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Very-high-performance concrete with ultrafine powders

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Abstract

The compactness and fluidity of binary and ternary compound paste systems containing ultrafine powders such as pulverized fly ash (PFA), pulverized granulated blast furnace slag (PS) and silica fume (SF) were quantitatively studied with the relative density (d/d_0) index. Through optimization of the proportions of compositions and applying heat treatment to specimens, a very-high-performance concrete (VHPC) including large quantities of ultrafine powders has been made successfully, which offers compressive strength up to 200 MPa. Two methods of overcoming the brittleness of VHPC were investigated.

Keywords: Very-high-performance concrete (VHPC); Ultrafine powder; Relative density (d/d_0); Compressive strength; Brittleness

1. Introduction

Much research work has been done over the years, aimed at obtaining high mechanical performance cementitious materials. More recently, two technologies have been adopted. The first concerns compact granular matrix concrete (such as DSP), with high superplasticizer and silica fume (SF), also incorporating ultrahard aggregate (calcinated bauxite or granite) [1]. The other relates to macrodefect-free (MDF) polymer pastes [2]. These pastes have very high tensile strength (above 150 MPa), particularly when mixed with aluminous cement. At the beginning of 1990s, the reactive powder concrete (RPC), with compressive strengths ranging from 200 to 800 MPa, was prepared by Richard et al., where main raw materials were SF, crushed quartz, steel fiber or steel aggregates [3–5]. These indicate that the high-performance cementitious materials are hot subjects studied by researchers. In addition, it is also noted that the emergence of high-performance cement-based materials has brought on interest in microfillers, coupled with the effect of superplasticizers. These ultrafine powders improve the particle packing density of cementitious system, its rheological properties in fresh state and its mechanical properties and durability [6,7].

To make the cement-based materials to be environmentally friendly is the aim of concrete technology. Therefore, not only the good workability in fresh state and excellent mechanical properties and durability but also the environmental friendliness and economic benefits must be possessed by concrete materials. Based on this, a research plan, attempting to use large quantities of mineral powders to develop very-high-performance concrete (VHPC), was undertaken. In this paper, firstly, the compactness of binary and ternary compound pastes containing ultrafine mineral powders, such as SF, pulverized granulated blast furnace slag (PS) or pulverized fly ash (PFA), and the relationships between relative density and fluidity of pastes, are analyzed quantitatively. Secondly, the effects of the contents of SF, PS and PFA on the strength of VHPCs are experimentally studied. Finally, two means of improving toughness of VHPC by steel fibers and steel tubes are investigated.

2. Experimental details

2.1. Raw materials

2.1.1. Cement

Chinese Standard 525# ordinary Portland cement, made by the Xiangxiang cement factory, with a 28-day compressive strength of 56.4 MPa, was used.

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Table 1
Chemical compositions and physical properties of PFA, PS and SF

	Compositions (%)						Ignition loss,	Mean diameter,	Density,
Type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	%	μm	g/cm^3
PFA	21.7	25.8	9.7	3.7	1.2	0.2	1.16	5.8	2.47
PS	28.3	13.6	0.62	38.4	7.2	7.4	0	6.5	2.78
SF	88.2	3.45	0.80	0.00	2.08	0.34	2.52	0.2	2.14

2.1.2. Ultrafine powders

The chemical compositions and physical properties of PFA, PS and SF are given in Table 1.

2.1.3. Aggregate

Quartz sand produced with maximum diameter less than 0.63 mm was also used.

2.1.4. Steel fibers

Two kinds of steel fibers with shape of cylinder and different length to diameter ratio (L/D) were incorporated into very-high-performance steel fiber cement-based materials.

2.1.5. Superplasticizer

A superplasticizer of sulfonated cyanuramide formaldehyde resin base denoted by DFS-2 was added in the mixtures.

2.2. Experimental procedures

2.2.1. Experimental methods

The pastes were mixed in a mixer with couple speed according to Chinese Standard GB1346-89. The fluidity of pure pastes, flowability of mortars and strength were measured according to GB8077-87, GB2419-94 and GB177-85, respectively.

The relative density (d/d_0) can be obtained when the values of d and d_0 are known. d stands for the density of pure paste, which was determined by its weight and volume measured by a balance and a cup with volume of 71 cm^3. The details of measurement were: (1) measuring the weight of the cup without paste, denoted as G_0 (g); (2) filling the ready-mixed paste in the cup, then plugging a knife into the paste five times and vibrating slightly the cup five times so as to expel out air entrapped in paste, and scrapping with straight steel ruler from the center of the upper face of the cup to sides one time; (3) measuring the weight of the cup full of paste, denoted as G (g); (4) then calculating $d = (G - G_0)/71$; and (5) repeating the above process again. The final result of d was the average of two times' values. d_0 was the density of solid mixtures when supposed to be compact.

2.2.2. Sample preparation

Two percent superplasticizer by weight of cement was added into all mortars. The content of cement, PFA, PS, SF and quartz sand was calculated by weight. The mixing process was described as follows. Firstly, the dry mixture was mixed at low speed for 1 min. Then, half quantity of mixing water containing superplasticizer was added and mixed for 2–3 min at low speed. Lastly, the remains of superplasticizer and water were added and mixed for more than 2–3 min at high speed.

The mortars were cast into 40 × 40 × 160 mm stainless-steel molds and immediately stored in a flog room at 20 °C. The specimens were demolded after 24 h, bathed in 20 °C water for 72 h and then placed in 95 °C steam room for 72 h.

3. Results and discussion

3.1. The effect of ultrafine powders on the relative density of compound pastes

Fig. 1 shows the variation of relative density of binary systems with the content of ultrafine powders. The water to binder ratio (W/B) of all pastes was 0.22. Two percent of DFS-2 by weight of binders was added. The binders were cement and PFA, PS or SF. The fluidity of all pastes ranged from 260 to 200 mm. It is noted that the relative density of pastes increases with an increment in the content of powders. From the slope of the curves, it can be found that SF is most effective in improving the relative densities of binary paste systems. The results may attribute to following factors: (1) In fresh pure cement paste, the space among cement particles is filled by water and air. When the ultrafine powders are added in mixtures, the powders will take the place of water filled in space and occupy pores in pastes. (2) The average diameter of SF particles is less than that of PFA or PS. The less the diameter of filling particle, the better the filling effect the particle is. This result was also obtained by T. Stovall et al. [8]. (3) The apparent density of SF is smaller than that of PFA or PS, so its volume is larger at the same weight.

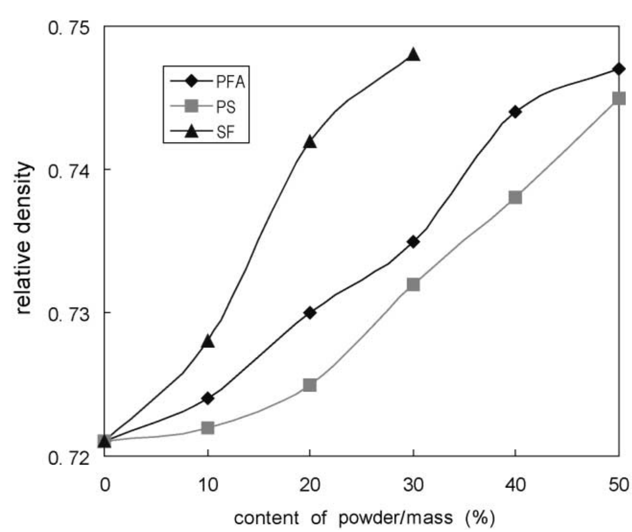

Fig. 1. The effects of powders on relative density of binary paste.

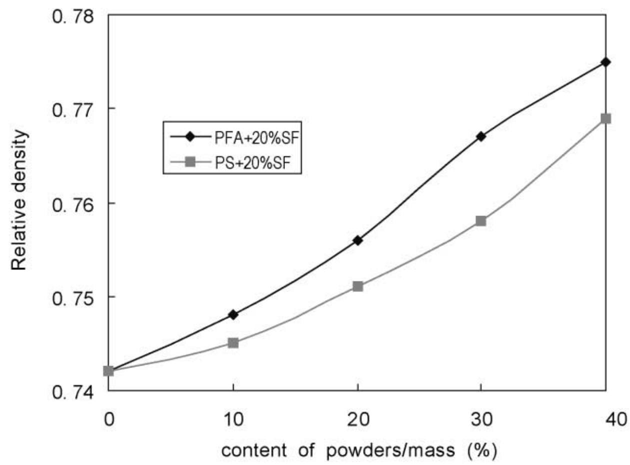

Fig. 2. The effects of powder on relative density of ternary paste.

The variation of relative density of ternary fresh pastes with the content of PFA or PS is shown in Fig. 2. In the experiment, the content of SF was kept constant and the content of PFA and PS changed. The other experimental conditions of all pastes were the same as those shown in Fig. 1. The results indicate that for ternary paste, its relative density can further increase compared with binary pastes. These may result from the interfilling effect, which reduces voids between particles with different sizes in ternary system.

3.2. The effect of W/B on relative density of fresh pastes

It is known that the properties of hardened pastes are determined by initial porosity of pastes. W/B is the key factor affecting the initial porosity. Fig. 3 demonstrates the experimental results of effect of W/B on the relative density of pastes. The fluidity of pastes ranged from 265 to 90 mm. The results indicate that with the decrease of W/B, the relative density of fresh pastes increase rapidly. It is obvious that with the reduction of water in mixtures, the distances between particles become shorter and the porosity of pastes is reduced, therefore, the relative density of pastes increases.

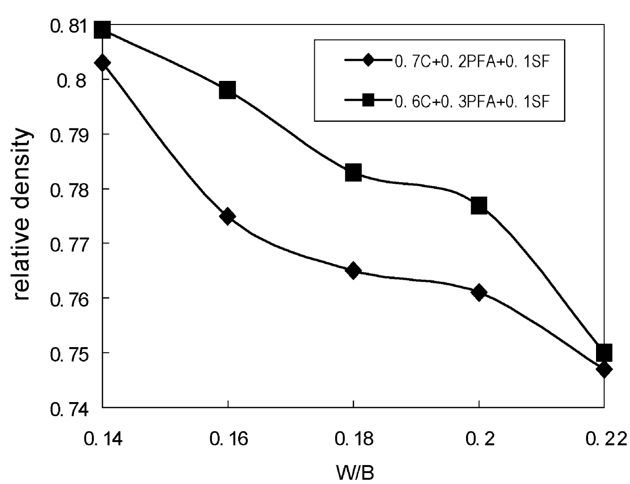

Fig. 3. The relationships between relative density of paste and W/B.

3.3. Relationship between fluidity and relative density of fresh pastes

The thickness of water film layer on particle surface is important for the fluidity of fresh paste. The high relative density of fresh paste means short distance between grains and small thickness of water film layer on grains surface compared with paste of low relative density. It seems that the fluidity of paste decreases with the increase of the relative density. Therefore, in the following section, the relationship between fluidity and relative density of fresh pastes are investigated experimentally.

The results of influence of relative density on fluidity of fresh pastes are listed in Table 2. The results illustrate that the fluidity of fresh pastes is improved when the relative density increase with the same W/B. These indicate that the addition of PFA, PS or SF into compound pastes not only benefits the increment of relative density of pastes but can also compensate the water demand owing to the increment of surface area of particles and further improves the fluidity of pastes.

Additionally, it can also be found in Table 2 that the fluidity of paste is reduced as the relative density of pastes increase with the same water to cement ratio. The addition of an amount of SF, which has extremely large surface area into pastes, may contribute to these results.

3.4. The optimization of VHPC compositions

The results above show that the ultrafine mineral powders and W/B are important to the relative density of fresh pastes, which directly determine the properties of hardened cement-based materials. Table 3 shows the experimental results of the strength and flowability of VHPC. One can clearly see that compressive and flexural strengths of VHPC show good correlation. In the area investigated, these

Table 2
The effect of relative density on fluidity of pastes

Type	C	UPFA	SF	DFS-2	Fluidity, mm	d/d_0
W/B = 0.22	1	0	0		225	0.715
	1	0.2	0	0.02	260	0.731
	1	0.2	0.1		265	0.747
W/B = 0.2	1	0	0		160	0.721
	1	0.2	0	0.02	225	0.742
	1	0.2	0.1		250	0.761
W/C = 0.22	1	0.3	0.1		170	0.78
	1	0.3	0.2	0.02	160	0.793
	1	0.3	0.3		135	0.806

W/B is the water to binder (cement, PFA or SF) ratio; W/C stands for the water to cement ratio.

Table 3
The experimental results of flowability and strength of mortars

No.	W/B	Proportions of raw materials (C/PFA/PS/SF)	Flowability, mm	R_f, MPa	R_c, MPa
1	0.180	1:0:0:0.10	190	20.4	151.4
2	0.167	1:0:0:0.20	185	22.2	175.4
3	0.160	1:0:0:0.25	175	22.5	187.8
4	0.154	1:0:0:0.30	160	21.1	186.6
5	0.16	1:0:0.2:0.25	170	28.4	178.6
6		1:0:0.3:0.25	185	29.5	198.2
7		1:0:0.4:0.25	200	30.5	193.6
8		1:0:0.6:0.25	165	27.6	190.0
9		1:0:0.3:0.30	180	28.4	207.0
10		1:0:0.4:0.30	190	29.6	200.8
11	0.16	1:0.2:0:0.25	180	24.7	188.2
12		1:0.3:0:0.25	190	28.5	208.4
13		1:0.4:0:0.25	200	30.4	197.8
14		1:0.6:0:0.25	175	30.3	184.0
15		1:0.3:0:0.30	185	31.0	204.8
16		1:0.4:0:0.30	195	29.9	213.2

properties consequently appear to be controlled essentially by the content of PFA, PS or SF. It can also be found that all concrete specimens have good workability though their W/B is only 0.16. The strength of concrete specimen only containing SF increases with an increment in the contents of SF, and the optimum content of SF is about 0.2–0.3 of the weight of cement. The most noteworthy is that the VHPC samples incorporating SF and PFA or SF and PS have higher compressive strength compared with those only containing SF. Furthermore, the compressive strength of VHPC samples including SF and PFA is slightly higher than that of the samples containing SF and PS. These results show that VHPC samples with SF and PFA or SF and PS have, within the limit set in the Introduction, quite the optimum compositions for cement/ultrafine powders. The optimum ratio is about C/PFA (or PS)/SF = 1:0.3–0.4:0.2–0.3 by weight.

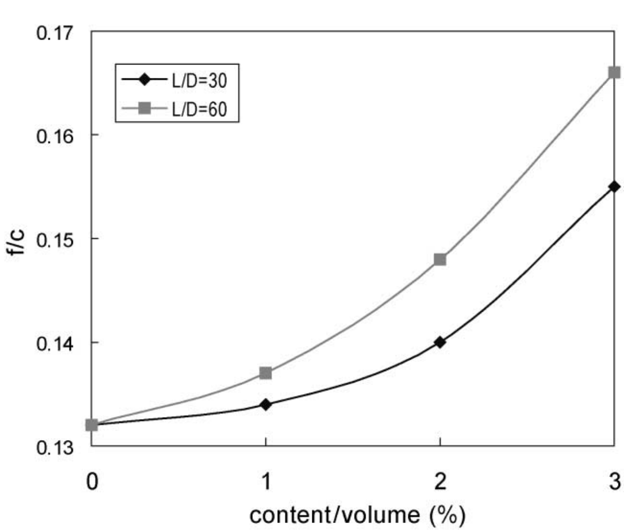

Fig. 4. The effect of the steel fiber on the brittleness of VHPC.

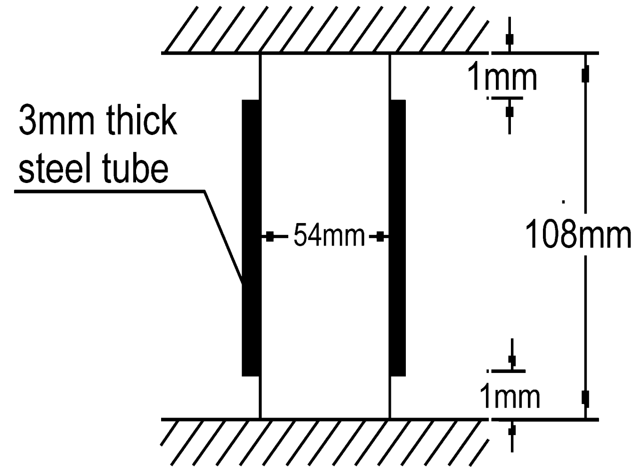

Fig. 5. Diagram of VHPC confined by a steel tube.

3.5. The methods improving toughness of VHPC

The high brittleness is the biggest disadvantage of concretes, especially of very-high-strength concrete. Many methods, such as the incorporation of all kinds of fibers into concretes, have been applied to attempt to upgrade the toughness for a long time [9,10]. The VHPC has also not enough toughness to meet the needs of engineering structure. In this paper, its toughness is expected to be enhanced through two methods: (a) incorporating a short steel fiber into concrete, and (b) restricting concrete with a steel tube.

Fig. 4 shows the experimental results of the variation of flexural strength to compressive strength ratio (f/c) with the volume content of steel fibers. From the testing results, one can find clearly that whether *L*/*D* of fibers is equal to 30 or 60, the value of f/c of VHPC sample increases gradually with the addition of steel fibers. However, the relationship between f/c and volume of steel fibers is not simply linear. Additionally, the results indicate that the greater the *L*/*D* of steel fibers, the better the toughness of VHPC sample including steel fibers is.

Fig. 5 is the diagram of test of VHPC confined by a steel tube. The testing result demonstrates that the compressive strength of VHPC confined by a steel tube comes up to 300 MPa (the average value of three specimens). The compressive strength of concrete core is 198.2 MPa. This indicates that with the limitation of a steel tube to VHPC, not only the toughness but also the compressive strength of VHPC can be improved significantly.

4. Conclusion

The results presented in this work show that ultrafine powders such as PFA, PS and SF can largely improve the relative density of compound pastes with low W/B, and that SF is most effective in improving the relative density of binary paste. The relative density of ternary cement pastes containing two kinds of powders of PFA and SF or PS and SF can further increase, compared with binary pastes only including one kind of powders. The relative density of pastes increases rapidly as W/B is reduced.

Through the optimization of the proportions of compositions and employing heat treatment, a kind of VHPC with large quantities of ultrafine mineral powder has been prepared successfully, which provides compressive strength up to 200 MPa. The brittleness of VHPC can be overcome by short steel fibers with $L/D = 60$. With the introduction of a steel tube, not only the toughness but also the compressive strength of VHPC can be greatly enhanced.

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