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A study of high-performance slag-based composite admixtures

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HIGHLIGHTS

- The SCAs consist of granulated blast furnace slag, steel slag, fly ash and boundary limestone.
- The effects of the composition of the SCAs on the shrinkage, stability and bleeding capacity of the mortar.
- The relationships between the raw material composition, performance and structure of the high-performance SCAs.
- The exceptional performance of SCAs results from the advantageous synergistic effects of GGBFS and SS.

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ABSTRACT

To promote the large-scale application of ground granulated blast furnace slag powder (GGBFS) in the cement and concrete industry, high-performance slag-based composite admixtures (SCAs) were prepared with GGBFS as the main raw material and converter steel slag powder (SS), limestone powder (LP) and fly ash (FA) as auxiliary raw materials. The effects of the fineness and content of each auxiliary raw material on the performance of the SCA were investigated. The experimental results showed that SS had multiple beneficial effects on mortar and concrete; it can increase the strength, reduce the bleeding and compensate for the shrinkage of the concrete. The best performance of medium- and low-strength concrete with a high SCA content was achieved using the SCA with the following composition: GGBFS: 64%; SS: 20%; LP: 6%; and FA: 10%. The fresh Portland cement (PC) + SCA concrete specimens had better fluidity and stability than the PC + GGBFS concrete specimen, and the compressive strengths of the PC + SCA concrete specimens were the same or slightly higher than that of the PC + GGBFS concrete specimen. The results of scanning electron microscopy, X-ray photoelectron spectroscopy and pore size analysis showed that the concrete specimens prepared with PC + SCA had significantly smaller and fewer large pores and a more uniform and dense interfacial structure than the concrete specimen prepared with PC + GGBFS. The exceptional performance of SCAs results from the advantageous synergistic effects of GGBFS and SS.

1. Introduction

Protecting the environment, reducing the consumption of natural resources and enhancing the performance of cement concrete are three important problems currently facing the cement and concrete development process [1–3]. One important approach for solving these problems is to prepare concrete admixtures with large amounts of industrial waste residue with latent hydraulic activity, such as fly ash (FA), ground granulated blast furnace slag powder (GGBFS), steel slag powder (SS) and silica fume (SF) [4–6]. Concrete prepared with GGBFS as the admixture has several performance advantages, such as exceptional mechanical properties, a low rate of slump loss with time and a low heat of hydration [7–10]. However, due to the limited production techniques and total amount of resources, the price of fine GGBFS in China is currently relatively high. As a result, optimal economic returns are difficult to attain when using only Portland cement (PC) and GGBFS to produce concrete. Moreover, the performance of concrete with a high GGBFS content is unsatisfactory in many respects, which must be addressed urgently. For example, fresh concrete with a high GGBFS content has a high tendency to segregate and bleed, shrinks and develops early strength relatively slowly [11,12].

Another important approach for increasing the engineering applications and the value of GGBFS is to combine it with other mineral additives and take advantage of their performance benefits [13,14]. Of the various types of slag-based composite admixtures (SCAs), GGBFS–FA composite admixtures are most frequently studied and are widely used [15–17], whereas other types of SCAs, such as GGBFS–SS and GGBFS–limestone powder (LP) composite admixtures, have been studied less frequently.

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Of the various raw materials used to produce admixtures, FA is characterized by its abundance and low cost. Research has shown that due to the morphological effect of FA particles, FA can be used to improve the fluidity and water retention capacity and significantly reduce the heat of hydration of concrete [18–20]. Moreover, compared to PC, GGBFS and SF, concrete prepared with FA has higher long-term strength. However, due to its low rate of hydration, the early strength of concrete prepared with FA is too low [21–23].

SS is a type of industrial waste residue produced during the steelmaking process. Of the various types of SS, converter SS is the most suitable for use as a cementing material because it is produced in large amounts and has high activity [24,25]. The common minerals in steel slag are olivine, merwinite, alite, belite, calcium aluminio-ferrite, calcium ferrite, RO phase and free-CaO. The presence of those cementitious phases endorses steel slag hydraulic properties. Generally, cement blending with steel slag has longer setting time and lower early strength compared with Portland cement, and sometimes causes much volume expansion due to its high content of dead-burned free-CaO. The use of a combination of GGBFS and SS has significant synergistic effects because SS has a lower hydration activity than GGBFS but a higher equilibrium alkalinity than GGBFS. The presence of SS increases the alkalinity of hydration system and maintain for a long time, which accelerates the disintegration and hydration of GGBFS glass. Meanwhile, the absorption of $Ca(OH)_2$ by GGBFS accelerates the hydration of cement and SS conversely. The hydration of free-CaO of SS engendering a sustainable expansion stress which can compensate for the shrinkage of concrete and promote the continuous growth of long-term strength. Moreover, SS has a very wide particle size distribution and can thus improve the particle size distribution of the cementing material. The presence of SS effectively destroys the flocculent structure that forms from the hydration of the cement, which causes the system to become more homogenous and increases the rate of hydration of each component [26–31].

Currently, high-quality limestone resources in China are limited, but reserves of boundary limestone, which cannot be used in the cement and metallurgical industries, are abundant. Adding a suitable amount of this type of LP can not only fill the cementing material and reduce the cost but also improve the working performance and early strength of the concrete [32–34].

In this study, high-performance SCAs were prepared with GGBFS as the main component and SS, FA and boundary limestone as auxiliary components, and their performance was investigated. The aim of this work was to substantially reduce the production costs while ensuring the original performance advantages of SCAs, address the bleeding, segregation and settlement issues that occur in fresh concrete mortar with a high GGBFS content and reduce the dry shrinkage of the hardened concrete during the construction process. The main contents of this study are as follows: (1) The relationships between the composition of the composite admixture and the fluidity and activity indices of the mortar were investigated. (2) The effects of the composition of the composite admixture on the shrinkage, stability and bleeding capacity of the mortar were explored. (3) Concrete specimens were produced with SCAs. (4) The structures of the concrete specimens and the mechanisms of the SCAs were analyzed. Based on these analyses, the relationships between the raw material composition, performance and structure of the high-performance GGBFS–SS–FA–LP multicomponent composite admixtures were determined.

2. Experimental materials and methods

2.1. Materials

The cementing material used in this study was composed of PC, GGBFS, SS, FA and boundary LP. Table 1 lists the chemical composition of each raw material.

Specifically, 42.5 P·II PC and grade II FA (residue on a 45 μm sieve: 12.6%) were used. The GGBFS and SS, which were obtained from Shaoguan Iron and Steel Group Co. Ltd. in China, were ground using a ball mill. By adjusting the grinding time, powders with various s of fineness were obtained, which were numbered G-1–G-5 and SS-1–SS-4. Figs. 1 and 2 show the particle size distributions and specific surface areas of the GGBFS and SS with various s of fineness, respectively. Natural river sand (maximum critical particle size: 5 mm; fineness modulus: 2.51; water content: 0.19%) was used as the fine aggregate to prepare the concrete specimens. Granite stones (particle size: 5–20 mm; water content: 0.5%) were used as the aggregates. In addition, a naphthalene sulfonate formaldehyde (FDN) water reducer was selected as an additive.

2.2. Experimental methods

PC–SCA composite mortar prisms measuring 40 × 40 × 160 mm were prepared for fluidity and strength measurements according to Chinese National Standard *Method of Testing Cements: Determination of Strength* (GB/T 17671-1999). The ratios of binder to sand, water to binder, and PC to SCA were 1:3, 1:2 and 1:1, respectively. After demoulding, the specimens were cured in water at 20 ± 2 °C. Strength measurements were conducted after 7 d and 28 d of curing.

The bleeding capacity of each composite mortar specimen was determined according to the method stipulated in the *Standard for Test Method of Performance of Building Mortar* (JGJ/T70-2009). A total of 1,350 g of a composite admixture and PC and 2,700 g of river sand were used to prepare each composite mortar specimen with the FDN water reducer at a content of 0.7%. The fluidity of each mortar specimen was limited to 250–260 mm. The dry shrinkage of each PC–SCA composite mortar specimen was determined according to the *Standard Test Method for Dry Shrinkage of Mortar* (JC/T603-2004).

According to the *Standard for Test Method of the Mechanical Properties on Ordinary Concrete* (GB/T50081-2002), C35 strength grade concrete specimens with a strength of 43.2 MPa were prepared. The mix proportion was as follows: cementing

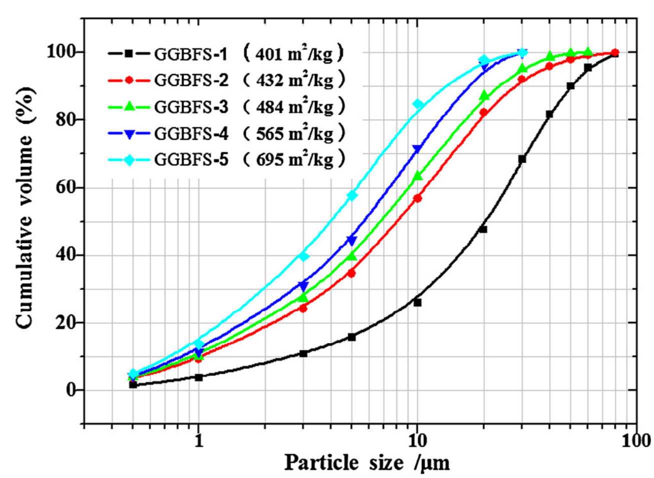

Fig. 1. Particle size distributions of GGBFS.

Table 1
Chemical composition and physical properties of materials.

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	f-CaO	LOI	Density (g/cm^3)	Blaine specific surface area (m^2/kg)
PC	63.38	20.82	5.83	3.43	2.65	–	2.45	3.14	343
GGBFS	34.24	31.14	19.33	1.03	11.75		0.01	2.92	–
SS	46.07	14.04	5.24	20.58	12.40	5.66	−2.03	3.35	–
LP	37.15	1.11	0.62	1.35	14.39	–	44.91	2.74	561
FA	2.62	52.42	30.31	4.89	0.91	–	5.75	2.09	370