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Evaluation of conductive concrete made with steel slag aggregates

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ABSTRACT

The incorporation of black steel slag (waste from steel production) in concrete responds to a greater awareness of sustainability. In addition, it is capable of increasing electrical conductivity. The objective of this work is to achieve multifunctional concretes with higher mechanical performance and which can modify the electrical characteristics.

In this work, natural aggregates have been replaced by different aggregates of steel slags from Spanish industries and the mechanical characteristics of compression, modulus of elasticity, indirect traction and electrical characteristics of these concretes have been studied with respect to reference mixtures.

Encouraging results have been obtained for concrete with slag and metallic fibers, improving the electrical conductive capacity by almost 70% and improving the mechanical performance by 14%.

1. Introduction

Given the current global situation in which we strive to find a balance with the environment and the development of new technologies and materials that are in line with this trend, recycling plays a fundamental role. The idea is to take advantage of waste from large industries that has no specific use, as is the case of the steel industry with steel waste.

Thus, extensive studies have been carried out to explore the possibility of utilizing steel slags as cement and concrete materials [1].

Steel slag as industrial by-products are annually produced in a huge quantity, which should be considered as a green resource. Modern steels can be broadly categorized into four types, carbon, alloy, stainless and tool steels. Carbon steel is produced either in a basic oxygen furnace (BOF) or an electric arc furnace (EAF), and then refined in a ladle furnace (LF) to achieve a better quality.

From among these alternatives, the current investigation focuses on the reuse of oxidizing slag, extracted from Electric Arc Furnace (EAF) steelmaking, in the manufacture of conductive concretes.

According to the CEDEX [2] report, there are 24 electric arc furnace steel mills operating in Spain, which produced a total of 13.6 MT of steel in 2005, of which, considering the generation of slag produced per ton, there is approximately 1.6 MT of black steel slag.

This slags has provided an optimal response to conductive characteristics and resistance to wear, and many of these good characteristics are due to their composition, which includes silica, calcium oxide, magnesium oxide, aluminum and iron, as a result of removing impurities from molten steel [3,4].

Steel slag properties will depend on the production process, curing conditions, and the type of recovery they involve [1].

Electrical conductivity in concretes is a combination of the ionic conductivity of cement paste and the electronic conductivity of carbonaceous and metallic materials [5].

This situation determines that conductivity depends on the presence of a triple percolation phenomenon: a) continuity of carbonaceous materials in the cementitious matrix, b) electrical continuity of the cement paste between the fine aggregate, and c) electrical continuity between the cement pastes and the coarse aggregate particles.

With this information, researchers explain that the electrical properties of compounds can be improved by adding different materials, experimenting with fibers, shavings and steel wool [6–11], fibers, dust and carbon nanotubes [10–17], graphite powder [8,9,11,16]. Researchers concerned about sustainability and improvement of the environment, have even proposed solutions for the recovery of waste materials and industrial by-products [5,18–21] that provide the same or better electrical properties.

With the different additions, they have endowed the building material with multifunctional properties, from overlapping snow melt

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Table 1
Properties of metallic fibers.

Property	3D 45/50 BL
Length (mm)	50.00
Diameter (mm)	1.05
Slenderness Ratio (L / D)	45.00
Tensile strength (N/mm^2)	1150
Minimum Dosage (Kg/m^3)	20.00
Fiber Network (m/m^3)	2.938
Presentation of Fibers	Loose

Table 2
Characteristics and physical properties of steel slag aggregates.

Denomination	Location	Fraction (mm)	Density (kg/m^3)	Water absorption (%)
Promsa	Sant Vicenç dels Horts, Barcelona	Sand 0/2	3310	2.47
		Sand 0/4	3570	0.81
		Gravel 10/20	3771.01	1.18
Sidenor	Basauri, Vizcaya	Sand 0/4	3782.14	2.01
		Gravel 10/20	3676.12	1.58
Hormor	Zestoa, Gipuzkoa	Sand 0/2	3785.33	0.95
		Sand 0/4	3257.72	1.22
		Gravel 10/20	3423.69	0.69
Calcinor	Altzo, Gipuzkoa	Sand 0/4	3515.24	1.65
		Gravel 10/20	3192.12	1.25
Adec	Vallirana, Barcelona	Sand 0/4	3621.74	1.78
		Gravel 10/20	3471.58	1.00

systems on road bridge decks, parking lots, sidewalks, driveways, and airport runways [5,6,11,15,22,23], steel reinforcement cathodic protection systems in concrete structures [23–26], self-detection systems and control of the structural state of intelligent infrastructures [10,17,27–34], and they have even determined that these compounds have great potential to be used as grounding systems, such as in central offices, electric power stations, and residential buildings, etc. [35,36].

This paper provides the use of steel slag as a replacement for natural aggregates, which not only contributes to the over consumption of natural raw materials, but also provides equal or better mechanical strength, improves the conduction of electricity and gives the concrete a multifunctionality.

Therefore, it has been determined the mechanical characteristics of compression, modulus of elasticity, and indirect traction, and the electrical characteristics determined by the resistivity values in the reference concretes and mixtures involving the replacement of natural aggregates with different steel slag aggregates from Spanish industries, as well as metallic fibers, taking into account current regulations.

2. Materials and experimental methods

2.1. Materials

2.1.1. Cement

Type II cement (CEM II/A-L 42.5 R) with a 28-day compressive strength of 42.5 MPa was used in mixes. The components mainly comprised: Clinker 80–94 % by mass, limestone 6–20 % by mass, and additional components: 0–5 % by mass ($SO_3 \leq 4.0$ %, CI: ≤ 0.10 %).

2.1.2. Additives

A plasticizer additive (Pozzolith 475 N) and a superplasticizer additive (Glenium SKY 886) were incorporate to improve workability, which reduces the amount of water incorporated into the mixes.

2.1.3. Steel fibers

SF with a tensile strength of 1150 MPa, a length of 50 mm, and a diameter of 1.05 mm were added to the mixes. Table 1 indicates their characteristics, due to their structural property, increasing the mechanical reinforcement and the conductive capacity of the set.

2.1.4. Aggregates

2.1.4.1. Coarse and fine natural aggregates. The coarse natural aggregates used in this study consisted of gravel with a maximum grain size of 20 mm and limestone sand with a density of 2750 kg/m^3 and water absorption of less than 2 %.

2.1.4.2. Steel slag. The slag studied is from Sidenor, Calcinor, Hormor, Adec Global and Promsa from electric arc furnaces. The production characteristics and the physical properties of steel slag used in the

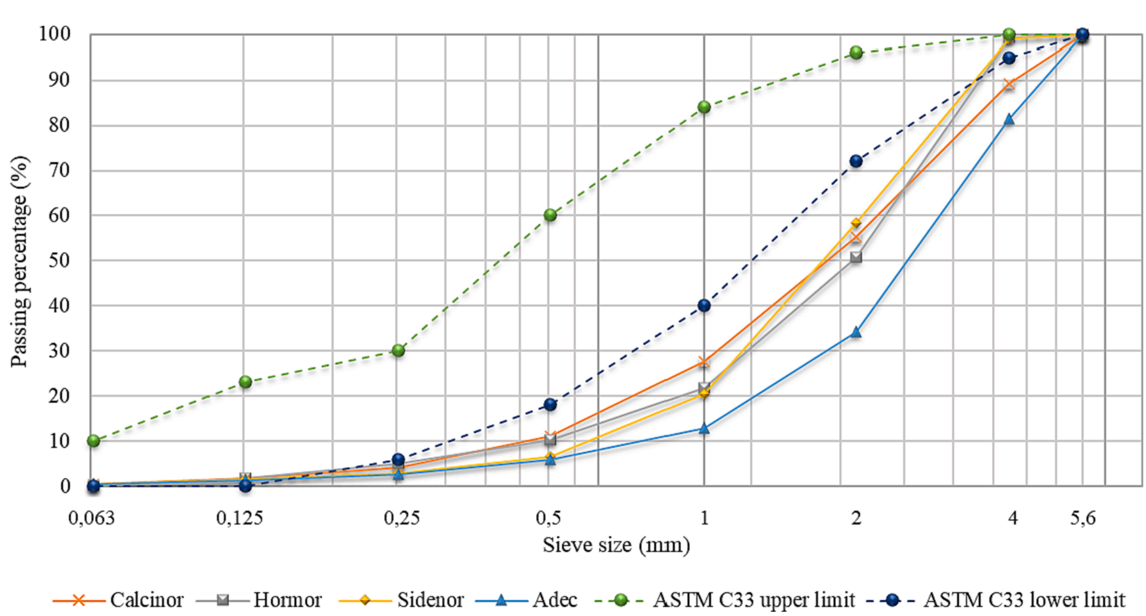

Fig. 1. Grain size distribution of fine steel slag aggregates.

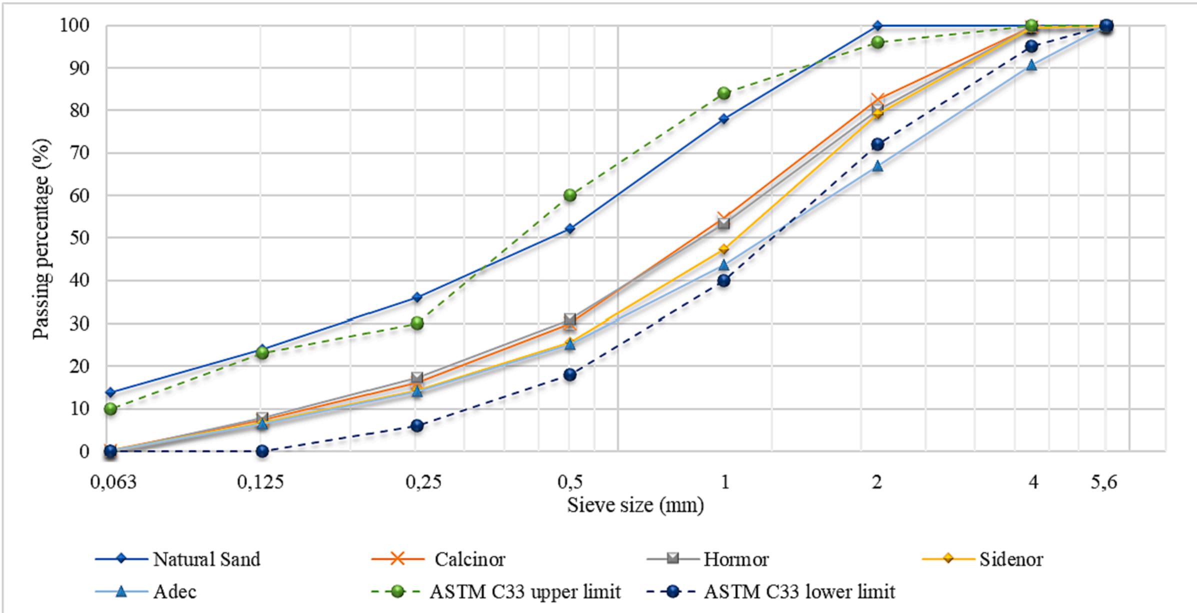

Fig. 2. Grain size distribution of corrected steel slag aggregates.

Table 3
Chemical composition of steel slag.

Chemical compounds (%)	Promsa	Sidenor	Hormor	Calcinor	Adec
CaO	30.20	22.54	27.70	27.40	27.30
Fe_2O_3	25.80	40.67	26.80	29.60	38.50
SiO_2	19.00	9.06	19.10	15.00	10.40
Al_2O_3	12.70	6.20	13,70	14.90	8.50
MnO	4.80	7.35	5.36	5.70	4.70
MgO	4.60	7.56	2.53	3.90	3.70
Cr_2O_3	1.60	3.00	2.48	2.40	2.80
TiO_2	1.00	0.43	–	0.79	0.74
LOI*	0.3	3.19	16.03	0.31	3.36

manufacture of the mixtures are describe in Table 2.

The water absorption of the different slag is given in very approximate values, which may be associated with a similar porosity of the different samples.

In the first process to describe the grain size distribution of fine slag aggregates with the corresponding upper and lower limits described in ASTM C33 [37] regulations, these were obtained by sieving (Fig. 1).

It can be seen that none of the slag is within the limits. The content of the fine fraction in the slag is lower (less than 3 %) and, therefore, we proceeded to add corrective natural sands, create the mix designs, and measure the mechanical and electrical characteristics of concretes.

The correction mixtures for the fine aggregate from Hormor was 40 % fine steel slag aggregate and 60 % 0/2 limestone sand. For the Sidenor aggregate, it was 50 % fine steel slag aggregate and the remaining 50 % 0/2 limestone sand. For the Adec fine aggregate, it was corrected with 35 % iron and steel fine slag aggregate, and 65 % of 0/2 limestone sand.

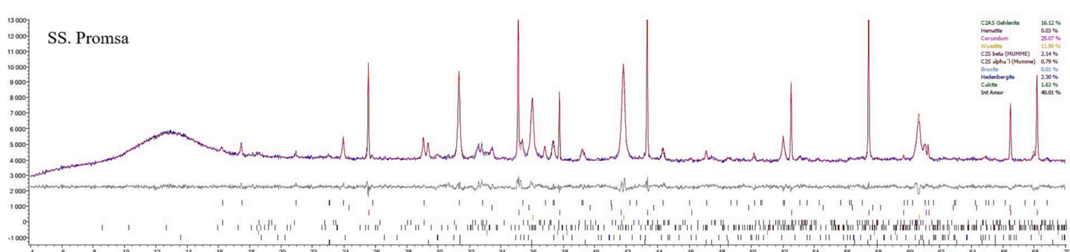

Fig. 3. XRD of Promsa steel slag aggregates.

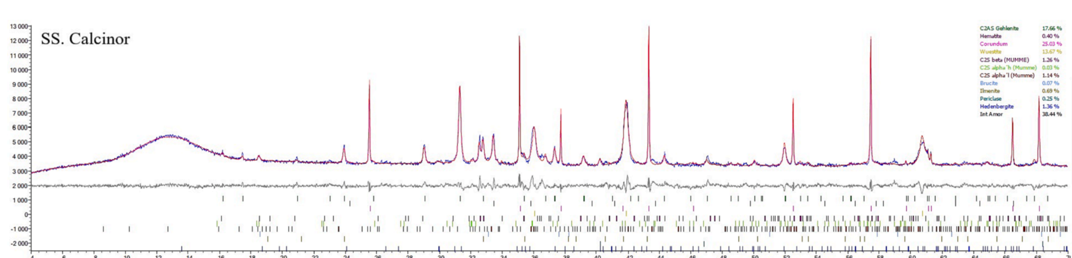

Fig. 4. XRD of Calcinor steel slag aggregates.

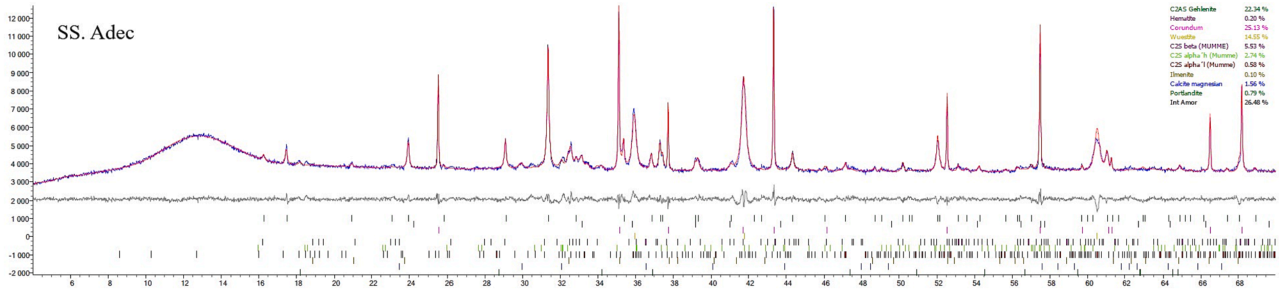

Fig. 5. XRD of Adec steel slag aggregates.

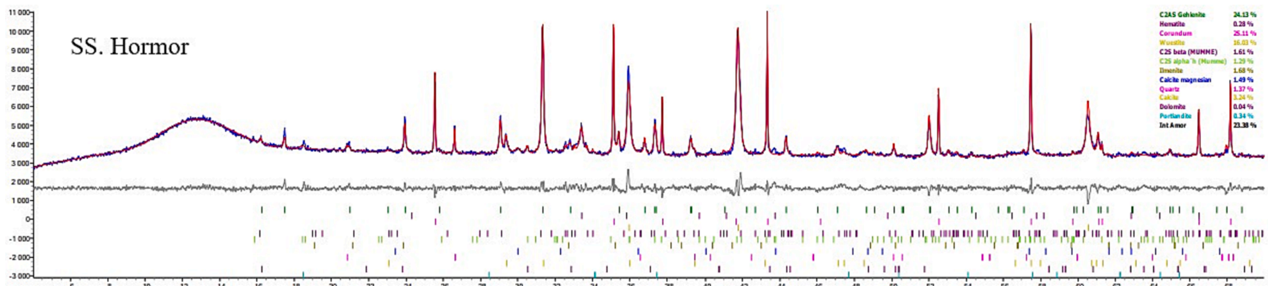

Fig. 6. XRD of Hormor steel slag aggregates.

Table 4
Crystalline phases of Promsa steel slag.

Crystalline Phase	Content	Crystalline Phase	Content
Amorphous content	53.0 %	C2S beta (MUMME)	2.9 %
"C2AS Gehlenite"	21.5 %	C2S alpha'l (Mumme)	1.0 %
Wustite	15.88 %	Hedenbergite	3.1 %
Calcite	2.17 %		

Table 5
Crystalline phases of Calcinor steel slag.

Crystalline Phase	Content	Crystalline Phase	Content
Amorphous content	51.0 %	Ilmenite	2.5 %
"C2AS Gehlenite"	22.8 %	C2S alpha'l (Mumme)	2.0 %
Hematite	0.46 %	Brucite	0.1 %
Wustite	18.6 %	Periclase	0.8 %
"C2S beta (MUMME)"	2.5 %		

Table 6
Crystalline phases of Adec steel slag.

Crystalline Phase	Content	Crystalline Phase	Content
Amorphous content	58.4 %	C2S alpha'h (Mumme)	0.6 %
"C2AS Gehlenite"	16.6 %	C2S alpha'l (Mumme)	1.5 %
Hematite	0.33 %	Calcite Magnesian	1.5 %
Wustite	13.02 %	Portlandite	0.32 %
"C2S beta (MUMME)"	1.2 %	Calcite	6.53 %
Ilmenite	0.1 %		

Therefore, the new grain size distribution (Fig. 2) is compliant with regulatory requirements.

2.1.4.2.1. Chemical composition. The chemical composition of steel slag was obtained by X-ray fluorescence (XRF). The XRF analysis revealed that the steel slag used in this study was mainly composed of CaO, Fe_2O_3, SiO_2 and Al_2O_3, as indicated in Table 3. This was confirmed by the results of the XRD analysis, as shown in Figs. 3–6, where corundum (Al_2O_3) wustite (FeO), and gehlenite (C_2AS) showed the highest intensities. (See Tables 4–7).

Table 7
Crystalline phases of Hormor steel slag.

Crystalline Phase	Content	Crystalline Phase	Content
Amorphous content	45.3 %	Calcite Magnesian	1.5 %
"C2AS Gehlenite"	19.0 %	Quartz	0.3 %
Hematite	0.38 %	Calcite	1.08 %
Wustite	15.61 %	Dolomite	1.8 %
"C2S beta (MUMME)"	9.3 %	Portlandite	0.49 %
Ilmenite	2.5 %	C2S alpha'h (Mumme)	2.7 %

As can be seen mainly from the Table 3, the slags have a high Fe_2O_3 content. Sidenor and Adec slags will be the ones that will contribute the most to the current conductivity through the fabricated specimens.

2.2. Mix design

2.2.1. Mix design with open grain size distribution.

Concrete mixes were prepared to investigate the characteristics of conductive concretes made with different steel slag aggregates, and steel fibers. For this purpose, four sets of concrete mixes were prepared in addition to two reference mixes. All the mixes with the different types of slag had the same proportion of aggregates, named I-1 (Promsa, Hormor, Adec and Calcinor).

Table 8
Concrete dosage used for the mixes.

Dosage (kg/m^3)				
Denomination		**P-1**	**P-2**	**I-1**
CEM II/A-L 42.5 R		235.00	235.00	235.00
Sand 0/2		432.00	432.00	432.00
Sand 0/4		336.00	336.00	500.00
Arid 10/20		1027.00	1027.00	1530.00
Water		145.00	145.00	145.00
Additives	Pozzolith (1.1 % spc)	2.59	2.59	2.59
	Glenium (0.47 % spc)	1.10	1.10	1.10
Fiber 3D 45/50 BL			36.00	36.00

Table 9
Concrete dosage with new granular skeleton.

Dosage (kg/m³) Denomination		Calcinor	Sidenor	Hormor	Adec
CEM II/A-L 42.5 R		235.00	235.00	235.00	235.00
Sand 0/2		384.00	384.00	460.80	499.20
Sand 0/4		510.39	549.14	439.68	352.84
Arid 10/20		1290.94	1515.23	1361.73	1396.48
Water		145.00	145.00	145.00	145.00
Additives	Pozzolith (1.1 % spc)	2.59	2.59	2.59	2.59
	Glenium (0.47 % spc)	1.10	1.10	1.10	1.10
Fiber 3D 45/50 BL		36.00	36.00	36.00	36.00

2.2.2. Mix design with corrected grain size distribution

To improve the volumetric homogenization between concretes and to comply with the requirements of the EHE- instruction. 08, Article 28.4.1, concrete mixes were prepared with corrective natural sands and slag aggregates. Table 9 shows the proportion mixes and their names.

2.3. Sample fabrication

In order to have control parameters, reference concretes (Table 8) were manufactured with natural aggregates with the same volumetric dosage, relating the specific weights of the materials to obtain *P*-1 (without fibers) and P-2 (mixture incorporating metallic fibers).

A total of 21 cylindrical specimens measuring 10x20 cm were manufactured to measure resistance to compression, and 18 specimens measuring 15x15 cm to conduct the Barcelona test. In addition, to measure electrical conductivity, 14 prismatic test tubes measuring 40x10x10 cm (UNE-EN 12390–1, [38]) were produced with the dosages indicated in Table 8 and Table 9, following Instruction UNE-EN 12390–2 [39], so that the dry materials (aggregates, cement and fibers) were mixed first. Subsequently, 70 % of the mixing water was incorporated and the additives were ultimately used along with the rest of the mixing water. A table vibrator was used for mixture compaction.

2.4. Characterization of concretes

The properties of concrete mixes were examined in the fresh and hardened states. In fresh concrete mixes, consistency and density were quantified and, in hardened state mixes, mechanical and electrical properties were evaluated.

2.5. Physical properties

Measurements were taken in the fresh state of the concrete, and consistency was measured according to UNE-EN 83313 [40]. Density was measured according to the UNE-EN 12350–6:2009 [41] Standard, based on the fact that fresh concrete is compacted in a rigid and watertight container, the mass and volume of which are known, and is weighed once compacted.

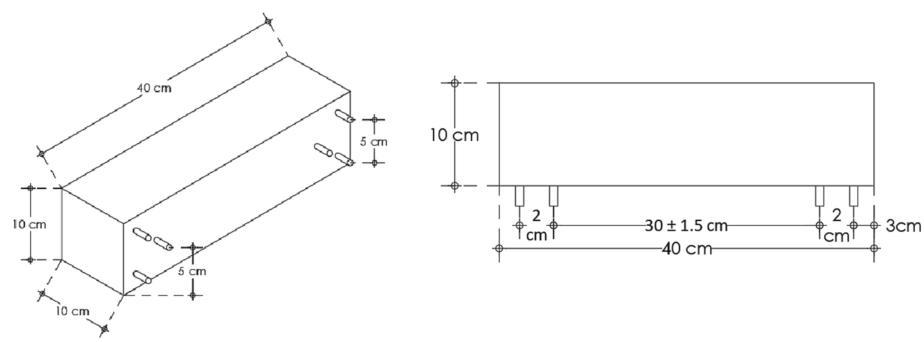

Fig. 7. Location of the electrodes in the specimens.

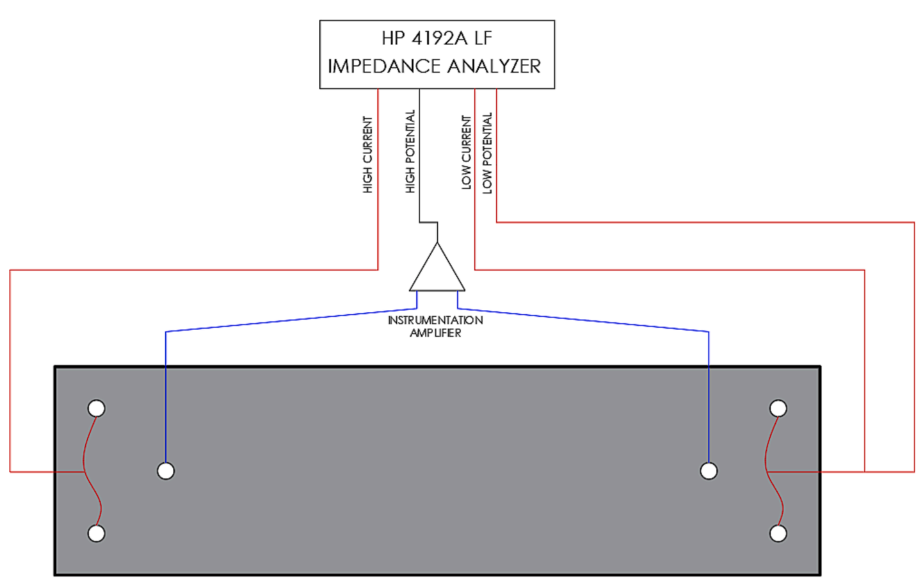

Fig. 8. Impedance Analyzer.

Table 10
Consistency of open grain size distribution mixes.

Sample	Consistency (cm)	Denomination
P-1	8	Wet
P-2	4	Standard
I-1 Promsa	4	Standard
I-1 Sidenor	2	Dry
I-1 Hormor	2	Dry
I-1 Calcinor	2	Dry
I-1 Adec	2	Dry

Table 11
Consistency of corrected grain size distribution mixes.

Sample	Consistency (cm)	Denomination
Sidenor	7	Wet
Hormor	6	Standard
Calcinor	6	Standard
Adec	5	Standard

2.6. *Mechanical properties*

The compressive strength and modulus of elasticity were quantified according to UNE-EN 83316 [42] on cylindrical specimens measuring 15 cm in diameter and 30 cm in height. The indirect traction test (Barcelona test) was conducted according to UNE-83515 [43] on cylindrical specimens measuring 15 cm in diameter and 15 cm in height.

2.7. *Electrical properties*

To conduct the electrical conductivity test, prismatic test tubes were used which incorporated 6 connectors through which current was passed, as shown in Fig. 7.

The AC electrical properties of the samples were characterized with a different circuit topology, an Agilent HP 4192A impedance analyzer (Fig. 8), using an instrumentation amplifier as a front-end to allow 4-probe measurements after Gersing [44], with an effective voltage of 1 V AC to avoid polarization effects in the electrodes [48].

The measurements were taken in the frequency scanning range of 10 Hz to 1 MHz providing the electrical impedance (Z, in Ω) and phase (ϕ, in degrees). The electrical impedance is described by Eq. (1) and is composed of a real part (resistance, R) and an imaginary part (reactance, X); R and X are given by Equation (2) and (3), respectively:

$$Z = R + j\cdot X \tag{1}$$

$$R = Z\cdot cos\left(\frac{\phi\cdot\pi}{180}\right) \tag{2}$$

$$X = Z\cdot sin\left(\frac{\phi\cdot\pi}{180}\right) \tag{3}$$

Once the electrical resistance is obtained, it is possible to calculate the electrical resistivity of the material ρ [Ω·m]. The electrical resistivity (ρ, in Ω·m) was calculated from the impedance data using Eq. (4), where S is the effective transverse section (0.01 m^2 in our study), and l is the measured length (30 ± 1.5 cm in our study). Lastly, the electrical conductivity (σ, S/m) of the samples was easily calculated as the inverse of resistivity. The electrical conductivity values are expressed as the mean values determined for three different specimens.

$$\rho = R\frac{S}{l} \tag{4}$$

Table 12
Compressive strength (fc) of mixes with open grain size distribution.

Denomination	Stress max (MPa)	Strain [e]	CV (%)
P-1	14.66	0.0103	2.79
P-2	43.68	0.0066	0.83
I-1 Calcinor	21.16	0.0056	1.44
I-1 Hormor	34.09	0.0115	2.21
I-1 Sidenor	22.66	0.0052	2.37
I-1 Promsa	37.34	0.0063	1.84
I-1 Adec	26.13	0.0068	2.82

Table 13
Compressive strength (fc) of mixes with corrected grain size distribution.

Denomination	Stress max prom (MPa)	Strain max [e]	CV (%)
Calcinor	27.80	0.00667	2.23
Sidenor	37.64	0.00473	5.10
Hormor	46.74	0.00688	2.69
Adec	49.74	0.00594	7.82

Table 14
Residual resistance of the Barcelona test in open gain size distribution mixes.

Denomination	Q_{max} (kN)	Run_{max} (mm)	Energy (J)			
			M1	M2	M3	Ave.
I-1 Calcinor	99	1.959	174	168	158	167
I-1 Hormor	130	1.601	207	182	234	208
I-1 Sidenor	99	1.844	122	130	124	125
I-1 Adec	158	1.773	199	215	271	228
I-1 Promsa	124	2	224	147	188	186

3. Results

3.1. *Physical properties*

Workability decreases significantly in concretes that incorporate metallic fiber and an open size grain distribution, obtaining a significant difference between concretes with metallic fibers and concrete with natural aggregates that do not contain them. The consistencies of the mixtures are shown in Table 10 and Table 11.

It can be seen that workability and consistency improve when we modify the granulometry of the slag. Without this modification of grain size distribution, the mixtures remain in a dry state, making it impossible to put them to work.

3.2. *Mechanical properties*

3.2.1. *Compressive strength*

In the hardened state, the different mixtures were subjected to simple compression. The results are shown in Table 12 and Table 13.

In Table 12, it is important to highlight the contribution to the compressive strength provided by the metallic fibers (P-2) in comparison with the reference sample *P*-1.

It is observed that the use of steel aggregates in the mixes leads to a loss of compressive strength, compared to the reference concretes. This loss of compressive strength is mainly due to the low workability of the different mixes, which causes a higher content of occluded air and, consequently, a higher porosity in the specimens.

However, by modifying the granular skeleton of the mixes, the following results are obtained, as described in Table 13.

It is observed that the compressive strength increases by 52 % for the samples with Adec steel aggregate, compared to those with open grain size. This shows that, with a better skeleton, the mechanical properties also increase.

Table 15
Residual resistance of the Barcelona test in corrected gain size distribution mixes.

Denomination	Q_{max} (kN)	Run_{max} (mm)	Energy (J)			
			M1	M2	M3	Ave.
P-2	146	1.113	258	235	203	232
Calcinor	132	2.440	203	168	–	185
Sidenor	161	1.962	251	287	167	235
Hormor	175	2.281	208	130	271	203
Adec	165	2	282	207	236	242

3.2.2. *The indirect traction test (Barcelona test)*

The indirect tensile strength of the open and corrected grain size mixtures obtained by the Barcelona test are shown in Table 14 and Table 15, respectively. It is important to clarify that this test was not performed on the reference specimens without fibers.

The indirect tensile results show that the samples with only steel aggregates do not reach the properties of the reference concretes, except for the samples produced with Adec slag, which minimally surpasses the control concretes.

However, by modifying its granulometry with corrective sands, the resistance to indirect traction is increased up to 20 %, and although most of the residual strength is provided by the fiber, the granular skeleton and the type of matrix also contribute to this strength.

3.3. *Electrical conductivity*

The electrical characteristics of cementitious compounds with slag are slightly influenced by the applied frequency in AC measurements. Fig. 9 shows Bode plots of reference mixtures and those containing slag and metal fibers. The reference sample behaves like an insulator with almost no variation in impedance with the frequency.

The incorporation of the steel slag modifies the electrical behavior of the samples, and the impedance reduces as the frequency of the applied current is increased.

Sidenor and Adec steel slag aggregates provide better electrical behavior, which is due to their mineralogical composition, reducing the resistivity of reference concrete with metallic fiber to below 50 %.

It can be observed that the mere incorporation of metallic fibers into conventional concrete mixes reduces the resistivity of the cementing compounds by almost 50 %.

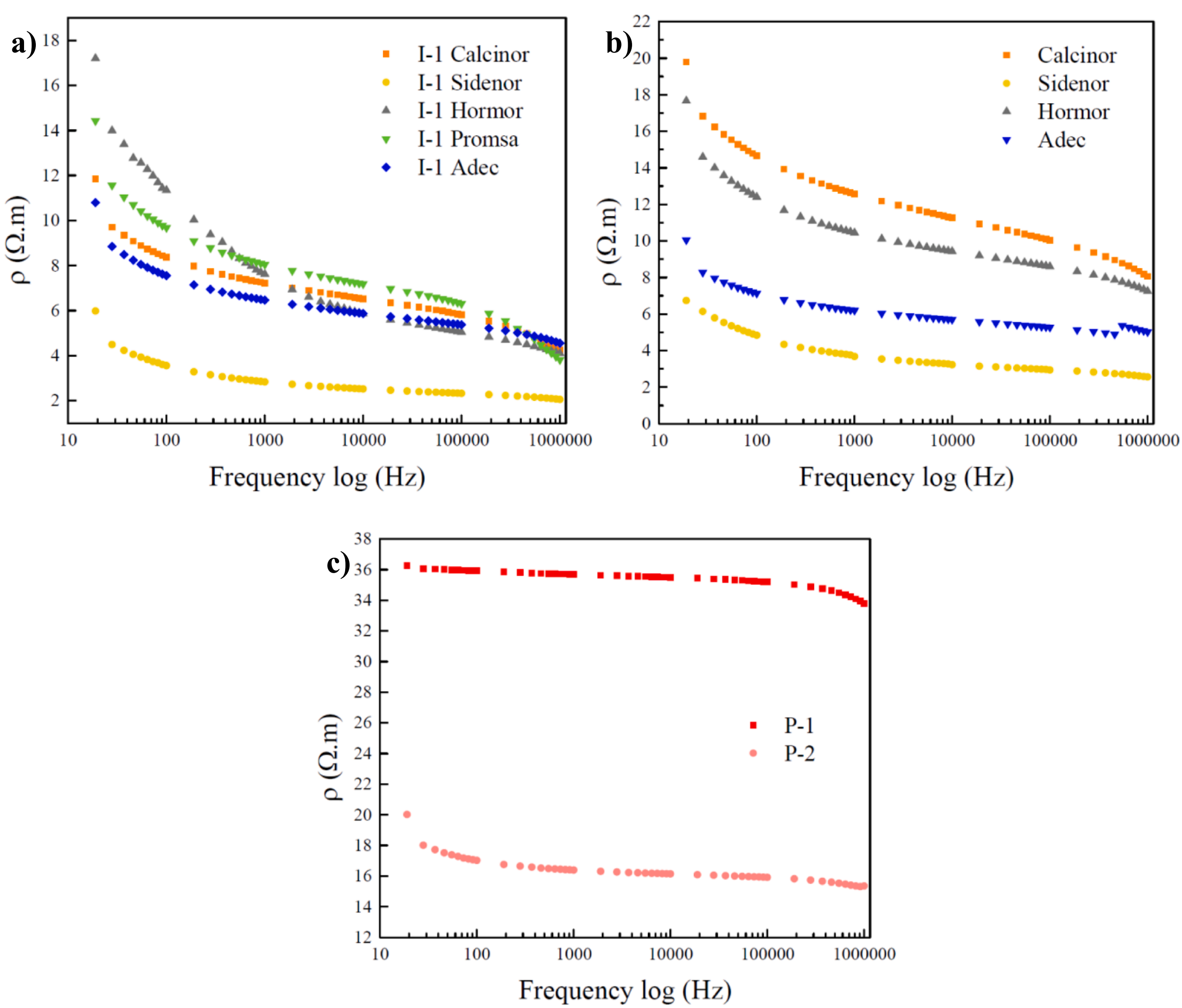

Fig. 9. Bode plots of the four-point measurement of the concrete samples. a) Open gain size distribution mixes. b) Corrected grain size distribution mixes. c) References mixes.

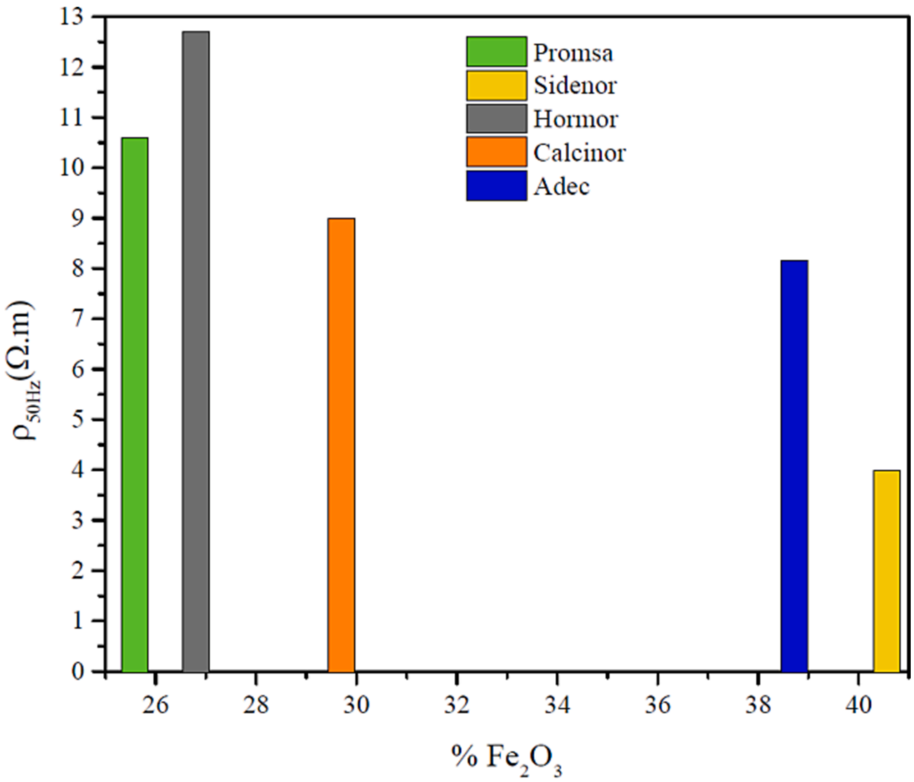

Fig. 10. Influence of Fe2O3 content in relation to the resistivity.

Furthermore, the samples containing slag and metallic fibers reduce the electrical resistivity by an average of 66 % in relation to concrete with natural aggregate and metallic fiber.

Sidenor slag stands out for the high conductivity it contributes to the mass, reducing the resistivity of conventional concrete with natural aggregate and fibers by almost 44 %.

4. Discussion

Several researchers have studied the properties of aggregates from steel slag in building materials. Thanks to the studies carried out by Amaral [46], it was decided to use electric arc furnace (EAF) slag. With regard to durability studies, Amaral analyzed EAF slag concretes subjected to various aggressive environments by testing carbonation, exposure to seawater, alkali–aggregate reactions and sulfate attacks. His study found no expansive behavior in the concrete following alkali–aggregate reactivity tests and sulfate attacks. The depths of carbonation, observed in the CEAF, were slightly higher than the values of the reference concrete, probably because of the greater permeability of its slag aggregate; however, chloride ion infiltration was lower. The author concluded that the durability of the concrete made with slag aggregates was comparable to ordinary concretes.

The first studies on this topic were presented by Wu et al. [47]. More recently, Guotong Wang et al. [48] presented a detailed study of Steel Slag Aggregate (SSA) on permeable concrete and its amelioration effect. Jiao et al. [49] verified the feasibility of adding steel slag to asphalt mixes as thermal aggregate to increase thermal conductivity for electrical-thermal snow melting. All these studies focused primarily on the use of steel slag in flexible pavements. With no data available on rigid concrete with aggregates of steel slag, the data obtained in the two experimental campaigns of the work presented will be compared.

Steel slag has compounds (Table 3) which modify the electrical capacities within the cementitious materials. As metallic compounds, they facilitate the flow of current and, consequently, reduce their resistivity.

The main compound to which this increase in conductivity is attributed is iron oxide, which is shown in detail in Fig. 10.

It is evident that the slags from Sidenor contain a higher content of this compound (more than 40 %), so that the resistivity of the material decreases significantly (36 % lower) compared to those with a lower content of this compound (Hormor and Promsa).

The bibliography shows that not only the use of slag facilitates this passage of electricity and, if we compare it with another type of material, one that has given excellent results is carbon fibers [10,50,51].

In fact, the incorporation of steel slag aggregates and metallic fibers affect the behavior in the fresh state of the concrete, reducing workability (Table 10 and Table 11), which generates a higher air content and, therefore, greater porosity in the mix. Due to their high content of potentially expansive elements in their interior, aggregates from slag must be stabilized before incorporating them into the concrete, so as not to generate undesirable internal stresses that could cause cracks or spalling.

In the first experimental campaign (Table 12), no mix made with slag exceeded the resistance of mixes made with natural aggregate, but significant resistance was obtained in concretes with Hormor and Promsa aggregate.

In the second experimental campaign (Table 13), by improving the workability conditions and slightly homogenizing the dosage, all the mixtures with slag increase their maximum resistance to simple compression. In the case of the mixtures with Hormor and Adec slag, the increase is significant, exceeding the resistance of concrete with natural aggregates, in excess of 45 MPa and almost reaching 50 MPa, respectively.

The residual resistances obtained in the Barcelona test respond to a similar behavior of the compression study, maintaining the trends.

The best results are given in the samples from Promsa, Adec and Hormor, which can be explained by the fact that the steel aggregates were larger.

This increase in resistance in all the mixtures observed in the second experimental campaign gives us evidence of the modifications in the granulometry of the steel aggregates, which are able to work in

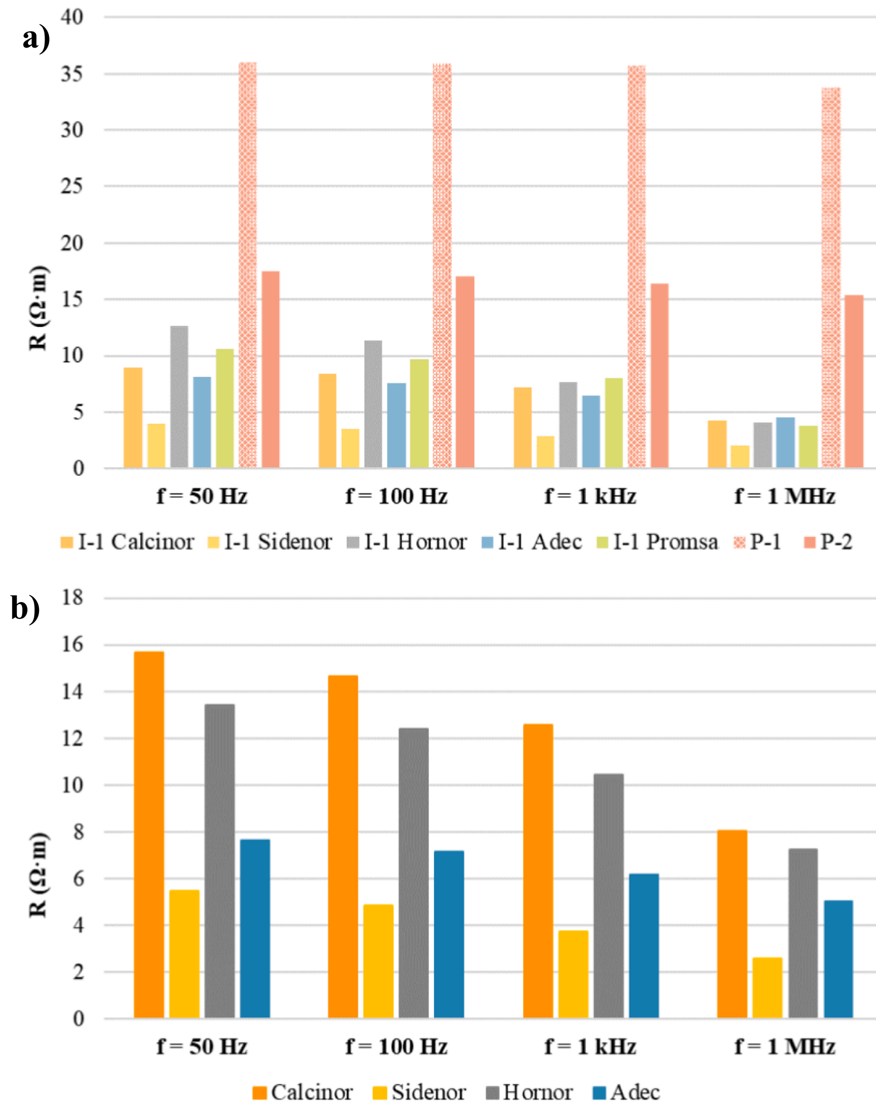

Fig. 11. Comparison of electrical resistivities at different frequencies; a) first experiment, b) second experiment.

conjunction with the cementitious matrix. It is evident that in the mixtures manufactured with Hormor and Adec aggregates, this modification exceeds the residual strengths initially obtained from concrete with natural aggregates, which is why it is determined that the steel slag aggregate offers a high performance in withstanding mechanical stress.

In addition to the mechanical characteristics, the difference in electrical properties in the two experimental campaigns is evident, as shown in the Fig. 11.

When comparing the results between the first experiment and the second, the electrical resistivity of the composites is not significantly affected, with the exception of the Calcinor samples which could be comparable to the reference concretes with natural aggregates and fibers (P-2).

Finally, it is concluded that the modification of the granular skeleton improves the mechanical characteristics, and that the electrical properties of the conductive concretes do not suffer greater variety, showing that these properties depend mainly on two parameters: the dispersion of the metallic fiber in the cementitious matrix and the chemical composition of the steel slag aggregates (Table 3). Both parameters will determine the presence of a continuous electrical flow path and, therefore, the electrical conductivity of the material will be higher.

This same behavior can be observed in a simpler way in the Fig. 12, where the Nyquist diagrams of the samples produced with natural aggregates, fibers and steel slag are compared.

In the Nyquist diagrams, two representative mass arcs are clearly observed for each type of sample; the first constitutes the impedance of the composite material and the second, the most notable or extensive, represents the extended impedance [52], which occurs when there is a difference in size between the electrodes and the sample and, as a result, the contact of the electrode with the sample is deficient [53].

5. Conclusions

The incorporation of steel slag aggregates significantly improves the conductive capacity of concrete, and the incorporation of fibers reduces the resistivity of the material.

In this article, we demonstrate that, with regard to the electrical capabilities of concrete made with steel slag, the material contributes to the current scenario in which sustainability must be in every field of engineering activity, reusing this useless waste, increasing its life cycle and, therefore, generating one more phase in the process. However, sustainability is not only implied by the use of this waste but also by its conductive capacity, which can be developed in several fields, from small situations, such as providing seats or roads without ice or snow for

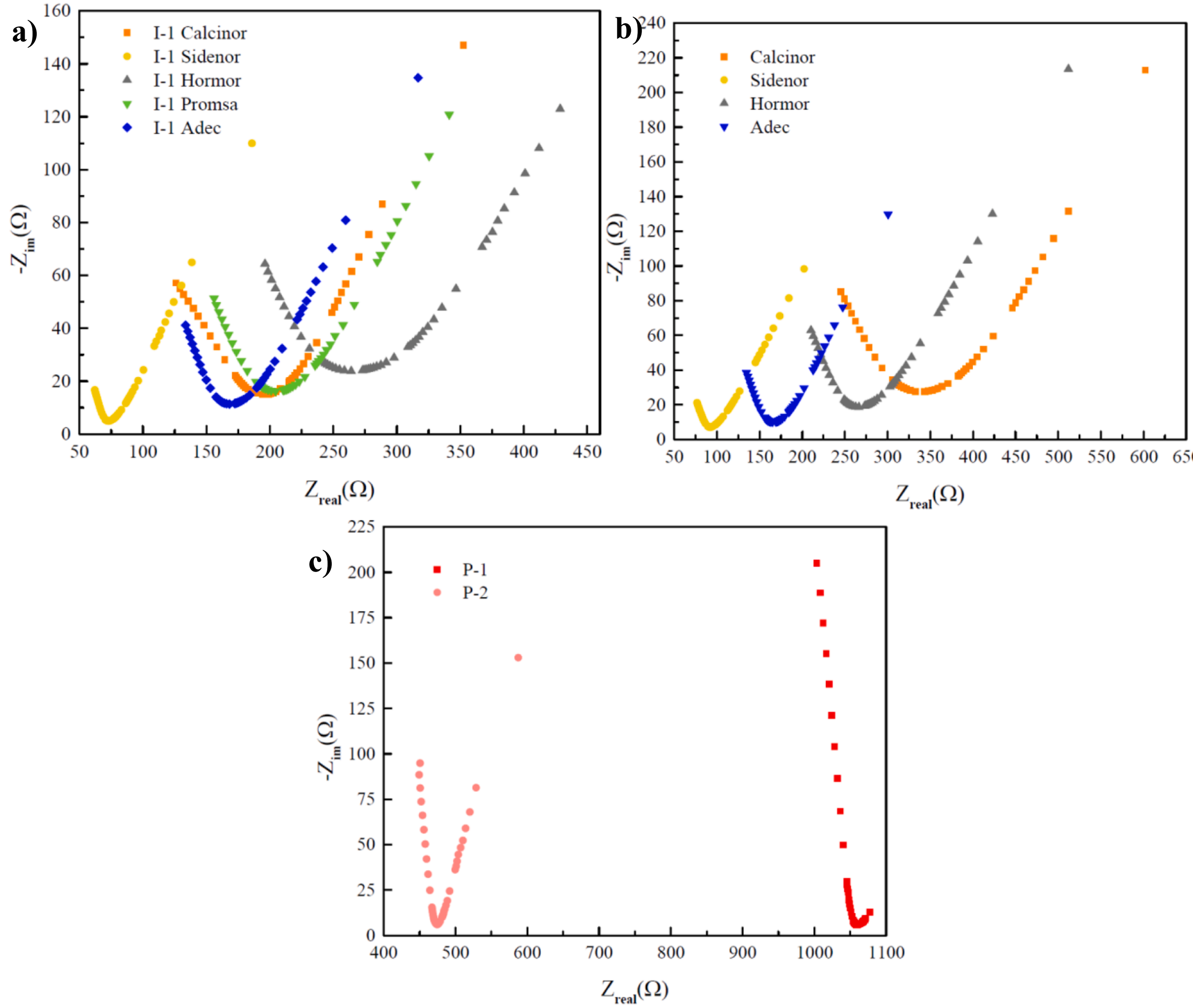

Fig. 12. Nyquist plots of the four-point measurement of the concrete samples. a) Open gain size distribution mixes. b) Corrected grain size distribution mixes. c) References mixes.

pedestrians, to the generation of greener energies that help drive energy to turn on a traffic light or, more ambitiously, to charge a small vehicle.

From the analysis of the mechanical tests, it was observed that in the case of the mixtures with Hormor and Adec slag, the increase is significant, exceeding the resistance of concrete with natural aggregates, in excess of 45 MPa and almost reaching 50 MPa, respectively. The increase compared to the reference mixes with steel fibers is about 15 %. This confirms that slag improves the mechanical properties of concrete.

From the analysis of the electrical, it was determined that all types of slag improve the electrical characteristics, reducing the resistivity of the material. The Sidenor and Adec steel slag aggregates provide better electrical behavior, which is due to their mineralogical composition, reducing the resistivity of the reference concrete with metallic fiber to below 50 %.

The major factor contributing to conductivity in slag is the mineralogical composition of iron and steel slag aggregates. They are, however, sensitive to all changes in dosage, from the amount of sand used to the particle size distribution in the dosage.

The weight of this material must be taken into account when calculating the structures, since the specific weight of the slag can make a significant difference in the final weight of the structure.

CRediT authorship contribution statement

N. Santillán: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **S. Speranza:** Conceptualization, Methodology, Investigation. **J.M. Torrents:** Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision. **I. Segura:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ninel Santillan Alarcon reports financial support was provided by Government of Catalonia Agency for Administration of University and Research Grants.

Data availability

No data was used for the research described in the article.

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