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FRACTURE TOUGHNESS EVALUATION OF FIBER-REINFORCED CONCRETE MANUFACTURED WITH SIDERURGIC AGGREGATES.

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ABSTRACT

Steel production in electric arc furnaces generates a principal waste stream in the form of Electric Arc Furnace Slag (EAFS), also known as “black slag”. The well-researched and advantageous properties of EAFS guarantee its successful use as aggregate in the manufacture of concrete (CEAFS). In contrast, fiber-reinforced concrete is widely employed, especially in concrete pavements and slabs, for improved cracking resistance and “ductile” post-cracking behavior. In this research, the toughness and ductile behavior of these fiber-reinforced CEAFS is tested with various methods, using different types of (metallic and synthetic) fibers in EAFS mixes. The metallic fiber concretes showed better results than the fiber concretes in terms of toughness, first-crack strength, limit of proportionality, and post-cracking behavior. The recycling process of EAFS makes a relevant contribution to the circular economy and therefore to global sustainability.

Keywords: Fiber-reinforced concrete, cracking resistance, fracture toughness, slag

1. INTRODUCTION

The civil engineering industry has a significant global environmental impact. The urgent need for greater sustainability has led to the exploitation of waste streams and by-products from the industry that are recycled as aggregates in structural and non-structural components. Reflected in the research strategies at a European level (in the HORIZON2020 program), this trend is echoed at both a national (in the Spanish program RETOS2018), and a regional level (RIS3 of Junta de Castilla y León-Regional Government).

The main expected benefits of this measure are a decrease in waste dumping in landfill sites and reduced consumption of natural aggregates, an end to over-exploitation of quarries, and reduced energy consumption and CO_2 emissions. The annual consumption of the construction sector in the EU was approximately 3,000 million tons of natural aggregates and around 112 MT/year in Spain (ANEFA 2018). Those hard facts have encouraged engineers to look for new raw materials to replace natural resources.

In consequence, a wide range of recycled aggregates have recently been introduced in replacement of natural aggregate for various construction applications (Shelburne and Degroot 1998, Maghool, Arulrajah et al. 2017), highlighting the use of several types of slags from metallurgical processes in industrial production (Geiseler 1996, Motz and Geiseler 2001, Wang, Wang et al. 2010, Le, Sheen et al. 2015, Yüksel 2017). The use of steelmaking slag in the construction industry was first advanced in the seminal papers of Shelburne, Motz, Geiseler, Koros et al. (Shelburne and Degroot 1998, Motz and Geiseler 2001, Koros 2003, Dippenaar 2005). Many researchers have since followed their lines of research, focusing their studies on the application of steel slags in concretes for infra- and superstructures, depending on the technical demands of each project.

In that regard, the addition of fibers presents some advantages over the traditional steel bars, such as better distribution of reinforcement, crack minimization; increasing the composite absorption of energy, and enhancing its residual strength (Turmo, Banthia et al. 2008, Colombo, Martinelli et al. 2017, Maya Duque and Graybeal 2017, Mo, Goh et al. 2017).

In this context, the authors of this paper have investigated the viability of using Electric Arc Furnaces Slags (EAFS) in the most common applications of current fiber reinforced concrete (FRC), such as rigid pavements. An experimental program of tests was proposed to achieve this goal, to examine the mechanical properties of concretes manufactured with Electric Arc Furnace Slag as aggregate (CEAFS), with special interest in the evaluation of their fracture toughness and post-cracking behavior.

1.1 Steelmaking Industry

The two main steel extraction processes will be briefly summarized in this section, for a better understanding of the global steelmaking industry. Firstly, there is the Integral Steel Industry, which uses iron ore as raw material, melted in a Blast Furnace, and followed by a decarburization phase, usually in Oxygen-Blow Converters (Basic Oxygen Furnace–BOF); on the other side, there is the Electric Steel Industry, in which scrap is melted in Electric Arc Furnaces (EAF). After this “primary metallurgy” phase, a second process in Ladle Furnaces (LF) produces carbon steel (“secondary metallurgy”). In these steel production processes, a series of wastes are generated, among which, steel slag constitutes the most voluminous residue (Yildirim and Prezzi 2011).

In the EU steel sector, a total of 44.4 Mt of slag are produced, of which 8.1 Mt corresponded to Electric Arc Furnace Slag (EAFS) and 3.6 Mt corresponded to secondary slags, according to data from most recently available report from EUROSLAG: "The European Association representing metallurgical slag producers and processors" (EUROSLAG 2013).

Spain, in particular, is the third producer of electric steel in the EU, below Germany and Italy, with production levels of around 10 MT of electric steel (70% of the total amount of steel production: 14 MT), together with almost 2 MT of EAFS and 0.5 MT of LFS by-products (EUROSLAG 2013, 2014). In Spain, approximately 28% of electric slag waste is currently dumped in landfill sites, despite the recycling possibilities also developed for these electric slags, such as their use in bituminous mixes (Pasetto and Baldo 2011, Skaf, Ortega-Lopez et al. 2016), concrete and mortars (Manso, Hernández et al. 2011, Santamaría, Orbe et al. 2017) and soil stabilization (Manso, Ortega-López et al. 2013, Ortega-López, Manso et al. 2014), among others.

1.2 Aim and Scope of the Research Work

The aim of this research is the use of EAF slag in the manufacture of concrete pavements and industrial slabs reinforced with metallic or synthetic fibers in amounts of 0.4-0.6 % by volume. This type of fiber-reinforced pavement is expected to be less prone to crack propagation during the initial drying of the concrete and to show better mechanical and fracture toughness behavior.

2. MATERIALS AND METHODOLOGY

The materials used in this research were: Ordinary Portland Cement (OPC) CEM I 42,5R, water from an urban water mains supply, natural siliceous aggregates provided in three granulometric sizes of 0/4, 4/12 and 12/25 mm, superplasticizers, EAFS aggregates provided in three granulometric sizes of 0/4, 4/10 and 10/20 mm, and (metallic and synthetic) fibers. The main characteristics of the fibers are shown in Table 1.

The main physical characteristics of the EAFS were: specific gravity of 3500 kg/m3, high water absorption, low fines content, and 24% Los Angeles Loss. The main chemical components were oxides of Fe, Ca and Si.

Table 1. Characteristics of fibers

Characteristic	Metallic Fibers (RL-45/50-BN)	Synthetic Fibers (M-48)
Material	steel	polypropylene
Length (mm)	50	48
Equivalent diameter (mm)	1.05	0.93
Length/diameter aspect ratio	45	50
Tensile strength (MPa)	>1000	>400
Density (kg/m^3)	7900	910
Young's modulus (GPa)	210	6

The methodology was based on the use of EAFS as coarse and medium aggregate in the concrete mix and the fine aggregate was prepared with 50% fine slag and 50% siliceous sand, in order to compensate the lack of the fines in the EAFS.

Two reference mixtures were designed: mixture P, manufactured entirely with siliceous aggregates, and mixture E, manufactured with EAFS in coarse and medium gravel and 50%-50% of siliceous-EAFS in sand. Their mix design is contained in Table 2.

Taking the dosage of mixture E as a reference, four experimental mixtures reinforced with metallic fibers identified as EM and with synthetic fibers identified as ES were manufactured. The fiber amounts were in each case as follows: EM1 (30 kg of fibers/m^{3}of concrete), EM2 (45 kg/m^3), ES1 (3.5 kg/m^3), and ES2 (5 kg/m^3).

Table 2. Mix design of the reference mixtures (kg/m^3)

Mix design kg/m^3	Cement	Water	Siliceous aggregates			EAFS aggregates			Admixture
			0/4	4/12	12/20	0/4	4/10	10/20	
P	360	180	800	575	465	-	-	-	3.63
E	360	180	500	-	-	515	670	550	5.44

3. RESULTS AND DISCUSSION

3.1 Concrete strengths

Compressive, flexural and splitting tensile strengths of the mixtures, measured at 28 days, are shown in Table 3.

Table 3. Concrete strengths

	Mixtures					
Property	P	E	EM1	EM2	ES1	ES2
Compressive Strength (MPa)	46.3	66.1	70.0	72.6	74.0	66.5
Flexural Strength (MPa)	5.2	6.8	6.9	7.0	7.1	6.8
Splitting Tensile Strength (MPa)	4.3	4.2	5.0	5.5	5.2	4.6

The compressive strength of the siderurgic concrete E (66.1 MPa) was 43% higher than that of natural aggregates P (46.3 MPa), even reaching values of 72-74 MPa for mixtures EM2 and ES1, respectively.

The flexural strength of the siderurgic concrete E (6.8 MPa) was also higher than that of conventional concrete P (5.2 MPa); mixtures EM2 and ES1 reaching values of around 7 MPa. This fact is attributed to the good (dense and not very porous) quality of the ITZ (Interfacial Transition Zone) of the siderurgic concretes and to high adhesion between all the components of the mixtures (aggregates, cement paste and fibers).

As regards the splitting tensile strength, little difference was observed between the reference concretes P (4.3 MPa, with fibers) and E (4.2 MPa, without fibers). An important improvement in the mixtures with fibers was observed once again, especially concretes EM2 (5.5 MPa) and ES1 (5.2 MPa).

In view of these first results, we conclude that the mixtures with the best results were EM2 and ES1, so they were the mixtures with which the fracture toughness was evaluated, in comparison with reference sample E.

3.2 Fracture Toughness by Compression

Compressive toughness was measured on cylindrical specimens with a diameter of 150 mm and a height of 300 mm conserved over 90 days in a moist chamber, in accordance with the UNE 83508 standard. Toughness under compression was measured by two electronic transducers, vertically centered and placed on the specimen at a distance of 150 mm, as can be seen in Figure 1, measuring specimen deformation in the direction of the load. The toughness results obtained from the load-deformation curves corresponded to the area under the curve between 0 and 1.125 mm of deformation and are shown in Figure 2. We observed reasonable and very close results for samples EM2 (1128 N · m) and ES1 (1032 N · m) (Marar, Eren et al., 2011), the mixture with metallic fibers showing slightly higher values. The metallic fibers can therefore be said to provide higher post-cracking strengths and energy absorption capacity than the synthetic fibers. The toughness of mixture E was significantly lower (478 N · m), as expected, after a rupture deformation of 0.76 mm. This last curve is not represented in the figure, because mixture E never reached the deformation limit of 1.125 mm.

Figure 1. Specimen in the toughness compression test

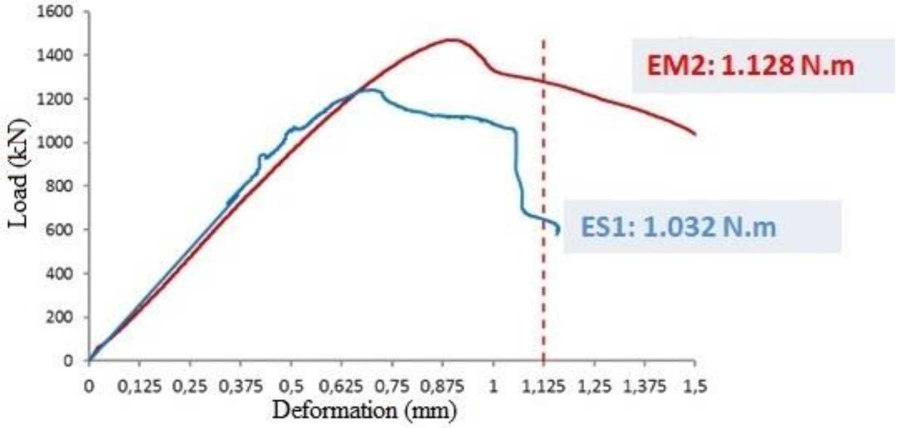

Figure 2. Load versus deformation curves in the toughness compression test

3.3 First Crack Strength and Fracture Toughness by Flexion

Flexural toughness and first-crack strength were measured on prismatic specimens of 100 x 100 x 400 mm, in accordance with the UNE 83510 standard. The samples were loaded in four-point bending test at intervals of one-third of the span length (300 mm). The arrangement of the samples (with the first crack and final breakage) is shown in Figure 3. The results of first-crack strength and toughness obtained in the flexural test are shown in Table 4.

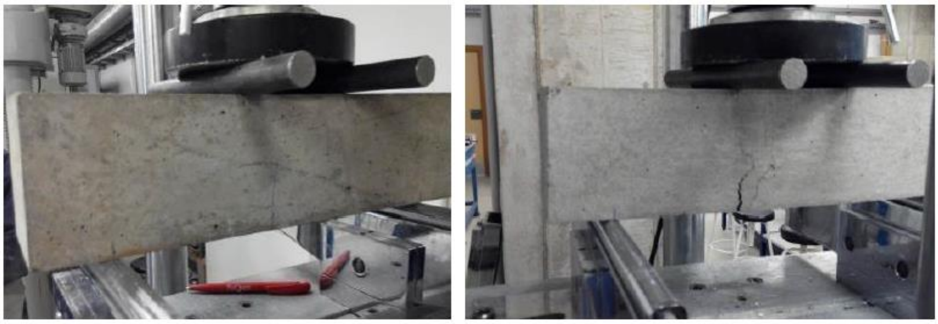

Figure 3. Specimen with first crack (left) and final breakage (right)

Table 4. First-crack strength in flexural test

Property	standard	E	EM2	ES1
First-crack strength (MPa)	UNE 83510	7.2	7.9	7.6
Flexural toughness (N · m)		8.7	40	35

We can see that the first-crack strength results are similar to those shown in section 3.1 (Table 3), with values of around 7 MPa, the concrete reinforced with metallic fibers EM2 (7.9 MPa) showing the higher strength, followed by the concrete reinforced with synthetic fibers ES1 (7.6 MPa).

With regard to the behavior after the first crack (post-cracking behavior and ductility), as was expected, the curve of mixture E (without fibers), once it reached the peak, suddenly fell, registering an area value under the curve of 8.7 N · m. In contrast, the concretes reinforced with metallic fibers (EM2) and with synthetic fibers (ES1) showed better post-cracking behavior that was reflected in the greater horizontality of the curve load-deflection and therefore, in a larger area under the curves. The toughness values of each type of concrete, EM2 and ES1, were 40 N m and 35 N m, respectively. These values were considered suitable for fiber-reinforced concrete (FRC) used in pavements and industrial slabs.

3.4 Barcelona Method: Cracking Strength, Toughness and Residual Tensile Strength.

Cracking strength, toughness and residual tensile strength determined by the Barcelona Method were evaluated according to the UNE 83515 standard in a double punching test on cylindrical specimens with a diameter of 150 mm and a height of 150 mm conserved over 90 days in a moist chamber.

In the performance of the test, steel loading discs were used, attached to the lower and the upper face of the specimen; the upper disk must be mounted on a spherical ball. The values of the applied load and the resultant circumferential deformation were recorded with a strain gauge.

The load, applied through the steel discs of one quarter of the diameter of the specimen, produced a conical compression zone underneath the discs. This situation caused an increase in the diameter of the specimen, producing tensile stresses perpendicular to the radial lines of the specimen. A tensional state in excess of the concrete strength will produce the fracture of the samples.

Radial cracks (perpendicular to this field of stresses) spread outwards from the center, due to the concentration of stresses along concentric planes, at the time of rupture. Once the first crack has appeared, it is usually followed by (one or two) other cracks.

The radial cracks that appeared in specimens after the test and the test set-up are shown in Figure 4. The results of cracking strength, toughness and residual tensile strength determined for deformation values of 2 mm, 2.5 mm, 4 mm and 6 mm, are contained in Table 5.

The results of cracking load by unit of area, f_{ct}, showed that

Figure 4. Barcelona test set-up (left) and radial cracks in specimens after the test (center and right)

With regard to the residual tensile strength, $f_{ct}R_x$, it can be observed that mixture ES1 began to decrease rapidly for circumferential deformations of 2.5 mm, while this decrease started at a circumferential deformation of 4 mm in mixture EM2.

The metallic and synthetic fibers provided greater ductility to the concrete, which can be seen in the toughness parameter TR_x. The cross-sectional area of mixture E without fibers disintegrated at circumferential deformations of less than 4 mm, while the integrity of the cross-sectional areas of mixtures EM2 and ESA with fibers remained up to circumferential deformations of at least 6 mm. Mixture EM2 recorded a toughness value of 686 N · m at a deformation of 6 mm and mixture ES at 503 N · m.

Table 5. Cracking strength, toughness and residual tensile strength results

Barcelona Method. UNE 83515 standard		E	EM2	ES1
Unit load of cracking, f_{ct} (MPa)		4.27	4.92	4.32
Residual tensile strength, $f_{ct}R_x$ (MPa)	2 mm	3.06	2.37	2.57
	2.5 mm	2.27	2.96	3.15
	4 mm	-	4.50	2.18
	6 mm	-	2.25	1.28
Toughness, TR_x (N · m)	2 mm	132.40	101.48	112.46
	2.5 mm	197.99	158.84	173.29
	4 mm	-	401.90	358.67
	6 mm	-	686.04	502.65

3.5 Flexural Tensile Strength, LOP and Residual Strength

Flexural tensile strength, limit of proportionality (LOP), and residual flexural strength were determined with the EN-14651 standard on prismatic specimen of 150 x 150 x 600 mm conserved over 90 days in a moist chamber and with a notch of 5 mm (crack mouth) in one of its sides. In this test, the load and the crack mouth opening displacement (CMOD) were registered. Figure 5 shows the arrangement of the test. The results for the maximum stress for the CMOD less than ≤ 0.05 mm (LOP) and for CMOD of 0.5 mm, 1.5 mm, 2.5 mm, 3.5 mm are shown in Table 6.

Once again, the curve load-CMOD after cracking of mixture E (without fibers) suddenly fell, preventing the recording of residual strength after the cracking-peak.

The residual strength of mixture EM2 provided better results (in the range of 5.5-4.7 MPa) than mixture ES1 (1.5-1.1 MPa). The same happened with the LOP of both concretes reinforced with fibers. This different behavior of the (metallic and synthetic) fibers was partly due to the uneven distribution of the synthetic fibers (Grünewald, Laranjeira de Oliveira et al. 2012).

Figure 5. Arrangement of specimen after cracking in flexural tensile strength test

Table 6. LOP and residual tensile strength after cracking

Flexural tensile strength test EN-14651 standard		E	EM2	ES1
LOP (CMOD ≤ 0.05 mm) (MPa)		6.1	6.4	6.2
Residual flexural tensile strength (MPa)	0.5 mm	-	5.5	1.5
	1.5 mm	-	5.4	1.1
	2.5 mm	-	5.1	1.1
	3.5 mm	-	4.7	1.2

4. CONCLUSIONS.

- Siderurgic concrete mixtures reinforced with either metallic or synthetic fibers showed good mechanical properties.
- The toughness and post-cracking behavior of siderurgic concretes reinforced with fibers (metallic or synthetic), evaluated under compressive and flexural tests (with and without initial notching) and with the Barcelona Method, were suitable for the use of these concretes in pavements and industrial slabs.
- The best siderurgic concrete evaluated in this study was the mixture reinforced with a volume of metallic fiber at 0.6% by volume of concrete.

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