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Performance of steel-making slag concrete reinforced with fibers

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Abstract. In this research, the possibility of making concrete reinforced with fibers and manufactured with recycled aggregates from carbon steel production was explored. Electric arc furnace slag (EAFS) was used as coarse and medium aggregate, and part of the sand sizes. Metallic and synthetic fibers were added in different amounts. Initially, the properties of EAFS and their suitability to be used in the manufacture fiber reinforced concrete were analysed. Then, a series of fiber reinforced concrete mixtures were developed incorporating EAFS, and they were compared with the reference mixtures, made with conventional components plus fibers and made with EAFS without fibers. A series of tests were performed, including concepts such as consistency, compressive strength, flexural strength, splitting tensile strength, resistance to water penetration or toughness. The results show that it is possible to make a suitable steel-slag concrete reinforced with fibers, complying with the standard requirements for it use in pavements and slab, and improving their proprieties respect to the control mixtures.

1 Introduction

Electric Arc Furnace Slag (EAFS) is a by-product of the steel electric industry, produced following the melting of scrap steel. It is usually presented as gravel sized aggregate.

In Spain, approximately 70% per cent of total steel production (14 millions of tons) is from steel electric furnaces, together with 1MT of EAFS [1].

The steelmaking industry is mainly concentrated in the north of Spain. Therefore, it is so important for us to reuse this by-product in order to reduce slags landfilling and contribute to global sustainability.

In general, steelmaking slags are products which have certain risk of expansion, mainly due to a potential presence of free lime and periclase. So, an outdoor weathering and some additional cautions are necessary to prevent the occurrence of any expansive phenomena [2-

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6]. In the last decades, important works on EAFS [7-10] and LFS characterization [11-13] have been published; it has been demonstrated the suitability of both slags in different applications, such as bituminous mixtures [14-18], concrete and mortars [19-34], self-compacting concrete [35-37], making clinker [38], soil stabilization [39-41] and others [42, 43]. Despite these recycling possibilities, in Spain, approximately 23% of the electric slag is accumulated in landfill sites.

On the other hand, the construction sector is an important consumer of natural aggregates. Total consumption of natural aggregates in Spain is around 90 MT per year, resulting in a consumption of natural resources and exploitation of quarries.

With this work, we tried to convert the EAFS in steel aggregate for manufacturing steel-slag concrete.

The aim of the research carried out to outline this paper, was based on the reuse of EAF slags in the construction of concrete pavements and concrete slabs reinforced with fibers, in order to avoid the spread of the superficial cracks during the initial drying of the concrete, to improve its flexural and splitting tensile strength and to increase its capacity to absorb rupture energy.

For that, the slag was used as coarse and medium aggregate in the concrete mixture, and the sizes of sand were completed with 50% of slag and 50% of siliceous sand; which is mean approximately 75% of EAFS and 25% of natural aggregate in the finale concrete mixture. The siliceous sand, with rounded morphology, counteracted the effect of the surface irregularity of the EAFS, improving the fluidity throughout the concrete mass [44]. Furthermore, different dosages and types of fibers (metallic and synthetic) were studied in order to determine which are the most suitable for the aim proposed.

2 Materials

The following materials were used in this research:

- Ordinary Portland Cement (OPC) CEM I 42,5R.
- Water from an urban water supply
- Natural siliceous aggregates: It has been provided in three granulometric sizes: 0/4, 4/12 and 12/25 mm; the size limestone aggregate employed in the EAFS concrete was the sand 0/4 mm, with fine content according with UNE-EN-933-1of [45, 46]1.58% and sand equivalent according with UNE-EN 933-8 of 89.
- Superplasticizers: Policarboxilato modified with water. Density of 1.08 g/cm3, pH of 5 and solid content of 36%.
- EAFS aggregates: It has been provided in three granulometric sizes: 0/4, 4/10 and 10/20 mm (Figure 1). The lack of fines is appreciated on the sand slag. EAFS is heavy, with density over 3500 kg/m^3 and a very resistant aggregate (loss Angeles Loss: 24%, Flakiness index: 3%). The main compounds of the EAFS are shown in Table 1.
- Metallic fibers (RL-45/50-BN): hard drawn steel filaments with formed ends to improve adhesion; Synthetic fibers (M-48): polyolefins curly monofilament (Figure 2).

Table 1. Main chemical composition of the EAFS.

Component	CaO	SiO2	MgO	Al_2O_3	Fe_2O_3	MnO
EAFS wt.-%	27.7	19.1	2.5	13.7	26.8	5.3

Fig. 1. EAFS granulometric sizes.

Fig. 2. Metallic and Synthetic fibers.

3 Mix design

Some dosages were used for the reference mixtures, which had previously been endorsed by other authors in bibliography:

- Reference mixture **P**, was a mixture with natural aggregates and 30 kg of metallic fibers per m^3 of concrete, according with Turmo et al [47].
- Reference mixture **E**, was a mixture with 75% of EAFS aggregates and 25% of siliceous sand without fibers, according with Manso et al [30].

Other mixes under study in this research (**EM1**, **EM2**, **ES1**, **ES2**) had the same dosage as the reference mix E, but including two types of fiber reinforcements (metallic and synthetic) in different quantities, within the range of 0.4-0.6% of fibers by unitary volume of concrete. Table 2 shows the compositions of the mixes under study.

For all mixtures, the following parameters were constant: amount of cement: 363 kg/ m^3; relation water/cement (w/c): 0.5; relation coarse aggregate/fine aggregate/cement: 3/3/1.

Table 2. Mix proportioning of components in manufactured concretes.

Mix design (kg/m^3)		P	E	EM1	EM2	ES1	ES2
Cement		360	360	360	360	360	360
Water		180	180	180	180	180	180
Siliceous aggregates	Size 0/4 mm	800	500	500	500	500	500
	Size 4/12 mm	575	-	-	-	-	-
	Size 12/20 mm	465	-	-	-	-	-
EAFS aggregates	Size 0/4 mm	-	515	515	515	515	515
	Size 4/10 mm	-	670	670	670	670	670
	Size 10/20 mm	-	550	550	550	550	550
Plasticizer (1-1.5% wt. of cement)		3.63	5.44	5.44	5.44	5.44	5.44
Metallic Fibers		30	-	30	45	-	-
Synthetic Fibers		-	-	-	-	3.5	5

4 Results and discussion

4.1 Consistency of freshly mixtures

The consistency of freshly mixed concrete was measured with Abrams Cone, according to UNE 12350-2, before and after including the fibers. The results show that the mixture with natural aggregates and fibers had soft/plastic consistency and the rest of the mixtures manufactured with EAFS or EAFS plus metallic/synthetic fibers had dry consistency.

4.2 Compressive strength

The compressive strength was measured on cylindrical concrete specimen, with 150 mm of diameter and 300 mm of height, cured during 28 days in moist chamber at 20+/-2 ºC and 95% of moisture. The assay was performed in triplicate. According to UNE 83507, the results obtained are shown in Table 3.

Results show higher compressive strength in the concretes with steel-slag aggregates than the concretes with natural aggregates, even when those contained reinforcing fibers. The mixture E (with EAFS without fibers) had an increase of 43% of compressive strength respect to the mixtures P (with natural aggregates and fibers).

EM2 and ES1 are the mixtures with better results in this test, with an increase of 10-12% of compressive strength with respect to the same concrete without fibers. These results are according with other authors who said that fiber volumes added to concrete mixes at 0.5%, 1.0% and 1.5% by volume of concrete improve the compressive strength between 4% and 19% [48].

Table 3. Compressive strength, Flexural strength and Splitting tensile strength.

Mixture	Compressive Strength 28 days (MPa)	Flexural Strength 28 days (MPa)	Splitting Tensile Strength 28 days (MPa)
P	46.30	5.15	4.33
E	66.05	6.80	4.20
EM1	54.00	5.95	5.01
EM2	72.62	7.00	5.45
ES1	74.04	7.13	5.23
ES2	66.50	6.88	4.59

4.3 Flexural strength

The flexural strength was measured on concrete specimen with dimensions 150x150x600 mm and 100x100x400 mm, cured in moist chamber during 28 days. According to the UNE 83509, the load was applied in two spaced points between them 1/3 of the length of the specimen (Figure 3). The results obtained are shown in Table 3.

All the steel-slag concretes had better results than the conventional one, even with fibers. The average of the flexural strength for steel-slag concretes with fibers had an increase upper than 30% respect to the reference mixture P.

It was well known that the steel-slag concrete improves the flexural strength [6] and that the fibers provide better deformation performance by flexion [49] according to the results obtained for concrete manufactured with EAFS and fibers.

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The results were similar to the previous ones of compressive strength, reaching the best results the mixtures EM2 and ES1.

Fig. 3. Flexural strength test.

4.4 Splitting tensile strength

The splitting tensile strength was measured on cylindrical concrete specimen with diameter of 150 mm and height of 300 mm, cured in moist chamber during 28 days. According to the UNE 12390-6, the load was applied over two opposite lines until failure. The results provide the maximum load that the pavement is able to support (Figure 4). The results obtained were also shown in Table 3.

All the mixtures with fibers had better performance at splitting tensile strength than the mixture E (without fibers), especially the mixtures with EAFS and fibers, EM2 and ES1. It is possible that higher amount of synthetic fibers in mixture ES2 than in mixture ES1 damages the strength characteristics of the hardened concrete, well by its problematic mix process or by the low hydration of the concrete components.

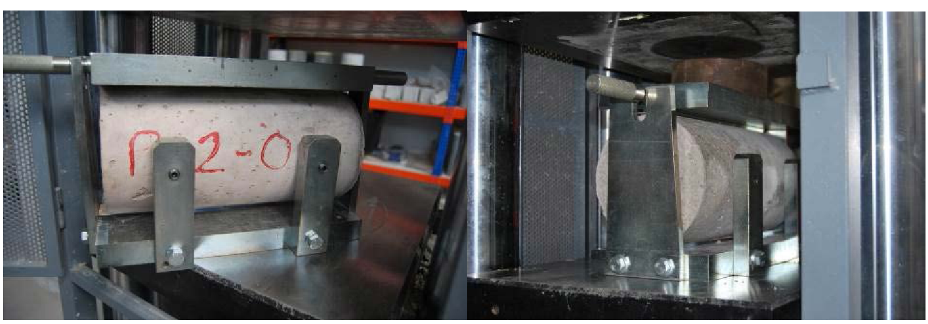


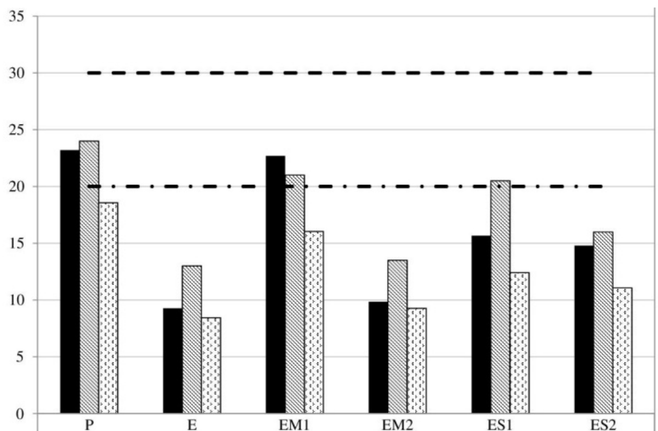
Fig. 4. Splitting tensile strength test

4.5 Resistance to water penetration

The resistance to water penetration under pressure was measured on cylindrical concrete specimen with diameter of 150 mm and height of 300 mm, cured in moist chamber during 28 days. According to the UNE EN 12390-8, the water was applied under pressure of 500+/-50 kPa during 72 hours in one of the specimen faces. After that, the specimen was broken and the depth of water penetration was measured. The results of the maximum depth of water penetration are shown in Figure 5.

All the mixtures with EAFS had better resistance to water penetration than the conventional concrete with natural aggregates. However, in this test, the fibers in the concretes manufactured with EAFS did not improve the results respect to concrete without them.

Even so, all the mixtures fulfilled the requirements of the EHE standard [50], which specifies, for the worst environmental exposure, the value of maximum depth of water penetration under 30 mm. Therefore, these concretes were considered impermeable enough for its use in pavements.



	P	E	EM1	EM2	ES1	ES2
Water penetration area (cm²)	23.21	9.28	22.70	9.85	15.67	14.79
Maximum depth (mm)	24.00	13.00	21.00	13.50	20.50	16.00
Average depth (mm)	18.57	8.44	16.04	9.28	12.42	11.07
Maximum depth in EHE (mm)	30	30	30	30	30	30
Average depth in EHE (mm)	20	20	20	20	20	20

Fig. 5. Depth of water penetration under pressure.

4.6 Toughness by compression

The toughness is the energy required for a prespecified total deterioration or breakage of the material. It is one of the most important characteristics that the fibers provide to the material.

The toughness by compression was measured on cylindrical concrete specimen with diameter of 150 mm and height of 300 mm. According to the UNE 83508, the results provide the area bounded by the load-deformation curve from the origin 0, and the ordinate corresponding to a deformation of 1.125 mm.

The mixture EM2 (toughness of 1949300 N.mm) had better results than the mixture ES1 (toughness of 1887900 N.mm), which means that metallic fibers provided greater post-cracking strength and higher increase of concrete ductility.

4.7 Impact strength

Another important characteristic that the fibers bring to the concrete, once again directly related with toughness, is increased concrete strength against impacts, collapse, and other dynamic loading. A drop weight impact test was applied to cylindrical concrete specimens, in accordance with the UNE 83514 [45] standard. The test results, shown in Table 4, record the number of hits until the first crack appears and the number of hits up until breakage of the specimen.

In view of test results, the fiber-reinforced concretes (i.e EM2, ES1, P) clearly appear to have much better impact strength than the equivalent not-reinforced concrete (E, P without fibers), both against the first signs of cracking and especially against breakage. Additionally, the concrete mixes with electric arc furnace slag (i.e E, EM2, ES1) showed better impact strength than the corresponding mixes made with conventional aggregates (P not fibers, P).

Table 4. Impact and abrasion resistance.

Property		E	EM2	ES1	P	$P_{not\ fibers}$
Impact	Number of hits until first crack	11	46	24	19	6
Strength	Number of hits until breakage	13	155	88	50	8

5 Conclusions

The conclusions from this work can be summarized as follows:

- Steel-slag concretes reinforced with fibers, metallic or synthetic, at around 0.4-0.6% by volume of concrete, provided concretes with suitable mechanical behavior.
- The mixture reinforced with metallic fibers provided slightly better results of Toughness and Impact Strength than the concrete reinforced with synthetic fibers.
- Due to the poor workability and docility of the fiber reinforced concretes manufactured with EAFS, it is recommended a water/cement ratio over 0.5 and the use of plasticizer additive, as well as the incorporation of siliceous sand in order to compensate the lack of fines of the EAFS.

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