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Performance of optimized electric arc furnace dust-based cementitious matrix compared to conventional supplementary cementitious materials

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HIGHLIGHTS

- The effects of EAFD on fresh and hardened properties of mortars were investigated.
- A direct relationship between extended setting time and EAFD content was found.
- Ettringite crystals vanished due to alteration reaction of Zn with Ca in C_3A phase.
- Optimized EAFD content provided an intermediate performance compared to FA and SF.
- Formation of hemimorphite-like material (Z–S–H) attributed to better performance.

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ABSTRACT

Sustainability in concrete construction necessitates exploration of industrial waste product materials as primary examples of renewable resources for use as fine powders in concrete construction. The disposal of electric arc furnace dust (EAFD), a by-product of the electric steelmaking industry, represents an environmental issue. The recycling of EAFD in concrete has been a subject of interest for several decades. The principal aim of this study is to evaluate an optimized quantity of fresh EAFD in a cementitious matrix and compare its performance against various matrices with different supplementary cementitious materials (SCMs). The effects of EAFD incorporation on the performance of fresh and hardened properties of different mortars prepared using different water-to-binder (W/B) and sand-to-cement (S/C) ratios were investigated and compared to those of mortars containing silica fume and fly ash. The results have shown that the incorporation of EAFD after certain dosage has led to a notable disappearance of ettringite crystals due to alteration reaction of Zn with Ca in C_3A phase. The microstructure of selected mixtures was analyzed using SEM-EDS, XRD, XRF, MIP and FT-IR techniques. The results showed that the optimum EAFD content provided an intermediate performance compared to the performance of SCMs. The improvement was attributed to the formation of naturally occurring hemimorphite-like material ($Zn_4(Si_2O_7)(OH)_2{\cdot}H_2O$). It is referred to as Z–S–H, which is resulted from the interaction of Zn with Ca (OH), C_3A and calcium silicate hydrate (C–S–H).

1. Introduction

The Kingdom of Saudi Arabia (KSA) is one of the largest steel producers in the Middle East. Modern electric arc furnace processes are used in the KSA to recycle steel from scrap and other steel wastes [1]. In general, steel, the most recycled and produced material worldwide [1–3], can be easily extracted from many different sources and wastes available. The consumption of iron and steel in the KSA reached approximately 26 Million Metric Tons in 2015 [4,5]. The cost-effective energy from gas available in the KSA has led to an intensive use of the electric arc furnace (EAF) process. This type of processing technology satisfies the ongoing increase in the demand for steel production due to the construction boom in the KSA. In the EAF process, a non-iron-making process, steel scrap can be largely recycled [6].

However, a large quantity of electric arc furnace dust (EAFD), a by-product of the electric steelmaking industry, is also produced, which poses an environmental threat. The total amount of steel produced is accompanied by an amount of EAFD that is approximately 2% of the steel weight [3]. Different investigations have been performed on EAFD [7,8]; the most abundant heavy metals

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found in EAFD were reported to be zinc (Zn), lead (Pb), Chromium (Cr), and Cadmium (Cd) [9]. Due to the presence of these metals, EAFD is classified as a hazardous material [10]. The research significance and history about EAFD can be categorized into 5 research areas discussing:

(a) the dust formation and proposed theory to explain, in 5 mechanisms, how dust formed during steel production in the electric arc furnaces, as shown in Fig. 1 [11];
(b) the variation in chemical and physical compositions showing the main phases present in EAFD and their main compositions and characterizations [12];
(c) the solidification/stabilization procedure to minimize the toxicity and leachability of heavy metal in EAFD [2,13–15];
(d) the investigation performed to explore the recovery of zinc metal from EAFD [8];
(e) the potential use of EAFD in different applications including ceramics, cement and concrete preparations [16–18].

In the current research the use of EAFD in cement paste and mortar is investigated. The retarding effect of zinc compounds in EAFD has led to the proposal of using EAFD as a set retarder in concrete. The retarding effect is a concentration-dependent and accordingly, the proposed dosage of EAFD relies on its content of zinc and the target extended setting time. Authors of this paper have published a research work about concretes containing different percentages of 0.5–5% EAFD. In that work EAFD itself is proposed as an effective set retarder as confirmed by others as well [19–22]. EAFD is reported as an effective concrete additive in normal and reinforced concretes [23]. It is shown that an improved resistance to corrosion of steel bars in concrete can be achieved upon the incorporation of EAFD in concrete [24]. EAFD is shown to have a potential application when disposed of in concrete.

To address the practical disposal of EAFD, recycling of EAFD in concrete has attracted the attention of many researchers [16,17,19,24,25]. The cementitious matrix of concrete is expected to encapsulate the heavy metals present in EAFD. Successful fixation of the heavy metals will minimize their negative environmental impact and lead to high volume use of EAFD. The use of fresh EAFD in concrete represents a serious challenge. It has been reported that fresh EAFD can be incorporated into concrete at a maximum replacement level of only 3%. This level of replacement by EAFD was reported to enhance concrete hardened properties [17,19]. However, the main drawback that restricts the use of higher EAFD dosages is its extensive retardation effect accompanied with elevated dosages [16,17,19,24,25]. This adverse effect on the setting time of concrete is undesirable in many cases. However, the delayed setting time led to the suggestion of using EAFD as a set retarder in hot climates to adjust the hydration rate [19]. The present investigation considered the effect of incorporating the optimum content of fresh EAFD on the fresh and hardened properties of different mortars prepared using different water-to-binder (W/B) and sand-to-cement (S/C) ratios. A comparative study between different supplementary cementing materials (SCMs), such as silica fume (SF) and class F fly ash (FA) with 3% EAFD, was conducted. The fresh and hardened performance of the cementitious mortar containing EAFD in comparison to that of SF and FA under different replacement levels was evaluated. The replacement levels of SF and FA equivalent to the optimum content of 3% EAFD that provide comparable workability, compressive strength and resistance to rapid chloride permeability were determined and characterized using pore-size distribution and microstructural analyses.

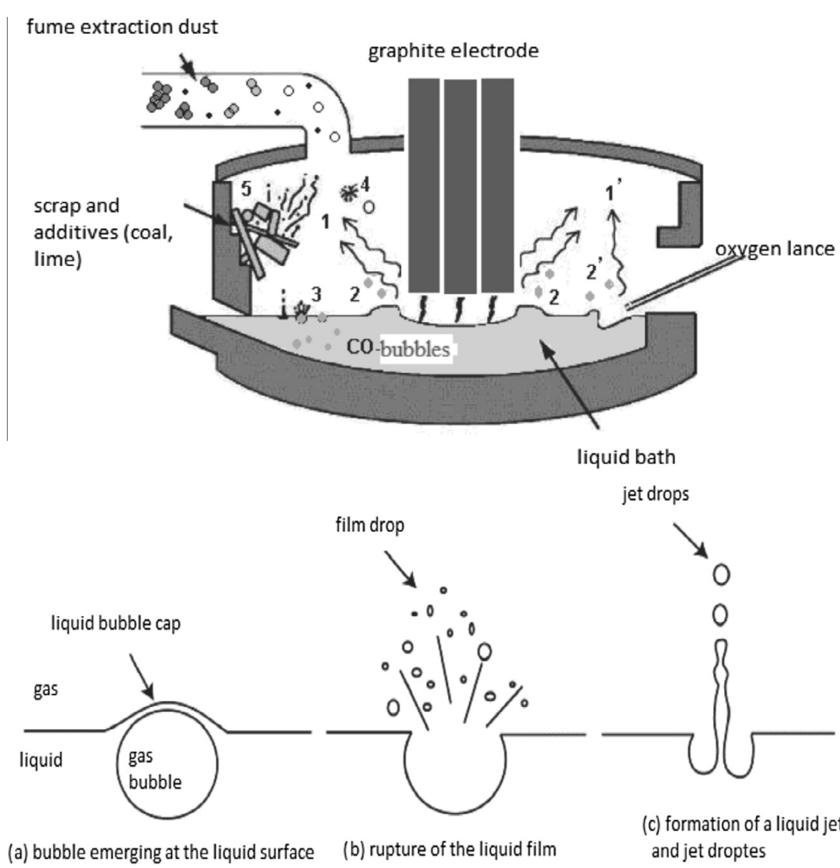

Fig. 1. Mechanisms of EAFD emission due to blowing out bubbles on a melt surface [11].