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The performance of steel-making slag concretes in the hardened state

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A B S T R A C T

The use of oxidizing slag from electric-arc furnaces as an aggregate is a sustainable option in the manufacture of concrete, the performance of which is similar to an ordinary aggregate concrete. This study examines the reuse of two different types of oxidizing slag in concretes designed for use in structural components and compares their performance against relevant specifications contained in current working standards. Fundamental aspects are discussed, among which density and workability that are related to the proportioning of the concrete and its mechanical and physical properties. The results show that overall concrete quality is maintained and that its performance is acceptable for the proposed application.

1. Introduction

The reuse of recovered waste and industrial by-products in the construction sector, as alternatives to raw materials of natural origin, represents one way of promoting further sustainability in the industry [1,2]. Once their technical, environmental and economic feasibility has been demonstrated, raw materials (raw correction materials, aggregates, and additions to cement), either in total or in partial substitution of industrial by-products, will potentially bring extensive industrial benefits.

In Spain, as much as in the majority of the EU28, industrial waste and by-products, due to their origin, generation, and characteristics, hold potential for use in construction: construction and demolition wastes [3], ladle furnace (white) slag from steelmaking [4–7], products resulting from the thermal activation of recycled paper sludge [8], ash from municipal solid waste incineration residues [9], Waeltz slag [10], and fly ash from combustion processes [11,12].

Traditionally, steelmaking slags have been used in civil works to improve the quality of soils [13], for the preparation of road beds, bases and rolling layers for roads and rural paths and even for railway beds [14,15]. Their use is justified by their excellent resistance to abrasion [16,17]. However, their application as a filler material accompanying larger rocks in rockfill material has only been very occasional, owing to the poor uniformity of the final product [18].

In the case of this research, we will focus on the use of oxidizing slag from electric arc furnace steelmaking in the manufacture of "Concrete made with Electric Arc Furnace Slag" (CEAF), some aspects of which have previously been studied by other authors [19–32], as have other aspects relating to their application in structural concrete [33,34], as specified in the relevant standards.

One of the first studies on concrete with slag aggregates was by Dr. Akinmusuru [35], in which several series of concrete specimens were tested with different percentages of LD-converter slag in substitution of cement and sand. The study established that the concrete specimens with slag aggregates were similar and even had better mechanical properties than conventional concrete specimens. The physical nature of the slag was shown to have contributed to the development of a better quality interfacial transition zone (ITZ) (aggregate/cementitious matrix).

Other researchers [36,37] have analysed the compatibility of slags and some hydraulic binders (mainly Portland cement). Dr. Sawaddee [38] completed a doctoral thesis on the use of slag as an inert addition to Portland cement with a micro-silica and a plasticizer admixture that has been applied in only a few cases within the European Union.

As regards proportioning, a further work [39] compared the properties of a concrete with 60% EAF aggregate (fraction 10–20 mm) and a limestone concrete, finding similar values for compression, flexion and split tensile strength. However, the moduli of longitudinal deformation under compression of the CEAF

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specimens yielded values higher than 23% of the reference concrete. In addition, Bäverman and Aran [40] analyzed the substitution of sand by the fine fraction of EAF and, following a comparison with conventional concrete, concluded that the incorporation of a fine fraction resulted in a concrete with a similar compression strength to the concrete without EAF and caused no negative environmental impacts (leaching), while the CEAF showed greater brittleness.

Other authors [41] reported increased compressive strength by as much as 7% in CEAF with 65% of crushed limestone substituted by EAF and even by as much as 38% [42], when all the coarse fraction was substituted, with no appreciable changes in the flexural and indirect tensile strength. High compressive strength increases (up to 21%) were also reported by Papayianni and Anastasiou [43], in the case of substituting 100% of the coarse and 50% of the fine aggregate by EAF.

Research conducted at the University of Padova [24] has highlighted the important function of additives (plasticizers and air occluding) in the CEAF. The 28-day compressive strength results revealed an increase of 30% as opposed to the natural aggregate concrete, as well as increases of 10% and 8% in the flexural tensile strength and the modulus of elasticity, respectively. These improvements were attributed to the increased roughness of the surface of the EAF (better cohesion between the aggregate and the cementitious matrix).

Some uncertainties relating to steelmaking slag concretes are described in the literature under review and further investigation is needed before these materials fully comply with all the relevant standards on structural concrete. Therefore, the main objective of this research concerns concrete that blends slag aggregates, as a 'noble' raw material, with Portland cement, for use in structural concrete components, while paying particular attention to aspects that relate to its performance in a hardened state.

Regarding standardization, the present study assesses the behaviour of CEAF against the yardstick of the Spanish structural concrete Standard EHE-08 [44]. The Kubik initiative at Tecnalia [45] may be mentioned in this context. CEAF was applied to the Kubik project as pumped and reinforced concrete, to the foundation and basement walls of the Kubik laboratory (Derio – Spain), the concrete design having close to 80% slag aggregate by volume.

2. Materials characterization

2.1. EAF slag

EAF slag, generated in the scrap melting and oxidizing phase of steelmaking work, has to undergo treatment before it is converted into an acceptable concrete aggregate. This treatment consists of six stages: (1) sprinkling and preliminary turning (within 48 h following the dumping of the EAF in a trench on a cold bed); (2) primary crushing (reduction of its initial size); (3) separation and rejection of up to 25 mm sizes; (4) magnetic separation of metallic elements; (5) screening and classification (three different fractions); and, (6) storage in silos.

No long-term stabilization treatment was implemented in this study, unlike in other research projects [7,21,46]. In this regard, after the treatment applied in this study, the measured expansion (according to UNE-EN 1744-1 [47]) on all EAF grading sizes yielded a maximum value of 0.6%. In view of this low measured expansion, the treatment applied here has shown satisfactory results in terms of slag aggregate stabilization.

In the present study, two steelmakers in the North of Spain supplied the oxidizing slag following treatment processes similar to those described above. However, the slag sample from the plant that produced the EAF2 underwent slower cooling with greater evacuation of occluded gases that induced lower porosity (in content and size) and lower water absorption, but higher specific gravity, contrary to the result of the process in the plant providing the EAF1 slag (Table 1).

Besides, in line with the conclusions of this research, the more porous slag aggregates could perform quite well in slag concrete for structural purposes, as the three main properties (workability, and physical and mechanical aspects) are well balanced.

A total of 75% in weight of the EAF slag treated in this way (Table 1) consisted of Fe, Ca and Si oxides, while a further 20% consisted of Al, Mg, Mn and other oxides. Compounds associated with expansive processes, such as free lime and free magnesia, were below 0.5% and 0.1%, respectively, and no significant volumetric instabilities associated with lime hydration and the transformation of periclase were anticipated [48].

Chemical characterization of EAF1 and EAF2 was by X-ray fluorescence, in a sequential spectrometer (WD XRF). The chemical composition of EAF1 and EAF2 was similar to the results of previous investigations [19,42,49,50]. A further relevant feature for reinforced and pre-stressed concrete is that the chloride content of EAF is usually well below the limits specified in standard EHE-08 [44]. These and other chemical properties of the EAF discussed in previous research [51], all support its use as a suitable aggregate in structural concrete.

Mineralogical analysis showed that EAF2 was mainly composed of wustite and magnetite, together with larnite (dicalcium silicate), gehlenite, and dicalcium ferrite, [37,52], while EAF1 was mainly composed of wustite and akermanite-gehlenite, together with magnetite and kirschsteinite. In general, these silicates have no hydraulic properties.

The particle size fractions of both slag aggregates EAF1 and EAF2 (0–5, 5–12 and 12–25 mm) possessed similar fineness moduli (3.8, 6.0 and 7.4, respectively) and, in no case were particles smaller than 0.063 mm found in the small fractions. In Fig. 1 (upper) these gradations are showed for EAF2 slag.

As anticipated, the EAF aggregates were up to 20% denser than the natural crushed limestone. However, slag density was considerably lower in EAF1 than in EAF2. Mercury Intrusion Porosimetry (MIP) analysis showed that EAF1 slag porosity was almost twice that of EAF2 and its average pore size was much higher; in the case of the limestone, despite pore-sizes of 70 μm, its porosity was very low.

Regarding water absorption (UNE EN 1097-6), it may also be appreciated in the table that the slag aggregates may absorb much higher amounts of water than the natural aggregates, which is a very relevant question for concrete workability and effective w/c ratio. Although less drastic, these trends also have been observed by other authors [24,53].

In relation to fragmentation strength, according to UNE-EN 1097-2 (Los Angeles test) [54], as can be seen in Table 1, the EAF concretes had a lower weight loss than the limestone, even less than the limit of 25 units specified in Standard EHE-08 [44] for high strength concrete.

2.2. Natural aggregates

Some of the main characteristics of the crushed limestone aggregates are listed in Table 1. These aggregates are categorized into four granulometric fractions (UNE EN 933-1 [55]) 0–1, 0–5, 5–12 and 12–25 mm, with fineness moduli of 0.1, 1.9, 6.0 and 7.3, respectively. They proceed from a fine grained, compact and highly cohesive dark grey stone that has calcium oxide (CaO) as its main chemical compound. It is fully compliant with all chemical specifications in the EHE-08 standard [44], with a mineralogy formed by calcite (95%) and dolomite (5%).