Materials and Design 63 (2014) 168–176

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Durability studies on steelmaking slag concretes

I. Arribas [a], I. Vegas [a], J.T. San-José [b,*], Juan M. Manso [c]

[a] *TECNALIA. C/Geldo, Parque Tecnológico de Bizkaia, Edificio 700, 48160 Derio, Spain*
[b] *UPV/EHU, Dep. Mining, Metallurgical and Mat. Science, Alameda Urquijo s/n, 48013 Bilbao, Spain*
[c] *Dept. of Civil Engineering, EPS Univ. of Burgos, C/Villadiego s/n, 09001 Burgos, Spain*

ARTICLE INFO

Article history:
Received 30 January 2014
Accepted 2 June 2014
Available online 13 June 2014

Keywords:
Aggregate–alkaline
Corrosion
Freeze/thaw
Marine environment
Steel slag
Sulfate resistance

ABSTRACT

Electric-arc furnace slag is proposed as a substitute for the conventional aggregate used in classical structural concrete. In the present research is studied the durability of these slag aggregate concretes and their resistance to both physical (freeze–thaw, high temperature and relative humidity) and chemical degradation (sulfate attack, alkali–aggregate reaction and marine environment), as well as their resistance to the corrosion of steel reinforcement bars (an assessment of the risks of corrosion) embedded in the concrete matrix. This approach requires laboratory studies. The main objective of this work focuses on evaluating the durability of slag concrete under the conditions specified in the Spanish structural concrete code. In general terms, the behavior of the concrete with slag aggregate was similar to or better than the reference concrete (natural aggregate), except in case of exposure to marine environments and seawater, which resulted in quicker chloride penetration. The study confirms the viability of producing steel-reinforced concrete with slag aggregate.

1. Introduction

In addition to other recyclable industrial waste [1–6], large quantities of by-products are generated in the European steel industry. For example, a possible 21.8 million tons per year of steel slag (http://www.euroslag.com) could theoretically be reused in the construction (building and civil works) sector, where there is high consumption of raw materials. [7–18]. The catalog of industrial waste from the production of steel (electric arc furnace EAF, basic oxygen furnace BOF, ladle furnace LF, etc.) presents a spectrum of possibilities for its reuse in building materials (concrete, cement, mortar, bitumen mixes, etc.). From among these alternatives, the current investigation focuses on the reuse of oxidizing slag, extracted from Electric Arc Furnace (EAF) steelmaking, in the manufacture of concrete. Recent research has addressed this area [19–27]. However, there are still many unresolved issues surrounding its physical and chemical durability (not reinforced or reinforced with steel) in structural applications.

With regard to durability studies, Amaral [8] analyzed EAF slag concretes (CEAF) subjected to various aggressive environments by testing carbonation, exposure to seawater, alkali–aggregate reactions and sulfate attacks. His study found no expansive behavior in the concrete following alkali–aggregate reactivity tests and sulfate attacks. The depths of carbonation, observed in the CEAF, were slightly higher than the values of the reference concrete, probably because of the greater permeability of its slag aggregate; however, chloride ion infiltration was lower. The author concluded that the durability of the concrete made with slag aggregates was comparable to ordinary concretes.

More recently, [10] other authors have reported poor results for durability tests of CEAF, in which the fractions of fine and coarse aggregate were substituted by EAF, compensating for the lack of fine fraction with the addition of limestone fillers. Other researchers [11] have tested substitutions of 25%, 50%, 75% and 100% EAF, and the addition of air-entrainment agents. These concretes showed similar mechanical properties (compression, flexion and indirect traction) to those of a conventional concrete and acceptable behavior against environmental attacks. However, unlike other research findings [8], durability against sulfates was slightly lower and the high porosity of the slag aggregate affected CEAF resistance to freezing/thawing cycles.

In contrast, other researchers [28] have demonstrated how CEAF resistance to freezing/thawing cycles is not only better than that of other concretes manufactured with recycled aggregates, but similar to conventional concretes. Moreover, in Ref. [11] the authors showed how EAF percentages of over 50% did not reduce the durability of the concrete in its resistance to freezing conditions, although premature rupture of the test piece with 100% replacement slag and no air-entrainment agents was observed.

---

* Corresponding author. Tel.: +34 946014080.
E-mail address: josetomas.sanjose@ehu.es (J.T. San-José).

http://dx.doi.org/10.1016/j.matdes.2014.06.002

Along these lines, more recent findings [29] have shown satisfactory results in concretes with slag substitutions of 100% of the coarse fraction and 50% of the fine fraction undergoing wetting/drying and freezing/thawing cycles, as well as following exposure to high temperature and relative humidity.

Pellegrino et al. [13,30] tested the durability of the CEAF in three types of trials: immersion in water at 70 °C (32 days), freeze–thaw (25 cycles) and wetting–drying (30 cycles). In the immersion tests, there were losses of 5% on the compressive strength of the CEAF, as against an increase of 9% in the conventional concrete. With regard to the freeze–thaw cycles, these researchers also noted how the compressive strength of the slag aggregate concrete fell to 7% after this test, as opposed to a slight increase in the strength of the traditional concrete. Also, in terms of compressive strength, the wetting–drying cycles weakened the CEAF slightly more than the conventional concretes. They concluded that the durability of the CEAF, at least under the aforementioned conditions of dosage and additives, was no better than the durability of the conventional concrete.

This comprehensive review has presented some of the uncertainties addressed in the literature on durability studies. The main objective of this work, therefore, focuses on evaluating the durability of slag concrete under the conditions specified in the Spanish structural concrete code [31].

This approach requires laboratory studies of CEAF behavior exposed to the principal causes of degradation: both physical (freeze–thaw and high temperature plus relative humidity) and chemical (sulfate attack, aggregate–alkali, marine environment). It also includes an assessment of the risks of corrosion and its appearance on the embedded reinforcement bars (rebars).

2. Materials characterization

2.1. Aggregates

The slag analyzed in this research was produced at two plants in northern Spain (EAF3 and EAF4). The chemical compositions of EAF3 and EAF4 were similar to those of other investigations [8,22,32,33]. The slag aggregate was mainly (75%) constituted by Fe, Ca and Si oxides and, partially (20%) by oxides of Al, Mg and Mn. Volumetric instabilities were not foreseen, as the free lime and free magnesia, the main ingredients in expansive processes, were below 0.5% and 0.1%, respectively [34]. The specific gravities were: EAF3, 3.73 Mg/m^3; EAF4, 3.11 Mg/m^3.

The slag aggregates were 20% heavier than the natural ones, but with higher fragmentation strengths (even better than the limit established for high strength concrete). In terms of their particle size fractions (0–5, 5–12 and 12–25), EAF presented a lack of fine fraction that required remediation with natural limestone fines (0–1 mm, specific gravity 2.67 Mg/m^3), the small sizes of which improved packing density. In addition, the incorporation of aggregates with a fine, rounded morphology (siliceous sandstone, 0–1 mm, specific gravity 2.62 Mg/m^3) counteracted the effect of the surface irregularity of the EAF, improving the fluidity throughout the concrete mass [35]. Besides, water absorption in the EAF slags was higher than in the natural aggregates, as observed by other researchers [13].

The natural limestone aggregates used in the reference concrete, with a mineralogy mainly constituted by calcite (95%) and dolomite (5%), had three particle size fractions: 0–5, 5–12 and 12–25 mm, specific gravity 2.67 Mg/m^3, in compliance with the chemical requirements of EHE-08 standard [36]. Apart from these limestone aggregates, the reference concrete also contained some amounts of the aforementioned limestone filler and rounded siliceous sand, in order to achieve the best particle packaging.

Table 1
Mix proportioning of slag and reference concretes.

Mix design	CEAF3	CEAF4	CR
(0–1 mm) Limestone filler (kg/m^3)	175	176	150
(0–1 mm) Siliceous sand (kg/m^3)	640	640	520
(0–5 mm) limestone aggregates (kg/m^3)	–	–	170
(0–5 mm) EAF3 aggregates (kg/m^3)	278	–	–
(0–5 mm) EAF4 aggregates (kg/m^3)	–	232	–
(5–12 mm) limestone aggregates (kg/m^3)	–	–	625
(5–12 mm) EAF3 aggregates (kg/m^3)	787	–	–
(5–12 mm) EAF4 aggregates (kg/m^3)	–	656	–
(12–25 mm) limestone aggregates (kg/m^3)	–	–	560
(12–25 mm) EAF3 aggregates (kg/m^3)	704	–	–
(12–25 mm) EAF4 aggregates (kg/m^3)	–	587	–
CEM I 52,5 R (kg/m^3)	300	300	300
Water (l)	202	210	170
W/C	0.67	0.7	0.57
Plasticizer admixture (kg/m^3)	3.6	3.6	3.6
Slump (mm)	210	200	200
Fresh density (Mg/m^3)	3.090	2.804	2.499

The concrete mixtures were prepared using OPC type CEM I 52,5R, as specified in UNE-EN 197-1:2011 standard [37]; the sulfate resistance test was conducted on mixtures prepared with CEM I 52,5SR.

2.2. Concrete mix proportioning

After several previous studies of CEAF proportioning mixes [32], the mix detailed in the last column of Table 1 was selected, as a reference concrete (CR). Two slag concretes (CEAF3 and CEAF4) were designed for structural purposes with a cement content of 300 kg/m^3 (a minimum content stated in the EHE-08 standard [36] in the presence of aggressive environments), including natural siliceous sand and ultrafine limestone filler, as well as plasticizers to aid concrete fluidity (a slump of approximately 200 mm slump in Abrams cone).

Slag concrete requires a higher water content, due in all probability to the greater porosity of EAF and the greater proportion of fine fraction (0–1 mm) [11,38]; part of the mixing water becomes trapped in the pores of EAF. The proportioning of both slag concretes was similar (in volume), the main factor behind their different water demand and global weight being differences in the density of the slags [32,39]. The reference concrete (CR) was dosed in a similar way to the slag concretes, with a lower ultrafine fraction suitable to obtain good workability, resulting in an excellent conventional concrete.

3. Durability experimental study

Concrete durability is, in general, determined by its permeability and the aggressiveness of its immediate surroundings [40–45], the most influential factors being the presence of water and the transport (capillary network) mechanism.

3.1. Freeze/thaw

Freeze–thaw cycles represent one of the main causes of concrete degradation in cold regions [46]. Similar to any other porous material, concrete has a porosity and permeability that, after successive freeze–thaw cycles, is detrimental to its durability.

As certain researchers have confirmed [29,30], there are different approaches to the problem and several test methods exist to assess the damage, [47–51], all of which have contributed to the procedure in this study. Based on ASTM: C666-03(2008), but with certain peculiarities [44], this procedure simultaneously analyses