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Preparation of Ultra-High Performance Concrete with common technology and materials

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ABSTRACT

The technology development of concrete and demand for high strength construction materials give momentum to the development of Ultra-High Performance Concrete (UHPC). Current UHPC preparation methods require costly materials and relatively sophisticated technology. To overcome these weaknesses, this paper focused on the preparation of UHPC with common technology and ordinary raw materials. Influence of binder content, water/binder ratio, ground granulated blastfurnace slag (GGBS) content, and limestone powder (LP) replacement on fluidity and compressive strength of concrete were researched, respectively. The test results show that the addition of superplasticizer and fine mineral additives enabled the UHPC to be produced at an extremely low water/binder ratio of 0.14–0.18, achieving excellent workability with a maximum slump of 268 mm and compressive strengths of 175.8 MPa at 90 d and 182.9 MPa at 365 d.

1. Introduction

The demand for high strength construction materials is the force behind the development of Ultra-High Performance Concrete. Bouygues was the first to start research in Reactive Powder Concrete, a kind of UHPC from 1990 to 1995 [1]. The pre-stressed hybrid pedestrian bridge at Sherbrooke in Canada completed in 1997 was the first engineering structure application of UHPC [1,2]. In 1997 and 1998, UHPCs were cast in beams of Cattenom and Civaux power plants as the first industrial application [1]. The first UHPC road bridge was designed and constructed at Bourg-lès-Valence in France in 2001 [1,3]. More recently, Nguyen Viet Tue [4] has researched the application possibilities for steel tubes filled with UHPC. The preparation and performance of UHPC have been investigated in other literatures [5–8].

Ultra high performance concrete is characterized primarily with high strength, and when it is reinforced with steel fibers or steel tubes, exhibits high ductility. However, the strength of UHPC is the crux of its preparation, though it must be supported by ductility. For example, RPC, a type of UHPC, is distinguished by its compressive strengths ranging between 200 MPa and 800 MPa after pressure and heat treatment, depending on the mixture proportions and the temperature of the heat treatment applied before and during its setting [9]; and Ductal®, a commercial RPC, demonstrates a compressive strength of approximately 150 MPa [10]. Therefore, how to improve the strength of a UHPC remains a key factor in the development of UHPC preparations. As an initial research into the preparation of UHPC with common technology and widely available materials, this research focused on the strength and workability of the concrete, while ductility will be considered in our later experiments.

Currently, to achieve excellent mechanical behavior, some special techniques and raw materials must be adopted in the preparation of UHPC, which include:

(a) Coarse aggregate is removed to enhance the homogeneity of concrete.
(b) Metal fiber or steel tube is introduced to improve ductility of composites.
(c) High quality superplasticizer and large quantities of superfine silica fume and quartz are added, to achieve a low water/binder ratio to reduce porosity and improve strength.
(d) Pressure may be applied before and during the setting to increase the compactness of the concrete.
(e) High activity micro-silica and/or precipitated silica may be mixed into cementitious materials to accelerate the hydration of cement and catalyze a strong pozzolanic reaction effect.
(f) Steam curing may be supplied to gain higher strength.

In short, to gain the desired strength of a UHPC, well-chosen raw materials and sophisticated technical procedures are conventionally required, which makes it too costly to meet the demand of large-scale project engineering. Therefore, it is of great significance to find appropriate ways to obtain the strength of UHPC cheaply.

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It would be desirable for UHPC to possess high fluidity performance to satisfy the pouring and compaction at the construction site. Previous engineering projects of UHPC, such as the Sherbrooke footbridge in Canada, the Seonyu footbridge in Korea, the Shawnessy tramway station in Canada, and the beams of Cattenom and Civaux power plants used mostly prefabricated concrete [1]. Only a few fresh UHPCs have been cast in place at the project site.

In this investigation, UHPC with good workability and a target compressive strength greater than 150 MPa was prepared with common technology and materials, especially without the removal of the coarse aggregate.

2. Experiment

2.1. Technical foundations for the preparation

In this study, the guidelines for preparing UHPC include the following: (a) common and easy to obtain raw materials and (b) no special machine nor special processes of concrete mixing, pouring and curing.

Based on the above principles, the experiment was designed as below:

(1) The water/binder ratio (W/B) was reduced to 0.14–0.18, which is often used in Reactive Powder Concrete (RPC).
(2) A maximum binder content of 900 kg/m^3 was adopted to obtain the necessary paste volume and to achieve high fluidity of UHPC.
(3) A Large quantities of superfine mineral additives such as silica fume (SF), ground granulated blast furnace slag (GGBS), and limestone powder (LP) were added to optimize the composition and micro-structure of the hydrated binder paste, and to reduce the hydration heat.
(4) To reduce the cost of UHPC, it is a good approach to utilize coarse aggregate with a maximum size of 20 mm in its preparation.
(5) Common technologies were adopted for preparation of UHPC, which include mixing of fresh concrete with normal forced mixer, pouring in case of good fluidity, compaction by vibrating, and curing at room temperature.

2.2. Raw materials

Grade 52.5 ordinary Portland cement (C) was manufactured by the Chongqing Tenghui Company. Semi-condensed SF was supplied by Elkem Company, China. GGBS was from the Chongqing Iron and Steel Company and ground in the laboratory. LP was made from limestone rock from the Chongqing Gele Mountain. As an essentially inert mineral material, LP was regarded as a component of the cementitious materials in this investigation. The chemical compositions and physical properties of each cementitious material are listed in Table 1.

The fine aggregate was medium sand with a fineness modulus of 2.3, an apparent density of 2.72 g/cm^3, and a bulk density of 1.60 g/cm^3. The coarse aggregate was crushed limestone with a maximum diameter of 20 mm, an apparent density of 2.70 g/cm^3, and a bulk density of 1.65 g/cm^3. The size distributions of the coarse and fine aggregates are listed in Table 2.

The aminosulfonic acid-based superplasticizer and citric acid as a retarder were obtained from the Chongqing Dianni Company.

2.3. Experimental methods

2.3.1. Workability and compressive strength test

A forced single-axis mixer with a rotational speed of 45 rpm was used to prepare fresh concrete in this study. The mixer is shown in Fig. 1. All Concrete mixtures were mixed using the following procedures:

$$\text{Coarse aggregate, fine aggregate, and binders} \overset{1\ \text{min}}{\rightarrow} \text{Water} \overset{2\ \text{min}}{\rightarrow} \text{Superplasticizer} \overset{2\ \text{min}}{\rightarrow} \text{Discharging}$$

The fluidity of fresh concrete, including slump and spread, was measured with a normal 300 mm slump cone in a laboratory with a temperature of (20 ± 3) °C. Spread refers to the average diameter of the concrete spread in this paper, which is obtained after slump testing:

$$\text{Spread} = (D_{\max} + D_{\min})/2$$

where $D_{\max}$ and $D_{\min}$ refer to the maximum and minimum diameter of the measured concrete respectively. A spread of 200 mm means that the fresh concrete has no flow ability.

Cube specimens of 100 mm × 100 mm × 100 mm were used for compressive strength testing. The casting and compacting of these specimens were performed after the fluidity test. The specimens were demolded approximately 24 h after casting, and then cured in the moist room at a temperature of (20 ± 2) °C and no less than 95% relative humidity until testing. At least three specimens were tested at each age to compute the average strength.

2.3.2. SEM investigation

To understand the strength mechanism of UHPC, the microstructure of hardened paste and interfacial transition zone between aggregate and cement paste (ITZ) was investigated using an SEM, The samples for SEM analysis were produced by taking small pieces from the concrete fractured specimen. The broken pieces were soaked and rinsed using anhydrous alcohol, oven dried at 60 °C, and then coated with gold powder before testing. The SEM study was carried out by using an accelerating voltage of 20 kV.

3. Results and discussion

3.1. Preparation of UHPC with common technology and materials

3.1.1. Influence of binder content on strength and fluidity of UHPC

In this experiment, three mixtures with the same binder component and W/B of 0.18 were tested. The mixture proportions are listed in Table 3, and the results are shown in Fig 2.

These three mixtures differed in their fluidity. Mix 1-1 with 500 kg/m^3 binder content exhibited a very dry fresh mixture with

Table 1
Chemical compositions and physical properties of binders.

Binders	Chemical compositions (%)								Specific surface area (m^2/kg)	Density (g/cm^3)
	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	TiO_2	SO_3	LOI		
C	59.37	20.86	9.28	2.07	3.74	0.47	2.49	1.47	330	3.10
SF	–	95.19	–	0.80	0.13	–	–	2.81	20,000	2.23
GGBS	50.44	30.36	16.90	1.84	0.34	0.57		2.42	870	2.75
LP	52.12	3.45	1.47	0.77	0.24	–	–	40.22	600	2.75

Table 2
The size distribution of coarse aggregate and fine aggregate.

Screen size (mm)	Cumulative sieve residue (%)	
	Coarse aggregate	Fine aggregate
26.5	0	0
19.0	9.3	0
16.0	22.8	0
9.50	61.7	0
4.75	89.9	5.2
2.36	98.4	13.4
1.18	/	24.4
0.6	/	38.0
0.3	/	67.2
0.015	/	98.8
Screen tray	100.0	100.0

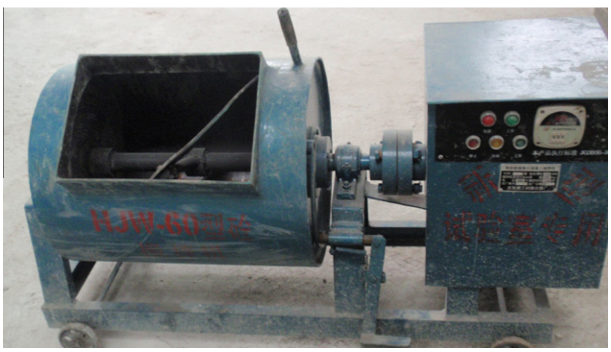

Fig. 1. The mixer for preparation of UHPC.

a slump of 0, mix 1-2 with 700 kg/m^3 binder content had a 130 mm slump, and mix 1-3 with 900 kg/m^3 presented a very good fluidity of 245 mm. The test results show that the slump and spread of fresh concrete improved with the increase of the ratio of mortar volume to coarse aggregate volume and ratio of paste volume to aggregate volume, while the binder content of UHPC rose from 500 kg/m^3 to 900 kg/m^3.

Due to the very low W/B, hardened paste with high fluidity obtains a very compact structure, and thus very high strength. Fig 2 shows that, in the case of fixed W/B in this study, the compressive strength improved with the increase of binder content. All three mixtures reached compressive strengths of more than 150 MPa after 90 d.

The experimental results show that it is very important to keep the paste volume high to gain high fluidity and ultra-high strength behavior. In this experiment, 900 kg/m^3 cementitious materials was set as the ceiling to balance between performance and cost.

In this investigation, a maximum cementitious material content of 900 kg/m^3 was used. Compared with the commonly adopted content of 300–600 kg/m^3, 900 kg/m^3 cementitious material in concrete is not impressive. However, contrasted with 1200 kg/m^3, that typically used in RPC, 900 kg/m^3 is much more desirable in project engineering. Particularly, the mineral additives used in this study are industrial by-products, such as silica fume, which is abundant in China, GGBS, and limestone powder from leftover fragments of crushed stone.

3.1.2. Influence of GGBS replacement of cement on strength and fluidity of UHPC

Among high activity mineral additives, such as SF, GGBS, fly-ash and metakaolin, GGBS is unique. It is latent in hydraulic reactivity, but it can be catalyzed by proper activators such as Portland cement clinker, lime, gypsum, and alkali metal hydroxides, carbonates or silicates to form cementitious materials. The main reaction product generally cited for alkali-activated slag is C–S–H gel similar to that found in hydration products of Portland cement, but with a lower Ca/Si ratios (around 0.7) [11]. Yazıcı et al. [12] presented a good illustration for preparing RPC with large replacement of about 15–45% GGBS successfully. The addition of GGBS in this study helps to optimize the hydration of the binder.

Three mixes with different GGBS replacement and 10% SF by mass content are listed in Table 4, and the experimental results are shown in Fig. 3. Compared with mixture 2-1 concrete, which had no GGBS, mixture 2-2 containing 20 wt.% GGBS replacement had higher fluidity, much lower compressive strength at early ages (28 d and 56 d), but approximately equal strength at later ages

Table 3
Mixture proportions for test of influence of binder content on strength and fluidity of UHPC.

Mix	Binder (kg/m^3)	Binder compositions (%)		W/B	Water (kg/m^3)	Superplasticizer (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
		C	SF					
1-1	500	90	10	0.18	90	18	797	1195
1-2	700	90	10	0.18	126	18	715	1073
1-3	900	90	10	0.18	162	18	616	923

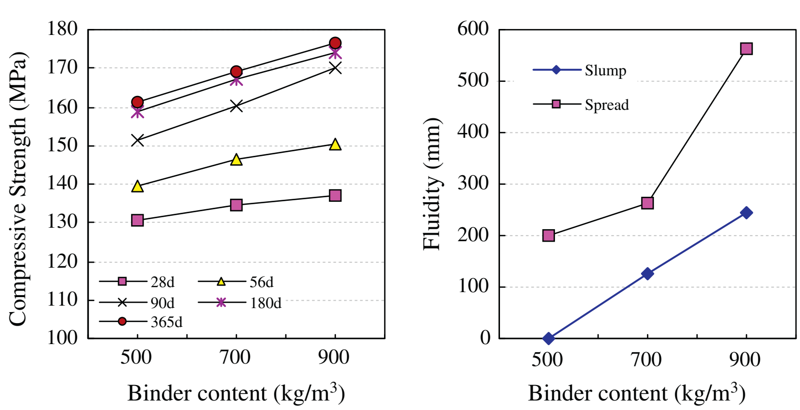

Fig. 2. Influence of binder content on strength and fluidity of UHPC.

Table 4
Mixture proportions for test of influence of GGBS replacement on strength and fluidity of UHPC.

Mix	Binder (kg/m^3)	Binder components (%)			W/B	Water (kg/m^3)	Superplasticizer (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
		C	SF	GGBS					
2-1	900	90	10	0	0.18	162	18	616	923
2-2	900	70	10	20	0.18	162	18	616	923
2-3	900	50	10	40	0.18	162	18	616	923

(90 d, 180 d and 365 d). Mixture 2-3 containing 40 wt.% GGBS had a very low compressive strength and fluidity at all ages compared to the control mixture 2-1.

3.1.3. Compressive strength and fluidity of UHPC with different W/B

Three mixtures containing 900 kg/m^3 binder material and W/B of 0.14, 0.16, and 0.18 respectively, were tested. The cementitious materials consisted of 10 wt.% SF, 20 wt.% GGBS and 70 wt.% ordinary Portland cement. The mixture proportions of these concretes are presented in Table 5, and the results are shown in Fig 4.

It is seen that, with the increase of W/B, the fluidity of concrete improved while the compressive strength at early ages (28 d) decreases, which is well known. However, the highest strength was achieved with a W/B of 0.16, not with W/B of 0.14 at later ages (56 d, 90 d, 180 d, and 365 d). The reason is that the unhydrated cement in a low W/B had a detrimental effect on the structure of the hydrated material. Wang Chong and Pu Xincheng' research [13] illustrated that the hydration degree of hardened cement paste with W/B of 0.16 is higher than that of W/B of 0.10 at all ages, and external water could migrate into the compact hardened paste to react with cement, as demonstrated by a non-evaporable water content increase with curing age in the case of standard curing conditions. For W/C less than about 0.36, there is insufficient capillary pore space available for the complete hydration of the cement [14]. In this investigation, it is suggested that more unhydrated cement in concrete with W/B of 0.14 had a more detrimental effect on the hydrated structure than that of concrete with 0.16 W/B.

3.1.4. Preparation of UHPC with ground LP

LP has been researched in high-fluidity concrete in some literatures [13,15,16]. In this study, LP was used to prepare the UHPC together with 10% SF, and 20% GGBS by mass. The mixture proportions with different LP replacements for cement are listed in Table 6. The test results are given in Fig 5.

Before the test, it was assumed that the incorporation of LP could improve the fluidity of the fresh concrete, but might be detrimental to the mechanical behavior of the hardened concrete with such a low W/B. Surprisingly, compared with mixture 4-1 with 0% LP as a control, mixture 4-2 with 20% LP replacement achieved a higher slump of 240 mm, and a greater compressive strength at ages from 28 d to 365 d. In comparison to the control, the mixture with 40% LP replacement had a higher fluidity but a lower strength at the same ages. Nevertheless, its compressive strength at 365 d was still 164.3 MPa.

In Section 3.1.2, the binder system of ordinary Portland cement + SF + GGBS has shown a good effect on strength performance enhancement. In this section, the concrete containing LP of proper content presented a greater strength and higher fluidity. As an inert mineral material, why could LP improve the structure and strength of UHPC?

The authors have proved that limestone powder accelerated the hydration process of cement and silica fume in another paper [13]. Shi et al. [15], Zhu and Gibbs [16], and Svermova et al. [17] have also claimed that LP was beneficial to concrete structure and performance. Tang [18] confirmed that addition of LP improved the hydration degree of cementitious materials. Refs. [19,20] have shown that calcium aluminate monocarbonate is preferably formed, the hydration of C_3S is accelerated and some carbosilicates are produced in pastes containing limestone constituents. Additional literatures [21,22] shows that LP in cementitious materials systems has a compaction filler and great dispersion effect on the hydration precipitation of $Ca(OH)_2$and C–S–H gel, and plays a core role in crystallization.

The test results show that LP can be applied to prepare UHPC, which we find, after extensive literature review, to be the first attempt of this kind.

3.2. UHPC fluidity loss with time

For ready-mix and pumpable concretes, a low fluidity loss with time for fresh concrete is a must. In the present study, the fluidity loss with time was measured to determine the possibility of applying UHPC prepared with our methodology to pumpable project engineering. To maintain a long workable time for UHPC, a retarder was added together with superplasticizer, and the mixture proportions are presented in Table 7. The results are given in Fig. 6.

It is observed that, with a W/B of 0.16, except for mixture 5-1 which had 10% SF cement replacement and a very low initial and

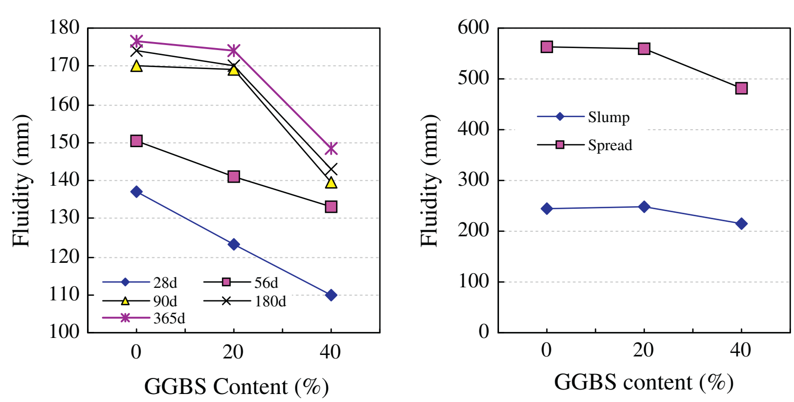

Fig. 3. Influence of GGBS content on strength and fluidity of UHPC.

Table 5
Mixture proportions of test for influence of W/B on strength and fluidity of UHPC.

Mix	Binder (kg/m^3)	Binder components (%)			W/B	Water (kg/m^3)	Superplasticizer (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
		C	SF	GGBS					
3-1	900	70	10	20	0.14	126	18	616	923
3-2	900	70	10	20	0.16	144	18	616	923
3-3	900	70	10	20	0.18	162	18	616	923

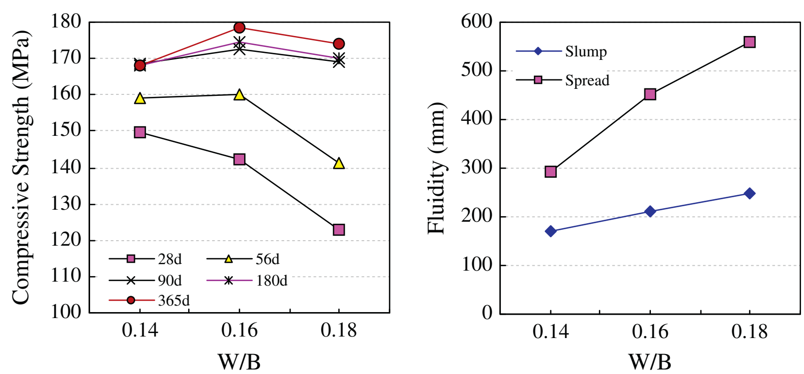

Fig. 4. Influence of W/B on strength and fluidity of UHPC.

Table 6
Mixture proportions for preparation of UHPC with ground limestone powder (LP).

Mix	Binder (kg/m^3)	Binder components (%)				W/B	Water (kg/m^3)	Superplasticizer (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
		C	SF	GGBS	LP					
4-1	900	70	10	20	0	0.16	144	18	616	923
4-2	900	50	10	20	20	0.16	144	18	616	923
4-3	900	30	10	20	40	0.16	144	18	616	923

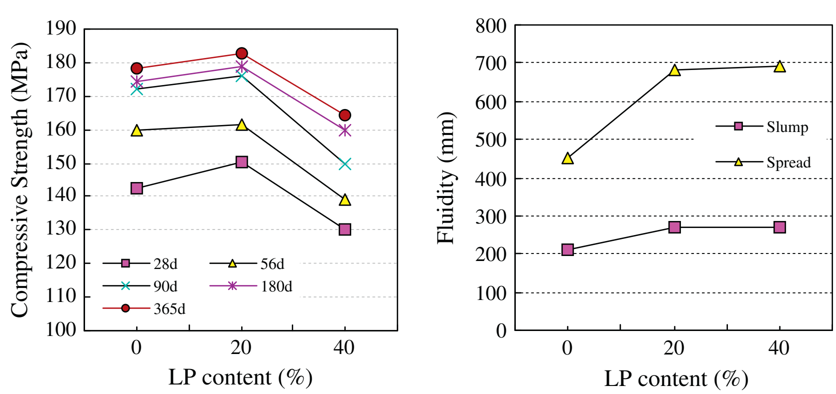

Fig. 5. Influence of amount of limestone powder on strength and fluidity of UHPC.

120 min slump, other mixtures with SF and GGBS replacement (mixture 5-2, and mixture 5-3), and with SF, GGBS and LP (mixture 5-4, mixture 5-5, and mixture 5-6) presented excellent workability service times. Even at 120 min after casting, the slumps were still maintained at more than 200 mm, which indicates that these UHPC can be used as a pumpable concrete when superplasticizer and retarder are added together.

3.3. Mechanism for fluidity and strength of the UHPC

This research successfully prepared UHPC with good workability using common technology and easy to obtain materials. Good workability resulted from the excellent fluidity at a very low water–binder ratio. The volume of cementitious material and the mixes of superplasticizer and mineral additives are the key factors for achieving the desired fluidity. Another key factor is the relationship between volume of mortar or paste and the void space of aggregates. In this experiment, for example, the void space of coarse aggregate of Mix 3-2 reached 0.658 m^3 and that in the fine aggregate 0.431 m^3. The mortar volume was 0.680 m^3 and paste volume 0.453 m^3, which made enough room for the coarse and fine aggregates to form a suspension structure in the mixture, thus the fluidity of the UHPC is assured.

Table 7
Mixture proportions for test of fluidity loss with time of UHPC.

Mix	Binder (kg/m^3)	Binder components (%)				W/B	Water (kg/m^3)	Superplasticizer (kg/m^3)	Retarder (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
		C	SF	GGBS	LP						
5-1	900	90	10	0	0	0.16	144	14.4	3.6	616	923
5-2	900	70	10	20	0	0.16	144	14.4	3.6	616	923
5-3	900	50	10	40	0	0.16	144	14.4	3.6	616	923
5-4	900	50	10	20	20	0.16	144	14.4	3.6	616	923
5-5	900	30	10	20	40	0.16	144	14.4	3.6	616	923

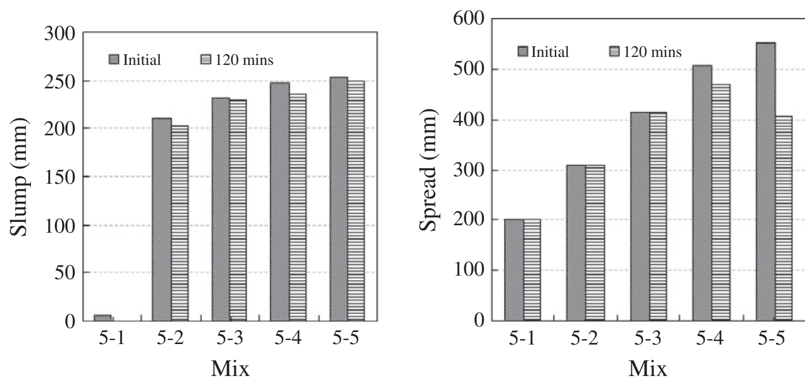

Fig. 6. Fluidity loss with time of UHPC.

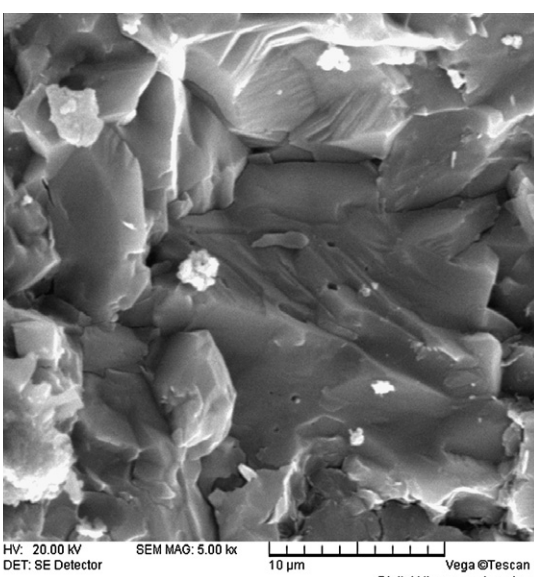

Fig. 7. SEM image of hardened paste in UHPC with 0.16 W/B.

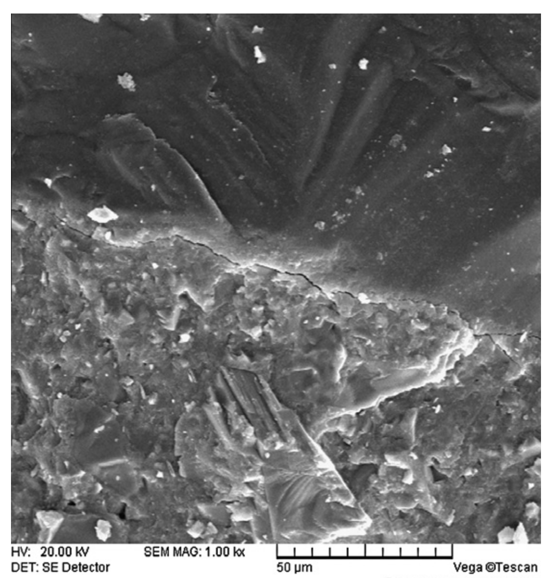

Fig. 8. SEM image of ITZ structure in UHPC with 0.16 W/B.

To explore the strength mechanism of the UHPC, the authors used SEM to investigate the microstructure of the UHPC mixture with 0.16 W/B at 180 d age. The W/B of the UHPC sample was 0.16, cementitious materials of the sample were composed of 70% cement, 20% GGBS and 10% SF by mass. The SEM image of hardened paste and the ITZ structure in the UHPC sample are shown in Figs. 7 and 8, respectively.

In the SEM images of the samples, one can observe a very dense structure in the hardened paste, and only a few air pores are seen in the SEM image of Fig. 7, which can be attributed to the very low W/B, and the hydration of cement and the pozzolanic effect of SF and GGBS. From the image which is shown in Fig. 7, one can observe that the main hydration product is a homogeneous morphology of C–S–H gel, and no $Ca(OH)_2$ and nor ettringite products can be seen.

Fig. 8 reveals that the UHPC prepared with very low water/binder ratio, and with hardened paste made of cement incorporating silica fume and ground granulated blastfurnace slag, and coarse aggregate made of crushed limestone, has a very compact ITZ structure. No distinct porosity is found in the ITZ, which is conducive to UHPC preparation. A homogenous morphology of the paste structure and the compact ITZ structure are the theoretical rationales for preparing UHPC without removing coarse aggregate.

4. Conclusion

From the results mentioned above, it can be concluded that, with extremely low W/B, high binder content, multi-addition of SF, GGBS, LP, and high standard superplasticizer (and retarder), UHPC can be prepared with common technology and without removing the coarse aggregate. In our experiment, UHPC with a maximum slump of 268 mm and the highest compressive strength of 175.8 MPa at 90 d, and 182.9 MPa at 365 d was successfully prepared. It is discovered that W/B of 0.16 and cementitious material content of 900 kg/m^3 which contained 50% cement, 10% SF, 20% GGBS, and 20% LP, as well as an appropriate dosage of superplasticizer to assure adequate fluidity are mandatory for the successful preparation. The test results also conclude that UHPC can be prepared as a pumpable concrete when standard superplasticizer and retarder are added together.

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