



# Corrosion behavior of reinforcement bars embedded in mortar specimens containing ladle furnace slag in partial substitution of aggregate and cement

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## HIGHLIGHTS

- ▶ Corrosion potentials decrease with the increase of humidity and the chloride ions.
- ▶ The increase in the humidity content, produces the increase in corrosion rate.
- ▶ Mortars with 0% and 0.4% chloride ions, reach corrosion rates for passive state.
- ▶ Mortars with 0.8%, 1.2% and 2% chloride ions, reach corrosion rate for active states.
- ▶ Mortars of reference and with LFS in presence of chlorides, behave in a similar way.

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## ABSTRACT

Corrosion will inevitably affect steel reinforcement bars embedded in mortar specimens. In this study, we examine the corrosion of rebars embedded in mortar made with Ladle Furnace Slag (LFS), in partial substitution of aggregate and cement. Prismatic specimens measuring  $6 \times 8 \times 2 \text{ cm}^3$  were prepared with variable amounts of chloride ions. Subsequently, their behavior in the presence of steel corrosion was analyzed by electrochemical techniques. Our analysis of the results concludes that rebar behavior in the LFS specimens is similar to rebar behavior in the conventional mortars that were used as the reference specimens.

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## 1. Introduction

Reinforced concrete is the most widely used structural material in construction, owing to its versatility and low cost, which means that the material and its usage require exhaustive controls, in order to guarantee the working life for which the reinforced concrete structures are designed. The EHE Instruction, Eurocode 2, the ACI Code and the Model Code [1–4] all clearly state the importance of concrete durability and cite as one of the most important factors, the corrosion of embedded reinforcements.

According to NACE [5], the direct costs of corrosion each year in the United States amount to 3.1% of GNP, of which between 20% and 35% could be saved by applying satisfactory preventive measures [6]. In Spain alone, the cost of corrosion in reinforced concrete structures amounts to 1200 million Euros each year [7].

Factors that cause corrosion are carbonation of concrete, the presence of chloride or a combination of both, while the presence of oxygen and humidity are necessary for corrosion to develop [8]. The importance of the presence of chlorides in reinforced concrete to guarantee its durability means that the different standards limit the total chloride-ion content of fresh concrete, accepting in general an average value of 0.4% in relation to the weight of cement, as proposed by the RILEM Technical Committee 60-CSC [9].

The continuous increase in steel production since the 19th century has led to an imbalance between waste products generated in steel production processes and their subsequent usage. As a consequence, mass dumping at waste disposal sites has caused a significant environmental problem over the years [10,11]. The primary materials used in the iron and steel industry are iron ores (oligist and limonite) and steel from recycled elements. This process generates different waste products, ranging from steel slags and steel dusts (that are present in larger volumes) to rolled-in scale, molding sands and refractory material [12–14]. The volume of slag produced by the steel industry each year in Spain in Electric Arc

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Furnaces and Ladle Furnaces amounts to 2.55 Mt, hence the importance of recycling by-products generated in steel production for their integration as a primary material in the manufacturing process of other materials [15–17].

Although there are numerous studies on the behavior in the presence of corrosion of steel rebars embedded in concrete [18–22] and on the various applications of white slags generated in the steel industry, such as masonry mortars, the preparation of synthetic cement flooring for surfaces and even the manufacture of durable hydraulic concretes [23–28], little or no research exists on the behavior of steel rebars embedded in mortars in which part of the aggregate and cement has been replaced by Ladle Furnace Slag (LFS), which forms the purpose of this present research.

## 2. Experimental

### 2.1. Materials

This experimental work is a continuation of research into Ladle Furnace (White) Slag (LFS) [28] that has studied the substitution of aggregate and/or cement in mortars and concrete by LFS. In this case, corrosion behavior is studied in steel rebars embedded in mortar specimens containing LFS after chloride ions have been introduced into the mixture.

The following materials were used for the manufacture of the mortar specimens:

- Portland Cement CEM I/42,5 R, specified as RC-08 [29], the characteristics of which are detailed in Table 1.
- Mains water.
- Siliceous sands specified as “0/4 fine aggregate rounded grain” the characteristics of which are shown in Table 2.
- Admixtures from the range of plastifiers-air entrainers and the group of retardants.
- Calcium chloride (CaCl<sub>2</sub>).
- Ladle Furnace (White) Slag.

The LFS used in these tests is a by-product of the steel manufacturing process at a factory in Amurrio (Spain) belonging to the Tubos Reunidos industrial group. The slag was taken from open-air slag heaps and deposited for a period of 2 years at the laboratory of the Superior Polytechnic School of Burgos University for volumetric stabilization. Once stabilized and sieved through a 1.0 mm mesh to eliminate impurities, it was then tested to characterize its physical properties and chemical composition (Table 3).

### 2.2. Dosage criteria

The following conditions were considered, in order to determine the composition of the dosages in this study:

- Components by weight: cement/sand/water at 1:6:w, with the necessary amount of water needed to achieve flows of  $175 \pm 10$  mm.
- Compressive strength at 28 days should be at least 7.5 N/mm<sup>2</sup>.

The points considered for the substitution of cement and sand by LFS are based on the results achieved in earlier investigations [24] which have yielded good results for physical and mechanical properties with substitutions of 30% cement and 25% sand.

The plastifier and setting retardant were very carefully dosed so that their impact on the mechanical strength of the mortar was as low as possible, calculating 0.5% of retardant and 1.5% of plastifier in relation to weight of cement.

Taking into account the earlier considerations, a series of mortars were prepared: one used as reference specimens (MBC) and another to which LFS was added (MBE). Furthermore, different amounts of CaCl<sub>2</sub> were introduced at the time of mix-

**Table 2**

Characterisation of the sand used in the tests.

Aggregate	0.78%
Sand equivalent	78
Real density	2.619 g/cm <sup>3</sup>
Normal absorption coefficient	15%
Saturated surface dry density	2.630 g/cm <sup>3</sup>
Clay lumps	0.01%
Low specific weight particles	0%
Coefficient of coarse aggregate shape	0.26%
Soft particles	0.93%
Total sulfur content (S)	0%
Acid soluble sulfates (SO <sub>3</sub> )	0%
Chlorides	0%

**Table 3**

Physical properties and chemical composition of LFS.

Density	265 g/cm <sup>3</sup>
Specific surface	2064 cm <sup>2</sup> /g
Chlorides	Absence
Total quantity of sulfur, expressed in sulfate ions	<1%
Clay lumps	Absence
Organic material	Absence
CaO	56%
SiO <sub>2</sub>	17%
Al <sub>2</sub> O <sub>3</sub>	11%
MgO	10%
Others (Fe <sub>2</sub> O <sub>3</sub> + MnO + TiO <sub>2</sub> + SO <sub>3</sub> + Na <sub>2</sub> O + K <sub>2</sub> O)	6%

ing with the aim of obtaining percentages of 0%; 0.4%; 0.8%; 1.2% and 2% of chloride ions by weight of cement in each series of specimen (Table 4), obtaining 10 different specimen types, the dosages of which are specified in Table 5.

### 2.3. Phases of the work

Prismatic mortar specimens measuring  $6 \times 8 \times 2$  cm<sup>3</sup> were made with the materials and dosages detailed above, in which three steel rebars each with a diameter of 6 mm were embedded. The steel–concrete–atmosphere interface was protected in each rebar with a 5 cm adhesive tape to prevent possible localized attacks, due to differences in aeration, so that the length of the steel in contact with the mortar was 6 cm (Figs. 1 and 2).

The mixture was prepared with a mechanical mixer for a period of 90 s. The mold was filled in two stages. In the first stage, a first layer of mortar was poured to the height at which the steel rebars should be positioned, which was immediately compacted with a metal rammer applied 25 times at regular intervals. Subsequently, the steel rebars were placed in position, leaving them embedded along their entire length. More concrete was then poured into the mold in the second stage until totally full. It was compacted again and the specimen was leveled with a trowel.

Each mold was separately covered and introduced into a damp chamber for 24 h. Once that time had elapsed, it was removed from the mold and placed in the damp chamber again for 28 days until setting and hardening was complete. Once the specimens were cured, they were left to dry normally.

Subsequently, they were placed in the damp chamber again, to study their behavior in the presence of corrosion, in accordance with the degree of humidification using electrochemical means (corrosion potential and rate).

Loss of mass in the rebars was gravimetrically estimated to complete the study. The first step involved breakage of the specimens and the removal of the embedded rebars. The bars were cleaned and the rust was removed. They were then cut by selecting their effective length (6 cm) and subsequently weighed and measured, to compare the results obtained by gravimetry with those obtained by electrochemical techniques.

**Table 1**

Characterisation of Portland Cement CEM I/42,5 R.

Components (%)		Chemical (%)		Physical		Mechanical compressive strength (MPa)	
Clinker	95	SO <sub>3</sub>	3.2	Specific surface area (Blaine method)	3.4 cm <sup>2</sup> /g	1 day	18
Limestone	5	Cl <sup>-</sup>	0.01			0 mm	2 days
		Calcination loss	3.2	Le Chatelier expansion	170 min	7 days	40
		Insoluble waste	1.4	Initial setting time	220 min	28 days	54
				Final setting time			

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