5.2. Self-compacting concrete incorporating electric arc-furnace steelmaking slag as aggregate

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Abstract

Electric arc-furnace slag (EAFS) is an industrial by-product that can be employed in hydraulic mixes used in the field of construction and civil engineering. The design and preparation of self-compacting mixes with this aggregate is a challenge, due to the loss of workability that always accompanies its use in concrete. Only through careful design of the characteristics and proportions of the components in each mixture will an acceptable workability be achieved. Thus, criteria and methods are proposed in this paper for successful preparation of these types of mixtures. Several concrete mixes are manufactured to obtain self-compaction characteristics and their main properties are analyzed with regard to their use as structural concrete. Electron microscopy observations and dispersive energy analysis are used to study the microstructural features of these mixes. Finally, a numerical simulation is proposed as a useful method that estimates the viscous properties of the mixes and their workability, based on the dosage and the characteristics of their components.

Introduction

Over some decades, sustainability has evidently come to form part of the main objectives in scientific research. Attention has focused on the sustainable aspects of employing steelmaking slags [1-8]. The re-use of ironmaking and steelmaking slags as promising and good quality materials has been studied in copious technical and scientific publications from research groups around the world. [9-15].

Ironmaking and steelmaking slags have demonstrable and direct results in sectors such as construction and agriculture. Both sectors are large-scale consumers of raw materials, so substitution of their raw materials for waste products from any other industrial sector, including steelmaking, could represent an important advance in relation to the issue of sustainability that is a high priority in the EU [16-28].

The steelmaking industry produces several types of slags. Interest is predominantly focused on the slags that are produced in large volumes. The most abundant in the EU are blast furnace slags, followed by oxygen-converter slag and then Electric Arc-Furnace slag (EAFS). The last-mentioned slag is preponderant in the northern region of Spain, where this research was conducted, and it forms the object of this work. More than a century ago, ground granulated blast furnace slag was found to demonstrate advantageous qualities when added to concrete exposed to maritime conditions. Hence, the hydraulic mixes used in construction and building can be considered suitable candidates to incorporate large amounts of steelmaking slags. In this way, a deep knowledge of the types, characteristics and proprieties of these materials is an indispensable objective that researchers diligently continue to pursue.

The most common hazard associated with the use of steelmaking slags in any application is that some of them are expansive materials [29-34], containing non-stable compounds, that represent unpredictable risks over the medium term (months, years) in the design and performance of engineering constructions. This problem of expansive behavior is widely studied and discussed in the scientific field and present-day knowledge of the problem means that, in most cases, it can be controlled.

Good quality mortars and concretes have been prepared by several research teams around the world using EAFS aggregates. The feasibility of these mixes has been demonstrated as having suitable performance levels and durability, resulting in competitive materials. The main drawbacks have been their poorer workability and their higher density than conventional mixes, made using natural aggregates. The solution to the high-density problem is resolvable by affordable increases in material strength, while keeping the strength-to-density ratio at the same values as conventional concrete [35-42]. The second problem, poor workability, can be analyzed, approached and almost solved by focusing investigative work on suitable chemical admixtures for the preparation of high-workability mixes [43-54].

Self-compacting mortar and concrete (described as self-consolidating mixtures by Mehta and Monteiro book) [4] are undoubtedly the most challenging. Largely under their own weight, these mixes can be adequately poured into moulds and formwork in which the reinforcing steel (ribbed bars or rebars) are distributed. Their viscosity and their internal cohesion have to meet particular conditions, even though, at the outset, their properties might appear contradictory [55-59].

The preparation of SCC (Self-Compacting Concrete) mixes with conventional natural aggregates must keep to well-established rules. The use of heavy and sharp aggregates (natural or artificial) complicate the task, due to the appearance of excessive cohesiveness and the risk of segregation and decantation of the coarse aggregate particles suspended in the cementitious matrix [60, 61]. Hence, the subject of this investigation is self-compacting structural concrete mixes, which our research team has successfully prepared.

Self-Compacting Concrete

Three decades ago, Okamura [55, 56] showed how to design a self-compacting concrete, which we may now consider the "classical" solution. This methodology is, in general, useful for the preparation of self-compacting mixtures using natural aggregates, limestone, and sandstone, with densities of below 2.7 Mg/m^3. The fundamentals are simple: water (density 1.0) transports fine particles sizes of under 0.15 mm (cement, natural rocks) of higher density (i.e. density 3.0 and 2.6) due to their small size; the resulting paste combines with fine aggregate particles (density 2.6, maximum size of 5 mm) and the resulting "mortar" then incorporates larger-sized aggregate particles (same density, with a maximum size of 20 mm) constituting the self-consolidating concrete.

EFNARC recommendations [62] provide guidance (concerning slump flow, viscosity, passing ability, and segregation resistance) to prepare several types and classes of Self-Compacting Concrete, according to the properties required in each particular case, using conventional aggregates. In this guide the typical proportions used for manufacturing self-compacting concrete with natural aggregates (Table 1) are also specified. These proportions will be useful for comparison with the final amounts used in this research to perform SCC mixes with EAFS as aggregates.

Constituent	Typical range by weight [kg/m3]	Typical range by volume [l/m3]
Powder	380 – 600	
Paste		300 – 380
Water	150 – 210	150 – 210
Coarse aggregate	750 – 1000	270 – 360
Fine aggregate (sand)	Content balances the volume of the other constituents, typically 48-55% of total aggregate weight	
Water/Powder ratio (by volume)		0.85 – 1.10

Table 1: EFNARC SCC [62] recommendations specifying guideline values for SCC.

According to the EFNARC document on viscosity modifying admixtures (VMA) for concrete [63], the rheology of fresh concrete can be characterized by its yield point and plastic viscosity in a Bingham viscous model:

- The yield point (cohesion) describes the shear stress needed to start the concrete moving. It may be assessed by practices such as the slump test.

- Plastic viscosity describes concrete resistance to flow under external stress. The speed of flow is related to the plastic viscosity of the mix.

The balance between the yield point and plastic viscosity is key to obtaining an appropriate concrete rheology. Viscosity modifier admixtures change the rheological properties of concrete, by increasing plastic viscosity, but usually only cause a small increase in the yield point. Admixtures known as plasticizers decrease the yield point and are often used in conjunction with a VMA for their optimization.

The characteristics and requirements of the EFNARC SCC guidelines [62] are shown in Table 2. Clearly, the initial requirements for concretes manufactured in this work are minimal, i.e. slump-flow SF1, viscosity class VF2, L-box PA1, and segregation resistance class SR1.

Characteristic	Preferred test metho(s)	Specification	Classes	Values
Flowability	Slump-flow test	Slump-flow in mm	SF1	550 to 650 mm
			SF2	660 to 750 mm
			SF3	760 to 850 mm
Viscosity (rate of flow)	T_{500} slump-flow test, or V-funnel test	T_{500}, in s, or V-funnel time in s	VS1/ VF1	≤ 2 / ≤ 8 s
			VS2/ VF2	> 2 / 9 to 25 s
Passing ability	L-box test	Passing ability	PA1	≥ 0,80 with 2 rebars
			PA2	≥ 0,80 with 3 rebars
Segregation	Segregation resistance (sieve) test	Segregation resistance in %	SR1	≤ 20 %
			SR2	≤ 15 %

Table 2: EFNARC prescriptions [62]

According to this EFNARC document, there are three classifications of self-compacting concrete:

- The powder type of SCC is characterized by large amounts of powder (all material < 0.15 mm), usually within the range of 550 to 650 kg/m^3. This provides the plastic viscosity and hence the segregation resistance. The yield point is determined by the addition of superplasticizer.

- In the viscosity type of SCC the powder content is lower (350 to 450 kg/m^3). The segregation resistance is mainly controlled by a VMA and the yield point by the addition of superplasticizer.

- In the combination type of SCC the powder content is between 450 to 550 kg/m^3, but the rheology is also controlled by a VMA and an appropriate dose of superplasticizer.

In these recommendations, an ASTM Nº 100 (0.15 mm) sieve [64] is stipulated as the limit size of “powder” in self-compacting mixes, and its amounts are specified within some limits. The aforementioned value is left aside in our investigation that uses EAFS as aggregate and substituted by the concept “bearing paste”; the upper limit particle size for “bearing paste” in self-compacting mortar has proved to be 0.6 mm (sieve Nº 30). In the present work that describes EAFS self-compacting concrete, this “bearing paste maximum value of particle size” was increased to 1.18 mm (Nº 16 sieve); additionally, appropriate admixtures (viscosity modifier, plasticizer…) must also be used to obtain suitable characteristics for self-consolidating mixes.

In the present article, the EAFS concrete with characteristics close to those of a self-compacting mix could be classified as "the powder type" or "the combination type" in the EFNARC classification [62], because the intention in this research is to prepare a mixture that is suitable in terms of plastic viscosity and segregation resistance.

Research background

Taking the above considerations into account, the challenge is to prepare a hydraulic mix with a suitable in-fresh rheology that may be considered a self-compacting concrete. Additionally, this goal should be attained using materials currently available in the field of construction and building: commercial cement and natural aggregates from the region, added to electric arc furnace slags aggregates from nearby steelmaking factories.

When the aggregates (fine, coarse) are denser than usual (>2.8 Mg/m^3), i.e. quartzite, granite or basalt, the recommended proportions in the guidelines for SCC mixes should be slightly corrected; finally, if the aggregate is especially heavier, rougher and sharper as in the case of the EAF slag, the innovative solutions that we describe in this paper are needed.

It is well-known that liquids have the capacity to keep in suspension for a long time and to transport solid particles of greater density dispersed within them, thereby preventing their decantation-deposition at lower layers. Stokes' Law, $R = 6\pi\mu r v$, allows us to calculate the decantation velocity, v, (or relative velocity) of spherical solid particles in a static liquid mass in a laminar flow regime, regardless of the interaction at the liquid-solid interface (surface tension, hydrophilia-hydrophobia). This drag force, R, will be in equilibrium with the resulting gravitational force, i.e. the submerged weight (based on the difference in densities between the solid pieces and the liquid mass) of the particles. The variables for consideration are the viscosity of the liquid mass μ and the radius r (size) of the coarse particles.

As with Stokes's Law, it also appears evident that the ratio between external surface extension and the weight of rounded particles is the main variable to consider: the lower this value, the stronger the drag. In the case of spheres, this quotient is 3/⍰·r, inversely proportional to the radius, r, of the particle and to its specific density, ⍰. According to the evidence from these empirical observations, we can state that it is easier to transport solid particles of both a moderate density (compared to the density of the liquid mass) and of a lower size in a moving viscous liquid.

There are experimental hydrodynamic laws in the literature, for example see Graf Walter Hans[65], which estimate the transport capacity of liquid masses in movement. Those laws clearly state that the transport capacity of liquid masses is enhanced when the velocity of their movement is increasing. The problem is not trivial in terms of empirical calculations, if we take into account that the velocity of movement of spreading concrete is always moderate, due to its high viscosity and low acting forces (its own weight), and if we consider the other characteristics of the particles to be transported (heavy, rough, sharp).

The quantity of coarse particles to be transported (volumetric amount) is also a key variable, because of the interaction between these particles during transport; if the amount is excessive their transport is increasingly difficult and, finally blocked, due to coarse particle migration and the associated "bridging" effect. Additionally, when we have a liquid (originally water in our case), in which we have a wide range of particle sizes in suspension, their influence on the viscosity and on the apparent density of the fluid mass is evident. In this case, an analysis of the drag and the transport of the coarser particles should consider the presence of suspended finer (smaller) particles and even their hydrophilic-hydrophobic character. Thus, a precise grading should be established for the smaller suspended particles, so that they work together in an active way in the transport of the coarser particles, as a "bearing paste".

According to the recommendations of EFNARC contained in Table 1 of the former section, a well-prepared SCC of conventional (density 2.6 Mg/m^3) aggregates, with a maximum aggregate size of ¾" (19 mm), could be formulated per cubic meter in the following way: paste 360 l (water 180 l plus powder smaller than Nº 100-0.15 mm 180 l), cement 300 kg, coarse aggregate 340 l, fine aggregate 380 l; density of aggregates 2.6 Mg/m^3, and fractions smaller than 0.15 mm, amounting to 12% of the total aggregate. According to those data, we have a well-prepared SCC containing 340 l (885 kg) of coarse aggregate transported by 360 l of paste, which has a density of 180+300+(80x2.6) kg in 360 l, resulting in 1.9 Mg/m^3. In other words, a certain volume of paste (bearing paste) transports a slightly lower volume of coarse aggregate of a size no larger than 19 mm, with densities that differs in the order of 0.7 units. The rest of the fine aggregate, 300 l of conventional aggregate sized under 4.75 mm (380 l minus 80 l included in the paste), is less significant because of its small size, which facilitates its easy transport. These volumetric proportions are very significant in the preparation of self-compacting mixes, and we will use them in our calculations as our "reference mixes".

Thixotropy is a property defined in the EFNARC SCC guidelines [63] as: "The tendency of a material to progressive loss of fluidity when allowed to rest undisturbed but to regain its fluidity when energy is applied". Usually, this definition refers to a pure fluid-liquid material, but it can also be applied to a composite material such as a concrete with a fluid paste-matrix composed of water and finer particles in suspension. This property is really useful in engineering practice, because it helps to avoid the segregation of heavy-coarse aggregates in concrete when the mass is in a static situation (after pouring into molds, until its initial setting), but it obviously compels us to evaluate the spread characteristics of the mix and to pour the concrete after the shortest possible time following the dynamic mixing of the raw materials. In real terms, the pouring of SCC concrete into a big mold is slow, and the initial characteristics of mass fluidity will differ from its ultimate fluidity during the final phases of pouring.

Materials and methods

Cement, water and natural aggregates

Two types of cement were used in the present research: 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. The type I cement includes 90% Portland clinker, 5% calcium carbonate powder fines and 5% gypsum. The composition by weight of the type IV cement includes 5% calcium carbonate powder fines, 40% fly ash type I, 50% Portland clinker, and 4% gypsum. Water was taken from the urban mains supply of the city of Bilbao, 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 medium-size aggregate (sized 5-12 mm, fineness modulus 6 units) was used partially or totally in the mixes; the main mineral component of these aggregates was calcite (95%) and can be considered a classical or conventional component of concrete. The same material was also used in the mixes after sieving through 0-0.6 mm and 0-1.18 mm sieve ranges (passing through ASTM [64] sieves Nº 30 and Nº 16), the fineness moduli of which were 0.7 and 1.5 units, respectively. The grading of all the above-mentioned fractions is shown in Figure 1.

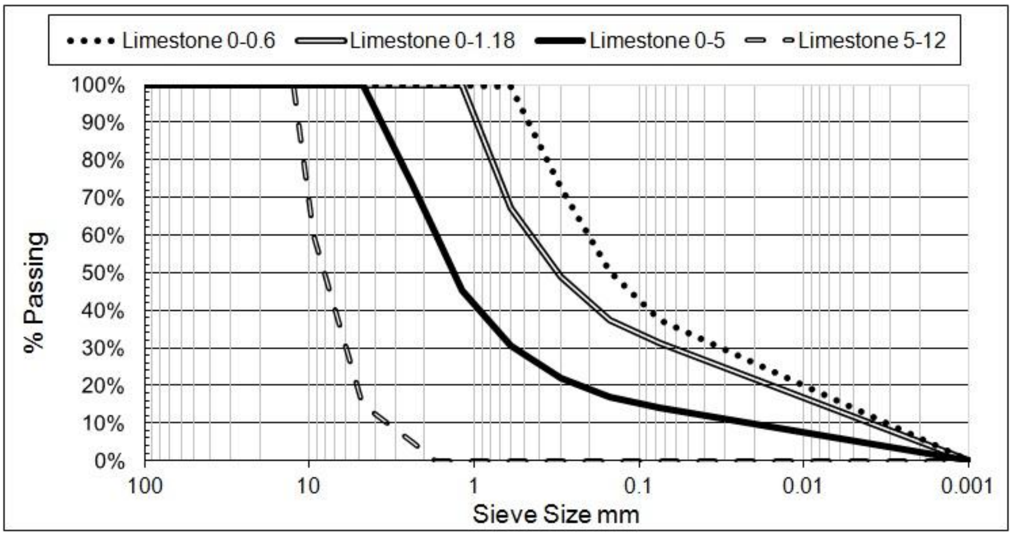


Figure 1: Grading of natural aggregates.

Slags

Crushed Electric Arc-Furnace slag (EAFS) in three size fractions (fine <4.75 mm, medium <12.5 mm, and coarse <20 mm with specific gravity 3.42 Mg/m^3), supplied by the company Hormor-Zestoa, was used in this research. The chemical composition and some physical properties are detailed in Table 3. Their grading is shown in Figure 2.

An additional high-silica low-alumina ladle furnace slag (LFS) was used in this work. It has a density of 3.03 Mg/m^3 and a fineness modulus of 0.75 units. Its chemical composition and X-ray diffraction analysis in Table 3 shows that its main compound was dicalcium silicate (olivine); see also its grading in Figure 2. A fraction of the total amount of LFS added to the hydraulic mixes could show binder properties such as supplementary cementing material (SCM), as suggested in [39, 66]; the rest of the LFS can be considered as an additional fine aggregate fraction.

Some earlier works by the authors [35, 66] contain more detailed descriptions of these kinds of slag; their main characteristics are considered indispensable for a full understanding of the mixes that are presented in the present article.

Compounds [%-wt]	EAFS (0-5 mm)	LFS
Fe_2O_3	22.3	1.0
CaO	32.9	59.2
SiO_2	20.3	21.3
Al_2O_3	12.2	8.3
MgO	3.0	7.9
MnO	5.1	0.26
SO_3	0.42	1.39
Cr_2O_3	2.0	--
P_2O_5	0.5	--
TiO_2	0.8	0.17
Loss on ignition	gain	0.5
Water absorption	1.12	--
Specific gravity [Mg/m^3]	3.42	3.03
X-ray diffraction main compounds	Wustite-Ghelenite Kirsteinite	Periclase-Olivine Mayenite

Table 3: Chemical composition and physical characteristics of slags

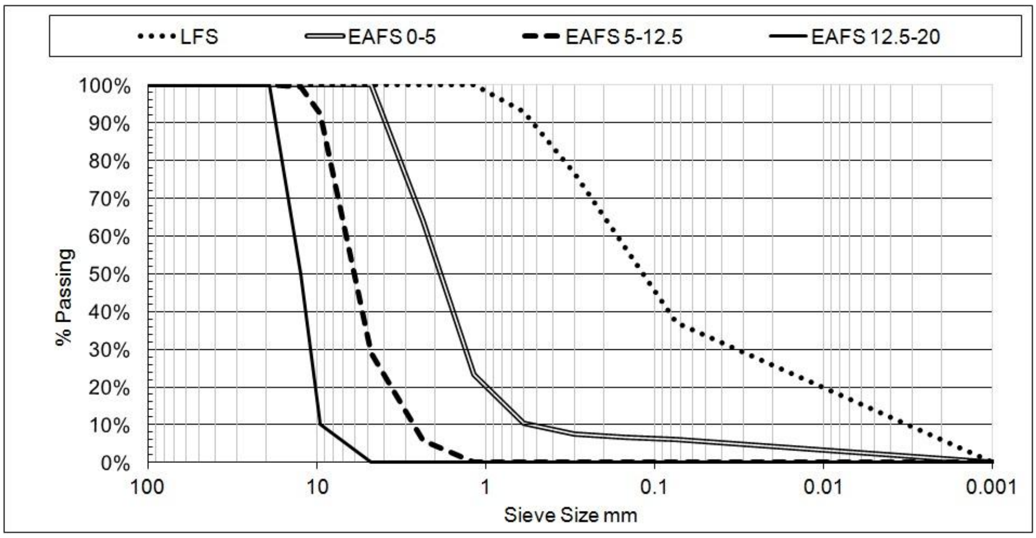


Figure 2: Grading of slags.

<u>*Mixes*</u>

Design of mixes

The primary objective for conventional concretes (with either low or high workability) is their good quality in the hardened state and, in general, it is accepted that their fresh state properties are controllable. The development of self-compacting concretes (SCC) differs, as their in-fresh characteristics are the priority. In this way, several concrete mixes containing EAFS as aggregate were designed and manufactured in this research, mainly to enhance their workability, so as to reach the standardized self-compaction conditions. The performance of some of them is not considered a self-compacting mix according to the specifications of the EFNARC [62], so they were considered as “pumpable” concretes that are also very useful in structural engineering. The high workability mixes obtained in this work were qualified as self-consolidating mixes or self-compacting concrete.

The most important objective in this study is to establish a global dosage in the aggregates mixture to reach the conditions of self-compacting mixes, including the additional condition of including the highest amount of EAF slag. It is evident that the inclusion of very small amounts of EAFS obtains an SCC in a relatively easy way; conversely, an excessive amount of EAFS makes that objective impossible. The global proportion of EAFS (of any size) by volume described for self-compacting mortars in a recent work by the authors of this study was around 35%; this value is an initial reference for the new concretes, but it could eventually be modified in accordance with the optimization of mixes.

The cement content was fixed in the range 300-350 kg per cubic meter of concrete; it is evident that the strength of these mixtures is not High-Strength-Concrete (HSC), which is unnecessary for most structural elements. Also, the contents of water and admixtures were considered consequences of the proposed targets, to obtain pumpable or self-compacting mixes; the water content had to be kept to amounts slightly lower than 200 kg per cubic meter. The recommendations from the manufacturers of the admixtures were observed, although the proportions were close to or slightly higher than the recommended maximum amounts.

At this point in the design of these mixes, the authors stated that a new “bearing paste” can be defined as the combination of water, cement and aggregate fine fractions, the sizes of which range from zero to a fixed value. This value was fixed at 0.6 mm in the structural mortars that have previously been analyzed by authors; while it was 1.18 mm in concrete mixes with a maximum aggregate size of 12 and 20 mm. The fixed value is easily recognizable as the “shoulder” of the mix grading curve as is shown below.

The simplest approach to obtaining a “bearing paste”, capable of transporting medium and coarse EAFS aggregates with a density of 3.4 Mg/m^3, could be to increase paste density to values close to 2.7 Mg/m^3 (3.4 minus 0.7 units), as was cited in the former section for SCC made with normal aggregates. But this idea is in practice unfeasible, because the components are always the same in this cementitious matrix (water, cement and mineral particles) and their proportions always similar (ratio water-cement-fines), accepting low variations. So, this bearing paste density will be considered an almost constant value close to 1.9 Mg/m^3, which cannot be efficiently increased. It is therefore compulsory to modify (enhance) the rheological characteristics of this bearing paste. The choice of increasing the amount of fine particles in the mix design of EAF concretes has been explored in some research works reported in the literature, as a resource to improve workability. In our mixes, the most affordable solution was to increase the amount and the size range of mineral particles from 0-0.15 mm (the original size limit for the paste in the EFNARC recommendations [62]) to 0-0.6 in mortars, or even to 0-1.2 mm for concrete, and to consider these amounts of particles as a part of the new “bearing paste”; its resultant rheology has changed with respect to a “conventional paste” of a standardized self-compacting concrete, and showed an acceptable drag coefficient of 1.2-1.3 units, a coefficient that represents the difference in densities between the bearing paste and the transported coarse pieces, bring our value suitable to transport pieces of heavier EAFS aggregate.

The internal composition of this bearing paste, in terms of its size grading and proportion of components, its proportion in relation to total concrete volume, and the global proportion of EAFS aggregate particles that form part of the SCC concrete, are the variables that have to be fixed through detailed experiments and the corresponding testing of the resultant properties. In this task, the collaboration of the “super-plasticizer” admixture is decisive, and a good choice is essential; however, it would be erroneous to see this component as the principle key to SCC manufacture. At this point, it should be said that not all super-plasticizers on the market are compatible with all types of aggregates; finding a suitable admixture for our purposes in the case of the EAFS aggregate was no easy task. Over thirty mixtures were prepared and tested in this investigation, although only the most significant are presented in the following section.

Preparation of mixes

EAF slag sized 0-5 mm was used as part of the fine aggregate in mixes, but its presence in the bearing paste was less significant, due to is low proportion of fines smaller than 1.18 mm in its grading (about 20%, see figure 2). The fine fraction of the mixture was increased with the addition of a significant amount of crushed limestone sized 0-1.18 mm, as mentioned in the former section. The coarse aggregate was EAF slag medium-gravel sized 5-12 mm; EAF gravel sized 12-20 mm was also used in one mixture. The EAFS aggregates were added in an almost-saturated “sprinkled” state, taking into account their outstanding capacity to absorb water. It is very difficult to fix a relevant value for this characteristic, which largely depends on the foundry parameters for heat at each stage of the steelmaking process. From an engineering point of view (during the construction of real structures), it is almost impossible to control the actual porosity and the water absorption properties of each EAF slag batch in a "practical" and consistent way, and its use in a saturated state gives a simple solution to this problem.

The water-cement ratio was kept close to 0.6 in the mixes. The cement was mainly type I 52,5R, and in one case a type IV cement was also used; the amount used was in the range of 300 to 350 kg per cubic meter, seeking to obtain a compressive strength of 40 MPa after 28 days, and 50 MPa after 90 days. Plasticizer and viscosity conditioner admixtures were used in these mixtures in the recommended proportions by the manufacturer.

Another important condition in the design of mixes was the proportion of fines (smaller than 0.15 mm, sieve Nº 100), which was kept slightly below 20% by volume in these SCC mixes. A very large amount is indispensable in a self-compacting mix, but their excessive presence could lead to an increase in water demand and eventual bleeding. The Spanish standard EHE-08 specifies a maximum content of these fines in 100 liter per cubic meter for general purpose concrete; in the case of SSC, this amount is unspecified in the standard and, in our experience, may be raised by 20%.

In Table 4, nine of these research mixes are detailed in their composition, and some fresh properties (density, workability) are also shown in the last rows. These nine mixes were chosen from previously manufactured lots, on account of their relevance. They reveal the successive steps followed in this study to find a suitable SCC containing EAFS as coarse aggregate. The first set of columns, P 1-5, corresponds to pumpable concretes, and the second set, SC 1-4, are self-compacting concretes. From an engineering standpoint, it would be helpful to remember that a maximum aggregate size of 12.5 mm (½") is suitable for use in concrete elements reinforced with steel bars, such as beams and floor framing; in other structural elements with fewer rebar reinforcements, such as columns and ground slabs, a maximum aggregate size of 20 mm (¾") is recommended. Both maximum sizes are analyzed in this study, so as not to overlook practical engineering aspects.

Mix Design[kg/m^3]		P1	P2	P3	P4	P5	SC1	SC2	SC3	SC4
CEM I 52.5 R		300	300	350	350	350	350	350	210(*)	350
Fly ash									140	
Limestone	Sieved fraction <0.6 mm		760	760						
	Sieved fraction <1.2 mm				450	680	680	900	900	900
	Fine aggregate <5 mm	1050					550			
	Medium aggregate 5-12 mm						720			
LFS			80							
EAFS	<5 mm		550	735	800	700		550	550	450
	5-12 mm	1050	750	735	1050	900		670	670	420
	12-20 mm									420
w/b		0.53	0.66	0.5	0.51	0.51	0.51	0.55	0.55	0.5
Superplastizicer [%]		2	2	1.47	2.5	1.82	2.5	2	2	2
Fresh density [Mg/m^3]		2.6	2.65	2.78	2.84	2.75	2.46	2.62	2.75	2.87
Slump/Spread in Abrams cone [mm]		160/	180/	190/	180/	220/450	/580	/680	/560	/520

Table 4: Mix designs

Referring to pumpable concretes, P1 to P5, they all contain coarse aggregate EAFS sized between 5 and 12 mm; the first shows a fine aggregate formed only of limestone. Compared to the Fuller's curve, Figure 3, a slightly low proportion of particles sized between 0.075 mm and 1mm is evident in this P1 mix, but it is useful as a reference mix for pumpable concretes. Perhaps an increase in the limestone fine aggregate produces a better global grading size, but our objective is to use the highest possible amount of EAFS, for which there are better options, as will be shown.

Mixtures described in column 2 to 5 of Table 4 show fine aggregate fraction (smaller than 5 mm) mixed between limestone (of several maximum sizes) and EAFS, in a progressive search for the ideal proportions. In Figure 3, the grading of these mixes by volume is shown to be close to Fuller's curve; the amount of aggregate fines smaller than 0.15 mm is visible in each curve, and a reference value could be 14%. Mixture P2 includes ladle furnace slag LFS, the influence of which is not positive for the workability, due to its high absorption. The fifth mixture of this set, P5, is the best-performing mixture face to workability, having 50% by volume of EAFS (density 3.4

units) and about 55% of "bearing paste" (cement, water and mineral fraction smaller than 1.2 mm), which contains 20% fines, mainly limestone and cement.

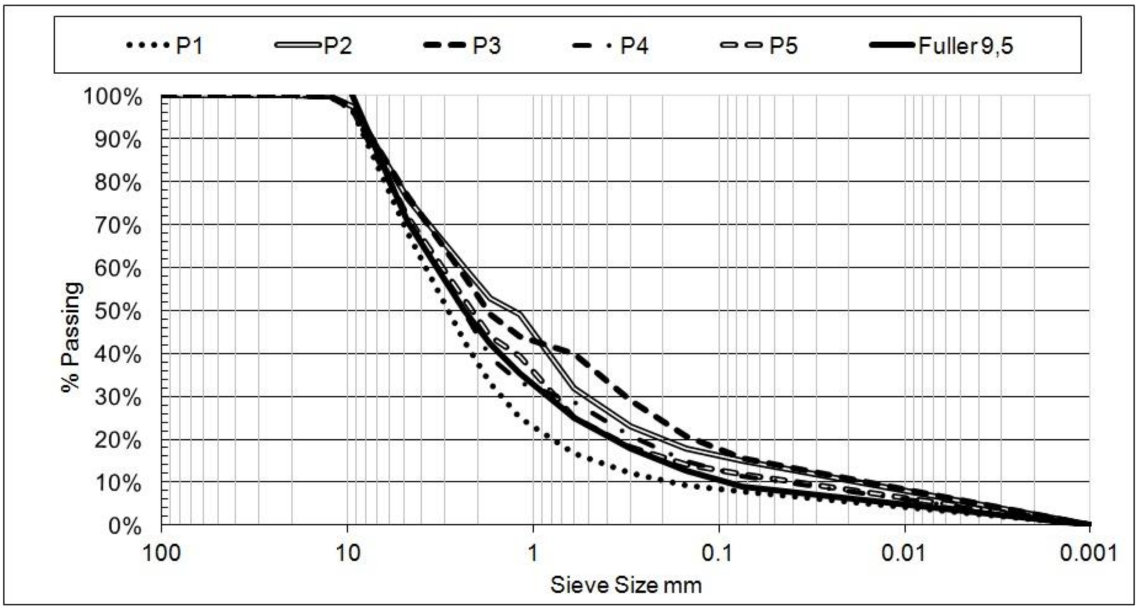


Figure 3: Grading of pumpable mixes in volume.

As regards the SCC mixes, the first reference concrete SC1 only contained limestone aggregates, and it easily reached the in-fresh conditions for SCC; it had a content of almost 20% in fine fraction aggregate particles under 0.15 mm. The water-to-paste ratio (<0.15 mm) in the fresh state yielded a result of around 0.46 (195 divided by 195+(300/3.1)+(40%·680/2.6)+(16%·500/2.6)). Fuller's curve with a maximum size of 12.5 mm with this dosage is shown in Figure 4.

SC2 is certainly an excellent and probably an exemplary self-compacting mix, and SC3 was manufactured in a similar way to SC2, using cement type IV containing fly ash; the visible effect was a loss of workability (due to a poor interaction between the admixture used and the fly ash) with respect to SC2. The self-compaction characteristics of the SC4 mix were not very good although it can be also considered a self-compacting mixture (slump over 500 mm). Considering the amount of aggregate particle sizes smaller than 0.15 mm, mainly limestone and cement, mixes SC2, SC3 and SC4 all showed a value close to 20%. Their in-fresh water to paste ratio was around 0.44 units.

Figure 4 shows the size grading in volume of these mixtures, and two versions of Fuller's curve are included, so as to compare all the SC mixtures, corresponding to maximum aggregate sizes ⅜" (9.5 mm) and ¾" (19 mm). The aforementioned "shoulder" (referring to Fuller's curve) is easily appreciated in the abscissa 1.18 mm.

The amount by volume of EAFS aggregate at 34% was similar in the SC mixes; in these cases the "bearing paste" content is close to 66% (two-thirds) in fresh volume.

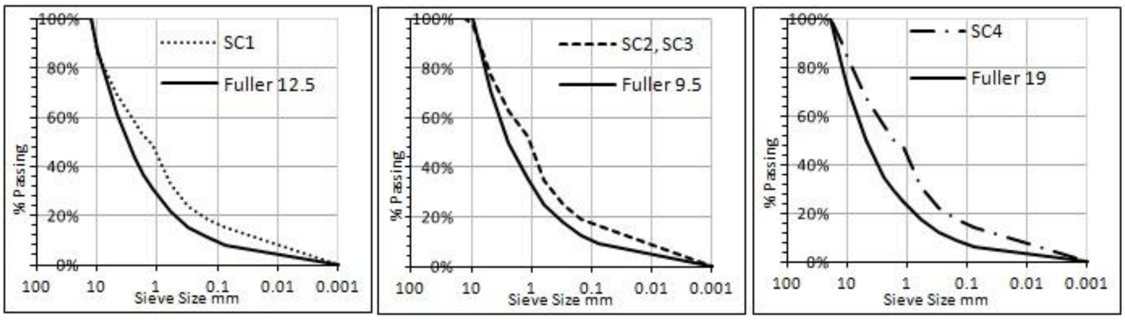
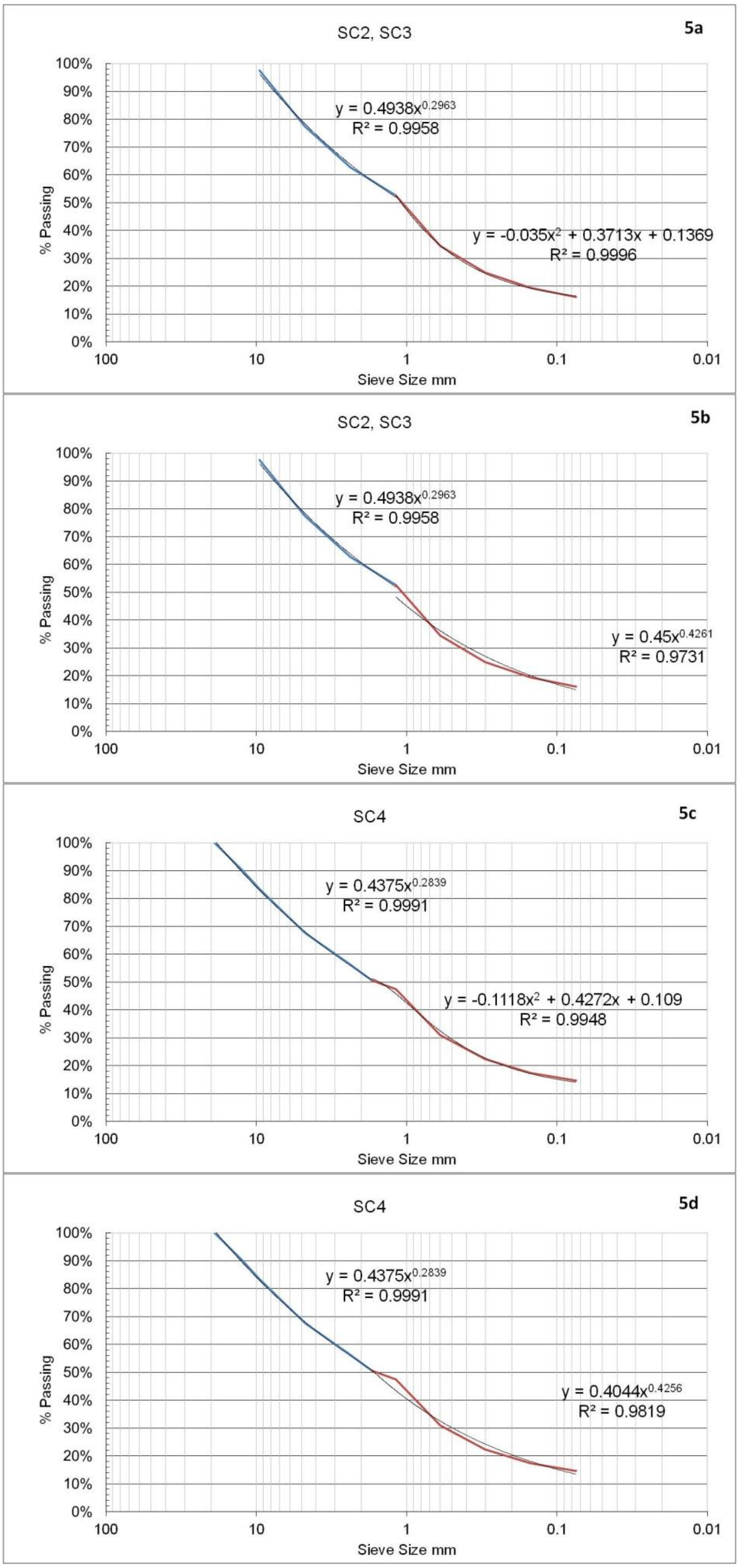


Figure 4: Grading of self-compacting mixes by volume.

Some equations could be proposed for the volumetric grading curve of the EAFS self-compacting mixes, shown in Figures 5a, 5b, 5c and 5d. The whole curve is composed of two monotonic regions separated by a shoulder. The first (the larger sizes) approximately corresponds to a variation in the exponent of Fuller's equation; the original Fuller exponent for round particles is n= 0.5 (square root) and, in this special case of SCC, the adjusted exponent is close to n=0.3 (SC2 and SC3 almost cube root).

The second monotonic curve (from the shoulder to smaller sizes) could be adjusted by a potential function (Figures 5b 5d) similar to Fuller's equation, or by a polynomial function (Figure 5a 5c). The polynomial adjustment is very precise (almost a straight line in a linear scale), but may not be extended to sizes under the ASTM № 250 [64] sieve (0.063 mm). The potential adjustment is less precise, but it is useful down to very low sizes. It should be remembered that we are using a commercial limestone fine aggregate (subsequently passed through a № 16 ASTM [64] sieve), the grading (see Figure 1) of which is acceptable and is adjusted to Fuller's curve. However, it is evident that other commercial products of this kind could give slightly different grading characteristics and, in consequence, could generate different coefficients when employed, requiring similar adjustments.



Figures 5a 5b 5c 5d: coefficient adjustments.

In-fresh characterization and rheological behavior

The in-fresh rheological characteristics of the self-compacting mixes are shown in Table 5. Among the three EAFS mixes (SC2 SC3, and SC4), the first shows very good properties of self-compaction (show Figure 6). The second, SC3, includes fly-ash in partial substitution of clinker; the loss of workability is evident, though it meets the minimal characteristics to be considered as SCC. The third, SC4, includes EAFS sized until 20 mm; its self-compaction performance is poor. The EAFS mixes neither showed evidence of segregation nor of blocking.

Mixture	Slump-flow in mm	Passing ability L-box
SC1	580 (SF1 class)	0.85 (PA2 class)
SC2	680 (SF2 class)	0.9 (PA2 class)
SC3	560 (SF1 class)	0.8 (PA2 class)
SC4	520 (SF1 class)	0.35 (2 rebar)

Table 5: Flowability characteristics of mixes

Figure 6: SC2 Slump cone

Computational Fluid Dynamics (CFD) techniques were applied, in order to establish a relation between the performance of the different concrete batches and their rheological parameters. In this case, an Eulerian multiphase simulation was performed. Among the several available methods, the Volume of Fluid (VOF) approach has been adopted. This method has proven suitable to simulate concrete flow [67, 68].

The constitutive stress-deformation equation of the selected viscoplastic material corresponded to the Bingham plastic model. Its equation, $\tau = \tau_0 + \mu \cdot \gamma$, will predict the behavior of the concrete mass when the shear stress, $|\tau|$, is higher than the yield stress, τ_0. If the threshold value is not exceeded, the shear rate, $|\gamma|$, is null, and the mass behaves as a solid with little or no flow. The dynamic viscosity is denoted by μ. Although other authors [69, 70] state that concrete flow is governed by a non-Newtonian generalized power law, such as the Herschel-Bulkley fluid with three unknown variables (consistency, flow index, yield shear stress), the consistency factor (K) and the power-law index (n) of that model are not easily determined. The Bingham model can lead to negative yield stresses, which are physically impossible, but since the aim of the study was to design a SCC with the highest amount of EAF slag, a not excessively flowable SCC was expected, avoiding the mentioned drawback. Moreover, in contrast, the Herschel-Bulkley model tends to overestimate the yield stress. It can be assumed that for standard quality control tests to be performed, where the flow time and flow distance are moderate and also the shear rate, the proposed Bingham model [71] is sufficiently accurate. The main difference between both models arise for high shear rates, i.e.: concrete pumping, etc, while the simulated tests depend only on the concrete mass weight. Once the mix with the best performance is selected, further studies will fine-tune the mix design according to the Herschel-Bulkley model, if necessary, to promote its commercial use on the market.

As shown in Figures 7a, 7b and 7c, the Abrams cone slump-spread flow test [72], the V-funnel test [72] and the L-Box test [72] were simulated for the four concrete mixes. The estimated rheological parameters, as a result of the computational modeling, were set to fulfill the requirements of the real tests that were performed (see Table 5).

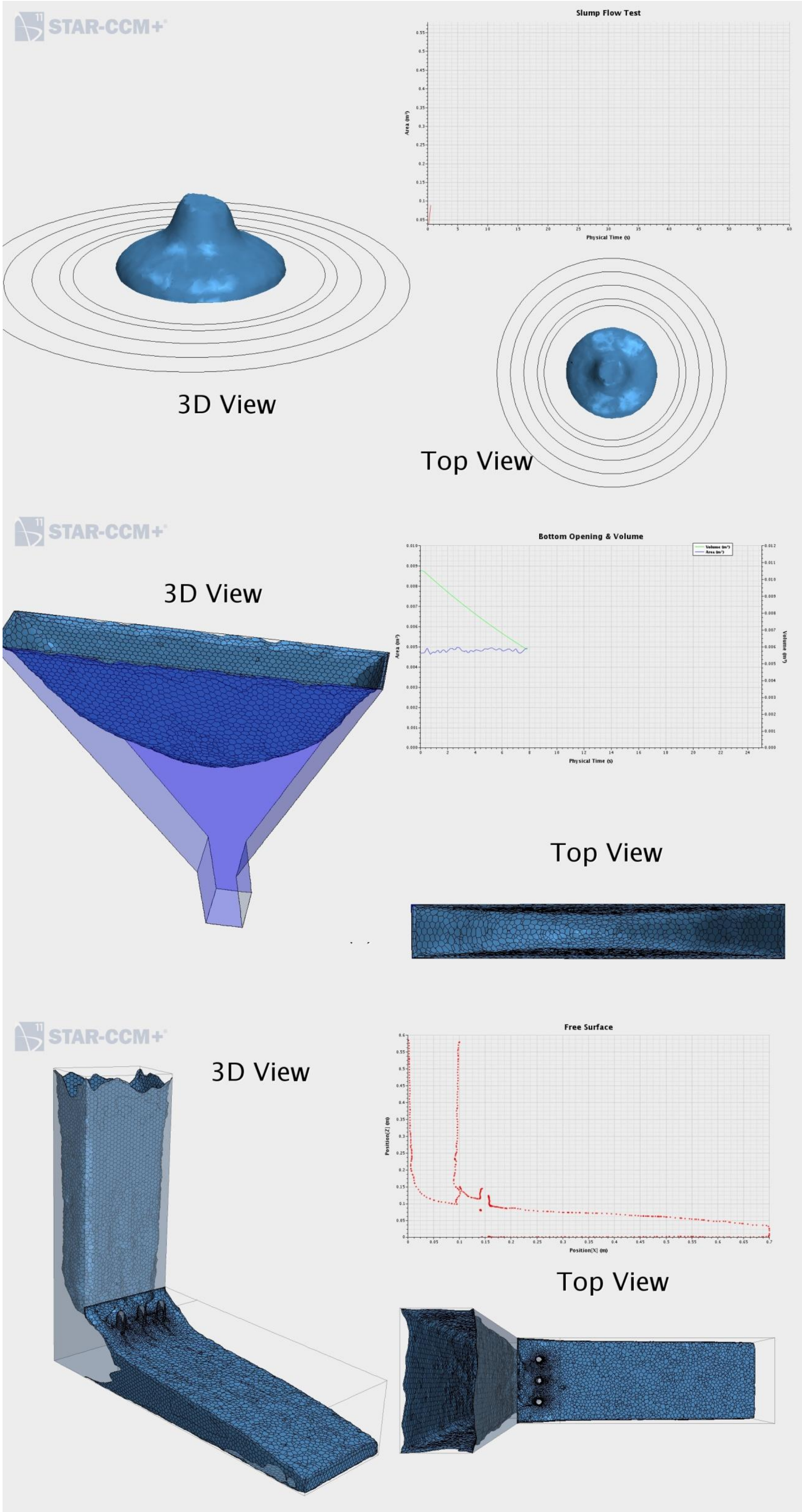


Figure 7a 7b and 7c: Slump flow, V-funnel and L-Box tests simulation

Table 6 summarizes the yield stress, τ_0, and dynamic viscosity, μ, parameters determined for each of the four concrete mixes. The discrepancies in the passing ability correspond to the low accuracy of the manual measurements compared to the result of the simulated fine mesh, but a relatively similar range of differences prevails. As expected, two of the mixes, SC1 and SC3, presented similar characteristics. On the contrary the most viscous mix, SC2, showed a reduced yield stress to achieve a higher spread during the slump flow test and a better passing ability in the L-box test. The SC4 mix showed low viscosity (segregation risk) and high yield stress (low passing ability), despite the difference in the number of rebars (two rebars) used in the trials and those used in the simulation (3 rebars).

Mixture	Yield stress [*Pa*]	Dynamic viscosity [*Pa·s*]	Slump-flow [*mm*]	V-funnel time [*s*]	Passing ability L-box *3 rebar*
SC1	125	65	580	23	0,7
SC2	60	80	680	19	0,8
SC3	170	55	560	21	0,65
SC4	220	35	520	15	0,1

Table 6: Results of computational simulations

A direct comparison with the corresponding mix designs (see Table 4) can be deduced from the results obtained in the computational simulations. The raw materials are similar in the self-compacting mixes, although SC1 includes only fine and coarse limestone aggregates, and the rest of mixes substitute the gravel for EAFS aggregates. Comparing the reference mix, SC1, with SC2, the increase of the fine fraction, by over 32%, clearly appeared to enhance flowability, due to the lubrication provided by the limestone fines; also the yield stress decreased, although a slight increment of the viscosity was noted due to the enlarged amount of bearing paste. This increase provided an improved stability to the mass and counteracted the loss of workability that may arise from the use of EAFS aggregates instead of conventional limestone aggregates.

Although mix SC3 was based on the design used for SC2, the change of cement type entailed a negative effect on flowability. The substitution of CEM I for CEM IV had a negative effect on the excellent behavior of SC2, probably due to the dispersive action of the admixtures which were only effective on the clinker particles, without exerting repulsive forces between the fly ash particles. Therefore, the lubrication between the EAFS aggregates was not so effective and as a result, the yield stress increased.

The last mix, SC4, included a coarser fraction of EAFS, which comprised particle sizes of between 12 and 20 mm up to the 30% of the EAFS aggregates. Obviously, a remarkable decrease in flowability was expected; this dosage adjustment is not sufficient to achieve similar self-compaction properties in the concrete than in the previous batches and will be followed up in future work.

Hardened properties

Density

The dry densities of the hardened concretes are shown in Table 7; these densities and the fresh densities in Table 4 are in good correlation, as may be expected. The samples were dried in a stove at 60ºC for one week, after an immersion-curing period of 28 days from their manufacturing.

It may be seen that the average density of the slag concretes increased by about 15% with respect to those of concrete made using classical aggregates (values close to 2.7 in almost all mixes versus 2.3 Mg/m^3 showed by the SC1 mix). This drawback is usually compensated by the increase in the strength and stiffness of EAFS concretes, as confirmed in recent articles by the authors [35, 39]. The “pumpable concrete” mixes include lower amounts of limestone fines and higher amounts of EAFS than the “self-compacting concrete” mixes, hence, the density of the former was, in general, higher than the density of SC2 and SC3.

Strength

The results of compressive strength on cubical 100x100x100 mm samples after 7, 28, 90 and 180 days of underwater curing appear in Table 7; the initial goal of preparing structural concrete with a strength of over 40 MPa at 28 days and a cement content of under 360 kg per cubic meter was in general achieved. The SC3 mix prepared with the type IV cement only reached these strengths at 180 days.

Property	P-1	P-2	P-3	P-4	P-5	SC-1	SC-2	SC-3	SC-4
Comp. str 7 days [MPa]	61	46	53	61	39	44	47	19	47
Comp. str 28 days[MPa]	67	54	61	69	46	51	53	31	58
Comp. str 90 days[MPa]	68	56	67	71	54	56	55	36	64
Comp. str 180 days[MPa]	73	60	71	74	62	64	61	41.5	67
Stiffness mod 28 day [GPa]	57.5	45.6	55	55.3	38	46.4	46.5	29	48
Dry density [Mg/m^3]	2.51	2.5	2.7	2.63	2.59	2.35	2.53	2.67	2.79
MIP Bulk density [Mg/m^3]	2.53	2.50	2.68	2.62	2.57	2.34	2.53	2.63	2.80
MIP App density [Mg/m^3]	2.89	2.97	3.05	3.09	2.96	2.59	3.03	3.19	3.21
MIP porosity [% vol]	12.3	15.5	12.2	15.2	13.5	9.9	16.6	17.5	12.8

Table 7: Strength and MIP of the mixes

In the pumpable concrete, the compressive strength results were rather similar in the P1, P3 and P4 mixes. The P2 mix containing ladle furnace slag showed a lower short- and medium-term strength, with a slightly enhanced long-term strength, probably due to the hydraulic reaction of ladle slag. Mixture P5 also showed a lower strength, perhaps associated with an excess of fine fraction among its components; however, this additional amount of fine fraction favored its workability, which is essential in this work, obtaining slumps as high as 220 mm in the Abrams cone without any segregation of heavy EAF slag. The P5 mixture was the last step in the work to obtain self-compacting mixes with this slag.

The self-compacting concretes showed, as expected, lower strength levels than the “good” pumpable concretes P1, P3 and P4; the results at 28 days were in the interval 50-60 MPa versus 60-70 MPa in pumpable concrete. The high amount of fine fraction materials and water (indispensable to obtain the appropriate workability) harmed the strength of self-compacting mixes, which reached strengths of 60-65 MPa after 180 days; at that point, the good P mixes exceeded 70 MPa in strength. The presence of fly ash was detrimental to short and medium term strength in SC3; the interaction of the admixture with this by-product produced no advantages, unlike other hydraulic mixes (performed with other sorts of admixtures) in which this active addition was of benefit [66].

The global results obtained in the SC2 mix can be qualified as excellent, showing better rheological characteristics than those of classical self-compacting concrete SC1 and similar mechanical characteristics. In this case, we cannot state that the increase in the mechanical performance of electric arc-furnace slag concrete compensates the increase in own weight, with a fresh or dry density, but it is well-known in structural engineering that this factor is of minor relevance in most cases (ordinary buildings); only in singular constructions such as large bridges or big roof-covers is it a factor decisive. In these cases, the use of self-compacting concrete made with EAF slag as aggregate is neither advisable nor recommendable.

The stiffness modulus, measured by ultrasonic pulse velocity after 28 days of curing, yielded results that were quite consistent with those of the compression test, but the use of the EAFS aggregate instead of the natural aggregate, produced a slightly lower stiffness, in general, in the hardened hydraulic mixes. Additionally, it should be said that these largely comparative results have no rigorous significance as a Young’s modulus of these materials. They must be tested under different conditions to obtain the true values of this magnitude.

MIP analysis

In the present research, the MIP (Mercury Intrusion Porosimetry) technique was employed, using an Autopore IV 9500 apparatus (Micromeritics) at a pressure of 33,000 psi to study the evolution of the pore structure. The results of the MIP analysis of the different concrete types showed that they were on the whole well-performed mixes. The obtained values were, in general, within the range of 12-16%, with the exception of mix SC1 containing classical limestone aggregates. It should be taken into account that the total porosity was the addition of porosity from the capillary water of the cementitious matrix and from the presence of porous EAF slag. In fact, the value of the only mix that contained no slag, SC1, was five units smaller than the average of the rest of mixes.

In Figure 8a, the cumulative intrusion curved for samples of mixes P1 and SC2 are shown and, in Figure 8b, the graphics of MIP pore size frequency in terms of differential intrusion, taken from the Figure for cumulative intrusion, is also shown. In all cases, a significant peak (maximum frequency) in the vicinity of 100 nm may be appreciated in our mixes (true for all the mixes, though only two are included in the figures) between the pore sizes of 20-200 nm, due to capillary porosity. The porosity amount of a size between 20 to 200 nm was close to the interval of 8 to 10%.

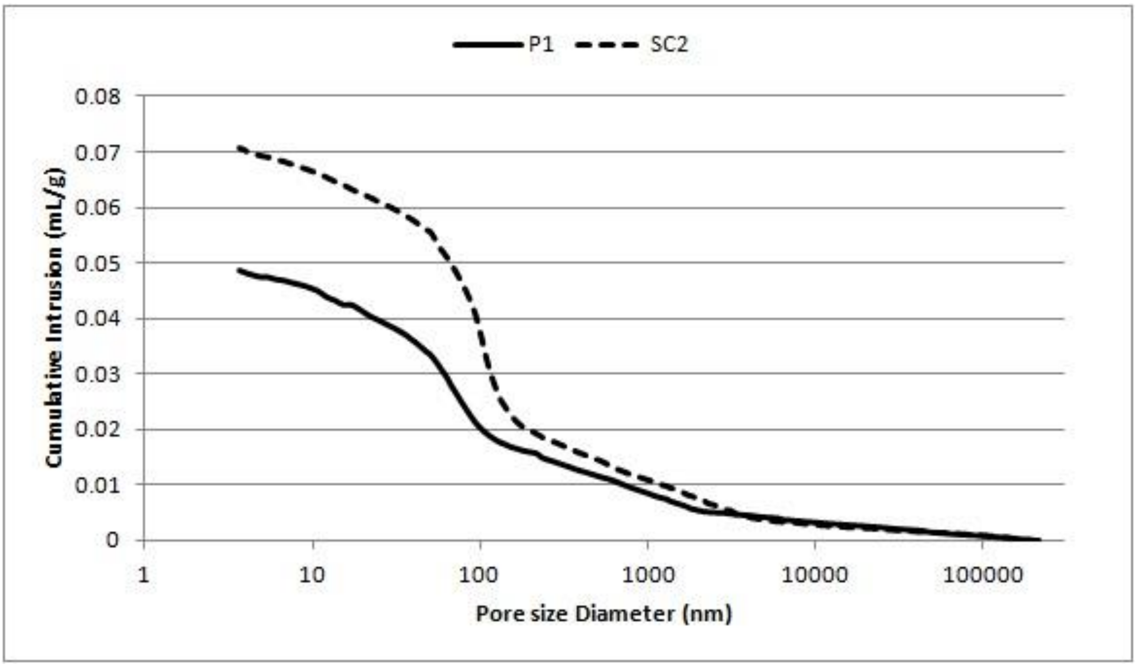


Figure 8a: MIP cumulative intrusion in mixes P1 and SC2.

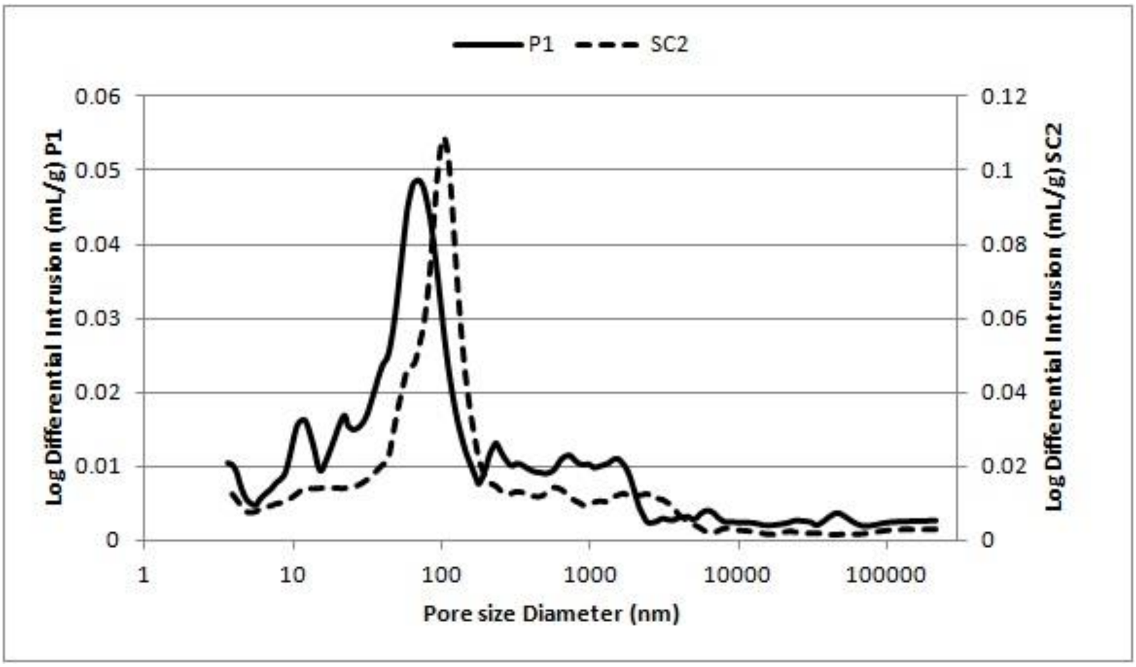


Figure 8b: MIP differential intrusion in mixes P1 and SC2

The additional pore size between 200 to 200000 nm depended on the porosity of the matrix added to that of the EAF slag. In the case of SC1, this last porosity (>200nm) was only 1.8% of a total 9.9%; in other mixes, this value varied in the interval of 4 to 8%. In general, it can be stated that the porosity value was slightly higher in the SCC (as SC-2 and SC-3) than in the pumpable mixes, due to the greater volume of water used in the preparation of the SCC mixes.

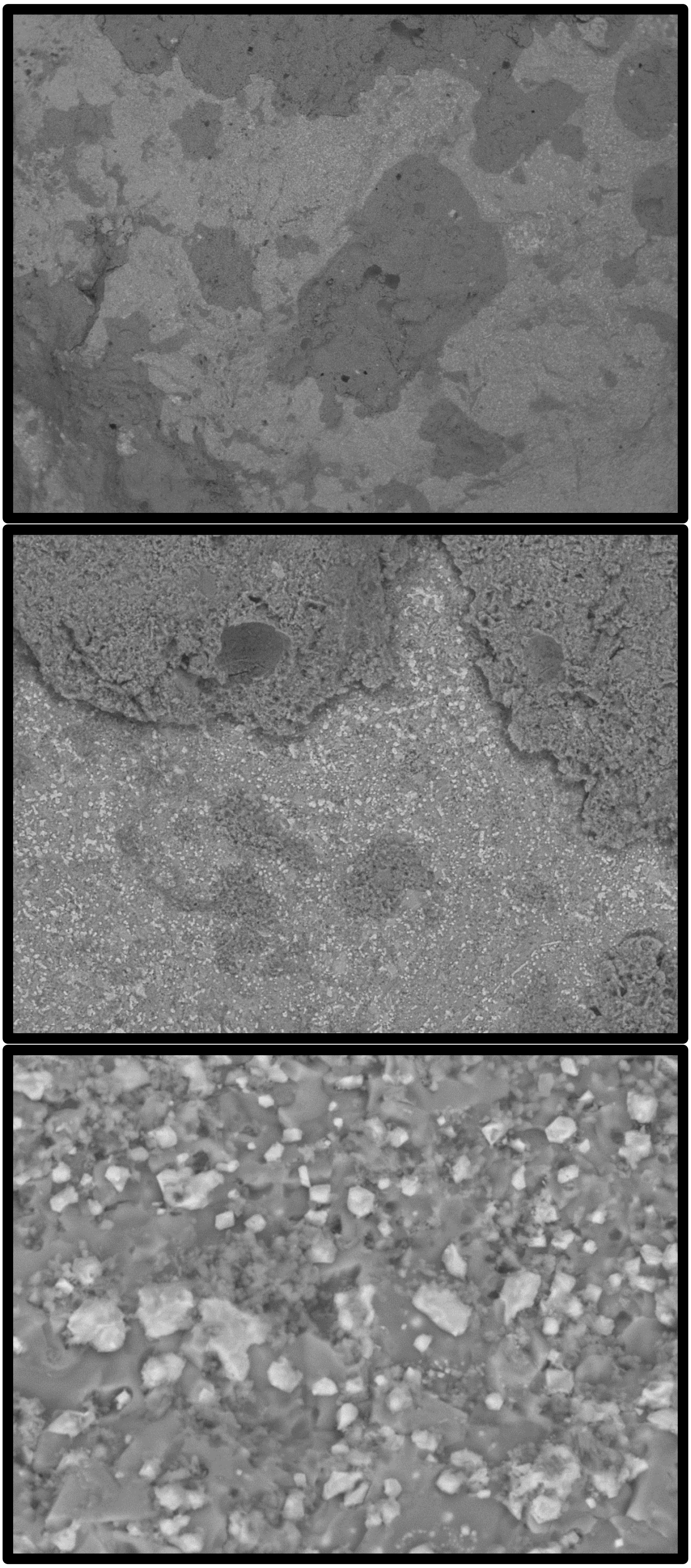
The bulk density and apparent density values provided by the MIP technique were, in general, coherent with the macroscopic density values measured using the conventional method of air weight and submerged weight. The bulk density MIP value of each mix was in general quite coherent with its dry density value measured by the conventional method; however, it was less coherent in the hydraulic mixes that included electric arc furnace slag. In general, the samples in the MIP tests were small-sized pieces (i.e. one cubic centimeter), without the addition of coarse aggregate (size > 5 mm). In the macroscopic measures of density, a whole cubic or prismatic sample was used and some discrepancy might therefore be expected.

Finally, the results for the apparent density for all of the EAFS mixes were similar and coherent between each other; and the same may be said of the SC1 reference mix.

SEM observations on concrete fracture surfaces

Fractographic observation of the SCC specimens revealed some interesting details that are illustrated and commented in this section. Pieces of mixtures P2 (“pumpable” concrete) and SC2 (self-compacting concrete), obtained after compression tests to failure, were observed using low-vacuum scanning electron microscopy (SEM) with the backscattered electrons technique, with no carbon or gold coating. No essential differences were observed between the characteristics of the above-mentioned mixtures and they all had similar features that could be analyzed and evaluated.

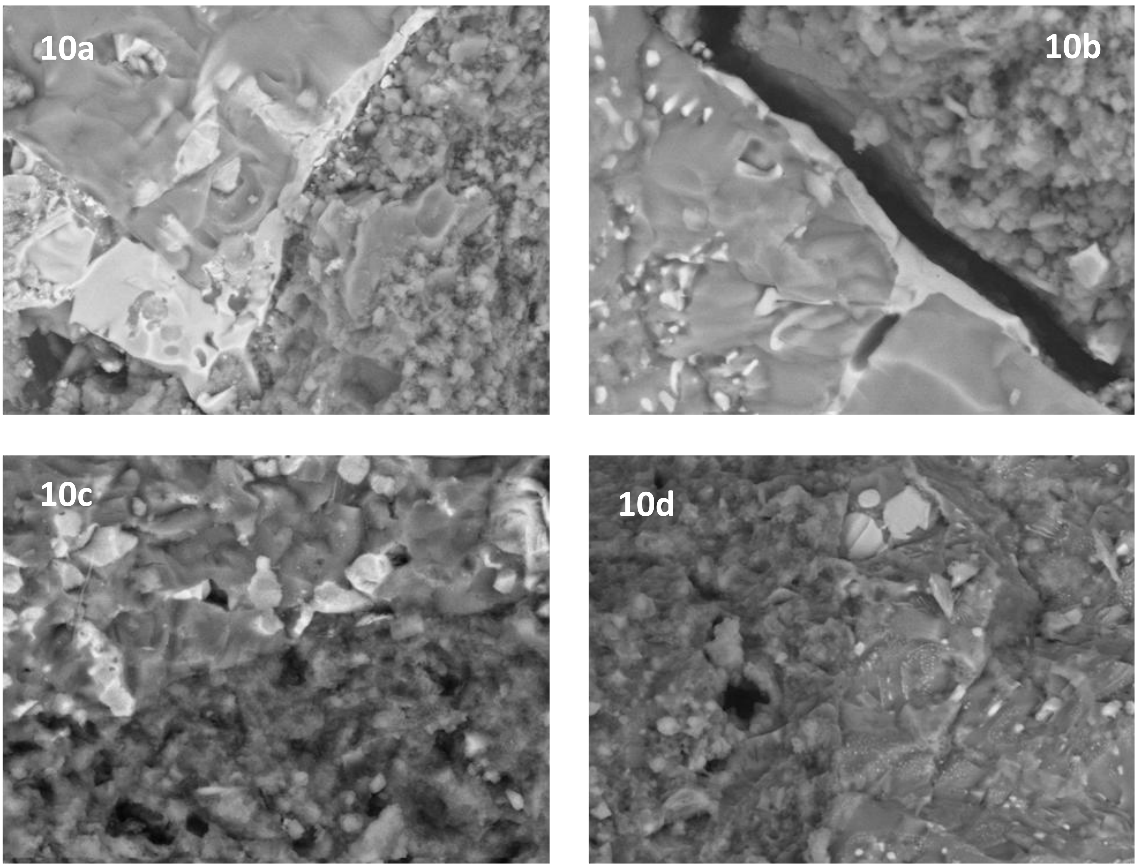
Figure 9a shows the contour (the “skin”) of an EAFS aggregate particle as part of the general fracture surface of an SC2 specimen. The existence of regions with good adherence of cementitious paste (dark, wrinkled) and regions of weaker adherence are visible, where the cementitious paste has separated from the EAFS pebble due to shear cracking. Figure 9b shows the naked surface of the EAFS sample (smoother, mottled by clearer small particles).



Figures 9a, 9b 9c: SEM images SC2

A higher magnification of this region, Figure 9c, reveals an outstanding presence of “white” particles of iron oxide (wüstite) in a grey matrix of silicates; in this grey region it is possible to distinguish some small “creased” zones of adhered cementitious paste on plate zones of silicates. It is reasonable to affirm that the adherence between paste and EAFS aggregate was good on the hydrophilic compounds of the slag (ghelenite, olivine, calcite, kirsteinite…), but the role of the hydrophobic iron oxides (wüstite and others) emerging on the surface contours was negative.

In Figure 10, the surface of P2 shows broken EAFS aggregate particles and broken cementitious paste in the vicinity of its contour, including the Interfacial Transition Zone (ITZ). Hence, examples of good as well as cracked and weakened adherence can be observed [35]. Figure 10a shows a poorly densified ITZ region (hole, rift) alongside an iron oxide coating of a piece of aggregate; in Figure 10b, the ITZ can be seen to have split open due to the shear stress effects of the test. In figures 10c and 10d, an “almost-perfect” ITZ is shown, the aggregate having a small proportion of “white” iron oxide particles on the surface contours; the apparent white particles correspond to the inside of the broken EAFS aggregate particles. In Figures 10a and 10b, the “clean” cleavage of the silicates on the inside of the EAFS particles may be seen.



Figures 10a, 10b, 10c, and 10d: SEM images P2

Dispersive energy X-ray micro-analysis (EDX) was performed on one of last samples, the images of which show the “almost white” coating of the EAFS aggregate particles in Figure 11. The results prove that this substance mainly consists of iron oxide (wüstite in solid solution with other metals as calcium, manganese…); Table 8 shows the results of this analysis.

Element	Weight%	Atomic%
O K	31.47	58.76
Al K	2.80	3.10
Si K	2.31	2.45
Ca K	6.04	4.50
Ti K	4.85	3.02
Mn K	5.82	3.17
Fe K	46.72	24.99

Table 8: EDX analysis

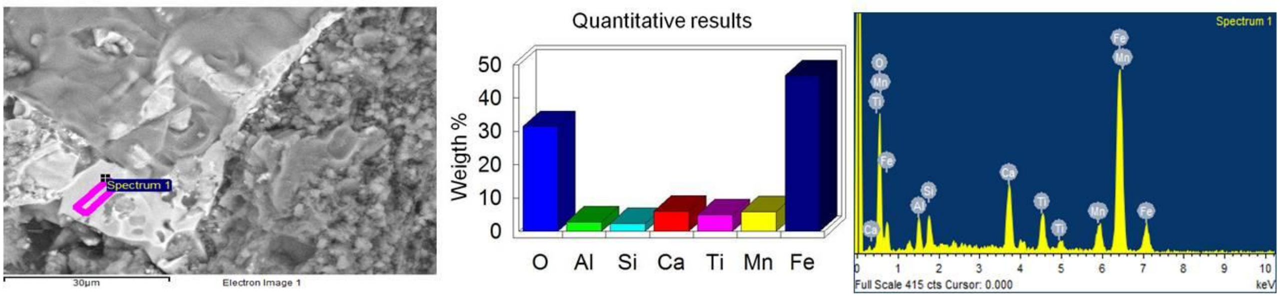


Figure 11: EDX analysis

Conclusions

The conclusions of this study are as follows:

- The reuse of electric arc-furnace slag in the manufacturing of pumpable structural concrete is a useful, affordable, and viable solution.
- It is possible to prepare self-compacting mixes using electric arc-furnace slag as coarse and fine aggregate, using appropriate doses and compatible chemical admixtures.
- The numerical simulation of the viscous flux of these self-compacting mixes using a suitable model leads to very acceptable results.
- The analysis of these self-compacting concretes in the hardened state points to a cohesive internal structure with reasonably good mechanical properties.

- SEM observation of the fracture surfaces in the SCC-EAFS concrete showed significant features to understand their structure and their mechanical behavior

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