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Effect of Silica Fume on Mechanical Properties of Concrete Incorporating Steel Slag Powder

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Abstract: This study investigated the effect of silica fume(SF) on mechanical properties of concrete incorporating steel slag powder (SSP). The compressive strength and splitting strength tests of concrete with different content of SF (0%, 4%, 8% and 12%) and of SSP (0%, 10%, 20%, 30% and 40%) were carried out, and the test results were analyzed and fitted. Obtained results showed that the brittleness, compressive strength and compressive strength discreteness of concrete increased due to the incorporation of SF. SSP weakened the compressive strength of concrete, which reduced within 10% when the content of SSP was less than 20%. SF and SSP showed synergistic hydration effect when they were mixed, and the optimal group was SF8SSP30, whose compressive strength was close to that of plain concrete, and whose brittleness as well as discreteness of compressive strength were lower relatively. With the content of SSF and of SSP as variables, the tension-compression ratio and compressive strength of concrete can be well estimated by surface fitting.

Key words: silica fume; steel slag powder; concrete; compressive strength; brittleness; discreteness; surface fitting

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0 Introduction

Characterized as being highly calcareous, siliceous and ferrous, steel slag, the main by-products generated in the metallurgical industry, are similar to cement to have the possibility of being concrete admixtures[1,2]. However, steel slag is less active than cement and contains large amounts of f-CaO and f-MgO, which are likely to cause poor volume stability[3,4]. What's more, the gel of steel slag compounding with cement is looser, resulting in deterioration to mechanical properties of cement-based concrete[5-7].

Research on the mechanical properties of cement-based concrete incorporating steel slag at domestic and foreign has made some achievements. Liu *et al*[8] has studied the fluidity of steel slag powder(SSP) cement mortar and the compressive strength of concrete with different SSP content. The results showed that mortar with steel slag has higher fluidity and the compressive strength of concrete decreases negligibly when the content of slag powder is less than 10%; Han *et al*[9] studied the compressive strength of the composition and the morphology of hydration products of five-year-old SSP concrete. The results showed that SSP concrete had lower compressive strength, and even after 5 years of age, there are still many SSP particles not fully hydrated. Preparing cementitious materials from steel slag, slag and gypsum, Cui *et al*[10] studied the hydration reaction mechanism of the gel by X-ray diffraction, infrared spectroscopy(IR), and scanning electron microscope (SEM). The results manifested that slag and steel slag showed synergistic effect under the excitation of gypsum, contributing in higher density of the gel.

Aiming at investigating the effect of silica fume(SF) on mechanical properties of concrete incorporating SSP, the compressive strength and splitting strength tests of concrete with different SF content and SSP content were performed, and the tests results were analyzed and fitted to provide reference for engineering practice.

1 Experimental Programs

1.1 Raw Materials

42.5# ordinary Portland cement PC), medium sand with fineness modulus of 2.6, crushed stone with particle size 5-15 mm, SF from Ganzhou Kemingrui Non-ferrous Metal Materials Co., Ltd. and SSP from Nanjing Alloy Compound Materials Co., Ltd. were used. The characteristic parameters of SSP and SF, provided by the manufacturer, are given in Table 1.

1.2 Mix Proportion and Test Results

Twenty groups of mix proportion were cast, containing unite (PC), binary(PC+SF, PC+SSP) and ternary (PC+SF+SSP) cementitious blends, in which a proportion of cement was partially replaced with SF and SSP by weight. Six specimens of dimensions 150 mm×150 mm× 150 mm were cast in each group, which were subjected to compressive strength splitting strength tests after 28 d standard curing.

Compressive strength and splitting strength tests are conforming to GB/T 50081-2002[11]. Mix proportion and test results are shown in Table 2, in which, for example, "C" means plain concrete, "SF4" strands for 4% of cement were replaced by SF, and "SF8SSP10" represents SF and SSP substituted for 8% and 10% of cement, respectively.

Table 1 Characteristic parameters of SSP and SF

Item	Composition/%					Loss of ignition/%	Water requirement ratio/%	Activity index/%	Specific surface area/$m^2 \cdot g^{-1}$
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO				
SSP	14.8	3.3	21.0	8.9	45.2	1	102	89	0.5
SF	95.0	0.2	1.0	1.3	1.5	6	115	98	15

Table 2 Mix proportion and test results

Groups	*W*/S	Cement /$kg \cdot m^{-3}$	Water /$kg \cdot m^{-3}$	Sand /$kg \cdot m^{-3}$	Stone /$kg \cdot m^{-3}$	SF /$kg \cdot m^{-3}$	SSP /$kg \cdot m^{-3}$	Compressive strength/MPa	Splitting strength/MPa
C*	0.44	450	198	599	1 148	0	0	39.88	3.01
SF4**	0.44	432	198	599	1 148	18	0	42.78	3.36
SF8	0.44	414	198	599	1 148	36	0	45.95	3.43
SF12	0.44	396	198	599	1 148	54	0	44.18	3.17
SSP10	0.44	430	198	599	1 148	0	20	39.25	2.99
SF4SSP10***	0.44	412	198	599	1 148	18	20	42.69	3.26
SF8SSP10	0.44	394	198	599	1 148	36	20	46.74	3.51
SF12SSP10	0.44	376	198	599	1 148	54	20	45.78	3.21
SSP20	0.44	410	198	599	1 148	0	40	37.95	2.85
SF4SSP20	0.44	392	198	599	1 148	18	40	38.44	3.10
SF8SSP20	0.44	374	198	599	1 148	36	40	45.70	3.40
SF12SSP20	0.44	356	198	599	1 148	54	40	44.13	3.16
SSP30	0.44	391	198	599	1 148	0	59	32.20	2.78
SF4SSP30	0.44	373	198	599	1 148	18	59	35.77	2.89
SF8SSP30	0.44	355	198	599	1 148	36	59	42.09	3.28
SF12SSP30	0.44	337	198	599	1 148	54	59	42.36	3.11
SSP40	0.44	371	198	599	1 148	0	79	30.68	2.64
SF4SSP40	0.44	353	198	599	1 148	18	79	35.61	3.03
SF8SSP40	0.44	335	198	599	1 148	36	79	40.17	3.21
SF12SSP40	0.44	317	198	599	1 148	54	79	39.46	2.99

*C means plain concrete; ** SF4 strands for 4% of cement were replaced by SF; *** SF8SSP10 represents SF and SSP substituted for 8% and 10% of cement

2 Compressive Strength of Concrete

2.1 Effect of SF on Concrete Compressive Strength

The relationship between concrete compressive strength growth rate and SF content are shown in Fig. 1.

As can be seen from Fig. 1, the compressive strength of concrete were increased by the addition of SF, and the effect is optimal when SF content is 8%, whose value of compressive strength growth rate is between 15.24% and 30.94%. The concrete compressive strength growth rate begin to decline when the content of SF beyond 8%. In addition, regardless of the amount of SF, the concrete compressive strength growth rate is always greater than zero. The reason for this phenomenon is that the SF undergo a secondary hydration reaction with $Ca(OH)_2$, the hydration product of cement, to form $3CaO \cdot 2SiO_2 \cdot 3H_2O$ (C—S—H) gel, contributing in the development of compressive strength[12,13]. However, when the content of SF increases to 12%, the $Ca(OH)_2$ produced by cement hydration is exhausted, so there is no new gel could be formed[14], resulting in a decrease of compressive strength.

In addition, it is observed from Fig. 1 that regardless the content of SF, the compressive strength growth rate of the concrete with SSP is almost greater than that of the concrete without SSP, indicating that the SF and the SSP can synergistically promote each other's hydration reaction hydration reaction of SSP, and secondary hydration reaction of SF). This may be due to the fact that the SSP contains C_2S, C_3S and a certain amount of f-CaO, which reacts with water to form $Ca(OH)_2$, and

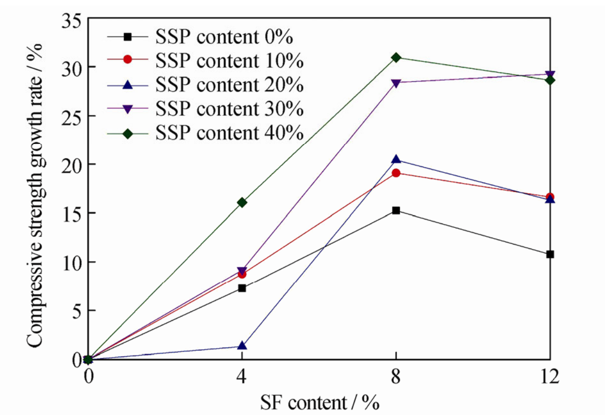

Fig. 1 Relationship between concrete compressive strength growth rate and SF content

SF shows its pozzolanic activity only in the strong alkaline environment. Then SiO_2, the main component of SF, consumes $Ca(OH)_2$ to form C—S—H gel, promoting the hydration of f-CaO to be continued, whose reaction formula are shown in Eq. (1) and Eq. (2)[15], so the C—S—H are generated continuously in this way.

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (1)$$

$$CaO + SiO_2 + H_2O \rightarrow C — S — H \quad (2)$$

In summary, the growth rate of the compressive strength is the largest when the SF content is 8%, and SF and SSP show synergistic effect when they are mixed.

2.2 Effect of SSP on Concrete Compressive Strength

Figure 2 shows the relationship between concrete compressive strength loss rate and SSP content.

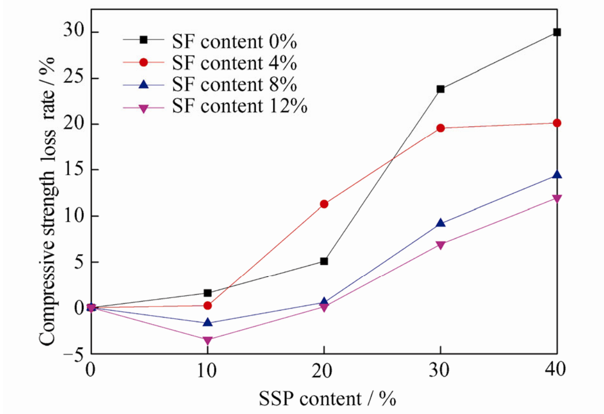

Fig. 2 Relationship between compressive strength loss rate and SSP content

From Fig. 2, we can see that when the amount of SF is constant, the concrete compressive strength loss rate tends to be greater with the increasing amount of SSP, and when the amount of SSP is 20%, the concrete compressive strength loss rate is not more than 10%. This is because the influences of SSP on the compressive strength of concrete reflected in two aspects: on the one hand, the amount of cement is reduced relatively after the incorporation of SSP, and the activity index of SSP is lower than that of cement, so the amount of C—S—H produced by hydration reaction are reduced relatively at the same time, resulting in the reduction of concrete compressive strength; on the other hand, the micro-filler effect[16-18], the SSP, which is finer than the cement, can fill the gaps in the cement and increase the compactness of the concrete, therefore the strength of the concrete increases to some extent. Under the synergetic effect of two factors, the compressive strength of concrete shows a downward trend, and only when the content of SSP is

10%, the compressive strength of concrete with 8% and 12% content of SF increases slightly, indicating that the low activity of SSP is stronger than the filling effect in respect to the influence on compressive strength concrete.

In summary, the compressive strength of concrete decrease with the increasing amount of SSP. When the SSP content is not more than 20%, the compressive strength loss rate is less than 10%, meeting the requirement of engineering.

2.3 Discreteness of Concrete Compressive Strength

We calculated the standard deviation of the concrete compressive strength by Eq. (3) and plotted the curve, shown in Fig. 3, of the relationship between the compressive strength of concrete and SF content. The normal distribution curve of concrete compressive strength can be obtained by Eq. (4) from Fig. 3(a).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} f_{\mathrm{cu},i}^2 - n m_{f\mathrm{cu}}^2}{n-1}} \tag{3}$$

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{4}$$

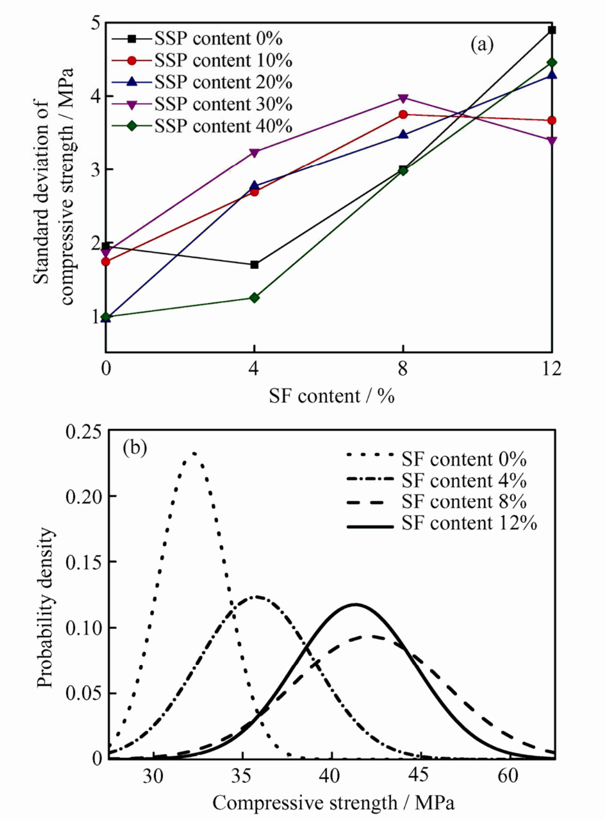

Fig. 3 Standard deviation and normal distribution curve of concrete compressive strength

where $f_{\mathrm{cu},i}$ denotes the measured intensity of the i-th group, $m_{f\mathrm{cu}}$ denotes the average intensity, n denotes the sample capacity, σ is the standard deviation of compressive strength, and μ is the average compressive strength.

It can be seen that the law of the influence of SF content on the discreteness of concrete compressive strength under different SSP content is identical, so only the concrete with 30% content of SSP is taken as an example to draw the normal distribution curve of concrete compressive strength shown in Fig. 3(b).

According to Fig. 3(a), the standard deviation of the compressive strength of concrete increases with the increasing amount of SF, indicating that the addition of SF leads to an increase in the discreteness of compressive strength of the concrete. As can be seen from Fig. 3(b), SF could increase the concrete compressive strength and its discreteness simultaneously.

3 Pozzolanic Effect of SF

Compared with the concrete strength only coming from the hydration reaction of the cement when there is no active mineral admixture, the strength of concrete with active mineral admixture is provided by both the hydration reaction of cement and the pozzolanic effect of mineral admixture. In order to numerically calculate the pozzolanic effect, the pozzolanic effect contribution rate for per 1% content of SF is introduced, whose calculation formula is shown in Eq. (5)[19,20].

$$P = 1 - \frac{R_0(1-q)}{100 q R_q} \tag{5}$$

where R_0 is the compressive strength of concrete without SF, q is the content of SF, and R_q is the compressive strength of concrete when the SF content is q.

The relationship curves between the pozzolanic effect contribution rates for per 1 % content of SF and SF content is shown in Fig. 4.

It can be seen from Fig. 4 that the average pozzolanic effect contribution rate for per 1% SF content of concrete incorporating 4%, 8% and 12% content of SF is 0.94%, 0.84% and 0.85%, respectively. In other words, when the content of SF is between 4% and 12%, every 1% amount of SF will increase the compressive strength of the concrete by 0.84%-0.94%.

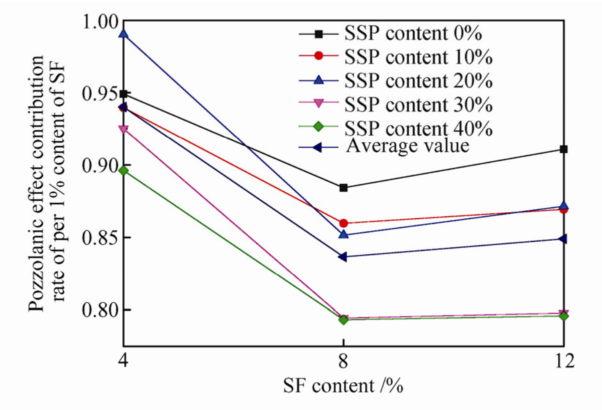

Fig. 4 Relationship between the pozzolanic effect contribution rate for per 1 % content of SF and the content of SF

4 Tension-Compression Ratio of Concrete

The ratio of splitting strength and compressive strength is the tension-compression ratio, which is one of the main indicators of concrete brittleness. Figure 5 shows the relationship curves and fitting surface between the tension-compression ratio of concrete and SF content.

From Fig. 5(a), it can be seen that the concrete tension-compression ratio tends to decrease with the increasing amount of the SF. This is because the SF incorporated into concrete has two functions: the first is the pozzolanic effect, by which the gel produced will increase the compressive strength and splitting strength of concrete simultaneously; the second is the micro-filler effect, which mainly increases the concrete compressive strength by improving the compactness of the concrete. Under the synergistic effect of two factors, the splitting strength increase smaller than compressive strength, which is reflected by the reduction of tension-compression ratio, that is, the concrete brittleness is increased by the incorporation of SF.

Figure 5(b) shows the fitting surface of concrete tension-compression ratio, and its regression formula is shown in Eq. 6, which is recommended to refer for predicting the brittleness of concrete with SF and SSP because its goodness of fit reaches 0.93.

$$z=\frac{0.76+0.01x-0.01y}{1+0.13x-0.09y} \tag{6}$$

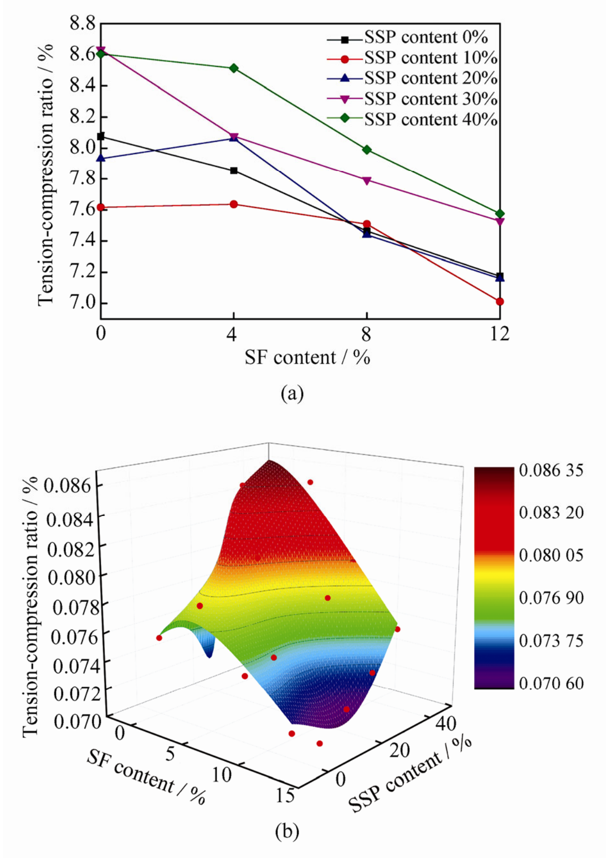

Fig. 5 Relationship curve (a) and fitting surface (b) of SF content, SSP content and tension-compression ratio

5 Optimum Dosage of SF and SSP

Histogram and fitting surface of concrete compressive strength are shown in Fig. 6. From Fig. 6(a), the compressive strengths of SF8SSP30 and SF12SSP30 are 42.09 MPa and 42.36 MPa, respectively, which are both close to 39.88 MPa—the compressive strength of plain concrete. When considering brittleness of concrete and discreteness of concrete compressive strength, the amount of SF should be as less as possible according to Section 2.3 and Section 4 of this paper. Therefore, SF8SSP30 was selected as the optimal group, and SF12SSP30 was the sub-optimal group. Figure 6(b) shows the fitting surface of concrete compressive strength, whose regression formula is shown in Eq. (7).

$$z=\frac{39.76-0.35x+0.53y+0.46y^2-0.03y^3}{1-0.02x+0.03y} \tag{7}$$

From Fig. 6(b), it can be seen that the measured data and the fitting surface coincide basically and the goodness of fit reaches 0.95. Therefore, it is recom-

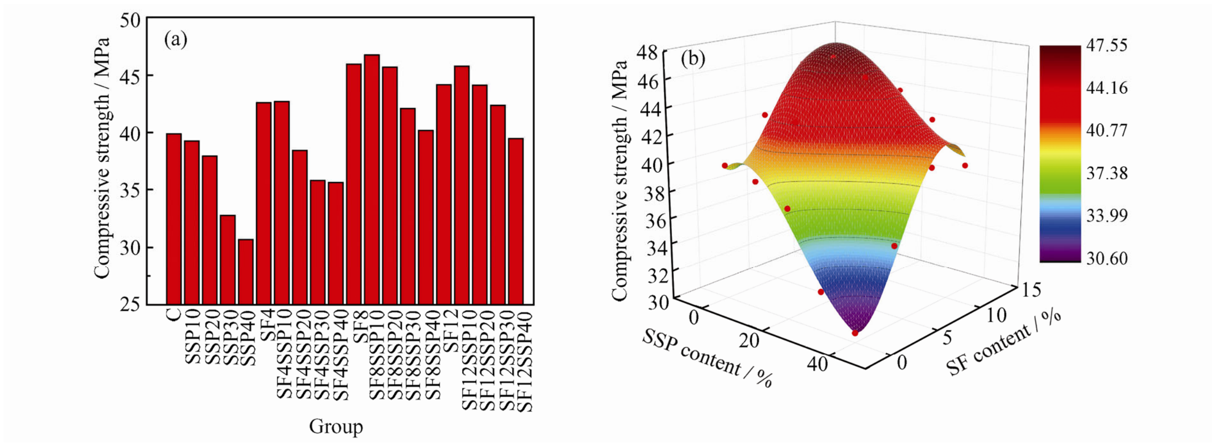

Fig. 6 Histogram(a) and fitting surface(b) of concrete compressive strength

mended to refer to Eq. (7) for estimating the compressive strength of concrete incorporating SF and SSP.

6 Conclusion

In this study, the effect of SF on mechanical properties of concrete incorporating SSP have been investigated. SF can increase the brittleness, compressive strength and compressive strength discreteness of concrete. Every 1% amount of SF will increase the compressive strength of concrete by 0.84%-0.94%, and the compressive strength of concrete increases the most when the content of SF is 8%. SSP will weaken the compressive strength of concrete. When the content of SSP is less than 20%, the compressive strength of concrete will be reduced within 10%, meeting the engineering requirements. SF and SSP show synergistic hydration effect when they are mixed, and the optimal group is SF8SSP30, whose compressive strength is close to that of plain concrete, and whose brittleness and discreteness of compressive strength are lower relatively. With the content of SSF and of SSP as variables, the tension-compression ratio and compressive strength of concrete can be well estimated by surface fitting.

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