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Performance of fiber-reinforced EAF slag concrete for use in pavements

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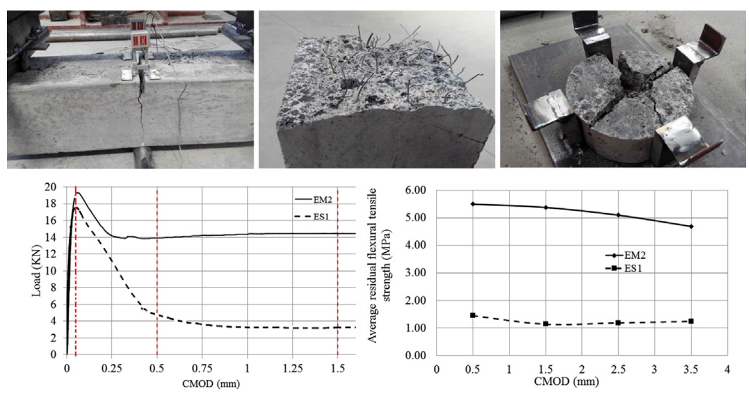
HIGHLIGHTS

- The performance of fiber-reinforced EAF slag concrete is evaluated.
- Mechanical tests on the fiber-reinforced EAF slag concrete showed good results.
- Metallic fibers provided better fracture toughness behavior than synthetic fibers.
- SEM analysis shows homogeneous concrete structures with good fiber adherence.

GRAPHICAL ABSTRACT



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ABSTRACT

The manufacture of concrete with Electric Arc Furnace slag as aggregate is known; in this work, fiber reinforcements are added to this concrete. The properties of several mixes, reinforced with 0.6% metallic and 0.4% synthetic fibers in volume, are studied both in the fresh and in the hardened state. Mechanical characterization of the fiber-reinforced concretes showed that they had good compression, flexural and tensile splitting strength. They also showed good toughness, post-cracking behavior, impact strength and tests on their abrasion resistance yielded suitable results. The concrete mixtures were characterized with SEM, to analyze their microstructure and the adherence of fibers.

1. Introduction

Sustainability in the European Union (EU) construction sector is an important trend. Taking into account that the consumption of natural aggregates in the EU is around 3000 Megatons per year, one relevant aim is the search for additional materials that can partially substitute those natural resources. Furthermore, one of the priorities in the European program HORIZON 2020 is waste recycling. If there is to be a reduction in the over-exploitation of quarries and waste dumping in landfill sites, then the reuse of waste and industrial by-products in the construction sector is an essential activity. In consequence, over recent years, several studies have looked into the possibility of incorporating slag from the steelmaking industry in construction and civil engineering applications [1–4].

Electric Arc Furnace Slag (EAFS) and Ladle Furnace basic Slag (LFS) are by-products of the electric steelmaking industry, produced during the melting of scrap steel and the secondary or basic refining of steel, respectively. The former is usually presented in

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the market as gravel sized aggregates, and the latter in the form of a grey powder. According to Euroslag [5], 32% of the metallurgical slags produced in Europe are of the EAF type, representing approximately 7 million tons per year in the EU. Spain in particular is the third producer of electric steel in the EU, below Germany and Italy, with production levels of around 10 MT of electric steel, together with 2 MT of EAFS and 0.5 MT of LFS by-products [6]. At present, research groups in Spain (Universities of Burgos, Cantabria and Basque Country), Italy (University of Padova), and Greece (University of Thessaloniki) are working in coordination to propose pre-normative rules on the use of these slags. The fact that the construction sector consumes around 90 MT of natural aggregates per year in Spain was the motive to look for new raw materials to replace natural resources.

In general, steelmaking slags are potentially expansive and entail certain risks, mainly due to the presence of free lime and periclase. So, outdoor weathering of slags and some additional precautions are necessary to prevent the persistence of any expansive phenomena [7–12]. Over recent decades, important works that characterize EAFS [13–16] and LFS [17–19] have been published; the suitability of both slags has been demonstrated in different applications, such as bituminous mixes [20–24], concrete and mortars [25–40], self-compacting concrete [41–43], clinker [44], soil stabilization [45–47], and others [48–50]. Despite these recycling possibilities, in Spain, approximately 23% of electric slag waste is currently dumped in landfill sites.

Nowadays, the use of EAFS as a coarse aggregate in hydraulic concrete is widely accepted. It has been demonstrated that the mechanical properties and the durability of concrete made with electric arc furnace slag (CEAFS) means it is suitable for use in construction and building works [33,40]. CEAFS has also been employed in structural and reinforced concretes. An important example is the construction of both the foundation and basement walls of the Kubik laboratory (Derio-Spain) [34], where the concrete design incorporates close to 80% EAFS aggregate by volume. Some authors [41] have even studied the behavior of mixes manufactured with steel slag and fiber reinforcement as self-compacting concrete at rates of 0.4% and 0.7% by volume, with encouraging results.

Artificial fibers, especially steel and synthetic fibers, are commonly used to strengthen the mechanical behavior of concrete, producing good results with numerous properties [51–55]. In general, tensile, flexural, impact, fatigue and wear strength, deformation capability, load-bearing capacity after cracking, and toughness are significantly improved with the use of fibers in concrete mixes [56–58]. Fiber-reinforced concrete (FRC) can be used in some structural applications with reduced amounts of conventional bar reinforcement, as is done with shotcrete and paving construction [59–62].

The aim of the research described in this paper is inspired by the use of EAF slag in the manufacture of fiber-reinforced concrete pavements and slabs that are less prone to the spread of cracking during the initial drying of the concrete. The flexural and splitting tensile strength of these concretes and their rupture energy absorption capacity and impact strength are all improved. The manufactured mixes, which show a higher density than ordinary concrete, will be used in the preparation of industrial paving slabs, without any need for steel reinforcing bars. Original aspects that may be mentioned include the use of coarse aggregate of a maximum size of 20 mm, with mixes of dry consistency for on-site vibration, poured from a concrete mixer truck to form an adherent upper layer that has a heavy load-bearing capacity.

Accordingly, EAFS is used as both coarse and medium aggregate in the concrete mix, and the fine aggregate is prepared with 50% fine slag and 50% siliceous sand; under these conditions, the mix has approximately 75% by weight of EAFS and 25% of natural aggregate. The fine siliceous sand, with a rounded morphology, should partially counteract the effect of the surface roughness of the EAFS, slightly improving its workability and flowability throughout the concrete mass [63]. Furthermore, different dosages and fiber types (metallic and synthetic) were studied, in order to determine the most suitable amounts.

2. Materials

2.1. Cement, water, additives and natural aggregates

- Ordinary Portland cement (OPC), CEM I/42.5R (EN 197-1:2001[64]) was used in this study. Its components determined by X-ray fluorescence analysis (XRF) were: CaO (60.4%), SiO_2 (21.3%), Al_2O_3 (6.1%), Fe_2O_3 (4.0%) and others such as Mg and Na. It was composed of 95% clinker and 5% limestone, having a density of 3.15 g/cm^3 and a Specific Blaine Surface of 3400 cm^2/g.
- Mixing water was taken from the urban mains supply of the city of Burgos (Spain), containing a negligible amount of compounds that could affect the preparation of hydraulic mixes.
- The plasticizer additive, employed to improve workability, was modified polycarboxylate polymer, with a density of 1.08 g/cm^3, pH of 5 and solid content of 36%.
- Natural rounded siliceous aggregate was provided in three size fractions (EN 933–1 [64]), 0/4 mm, 4/12 mm and 12/20 mm (the gradation curves of which are represented in Fig. 1), with a content of fines smaller than 0.075 mm 1.58%, 0.25% and 0.41%, respectively. The main component of this rounded aggregate was SiO_2 (96%). Its characteristics, listed in Table 1, comply with the specifications in the EHE-08 standard [65].

2.2. Electric Arc Furnace Slag (EAFS)

The crushed and weathered Electric Arc Furnace Slag (EAFS) used in this research was supplied by a slag manager in the North of Spain in three size fractions (EN 933-1[64]), 0/4 mm, 4/10 mm and 10/20 mm, with a fines content of 0.35%, 0.24% and 0.23%, respectively. Their gradation curves are shown in Fig. 1, together with curves of the siliceous material. These EAFS presented low fines fractions that required remediation with natural siliceous fines.

According to their main physical properties detailed in Table 1, the slag aggregates were up to 35% denser than the natural crushed aggregates. They had a low flakiness index and low weight loss in the Los Angeles test under the limit of 25 units specified for high strength concrete [65]. Besides, water absorption in the EAFS was higher than in the natural aggregates, a trend also observed by other researchers [36,63]. Their main crystalline components (obtained by XRD) were wüstite, ghelenite, olivine and magnetite [a]. As we can see in Table 2, nearly 75% by weight of the EAFS contained Fe, Ca and Si oxides, while a further 20% contained Al, Mg, Mn and other oxides (K_2O, Na_2O, P_2O_5, and TiO_2). Compounds associated with expansive processes, such as free lime and free magnesia, were below 0.5% and 0.1%, respectively, with no significant volumetric instabilities associated with lime hydration and the transformation of periclase [40,66].

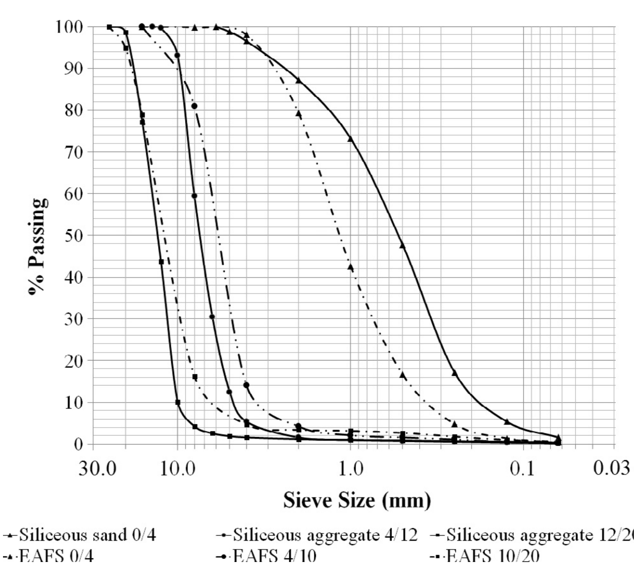

Fig. 1. Grading of the raw materials.