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Application of gamma-ray radiography and gravimetric measurements after accelerated corrosion tests of steel embedded in mortar

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ABSTRACT

The accelerated corrosion by the impressed current technique is widely used in studies of concrete durability since it has the advantage that tests can be carried out within reasonable periods of time. In the present work the relationship between the applied current density and the resulting damage on the reinforcing steel, by applying optical microscopy, scanning electron microscopy, gamma-ray radiography and gravimetric measurements, was studied by means of the implementation of accelerated corrosion tests on reinforced mortar. The results show that the efficiency of the applied current is between 1 and 77%, regardless of the applied current density, the water/cement ratio and the mortar cover depth of the specimens. The results show the applicability of the gamma-ray radiography technique to detect localized corrosion of steel rebars in laboratory specimens.

1. Introduction

The corrosion of steel bars is the major cause of premature deterioration of reinforced concrete structures. Initially, due to the high alkalinity of the solution contained in the pores of the concrete (pH > 13), steel bars are passivated by the presence of a protective oxide film. However, under certain circumstances, this protection is broken by destruction of the passive film due to the presence of aggressive ions (chloride, for example) or by the acidification of the medium in the vicinity of the steel rods (carbonation) [1–3]. Under natural conditions, the corrosion process of reinforcing bars is very slow and usually the first signs of deterioration appear after many years of exposure, so the tests require long exposure times. Therefore, there is a tendency to perform what is called "accelerated corrosion tests", in order to obtain results in the short term. These tests can be performed applying a constant current density or a constant potential. After (or while) these tests are performed, it is necessary to determine or measure some outputs to establish relationships between the variables involved. Among these outputs, time-to-cracking, loss weight, stress–strain behaviour, etc. are the most frequently employed to evaluate the system [4–15]. However, in spite of the fact that several researches have been made on this subject, there is not a complete agreement concerning the effect of the different parameters on the results.

The objective of this work was to determine the effect of several variables such as the applied current density; the water/cement ratio and the mortar cover depth, on the efficiency of the accelerated corrosion test, evaluated by means of gravimetric test and gamma-ray radiography. Gamma rays have been employed to study the condition of concrete structures for more than five decades [16]. The extension of this application for locating steel reinforcing bars was proposed shortly after the first reports on the use of gamma rays in this field were published [17]. However, probably owing to the requirement of licences and the current social apprehension towards radiation, the interest for this particular non-destructive test (NDT) tool for civil engineering has until now been limited and has not been developed to its full potential. Gamma-ray radiography has the advantage over other techniques (i.e. X-ray radiography) that the radiation used is emitted spontaneously so that electrical power is not needed. This technique can be applied for non-destructive inspection and diagnosis of reinforced concrete structures with cleanliness and convenience. In spite of the fact that this technique has been applied for real structures, little information is found in the literature concerning its applications for basic studies on corrosion of reinforced concrete.

2. Experimental technique

The cement used was an ordinary Portland cement (OPC) with a chemical composition shown in Table 1 (the table also includes the total chloride content of the sand used). The sand/cement proportion used in this study was 3, while for studying the effect of the water/

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Table 1
Chemical composition of the cement, and chloride content of the sand used in the present work.

	% w/w
Cement	
Insoluble residue	3.22
Loss by calcination	11.10
Sulphur trioxide (SO_3)	2.00
Magnesium oxide (MgO)	1.24
Chloride (Cl^-)	0.06
Sulphide (S^{2-})	0.05
Silicon dioxide (SiO_2)	16.30
Calcium oxide (CaO)	56.96
Aluminium oxide (Al_2O_3)	4.26
Iron (III) oxide (Fe_2O_3)	4.02
Sodium oxide (Na_2O)	0.10
Potassium Oxide (K_2O)	0.69
Total alkaline ($Na_2O + 0.658K_2O$)	0.55
Sand	
Chloride (Cl^-)	0.08

cement (w/c) ratio, two proportions were used: (a) w/c = 0.5 and (b) w/c = 0.6.

The reinforcement was a 1040 carbon steel rod, 5 mm in diameter and 50 mm long. The chemical composition of the steel is shown in Table 2. After being polished with silicon carbide abrasive papers up to grade 600, rinsed with distilled water and degreased with ethyl acetate, the roads were weighted (up to 0.0001 g). Then the steel surface was coated with an electric insulator, except for a zone with an area of 4.6 cm^2. This uncoated area was embedded in the mortar.

A typical lollypop reinforced mortar test specimen was used. After mixing (according to ASTM C 305-11 standard) [18], the fresh mortar was poured into cylindrical plastic mould of 2 different sizes: 30 mm in diameter and 50 mm high in one case (specimens type A), and 71 mm in diameter and 50 high in the other (specimens type B), where the reinforcement was previously placed along its longitudinal axis (Fig. 1). So, the cover thickness of the specimen A was 12 mm, while for specimen B was 33 mm. The specimens were then compacted during 60 s by using a vibrating table and then they were stored at room temperature and 98% relative humidity (RH) during 28 days before testing. Several prismatic specimens (4 cm × 4 cm × 16 cm) were cast and stored as previously mentioned, in order to determine the mechanical properties of the mortars. The results are shown in Table 3.

For the accelerated corrosion tests, the working electrode is the steel bar embedded in mortar, to which the current is applied. The counter-electrode is a 316 stainless steel grid that is placed all around the cylindrical concrete. The specimens were then wrapped with a damp cloth. Previous to the tests, the mortar specimens were placed in a plastic container containing tap water (up to 400 mm height) for 24 h to ensure its complete wetting.

A power supply was used for applying a constant, direct current between the reinforcement and the counter-electrode. The rebar was connected to the positive pole of the power supply, and thus became anodic. The counter-electrode was connected to the negative pole.

Table 2
Chemical composition of the steel bars used in the present work.

Element	% w/w
C	0.36
Si	0.21
Mn	0.73
P	0.007
S	0.013
Cr	0.05
Ni	0.03
Mo	<0.01

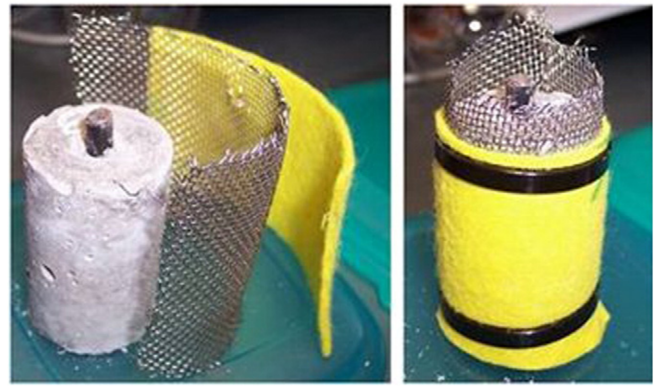

Fig. 1. Mortar specimen before (left) and after (right) wrapping a steel grid and a damp cloth around them.

Two or three specimens, kept in different containers, were connected in series for each set of experiences. The reinforcing steel was polarized by a constant current. Several levels of current density (i_{app}), between 50 μA/cm^2 and 750 μA/cm^2 were applied to accelerate the corrosion processes.

After finishing the tests (in most cases after 15 days), gamma-ray radiography was performed on the specimens. Gamma rays from a radioactive source (in the present work, a ^{137}Cs source that emits 0.67 MeV gamma rays was used) illuminate the specimens to be examined, and the transmitted beam is collected and turned into an image on a photographic film. The image obtained is in the form of a two-dimensional projection which provides information about the physical characteristics of the specimens. After that, the image was digitalized and an image analysis was performed using the Software Image J™. After calibrating the technique, a detection limit of 90 μm was determined.

After the gamma-ray radiography, the steel bars were removed from the mortar specimen and cleaned of rust using cleaning chemical procedures according to a standard [19] in order to obtain the weight loss produced by the accelerated corrosion test.

The theoretical mass of rust produced per unit surface area of the bar due to the applied current over a given time can be determined using the following expression based on Faraday's law:

$$M_{th} = \frac{i_{app} \cdot A \cdot t}{n \cdot F} \quad (1)$$

where M_{th} is the theoretical mass of rust per unit surface area of the bar (g/cm^2); i_{app} is the applied current density (A/cm^2), A is the atomic weight of iron (55 g/mol), t the duration of the induced corrosion (s); n is the valence of iron (2); and F is the Faraday's constant (96,487 Amp/mol).

The weight loss of steel per unit surface area and time (corrosion rate = CR) is determined by gravimetric tests in accordance with ASTM G1-90 standard performed on the steel bars extracted from the mortar by breaking the specimens after the accelerated corrosion test is completed:

$$CR = \frac{\left(W_f - W_i\right)}{\pi \cdot D \cdot L \cdot t} \quad (2)$$

Table 3
Mechanical properties of the mortar used in the present work, after 28 days curing at 98% relative humidity.

w/c	Flexural modulus (MPa)	Compressive strength (MPa)
0.5	4.0 ± 0.3	32 ± 5
0.6	3.5 ± 0.8	24 ± 2