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Performing self-compacting concrete with electric arc-furnace slag as aggregates

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Abstract. The electric steelmaking industry is of great importance to the economy of the Basque Country (Spain). In all, 600,000 tons of electric arc-furnace (EAF) slag are produced every year; a by-product that this research group believes can be transformed into a useful resource. One of the uses of this material is as an aggregate in hydraulic mixes. Many studies have demonstrated that hydraulic mixes manufactured with EAF slag have at least the same mechanical behaviour and durability as ordinary concrete. However, their weaknesses are their higher density and poorer workability. In this paper, the aim is to demonstrate that manufacturing slag concrete to an acknowledged standard of workability is possible; so the objective is to manufacture self-compacting concrete using EAF slag in partial substitution of aggregates. Our analysis of the successful manufacture of three different self-compacting mixes, their properties in the fresh state and their mechanical behaviour yielded very encouraging results.

1 Introduction

Increased global steel production is mainly due to unrestricted growth in the Asian market. The economic crisis and the Asian market are the factors that have influenced European production of steel over the past years. There was a decrease of 16% in EU production between 2000 and 2010, being almost constant this production over the past 5 years.
Our interest centres on the production of steel in electric arc-furnaces (EAF). In all, 15% of the global production of this product is in the European Union, of which most of it is produced in Italy, followed by Germany and in third position, Spain, with 15% of all EAF steel produced in the EU.

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Table 1. EAF steel production [1,2].

Per year	EAF steel (Million tons)	Land extension ($x10^3km^2$)	t EAF steel/ km^2 land	Population (million)	t EAF steel/ person
World	430	148,940	2.88	7,376.5	0.058
European Union	66	4,442	14.85	508.45	0.13
Spain	10	506	19.76	46.77	0.21
Basque Country	4	7.23	552.94	2.19	1.83

In the Basque Country, a small territory in the north of Spain where this research was carried out, all steel production use this type of electric furnace. The data presented in Table 1 show that the production per square kilometre is 200 times higher when compared with global production, 36 times higher when compared with Europe, and 28 times higher in comparison with Spain. If we compare these figures against population density, the results are similar [1,2]. These data imply that the sector generates large amounts of steelmaking waste, which have to be stockpiled within a small territory.

Nowadays, the European Union is trying to support the transition towards a more circular economy, where the waste generated in one industry becomes a secondary raw material for another industry. So, in line with European policy, in the Basque Country 600,000 tn. of EAF slag are generated every year, which this research group is convinced can be turned into a useful by-product, investing it with added value. Due to its physical and chemical properties, many researchers have proposed its use as an aggregate in hydraulic and bituminous mixes [3-6].

This research group has been studying the use of EAF slag in concrete since the late 1990s. Since then, many published works from these and other authors have concluded that concrete manufactured with EAF slag has at least the same mechanical properties as concretes manufactured with natural materials [7,8], and of similar durability [9,10]. The disadvantages of using this raw material in the aforementioned way are its higher specific weight and the lower workability of its mixes.

In the opinion of this research group the higher density of slag concretes can be compensated by its gain in strength, making this EAF slag concrete suitable for manufacturing structural elements [11]. Its poor workability can be solved through slight modifications to the traditional mix design. The objective of this research is to demonstrate that it is possible to perform EAF slag concrete with good workability, even by manufacturing a self-compacting concrete, with electric arc furnace slag in substitution of a percentage of the conventional aggregate.

In the 1980s, Okamura [12] communicated the technique of manufacturing self-compacting concrete to the world, a concrete that can fill a formwork with no need for vibration and with no segregation of the coarse aggregate. His procedure to produce these kinds of mixtures can today be considered as "the traditional or conventional way to make self-compacting mixes".

That traditional or conventional method for manufacturing self-compacting concrete in brief consists in slightly decreasing the coarse aggregate content, so as to obtain good matrix flowability [13]. This matrix phase must be of sufficient deformability to be able to compact by its own weight, but also it must be highly viscous so that the coarse aggregate fraction is efficiently transported.

Some months ago, this research team successfully prepared self-compacting mortars [14] that satisfy the specifications of current standards [15]. In the present work, the manufacture of self-compacting concrete is the relevant objective.

2 Material and methods

2.1 Materials

Two types of cement were used: first, a Portland cement type I 52.5 R; second, a Portland cement type IV/B-V 32.5-N; both in accordance with UNE-EN 197-1 standard. Water from the urban mains supply of the city of Bilbao was used containing no compounds that could affect the hydraulic mixes.

A commercial crushed natural limestone qualified as fine aggregate (maximum size 4.75 mm, fineness modulus 2.9 units, bulk density 2.6 Mg/m^3), and a medium-size limestone aggregate (sized 5-12 mm, fineness modulus 6 units) were used partially or totally in the mixes; the main mineral component of both aggregates was calcite (95%) and they can be considered classical or conventional components of concrete.

The same material mentioned as fine aggregate was also used in the mixes as an ultrafine fraction after sieving through 1.18 mm (passing through ASTM sieve Nº 16), the fineness modulus of which was 1.5 units. The grading of all the above-mentioned fractions is shown in Figure 1.

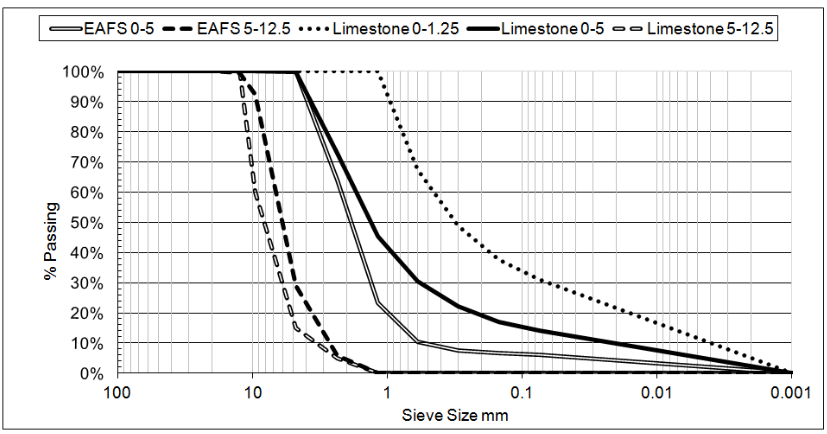

Fig. 1. Grading of the aggregates.

Crushed Electric Arc-Furnace slag (EAFS) in two size fractions (fine <4.75 mm and medium 4.75-12.5 mm), was used in this research, supplied by the company Hormor-Zestoa. Its main chemical compounds are Fe_2O_3, CaO, SiO_2 Al_2O_3, having also minor presence of MgO MnO, Cr_2O_3 and other oxides. Its main crystalline components, obtained after X-ray diffraction test, were Wüstite, Ghelenite and Kirsteinite. Its physical properties are related to water absorption of 1.2%, and specific gravity of 3.42 Mg/m^3. Their grading is also shown in Figure 1, and it is a crushed aggregate whose particles are sharp and rough form.

2.2 Design of the mixes

Several attempts took place to manufacture self-compacting concretes, using the method proposed by Okamura. The results were not as expected, obtaining concretes with good workability but they did not fulfil the requirements of a self-compacting concrete. Two indispensable factors had to be changed to obtain self-compacting concretes.

The first one was to find a suitable admixture, plasticizer and viscosity conditioner. Some of the commercial superplasticizers had effects on the concretes manufactured with natural aggregates that differed from the effects it had on the concretes manufactured with EAF slag. This observation means that in spite of the supposedly unique interaction between the superplasticizers and the cement particles, the aggregate also influences this chemical process.

Table 2. Mix proportions.

Mix Design (kg/m^3)		SCC1	SCC2	SCC3
CEM I 52.5 R		300	300	210
Fly ash				140
Limestone	Sieved fraction <1.18 mm	670	900	900
	Fine aggregate <5 mm	500		
	Medium aggregate 5-12 mm	670		
EAFS	<5 mm		535	535
	5-12 mm		685	685
Water		195	195	185
Superplasticizer		2%	2%	2%

The second indispensable factor was the need to use a suitable proportion of fine aggregate of a size below 1.18mm (Figure1). EAF slag has insufficient fine fractions to behave as a conventional aggregate and it is necessary to add a selected fraction of natural fine aggregate. In addition, due to the rough shape of the coarse EAF slag, the fine fraction must be increased comparing with the quantity needed for manufacturing self-compacting concretes with natural aggregates.

With this adjustment, three different self-compacting mixes were manufactured with the proportions shown in Table 2 and the grading shown in Figure 2. The first mix SCC1, the reference mix, is manufactured with natural limestone aggregate. Both SCC2 and SCC3, manufactured with EAF slag aggregate, are of similar grading. The only difference between them is the cement type: cement type I and type IV were used in the manufacture of mixes SCC2 and SCC3, respectively.

The components of concrete were put in a vertical-axis concrete mixer, and were kneaded over ten minutes. These mixtures were poured in cubic moulds of 100x100x100 mm after performing the flowability tests; they were demoulded after 24 hours and kept immersed in water until their mechanical testing.

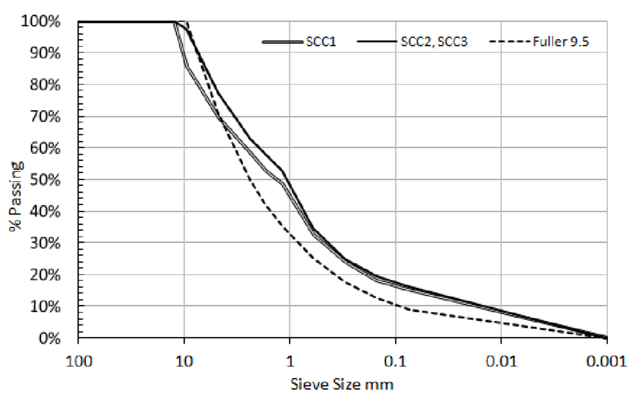

Fig. 2. Grading of mixes.

3 Fresh properties

The slump flow test and the L-box test [15] were respectively used to evaluate the flowability of the concretes, and their the passing ability through the reinforcing bars in formworks. The results of these tests are shown in Table 3. Remarkably, none of the mixes showed evidence of either segregation of coarse aggregate or blocking.
A self-compacting concrete is considered so if it has the minimum required value of 550mm in the slump flow test. Three different classes of self-compactablity are stabilized in the EFNARC [15] according to the flowability of the concretes:

- SF1 550-650 mm.
- SF2 660-750 mm.
- SF3 760-850 mm.

Table 3. Fresh properties test result.

Mixture	Slump-flow in mm	Passing ability L-box
SCC1	580 (SF1 class)	0.85 (PA2 class)
SCC2	680 (SF2 class)	0.9 (PA2 class)
SCC3	560 (SF1 class)	0.8 (PA2 class)

In this research, the aim was to reach a minimal standard of the SF1 class. Both SCC1 and SCC3 met the SF1 standard, even though SCC2 obtained a flowability class of SF2, all which were nevertheless really encouraging results.
Taking into account the passing ability, two different classes of self-compacting concrete also showed differences in the EFNARC [15]:

- PA1: ≥ 0.80 with 2 rebars.
- PA2 : ≥ 0.80 with 3 rebars.

In this case, the L-box used to evaluate the passing ability had three rebars, so all the concretes were shown to have a passing ability class of PA2. Due to the classical loss of workability in mixes using electric arc furnace slag as aggregate, it could be logic to use a L-box with two rebars, class PA1.
In spite of some results at the limit of fulfilling the requirements for self-compacting concretes, it can be said that the challenge of mixing a self-compacting concrete using EAF slag aggregate was achieved in relation to its fresh properties.

4 Hardened properties

4.1 Density

The dry and fresh densities of concretes are shown in Table 4; the correlation between both is good, as may be expected. The dry density was obtained after drying the samples in an oven at 60ºC for seven days, after a curing period of 28 days following their casting.

Table 4. Density results.

Mixture	Fresh density [Mg/m^3]	Dry density [Mg/m^3]
SCC1	2.36	2.34
SCC2	2.62	2.53
SCC3	2.67	2.63

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4.2 Strength

Even if the aim of this research was focused on obtaining concretes that in the fresh state fulfil the requirements to be considered self-compacting concrete, a minimum value of 40 MPa at 28 days was considered sufficient threshold for the use of these concretes in structural applications. The aim of this research team was to obtain this threshold without increasing the cement content, 300 kg per cubic meter, in its attempts to manufacture a more sustainable concrete. After 7, 28, 90, and 180 days immersed in water, the specimens were removed and their compressive strength was tested. The results are shown in Figure 3

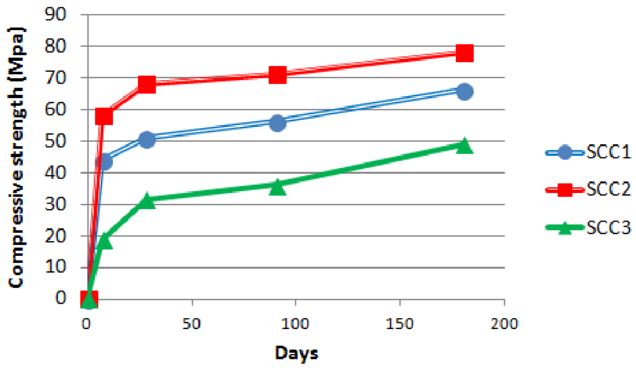

Fig. 3. Compressive strength.

The reference concrete reached 50MPa at 28 days, a higher than expected value, and at 180 days this mix reached a value 65 MPa. Mix SCC2 obtained the highest strength of all three, due to the influence of the EAF slag, reaching a value of 68MPa at 28 days and 76MPa at 180 days.

Mix SCC3 reached a value of 32 MPa at 28 days, exceeding the required strength of 40 MPa after 180 days.

5 Discussion

Enhancement of the mix flowability of SCC2 compared with mix SCC1 was achieved by over a 32% increase in the limestone fine fraction. It was expected due to the higher density and more irregular shape of the EAF slag to be worse the workability of SCC2. But the increase in the fine fraction allows achieving this good value, without increasing the cement content.

Even though mix SCC3 had the same mix proportions used to manufacture mix SCC2, the change of cement type entailed a negative effect on flowability. This effect is probably due to the dispersive action of the admixtures that were only effective on the clinker particles, without exerting repulsive forces between the fly ash particles.

The average density of the slag concretes may be seen to increase by about 12% with respect to those of concrete made with conventional aggregates (the values shown in the SCC1 mix were 2.35 Mg/m^3 and close to 2.65 Mg/m^3 in EAFS slag mixes). This is an expected value; explain with the higher density of the EAF slag in comparison with the density of natural aggregates (2.6 Mg/m3 vs 2.42 Mg/m^3). This issue is advantageous in the constructions where the concrete works by gravity. Contrary, in structural elements it seems to be a problem, but this issue is normally compensated by the increase in the strength and stiffness of EAF slag concretes.

As it has been stated in the previous section the concrete that reaches the higher compression strength value was the one manufacture with EAF slag and manufactured with Cement I. It has enhanced strength 32% higher than the natural aggregate concrete. As stated in a previous work [16] from this research group, the ITZ between EAF slag aggregates and the cement matrix will often be of better quality than the ITZ of natural aggregates and cement matrix with a consequent increase in its macroscopic compressive strength.

These values are encouraging taking into account that cement Type IV/B 32.5 N, according EN-1015, containing a high proportion of fly ash (see Table 2) was used to manufacture this mix rather than cement I 52.5 R that was used in the manufacture of the other mixes.

A full analysis of all the data confirms the successful manufacture of a self-compacting structural concrete containing EAF slag in partial substitution of conventional aggregate in terms of its mechanical strength.

6 Conclusions

The conclusions of this study are as follows:

- Manufacturing self-compacting concrete with electric arc furnace slag as aggregate is feasible.
- A suitable increase of the fine aggregate fraction is advisable when EAF slag is used.
- Finding a compatible admixture is essential, as not all admixtures will work appropriately with the EAF slag aggregate;.
- The mechanical strength tests on these concretes showed encouraging results.
- In the absence of performing durability tests, it could be said that well-performed self-compacting concrete with EAF as aggregate have been manufactured.

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