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The influence of superplasticizer and superfine mineral powder on the flexibility, strength and durability of HPC

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Abstract

This paper presents a study on the change of workability, strength and durability, including the resistance to freezing and thawing, salt attack and diffusion coefficient of chloride, of high-performance concrete (HPC) in which part of the ordinary portland cement (OPC) was replaced by superfine mineral powder of phosphoric slag (SFPS). The results of this study show that the partial replacement of OPC by SFPS can increase the fluidity, improve the compressive strength, decrease the chloride diffusion coefficient of concrete and obtain good durability of HPC.

Keywords: Superplasticizer; Superfine phosphoric slag; Workability; Durability; High-performance concrete

1. Introduction

Traditional concrete, which is primarily made of only three fundamental ingredients, i.e., aggregates, cement and water, has been used for over a century. In recent years, a new type of concrete termed high-performance concrete (HPC) has become popular in the concrete construction industry. This type of concrete usually uses superplasticizer (SL), superfine powder, segregation reducing powder, aggregates and cement. One of the most important principles is to use the least amount of cement in the HPC. The reasons for supporting this standpoint are threefold. The first is for preserving our natural resources, since cement is the most expensive and energy-consuming ingredient compared with the other constituents in concrete. The second is for economic reasons of saving the cost of materials and energy. The third reason is for long-term durability considerations, since an excessive amount of cement in concrete results in a higher heat of hydration, a higher creep and shrinkage and a higher risk of cracking.

China started the high-strength-concrete research program in the 1980s. A strength Grade C_{50} resulted from the research on HPC, but in the mid-1990s, the strength reached a strength Grade C_{80}. The research program on HPC in China has the following characteristics.

(1) Research and application of superfine mineral powders. Silica fume and other kinds of superfine powders, with specific surface area 600–800 m^2/kg, are made of blast-furnace slag (GBFS), natural zeolite and fly ash, etc. These are mixed with concrete to replace a part of the cement, improving the workability of fresh concrete and the strength of hardened concrete.

(2) Application of inorganic powders for controlling slump loss [1]. Some kinds of inorganic powders can absorb SL and retarder. When the powders are added to concrete, they can release the admixtures gradually to retain the concentration of SL and retarder in fresh concrete; thus the surface zeta potential of cement particles is kept and the slump loss is controlled.

(3) Efficient application of electrochemistry. The methods of electrochemistry are adapted in measuring the diffusion coefficient of chloride in HPC, testing the steel corrosion and protection of the reinforcement.

Using SL and superfine mineral powder in concrete is one of the most essential principles in the mix proportioning of HPC [2,3]. It is well known that silica fume is a highly reactive mineral admixture in preparing HPC. Due to the high price of silica fume and its big demand for

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water, silica fume is not usually used in China. On the other hand, a superfine powder made from natural zeolite has a strengthening effect, but no dispersing effect, on the concrete [4]; thus, it is not usually used to replace silica fume. The GBFS superfine powder has filling, dispersing and strengthening effects, but it is usually used as a blend material to produce cement and road-construction materials, which makes it scarce in some areas; therefore, it is of realistic significance for finding a highly reactive mineral admixture to produce HPC.

Superfine mineral powder of phosphoric slag (SFPS) with average particle size less than about 10 μm and Blaine surface area greater than 600–800 m^2/kg can greatly improve the properties of concrete due to its filling and dispersing effects and chemical reactivity in concrete [5,6].

Adding SL and SFPS simultaneously leads to better filling and dispersing effects in concrete because the particles of this fine powder cannot fill in effectively the space between the cement particles unless the flocculation of the superfine powder is destroyed by absorbing SL. Therefore, the W/C ratio and total porosity of HPC can be decreased, and a high strength and flowing concrete can be obtained [7].

Most previous research centered on the reactive mineral powders, including silica fume and pozzolanic materials such as zeolite, fly ash and GBFS used to prepare HPC [8], but there is no research in the literature on the influence of SFPS and SL on the workability, strength and durability of HPC. This paper presents a study on the change of the workability, strength and durability of HPC in which part of ordinary portland cement (OPC) is replaced by SFPS.

2. Experiments

2.1. Materials

Cement, Chinese 525# OPC, produced in Shandong cement plant, and SFPS, from Zang Jiakou chemical plant, fineness 600–800 m^2/kg, were used. The chemical compositions of these materials are shown in Table 1.

The coarse aggregate was gravel with a 5- to 20-mm particle size distribution. The fine aggregate was graded silica sand with a fineness modulus of 2.7. The SL was a dry naphthalene powder product from Tsinghua University, with the commercial name of NF.

Table 1
Chemical compositions of materials (wt.%)

Item	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	P_2O_5	E
Cement	65.11	21.82	5.43	3.72	1.55	0.67	–	1.62
SFPS	44.40	36.88	3.92	2.93	1.56	0.18	0.60	

$E = Na_2O + K_2O + LOI = 0.15 + 1.20 + 0.27 = 1.62$.

Table 2
Mix proportions (kg/m^3), slumps (mm) and strengths of concrete (MPa)

								Compressive strength	
Item	Water	NF	SFPS	Ce	FA	CA	Slump	7 days	28 days
1	175	0	–	550	640	1080	20	38.3	42.4
2	175	4.4	–	550	640	1080	105	57.1	83.4
3	175	5.5	–	550	640	1080	130	59.5	81.6
4	175	6.6	–	550	640	1080	160	57.8	76.1
5	175	7.7	–	550	640	1080	205	58.8	79.0
6	175	0	110	440	640	1080	55	32.9	55.0
7	175	4.4	110	440	640	1080	150	55.4	86.4
8	175	5.5	110	440	640	1080	180	57.5	85.3
9	175	6.6	110	440	640	1080	205	45.8	84.6
10	175	7.7	110	440	640	1080	230	43.0	80.8

Ce, cement; FA, fine aggregate; CA, coarse aggregate.

2.2. Methods

According to stipulations in the Chinese national standard GB82-85, the concrete specimens are cubes with dimensions $10 \times 10 \times 10$ cm for testing compressive strength and resistance to freezing and thawing. After demoulding for 1 day, the specimens were cured in water at 20 ± 3°C for 28 days and then tested. The specimens for freeze–thaw resistance were tested in accordance with GB82-85. For each cycle, the specimens were frozen at −15 to −20°C for 6 h and then thawed at 15–20°C for 6 h. This test was terminated after 50 cycles. The changes in compressive strength and in mass of the specimens compared to those of control concrete that was not subjected to freezing and thawing cycles were determined.

The mortar strength was measured in accordance with the Chinese national standard GB177-85. The size of the specimens was $4 \times 4 \times 16$ cm for testing resistance to salt attack. The salt attack was tested as follows: after curing in water (20 ± 3°C) for 14 days, the specimens were placed into salt solutions (5 wt.% NaCl + 5 wt.% Na_2SO_4) up to 90 and 180 days, after which the strengths were measured.

The specimen preparation and measurement of chloride permeability were conducted using ASTM C 1202 apparatus. For each batch, one prism measuring $10 \times 10 \times 30$ cm was cast and cured under 20 ± 3°C with 90% RH for 28 days. Then it was cut into slices with a thickness of 5 cm and immersed in 4 mol/l NaCl solution. The specimen was subjected to different dc voltages on both plate sides, and the chloride diffusion coefficient of concrete (D_{Cl}) was calculated from the Nernst–Einstein equation:

$$D_{Cl} = RT\sigma_i/(Z_i^2 F^2 C_i)$$

where R is the gas constant, 8.314 J/mol K; T the absolute temperature, K; σ_i the partial conductivity of species i, S/cm; Z_i the charge of species i; F Faraday's constant, 96500 C/mol; and C_i the concentration of species i, mol/cm^3.

3. Results and discussion

3.1. Workability

Table 2 gives the results of slump and strength of concrete.

Under the same condition of water–binder ratio, the slump results show that concrete (6#) with SFPS replacing about 20% of OPC had higher slump value than the control concrete (1#) made with only OPC. The results mean that SFPS can improve the fluidity of concrete due to its dispersing effect on concrete.

The addition of SL increases the slump of concrete. The addition of SL, and at the same time substitution of 20% SFPS for OPC, increases the slump of concrete more than with SL alone. These results demonstrate a fluidizing effect of SFPS and SL on the workability of concrete. This trend is shown from another aspect, that when reaching the same slump level, compared to the control concrete, concrete with SFPS needed less SL or lower water–binder ratio could be obtained. This may be due to the flocculation of SFPS being destroyed by absorbing SL; thus, the fluidizing effect can be better, and the slump is higher.

3.2. Strengths

Without SFPS, the strengths of concrete increased greatly due to the use of SL; the compressive strengths increased 56% at 7 days and 99% at 28 days compared to the control concrete (1#).

When the weight of SL was varied from 4.4 to 7.7, there was no substantial change of strength of HPC observed (2# to 5#). The optimal weight of SL is 5.5 (3#) for the early compressive strength and 4.4 (2#) for later compressive strength. The later compressive strength (28 days) varied from 76.1 to 83.4 MPa.

When OPC is partially replaced by SFPS in concrete (6#), the early strength is lower but the later strength is higher compared to the control concrete (1#). The compressive strength decreases 14% at the early period (7 days), but increases 31% at the later period (28 days).

The compressive strengths decreased 27% at the early period but increased 11% at the later period for the same content of SL in concrete, of which OPC is replaced by SFPS, compared to concrete without SFPS. The optimal weight of SL is still 5.5 for the early and 4.4 for the later compressive strength of concrete containing SL and SFPS.

When SFPS partially replaced OPC in concrete, it improved the strength of HPC by an overlap of two properties: adsorption at the solid–liquid interface of SL and the strengthening effect of SFPS. At the same time, the amount of SL required in the concrete decreased and comprised between 4.4 and 5.5 kg/m^3 (0.8–1.0 wt.%).

Table 3
The formulation of HPC (kg/m^3)

Item	Water	NF	SFPS	Ce	FA	CA
1	170	3	0	500	640	1150
2	170	2.5	150	350	640	1150
3	170	2	250	250	640	1150

Table 4
The chloride diffusion coefficients at different voltage measurements

	Chloride diffusion coefficients ($\times 10^{-12}$ m^2/s)			
Item	2 V	3 V	4 V	5 V
1	7.52	7.85	8.20	8.27
2	5.78	5.47	5.51	5.60
3	5.80	5.68	6.12	6.19

3.3. Freeze–thaw resistance

In order to determine the resistance of HPC exposed to freezing and thawing, three types of HPC were used. The formulations are shown in Table 3.

The specimens were subjected to up to 50 freezing and thawing cycles, and the weight and compressive strength losses were measured. The results show that no weight and compressive strength losses were found after 25 freezing and thawing cycles. After 50 freezing and thawing cycles under the same conditions, the weight losses of HPC 1#, 2# and 3# were 2.4%, 2.1% and 2.8%, respectively, and the changes in compressive strength were +1.1%, +5.2% and −2.1%, respectively. These results showed no significant difference to that of concrete with and without SFPS.

3.4. Diffusion coefficient of chloride

The chloride diffusion coefficient of concrete was determined on concrete with the formulation of Table 3. The results are shown in Table 4.

It is seen in Table 4 that replacement of OPC by SFPS in HPC can significantly reduce chloride diffusion coefficients. When 30% OPC is replaced by SFPS, the chloride diffusion coefficients measured on the specimens decreased between 23% and 33% compared to the control HPC (1#). When the replacement of SFPS increases from 30% to 50%, the specimens with 50% SFPS replacement (3#) gave a chloride diffusion coefficient slightly higher than that of 30% replacement (2#). These results prove that the SFPS partial replacement for OPC can reduce the chloride diffusion coefficient.

Table 5
Mix proportions (kg/m^3) and strengths (MPa) of mortar for salt attack

					90-day strength (MPa)		180-day strength (MPa)	
Item	OPC	SFPS	W	Sand	Flexural	Compressive	Flexural	Compressive
1	540	0	238	1350	10.1	57.5	11.0	62.4
2	378	162	238	1350	11.4	66.4	12.5	67.6
3	270	270	238	1350	10.5	62.1	11.6	63.3

3.5. Salt attack

The formulation of mortar subjected to salt attack is shown in Table 5. The salt solution was made from 5 wt.% NaCl + 5 wt.% Na_2SO_4. After curing for 90 and 180 days, the strengths of mortar specimens were measured; the results are shown in Table 5.

In Table 5, it can be seen that the mortar flexural strength and the compressive strength increase when some OPC is replaced by SFPS. The values of the strength vary with the replacement amount of SFPS. When the replacement amounts of SFPS increase, the strength decreases slightly; in other words, the deterioration due to salt attack increases. It may be concluded from above results that when some OPC is replaced by an appropriate amount of SFPS (30%), the resistance to salt attack of concrete is improved, but the effects are not significant.

4. Conclusion

SFPS with small particle size and high chemical activity can be used as a mineral addition to concrete. In the presence of SL, the filling, dispersing and strengthening effects of SFPS in concrete can be greatly improved; thus, the W/C ratio of concrete can be decreased and high-strength and flowing concrete can be obtained.

In the presence of SL, with the partial replacement of OPC by SFPS in concrete, the diffusion coefficient of chloride can be reduced, hence the durability of concrete may be improved. The resistance to freezing, thawing and salt attack showed no significant difference to that of concrete with and without SFPS.

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