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A study on the durability of structural concrete incorporating electric steelmaking slags

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HIGHLIGHTS

- Self-compacting concretes containing EAF slag are shown to be of good quality.
- The accelerated ageing test results are positive in all concrete samples.
- The limestone fines content of the concrete greatly influences its durability.
- The EAF slag concretes exposed to marine environments show satisfactory behavior.

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ABSTRACT

The durability of structural concrete mixes prepared with electric steelmaking aggregates is tested for use in normal and aggressive environments. Samples of "pumpable" and "self-compacting" concrete mixes are shown to have good physical characteristics, mechanical properties and dimensional stability. The mixes were subjected to severe freezing-thawing and drying-wetting tests up until deterioration, to assess their resistance to inland environments. Real immersion in the tidal zone of a harbor and laboratory tests on reinforcement bar corrosion were also performed to evaluate the quality and utility of this sort of concrete in marine environments. The behavior of the mixes in these exposure tests was satisfactory, confirming their suitability for use in structural applications exposed to different environments.

1. Introduction

Some decades ago, the pioneering proposals to use electric steelmaking slags as aggregates in concrete were welcomed as a potential means of reusing steelmaking slag waste. In these initial studies [1–15], several areas were proposed for the application of these products; among which their reuse in construction and civil engineering sectors that are consumer of vast amounts of natural resources [16–28]. The target is to substitute that consumption for reasonable amounts of by-products that would otherwise be transported to dumping sites. Electric arc furnaces are used for most steel manufacturing in southern Europe where the by-products from industrial steelmaking processes are now a topical research area, aiming to produce viable products for use in construction and engineering projects [29–45].

Over the last decade, several international research groups outside the EU have also been engaged in research into hydraulic and bituminous concrete including electric arc furnace slag (EAFS, oxidizing slag, from the acid refining of liquid steel) and ladle furnace slag (LFS, reducing, from the basic refining of steel) for use in construction [46–57]. The authors of this paper form part of an EU research group that is also engaged in this task. After investigating efficient manufacturing methods of non-reinforced (massive) concrete containing EAF and LF slags as aggregates over the past decade, this research group in Spain is now investigating efficient manufacturing methods for structural concrete containing these slag aggregates. Recent publications of these authors have shown advances in this field, in which there is still a significant way to go [58–63].

The three main obstacles to this objective are as follows: the reduced workability of concrete in the fresh state, the increased density of the hardened concrete, and the risk of losing its good properties after a long service life, taking into account the singular characteristics of these aggregates and their potential expansiveness [64–68]. Each of the above-mentioned drawbacks, and others

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that further studies might unearth, will have to be successfully negotiated, to produce a manufacturing method for the construction sector in relation to the use of EAF slag and LF slag in structural concrete.

In this paper, the results of incorporating EAFS and LFS in structural concretes are reported. Two different types of concrete were manufactured, to assess their fresh state workability: "pumpable" concrete of high workability, class S3 and S4, and self-compacting concrete with good flowability showing a spread of over 500 mm from the Abrams cone [69–76]. Considering the inherent and well known loss of workability [31,41,59,77] associated with the use of these aggregates, a careful dosing and the use of appropriate admixtures is indispensable.

The aim of this article is to analyze the results of several durability tests and long-term behavior tests on various structural concretes (pumpable and self-compacting mixes) made using slag aggregates. The main result reaffirms the suitability of slag aggregate concrete under severe environmental conditions. The preparation of these concrete mixes and their characteristics have recently been published in a paper by the authors [78]; therefore, previously published details on the main features of these manufactured concretes will only be very briefly described in this paper.

2. Scope of the research

The specificity of concrete made with electric steelmaking slags that performs as a self-compacting mixture is a singular challenge. At present, little research in the scientific literature [79,80] has been reported on this question, and there is a gap in the literature relating to the durability studies of these concretes. These EAFS concretes will, undoubtedly, still require considerable analysis before their global behavior is comparable to conventional concrete mixes.

An initial assessment might suggest that concrete manufactured with electric steelmaking slags can be of lower durability than conventional concrete when exposed to aggressive environments, due to the porosity of these aggregates and other uncertain long-term characteristics of them. Some researchers with significant experience in this field also consider that these concretes are of poorer durability than conventional concrete [31,81], although the chlorine intake is fairly similar in both types [82]. In this paper, these durability issues are studied and the results reveal that, where possible, the aforementioned disadvantages may to some extent be mitigated.

There are mainly two types of EAF slag aggregates that may be identified in the scientific literature: one with greater cohesiveness, almost without porosity, higher stiffness, strength, and specific weight [82–84]; another, also with greater porosity and characterized by a lower stiffness and specific weight, even though it has good mechanical strength [81]. In this work this second type of slag is used; thus the conclusions are only valid for one kind of EAF slag and they have no universal validity.

Molds of cubic and prismatic specimens were prepared, using the same mixes proposed by the authors in a recent article on this subject [78]. The main properties of the hardened concrete are discussed, i.e. mechanical strength, porosity, capillary absorption and water penetration under pressure, as well as the results of measuring long-term concrete shrinkage in the atmosphere.

To analyze the durability autoclave tests were performed on the mixes, anticipating an eventual expansion of the aggregates. A series of classical freezing-thawing and wetting-drying cycles were also developed as part of the inland durability tests; throughout which damage to the material was controlled by means of measuring the propagation speed of ultrasonic waves through its mass and a final evaluation of compressive strength.

Subsequently, the long-term durable structural behavior of this material is analyzed as "reinforced concrete" for use in saline-marine environments. For that purpose, several non-reinforced concrete samples were exposed to coastal seawater in intertidal zones over varied periods of time. Chloride and sulfate ion penetration within the specimens was monitored in those samples. Likewise, laboratory tests to evaluate corrosion in reinforcement steel bars of these concretes were also performed. In this way, samples of slag concrete reinforced with embedded ribbed steel bars were exposed in the laboratory to simulated seawater, to estimate the electrochemical corrosion resistance of this steel-concrete ensemble widely used in marine structures.

Finally, some conclusions are advanced to facilitate the practical use of this sort (pumpable, self-compacting) of reinforced concrete mixtures using electric arc furnace slag as aggregate (coarse and fine) and ladle furnace slag in construction, and the reliability of structural engineering elements in marine environments.

3. Materials and mixes

3.1. Cement, water and natural aggregates

A Portland cement type I 52.5 R was used in this research, except in one sample prepared with a Portland cement type IV/B-V 32.5-N that included pozzolanic (fly ash) material in the mix; both in accordance with UNE-EN 197-1 standard. Water with no compounds that might adversely affect the hydraulic cement mixes was taken from the urban mains supply of the city of Bilbao (Spain).

A commercial crushed natural limestone with a fineness modulus of 2.9 units, a maximum size of 5 mm, and a bulk density of 2.6 Mg/m^3 was used as a fine aggregate in certain mixes. The same material was also used to increase the workability of other mixes (see Table 1) after screening through 0–0.6 mm and 0–1.18 mm sieve sizes, with fineness moduli of 0.7 and 1.5 units, respectively. Coarse crushed limestone aggregate (5–12 mm) of the same density was also used in one case, see Table 1. The main mineral component of all these aggregates was calcite (95%). The gradation of all of the above-mentioned fractions is shown in Fig. 1. A suitable plasticizer and viscosity conditioner admixture was used to reduce the mixing water and to obtain a good rheological behavior of mixes.

3.2. Slags

Electric Arc-Furnace slag (EAFS) crushed and sieved into two size fractions (fine <5 mm, coarse 5–12.5 mm), with a specific gravity of 3.42 Mg/m^3 and fineness modulus 3.9 and 6.1 respectively [78], supplied by the company Hormor-Zestoa, was used in this research. The chemical composition, some physical properties and mineralogical main components are detailed in Table 2. The grading of both fractions is shown in Fig. 1.

An additional high-silica low-alumina ladle furnace slag (LFS) with a density of 3.03 Mg/m^3 and a fineness modulus of 0.75 units was also used; the amount of material passing the 40 μm sieve is 19%. Its chemical composition and other physical properties are detailed in Table 2 and its grading in Fig. 1. A minor fraction of the total amount of LFS added to the hydraulic mixes could show binder properties in the same way as a supplementary cementitious material (SCM), as suggested in [85]; the rest of the LFS can be considered as an additional fine aggregate fraction. Some earlier works by the authors [86,87] contain more detailed descriptions of this type of LFS slag, also specifying properties complementary to the analyses presented in this study.