Threshold concentration of chlorides in concrete for stainless steel reinforcement: Classic austenitic and new duplex stainless steel

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HIGHLIGHTS

- A relationship between threshold concentration of chlorides and PRE values is shown.
- The corrosion rate depends on chloride concentration for specific cement.
- A new methodology has been developed to avoid the steel rebars polarization.
- Calculations of service life have been made for a specific exposure conditions.

ARTICLE INFO

ABSTRACT

Stainless steel rebars is used to lengthen the service life of structures in aggressive media. Corrosion resistance was studied in five grades of mortar-embedded stainless steel: EN 1.4307, EN 1.4404, EN 1.4482, EN 1.4362 and EN 1.4462. A modified accelerated chloride attack was applied to prevent steel rebar polarisation and artificial re-passivation. The critical chloride concentration was determined. Based on corrosion rate, service life was calculated for a given exposure at two probability levels.

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1. Introduction

To concern around chlorides-induced reinforcement corrosion has prompted host of studies on the use of carbon steels in concrete. The amount of chloride required for depassivation can be expressed in a number of ways: free chlorides concentration $[Cl^-]$, the chloride/hydroxide concentration ratio $[Cl^-]/[OH^-]$ or total chlorides as a percentage by weight ($\%_{bwoc}$) [1]. A number of methodologies are likewise in place to measure chloride content. Primarily electrochemical, they include anodic potentiostatic polarization, measurement of the natural corrosion rate, I_{corr}, gravimetric measurements, electrochemical impedance and others [1–16].

Several studies have been conducted to calculate the range of the threshold chlorides concentrations required to induce carbon steel depassivation [1,17]. The exact value found normally depends on electrochemical technique used, whether the electrolyte is in solution or in mortar or concrete and whether the tests were performed in a laboratory or an outdoor saline environment [1–5,7–16,18].

Spaińs structural concrete code EHE-08 establishes a $0.6\%_{bwoc}$ total chlorides threshold for passive carbon steel reinforcement, ranging from 0.632 ± 0.112 wt%$_{cem}$ to 0.771 ± 0.236 wt%$_{cem}$ at 95% probability [19].

The introduction of stainless steel to reinforce concrete has spurred studies on its depassivation limits. The initial findings show such limits to be from four to six times higher than in carbon steel at, pH values of 9 to 13 and at a standard temperature of 20 °C. At 40 °C, however, the critical depassivation value declines by nearly half, except in alkaline media [20]. Other authors have reported that overall, chloride limits are 10-fold higher in EN 1.4307 and EN 1.4404 austenitic stainless than in carbon steel [21].

A common threshold for all the grades of stainless steels used in construction is difficult to establish, for their resistance to chloride

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varies depending on microstructure, type of alloy and composition [20,22–25].

Tuutti's model for reinforcement service life envisages two stages: initiation time (t_i), when chlorides are assumed to reach the steel and induce depassivation, i.e., to break down the passive layer; and the propagation time (t_p) after which corrosion occurs, prompting structural deterioration [26]. The initiation time in depassivation of the stainless steels is a question of interest, given the significant differences among the various types of material and between each and carbon steel as a result of the re-passivation capacity of stainless steels.

This study explored the chloride threshold concentration in concrete for five types of stainless steel rebar. Two were austenitic steels (European/US nomenclature: EN 1.4307/AISI-304L and EN 1.4404/AISI-316L) and the other three duplex steels (EN 1.4482/2001, EN 1.4362/2304 and EN 1.4462/2205). The test method proposed estimates steel service life based on variations in material loss with variations in chloride concentration in the mortar in contact with the rebar.

2. Methodology

Spanish and European standard UNE 83992-2 describes an accelerated testing method to determine concrete resistance to chloride penetration.

The test consists in applying an electrical field to a bar embedded in a cubic mortar specimen. The bar is positioned perpendicularly to the electric current flowing between a steel mesh cathode and a copper anode. The latter is placed in a cylindrical cylinder containing a 0.6 M NaCl, 0.4 M CuCl$_2$ solution and attached to
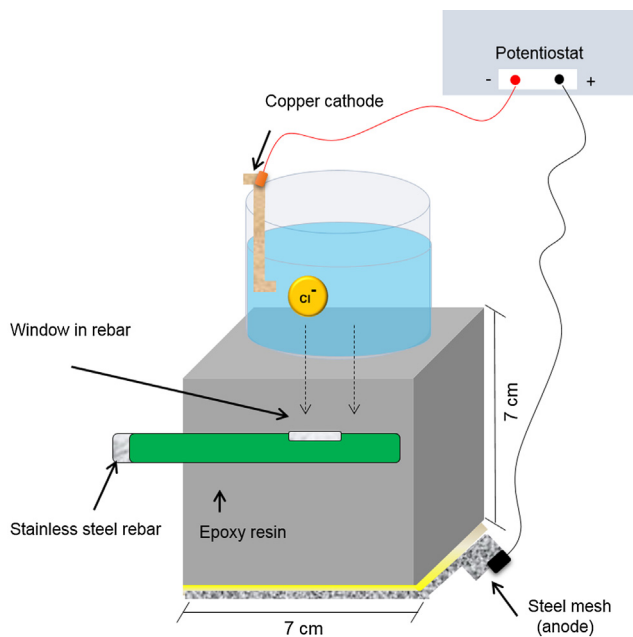
one of the sides of a mortar specimen. The other electrode is attached to the opposite side of the specimen. Chlorides penetration is accelerated by the electric field, with the ions migrating from the container to the steel mesh electrode on the opposite side across the stainless steel bar, triggering the corrosion [27]. Steel depassivation by the ions coming into contact with the rebar is detected by a change in the corrosion potential or a rise in the bar corrosion rate (I_{corr}), calculate from linear polar resistance (LPR) measurements [28,29]. The critical chloride concentration is found by stopping the test, splitting the specimen open and removing a small sample of mortar near the corroded rebar.

The $7 \times 7 \times 7$ cm^3 specimens used in this study were moulded with CEM I cement prepared with a water/cement ratio of 0.5. Three series of tests were performed with two specimens of each grade of steel, for a total of six specimens per grade. The test set-up is depicted in Fig. 1.

The chemical composition of the five grades of corrugated, cold-rolled, 12 mm diameter bars is given in Table 1.

2.1. Test modification

Whilst the polarization induced in the rebar had no impact on the behaviour of the passive film in the carbon steel [30], the stainless steel failed to depassivate despite the high corrosion rates detected, or more precisely, depassivation was consistently observed to be followed by re-passivation. That was attributed to the polarisation of the passive layer induced by the external field, which impeded accurate detection of the critical chloride content. The modification introduced consisted in coating all but a small area of the rebar prior to embedment in the mortar specimen. The entire bar with the exception of a 2×1 cm^2 window, positioned on the upper side of the bar in line with the chloride ion flow, was coated with SIKAGUARD 62, an epoxy resin. Under these conditions, corrosion occurred naturally and the rebar did not re-passivate after initial depassivation.

The finite element calculation of how the current flow is affected by epoxy-coating the bar is illustrated in Fig. 2. Simulation was performed assuming conductivity to be $4 * 10^6$ S/m in the steel and $2 * 10^{-2}$ S/m in the concrete. The voltage between the electrodes dropped by 12 V. The epoxy resin was regarded as insulation for the intents and purposes of calculation. As the diagram on the left in Fig. 2 shows, the currents lines tended to penetrate the unprotected bar due to its higher conductivity. The diagram on the right, in contrast, shows that the coated bar was barely affected by the current lines, which flowed around the outside of the steel.

2.2. Procedure

The electrical current was disconnected daily and an hour later the corrosion rate (I_{corr}) and corrosion potential (E_{corr}) were measured, the latter using the silver reference electrode as the standard. Corrosion rate was measure in terms of linear polarisation resistance, a non-destructive method. The readings were entered into the Stern and Geary equation, in which the value for constant B [31–33] was assumed to be 26 mV, as per Spanish and European

Fig. 1. Accelerated test set-up.

Table 1
Rebar chemical composition (alloy concentration) and pitting resistance equivalent numbers (PREn).

EN/AISI	C	Si	Mn	Cr	Ni	Mo	P	S	N	PREn
1.4307/304-L	0.028	0.308	1.376	18.099	7.978	0.243	0.033	0.034	0.07	19.6
1.4404/316-L	0.020	0.291	1.363	16.797	10.481	2.025	0.035	0.03	0.045	23.5
1.4482/2001	0.018	0.687	4.175	20.124	1.815	0.166	0.029	0.0009	0.099	19.5
1.4362/2304	0.016	0.647	1.609	22.730	4.226	0.107	0.034	0.0008	0.143	25.8
1.4462/2205	0.032	0.395	1.616	22.408	4.695	3.341	0.03	0.002	0.173	37.0