Mixture design, Preparation and Properties of Lightweight Ultra-high Performance Concrete (LUHPC)

Jing Wu* (corresponding author) –Associate Professor, Wuhan Textile University, State Key Laboratory of New Textile Materials & Advanced Processing Technology, School of Material Science and Engineering, Wuhan 430200, China, Phone: 8613476233919, Email: wujing313@whut.edu.cn

Qingjun Ding* (corresponding author) – Professor, Wuhan University of Technology, State Key Laboratory of Silicate Materials for Architectures, Wuhan 430070, China, Phone: 8613720287278, Email: dingqj@whut.edu.cn

Yongqiang Liu – Graduate student, Wuhan University of Technology, School of Material Science and Engineering, Wuhan 430070, China, Email: 11423625@qq.com

Junshuai Mei – Graduate student, Wuhan Textile University, School of Material Science and Engineering, Wuhan 430200, China, Email: 13183204638@163.com

Gaozhan Zhang – Anhui Jianzhu University, School of Materials and Chemical Engineering, Hefei, 230601, China, Email: gaozhanzhang@126.com

Abstract:

In this study, the natural river sand was completely replaced by high strength lightweight sand (LWS) to reduce the density of ultra-high-performance concrete (UHPC). The mixture design and preparation method of lightweight ultra-high performance concrete (LUHPC) was studied based on the principles of particle compaction skeleton stacking and fiber toughening. The P. II 52.5 cement, silica fume and fly ash cenosphere were used as the cementitious materials, and the fine steel fiber was used to improve the mechanical strength and flexural toughness of LUHPC. The effects of the proportion of cementitious materials, water-to-binder ratio (W/S), binder-to-sand ratio (B/S) and steel fiber content on the mechanical key properties of LUHPC were discussed. Results showed that the LUHPC had ultra-high performance and low density (lower than 2090 kg/m^3). The microhardness and microstructure analyses of the interface zone between cement matrix and sand indicate a dense transition zone is produced in the presence of pre-saturated lightweight sand, which resulted in the highest compressive strength (114.5 MPa at 28d), flexural strength (16.8 MPa at 28d), and high bending toughness index I_{20} (21.2).

Keywords: Mixture design, Lightweight, Preparation, Strength, Density, Microhardness

1. Introduction

Ultra-high performance concrete (UHPC) has high compressive strength, flexural strength and good durability, so it has unique advantages in large bridge engineering, special engineering, marine engineering construction and other fields [1-3]. In the previous study, it is found that the mechanical properties of high performance concrete composed of river sand are excellent, but the apparent density of it is too high [4]. By a large number of statistical calculations, the apparent density of the ultra-high performance concrete composed of river sand is about 2500-2600 kg/m^3, which affect its application in some special constructions, such as high-rise buildings, long-span bridges and prefabricated construction. Therefore, the collaborative design method of high strength and light weight is a key problem need to be investigated in the development of UHPC. The raw materials of UHPC mainly include high quality cement, superfine mineral admixture, fine aggregate and steel fiber, etc. [5]. On the premise of ensuring the strength and durability of UHPC, high strength lightweight aggregate is adopted to replace river sand to reduce the density of UHPC, and the lightweight ultra-high performance concrete (LUHPC) will be obtained.

In this paper, referring to the design method of UHPC, high strength lightweight ceramic sand (LWS) was used to replace river sand, and cement, silica fume and fly ash cenosphere are used as cementitious materials to prepare LUHPC. The effect of these parameters on the working and mechanical properties of concrete samples were discussed.

2. Background

Concrete is multiphase composite material, composed of cement matrix continuous phase and aggregate dispersed phase. Generally, according to continuous phase and dispersed phase, it can be divided into composite hard base material and composite soft base material [4]. The elastic modulus (E_a) of river sand and quartz sand aggregate in UHPC is higher than that of cement matrix (E_m), which can be regarded as composite soft base material. The LUHPC proposed in this paper is composed of lightweight aggregate dispersion phase and cement matrix continuous phase, and the elastic modulus of lightweight ceramic sand is lower than that of matrix-matrix, so LUHPC can be regarded as composite hard base material. Therefore, the amount and distribution of ceramic sand in cement matrix has an important influence on the performance of LUHPC. The initial mix proportion design of LUHPC should be mainly based on the aggregate composition design. For the concrete which normal aggregate partially is replaced by lightweight aggregate, its elastic modulus meets the Eq. (1):

$$E = E_{NA} E_{LC} / [E_{NA} - V_{NA} (E_{NA} - E_{LC})] \tag{1}$$

Where V_{NA} represent the absolute volume of ordinary aggregate in concrete (%). E, E_{NA} and E_{LC} represent the elastic modulus of concrete, ordinary aggregate and pure lightweight aggregate concrete, respectively. It can be seen from Eq. (1) that the elastic modulus of concrete gradually decreases with the increase of the volume dose of lightweight aggregate replacing ordinary aggregate. Thus, the mixture design, preparation and properties of LUHPC are different with UHPC.

2. Experiment

2.1. Raw Materials

The P. II 52.5 cement (C) produced by Huaxin Cement Co., Ltd, and its specific surface area and Standard consistency water consumption are 385 m^2/kg and 26.7%, respectively. Fly ash cenosphere (FA) and Silica fume (SF) were used as mineral admixtures in this study, with a specific surface area of 1300 and 19500 m^2/kg, respectively. The chemical composition of C, FA and SF are shown in Table 1. Solid content and water reducing ratio of polycarboxylic acid superplasticizer are 18% and 28%, respectively. Tap water was used for mixing concrete.

Table 1. Chemical Composition of Cement and Mineral Admixtures (wt. %)

sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Loss
cement	22.57	6.88	3.13	60.58	2.46	2.73	0.56	0.14	0.95
FA	58.50	32.40	3.01	1.60	0.53	0.33	1.72	0.42	1.22
SF	96.34	0.61	0.16	0.54	0.25	0.13	0.21	0.08	1.68

Steel fiber produced by Wuhan new way engineering new material technology Co., Ltd, and nominal length is 13 mm, equivalent diameter is 0.3 mm, breaking strength is about 1800 MPa and elastic modulus is about 52 GPa.

The high strength lightweight sand (LWS) produced by Yichang Langtian building material Co., Ltd, the particle size distribution range is 1-5mm continuous grading, the cylinder compressive strength is 6.2 MPa, the saturated water absorption rate at 24 h is 16.0%, the bulk density and apparent density are 745 kg/m^3 and 1725 kg/m^3, respectively.

Figure 1. The Fine Steel Fiber

Figure 2. The High Strength Lightweight Sand

2.2. Experimental Method

2.2.1 Initial Mix Proportion Design of LUHPC

Based on the principles of particle compaction skeleton stacking and fiber toughening, the initial mix proportion of LUHPC was designed: The percentage of cement, silica fume and fly ash cenosphere in cementitious materials were 67%, 14% and 19%, respectively. The binder-sand ratio and water-binder ratio were designed as 1.8 and 0.2, respectively. The lightweight sand was pre-wetted in water for 24h, and water-binder ratio includes the water in the pre-saturated lightweight sand. The steel fiber content was 2%. On the basis of the initial mix proportion ratio, LUHPC was prepared by adjusting the composition of the cementitious material, binder-sand ratio (B/S), water-binder ratio (W/B) and steel fiber content.

2.2.2 Mixing Procedure

The cementitious materials and lightweight sand were dry mixed for 90 seconds with low mixing rate of 140 r/min. The 80% mass of mixing water with superplasticizer was added into the dry mixtures, and the blender was ceased for 60 seconds. Then, the last 20% water and superplasticizer were added into the blender and blended for an extra 120 seconds with a high mixing rate of 280 r/min.

2.2.3 Test Method

Workability of the designed concrete was measured following EN 1015 [6]. The fresh LUHPC paste was cast into 100×100×100 mm mold for compressive strength, 100×100×300 mm for flexural strength, and 100×100×400 mm four points bending experiments. The microhardness of interfacial transition zone (ITZ) was tested by HVS-1000 Vickers microhardness tester.

3. Results and Discussions

3.1. The Influence of Cementitious Material Composition on the Performance of LUHPC

Table 2. Mix Proportion and Properties of LUHPC with Different Cementitious Material Composition

LUHPC mix proportion							LUHPC properties				
							Flowability /mm		Compressive strength /MPa		
No.	Cement	FA	SF	B/S	W/B	Steel fiber	Slump flow	Slump	3d	7d	28d
L-1	70%	16%	15%	1.8	0.20	2.0%	655	245	57.1	66.5	73.4
L-2	69%	17%	15%	1.8	0.20	2.0%	665	255	53.2	64.3	70.5
L-3	67%	19%	14%	1.8	0.20	2.0%	670	265	48.4	56.3	69.7
L-4	67%	17%	16%	1.8	0.20	2.0%	655	250	58.8	65.1	78.5
L-5	67%	16%	17%	1.8	0.20	2.0%	645	245	62.2	72.6	81.0

It can be seen from Table 2 that the working performance of LUHPC increase with increasing the dosage of fly ash cenosphere, which because of the ball effect of fly ash cenosphere. When the fly ash cenosphere dosage accounts for 19% of the total cementing material, the slump flow and slump of newly mixed LUHPC is 670 and 265mm, respectively. Meanwhile, there was a slight bleeding phenomenon on the surface of the mixture, indicating that the fly ash cenosphere plays a good role in reducing water. It can be found from the compressive strength that, with the increase of the dosage of fly ash cenosphere, the 3d compressive strength of LUHPC is 57.1MPa, 53.2MPa and 48.4MPa, respectively, and the compressive strength all decreases. With the extension of the curing time, the compressive strength at 7d~28d increases significantly, indicating that the pozzolanic reaction of mineral admixtures promotes the development of strength.

Due to the high pozzolanic activity of silica fume, it has a great promoting effect on the strength development of concrete. It can be seen from the Table 2, with the increase of silica fume content, the working performance of LUHPC mixture is reduced, but its cohesion and inclusion performance are gradually improved. When silica fume content reaches 17%, the slump flow and slump is 645 and 245mm, respectively. Therefore, considering the influence of the composition of cementitious materials on the working performance and mechanical properties of LUHPC comprehensively, it is determined that cement, fly ash cenosphere and silica fume account for 67%, 16% and 17% of the total cementitious materials, respectively.

3.2. The Influence of Water-binder Ratio on the Performance of LUHPC

The ultra-low water-binder ratio is the key factor for preparing UHPC. Therefore, it is necessary to study the influence of water-binder ratio on the working performance and mechanical properties of LUHPC.

Table 3. The Mixture Proportion Ratio and Performance of LUHPC with Different Water-binder Ratio

LUHPC mix proportion							Performance of LUHPC				
							Flowability /mm		Compressive strength /MPa		
No.	Cement	FA	SF	B/S	W/B	Steel fiber	Slump flow	Slump	3d	7d	28d
L-6	67%	16%	17%	1.8	0.17	2.0%	575	200	80.3	92.7	102.4
L-7	67%	16%	17%	1.8	0.18	2.0%	610	210	77.4	88.5	96.2
L-8	67%	16%	17%	1.8	0.19	2.0%	620	225	71.3	81.4	89.5
L-9	67%	16%	17%	1.8	0.20	2.0%	645	245	62.2	72.6	81.0

It can be seen from Table 3, the working performance of LUHPC decreases with the decrease of water-binder ratio. When the water-binder ratio is 0.17, the slump flow and slump of fresh concrete are only 575 and 200mm, respectively, which is significantly worse than that of the samples with a water-binder ratio of 0.18. According to the analysis of mechanical properties, with the decrease of water-binder ratio, the compressive strength of LUHPC at all ages increases gradually. Considering the influence of water-binder ratio on the working performance and mechanical properties of LUHPC, the water-binder ratio was determined to be 0.18.

3.3. The Influence of Binder-sand Ratio on the Performance of LUHPC

As can be seen from Table 4, with the increase of binder-sand ratio, the working performance of LUHPC gradually improves, but the compressive strength first increases and then decreases. When the binder-sand ratio is 1.9, the compressive strength of samples at 3, 7 and 28d are 80.2, 94.3 and 105.2 MPa, respectively. The apparent density of LUHPC increase with the increase of binder-sand ratio, when the binder-sand ratio is 1.9 and 2.0, the apparent density is 2045 and 2105 kg/m^3, respectively. Considering the influence of binder-sand ratio on the working performance, mechanical properties and apparent density of LUHP, it is advisable to determine the binder-sand ratio of 1.9.

Table 4. The Mixture Proportion Ratio and Performance of LUHPC with Different Binder-sand Ratio

LUHPC mix proportion							Performance of LUHPC					
							Flowability /mm		Compressive strength /MPa			Apparent density /kg/m^3
No.	Cement	FA	SF	B/S	W/B	Steel fiber	Slump flow	Slump	3d	7d	28d	
L-10	67%	16%	17%	1.7	0.18	2.0%	600	205	72.3	85.1	92.0	1950
L-11	67%	16%	17%	1.8	0.18	2.0%	610	210	77.4	88.5	96.2	2008
L-12	67%	16%	17%	1.9	0.18	2.0%	625	225	80.2	94.3	105.2	2045
L-13	67%	16%	17%	2.0	0.18	2.0%	640	240	79.5	94.8	103.4	2105

3.4. The Influence of Steel Fiber on the Performance of LUHPC

Table 5. Performance of LUHPC with Different Steel Fiber Content

No.	Steel fiber	Flowability /mm		Compressive strength /MPa			Flexural Strength /MPa			Bending toughness index I_{20}	Apparent density /kg/m^3
		Slump flow	Slump	3d	7d	28d	3d	7d	28d		
L-14	1.0%	650	240	72.3	86.0	94.8	8.8	9.4	10.2	13.6	1958
L-15	1.5%	635	230	78.1	90.1	100.6	9.1	10.3	11.7	16.1	2105
L-16	2.0%	625	225	80.2	94.3	105.2	12.6	13.2	14.8	18.3	2045
L-17	2.5%	610	210	85.7	97.6	114.5	14.5	15.3	16.8	21.2	2085
L-18	3.0%	575	205	86.8	98.5	116.9	15.1	15.9	17.5	23.8	2136

Figure 3. Load-deflection test

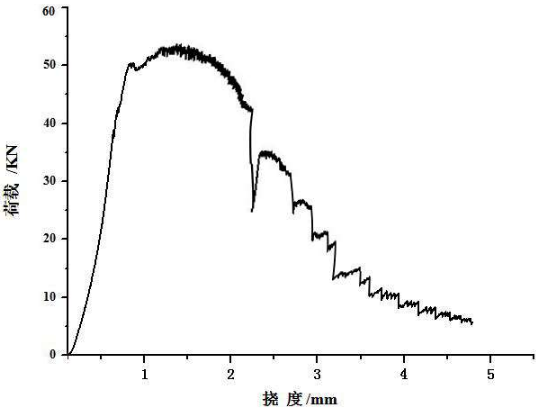

Figure 4. Load-deflection Curve of L-17

The uniform dispersion of steel fiber in concrete is the key factor affecting the mechanical performance of LUHPC. In the mixing process of LUHPC, the cementitious material and ceramic sand were mixed firstly and evenly, and then 80% water and superplasticizer were added. When the slurry with a certain fluidity was formed, then steel fiber, the remaining water and superplasticizer were added finally. The workability of fresh concrete was good and no agglomeration of steel fibers was found.

It can be seen from table 5, with the increase of steel fiber content, the working performance of LUHPC deteriorate gradually, the reason is the friction resistance reduce the flowability of concrete. However, the compressive, flexural strength and bending toughness of LUHPC are improved by steel fiber. When the steel fiber content is 3.0 %, after curing for 28 days, its compressive strength and flexural strength are 116.9 and 17.5 MPa, respectively, and bending toughness index I_{20} is up to 23.8. Fig. 4 is the Load-deflection curve of the sample of L-17, which shows that the toughness of LUHPC is good. The destruction of concrete caused by the internal stress concentration will lead to the propagation of microcracks and destroy the concrete finally. The introduction of steel fiber changes the destruction form of concrete, and the concrete will be cracked rather than shatter into bits [7].

Due to the density of steel fiber is bigger than other components of concrete, the apparent density of LUHPC increases with increasing steel fiber content. When the content of steel fiber is 3.0 %, the apparent density of LUHPC reaches 2136 kg/m^3. Considering the influence of steel fiber on the working performance, mechanical properties and apparent density of LUHPC, the volume content of steel fiber should not be more than 2.5%. After curing for 28 days, the compressive and flexural strength are 114.5 and 16.8 MPa, the bending toughness I_{20} is up to 21.2, and the apparent density is only 2085 kg/m^3.

3.5. Microstructure Analysis

The microstructure and microhardness analyses of the interface zone between cement paste and sand indicate a dense transition zone is produced in the presence of pre-saturated lightweight sand, which resulted in the excellent properties.

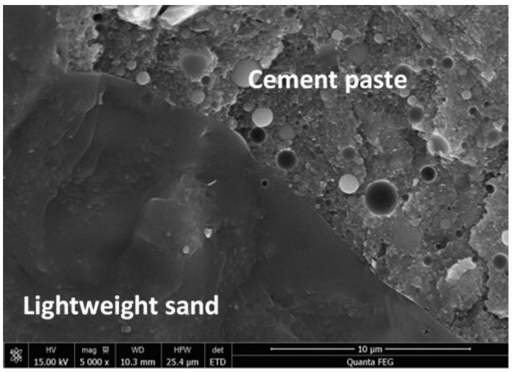

Figure 5. SEM of ITZ in LUHPC

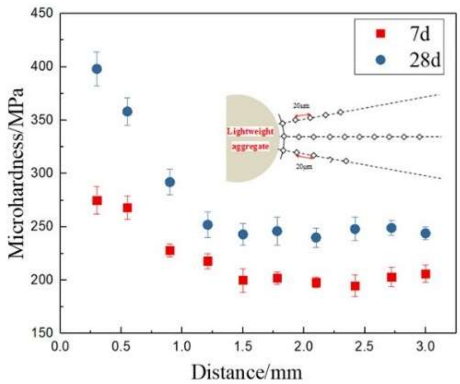

Figure 6. Microhardness of ITZ in LUHPC

Fig. 5 shows the microstructure of interfacial transition zone (ITZ) between cement matrix and lightweight ceramic sand in LUHPC. Fig. 6 shows microhardness of ITZ in LUHPC. It can be seen from Fig. 5 and 6 that, the internal curing effect of pre-saturated lightweight sand promotes the hydration degree of the cementitious material and the microhardness of the ITZ [8,9], forming a dense and high-strength interface zone around the aggregate.

4. Conclusion

(1) The mixture design and preparation method of LUHPC was proposed. The appropriate proportion of P. II 52.5 cement, fly ash cenosphere and silica fume that account for the total cementitious materials are 67 %, 16 % and 17 %, respectively.

(2) When the water-binder ratio is 0.18, the binder-sand ratio is 1.9, and the volume content of steel fiber is 2.5%, the compressive and flexural strength of LUHPC at 28 days are up to 114.5 and 16.8 MPa, respectively, bending toughness I_{20} is 21.2, and apparent density is only 2085 kg/m^3.

(3) The addition of pre-saturated high strength lightweight sand not only reduce the apparent density of UHPC, but also provide internal curing effect to improve the microhardness of interface zone in LUHPC.

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