Performance of fiber-reinforced sustainable concretes manufactured with aggregate and binder from steelmaking slag

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Abstract.

It is well known that the construction industry generates a huge amount of CO_2 emissions into the atmosphere, mainly emitted during the manufacture of cement and the exploitation of quarries for aggregate production. On the other hand, steelmaking industry landfills millions of tons of waste (slag) that can be reused as raw materials in innovative processes. For these reasons, in order to preserve natural resources and improve the sustainability of concrete manufacturing, this paper addresses the design and behavior of high-workability and fiber-reinforced concrete, produced with electric arc furnace slag in substitution to aggregates and with cement that contains ground granulated blast furnace slag and/or ladle furnace slag as supplementary cementitious materials. The main in-fresh, mechanical and durability properties were experimentally evaluated, which showed good performance results in all the cases. Good adhesion between fibers, aggregates and cementitious matrix within the concrete specimens was also observed. Furthermore, these sustainable concretes reached self-compactability, which enable an energy-saving placement and its use in a wide range of building applications, thus contributing to the circular economy in the construction sector.

Keywords: *electric arc furnace slag, ground granulated blast furnace slag, ladle furnace slag, supplementary cementitious material, fiber-reinforced concrete, self-compacting concrete.*

1 Introduction

The building sector, especially the manufacturing of different kinds of cement, is recently looking for new ways to avoid the great deals of contamination it generates every year, being one of the most polluting industries [1].

The steelmaking industry generates, every year, tons of waste and the transformation of this by-products in valuable inputs to other processes is one of the most important efforts of the construction sector in the past years, trying to favor towards recycling, circular economy and sustainability overall [1, 2].

Among these numerous efforts, cement has always been the main character of this movie, due to its high demand and important characteristics [3].

New sustainable strategies have chosen to use Supplementary Cementitious Materials (SCM) instead of high quantities of Portland Cement [1, 3], so as per EN 197-1, cement types II/B-S and III have been used, adding different proportions of Ground Granulated Blast Furnace Slag (GGBFS), which use has been already proven for maritime and geotechnical engineering [4], as well as lower quantities of Ladle Furnace basic Slag (LFS), also successfully used in various engineering fields [5].

Other innovative approach of this paper is the use of Electric Arc Furnace Slag (EAFS) as massive aggregate in the concrete mix. The successful use of EAFS in other fields has already been widely demonstrated [2] and suitability for Self-Compacting Concrete (SCC) is to be determined, as they have significant advantages in terms of laying ranges. However, some issues are being studied, as their flowability, seggregation and decantation [6] can be challenging to accommodate in the correct ranges and its mix design has to be done carefully.

In addition, the popularity of adding different types of fibers to the concrete is increasing, due to their wide application range [7] as the mechanical behavior of the elements is enhanced [8], as well as the fractural behavior, strength and toughness [9].

Therefore, this paper contains a study about the suitability of use EAFS in substitution of aggregates and GGBS/LFS as SCM in making high-workability fiber-reinforced concretes, evaluating their fresh and mechanical properties, in order to a obtain a sustainable concrete which uses less amount of energy in its production and it also produces very less carbon dioxide than a conventional concrete.

1.1 Cement, water, admixture, natural aggregates, EAFS, LFS and fibers

Two different cements were selected to determine their influence in terms of workability and mechanical strength of the resulting concretes. The first one was a Portland cement type II/B-S 42.5-N with 30% GGBFS and the second one was a Portland cement type III/B 32.5 – N with 70% GGBFS, as per EN 197-1 [10]. Besides, the pumpable mix was used LFS as a SCM, with a replacement of 6% of total binder with LFS (**Fig. 1**) [11].

A carboxylate-based water emulsion was used as admixture, enhancing the workability and viscosity of the mixture and acting as a plasticizer. The mix water was taken from the urban supply of the city of Burgos (Spain).

The calcite (< 95%) limestone fines used (**Fig. 1**) tried to improve the workability and avoid segregation of the mix, due to the lack of fine fraction particles in the EAFS. These fines, which gradation curve is shown in **Fig. 2**, had a gradation fraction of 0/0.18 mm, a fineness modulus of 1.5 units, a water absorption rate of 0.53% and a specific gravity of 2.65 Mg/m^3.

Fig. 1. Used aggregates and LFS: EAFS 4/12 mm (left); EAFS 0/4 mm (middle-left); limestone fines 0/1.18 mm (middle-right); LFS 0/1 mm (right).

EAFS was used in two grading sizes (<4 mm being fine and 4/12 mm being medium, Fig. 1) of high-density angular-shape aggregate, with around 3.4 Mg/m3 [12].

LFS was a powdery appearance, with high amounts of silica and low amounts of alumina in its composition. Its grains are smaller than 1 mm and it has a fineness modulus of 0.75 units. This material is remarkable as it has shown SCM-like binding properties [11].

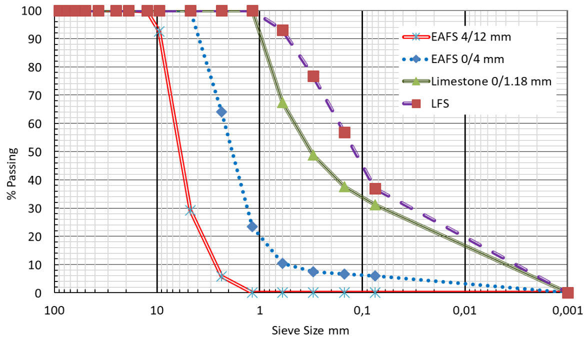

Fig. 2. Grading: aggregates and LFS

Synthetic and metallic fibers (length of 35 mm) were added to the concrete mix separately. Steel fibers (M, hooked-end wire pieces) had a tensile strength of 1,200 MPa and polypropylene fibers (Y, surface dimpled) of 400 MPa.

1.2 Mix Design

In the present study, four concrete mixes were designed with a high amount of EAFS, around 0.5 water/binder ratio and a fibers volume around 0.5% of the total mass. The different types of cement were added, being about 320 kg/m^3 of the mix [12]. The maximum percentage of admixture was 2% in order to achieve the set values for the slump-flow test and the Abrams cone test, avoiding any possible segregation. The actual mix proportions are shown in **Table 1**.

- Self-compacting (SC) concrete: labeled as IISC (reference mix), IISC-M (using metallic-M- fibers) and IISC-Y (using synthetic-Y- fibers), elaborated using CEM II /B-S 42.5-N. The slump-flow test of these mixes was about 600 mm and had a t_{500} lower than 5 seconds. The mix with natural aggregates is omitted because many previous contributions of the authors have already demonstrated the suitability of employ EAFS as aggregate in concrete mixes [12-14].
- Pumpable (P) concrete: labeled as III-P, used CEM III/B 32.5-N and a 6% of LFS as SCM [11], and metallic fibers. The result of the Abrams cone test was a slump higher than 160 mm (S4 consistency).

Table 1. Mix proportions in kg/m^3

Components in kg	IISC	IISC-M	IISC-Y	IIIP-M
Cement II/B-S 42.5R	325	325	325	-
Cement III/B 32.5N	-	-	-	315
LFS	-	-	-	25
Water	170	180	185	160
EAFS medium (4/12 mm)	755	755	755	935
EAFS fine (0/4 mm)	545	545	545	685
Limestone fines (< 1.18 mm)	955	955	955	655
Admixture	5.0	5.0	5.0	4.2
Fiber reinforcement: type/kg (0.5% vol.)	-	M/40	Y/4.5	M/38

Experimental plan: The fresh state testing program is performed following the EFNARC recommendations [12] and the EN 206 standards, and then, the specimens were prepared to carry out the mechanical tests in the hardened state.

2 Fresh State Results

The results obtained under the different test are the following (**Table 2** and **Fig. 3**).

Table 2. Fresh properties of the concretes

Test	Standard	IISC	IISC-M	IISC-Y	IIIP-M
Slump (mm)	EN 12350-8/-2	720 (SF2)/-	650 (SF1)/-	620 (SF1)/-	-/175 (S4)
Blocking ratio	EN 12350-10	0.82 (PA2)	-	-	-
Air content (%)	EN 12350-7	2.3	2.1	1.8	3.5
Fresh density (Mg/m^3)	EN 12350-6	2.72	2.68	2.61	2.72

Fig. 3. From left to right: slump flow test, Abrams cone test and L-boxt test

Slump Flow Test:

- IISC: 720 mm, classified as SF2 (660 - 750 mm)
- IISC-M: 650 mm, classified as SF1 (550-650 mm)
- IISC-Y: 620 mm, classified as SF1 (550-650 mm)

Abrams Cone Test: performed to the IIIP-M pumpable concrete mix, which had a 175 mm slump, classified as S4 consistency class (160-210 mm)

L-box test: It determined the IISC mix as PA2 (≥0.80 with 3 rebars), with a result of 0.82, which means that the mix can be considered self-compactable.

The IISC-M and IISC-Y mixes worsened the results of the flowability and spreading tests respect to IISC, which can be due to the existence of fibers and the high density of the slag combined [9]. On the other hand, The IIIP-M mix needed a slight vibration in order to achieve better results.

The density values of the fresh state mixes were around 2.60-2.70 Mg/m^3, as the EAFS aggregate has a greater specific gravity [2]. When fibers where added, due to their light weight and the need for increasing amounts of water to achieve the needed flowability, the density value decreased.

Besides, the occluded-air test returned correct results in almost all mixtures, being it around 2%. In the IIIP-M mixture, the result was 3.6%, due to the higher content of GGBFS and LFS and the interactions of these binders with the admixture that create air bubble micro-pores [15].

3 Mechanical Properties Results

3.1 Hardened Density, Compressive Strength and Stiffness

The results of the hardened density tests were in the 2.54 -2.65 Mg/m^3 range, being the one with greater proportion of slags the densest and the one with greater proportion of lighter fibers the least dense.

The results from the compressive strength test are shown in **Fig. 4a**. These results were measured at 7, 28, 90, 180 and 360 days of curing. As can be observed, the IIIP-M mixture had significantly lower results (20-42 MPa) than the SCC mixtures (40-80 MPa), even though, both of them had enough strength to be considered as appropriate structural concrete.

The strength of the pumpable mix was around 50% of the strength of the self-compacting concrete mixtures in all ages, hence saying the greater amount of GGBFS in the mix, the less compressive strength the specimen has, as the evolution of this property was equivalent for all the different mixtures.

The SCC mixtures achieved great values of long-term compressive strength, due to the limestone fines balance [16] and an appropriate gradation, which resulted in a high quality matrix of the concrete. The fibers had a slight impact in the compressive strength of the specimens, result that differs when using natural aggregate in the concrete mix [17], as they required higher quantities of water and water/binder ratio in order to achieve the desired workability.

Fig. 4b. shows the concrete stiffness parameters (elasticity modulus and Poisson coefficient). The elasticity moduli were higher in the SCC mixtures than in the pumpable mix, as the first ones yielded results between 31.6 and 40.1 GPa and the second one of 26.1 GPa, according with the compressive strength. The Poisson´s coefficient was around 0.22 for all the mixes but the IIIP-M one, which was a bit lower (0.19).

These phenomena showed behaviors similar to the SCC mixes with natural aggregate [17], therefore, when fibers are added to the mix, the strength and stiffness of the resulting concrete decreases, despite the addition of reinforcement fibers to the matrix of the specimens [18].

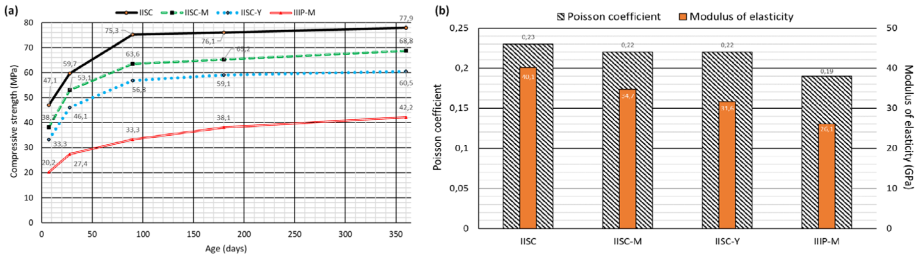

Fig. 4. a) Evolution of the compressive strength. b) stiffness parameters

3.2 Fiber Behavior

The synthetic and metallic fibers behavior was tested using a clamp attached to a loading system that tries to raise an embedded fiber upwards, following the instructions in ASTM C900-19 and ACI228.1R-03 and recording the load versus the displacement of the actual fiber (shown in **Table 3**). The adhesion of the fibers to the matrix of the specimens was great, as the 13 fibers tested per mix broke before recording any movement within the specimens due to their materials, geometry and superficial characteristics of the actual fibers and the depth of the fiber that was embedded to the tough cementitious matrix [19].

Table 3. Pull-out test results

Property		IISC	IISC-M	IISC-Y	IIIP-M
Pull-out test	Ultimate load (N)	-	310	191.4	250.1
(at 180 days)	Pull out length (mm)	-	1.5	1.9	1.3

3.3 Indirect Tensile Strength

The tensile strength was determined by the use of indirect testing of the specimens, using the Brazilian splitting test on cylindrical 150x300 cm specimens and the three-point bending test on 100x100x400 cm specimens to determine the flexural strength, showing the results in **Table 4**.

These tests showed that the specimens containing fibers had significantly lower tensile strength results than their reference mix, being homogeneous in both of the tests performed. After failure of the specimens due to the performing of the tests, cracks could be seen sewn by the fibers, but these fibers did not increase the actual tensile strength of the mix [20] as in EAFS-high-containing vibrated concrete [9] or conventional aggregate SCC [17], but did the opposite. As the fibers needed greater amounts of water to achieve the desired fresh state properties, it turned out in a weaker cementitious matrix and a decrease of the tensile strength of both the SCC mixes and the pumpable mix.

The results in the pumpable mix were the lowest in both of the carried-out tests, due to the influence of the cement type used and the bonds of the cementitious matrix, fibers and EAFS of the Interfacial Transition Zones [21].

Table 4. Indirect Tensile Strength testing results

Property		IISC	IISC-M	IISC-Y	IIIP-M
Flexural strength (MPa)	90 days	7.93	5.97	5.04	4.43
Splitting tensile strength (MPa)	90 days	5.11	4.84	4.35	3.36

3.4 Fracture Toughness Evaluation

Fibers have a great impact in terms of fracture toughness, as it enhances the ductility [20] after cracks have already taken place. In order to evaluate it, two bending tests were performed according to EN 83510 (no notching four-point test in 100x100x400mm prismatic specimens) and EN 14651 + A1 [10] (three-point test in 150x150x600 mm prismatic specimens with a notch of 5 mm in width), which set-ups are shown in **Fig. 5** and their results in **Fig. 6** and **Table 5**.

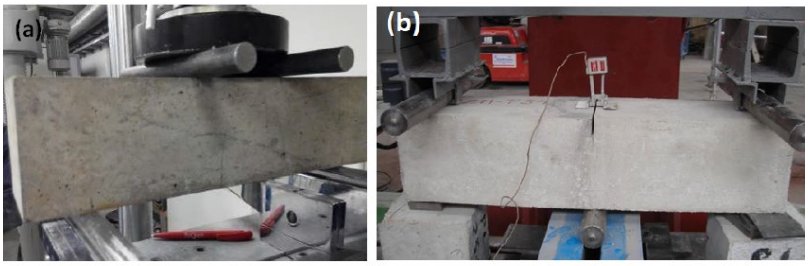

Fig. 5. Bending test set-up: (a) No notching four-point test; (b) Notching three-point test

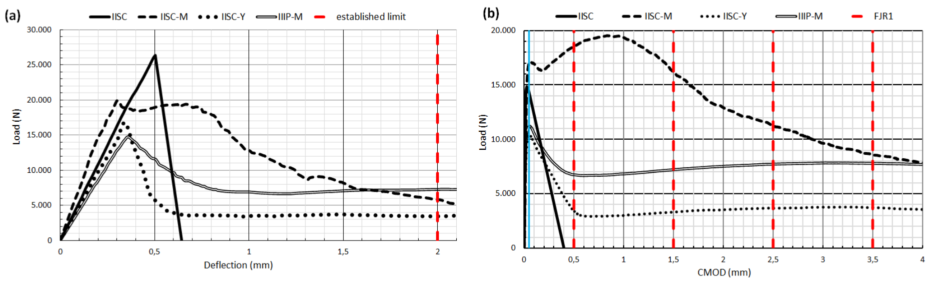

Fig. 6. Load versus deflection curves in: (a) four-point test; (b) three-point test

Results show that the reference mix IISC had a brittle failure (flexural toughness of 8.61 N·m), as crack tips concentrated the stress causing fast propagation. When fibers were added into the mixture and the specimen was cracked, the load carrying capacity was maintained after peaking, as the fibers failed after the concrete had already failed in both of the bending tests, ensuring an optimal adherence of the actual fiber to the cementitious matrix (flexural toughness of: 21.38 N·m for IISC-M, 11.72 N·m for IISC-Y and 1515 N·m for IIIP-M).

The effect of the fibers was remarkable, and even more important in the metallic ones [9], due to their nature, resulting in a higher slope of the linear elastic field in a load-deflection graph. The synthetic fibers had a slope similar to the reference mix and the pumpable concrete had the smallest slope.

It can be also seen that steel fibers yield the greater values in all of the performed tests, being more efficient than the polymeric fibers in the post-crack behavior, as results were increased between 3-6 times in some of the performed tests. In the notched specimen, the influence of the fibers, especially the metallic ones, was even greater, as can be observed in the residual flexural tensile strength values (F_{RJ}), in the range of 6.52-3.01 MPa for the mixture IISC-M.

Table 5. Post-cracking behavior and fracture toughness results.

Test	**Property**	**IISC**	**IISC-M**	**IISC-Y**	**IIIP-M**
No notching four-point test (EN 83510)	Flexural toughness (N·m)	8.61	21.38	11.72	15.15
	First crack strength (MPa)	7.59	4.89	4.13	4.23
Notching three-point test (EN 14651 +A1)	LOP (CMOD≤0.05 mm) (MPa)	5.20	5.98	3.66	3.94
	F_{RJ1} (CMOD=0.5)	-	6.52	1.21	2.37
	F_{RJ2} (CMOD=1.5)	-	5.70	1.17	2.54
	F_{RJ3} (CMOD=2.5)	-	3.96	1.29	2.72
	F_{RJ4} (CMOD=3.5)	-	3.01	1.31	2.74

4 Potential Expansion Results

An accelerated-aging test was carried out using 75x75x285 mm specimens, according to standards ASTM D4792, in order to evaluate dimensional stability by submerging the specimens in 72±2ºC for 30 days and then leaving them to environmental temperature at 22 ± 2ºC for another 30 days. This test tries to determine the possibility of the slags (GGBFS, EAFS and LFS) expanding at mild temperatures, causing microcracks that are the entrance of external agents [22].

Table 6. Strain and linear thermal expansion coefficient of specimens in accelerated-aging test.

	IISC		**IISC-M**		**IISC-Y**		**IIIP-M**	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
Strain (mm/m)	0.65	0.83	0.63	0.98	0.75	0.98	0.70	1.10
Linear Thermal Expansion Coefficient	$1.9\text{-}10^{-5}$ ºC^{-1}		$1.5\text{-}10^{-5}$ ºC^{-1}		$1.6\text{-}10^{-5}$ ºC^{-1}		$2.2\text{-}10^{-5}$ ºC^{-1}	

The results contained in **Table 6** show all the mixes underwent a slightly and hardly significative lengthening, and their linear thermal expansion coefficient were higher in the experimental mixes than in conventional concrete (1.0-10^{-5}) [23], result of using EAFS as majoritarian aggregate in the mixes, and it was even enhanced by the use of GGBFS, LFS and fibers.

5 Conclusions

The main goal of this paper was to determine the feasibility of high-quality concretes regarding the addition of sustainable aggregates and binders (such as EAFS and GGBFS), fibers (synthetic and metallic) and using SCM (such as LFS). The conclusions of this paper are the following:

- The addition of fibers and EAFS resulted in a less flowable mix.
- The water/binder ratio is rather important, as it affects directly to the quality of the cementitious matrix, resulting in a mixture with less strength and less stiffness than the reference mix in the case of the SCC mixes. In the pumpable mix, the cementitious matrix was weakened even more by the presence of high amounts of GGBFS and LFS, which led to lower values for all the mechanical-properties.
- Fibers were well adhered to within the concrete specimens, as revealed by the pull-out test.
- Metallic fibers in amounts around 0.5% vol. had an important positive impact in the toughness, ductile and post-cracking behavior of the concrete specimens.
- The dimensional variation of all the specimens studied in the accelerated-aging test was small.

By this work, it has been demonstrated that the massive use of slags as aggregates and binders result in a structural use high-workability fiber-reinforced concrete, as shown by the results of mechanical testing.

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