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Study of mechanical properties of corroded steels embedded concrete with the modified surface length

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HIGHLIGHTS

- Different bar lengths are corroded and tested to tensile strength.
- The length of a corroded rod is a determining factor for all the parameters studied.
- The slope of tendency lines increases as the corroded bar length increases.
- The use of ductility criteria based on the concept of equivalent steel is appropriate.
- The values of ductility are greater with smaller corroded rod lengths.

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ABSTRACT

This paper studies the effect of corrosion on the mechanical performance of steel embedded in reinforced concrete when different bar lengths are corroded. On seventy-two corrugated steel bars B500SD (with high ductility properties) that had been previously subjected to an accelerated corrosion process, corrosion was located in three different bar lengths that were tested to tensile strength. The influence of corrosion on the mechanical properties of the steel was assessed considering them individually and in relation to the concept of equivalent steel. The results obtained show that (i) significant variations are produced in the stress-strain curve obtained in tensile strength tests, even with corrosion degrees below 1%; (ii) the use of the equivalent steel concept is advantageous; (iii) the length of the corroded rod influences the value of the properties analyzed and their evolution.

1. Introduction

The degradation processes of reinforced concrete structures (RCS) throughout time are unavoidable [1], especially in harsh environments where the material can react with the environment, causing corrosive phenomena that may affect the service state and durability of the concrete structure [2–5], resulting in major economic losses [6] and giving rise to the need for an in-depth study of this phenomenon.

In normal situations, concrete provides protection to steel – both physical and chemical protection – but most alkaline compounds providing chemical protection are unstable, and therefore, their durability might not be reliable due to a large number of environmental circumstances. The presence of depassivating ions (chlorides) can alter the protective steel passive barrier, while if alkalinity decreases due to the effect of CO_2, that protection can even disappear [7,8].

In RC structures, corrosion initiates at the interface of the rebar and concrete. Once corrosion initiates, the diameter of the rebar reduces and there is a volumetric expansion around the rebar due to the corrosion products. These expansive corrosion products cause three kinds of material deterioration: losses in the effective cross-sectional area of concrete due to cracking in the cover concrete, losses in the mechanical performance of reinforcing bars due to the losses in their cross-sectional area, and losses in the bond performance of concrete with reinforcements [9–13]. Cabrera [14] evaluated the relationship between the corrosion rate and loss of structural serviceability from measurements of bond strength. He found that the bond strength measured in pullout specimens is significantly affected by the level of corrosion.

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Table 1
Requirements of the concept of equivalent steel regarding each regulation.

Parameter	Regulation		
	MC2010	EC-2	EHE-08
ρ [Cosenza]	0.69	0.82	0.86
A^* (N/mm^2)[Creazza]	2.87	3.6	3.87
Id [Ortega]	50.45	63.35	67.65

Table 2
Minimum mechanical characteristics required for B500SD steel.

f_y	f_s	f_s/f_y	$\varepsilon_{máx}$	$\varepsilon_{5Ø}$
500 MPa	575 MPa	1,.15 ⩽ fs/fy ⩽ 1.35	⩾8%	⩾16%

Where f_y is the yield strength, f_s is the maximum strength, ε_{max} is the deformation corresponding to the maximum strength and $\varepsilon_{5Ø}$ is the ultimate strain measured on the basis of 5 diameters.

The direct consequence on steel is mainly section reduction and loss of ductility, which causes variations in the stress-strain behaviour [15–18]. Hence, the load-bearing capacity of the RCS decreases to values far below those initially expected in the project [19,20,10]. Recent estimates [21] have calculated the cost of repairs and replacements due to damage caused by corrosion in RCS reinforcements as 1200 million Euros per year in Spain.

Numerous works study the mechanisms controlling corrosion of the reinforcement. However, the influence of corrosion on the mechanical properties of steel has been a scarcely studied topic [22–25]. Maslehuddin et al. [26] evaluated the effect of atmospheric corrosion on the mechanical properties of steel bars, concluding that no significant effects could be observed in them.

Recent studies [27] have stated important changes in the stress-strain curve diagram of corroded steel, proving a systematic deformation decrease under maximum stress, as the degree of corrosion increases up to values which, in many cases, fall below the minimum required by the standards and regulations. In these cases [28–32], the use of the concept of equivalent steel as a ductility criterion, based on the joint consideration of deformation under maximum stress and the quotient between maximum stress and elastic limit, can be very advantageous. Table 1 shows the minimum values of the equivalent steel concept defined by Cosenza (ρ), Creazza (A^*) and Ortega (Id) required by the Mode Code 2010 [33], the EUROCODE 2 [34] standard and the EHE-08 regulations [35].

In all the literature found on the matter, and included in the reference list, the corrosion effect on steel's mechanical properties is analyzed by testing the tensile strength of a rebar corroded along its entire length. However, in real situations, corrosion often occurs just in part of the steel bar.

The present article simulates the previous situation, analyzing the mechanical behaviour of steel under the influence of the degree of corrosion when it affects different corroded bar lengths. An accelerated corrosion was activated on 72 high ductility corrugated steel bars, B500SD, 12 mm in diameter embedded in concrete, to study the effect that different corrosion levels generate on various bar lengths, by performing tensile tests and at the same time, analyzing the effects it has on the mechanical properties of the steel bars.

2. Experimental process

2.1. Materials

To study the evolution of steel's mechanical properties regarding the level of corrosion and the affected bar length, six concrete slabs were prepared with 72 embedded steel bars. Two slabs for each corroded length were fabricated using moulds of three different dimensions (Fig. 1); short length (s): 75 × 100 × 400 mm; medium length (m): 150 × 100 × 400 mm, and complete length (c): 300 × 100 × 400 mm.

The studied steel, defined in the UNE 36065 standard [36], has special ductility characteristics and can therefore be used in seismic areas. In addition, it is the most commonly used in construction in Spain. Table 2 shows the minimum mechanical characteristics, which must be met in accordance with the EHE-08, and Table 3 shows the ductility requirements of the standards studied in this research for the B500SD steel used.

During the casting of concrete slabs, calcium chloride was added to destroy the steel's passive state, with a 2% concentration of ion chloride per cement weight. After concreting and removing the formwork, the six slabs were cured for 28 days in a humid chamber (Fig. 1) at 25 °C with a relative humidity of 99%.

To avoid preferential attacks, insulating tape was placed at the concrete-air interface in order to avoid corrosion initiators and propagating points, so the tape would surround the reinforcement with an approximate length of 3 cm inside and outside the concrete.

2.2. Accelerated corrosion techniques

The steel bars were externally short-circuited and corrosion was forced by applying a constant anodic current between the reinforcement and a lead sheet placed on the surface of the slabs acting as a cathode. The uniform distribution of the electric current was achieved by the introduction of a water-soaked cloth between the slab surface and the sheet. To ensure the required moisture supply, the cloth was dampened as it dried (Fig. 2).

During the process, current passing through each of the rebars was periodically recorded using a digital multimeter, performing periodical readings and correcting any electricity drop by the electrical power supply potential variation. The mean density of the current in each bar was approximately 10 μA/cm^2. After 180 days, when cracks appeared, the bars were disconnected. Once the accelerated corrosion process finished, the rebars were extracted from the concrete and the oxide coating was then removed using a brush, in accordance with ASTM G190-06 [37], and chemical pickling, following the UNE-EN ISO 8407 standard [38].

The degree of corrosion (Q_{corr}) produced in each bar was determined by the gravimetric loss, weighing the bars once the corrosion products had been removed and considering that the weight loss had occurred uniformly along the rod length in contact with the concrete, through the equation:

$$Q_{corr} = [(P_i - P_c)/P_i] * 100$$

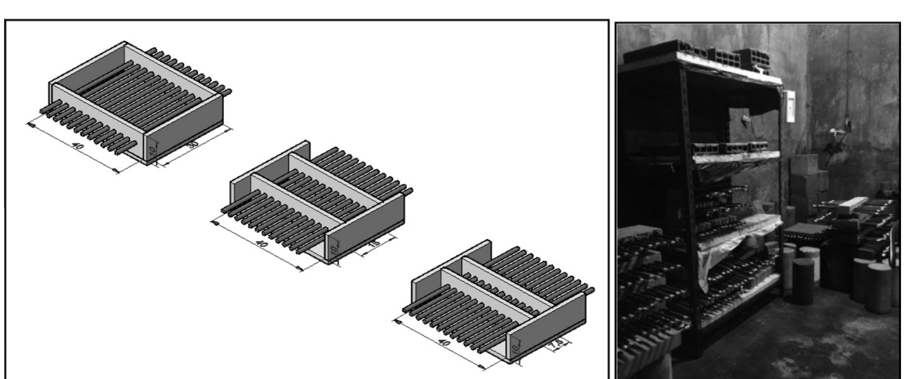

Fig. 1. Molds used to manufacture the slabs. Picture on the right shows the slabs being cured in the moisture chamber.