Waste Management 41 (2015) 85–93

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Valorization of electric arc furnace primary steelmaking slags for cement applications

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ARTICLE INFO

Article history:
Received 12 December 2014
Accepted 5 March 2015
Available online 8 April 2015

Keywords:
Electric arc furnace slag
FeO
REAFS
Cement addition
Confocal laser scanning microscopy

ABSTRACT

To produce supplementary cementitious materials from electric arc furnace (EAF) slags, FeO was reduced using a two-stage reduction process that included an Al-dross reduction reaction followed by direct carbon reduction. A decrease in FeO was observed on tapping after the first-stage reduction, and further reduction with a stirred carbon rod in the second-stage reduction resulted in final FeO content below 5 wt%, which is compatible with cement clinker applications. The reduced electric arc furnace slags (REAFS) mixed with cement at a unit ratio exhibited physical properties comparable to those of commercialized ground granulated blast furnace slags (GGBFS). Confocal laser scanning microscopy (CLSM) was used to obtain fundamental information on the cooling characteristics and conditions required to obtain amorphous REAFS. REAFS can be applied in cement mixtures to achieve the hydraulic properties needed for commercial use.

1. Introduction

The production of crude steel in South Korea surpassed 70 million tons in 2012, and approximately 24 million tons of slag was produced (Korean Iron and Steel Association, 2012). While more than 75% of the ground granulated blast furnace slag (GGBFS) is used as supplementary cementitious materials (Osborne, 1999; Roy and Idorn, 1982; Kumar et al., 2008; De Schutter and Taerwe, 1995; Wu et al., 1983; Richardson and Groves, 1992; Cheng and Chiu, 2003), steelmaking slags, including electric arc furnace (EAF) slags and basic oxygen furnace (BOF) slags, which contain more than 20 wt% FeO, cannot be fully utilized in this capacity and are typically used in road-bed materials or as backfill after the magnetic separation of FeO (Manso et al., 2006; Jones, 2004; Geiseler, 1996). Thus, lowering the total Fe content of steelmaking slags is of primary concern. The typical compositional range of blast furnace and steelmaking slags analyzed from various plants in Korea is provided in Table 1.

Unlike blast furnace slags, applications of steelmaking slags in higher-value-added by-products have been limited due to the aforementioned high FeO content and density, which make it unsuitable for cement. Previous studies have demonstrated the potential utilization of EAF slag in concrete, road construction, and cement applications without decreasing the initial FeO content. Manso et al. (2004) determined that EAF slags are applicable for aggregates in concrete when added with fine mineral binders, although the durability of the resulting concrete under ice and water conditions was slightly lower than that of conventional concrete. Ahmedzade and Sengoz (2009) reported that the use of steel slags as coarse aggregates in asphalt concrete results in increased stability and stiffness, resulting in higher resistance to permanent deformation compared to mixtures containing limestone. A review of the opportunities for coarse steel slag utilization for road construction material in Europe revealed that steelmaking slags provide stronger bearing capacity due to their high density and abrasion resistance (Motz and Geiseler, 2001). Adolfsson et al. (2007) studied the hydraulic properties of sulpho-aluminate belite cement with steelmaking slags finding the compressive strength to be satisfactory after 28 days hydration. Muhmood et al. (2009) observed that re-melting and water quenching treatment enhanced the cementitious behavior of EAF steelmaking slag and substitution of BF slags with up to 20% EAF slags resulted in compressive strength comparable to that of current GGBFS cements. However, applications of these studies and the amount of EAF slags used in the mixtures were limited. As the steel industry continues to decrease the outgoing FeO content in steelmaking slag via the application of new technologies, fundamental studies of FeO

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http://dx.doi.org/10.1016/j.wasman.2015.03.019
0956-053X/

Table 1
Major compositional range and application of the typical ironmaking and steelmaking slags obtained from various plants within Korea.

Classification		Composition (wt%)				Current applications
		CaO	SiO_2	Total Fe	Al_2O_3	
Ironmaking	BF slag	35–45	30–40	<1	10–20	– Supplementary cementitious materials
Steelmaking	BOF slag	35–45	10–20	20–30	<5	– Road bed
	EAF slag	20–30	10–20	20–30	<10	– Fertilizer

reduced electric arc furnace slags (REAFS) and the possible application of REAFS as a supplementary cementitious material like GGBFS are needed.

The objective of this study was to evaluate possible applications of EAF slags in higher-value-added products such as cements after lowering the FeO content in the slag using a two-stage reduction process. In the first stage, the steelmaking practice was modified by adding Al briquettes (30% Al–70% Al_2O_3) to decrease the outgoing FeO in the slag from a commercial scale EAF. In the second stage, the slag was further reduced on a laboratory scale to produce REAFS with low FeO. The reduction behavior and kinetics of REAFS production from the industrial plant to the laboratory-scale induction furnace are presented. The REAFS was then mixed with ordinary Portland cement (OPC) as a supplementary cementitious material and the physical properties of the normalized mortar was elaborated. The compressive strength as a function of curing time for the standard prismatic specimens using REAFS was compared to that of typical GGBFS cements. To identify the cooling conditions and the compositional effects on the generation of amorphous phases to increase the hydraulic properties of the slag, confocal laser scanning microscopy (CLSM) was used to study the in-situ crystallization behavior of the slags. Within the scope of the present study, the oxygen partial pressure at steelmaking temperatures for the EAF is low enough that the dominant iron oxide phase existing would be the wustite (Fe_xO) phase. Thus, for simplicity Fe_xO has been uniformly represented as FeO throughout the manuscript.

2. Experimental work

2.1. Experimental procedure overview

Fig. 1 shows the flow of the current research work. The reduction of the FeO content in EAF slags was initially performed in the steel plant. This increases the metal yield for the steelmakers and decreases the load in the second stage of the reduction in a two-stage reduction process. After the steel is tapped, the slag is poured into the slag pot and then cooled in the slag yard. A small portion of the cooled slag, which contained approximately 21 wt% FeO, was sampled and re-melted in a laboratory-scale induction furnace for the second-stage reduction. To inhibit premature solidification of the slag during the reduction of FeO, the reducing agent was switched from Al-dross to carbon via graphite rods. This reaction of FeO in the slag with the carbon resulted in a FeO content of less than 5 wt% and produced the supplementary cementitious REAFS material needed for further testing. In the actual industrial scale application and production of the REAFS, the reduction with carbon would occur within the slag pot of the plant, where the excess slag heat is utilized during the smelting reduction. In the present work, the second-stage reduction was accomplished after the slag was completely solidified and thus additional heating in a controlled laboratory environment was designed to test the viability of reduction and subsequent changes in the slag composition. Once the first- and second-stage reductions were completed and the REAFS produced, the slag was water-quenched to obtain an amorphous REAFS. The amorphous REAFS was then blended into the cement admixture and preformed into standard prismatic specimens to evaluate its compressive strength. To obtain the conditions for cooling the reduced slag, fundamental studies of initial crystallization at various FeO contents and cooling conditions were performed using the CLSM. Both the calcium silicate-based and calcium aluminate-based slags were studied to compare and establish the minimum cooling rate for an amorphous slag production.

2.2. Reduction of EAF slags using agitated carbon rods

To produce REAFS suitable for use as supplementary cementitious materials similar to GGBFS, FeO-containing EAF slags obtained after the first-stage reduction in the industrial EAF must be further reduced. An agitated carbon rod manifold with 4 carbon rods was immersed into an induction furnace (Serial No. 08150-425, DongYang Induction MFC LTD., Inchon, Korea) with an Al_2O_3 crucible diameter of 7 cm and a height of 17.5 cm containing 0.3 kg of slag, as previously illustrated in Fig. 1. A graphite outer crucible with a diameter of 9 cm and a height of 15.5 cm was used as the susceptor. The temperature of the furnace was controlled to a target temperature of 1773 K (1500 °C) with a precision of ±3 K using a PID (proportional integral derivative) controller. The detailed chemical composition of the initial slag is provided in Table 2. It should be noted that the P within the EAF slag for

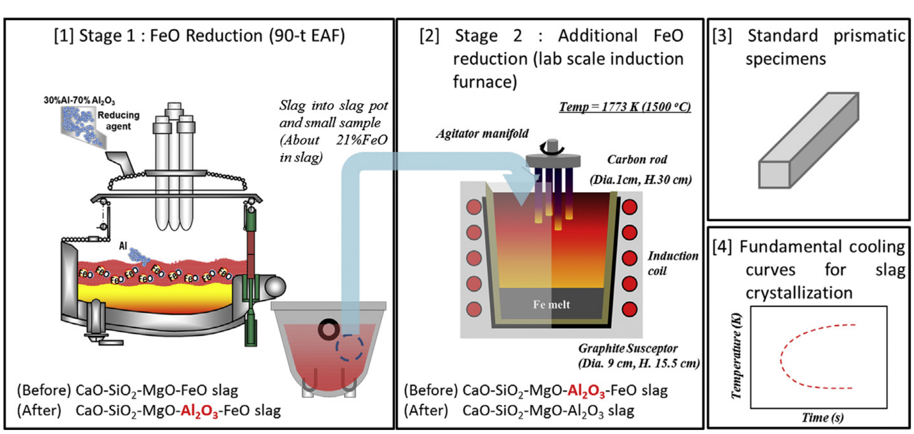

Fig. 1. Schematic overview of the experimental work conducted in the present research.