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Durability Studies of Self-Compacting Concrete containing Electric Arc-Furnace Slag Aggregate

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Abstract. *The structure of self-compacting concretes containing electric arc-furnace slag, their mechanical behavior, and their durability are all studied in an extensive experimental campaign, to evaluate the suitability of three concrete mixes for use in real construction works. Specimens manufactured with self-compacting electric arc-furnace slag concrete are subjected to wetting-drying and freezing-thawing test procedures, for their study in aggressive environments, especially marine environments. In general, all the test results were quite encouraging. It was once again demonstrated that the use of electric arc-furnace slag in concrete represents an opportunity to reduce both the volume of siderurgical waste generated in our society, and the consumption of fresh raw materials.*

Keywords: *Self-Compacting Concrete, Electric Arc-Furnace Slag, Durability, Marine Environment.*

1 Introduction

The future of the environment is a source of growing concern in present-day society that is calling for increasingly sustainable development. The sustainability of production processes must be carefully studied and waste-streams must wherever possible be reutilized and recycled. However, waste reduction also implies the manufacture of products of greater durability. Sustainable production processes are already dynamizing the circular economy while maintaining relevant standards and properties. Concrete products that reuse waste must therefore at the very least equal those of conventional Portland mixes.

This study is focused on the reuse of Electric Arc-furnace Slag (EAFS), a residue from the steelmaking industry, as aggregate in concrete mixtures. The reuse of slag in cement-based material has been a recurrent topic since Motz, Geiseler and Koros (Geiseler, 1996; Koros, 2003; Motz and Geiseler, 2001) published the first studies on the reuse of slag in the construction industry.

Since those first initial studies, the mechanical behavior and the hardened properties of concretes manufactured with EAFS as aggregate have been evaluated in several studies (Abu-Eishah, El-Dieb, and Bedir, 2012; Faleschini *et al.*, 2015; Manso, Gonzalez, and Polanco, 2004). Studies have also been performed on the durability of those types of concretes (Arribas, Vegas, San-José, and Manso, 2014; Manso, Polanco, Losañez, and González, 2006). In general, most of the tests on their mechanical behavior and durability have demonstrated that EAF concretes can at least equal the behavior of natural aggregate concrete.

In some of the above works, poorer workability than natural concrete aggregate has been identified as a disadvantage of EAFS concrete. In this work it will be demonstrated that with the correct mix design, self-compacting concrete can be made using EAFS as aggregate. Its durability will also be evaluated, lending special attention to the durability of EAFS self-compacting concretes in highly saline marine environments.

There are two principal reasons for this study: on the one hand, there are few studies on the evaluation of the behavior of EAFS concrete in marine environments and, on the other hand, the mechanical and the physical characteristics of EAFS concrete point to its suitability for the construction of dykes and blocks to form protective seawalls. In fact, work is underway with this type of concrete for that same purpose in coastal areas of the Basque Country, a region of northern Spain, where the evaluation of the durability of EAFS concrete in marine environments assumes special importance. In Bilbao, the port authority is pioneering the use of electric arc-furnace slag concrete in port construction works

2 Materials and Mixes

Two different cements were used: a Portland cement type I 52,5 R and a Portland cement type IV/B-V 32.5N, which included fly ash, as per standard EN 197-1.

Water was used from the urban mains supply of the city of Bilbao, free from additional particles that might adversely affect the mixes.

The commercial limestone aggregate was of three different sizes 0-1, 0-5, and 5-12. Likewise, the Electric Arc-furnace Slag (EAFS) had aggregate fractions of 0-4 and 4-12. Finally, a superplasticizer supplied by CHRYSO was selected to adjust the workability of the mix.

Three different mixes designs, shown in Table 1, were prepared with these materials:

- A reference mix, labeled NATI, manufactured with Portland cement type I and limestone aggregates,
- A mix labeled EAFSI, in which Portland cement-type I was used, although unlike in the reference mix, EAFS was used in partial substitution by volume of the limestone aggregates. Nevertheless, proportional amounts of the different aggregate fractions were not exactly the same. The higher density and the rougher surface of the EAFS particles require higher proportions of fines, to manufacture mixes with this type of aggregate (Santamaría *et al.*, 2017).
- An EAFSIV mix, with exactly the same design as the EAFSI mix, except that Portland cement-type IV, rather than Portland cement-type I, was used.

Table 1. Mix design.

	NAT I	EAFSI	EAFSIV
Cement I	330	330	
Cement IV			330
Water	165	165	165
EAFS 4-12		760	760
EAFS 0-4		550	550
Limestone fines 0-1,2	690	900	900
Limestone 0-5	560		
Limestone 5-12	730		
Superplasticizer (% cement weight)	2%	2%	2%
Density (t/m^3)	2.41	2.69	2.58
Slump flow spread. Abrams Cone (mm)	630	680	700
L-box	1	1	1

The NATI mix was manufactured in a conventional laboratory mixer and cast in different molds. An industrial concrete mixer, depicted in Figure 1, was rented to prepare the mixes for the manufacture of EAFSI and EAFSIV. From the total batch of 600 lts., two beams of each mix and several molds were precast and their mechanical and durability properties were evaluated.

Figure 1. Concrete mixer.

3 Test Method

Two tests were used to evaluate the workability of the mixes, a slump flow cone in accordance with ASTM C1611 and the L-box test, in accordance with the EFNARC standard.

The bulk density of the mixes was measured as specified in the EN 1015-10 standard. The compressive strength of the mixes was evaluated at 7, 28, 90 and 180 days, as recommended in EN-12390-3.

The Fagerlund test described in the UNE 83982 standard, based on Darcy's law, was used to analyze water absorption by capillarity.

Mix durability was evaluated with wetting-drying and freezing-thawing tests. Both tests were performed on 2 different specimens of each mix, after 90 days of curing. 148 cycles were performed for each wetting-drying test. Each cycle involved leaving each specimen in water for 16 hours, in an oven at 60°C for 6 hours placed, and at room temperature for 2 hours, to prevent thermal shock. The freezing-thawing test involved 122 cycles, in which the specimens were kept in a freezer at -15°C for 24 hours and in water, at room temperature, over the following 24 hours. The mechanical properties of the specimens were evaluated both before and after the durability test.

Three batches of specimens (100x100x100mm^3) of each mix, as shown in Figure 2, were enclosed in cages suspended from a dock wall in Pasaia Donibane port, with the purpose of analyzing EAFS concrete durability in marine environments. The cages were suspended in an intertidal zone where they would be submerged under the seawater at high tide and exposed to the atmosphere at low tide. The specimens were left in the cages for one year. After their removal, chlorine and sulphate ion infiltration was evaluated, by cutting each specimen and placing it in a vacuum chamber that was filled with nitrogen at low pressure for Scanning Electron Microscopy (SEM) analysis. Energy-dispersive X-ray spectroscopy was used to obtain the chemical composition of the first 50mm of the fracture surface and to generate backscattered electron images.

Figure 2. Specimens placed in cages at Pasaia Port.

4 Results

4.1 Workability

The workability test results of the mixes are shown in Table 1. All the mixes could be classified as self-compacting mixes. The reference mix had a lower spread than the EAFS aggregate mixes, which was a somewhat surprising result, thought to be due to the different scale of the mixes. A large number of laboratory trials had been performed before manufacturing the 600 lt. of concrete used in the mixes. The workability of the mixes with the same dosages manufactured on a small scale was worse than in the larger mixes, due in all likelihood to the skin effect. Nevertheless, such a slight difference in workability was marginal for the purposes of this research, alongside the key aspect: the self-compacting properties of the mixes.

4.2 Density and Mechanical Strength

As might be expected, the density of the concretes manufactured with EAFS was higher than the density of the concrete manufacture with natural aggregates, with increases of around 11% in the case of EAFSI and 7% in the case of EAFSIV.

Concrete strength over time is depicted in Figure 3. The behaviors of both concretes manufactured with Portland cement type I were very similar. The EAFSI mixes gained slightly higher strengths, compensating their higher density than the other mixes. The higher strength of EAFS concretes has been explained in a previous paper (Arribas, Santamaría, Ruiz, Ortega-López, and Manso, 2015), by the denser aggregate and cement-paste interface.

The hardened strength of EAFSIV was lower than its EAFSI counterpart, reflecting the characteristics of the Portland cement type IV.

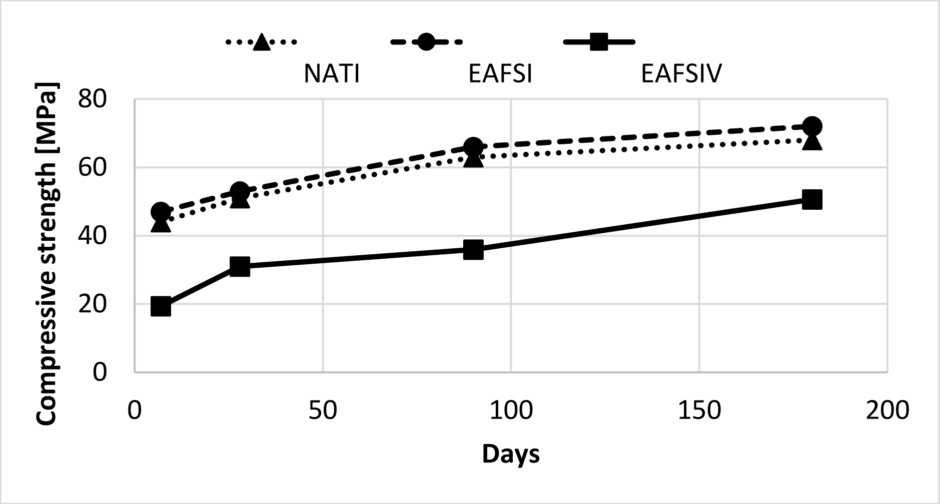

Figure 3. Compressive strength.

4.3 Capillarity Water Absorbtion

The results obtained in the capillarity water test are shown in Figure 4. The results for NATI and EAFSI were similar, unlike for EAFSIV. The curves can be divided into two zones: an initial rising zone; and, a second zone, where capillarity porosity was not evaluated as it involved other types of porosities. The less inclined slope (K coefficient 0,106 $kg/m^2s^{1/2}$) of the EAFSIV, in the first zone, represents low permeability. The value of the second zone shows us that the total porosity of the mix was high, which means that this mix may have a high number of single, unconnected spherical pores, which could also explain the lower density of the mix in comparison with the EAFSI mix. Both for NATI and for EAFSI, the slope of the curve was the same in the first zone (K coefficient 0,156 $kg/m^2s^{1/2}$), so the capillarity porosity was similar in both mixes, in the second zone, mix EAFSI achieved higher values, which might be explained by the higher porosity of the EAFS aggregate when compared with the limestone aggregate.

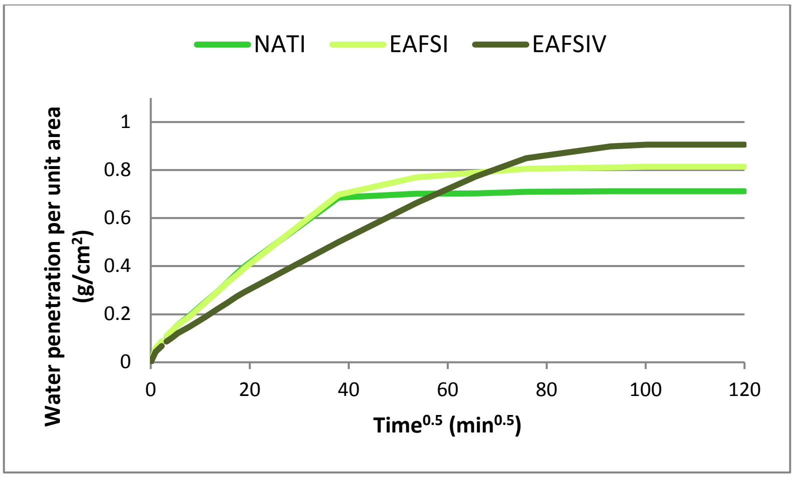

Figure 4. Capillarity test results.

4.4 Wetting-Drying and Freezing-Thawing Tests

The variation of the mechanical properties and weight of the mixes after performing durability tests are shown in Table 2. The mechanical properties of mixes NATI and EAFSI achieved similar levels. The mass loss of the EAFSI mix was higher than the mass loss of mix NATI, although if we take into account the different densities of both mixes, then their loss of volume was similar.

The behavior of mix EAFSIV during the durability test differed from the results obtained in mixes NATI and EAFSI. Strength gains were shown, rather than a loss of strength, due to the aggressive cycles. Results that are explained by the presence of fly ash associated with long-term pozzolanic reactions.

Table 2. Results of wetting-drying and freezing-thawing tests.

Mixture	Variation Strength frozen	Variation Stiffness frozen	Mass loss Frozen (g)/2500	Variation Strength wet	Variation Stiffness wet	Mass loss Wet (g)/2500
NATI	-21%	-2.8%	37.5	-2.1%	-0%	131
EAFSI	-25%	-5.1%	55.9	0%	-1.1%	158.5
EAFSIV	+6.5%	+9.4%	24	+7.5%	+13%	201.9

4.5 Marine Environment Test

In Figure 5, it is possible to see the specimens before and after exposure to a highly saline marine environment after one year. *I*t would appear, *a priori*, that this concrete has no compounds that could harm the marine ecosystem, as the specimens were teaming with mussels, oysters, and small crabs.

The behavior of EAFS concrete in marine environments was good, and even better than the behavior of natural aggregate concretes, showing slightly better strengths. The results of the analysis are in the Figure 6. No data on sulfate ions are included, as no ions of that type were found.

Figure 5. Specimens before and after the marine environment test.

Taking into account that 0.1% is a typical chlorine ion content of a cement paste, chlorine-ion penetration was around 35mm in NATI, and approximately 25mm and 15mm, in EAFSI and in EAFSIV, respectively. The higher resistance of EAFSIV to chlorine-ion penetration can be explained by looking at the results of the capillarity water test.

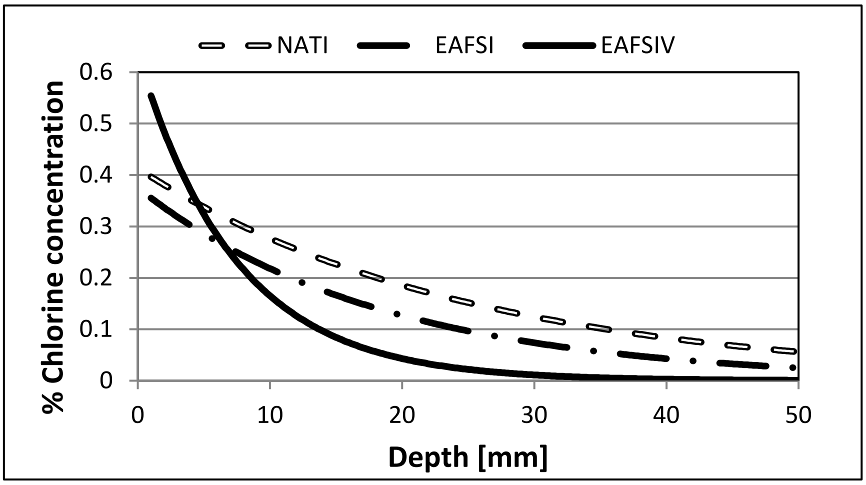

Figure 6. Specimens before and after the marine environment test.

5 Conclusion

Following the research campaign tests developed for this study, the following conclusions have been drawn:

- Mixes containing EAFS aggregate may be manufactured to the required workability, using the correct mix design. Self-compacting mixes have been successfully manufactured
- Both the mechanical behavior and the structure of the mixes manufactured with electric arc-furnace slag were fairly similar to the behavior and the structure of the mixes manufactured with natural aggregates. The main differences were observed when a different type of cement was used, in addition to the observably lower mechanical

strengths, as may be expected, in the cement type IV mixes, which also had different pore structures with larger pore volumes.

- The use of electric arc-furnace slag as a concrete aggregate was not detrimental to the durability of the concrete. The great similarities with no major differences between the natural and the EAFS aggregates were confirmed by the test results.

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References

Abu-Eishah, S. I., El-Dieb, A. S. and Bedir, M. S. (2012). Performance of concrete mixtures made with electric (EAF) steel slag aggregate produced in the Arabian Gulf region. Construction and Building Materials, 34, 249-256. doi:http://dx.doi.org/10.1016/j.conbuildmat.2012.02.012

Arribas, I., Santamaría, A., Ruiz, E., Ortega-López, V. and Manso, J. M. (2015). Electric arc furnace slag and its use in hydraulic concrete. Construction and Building Materials, 90, 68-79. doi:10.1016/j.conbuildmat.2015.05.003

Arribas, I., Vegas, I., San-José, J. T. and Manso, J. M. (2014). Durability studies on steelmaking slag concretes. Materials & Design, 63, 168-176. doi:http://dx.doi.org/10.1016/j.matdes.2014.06.002

Faleschini, F., Alejandro Fernández-Ruíz, M., Zanini, M. A., Brunelli, K., Pellegrino, C. and Hernández-Montes, E. (2015). High performance concrete with electric arc furnace slag as aggregate: Mechanical and durability properties. Construction and Building Materials, 101, 113-121. doi:10.1016/j.conbuildmat.2015.10.022

Geiseler, J. (1996). Use of steelworks slag in Europe doi:http://dx.doi.org/10.1016/S0956-053X(96)00070-0

Koros, P. J. (2003). Dusts, scale, slags, sludges... not wastes, but sources of profits. Metallurgical and Materials Transactions B, 34(6), 769-779. doi:10.1007/s11663-003-0083-0

Manso, J. M., Gonzalez, J. J. and Polanco, J. A. (2004). Electric arc furnace slag in concrete. Journal of Materials in Civil Engineering, 16(6), 639-645. doi:10.1061/(ASCE)0899-1561(2004)16:6(639)

Manso, J. M., Polanco, J. A., Losañez, M. and González, J. J. (2006). Durability of concrete made with EAF slag as aggregate. Cement and Concrete Composites, 28(6), 528-534. doi:10.1016/j.cemconcomp.2006.02.008

Motz, H. and Geiseler, J. (2001). Products of steel slags an opportunity to save natural resources. Waste Management, 21(3), 285-293.

Santamaría, A., Orbe, A., Losañez, M. M., Skaf, M., Ortega-Lopez, V. and González, J. J. (2017). Self-compacting concrete incorporating electric arc-furnace steelmaking slag as aggregate. Materials and Design, 115, 179-193. doi:10.1016/j.matdes.2016.11.048