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Strength Activity Index of Air Quenched Basic Oxygen Furnace Steel Slag

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Abstract: Air quenched basic oxygen furnace steel slag (BOF-SS) is processed at very high cooling rate, which is expected to have different cementitious properties from conventional slowly cooled BOF-SS. For this purpose, the strength activity indexes of air quenched and slowly cooled BOF-SS are investigated. The results reveal that, under the specific surface area (S) of 490 m^2/kg, the compressive strength activity index reaches 1.24 after 28 days with replacement of 15% air quenched BOF-SS and reaches 1.05 after 28 days with replacement of 20% air quenched BOF-SS and 30% granulated blast furnace slag (GBFS). The cementitious activity of air quenched BOF-SS is obviously higher than that of slowly cooled BOF-SS, mainly because it contains more C_3S and glassy phases.

Key words: basic oxygen furnace steel slag; strength activity index; mineral characteristics; cementitious property; tricalcium silicate (C_3S)

Steel slags are the primary by-products in steelmaking processes. They are formed by the combination of impurities from blast furnace molten iron, fluxes and iron oxides. Basic oxygen furnace steel slag (BOF-SS) is the steel slag generated from basic oxygen furnace steelmaking. It primarily consists of CaO, SiO_2, FeO and MgO, also with some minor component like Al_2O_3, MnO and P_2O_5. BOF-SS is one of the most abundant by-products in steel plants. According to the steel production by basic oxygen furnace[1], it is estimated that 70% of the steel slags around the world is BOF-SS. The proportion is even higher in China, and exceeds 90%. Approximately 100 — 150 kg BOF-SS is discharged when one ton crude steel is produced. For example in China, about 85 Mt BOF-SS has been produced in China in 2014. Thus recycling of the slags is a critical issue for both steel plants and societies.

BOF-SS has some useful components like CaO and MgO; therefore, it can be charged in sintering and ironmaking process to make better utilization of calcium values[2,3]. Beside recycling in steel plants, BOF-SS is always used as construction and building materials in roads and civil engineering due to its hard characteristics and used as cement additives based on its cementitious properties[4,5]. It is suggested that maximum environmental credit of the slags recycling occurs when recycled to raw materials for slag cement and Portland cement[6], therefore many efforts have been made to investigate the characteristics of steel slag cements[7-13].

Despite the potential energy cost reduction, it is estimated that only about 10% of the BOF-SS is reused for slag cement production in China[14]. BOF-SS has compositions similar to that of Portland cement. Nevertheless, its hydraulic activity is much weaker, mainly because steel slags have higher content of iron oxide and lower content of cementitious minerals such as tricalcium silicate (C_3S) and β-dicalcium silicate (β-C_2S)[15]. Sometimes RO phase (CaO-FeO-MgO solid solution) or γ-C_2S, which has no cementitious activity, is a predominant mineral of BOF-SS[16,17].

Conventionally, most of the molten steel slags around the world and in China are slowly or semi-fast cooled, by methods like natural air cooling, water spray and hot-spot disintegration[7,18]. Only a small portion of the slags are quenched in the air or water[19,20]. The steel slags cooled under different cooling rates will crystallize in much different ways.

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Under very fast cooling, the mineral may retain its high temperature composition and structure, and present in metastable states in the cooled steel slag. It is well known that cementitious C_3S is thermodynamically stable only above 1250 ℃, and it will decompose to CaO and C_2S at lower temperature[21]. Besides, the other major cementitious component, β-C_2S, turns to non-cementitious γ-C_2S when the temperature drops below 500 ℃ during slow cooling. Therefore, in cement clinker production, the clinker is sharply cooled down to low temperature. The decomposition rate of C_3S is minor or negligible at such cooling rate. And also there is no enough time for the lattice rearrangement of C_2S, so the C_2S in clinker exists in metastable state, which is hydraulic active. For the same reason, the quenched steel slags, which undergo very high cooling rates, are expected to contain higher content of cementitious component like C_3S and β-C_2S than slowly cooled slags, and then result in better cementitious activities.

The mineragraphy of a material depends on both its chemical compositions and thermal history. The effect of chemical composition of steel slag on its mineragraphy has already been known[22]. However, there are few reports on the effects of thermal history, or more specifically to steel slag, the cooling methods of molten slag, on its mineragraphy and cementitious properties[23,24]. Murphy et al.[23] and Reddy et al.[24] have confirmed that the cementitious properties of steel slags can be improved by quenching of molten slag. However, these works focused on the water quenching of molten slag.

Recently, the air quenching method for processing molten steel slag has become more popular in China[25,26], due to its high efficiency and potential ability to recover the waste heat of molten slag. So in present work, the mineragraphy and cementitious of air quenched BOF-SS were studied. The comparison between air quenched BOF-SS and slowly cooled BOF-SS was also presented. This study aims to improve the cementitious properties of steel slag by controlled cooling of molten slag.

1 Materials and Methods

1.1 Materials

Three kinds of slags were used in present work: air quenched BOF-SS which was atomized by high pressure air, slowly cooled BOF-SS which was naturally cooled in the air, and granulated blast furnace slag (GBFS) which was quenched by high pressure water. All of the slags were supplied from a steel plant in China. The air quenched and slowly cooled BOF-SS were obtained from the same furnace to ensure their similar compositions. The chemical compositions of slags are listed in Table 1. It is shown that the GBFS has a lower basicity (w_{CaO}/w_{SiO_2}) than steel slags, and both two steel slags have a high level of free lime content.

Table 1 Chemical compositions of experimental slags

Slag	Composition/mass%									w_{CaO}/w_{SiO_2}
	SiO_2	Al_2O_3	CaO	MgO	MnO	TFe	P	S	f-CaO	
GBFS	32.10	17.62	39.66	8.48	<0.10	0.45	<0.10	1.17	0.48	1.24
Air quenched BOF-SS	14.81	1.65	44.46	7.64	1.52	19.32	0.38	0.06	6.97	3.00
Slowly cooled BOF-SS	15.94	3.50	45.97	10.16	1.42	14.88	0.88	0.15	5.80	2.88

Ground slag powders were obtained by grinding the slags in a laboratory batch ball mill, which was charged with steel ball of 5 — 10 mm in diameter. The specific surface area (S) of slag powders was detected in an ST-08 specific surface area analyzer using BET method. The minerals of slags were identified by X-ray diffractometry (XRD, PANalytical® X'pert Pro MPD) method, and the morphologies of slags were observed in a scanning electron microscope (SEM, Hitachi S-4800). The differential scanning calorimetry-thermo-gravimetric (DSC-TG, STA 449 C Jupiter®) method was used to determine the existence of glassy phase in air quenched BOF-SS.

1.2 Strength activity index of slag

Blend cement were made by mixing slag powders with control cement at set ratios. Cement mortars were made by mixing blend cement, standard sand and water with ratio of 1 ∶ 3 ∶ 0.5. The compressive and flexural strength of mortars were tested after 1, 7 and 28 days according to Chinese national standard GB/T 17671—1999. Strength activity index is defined as the ratio of the strength of blend cement mortar to that of control cement mortar at the same age.