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Using foundry slag of ferrous metals as fine aggregate for concrete

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ABSTRACT

Foundry slag, obtained by induction, is waste from the ferrous industry whose destination is landfills. Due to its huge production and the main materials used, concrete can be a very interesting solution to incorporate this residue, turning it into a by-product. However, there is a need for more durability research studies regarding alkali-silica reactions, resistance to sulphates and susceptibility to corrosion, which sometimes, in practice, can make some slags in concrete impracticable. This study aims to evaluate the possibilities of the effective incorporation of this slag in concrete mixtures as a substitute for fine aggregates. Within this context, an experimental programme was carried out in order to evaluate the performance of concrete mixtures incorporating grey cast iron furnace slag. Properties of fresh and hardened concrete were experimentally investigated. All the results of the performed tests indicate a better performance of mixtures containing this furnace slag compared with plain cement reference concrete in terms of mechanical properties and durability indicators, excluding the results of alkali-silica reaction. Regarding the accelerated test for alkali-silica reaction and the standards for this effect, the selected slag is classified as potentiality reactive, making this application in cementitious based materials unfeasible.

1. Introduction

According to the European Slag Association (EUROSLAG), in Europe, the following four different ferrous slag families can be identified: i) blast furnace slag (BF) also called iron slag, air-cooled (ABS) or granulated (GBS); ii) basic oxygen furnace slag (BOS); iii) electric arc furnace slag from carbon (EAF C) or stainless/high alloy steel production (EAF S); and iv) steelmaking slag (SMS) (EUROSLAG and EUROFER, 2012). Usually, BF and ABS are summarized as “blast furnace slag”, while BOS, EAF C, EAF S and SMS are called “steel slags” (EUROSLAG and EUROFER, 2012). The use of BF slag as a partial substitute of aggregate in concrete (Baricová et al., 2010; Bodor et al., 2016; Kawamura et al., 1983; Krishna Rao et al., 2015; Motz and Geiseler, 2001) or in the manufacturing of cement as a partial substitute of Portland cement clinker (Miyazawa et al., 2014, Özbay et al., 2016) is a well-known practice. In Europe, this type of application represents about 66% of the generated BF slag, and most countries have a utilization rate of about 100% (EUROSLAG and EUROFER, 2012). Concerning the steel slag, various studies have confirmed the suitability of its application in concrete, both as fine or/and coarse aggregate replacement material (Adegoloye et al., 2015; Arribas et al., 2014; Faleschini and Pellegrino, 2013; Faleschini et al., 2015; Monosi et al., 2016) and also for cement production and as a supplementary cementitious material for concrete production namely BOS (Carvalho et al., 2017; Jiang et al., 2018; Guo et al., 2018). However, some authors express the need for more detailed long-term research regarding alkali-silica reactions (ASR) (Arribas et al., 2014), resistance to sulphates (Arribas et al., 2014), susceptibility to corrosion when used in reinforced concrete, as well as a careful assessment of production costs (economic and environmental ones) (Arribas et al., 2014; Monosi et al., 2016; Pasetto and Baldo, 2015). The main fields of application for steel slag in Europe are the production of aggregates for road construction (48%) (Pasetto and Baldo, 2015, 2016; Skaf et al., 2017).

Foundry slags (FS) are waste materials generated by metal casting processes at metal foundries (Industrial Resources Council, 2018). Ferrous alloys in foundry processes can be melted using various types of furnaces: cupola, electric arc, rotary and mainly induction furnaces (European Commission, 2005). All foundries produce castings by pouring molten metal into moulds, typically consisting of core and moulding sands (Deshmukh and Vidhate et al., 2015). While operating

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electric induction melting furnaces (EIF), an oxidic slag is produced from the various sources, such as scrap, oxidation of molten metal, chemical reactions with other elements such as sulphur and phosphor, as well as additions made to correct composition and de-slagging agents. Depending on the specific process used and the type of iron or steel melted, the composition of slag will vary (Deshmukh and Vidhate et al., 2015, 1 Gandhewar et al., 2011). If these materials are not useful, they will be dumped in the vicinity of the industry (John and John, 2013) or landfilled (Castro, 2004). For this reason and to avoid this, finding uses for these FS materials is very important. The type of slag selected for this study results from the grey cast iron foundry sector by sand moulding. Slag fragments, after processing, can produce an aggregate for construction. The aim of this study is to evaluate the potential of ferrous slag application, obtained by EIF, as a replacement for fine aggregates in the concrete. In order to study the properties of concrete, various mixes were made to evaluate the effect of partially and totally replacing common fine aggregates by EIF slag. Several experimental tests were carried out to study the performance both in a fresh state: i) workability of mixtures, ii) fresh density, and iii) air volume introduced; and in a hardened state: i) compressive strength and its evolution over time, ii) shrinkage, and iii) the durability indicators of produced mixtures, particularly chloride diffusion coefficient, carbonation resistance and water absorption, both by capillarity and immersion.

2. Literature review

The suitability of ferrous slags as aggregate, or other applications, is determined by their chemical and mineralogical characteristics (Andrews et al., 2012). Mostly, FS consists of acidic oxides such as SiO_2 and Al_2O_3 (31.4–70.2 % and 8.2–20.6 % of composition), and basic oxides such CaO (3.3–33.6 %), Fe_2O_3 (2.6–25.9 %), MgO (1.2–11.0 %) and MnO (2.81–10 %) (Andrews et al., 2012; APF, 1999; Devi et al., 2016; European Commission, 2005).

Successfully incorporating FS as aggregates in concrete products needs certain minimum geometric, physical and chemical requirements that can be determined in accordance with EN 12620 (IPQ, 2008). In ordinary Portland cement concrete, ASR takes place between potentially reactive aggregates and the alkalis present in cement ($Na_2O + K_2O$), $Ca(OH)_2$ under favourable humidity conditions (Fernández-Jiménez and Puertas, 2002). The absence of one of these factors reduces or may prevent the reaction and consequently the expansion (Fernández-Jiménez and Puertas, 2002). Various tests that focus on the characteristics of FS considering their application in the concrete industry have been, for example, about replacing aggregates or cement. Ceccato et al. (2009), Devi et al. (2016) and Sachithanantham et al. (2012) studied the utilization of FS as a partial replacement of cement. Ceccato et al. studied concrete with different percentages of cement replaced by FS (10%, 30% and 50%) and tested different water/binder rates (0,40; 0,55; and 0,70). The results showed that although granulated slag presents an adequate performance (mechanical properties), the granulated slag addition decreases the resistances. It can be observed that the resistances with 10% slag are close to those of the reference composition and the water/binder ratio increases (from 0.40 to 0.70) (Ceccato et al., 2009). Sachithanantham et al. studied the replacement of cement by slag powder at different percentages (5, 10 and 15%). In this case, the workability of the fresh concrete increases by adding foundry slag and the compressive strength of concrete increases by adding slag to a maximum of 10% Sachithanantham et al., 2012). Devi et al. studied the performance of FS as a partial replacement for cement and sand in concrete, from 10, 20 and 30% by weight, in terms of compressive strength, flexural strength and splitting tensile strength. The result showed an increase in all evaluated mechanical strengths and durability indicators of concrete at all ages when compared to normal concrete. However, it must also be noted that, as replacement of sand, the slag addition was more efficient, with an increase of resistance in all percentages added. As a substitute for cement, there is no advantage in using more than 20% of slag, as the resistances obtained with 30% decrease, and are similar to those obtained with 10% (Devi et al., 2016). As a substitute of concrete aggregate, there is other recent work available focused on mechanical properties of concrete and in its workability (Sharma et al., 2016). In this study, Sharma et al. studied the strength development of concrete using FS as a partial replacement for conventional fine aggregates (10, 20, 30, 40, 45 and 50%). The result showed an increase at all ages but showed a decrease in these properties with 50% of FS. Concerning the workability, it can be observed that as the percentage of slag is increased, the slump value is also increased. Sharma et al. mentioned that this has happened due to the fact that water absorption of slag is much less than the one that uses fine aggregate. The authors also commented that with the increase in slag, free water content also increases which helps in increasing the slump (Sharma et al., 2016).

It has been reported (Saha et al., 2018) that the use of furnace ferronickel slag (FNS) as a fine aggregate can improve the strength and durability properties of concrete. Nevertheless, according to Saha et al. (2018) the use of some FNS aggregates containing reactive silica may potentially cause alkali-silica reaction (ASR) in Portland cement concrete. However, concerning the main properties of FS, there is no literature available on the chemical alkali-aggregate reactivity. Thus, it may be considered that there is a need for more research considering alkali-silica reactions, resistance to sulphates and susceptibility to corrosion, which in practice may sometimes make the use of slag in the concrete impracticable.

3. Materials, mixtures and methods

3.1. Slag preparation

A ferrous FS obtained from grey cast iron melted in EIF was selected for this study to replace fine aggregate in a ready-mix concrete plant. The producer usually uses two types of crushed granitic sand in the concrete mix-designs, with the dimensions of 0–2 mm and 0–4 mm. For this purpose, we chose to replace just the fine crushed aggregate in the referred dimensions due to the mineralogical quality of fine aggregate, granitic source, and also due to the small amount of residue available on the national market. Preliminary parametric studies in mortars made with slag 0–2 mm were performed and validated the incorporation of FS up to 100%. The results showed an increase in mechanical strengths for all studied percentages (25, 50, 75 and 100%), both compressive and flexural strength, about 21% (7.4 MPa) and 68% (38.1 MPa) for the percentage of 100%, representing an average gain at 28 days of 1.3 MPa and 15.5 MPa when compared to reference mortar. The water/cement ratio (W/C) needed to attain a constant workability (flow table spread of 140–170 mm) decreases with the introduction of crushed aggregate of slag from 0.67 to 0.53 for total replacement. For a percentage of 25%, the gain in the compressive strength was 6% (26.5 MPa), representing an average gain at 28 days of 3.9 MPa at 28 days and keeping W/C constant. The fact that fine crushed aggregate (0–2 mm) showed excellent results on the mechanical strength of mortars resulted in testing it in concrete, also replacing the sand of 0–4 mm dimension.

The coarse granular slag used in this study was obtained from a foundry located in the north of Portugal. It was impossible to use it directly, as received, in concrete because of its dimensions, typically from 30 to 200 mm. Thus, it was necessary to transform the coarse particles of slag through a fragmentation process by crushing, obtaining a particle size compatible for use as fine aggregate in concrete. In Fig. 1 a piece of slag, before the crushing process, is shown.

The crushing process was conducted in the laboratory using a crusher Retsch, model BB200 (see Fig. 2(a)). Due to the presence of ferrous and non-ferrous metals in the slag, the crushing process was developed in various steps of fragmentation. The final particle size distribution of crushed slag with a dimension of 0–2 mm was obtained