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Corrosion and mechanical performance of reinforced mortar and concrete made with MSWI bottom ash

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ABSTRACT: Electrochemical monitoring was performed to evaluate the influence of municipal solid waste incineration residues (MSWI) made concrete, on reinforcement corrosion, using four different steel reinforcements grades, traditional carbon steel B-500-SD and three stainless steels, the austenite AISI 304, duplex AISI 2304, and lean-duplex AISI 2001, embedded in mortars manufactured using bottom ash as aggregates from the incineration of municipal solid waste (MSW), in partial and total substitution of natural aggregate. In addition, it has been studied the mechanical behaviour of the mortar and concrete matrix in the presence of MSWI aggregates. The use of MSWI bottom ash as an aggregate, results in a notable improvement of the resistance characteristics of conventional mortar and concrete, made out only of natural aggregate. Moreover, electrochemical measures show that the steels remain in passive state throughout all the exposure period (3 years).

KEYWORDS: Bottom ash; Corrosion; Municipal solid waste (MSW); Reinforced concrete

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RESUMEN: *Comportamiento mecánico y frente a corrosión de mortero y hormigón armado fabricado con escorias de incineradora de residuos sólidos urbanos*. Se ha evaluado mediante monitorización electroquímicas la influencia de la utilización de escorias procedentes de incineradoras municipales de residuos sólidos urbanos (RSU), en la corrosión de muestras de hormigón armado, utilizando para ello cuatro aceros corrugados, el tradicional acero al carbono B-500-SD y tres aceros inoxidables: el austenítico AISI 304 (EN 1.4301), el dúplex AISI 2304 (EN 1.4362) y el dúplex de bajo contenido en níquel AISI 2001 (EN 1.4482), embebidos en morteros elaborados sólo con escorias como sustituto del árido. Además, se ha estudiado el comportamiento mecánico de morteros y hormigones de cemento Portland elaborados con escorias, procedentes de la incineración de residuos sólidos urbanos, en muestras elaboradas con sustitución total o parcial del árido natural por escoria de RSU. De los resultados obtenidos se deduce que la utilización como árido de las escorias procedentes de la incineración de RSU, mejoran sensiblemente las características de resistencia del convencional mortero y hormigón elaborados sólo con árido natural. En cuanto al estudio de corrosión de las armaduras, las mediciones electroquímicas demuestran que los aceros permanecen en estado pasivo durante todo el periodo estudiado (3 años).

PALABRAS CLAVE: Corrosión; Escorias incineradora; Hormigón armado; Residuos sólidos urbanos (RSU)

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1. INTRODUCTION

Municipal Solid Waste (MSW) generated in the cities has become in the 21st century a worldwide concern for the environmental impact they cause. In modern waste disposal strategies, it is a priority to reduce, reuse and recycle (Del Valle-Zermeño *et al.*, 2013). More than 30 years ago, an advantageous solution was implemented, its incineration in kilns with or without energy recovery (Goñi *et al.*, 2007), a technique increasingly used since the new European regulations prohibit the storage of untreated waste in landfills (Müller and Rübner, 2006). MSW incineration has several advantages, such as the significant reduction of both volume (about 90%) and mass (about 70%) (Chimenos *et al.*, 1999), complete disinfection of waste (Li *et al.*, 2004) and energy recovery from the combustion by heat (Lam *et al.*, 2010).

MSW incineration produces two by-products: slag (75-80%) and fly ash (the rest). Slags are residues that remain on the bottom of the furnace after combustion, are greyish and have a porous appearance, and contain small amounts of residual organic matter, pieces of glass, ceramics, minerals, and metals, and non-hazardous waste, rich in calcium oxide and silica with minimal amounts of heavy metals (Del Valle-Zermeño *et al.*, 2013). On the other hand, fly ashes are very fine particles entrained by the gas stream to the outside of the combustion chamber (Siddique, 2010), and consists of fine particles with a high content of heavy metals, organic compounds and chlorides. They are classified as hazardous waste and require appropriate management to minimize their effect on the environment (Ginés *et al.*, 2009). The physical and chemical characteristics of slag and fly ash depend on many factors, such as the air pollution control device, operating conditions and combustion efficiency. Also it is dependent on MSW composition itself and the type of combustion furnace, which may be incineration in a grill oven, a rotary kiln or a fluidized bed.

The cement and concrete industry uses large amounts of industrial waste as secondary raw materials, including carbon fly ash (CFA), silica fume (SF) and granulated blast furnace slag (GBFS). By replacing the active part of the Portland clinker with these mineral additions, energy and raw materials are saved in cement manufacturing, reducing atmospheric pollution, as well as being beneficial for mechanical and durability characteristics and to facilitate commissioning.

The traditional mineral additions of CFA, SF and GBFS, have some analogy with the fly ash of MSWI (Bertolini *et al.*, 2004). The studies by Polettini *et al.* (2001) and Aubert *et al.* (2006), have shown that cement maintains its mechanical strength with a maximum addition of 20% of MSWI fly ash. Studies performed by Juric *et al.* (2006), determined that for the preparation of concrete showing 40 MPa of compressive strength, it is acceptable to replace up to 15% of cement by MSWI fly ash, as they have resulted that at 28 days, flexural strength and compression strength show only a linearly decreased of 0.03 and 0.02 MPa respectively for each 1% increase in weight of the fly ash dosage of slags.

Currently, the most widespread use of MSWI slags it is as substitute for aggregates in road sub-bases, but another possible application it is as aggregate for concrete. Studies by Rashid and Frantz (1992) and Pera *et al.* (1997), showed that natural gravel substitution of up to 50% by slags (by pre-treatment of sodium hydroxide) is possible without affecting the durability or compressive strength of the concrete (for a compressive strength of 25 MPa at 28 days). The reutilisation of MSWI natural weathered bottom ash (WBA) in many applications such as roads and underground constructions, embankments or as an aggregate replacement is a common practice in many developed countries. The quest in finding viable solutions to the chloride-induced corrosion phenomenon in WBA made reinforced concrete is an important task that has to be performed in order to guarantee their long-term stability and therefore their sustainability (Del Valle-Zermeño *et al.*, 2017).

Nevertheless, there are several drawbacks presented by slags for use in concrete as aggregate. The main one is the amount of aluminum hydroxides, aluminates and release of hydrogen gas from aluminum particles that can react with Portland cement due to its high alkalinity, leading to an increase of porosity, causing expansion and cracking of the concrete (Pecqueur *et al.*, 2001). In addition, due to the glass content in the slags, an alkali-silica reaction has been detected in concrete, although less severe than for aluminum compounds (Müller and Rübner, 2006). Other drawback is the high content of zinc, copper, lead, chromium, chlorides, sulfates and other anions (Del Valle-Zermeño *et al.*, 2014). The high content of chlorides present in some slags and their possible effect on the corrosion of reinforcements has been studied by Prieto *et al.* (2013), which showed that the presence of white spoon furnace slag (LFS), as a partial replacement of aggregate (25%) and cement (30%), does not adversely affect the corrosion of steel reinforcements embedded in mortars, when the percentage of chlorides is higher than 0.4%, which is a good choice in economic and environmental terms.

Some disadvantages can be remedied by leaving the slag in the open air between 30 and 90 days, period in which oxidation of some metals occurs and dissolution and precipitation of the hydroxides and the salts of the main cations. This practice also decreases the chlorine content and, finally, leads to the new formation of clay minerals of glass (Chimenos *et al.*, 2003). The authors Forteza *et al.* (2004), have concluded that by storing the slags for at least a month, allows the mechanical properties of WBA to be assimilated to that of natural aggregates. In addition, aluminum containers can be separated automatically at the MSWI treatment plants using the Van der Waals principle, and it is increasingly common to recycle these containers and glass containers with specific vessels.

The present work investigates the partial and total substitution of natural aggregates (sand and gravel) in Portland cement mortars and concretes by slag from MSWI bottom ash to analyze the influence on the mechanical properties and the corrosion behaviour of carbon steel and stainless steel reinforcements.

2. EXPERIMENTAL

In order to carry out this work, MSWI slags from the Valdemingómez (Madrid) incinerator plant have been used. This municipal incineration plan uses a fluidized bed furnace above temperatures of 850 °C. Slags have been left in the open air for at least two months in a controlled landfill, thus allowing leaching of chloride contents (Chimenos *et al*., 2003). The chemical analysis of the slag is shown in Table 1, obtained by gravimetric methods and X-ray fluorescence emission spectroscopy by wavelength dispersion (FRX-dλ) on a grinded sample of slag. The analysis was repeated with another sample of slag previously calcined at 950 °C, giving similar percentages of composition, and with a third sample calcined at 1100 °C, varying the percentages between + 0.14% and −0.35%, allowing only losses by calcination. Apart from the first determination, for others calcinations gains are observed. Slags density, between 2.60 and 2.70 gcm^{-3}, surface area between 0.22 and 0.39 m^2g^{-1} (% weight) and water absorption, 2.36% (Pera *et al*., 1997) have been determined.

In order to make the mortar and concrete specimens, the slags were first subjected to a crushing process until a maximum size of 20 mm was obtained. Subsequently, the particle size was determined according to UNE-EN 933-1 (2012), distribution particle size plot is shown in Fig. 1, dividing the crushed slag into two parts: fine slags of maximum size 4 mm and thick slags of size comprised between 4 and 20 mm.

TABLE 1. Chemical composition of slag from the waste incineration plant of Valdemingómez (Madrid).

Element	wt,%	Element	wt,%
Na_2O	0.51	TiO_2	0.62
MgO	5.44	V_2O_5	0.08
Al_2O_3	9.70	Cr_2O_3	1.60
SiO_2	20.48	MnO	4.53
P	0.14	Fe_2O_3	32.04
S	0.31	CuO	0.05
Cl	0.03	ZnO	0.20
K_2O	0.13	PbO	0.01
CaO	23.39	Rest	0.68
		Total	100

The mortars were made with the fine fraction, and the concrete with a mixture of both. The plot also shows the particle size resulting from two possible blends of fine slag and coarse slag to make concrete. Mixture 1 contains 70% fine slag an 30% coarse, it corresponds to the one that theoretically best approximates Fuller's distribution. Mixture 2 contains 36% of fine slag and 64% of coarse, which is the ratio used to make concrete specimens because it is the same amount used for sand and gravel in conventional concrete.

Slags have not been submitted to any other treatment, which in practice would be an extra cost for the preparation of mortars and concrete.

2.1. Study of MSWI slag mortars

In order to study the mechanical properties of traditional Portland cement mortars made with MSWI slag in partial or total substitution of the natural aggregate, five different mortars have been prepared, composition is given in Table 2. The M1 is a reference mortar made with natural river sand, with no slag. M2, M3 and M4 are mortars with partial substitution of sand by slags. The M5 is a mortar made only with slag, without natural aggregates. The water/cement (W/C) ratio was 0.5/1, and the same in all cases.

To prepare the mortars has been used Portland cement Valderribas CEM II B-L 32,5 N, river sand and fine slags, both of 4 mm of maximum size. The kneading has been done with an automatic kneader Ibertest. From each kneading the fresh mortar runoff value was obtained according to UNE-EN 1015-3 (2000), in the shaker table, and the density (kneading weight between the capacity of the standard vessel 361 ml), values are summarized in Table 2. Mortars made of slag show a softer consistency compare to the reference, due to the slight content of metals and

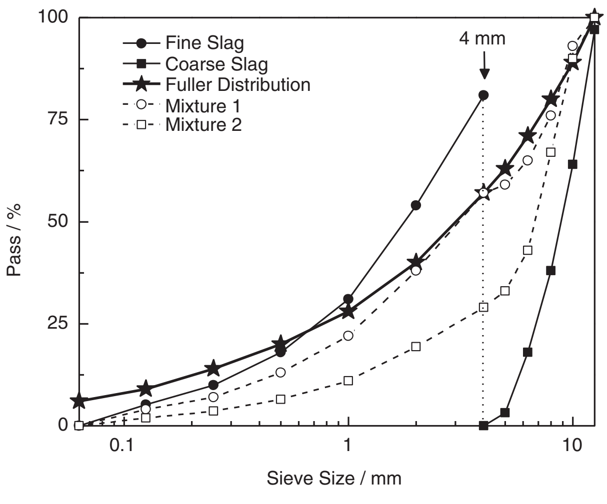

FIGURE 1. Mixture of fine and coarse slag after crushing process, Fuller distribution for the reference, two different particle size and two aggregate mixtures: Mixture 1 with 70% fine slag and 30% coarse slag, and Mixture 2 with 36% fine slag and 64% coarse slag.

metalloids. Plastic consistency has been obtained according to UNE-EN 1015-6 (2007). It is also verified that the density of mortar made with slag increases as the slag content is increase in relation to mortar made only with natural aggregates.

Three prismatic specimens of 160×40×40 mm were made, and cured for 28 days in a curing chamber, model Ibertest CM200, regulated at 20 °C and 95% relative humidity (RH).

2.2. Study of MSWI slag concrete

Influence of slag dosage on the mechanical properties of concrete was studied, in partial or total substitution of the natural aggregates. Four concretes samples of different dosages by weight have been prepared, as shown in Table 3. H1 is a reference concrete made with natural river sand and gravel, without slag. The H2 and H3 samples present partial substitution of sand and gravel by fine and coarse slags, at different ratios (Table 3). The H4 is a concrete sample made entirely with slag, without natural arid. The W/C ratio used was 0.5/1.

To prepare the concrete samples, Portland cement, 4 mm river sand, 20 mm gravel, 4 mm thin slags and 20 mm thick slags, were used. The mixing of concrete has been done with concrete mixer with vertical axis. The consistency of the blend has been determined by the Abrams cone according to UNE-EN 12350-2 (2009), obtaining in all cases values between 10 and 15 cm (fluid consistency for chopping with bar), resulting in slightly larger seats values in concrete made with slag.

Five cubic specimens of 100 × 100 × 100 mm were prepared according to UNE-EN 12390-1 (2001). The specimens were cured during 28, 105 and 180 days in a curing chamber at 20 °C and 95 % RH.

2.3. Reinforcement Corrosion Performance in MSWI specimens

Electrochemical monitoring of reinforcement corrosion was performed in order to study the dosage of slag influence on corrosion of reinforcements. Four prismatic 8×5.5×2 cm mortar test samples of type M5 previously described, made only with slag without natural sand, were prepared. Another four reference samples with mortar type M1, elaborated only with natural river sand, have been elaborated for comparatives purposes. Cold-rolled ribbed reinforcements of 6 mm diameter and 8.5 cm length have been embedded in different mortar samples. Electrochemical monitoring of the corrosion potential, E_{corr}, and the linear polarization resistance (LPR) or $R_{p,}$ was performed during an exposure time of three years.

Electrochemical measurements of E_{corr} and R_p were performed using a potentiostat-galvanostat model 273 A of the brand EG & G Princeton Applied Research and the software Corware 3.1c. An electrochemical cell with three electrodes configuration was used: the standard calomel reference electrode (SCE), the counter electrode or guard ring (solid stainless steel disc 7 cm diameter and 4 cm high with a central hole of 8 mm to house the reference electrode) and the working, which is the rebar itself. The measurements were made in triplicate and repeated periodically for three years in both steel rebars embedding each test samples.

Four different reinforcement type were studied, traditional carbon steel B-500-SD, austenitic AISI

TABLE 2. Dosage of the studied mortar specimens: cement (c), sand (s), fine slags (f), water (w); density and leaching values.

Type of Mortar	Dosage				Density (gcm^{-3})	Leaching (mm)
	c	s	f	w		
M1	1	3	-	0.5	2.19	137.50
M2	1	2	1	0.5	2.31	149.50
M3	1	1.5	1.5	0.5	2.39	157.50
M4	1	1	2	0.5	2.46	155.00
M5	1	-	3	0.5	2.61	159.00

TABLE 3. Dosage of the studied concrete specimens: cement (c), sand (s), gravel (g), fine slags (f), coarse slag (cs), water (w); density and leaching values.

Type of Concrete	Dosage						Slag(*)	Cone Abrams Seating (cm)
	c	s	g	f	cs	w	(%)	
H1	1	1.85	3.32	-	-	0.5	0	10
H2	1	1.23	2.22	0.62	1.11	0.5	33	14
H3	1	0.62	1.11	1.23	2.22	0.5	66	12
H4	1	-	-	1.85	3.32	0.5	100	15

(*) Percentage of fine and coarse slag with respect to the total content of the aggregates.

304 (EN 1.4301), duplex AISI 2304 (EN 1.4362) and new lean-duplex AISI 2001 (EN 1.4482).

The rebars were embedded in pairs of the same steel in the test specimen, leaving one end peeking outside to connect each rebar to the electrochemical measuring equipment. A 10 cm^2 surface of each rebar was defined, being the rest of the surface protected with insulating tape, at its final end and in the triple (air/mortar/steel) interface area. The minimum mortar cover thickness on the exposed area is 6 mm.

The specimens have been cured for 28 days in a curing chamber at 20 °C and subsequently, during the three years exposure time, they have been kept inside a hermetically sealed container with a constant relative humidity of 95%, being only removed for electrochemical measurements purpose.

3. RESULTS AND DISCUSSION

3.1. Study of mortar made with MSWI

At the age of 28 days, the mortar specimens were tested in flexural mode (in an Ibertest machine, model Autotest 200-10 SW, which applies a force of 10 kN at a rate of 0.03 kN/s) and compression mode (Applying a force of 200 kN at a rate of 0.05 kN/s) according to UNE-EN 1015-11 (2000), see Fig. 2.

The values of the flexural strength (3 specimens for each type of mortar), and compression (the 6 specimens "a" and "b" of each type of mortar resulting from the previous test) are shown in Table 4.

The average values of the flexural and compression strengths are compared in Fig. 3. It is verified

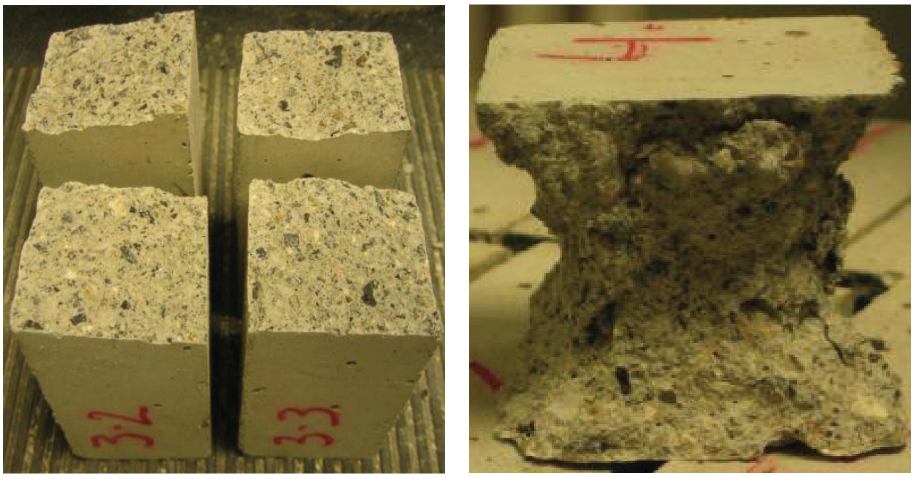

Figure 2. Mortar specimens after flexural and compression test.

Table 4. Flexural and compression test results, at 28 days, for the tested mortar specimens

		Flexural Strength (MPa)			Compression Strength (MPa)			
Type of mortar	Sample	Value	Average Value	Standard deviation	Specimen "a"	Specimen "b"	Average Value	Standard deviation
M1	1.1	5.02			24.99	23.93		
	1.2	5.42	5.40	0.37	25.25	24.62	24.77	0.54
	1.3	5.76			25.37	24.47		
M2	2.1	5.49			28.38	26.86		
	2.2	5.92	5.80	0.27	27.01	26.72	27.26	0.59
	2.3	5.98			27.28	27.28		
M3	3.1	5.74			27.55	26.41		
	3.2	5.58	5.91	0.45	26.03	25.50	26.33	0.92
	3.3	6.42			27.23	25.25		
M4	4.1	5.83			27.85	25.43		
	4.2	5.53	5.78	0.23	26.06	26.03	26.28	1.20
	4.3	5.98			27.54	24.76		
M5	5.1	5.39			26.77	25.85		
	5.2	4.81	5.23	0.37	25.91	26.35	26.08	0.45
	5.3	5.50			26.16	25.46		

that the flexural strength of the mortar made with a ratio 1:1 of slag to natural sand is slightly higher than that of the reference mortar (M1), moreover the compressive strength has always been found to be higher in slag-containing specimens than for reference mortar, at least 6% higher for mortar made entirely with slag.

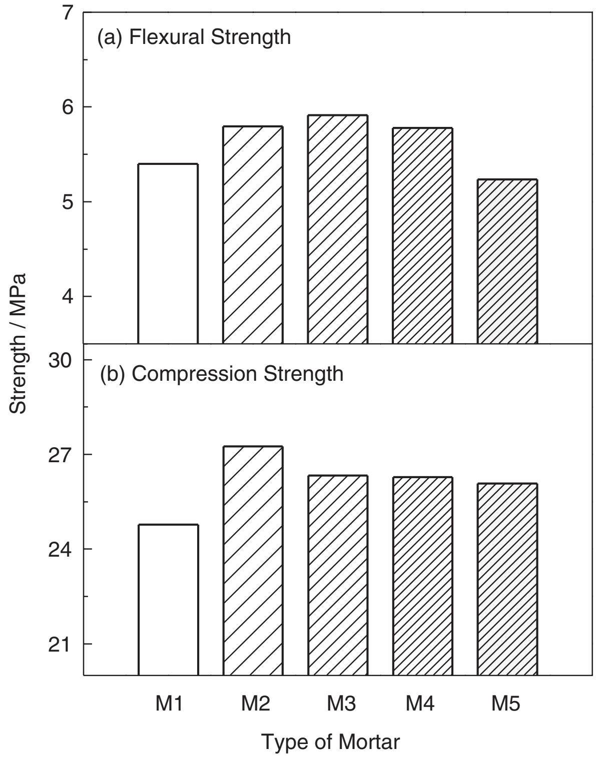

FIGURE 3. Flexural and compression mechanical resistances for the tested mortar specimens: a) flexural mode and b) compression mode.

3.2. Study of concrete made with MSWI

The concrete specimens were tested to compression according to UNE EN 12390-3 (2009), (see Fig. 4), in an Ibertest model MIB 60/AM machine, at the age of 28 days, 105 days and 180 days, assays were done in duplicate. The results are reported in Table 5 and the mean values are compared in Fig. 5.

The average resistance of each concrete sample made with slag, replacing partially or totally the natural aggregate, has always been higher than that of reference concrete (H1), elaborated only with natural arid. Obtained values at 28 days, present and increase of 0.2% H2, 18.88% H3 and 10.56% H4. All MSWI made concretes have obtained better results, even those made with total substitution of slag (H4), and for the whole exposure time period between 28 and 180 days.

3.3. Corrosion Monitoring of Reinforcements embedded in MSWI slags

E_{corr} was first recorded after allowing the system to stabilize for at least 20 min. Fig. 6 shows the E_{corr} results obtained as a function of time, for the conventional carbon steel and the three stainless steels, embedded in M5 (made with 100% of MSW slag) and also those embedded in the reference mortar M1 (made with 100% natural arid). During the three years studied, E_{corr} values presented similar values for all steels, varying between − 68 and

FIGURE 4. Concrete specimens after compression test.

Table 5. Compression test results performed at 28, 105 and 180 days, for the tested concrete specimens

Type of concrete	Age: 28 days Sample	(MPa)	Average Value (MPa)	Standard deviation	105 days Sample	(MPa)	Average Value (MPa)	Standard deviation	180 days Sample	(MPa)
H1	1.1	18.44	18.75	0.44	1.3	24.09	23.23	1.22	1.5	26.43
	1.2	19.06			1.4	22.36				
H2	2.1	19.97	18.79	1.67	2.3	25.49	25.98	0.69	2.5	27.10
	2.2	17.61			2.4	26.46				
H3	3.1	20.18	22.29	2.98	3.3	28.53	28.25	0.40	3.5	29.50
	3.2	24.40			3.4	27.97				
H4	4.1	21.32	20.73	0.83	4.3	27.90	28.37	0.66	4.5	32.90
	4.2	20.14			4.4	28.83				

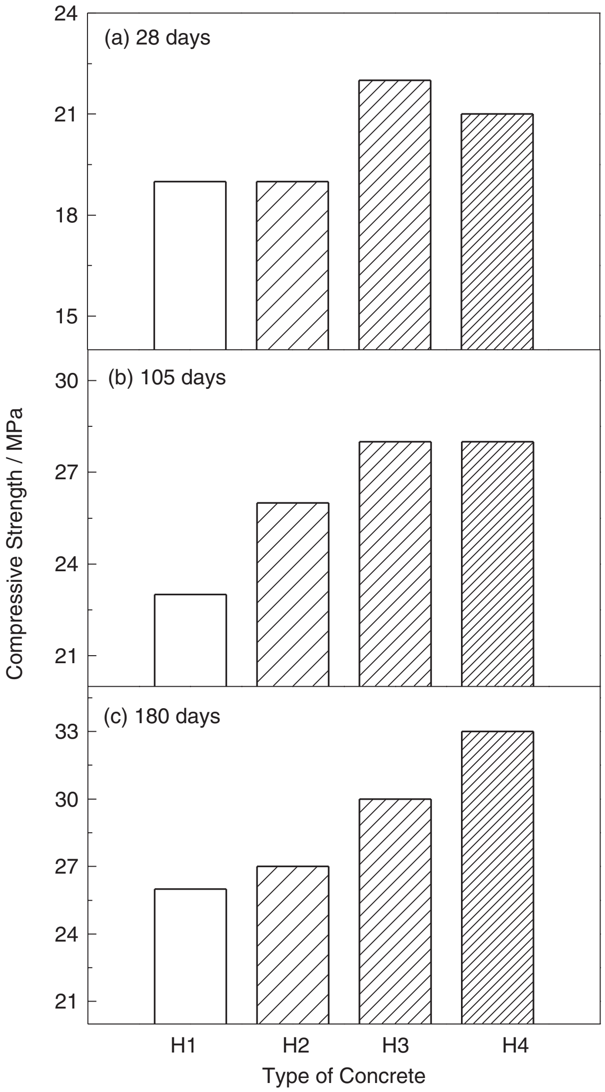

Figure 5. Compression mechanical resistances for the tested concrete specimens at different ages: a) 28 days, b) 105 days and c) 180 days.

−173 mV for those embedded in the M5 specimens, stabilizing in values between−100 and −150 mV after three years.

For carbon steel, it is considered that for E_{corr} greater than −120 mV, the probability of corrosion occurring in the reinforcement is less than 10%, if it is between −120 mV and −270 mV the probability is uncertain, and if it is less than −270 mV the probability is higher than 90% (ASTM-C876, 1999). In the present study, according to the results obtained from E_{corr}, it can be considered that all studied steels are kept in passive state.

After each E_{corr} measurement, the linear polarization resistance (LPR) method was applied to the specimen to determine R_p. For this purpose, a small polarization of ± 15 mV with respect to E_{corr} was used at a scan rate of 0.1667 mVs^{-1}. The value of the corrosion current density, i_{corr}, of the steel has been obtained using the previously recorded value of R_p, and by the Stern & Geary Eq. (1):

$$i_{corr} = \frac{B}{R_p} \quad (1)$$

Taking 52 mV as the Stern-Geary value of B coefficient (Stern and Geary, 1957), which corresponds to the steel in the passive state (as indicated by E_{corr} values).

The B value is obtained from the Eq. (2), being related to the anodic and cathodic slopes of the polarization curve:

$$B = \frac{\beta_a \cdot \beta_c}{2.303(\beta_a + \beta_c)} \quad (2)$$

The evolution of i_{corr} values over time in the studied period is shown in Fig. 7. The values are very low in all cases, varying between 0.0049 and 0.095 μAcm^{-2}, indicating that all the reinforcements are in the passive state, as they are below

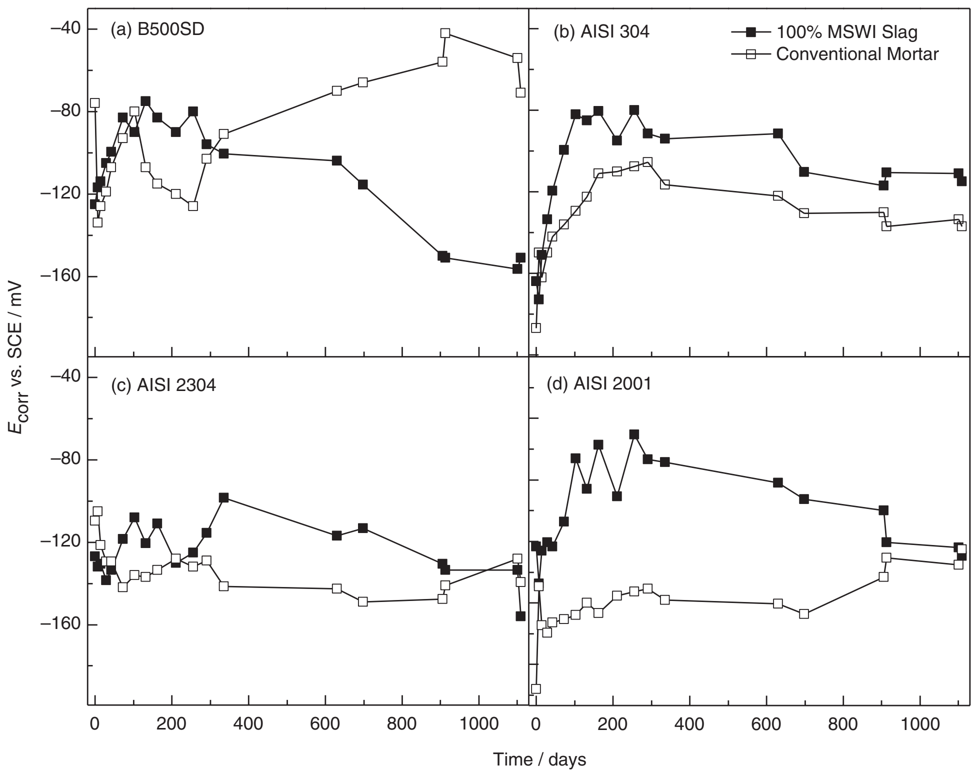

FIGURE 6. E_{corr} vs. time plot of the four tested reinforcements embedded in Portland type mortar made with 100% MSWI bottom ash and for the reference samples made with river sand: a) B-500-SD, b) AISI 304, c) AISI 2304 and d) AISI 2001.

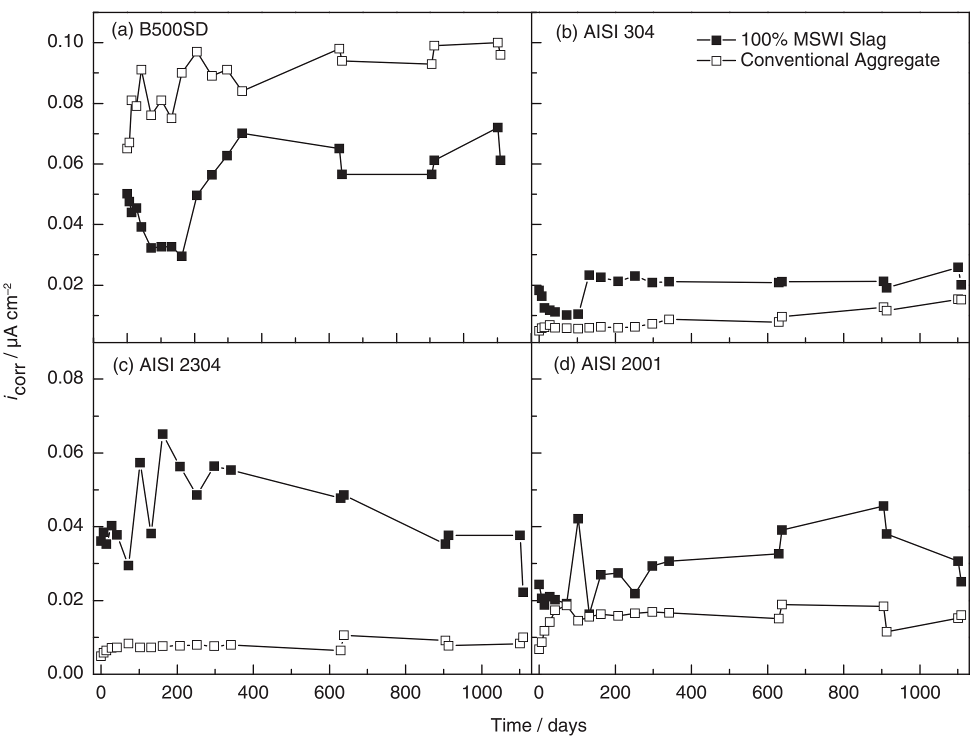

FIGURE 7. i_{corr} vs. time plot of the four tested reinforcements embedded in Portland type mortar made with 100% MSWI bottom ash and for the reference samples made with river sand: a) B-500-SD, b) AISI 304, c) AISI 2304 and d) AISI 2001.

0.1 μAcm^{-2} (Bastidas *et al.*, 2008; Medina *et al.,* 2012), i.e. their i_{corr} value is sufficiently low, therefore the corrosion rate in μm/year is less than unity, which is negligible in terms of the durability of the concrete structure.

Carbon and stainless steel reinforcements embedded in mortar made with Portland cement and fine slag as substitutes for natural sand, as well as steels embedded in the reference mortar, have remained in the passive state for the entire studied exposure time, as demonstrated by the electrochemical measurements performed, showing no significant differences between the different types of steel.

After remaining the specimens for more than three years in a closed vessel with a relative humidity of 95%, no cracks or deteriorations are visible on the surface of the specimens that could induce the existence of alkali-silica reactions or of another type between the slags and the mortar cement.

4. CONCLUSIONS

- MSWI slag mortars made from a variable mixture of natural aggregates and bottom ash have shown better mechanical strengths than those from reference mortars made only with natural aggregates except those with 100% slag, where the flexural strength has been slightly lower. On the other hand, the compressive strength of the slag mortars with MSWI always improves with respect to the reference mortar, regardless of the percentage of slag dosage.
- The average compressive strength of concrete slabs made with MSWI slag, considering all the dosages and ages studied, was 25.90 MPa, while the average resistance of the reference specimens made only with natural aggregates was 22.80 MPa, or 12% less. Therefore, in all cases it has been found that the use of MSWI slags as a substitute for natural aggregates for the manufacture of Portland cement mortar and concrete has improved the compressive strength of the test specimens, regardless the substitution ratio, even when that substitution is 100% of the natural aggregate by slags.
- On the other hand, electrochemical measurements of corrosion resistance were performed for up to three years in reinforced samples made of carbon steel and stainless steel of different grades. Cement mortar and slag as sand substitutes, compared to each other show that the reinforcements have remained in a passive state during the whole studied exposure time. The i_{corr} values were very low in all cases, between 0.0049 and 0.095 μAcm^{-2}, indicating that all the reinforcements are in the passive state, as they are below 0.1 μAcm^{-2}. Therefore, the use of MSWI slags in steel reinforced concrete do not present any corrosion concerns for its application.

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