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Review

Characteristics of steel slags and their use in cement and concrete—A review

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ABSTRACT

Steel slags are industrial by-products of steel manufacturing, characterized as highly calcareous, siliceous and ferrous. They can be categorized into basic oxygen furnace (BOF) slag, electric arc furnace (EAF) slag, and ladle furnace (LF) slag. They are found to be useful in many fields, such as road construction, asphalt concrete, agricultural fertilizer, and soil improvement. However, better utilization for value-added purposes in cement and concrete products can be achieved. In this paper, an overview of the recent achievements and challenges of using steel slags (BOF, EAF and LF slag) as cement replacement (usually ground into powder form with the size of 400–500 m^2/kg) and aggregate in cement concrete is presented. The results suggest that the cementitious ability of all steel slags in concrete is low and requires activation. For the incorporation of steel slags as aggregate in concrete, special attention needs to be paid due to the potential volumetric instability associated with the hydration of free CaO and/or MgO in the slags. Studies have indicated that adequate aging/weathering and treatments can enhance the hydrolyses of free-CaO and -MgO to mitigate the instability. Considering the environmental and economic aspects, steel slags are also considered to have a potential use as the raw meal in cement clinker production.

1. Introduction

Recently, the green supply chain (e.g., waste-to-resources) has been aggressively established in industrial parks around the world to realize a circular economy (Li et al., 2015). Steel slags, industrial by-products of steel manufacturing, are annually produced in a huge quantity, which should be considered as a green resource. Modern steels can be broadly categorized into four types, i.e., carbon, alloy, stainless and tool steels. Carbon steel is produced either in a basic oxygen furnace (BOF) or an electric arc furnace (EAF), and then refined in a ladle furnace (LF) to achieve a better quality. As for stainless steel, it can be produced in an EAF, an LF, or an argon oxygen decarburization (AOD) furnace (Iacobescu et al., 2016; Kriskova et al., 2012; Zhang and Xin, 2011). During the manufacturing of carbon and stainless steels, a significant amount of by-product steel-slag is produced, accounting for about 15–20 wt.% of the total steel output (Han et al., 2015; Shi, 2004). The compositions of the generated steel slags are highly variable and basically, they can be classified into BOF slag, EAF slag and LF slag.

The annual production of steel slags is about 14 million tons in Japan (NSA, 2017), 21 million tons in Europe (Euroslag, 2012) and over a hundred million tons in China (Zhang et al., 2011). Compared with the widespread use of blast furnace slag, steel slags undergo less upgrading since they usually encounter several technological barriers to valorization such as volume instability (Pan et al., 2016). More than 400 million tons of steel slags have been deposited in China, with an annual accumulation rate of 100 million tons, leading to occupation of lands and potential pollution of water and soil due to the alkaline leachates from steel slags (Mayes et al., 2008; Shi and Qian, 2000; Zhang et al., 2011). Currently, steel slags can be recycled for internal metallurgical purposes (Yi et al., 2012) or used in road construction (Pasetto and Baldo, 2010a,b, 2015, 2016), cement and concrete (Carvalho et al., 2017; Yi et al., 2012), bituminous mixes (Skaf et al., 2017), fertilizer (Yi et al., 2012) and soil improvement (Poh et al., 2006). Several studies have also evaluated the feasibility of steel slags for CO_2 mineralization (Pan et al., 2017; Yu and Wang, 2011) and water pollution control (Drizo et al., 2006). In the US, about 60.3% of the total steel slag production is directly used as road base, while the remainder is used for asphaltic concrete (10.9%), fill (10.8%) and cement clinker production (5.0%) (Ilyushechkin et al., 2012). In China, the utilization ratio of steel slags is less than 30%, found in cement production, chemical admixture for concrete, brick and block manufacturing (NDRC, 2014; Yi et al., 2012).

Due to the high demand for cement and concrete production worldwide, the cement and concrete industries have an increasing

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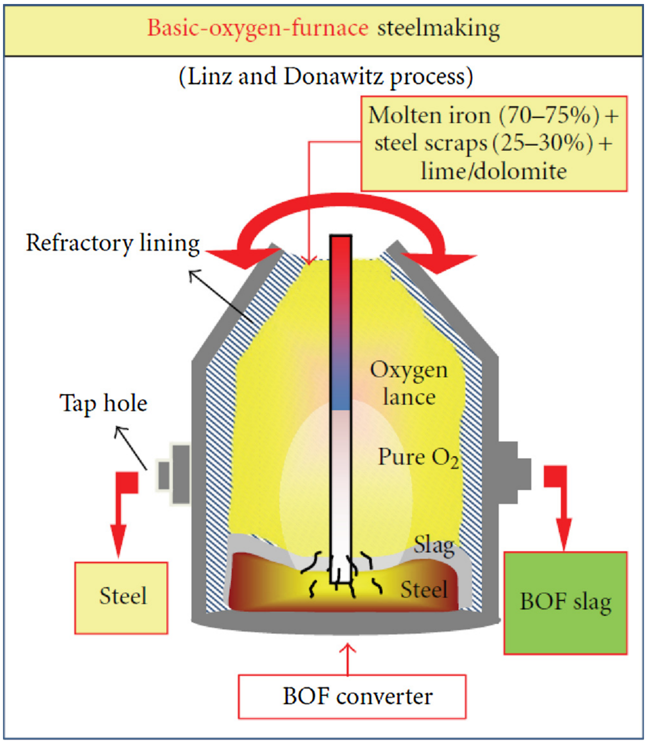

Fig. 1. Schematic representation of a basic oxygen furnace process (Yildirim and Prezzi, 2011).

interest in finding alternative materials to replace the use of natural resources. Thus, extensive studies have been carried out to explore the possibility of utilizing steel slags as cement and concrete materials. Alternatively, they are involved in cement clinker production, which in turn reduces CO_2 emissions and the total cost of the materials used (Reddy et al., 2006). This paper provides a critical review of the valorization of steel slags in cement, concrete and clinker production. The challenges and opportunities of using BOF, EAF and LF slags as supplementary cementitious materials and/or aggregates in cement and concrete are illustrated. The use of steel slags for cement clinker production is also discussed.

2. Basic oxygen furnace (BOF) slag

2.1. Generation processes

In China, BOF slag accounts for about 70% of the annual steel slag production (Cheng and Yang, 2010). In the BOF process (Fig. 1), minor steel scrap and a large amount of molten iron from ironmaking as well as fluxes (lime/dolomite) are added into the furnace, and a 99% pure oxygen flow is applied at supersonic speed through a lance to initiate intense oxidation reactions at a temperature of 1600–1650 °C. Once the desired chemical composition is achieved, the oxygen supply is stopped and the slag, composed of the impurities combined with burnt lime or dolomite, floats on top of the molten steel (Yildirim and Prezzi, 2011).

There are numerous available methods for cooling steel slags, including natural air cooling, water spraying, air quenching, and shallow box chilling (Shi, 2004). The cooling medium and cooling rate of the above methods are quite different, thereby resulting in variable compositions, morphology, hydration properties and leaching characteristics of the steel slag produced. Prior to valorization, steel slags may also undergo metal recovery processes (e.g. crushing, screening and magnetic separation) to recover valuable components such as iron (Shen and Forssberg, 2003; Zhang et al., 2011).

2.2. Physico-chemical characteristics

The chemical compositions of BOF slag are highly variable because of the diversity of iron ores, admixtures, steel-making methods and cooling processes. Table 1 summarizes the chemical properties of BOF slag used from the literature. BOF slag is composed mainly of 40–60% CaO, 10-20% SiO_2, 20–30% Fe_2O_3 (FeO/Fe), 1–6% Al_2O_3 and 2–10% MgO and the remaining minor oxides are MnO, P_2O_5, Na_2O, SO_3, etc. The presence of a high content of CaO and MgO in BOF slag is mainly attributed to the high fluxes dosage for minimizing the impurities, while the iron oxides come from the iron residue that was not reclaimed during the conversion of molten iron to steel (Geiseler, 1996; Yildirim and Prezzi, 2011).

BOF slag usually possesses relatively high basicity (ratio of alkaline oxides to acidic oxides) and presents in different mineral phases, including tricalcium silicate (C_3S), dicalcium silicate (C_2S), dicalcium ferrite (C_2F), MgO, CaO and RO phase (CaO, MgO, MnO and FeO solid solution) (Belhadj et al., 2012; Han et al., 2015; Wang et al., 2013a; Yildirim and Prezzi, 2011). Shi and Qian (2000) reported that the content of lime (*f*-CaO) increases with the basicity of steel slag and thus the *f*-CaO content in BOF slag could be as high as 10%. This is relatively higher than that of other steel slags (Geiseler, 1996; Reddy et al., 2006). The iron may exist in forms such as wustite and magnetite, compounds that have a negligible cementitious capability (Lizarazo-Marriaga et al., 2011).

BOF slag is a rock-like and dark (due to the high content of iron) material with an angular surface and cavernous inside (Fig. 2). Table 2 summarizes the physical properties of BOF slag used from the literature. It is found that the average specific gravity of the slag is around 3.4, which is ~30% higher than normal aggregate. It also possesses low crushing value (i.e., high hardness) and contains highly porous structures (Pang et al., 2015; Adegoloye et al., 2015).

Table 1
Chemical compositions of BOF slags (wt.%) used from the literature.

References	Sources	SiO_2	Al_2O_3	Fe/FeO/Fe_2O_3	CaO	MgO	SO_3	MnO	P_2O_5	*f*-CaO	Others	LOI	Treatment
Palankar et al. (2016)	India	15.0	4.1	22.5 (Fe_2O_3)	41.5	6.2	0.1	–	–	5.3	0.14(Na_2O)/0.05(K_2O)	0.25	Before weathering
Pang et al. (2016b)	China	14.8	5.5	18.4 (Fe_2O_3)	46.7	6.3	–	2.8	1.7	7.5	–	3.04	–
Wang et al. (2013a)	China	15.5	5.4	25.5 (Fe_2O_3)	38.6	7.7	0.2	1.9	1.6	–	–	–	–
Liu et al. (2016)	China	11.0	1.4	12.7 (Fe_2O_3)/12.7 (FeO)	41.4	8.6	–	–	–	–	–	–	Cooled by hot stuffy method
Li et al. (2013)	China	18.9	2.9	8.9(Fe_2O_3)/13.5(FeO)/1.22(Fe)	40.0	5.4	0.9	2.8	1.3	–	–	–	–
Lizarazo-Marriaga et al. (2011)	U.K.	11.5	2.3	27.3(Fe_2O_3)	37.4	9.3	0.3	3.7	1.3	–	0.37(TiO_2)/0.03(Na_2O)/0.01(K_2O)	3.12	Weathered
Monshi and Asgarani (1999)	Iran	10.4	2.0	21.0(Fe_2O_3)	56.4	1.7	–	2.5	–	–	3.1(TiO_2)/0.2(S)/2.4(V_2O_5)/0.3(Na_2O+K_2O)	–	Magnetic separated

Remark: – means not detected or clarified, LOI = Loss on ignition. Hot stuffy, a heat pyrolytic pulverization technology.