Construction and Building Materials 54 (2014) 70–77

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The efficiency of surface-applied corrosion inhibitors as a method for the repassivation of corroded reinforcement bars embedded in ladle furnace slag mortars

María Isabel Prieto [a,*], Alfonso Cobo [a], Ángel Rodríguez [b], María de las Nieves González [a]

[a] University Politécnica of Madrid, Escuela Universitaria de Arquitectura Técnica, Avda. Juan de Herrera, 6, 28040 Madrid, Spain
[b] Escuela Politécnica Superior, University of Burgos, Calle Villadiego s/n, 09001 Burgos, Spain

HIGHLIGHTS

- The corrosion process in reference specimens and LFS specimens is similar.
- In reference specimens with 0.8% Cl^-, the inhibitor reduces the corrosion rate.
- Reference specimens with 1.2 and 2% Cl^-, inhibitor does not reduce the corrosion rate.
- In LFS specimens and Cl^- of over 0.4%, the bars remain in an active state.
- The surface inhibitors are not effective in states of advanced corrosion.

ARTICLE INFO

Article history:
Received 12 April 2013
Received in revised form 23 November 2013
Accepted 2 December 2013

Keywords:
Corrosion
Mortar
Slag
LFS
Inhibitor

ABSTRACT

Surface-applied corrosion inhibitors are investigated as an efficient method for the repassivation of corroded rebars embedded in mortar specimens, with ladle furnace slag. Prismatic specimens measuring $6 \times 8 \times 2\ cm^3$, into which 3 steel rebars had been embedded, were analyzed through electrochemical and gravimetric tests. The results show that the corrosion inhibitors are more effective on the reference specimens than on the specimens with LFS and are capable of lowering corrosion rate in specimens with chloride ion percentages of 0.8%, but are not effective on any of the specimens with chloride ion percentages of 1.2% and 2.0% by weight of cement.

1. Introduction

The durability of reinforced concrete is, among other factors, affected by the corrosion of its reinforcements. One factor that triggers rebar corrosion is the presence of chlorides in quantities above the critical threshold proposed by the Technical Committee 60 CSC, RILEM (International Union of Testing and Research Laboratories for Materials and Structures) [1] and widely applied in various standards. This threshold is defined as total chloride ion content in fresh concrete of 0.4% by weight of cement [2–5] and numerous investigations have studied the behavior of concrete in the context of exposure to the action of chlorides [6–10].

Given the importance of environmental protection and the conservation of natural resources [11,12], recycling strategies have to be established for the use of industrial waste as a raw material in other materials. At present, various studies are underway on the use of waste products in reinforced concrete, such as fly ash, additions of boron, white slag from oxygen furnaces and black slag from electric arc furnaces [13–19]. In this study, Ladle Furnace (white) Slag (LFS), a by-product of the steel manufacturing process, is used in partial substitution of aggregate and cement, with its consequent economic and environmental advantages [20–22].

The corrosion behavior of the rebars embedded in the LFS mortars, which were contaminated by chloride, has been investigated in our earlier works [23,24], which confirmed that there are no significant differences between the reference specimens and the LFS mortars.

In these studies, it was confirmed that the percentages of chloride ions above 0.4% by weight of cement produced the depassivation of the steel, regardless of the type of mortar that was used. In

* Corresponding author. Tel.: +34 913367613; fax: +34 913367637.
E-mail addresses: mariaisabel.prieto@upm.es (M.I. Prieto), alfonso.cobo@upm.es (A. Cobo), arsaizmc@ubu.es (Á. Rodríguez), mariadelasnieves.gonzalez@upm.es (M.N. González).

0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2013.12.014

addition, similar corrosion rate were observed between the reference specimens and the LFS specimens, for percentages of chloride ions of 0.8%, 1.2% and 2% by weight of cement.

Surface-applied corrosion inhibitors are at present one of various methods in use that aim to extend the useful life of reinforced concrete structures, in order to prevent or at least to delay corrosion in reinforced concrete structures. There are numerous investigations on both organic and inorganic inhibitors, due to the economic and environmental impact of corrosion on reinforced concrete, which study their influence on reinforced concrete and the conditions under which they may be effective [25–32]. There are also investigations on the efficiency of surface-applied corrosion inhibitors in mortars with fly-ash additives [33] and in the case of aminoalcohol-based inhibitors, a study has shown that the most efficient transport mechanism is diffusion in a dissolved state, so the greater absorption of the mortars with LFS slags could facilitate penetration of the inhibitor [34].

However, no investigations have reported on the efficiency of inhibitors that are applied to concrete that contains LFS, which is the aim of this present work.

The influence of the addition of LFS slags on the efficacy of surface corrosion inhibitors are studied in this work as a method for the repassivation of corroded reinforcements. In the case that the corrosion inhibitors behave in a similar way to the reference mortar specimens and the specimens with LFS slags, then that would imply a further positive point in favor of the recycling of slags employing them as a raw material in concrete, with the consequence economic and environmental advantages.

2. Experimental work

2.1. Materials

The materials used in this investigation for the preparation of the mortar specimens were Portland cement CEM I/42.5 R, as defined by RC-08 [35], urban mains water, and silica sand. The chemical compositions and physical characteristics of these materials are found in Table 1.

The LFS slags, a by-product of the Tubos Reunidos factory in Álava (Spain), were weathered for a period of two years at the Materials Laboratory of the Superior Polytechnic School of the University of Burgos. Characterization of the LFS classified it as a 0/1 sand according to European standard UNE-EN 13139 [36] and determined its physical and chemical properties that are detailed in Table 2 [22].

A surface-applied corrosion inhibitor is a combination of amino alcohols and organic and inorganic inhibitors that protect both the anodic and the cathodic part of the corrosion cell. It is designed to penetrate through the concrete pores by diffusion and to migrate to the steel rebars at a rate of 2 to 20 mm/day, depending on concrete compactness. The product, once it reaches the steel surface, forms a continuous protective layer that is resistant to water and to aggressive agents without modifying the physical properties of the concrete. The characteristics of the inhibitor are shown in Table 3.

Table 2
Physical characteristics and chemical composition of Ladle Furnace (white) Slag.

	Chemical composition		Physical characteristics	
LFS	CaO	56%	Density	2.65 g/cm^3
	SiO_2	17%	Specific surface area	2064 cm^2/g
	Al_2O_3	11%	Chlorides	None
	MgO	10%	Total sulfur, expressed as	
	(Fe_2O_3 + MnO + TiO_2+		Sulfate ions	<1%
	+SO_3 + Na_2O + K_2O)	6%	Clayey clumps	None
			Organic material	None

2.2. Dosage criteria

Two series of mortars were fabricated to evaluate the efficiency of the corrosion inhibitors: one in which the aggregate and the cement were partially substituted by ladle furnace (white) slag (MAE) and another as a reference specimen (MAC). All the dosages were based on the following specifications, which have previously been evaluated in earlier studies [22]:

- A ratio of cement/sand/water by weight of 1:6:w, with the necessary quantity of water to achieve a slump of 175 ± 10 mm.
- A compressive mechanical strength at 28 days of at least 7.5 N/mm^2.
- 30% of cement and 25% of sand were substituted for ladle furnace white slag in the LFS specimens.

Moreover, different amounts of $CaCl_2$ were introduced during mixing, in order to obtain chloride ion percentages of 0%, 0.4%, 0.8%, 1.2% and 2% by weight of cement in each series of specimens. A total of 10 different specimens were obtained, all of which in duplicate, the dosages for which are specified in Table 4.

The dosage of the surface-applied inhibitor in the amounts recommended by the manufacturer amounted to a total of 0.500 kg/m^2, after impregnation up until saturation of the substrate with 5 layers of inhibitor.

2.3. Phases of the study

First of all, $6 \times 8 \times 2$ cm^3 prismatic mortar specimens were prepared, into which 3 steel rebars with a diameter of 6 mm and a length of 15 cm, were embedded in the mortar to a depth of 6 cm. The interface was sealed with an adhesive tape, 5 cm in width, to protect the steel–concrete from any possible local attack by differential aeration (Fig. 1). The mould was filled in layers for the preparation of the specimens: the first up to the position of the rebars and the second up to the upper part of the mould. Both specimens were compacted through the application of 25 evenly spaced blows.

Table 1
Physical characteristics and chemical composition of cement, sand, and water.

	Chemical composition		Physical characteristics	
Cement	SO_3	3.20%	Blaine specific surface area	3400 cm^2/g
	Cl^-	0.01%	Le Chatelier expansion	0 mm
	Loss on ignition	3.20%	Time setting began	170 min
	Insoluble residue	1.40%	Time setting ended	220 min
Sand	S, S0$_3$, Cl^- and particles of low specific weight		Sand equivalent	78
		0.00%	Real density	2.619 g/cm^3
	Fine	0.78%	Normal absorption coefficient	15%
			Saturated	
			Surface dry (SSD) density	2.630 g/cm^3
			Clayey clumps	0.01%
			Coefficient of	
			Course aggregate type	0.26%
			Soft particles	0.93%
Water	Ammonium	0.01%	pH	8.86
	Steel	0.06%	Turbidity	0.17 NTU
	Manganese	0.00%	Conductivity	47.70 mS/m
	Aluminium	0.06%		
	Free chloride	0.39%		
	Total chloride	0.45%		
	Calcium	4.68%		