bottom of the specimen, resulting in non-uniform performance of the specimen. The specimens were then placed in a standardized room with a temperature of $20 \pm 0.5^\circ\text{C}$ and a humidity of more than 95% for 48 hours before being demolded and continued to be conditioned.

Table 1. Mechanical property indexes of common silicate cement

Fineness	Compressive Strength (MPa)		Flexural Strength (MPa)		Loss on Ignition
	3 d	28 d	3 d	28 d	
<10%	22	52.5	4.0	7.0	<5.0%

Table 2. Silica fume performance parameters

SiO ₂	Cl ⁻	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	K ₂ O	H ₂ O	Loss on Ignition	granularity
>92%	<0.02%	<1.0%	<1.0%	<1.0%	<1.2%	<1.2%	<3.0%	<6.0%	<6.0%

Table 3. Technical parameters of polycarboxylic acid high-efficiency water reducing agent

Bulk Density (g/L)	Active Ingredient	Residual Moisture	pH Value	Mortar Water Reduction Rate
500-700	≥90%	≤3%	6.0-8.0	≥21%

Table 4. UHPC mixing ratio (kg/m³)

Clinker	Silica Fume	River Sand	Water	Water Reducing Agent (powder)	Steel Fiber
890	157	934	193	10.47	140



Figure 1. UHPC fluidity test

2.2. Mechanical properties of UHPC

After 28 days of maintenance, compression as well as tensile tests were done on the UHPC specimens. The compressive strength value of this economical UHPC reached 129.3 MPa, which is the the domestic specified strength requirement (120 MPa) for ultra-high performance concrete [10]. In order to better enable UHPC to play a role in flexural specimens, more attention is paid to its tensile strength and material ductility, the tensile strength of this economic UHPC reaches 8.6 MPa, which can be seen in Figure 4 from the high tensile strength, but also reflects a very good ductility.

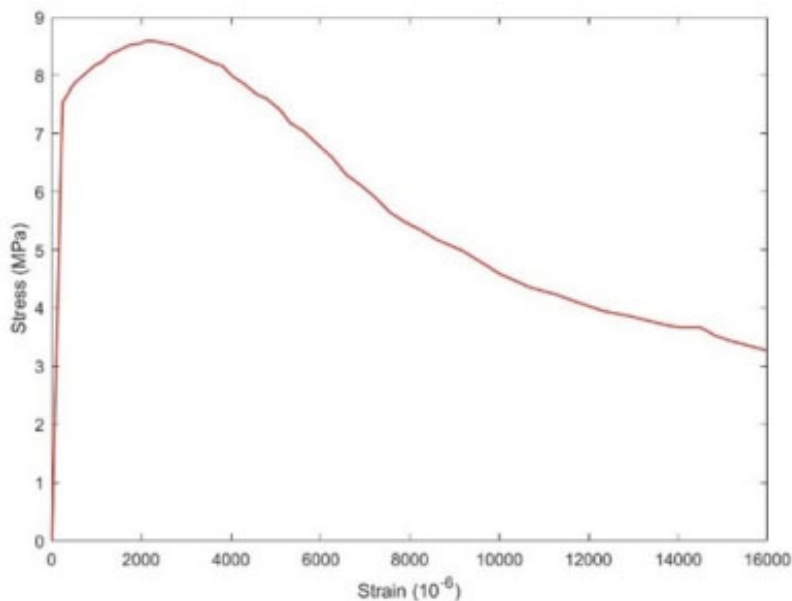


Figure 2. Direct tensile stress-strain curve of UHPC

3. FLEXURAL PERFORMANCE ANALYSIS OF UHPC-NC COMPOSITE SLABS

This section uses Abaqus software to carry out finite element analysis, the proposed specimen size of 4000mm×2000mm×140mm, in which the thickness of the bottom layer of UHPC is 40mm, and the longitudinal reinforcement of HRB400 is used for the stress, which is arranged in the layer of UHPC at a spacing of 200mm. The displacement-controlled three-point flexural loading is used to conduct comparative analysis of different reinforcement forms in order to study the change rule of its bearing capacity as well as ductility, and the specimen modeling is shown in Fig. 3.

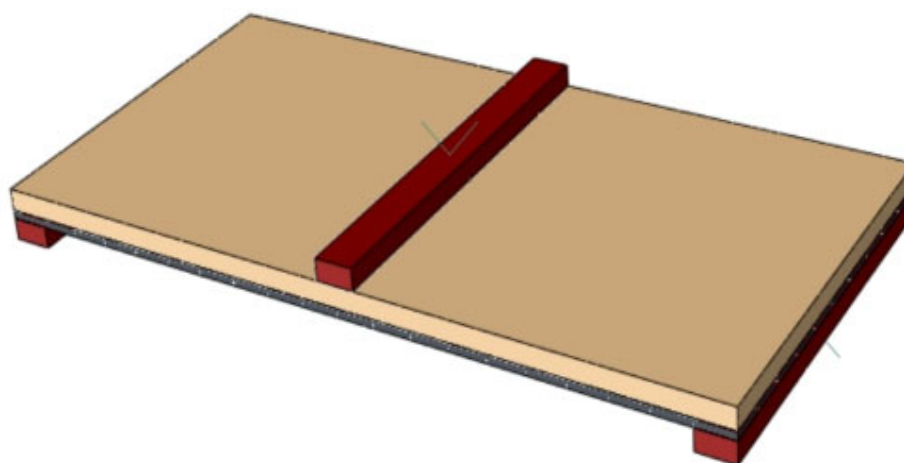


Figure 3. Specimen modeling

In order to compare and analyze the UHPC-NC slab and pure NC slab more intuitively, pure NC slab of the same size was also modeled and analyzed in this study, and the data were extracted and the load-displacement curves were plotted, as shown in Fig. 4

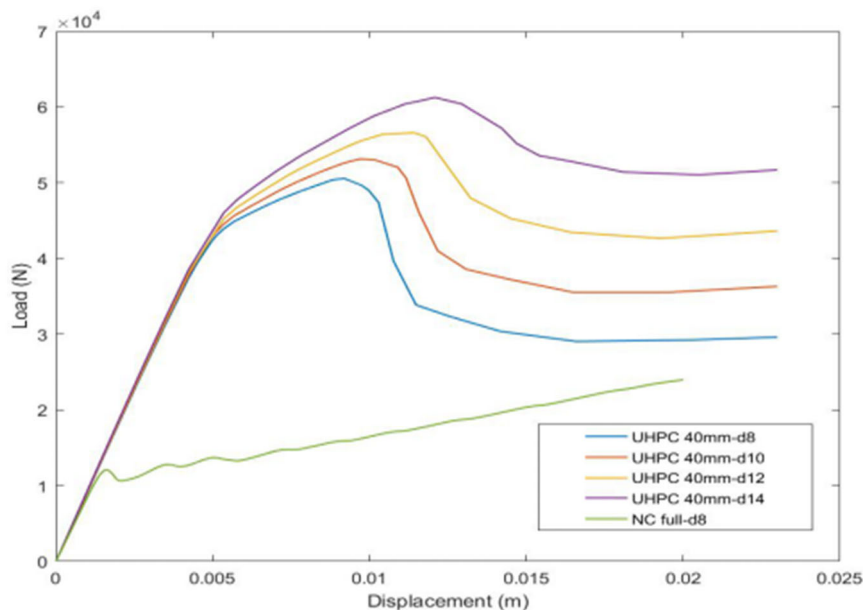


Figure 4. Load-displacement curve

As can be seen from the results of the analysis in Figure 4, the composite slab reinforced with UHPC layer is significantly improved in load carrying capacity compared to the NC slab. And has sufficient safety reserves (protruding part), but also through the finite element analysis can be concluded: (1) When the diameter of the reinforcement 8mm, UHPC-NC slab, although the load carrying capacity of the obvious enhancement, but also showed obvious brittleness, which means that the traditional sense of the minimum reinforcement rate requirements are not applicable to UHPC-NC or UHPC flexural specimens, but even so, the specimen is also better than the NC slab in terms of load bearing capacity in the smooth section after the falling section.(2) When the load carrying capacity increases as the reinforcement rate increases the ductility of the specimens also improved, which indicated that the ability of the reinforcement and UHPC layers to work together improved.

4. CONCLUSION

From the above material performance tests and finite element analysis it can be concluded that:

1. Economic UHPC has good working performance, and compressive strength, tensile strength are up to standard, have good toughness, suitable for reinforcement, strengthen and other engineering fields.

2. UHPC and reinforcing steel synergistic working ability is still to be studied, and to find a reasonable UHPC-NC and UHPC flexural specimens of the minimum reinforcement rate is also very worthy of study, which will be more favorable to guide the engineering practice and accelerate the popularization of the use of UHPC in engineering applications.

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