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Cementitious properties of super-fine steel slag

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ABSTRACT

In this study, a super-fine steel slag with the specific surface area of 786 m^2/kg was prepared by mechanical grinding. Its cementitious properties were investigated by comparing the results obtained from it with those obtained from ordinary steel slag, fly ash, and cement. The results show that the super-fine steel slag exhibits a much higher activity at early and middle ages but a lower activity at late ages than the ordinary steel slag. Though the specific surface area of the super-fine steel slag is much larger than that of cement, the activity of the super-fine steel slag is still obviously lower than that of cement. The super-fine steel slag replacement tends to weaken the cementitious properties of the composite binder. As compared to fly ash, the super-fine steel slag tends to make more contributions to the hardening of concrete at early ages but far less contributions at late ages. Overall, it seems that it is uneconomical to produce super-fine steel slag by mechanical grinding.

1. Introduction

Steel slag is a kind of solid waste from the steel production. It makes up a proportion of approximately 15% by mass of the steel output [1,2]. In China, about 80 million tons of steel slag is discharged every year [3]. Most of the steel slag is disposed of in rubbish dumps, polluting the environment and occupying massive lands. In recent years, steel slag has been studied for many utilizations, such as aggregates for concrete or asphalt mix [4–8], fillers for foundation engineering [9,10], raw material for brick production [11,12], filtering media for waste water treatment [13–15], mineral admixture for cement or concrete production [16–20], and so on.

The presence of C_3S, C_2S, C_4AF and C_2F in steel slag endorses some cementitious properties. The use of steel slag as a mineral admixture should be given a priority from economical and environmental considerations [10]. However, the hydration activity of steel slag is very low due to its slow cooling history and high content of non-active components [21–23]. Some studies were carried out to improve the cementitious properties of steel slag. Li et al. [3] obtained a new kind of steel slag with higher activity by adding adjusting minerals during the discharging process of steel slag. Wang et al. [24] found that removing some large particles of steel slag could reduce the RO phase (CaO–FeO–MgO–MnO solid solution) content and thus improve its activity. Liang et al. [25] found that the activity of carbonated steel slag was higher than the original steel slag.

The specific surface area of steel slag is generally between 300 and 500 m^2/kg when it is used as a mineral admixture for cement or concrete production. Some studies showed that, in this range, increasing the specific area of steel slag was beneficial to its activity [26–28]. It is interesting to know the activity of steel slag with even higher specific surface area. In this study, the cementitious properties of a super-fine steel slag were investigated.

2. Experimental

2.1. Raw materials

The cement used was Portland cement with the strength grade of 42.5 and the specific surface area of 342 m^2/kg which conformed to the Chinese National Standard GB175-1999. The fly ash used was low-calcium fly ash with a specific surface area of 358 m^2/kg which conformed to the Chinese National Standard GB/T1596-2005. The steel slag used was basic oxygen furnace steel slag. Two steel slags with different fineness were obtained by mechanical grinding: one with a specific surface area of 442 m^2/kg (denoted by coarse steel slag) and the other with a specific surface area of 786 m^2/kg (denoted by fine steel slag). The chemical compositions of the materials used are listed in Table 1. Fig. 1 shows the particle size distributions of the two steel slags. It is evident that the fine steel slag has much less coarse particles larger than 100 μm and more fine particles smaller than 5 μm than the coarse steel slag.

2.2. Test methods

Pastes were prepared for the determination of non-evaporable water content. Five pastes were prepared: coarse steel slag paste, fine steel slag paste, pure cement paste, composite paste containing 45% coarse steel slag, and composite paste containing 45% fine steel slag. The water-to-binder ratio of the two steel slag pastes is 0.30. The water-to-binder ratio of the other pastes is 0.40. All the pastes were cast into plastic centrifuge tubes after mixing and then cured

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Table 1
Chemical composition of materials/%.

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MnO	SO_3	MgO	P_2O_5
cement	63.46	21.76	4.38	2.76	–	2.57	2.14	–
fly ash	2.86	53.33	27.65	6.04	–	0.45	1.35	–
steel slag	43.38	17.03	5.64	22.69	1.59	0.23	5.98	0.33

at 20 ± 1 °C to testing ages. At the ages of 3, 28, 90, 360, and 720 days, the hydration was stopped by soaking the pastes in acetone. The non-evaporable water content of paste was obtained as the difference in mass between the sample heated at 105 °C and 1000 °C normalized by the mass after heating at 105 °C, and correcting for the loss on ignition of the unhydrated sample [29,30].

For studying the compressive strength of steel slag paste, cube samples (4 × 4 × 4 cm) were prepared by adopting a water-to-binder ratio of 0.30. The cube samples were first cured in a fog room at 20 °C and 95% relative humidity for 28 days, and then they were cured in water at 20 °C. For studying the activity index of steel slag, mortar bars (4 × 4 × 16 cm) were prepared by adopting a water-to-binder ratio of 0.50 and a sand-to-binder ratio of 3.0. The mortars were first cured in a fog room at 20 °C and 95% relative humidity for 2 days, and then they were cured in water at 20 °C. The activity index of steel slag was the ratio (in percent) of the compressive strength of a mortar made with 50% steel slag and 50% cement to that of a mortar made with 100% cement. At the ages of 3, 28, 90, 360, and 720 days, the compressive strengths of pastes and mortars were tested.

The mix proportions of 7 concretes are shown in Table 2. Crushed limestone with a particle size between 5.0 and 20.0 mm was used as the coarse aggregate. The fine aggregate was natural river sand with a maximum particle size of 5.0 mm. The binder: fine aggregate: coarse aggregate: water ratio for all the concrete is the same, but the compositions of the binders are different. Sample 1 is a pure cement concrete; Samples 2, 3, and 4 are prepared by replacing 25% (by mass) of cement by coarse steel slag, fine steel slag, and fly ash, respectively; Samples 5, 6, and 7 are prepared by replacing 45% (by mass) of cement by coarse steel slag, fine steel slag, and fly ash, respectively.

Concretes of 10 × 10 × 10 cm were prepared. The concretes were cured in a fog room at 20 °C and 95% relative humidity until testing ages. At the ages of 3, 28, 90, 360, and 720 days, the compressive strength of concrete was tested. At the ages of 28, 90, 360, and 720 days, the ability to resist chloride ion penetration of concrete was tested according to ASTM C1202. At the ages of 90 and 720 days, the porosity of concrete was tested by the following method: (1) cut the concrete into slices of 10 × 10 × 1 cm; (2) place the slice in acetone for 2 days; (3) dry the slice at 80 °C for 30 days and then weigh its mass (m_1); (4) weigh the mass (m_2) and volume (V) of water-saturated slice; (5) the porosity is $(m_2 - m_1)/V\rho$, ρ is the density of water.

Table 2
Mix proportion of concrete.

Samples	Mix proportion (kg/m^3)						
	cement	coarse steel slag	fine steel slag	fly ash	fine aggregate	coarse aggregate	water
1	360	0	0	0	830	1050	165.6
2	270	90	0	0	830	1050	165.6
3	270	0	90	0	830	1050	165.6
4	270	0	0	90	830	1050	165.6
5	198	162	0	0	830	1050	165.6
6	198	0	162	0	830	1050	165.6
7	198	0	0	162	830	1050	165.6

3. Results and discussion

3.1. Non-evaporable water content

Fig. 2 shows the non-evaporable water contents of the two steel slag pastes. It is clear that at each age, the non-evaporable water content of the fine steel slag paste is higher than that of the coarse steel slag paste. It is an indication that the fine steel slag produces more hydration products than the coarse steel slag at each age. This is believed to be due to the beneficial effect of mechanical grinding, which increases the lattice defect and specific surface area of particle.

It can also be seen from Fig. 2 that within 28 days, the difference between the curves of the pastes becomes larger. From 28 to 90 days, the difference remains almost unchanged. However, the difference becomes smaller after 90 days. It is an indication that mechanical grinding enhances hydration activity of steel slag at the early and middle stages. Whereas the late hydration activity of the fine steel slag is lower than that of the coarse steel slag, which is believed to be due to the rapid reduction of active components with age in the fine steel slag.

Fig. 3 shows the non-evaporable water contents of the cement paste and two composite pastes. The non-evaporable water contents of the composite pastes are obviously lower than that of the cement paste at each age, indicating that the activity of both the fine steel slag and coarse steel slag is much lower than that of the cement. As expected, the non-evaporable water content of the paste containing fine steel slag is higher than that of the paste containing coarse steel slag. It is notable that the deference between the curves of the two composite pastes becomes larger within 28 days but smaller after 90 days, which is consistent with the trend observed from Fig. 2.

3.2. Strength of paste and mortar

Fig. 4 shows the compressive strengths of the two steel slag pastes. At the age of 3 days, the compressive strengths of both the coarse steel slag paste and fine steel slag paste are very low. The fine steel

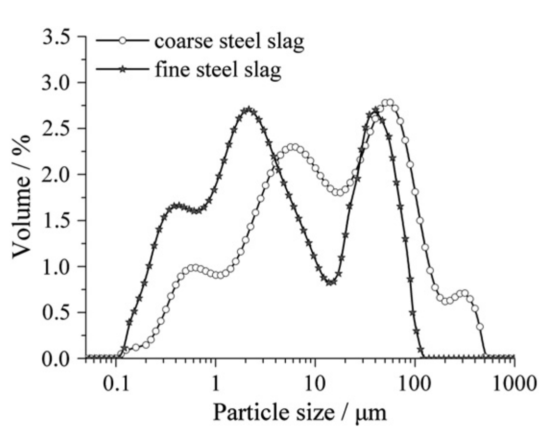

Fig. 1. Particle size distributions of steel slags.

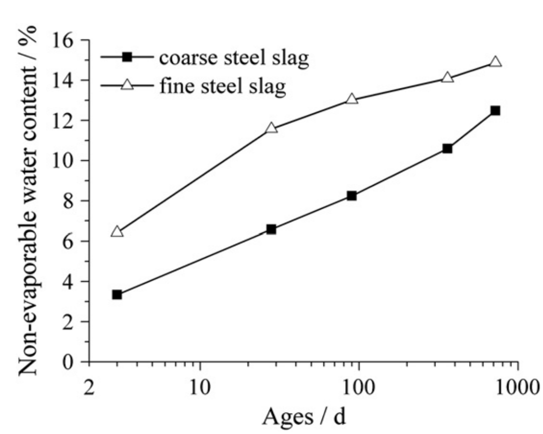

Fig. 2. Non-evaporable water contents of the steel slag pastes.