

## **Performance parameters for the durability design of reinforced concrete structures with stainless steel reinforcement**

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# **Performance parameters for the durability design of reinforced concrete structures with stainless steel reinforcement**

Stainless steel reinforcing bars can be a suitable choice to guarantee the target service life of reinforced concrete structures exposed to aggressive chloride-bearing environments. Usually the choice of the stainless steel grade is based on experts opinion or practical codes, whilst the adoption of performance-based approaches would allow to quantify the service life. To apply these models, when stainless steel reinforcement is used, the evaluation of the parameter which describes its performance when used in a chloride-bearing environment, i.e. the critical chloride threshold for the initiation of corrosion, is an indispensable requirement. This parameter cannot be easily determined since it is influenced by many factors and a standardised methodology for its evaluation has not been proposed yet. This paper describes the results obtained in an experimental research aimed at developing a test methodology which allows to evaluate the cumulative density function of the critical chloride threshold for the corrosion initiation. A test procedure based on mixed-in chloride and potentiostatic polarisation was proposed and applied to a duplex stainless steel reinforcement (1.4362). Corrective factors, which have to be applied in order to use these data for the design of structures in different exposure conditions, are discussed.

Keywords: chlorides; service life; tests; reinforcement; concrete&cement

## **Introduction**

In the design of reinforced concrete structures exposed to environments contaminated by chloride, the use of stainless steel reinforcement instead of traditional carbon steel bars can be a means for achieving the durability targets, due to their higher resistance to pitting corrosion initiation. Usually the choice of the stainless steel grade for a specific application is made through empirical criteria or practical codes developed by producers and public or private institutions (e.g. the Technical Center on Consulting for Cement and Concrete, Switzerland (Hunkeler, 2000)). Few European Standards and Design Codes provide information, which are often limited, for the durability design

with stainless steel reinforcement. For instance, the BS 6744 Standard (2001) provides general guidance related with the suitability of different grades (e.g. the stainless steel of grades 1.4301, 1.4436, 1.4429, 1.4462, 1.4529 and 1.4501) for a range of service conditions. In particular, the suitability of a specific grade is simply indicated by ranking (from 1 to 5) for the different combinations of exposure conditions and expected service life. According to the Eurocode 2 (EN 1992-1-1, 2004) the use of stainless steel bars would allow to reduce the minimum value of the concrete cover to guarantee the required durability; this may lead also to additional economic advantages. The reduction of the concrete cover when stainless steel bars are used is generally recommended but many National standards do not provide until now respective values.

The Recommendations for Design and Construction of Concrete Structures Using Stainless Steel Bars, developed in 2009 by the Japan Society of Civil Engineers (JSCE) consider the use of three different types of stainless steel rebars, 1.4301, 1.4436 and 1.4000, and suggest a corrosion verification of stainless steel bars, in order that concrete structures, in which stainless steel bars are used, maintain the required performances through their design service life. The verification for the resistance to corrosion of stainless steel bars due to the penetration of chloride ions may be conducted by confirming that the ratio of the design chloride ion concentration at the end of the service life at the bar surface to the critical chloride threshold for corrosion initiation of the stainless steel bars, multiplied by a safety factor, is not more than 1. Values of the critical chloride threshold concentrations for the three types of stainless steel bars are provided in the Recommendations. However, these available standards do not take into consideration new types of stainless steel recently proposed on the market (such as low nickel grades).

Performance-based approaches could be valid tools for the design with stainless

steel, since these would allow quantifying the service life of a structure and hence assessing the benefits in relation to the whole life cycle costs (Lollini, Carsana, Gastaldi, Redaelli, & Bertolini, 2015). Indeed, a performance-based approach could be used to compare different scenarios that comprehensively take into account the environmental exposure conditions, the concrete properties, the concrete cover and the specific type of reinforcement (Bertolini, Lollini, & Redaelli, 2011; Bertolini, Lollini, & Redaelli, 2012). The first three items are usually considered in some of the nowadays available performance-based approaches, especially the Model Code for Service life design proposed by the *fib* (2006). For instance, to evaluate the concrete properties in relation to the resistance to the penetration of chlorides, an apparent diffusion coefficient,  $D_{app}$ , is defined. To determine this coefficient, the *fib* Model Code proposes the rapid chloride migration test, which allows to evaluate the migration coefficient,  $D_{RCM}$  (NT Build 492, 1999). This coefficient, however, is not a real diffusion coefficient since it is evaluated through an accelerated test, where the chloride penetration is forced by an electric current, and, hence, cannot be directly used to estimate the chloride penetration in a real structure. This aspect is common to all the accelerated tests, that allow an estimation, in a short time, of the behaviour of a material in a certain environment of exposure and a comparison of different materials; nevertheless they need to be modified through a series of coefficients that take into account, for instance, the real exposure conditions. In the *fib* Model Code,  $D_{RCM}$  is modified through several functions: the environmental factor,  $k_e$ , which takes into account that the chlorides diffusion varies as a function of temperature, the transfer parameter,  $k_t$ , and the ageing function,  $A(t)$ , which is introduced to consider that the diffusion coefficient decreases increasing the exposure time.

Conversely, designers fail in finding any indication for the critical chloride threshold for the stainless steel bars and their estimation is demanded to the experience of the designer (Lollini, Carsana, Gastaldi, Redaelli, & Bertolini, 2015). Furthermore, the determination of this parameter is not an easy task, since it is influenced by many parameters (exposure environment, steel composition, surface conditions, etc.) and can be evaluated only through a statistical approach which takes into account its variability, since the initiation of corrosion induced by chlorides represents a stochastic phenomenon (Manera, Vennesland, & Bertolini, 2008; Lambert, Page, & Vassie, 1991; Thomas, 1996; Hartt & Nam, 2008, Randström, Almén, Pettersson, & Adair, 2010; Gastaldi & Bertolini, 2014). In the literature, several types of test have been proposed as, for instance, tests in solution, test in concrete or mortar with chlorides penetrating from an external source or mixed-in chloride (Page, 2009; Bertolini, Gastaldi, Pastore, & Pedefferri, 2000; Hartt, Powers, & Kessler, 2009; Bertolini & Gastaldi, 2011; Gastaldi, Lollini, & Bertolini, 2014). Unfortunately the comparison among results obtained in different studies and between different steel grades is rather difficult and does not allow a statistical estimation to account the variability of this parameter. Hence, there is the need to develop an experimental test that allow the evaluation of this parameter to be used as a compliance test within the performance-based approaches.

This paper summarizes the requirements of such an experimental test in order to estimate the critical chloride threshold even for the high values representative for the stainless steel bars. A test procedure is proposed based on these requirements and results obtained on rebars of austenitic-ferritic stainless steel type 1.4362 are provided. Limits of this test are also discussed in relation to the need of corrective coefficients, which have to be applied for the design of structures exposed to different environmental exposure conditions.

## Test requirements

The test procedure for the determination of the critical chloride threshold for the initiation of corrosion ( $Cl_{th}$ ), to be used as input parameter in the performance-based approaches, should fulfil some requirements. On the basis of the factors which mainly influence this parameter, the test should allow to:

- evaluate the dependence of the  $Cl_{th}$  from the exposure environment:  $Cl_{th}$  decreases when temperature increases, whilst it increases when the corrosion potential of passive steel, which depends on the humidity, decreases (Pedferri's diagram) (Pedferri, 1995);
- consider the role of the steel-concrete interface, which includes the surface finishing of the steel, as well as the composition and the compactness of the concrete. Several studies showed that the corrosion resistance is strongly influenced by the characteristics of the steel-concrete interface (Page, 2009); in particular, for stainless steel bars, the metallurgic conditions and the superficial finishing (which are strongly influenced by the production processes) can have a significant effect on the critical chloride threshold;
- take into account the variability of the results: the  $Cl_{th}$  is a parameter strongly affected by a statistical variability and in the performance-based design approach the input parameters are treated as random variables with a probability density function PDF and a cumulative distribution function CDF;
- guarantee reasonable time to obtain the results, even if a high amount of chlorides is necessary for the corrosion initiation.

Furthermore the test should allow the study of the effects of different factors such as: concrete composition, compaction, superficial finishing, etc.

## **Proposed test procedure**

To satisfy the requirements described in the previous section, an experimental test was studied, developed and applied to different types of stainless steel. To consider the steel-concrete interface, tests on concrete specimens were considered (tests in solution were excluded since they can provide very different results in comparison to tests in concrete; Bertolini & Gastaldi, 2014). Tests with chlorides mixed-in, in the form of  $\text{CaCl}_2$ , were accounted in order to avoid long time for the chloride penetration (the direct contact of rebars with chloride contaminated concrete could affect the initial passivation and might affect the test results). Tests with penetrating chlorides have a practical limitation due to long duration needed to reach the  $Cl_{th}$ , particularly considering the use of stainless steel bars and the time required for the penetration of chlorides through the cover concrete (the test duration increases increasing the concrete cover, decreasing the chloride diffusion coefficient and increasing the corrosion resistance of the bars). When chlorides are mixed-in, the test duration is independent on the water/cement ratio, the concrete cover and, then, this test procedure can be applied for the study of every type of concrete and steel grade even those characterized by high values of the critical chloride threshold. To consider the variability of the critical chloride threshold, the test was carried out on 10 replicate specimens.

After casting, specimens were cured in a climatic chamber at  $23^\circ\text{C}$ ; 24 hours after casting specimens were demolded and immersed individually in a container filled with  $\text{Ca}(\text{OH})_2$  saturated solution for 6 days before the beginning of the test and corrosion potential was measured in time. Afterwards a constant potential of +200 mV vs SCE was imposed for 24 hours (potentiostatic test) and the polarization current was monitored. Tests were carried out at  $23^\circ\text{C}$ . At the end of the polarisation test, the potential was monitored for further 4 hours (depolarisation phase) and then the steel

bars were extracted and their surface was visually observed, and if necessary with a stereomicroscope, in order to detect corrosion attacks.

The detection of the corrosion initiation on the single specimen was determined according to the following set of criteria, defined on the basis of results obtained by means of polarization potentiostatic tests carried out by different Authors and discussed in Hansson, 2016:

- the polarisation current density at the end of the 24-hour polarization test reached values higher than 80-100 mA/m<sup>2</sup>;
- the steel potential dropped below -200 mV vs SCE after 4 hours of depolarisation;
- corrosion attacks visible at the naked eye, i.e. higher about 500 µm, could be observed on the bars extracted from the concrete specimens.

In most of the tests, the three criteria were fulfilled by each single bar that underwent corrosion initiation. In some cases, however, the trend of the current density during the test was not clear (for instance, an increase was observed but at the end of the test the current value was lower than 80 mA/m<sup>2</sup>). In such cases only the visual observation of corrosion attacks visible at the naked eye on the surface of the bars at the end of the tests can give a definitive response about the onset of corrosion. For each set of 10 replicate specimens, the number of specimens on which corrosion initiated (i.e. the number of specimens out of ten that failed during the tests) was defined.

### **Application of the test to the stainless steel type 1.4362**

In the last years, the interest in the use of stainless steel with duplex austenitic-ferritic microstructure and low nickel content is growing, due to the lower cost



compared with traditional austenitic stainless steel reinforcement (Bertolini & Gastaldi, 2011) and the mechanical properties (achieved directly after hot forming). For this reason the testing procedure was applied to determine the critical chloride threshold for the initiation of corrosion on reinforcing bars, with a diameter of 20 mm, of stainless steel of type 1.4362 (UNS S32304) which is used in several structures worldwide (Gupta, 2016).

Table 1 shows the mechanical properties and the chemical composition provided by the manufacturer (Valbruna SpA). The bars were subjected to commercial sandblasting and pickling, in order to remove the oxide scale produced during hot forming. Before testing they were degreased with acetone and were visually observed also with the aid of a stereomicroscope, recording the presence of any imperfection not removed by cleaning with acetone (Table 2 and Figure 1). Concrete with water/cement ratio of 0.5, 400 kg/m<sup>3</sup> of ordinary portland cement (CEM I 52.5R, according to the standard EN 197-1), 200 l/m<sup>3</sup> of deionised water and 1704 kg/m<sup>3</sup> of crushed limestone aggregate (with maximum size of 9 mm) was utilised. Chlorides were added as CaCl<sub>2</sub> to the mixing water, to reach chloride contents of 2.7%, 3%, 4% and 5% by mass of cement. An acrylic-based superplasticizer, in an amount equal to 1.5% by mass of cement, was added to the mixing water, to reach a suitable workability, and specimens were well compacted.

Specimens were cylinders with diameter of 75 mm and height of 100 mm, with a stainless steel reinforcing bar along the axis (Figure 2). The two ends of each bar, before casting, were masked with a styrene-butadiene-modified cement mortar and coated with a heat shrinkable sleeve; a surface of the bar 60 mm long was exposed to the concrete. One end of the bar was drilled to allow the electrical connection.

Some tests, in concrete with the chloride content of 5% by mass of cement, were repeated also at a temperature of 10 and 40°C (to simulate cold and warm weather), and at potential of +0 mV vs SCE and +100 mV SCE to evaluate respectively the effect of temperature and of potential (tests at +0 mV and +100 mV SCE were carried out on the same set of specimens).

Figure 3 shows, as an example, the results of anodic polarisation tests carried out on specimens with 5% of chlorides by cement mass reinforced with 1.4362 stainless steel bars. Free corrosion potential values between -100 and -200 mV vs SCE were measured on the 10 bars before the polarisation after casting (Figure 3a), representative of passive conditions. Figure 3b shows the polarisation current density of the bars measured during the 24 hours of anodic polarisation at +200 mV vs SCE (Figure 3a). Initially, values around 500 mA/m<sup>2</sup> were measured which decreased to 35-70 mA/m<sup>2</sup> after 1 hour. On four (C5-2, C5-4, C5-6 and C5-7) of the ten replicate specimens the current density continued to decrease in time, approaching values of 5-7 mA/m<sup>2</sup> after 24 hours. After switching off the polarisation (depolarisation phase), the potential of these steel bars showed a slow decrease, reaching, after 4 hours, values around 0 mV vs SCE (Figure 3a). This behaviour indicated that corrosion did not take place, and therefore, passive conditions were maintained. This was confirmed by the visual observation of the reinforcement surface at the end of the test, after the demolition of the specimens, since the presence of corrosion attacks was not observed (Table 3; Figure 4a shows, as an example, the bar removed from the specimen C5-4 at the end of test).

Conversely, in other 5 specimens the current density showed a sharp increase during the polarisation test and reached values higher than 100 mA/m<sup>2</sup> at the end of the 24-hour polarisation (Figure 3b). This indicated the initiation of corrosion on these bars, confirmed during the subsequent depolarisation (Figure 3a), when the corrosion

potential reached values lower than -300 mV vs SCE. The visual observation of the surface of these bars showed several severe corrosion attacks (Figure 4b shows, as an example, the bar removed from specimen C5-5 at the end of the test). As a matter of fact these bars showed a number of pits higher than 10, with dimension between 1 and 4 mm (Table 3). In the bar of specimen C5-8 the current density reached a value of about 90 mA/m<sup>2</sup> at the end of 24 hours (Figure 3a) and a potential of -160 mV vs SCE during the subsequent depolarisation (Figure 3b); two corrosion attacks (about 1.5 mm wide) were observed on the bar surface at the end of the test (Table 3). Therefore, in concrete with 5% of chloride in mass of cement, corrosion occurred on six out of ten specimens, i.e. the 60% of reinforcement showed initiation of corrosion.

Figure 5 summarises the results of the tests carried out at 23°C on specimens with different chloride contents. In concrete specimens with 2.7% of chlorides by cement mass corrosion did not take place on none of the specimens. Even the visual observation of the surface of the bars, carried out at the end of the test, after their removal, did not reveal the presence of corrosion attacks, in spite of the imperfections observed before the specimens casting (Tables 2 and 3). In concrete with 3% Cl<sup>-</sup>, one of the ten bars (i.e. C3-10) showed corrosion attacks; visual observation at the end of the test showed that the initiation occurred under a scale present on the bar surface. In the other bars, although they presented superficial imperfections, no corrosion attacks were observed (Table 3). In the specimens with 4% Cl<sup>-</sup> no corrosion initiation was noted (values lower than 10 mA/m<sup>2</sup> were measured at the end of the 24-hour polarisation). After the demolition of the specimens, no pits were visually observed (Table 3); with careful observation with a stereomicroscope some small rust spot with maximum size of 100-200 µm, were noted on the surface of the reinforcement in six specimens. Their presence was not detected neither by the current during polarisation tests, nor during the

24-hour polarisation; thus no stable propagation of the corrosion occurred during the test. With 5% of chloride by cement mass, as previously described, corrosion took place on six bars.

Tests carried out on concrete with 5%  $\text{Cl}^-$  in mass of cement at different potential and temperature showed the effects of these parameters on the corrosion initiation on reinforced concrete specimens. Figure 6 shows the results of the tests carried out at different potentials, +200 / +100 / 0 mV vs SCE, imposed during the 24-hour potentiostatic test, at 23°C. It can be observed that, as expected, when the imposed potential decreased, the number of bars in which corrosion occurred decreased; with an imposed potential of +200 mV vs SCE, corrosion initiated on 6 bars out of 10; imposing a potential of +100 mV vs SCE corrosion occurred during the test only on 2 out of 10 bars, whilst with a potential of +0 mV vs SCE all the bars remained passive.

Figure 7 shows the results, performed on concrete with 5%  $\text{Cl}^-$  in mass of cement, obtained modifying the temperature and imposing a potential of +200 mV vs SCE. Increasing the temperature, the number of bars where corrosion occurred during the polarisation test increased; corrosion was observed only on one bar out of ten when test was performed at 10°C, one six bars at 23°C and 8 bars at 40°C. Therefore, preliminary tests showed that temperature and potential influenced significantly the test results.

## **Discussion**

The proposed test allowed to obtain, in a reasonable period of time (few weeks), an estimation of the corrosion resistance of stainless steel bars. It can, hence, be used to compare the performances of different types of steel reinforcement bars; as a matter of fact, performing the test at the same amount of admixed chlorides, on a statistically significant number of specimens, the type of reinforcement with the higher corrosion

resistance can be detected (i.e. the type of bar which had the lower number of specimens where corrosion occurred). Furthermore, this test can also be used to study the influence of factors which affect the corrosion resistance. The number of specimens to be tested is a critical issue, since the reliability of the test results depends on it. 10 replicate reinforced concrete specimens can be considered a good compromise between the possibility of obtaining reliable results and the real feasibility of the test (i.e the test should not be too much onerous and complex also in relation to the needed instruments as, for instance, the number of reference electrodes). It should be considered that in the available standards, tests should be performed on a lower number of specimens; for instance the ASTM A955 indicates 5 replicate reinforced specimens. However, the optimum number of replicate reinforced concrete specimens, that consider statistical uncertainty, needs to be assessed in order to guarantee the replicability and reliability of the test result at each chloride content and to take into account the several parameters which can affect the result, e.g. the effects of test method and execution of specimens.

The result of the proposed test is, for the amount of admixed chlorides at which it is carried out, the number of specimens in which corrosion occurred. Hence, the result is not directly the critical chloride threshold. However, it can be considered that the number of specimens on which initiation of corrosion occurred represents the probability that corrosion initiates at that chloride content. In case the test is carried out at different amounts of admixed chloride content, as for the application on the stainless steel type 1.4362 previously shown, by fitting the number of specimens out of ten that failed during the tests with the admixed chloride content, the cumulative distribution function (CDF) of the critical chloride threshold can be determined. The higher the number of amount of chlorides at which the test is performed, the higher the probability of corrosion initiation is. However, these tests are onerous and the number of amounts

of admixed chlorides to be tested cannot be excessive, also taking into account that the total duration of the test would depend on this number (a good compromise should be defined between the reliability of the CDF and the feasibility of the test).

A maximum chloride content of 6% in mass of cement could be considered for the test (value higher than this are not experienced in real structures, as confirmed by the surface chloride concentration values measured on real structures; Lollini, Carsana, Gastaldi, Redaelli, & Bertolini, 2015). The type of distribution to fit the data should have upper and lower limits (in order that the critical chloride threshold would be within a range). According to the proposal of the *fib* Model Code for Service Life Design (2006) for the critical chloride threshold of carbon steel, a Beta distribution can be considered, which is characterized by a mean value,  $m$ , a standard deviation,  $\sigma$ , and lower and upper limits,  $a$  and  $b$ . The continuous line in Figure 8 shows, for the stainless steel type 1.4362, the experimental results (obtained, for each chlorides content, from the ten concrete specimens) and the CDF of the critical chloride threshold, for the test conditions ( $T = 23^{\circ}\text{C}$  and potential = +200 mV vs SCE). The following parameters were, then, evaluated: mean value and standard deviation respectively equal to 5.5% and 1.6% Cl<sup>-</sup> by cement mass and lower and upper limits of 2.7% and 10%.

This CDF could be considered as an input parameter for the critical chloride threshold in performance based models. However, intrinsic limitations of this type of approach should be considered. As a matter of fact, the cumulative density function of the critical chloride threshold estimated from this test,  $Cl_{th,test}$ , has to be treated as the result of an accelerated test, which is only valid for the tested material and the test conditions (type of concrete, temperature, applied potential, etc.). Hence, according to the proposed test procedure, it is valid to evaluate the critical chloride threshold at a temperature of  $23^{\circ}\text{C}$  and for a reinforcement corrosion potential of +200 mV vs SCE.

Following the approach proposed by the *fib* Model Code for the diffusion coefficient, if the test proposed in this work were used as a compliance test in order to predict the behaviour of steel in real exposure environment, the critical chloride threshold,  $Cl_{th,test}$ , should be modified through appropriate corrective coefficients,  $k_i$ , that take into account the role of the factors which can affect it. In this way, the critical chloride threshold in field,  $Cl_{th,field}$ , can be evaluated as:

$$Cl_{th,field} = k_1 \cdot k_2 \cdot \dots \cdot k_n \cdot Cl_{th,test}$$

The corrective coefficients should, first of all, take into account the role of the test type; i.e. how the results of such an accelerated method, with mixed-in chloride, are representative of real exposure conditions, where chlorides penetrate from an external source. These coefficients could be evaluated by comparing results of this test with mixed-in chlorides with tests where chlorides penetrate from external sources, i.e. with tests more representatives of natural exposure conditions, or with data from real structures. However, tests where chlorides penetrate from external source require long time, especially when stainless steel bars are considered, and, nowadays, data on real structures are not available. Also for carbon steel, tests where chlorides penetrate from external source showed to be unfeasible (Lollini, Redaelli, & Bertolini, 2016). To evaluate this corrective coefficient, also the other characteristic factors of the test has to be considered: the type of used salt ( $CaCl_2$ ) could lead to more critical initiation conditions compared to those expected in real exposure conditions, where the main salt is the sodium chloride (Hansson, Frølund, & Markussen, 1985; Xu, Jiang, Wang, & Jiang, 2011); whilst the duration of the test is limited to 24 hours and in real conditions the initiation could occur in longer times. Further tests will be required to better investigate the effects of these factors.

The corrective coefficients should then also consider the environmental exposure conditions, the real concrete characteristic (i.e. the type of binder), the surface bars conditions, etc. To evaluate them, the same methodology can be applied, varying the parameter to be studied. For instance, for studying the effect of the type of cement, the tests can be performed by changing the concrete composition.

Among the different factors which can influence the critical chloride threshold, attention should be paid to the environmental factor, which depends on the concrete humidity and the temperature. Hence, two corrective factors need to be introduced:  $k_{ENV}$ , which takes into account the concrete humidity and  $k_T$ , which considers the temperature.

### ***Role of concrete humidity***

The concrete humidity depends on the exposure zone (for instance, for a bridge exposed in a marine environment: the atmospheric, the spray and tidal and the submerged zones) and influences the critical chloride threshold since it modifies the corrosion potential of passive steel. To evaluate the effect of the humidity on the critical chloride threshold the correlation between the exposure zones and the reinforcement corrosion potential is useful. At this regard, since the corrosion potential is an electrochemical parameter often used to identify the reinforcement corrosion conditions, a literature survey was carried out to find corrosion potential values measured on passive bars during inspection on real structures and during laboratory tests (Gonzales, Miranda, & Feliu, 2004; Alhozaimy, Hussain, Al-Zaid, & Al-Negheimish, 2012; Montemor, Cunha, Ferreira, & Simoes, 2002; Frølund, Klinghoffer, & Sørensen, 2003; Pech-Canul & Castro, 2002; Sosa et al., 2011; Pacheco, Fajardo, & Valdez, 2010; Dong, Lin, Hu, Li, & Du, 2011; Xu, Jiang, Wang, Xu, & Jiang, 2011; Akira, Iwanami, Yamaji, Shimazaki, & Ishinaka, 2010; Pradhan & Bhattacharjee, 2009; Bouteiller et al.,



2012; Poupard, L'Hostis, Catinaud, & Petre-Lazar, 2006; Lau, Sagues, & Yao, 2005; Choi, Kim, & Lee, 2006; Pakshir & Esmaili, 1998; Loto & Odumbo, 1989, Topcu & Boga, 2010). Figure 9 summarizes the results obtained by the several Authors. Both data from inspections and from laboratory tests presented some limits and their interpretation was not an easy task. The laboratory tests had often a limited duration and were usually carried out in accelerated conditions (i.e. in comparison to real structures, lower concrete cover thicknesses and solutions more concentrate than seawater are usually employed, leading to the initiation of corrosion in a shorter time), whilst on real RC elements the effective exposure conditions were often ambiguous, since the potential was rarely continuously monitored and, hence, information about the trend of the potential in time was missing. In Figure 9, it can be observed that the corrosion potential measured on RC elements significantly varies as a function of the concrete humidity and, hence, as a function of the exposure zone. Furthermore, it also varies within the same zone and differences can be observed between values measured on real structures and in the laboratory conditions, also due to limits previously indicated. In particular a high variability of corrosion potential can be observed in real structures than in the laboratory specimens, which might be due to more variable exposure conditions and to the higher intrinsic variability of concrete itself (laboratory specimens are usually well compacted and cured). It can be observed that, in the atmospheric zone, considering the different humidity conditions, the average values are around -50 mV vs SCE and maximum values of +150/+300 mV vs SCE can be reached (the higher values were measured on the laboratory specimens, exposed to dry conditions; on real structure higher values of +200 mV were measured). In the tidal zone, average values around -200 mV vs SCE can be detected, which decrease in the submerged zone. On the basis of these considerations, to be conservative, i.e. assuming the highest and realistic values

that can be reached, it is reasonable to assume that the PDF of  $C_{l_{th, test}}$ , performed at +200 mV vs SCE, would be suitable for the atmospheric zone (and hence  $k_{ENV}$  is equal to 1). This PDF can be considered valid also for the splash zone, since the aeration condition of concrete, and hence of corrosion potential of steel, are comparable to those of the atmospheric zone. For the other zones, since the potential is lower in comparison to the atmospheric zone  $k_{ENV}$  needs to be determined. Preliminary experimental results of the research, previously presented, showed that considering the same amount of admixed chlorides, the number of specimens where corrosion occurred during the test, decrease, decreasing the corrosion potential. Hence, for the tidal and submerged zones  $k_{ENV}$  should be higher than 1 and, consequently the critical chloride threshold will be higher. Further tests at different admixed chloride contents and on different types of stainless steel, should be carried out to confirm the trend and define proper values for this corrective coefficient. At this regard, Pedferri's diagram (Pedferri, 1995), which allows to study the relationship between the corrosion potential and the critical chloride threshold should be useful.

### ***Role of temperature***

As far as the  $k_T$  coefficient is concerned, it is important to investigate how temperature affects the critical chloride threshold. As a matter of fact, it acts on the corrosion resistance of steel bars in a different way in comparison with how it acts on the penetration of chlorides. Chloride diffusion rate varies as a function of temperature and it is not constant through the year and, usually, an average annual value is considered. Conversely, if initiation of corrosion is considered, it is promoted when the temperature is highest; hence, it is more significant to consider the values reach in the warmest period of the year, i.e. in the period when there is the higher probability that corrosion occurs. Furthermore, it should be noted that two different climates (i.e.

continental and coastal climate) can be characterized by similar average annual temperature, but different magnitudes of extreme temperatures and, hence, considering the average annual temperature might lead to overestimate the critical chloride threshold in the harshest climate.  $k_T$  coefficient should, hence, be determined considering an average value of the maximum yearly temperature. A maximum yearly temperature of 23°C can be, for instance, reached in the north Europe (e.g. the North Sea Coasts), and, hence, it is representative of cool temperate climate. Conversely, temperature of 40°C can be, for instance, reached in tropical climate. Preliminary experimental tests showed that temperature significantly influences the test results and an increase of number of specimens where corrosion occurred was observed increasing the temperature. Hence, for temperatures higher than 23°C,  $k_T$  should be lower than 1; conversely it should be higher than 1 for temperatures below 23°C. Further tests will be needed to determine the corrective coefficient to be applied in the design stage.

From this analysis, it emerges that the proposed test can be applied for the design of reinforced concrete structures exposed in atmospheric and splash zones in cool temperature climate. However, some open issues are still present and they need to be evaluated, in order that the proposed test can be applied to determine the PDF of the critical chloride threshold of stainless steel bars in concrete to be used as input parameter in the performance-based probabilistic approach in any environmental exposure condition. Further tests are on going to study the role of the different factors.

## **Conclusions**

In this paper the main requirements that an experimental procedure should have to determine the cumulative density function of the critical chloride threshold for the initiation of corrosion of stainless steel bars were detected. To satisfy these requirements, a test procedure based on mixed-in chloride and potentiostatic

polarisation was proposed. This test revealed to be also suitable to evaluate the influence of different parameters as, for instance, the type of cement, the temperature and the exposure environment on the initiation of corrosion and to rank different grades of stainless steel.

Experimental tests carried out on bars of stainless steel type 1.4362 allowed to estimate the cumulative density function (CDF) of the critical chloride threshold for this steel, which could be representative for a RC structure made with portland cement exposed to the atmospheric conditions at 23°C. Preliminary experimental tests showed that both temperature and corrosion potential significantly influenced the test results, and a decrease of number of specimens where corrosion occurred was observed decreasing the temperature and the potential.

The proposed test can be applied to determine the PDF of the critical chloride threshold of stainless steel bars in concrete to be used as input parameter in the performance-based probabilistic approach for the design of RC structures exposed in atmospheric and splash zones in cool temperature climates. In order that the results of this accelerated test are valid for any condition, corrective factors, which take into account the effect of different parameters, as the exposure conditions and the type of concrete, need to be defined.

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Table 1. Mechanical characteristics and main alloy elements of the stainless steel 1.4362 reinforcing bars.

<i>Mechanical properties</i>		<i>Major alloy elements (%)</i>					
$R_{s0.35\%}$	$R_m$ (MPa)	<i>C</i>	<i>Cr</i>	<i>Mo</i>	<i>Ni</i>	<i>Mn</i>	<i>N</i>
496	819	0.03	23.5	0.45	4.61	1.41	0.13

Table 2. Visual observation at a naked eye of the bars surface before the polarization tests, carried out on specimens with different amounts of chlorides  $Cl^-$  (by cement mass), at different applied potentials  $E$  (mV vs SCE) and temperatures  $T$  ( $^{\circ}C$ ) (R = rust spot; S = presence of scale; B = presence of dark areas; D = presence of scratch; “-” = absence of the defect).

$E$	+200																				+0/+100											
$T$	23																10				40				23							
$Cl^-$	2.7%				3%				4%				5%				5%				5%				5%							
$Bar$	R	S	B	D	R	S	B	D	R	S	B	D	R	S	B	D	R	S	B	D	R	S	B	D	R	S	B	D	R	S	B	D
1	X	-	-	-	-	-	X	-	-	-	X	X	X	-	-	-	X	-	-	X	X	-	-	-	-	-	-	-	-	-		
2	X	-	-	-	X	X	-	-	X	-	X	X	-	-	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-		
3	X	-	-	-	X	X	-	-	X	-	-	X	-	X	X	-	X	X	-	-	X	-	-	-	X	-	X	-	-	-		
4	X	-	-	-	-	X	X	-	X	-	X	X	-	-	-	-	X	-	-	-	X	-	X	-	-	-	-	-	-	X		
5	-	-	-	-	-	-	-	-	X	-	-	X	X	X	-	-	X	-	-	-	-	-	-	-	X	-	-	-	-	-		
6	-	-	-	-	-	-	X	X	X	-	-	X	-	-	X	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-		
7	-	-	-	-	-	-	-	X	X	X	X	-	-	X	X	-	X	X	X	-	X	-	-	-	-	-	-	X	X	-		
8	X	-	-	-	X	-	-	X	X	-	-	-	-	X	X	-	X	X	-	-	X	-	-	X	-	X	-	X	X	X		
9	X	-	-	-	-	X	X	-	-	X	X	X	X	X	-	-	X	X	X	-	-	-	-	X	-	X	X	-	-	-		
10	X	-	-	-	-	X	-	X	X	-	-	-	-	X	X	-	X	-	-	-	X	X	X	-	-	-	-	X	-	-		

Table 3. Visual observation at a naked eye of the bars surface after the polarization tests, carried out on specimens with different amounts of chlorides  $Cl^-$  (by mass of cement), at different applied potentials  $E$  (mV vs SCE) and temperatures  $T$  ( $^{\circ}C$ ) (# = number of pits;  $D$  = maximum dimension of the pits, in mm).

$E$	+200												+100	
$T$	23								10		40		23	
$Cl^-$	2.7%		3%		4%		5%		5%		5%		5%	
$Bar$	#	$D$	#	$D$	#	$D$	#	$D$	#	$D$	#	$D$	#	$D$
1	-	-	-	-	-	-	>10	2	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	>10	2	-	-
3	-	-	-	-	-	-	>10	3	1	0.5	1	2	-	-
4	-	-	-	-	-	-	-	-	-	-	2	2	-	-
5	-	-	-	-	-	-	>10	1	-	-	>10	2	-	-
6	-	-	-	-	-	-	-	-	-	-	3	<1	-	-
7	-	-	-	-	-	-	-	-	-	-	>10	2	-	-
8	-	-	-	-	-	-	2	1.5	-	-	>10	2	-	-
9	-	-	-	-	-	-	>10	1	-	-	>10	2	~10	<1
10	-	-	1	1	-	-	>10	4	-	-	-	-	4	2

## List of figures

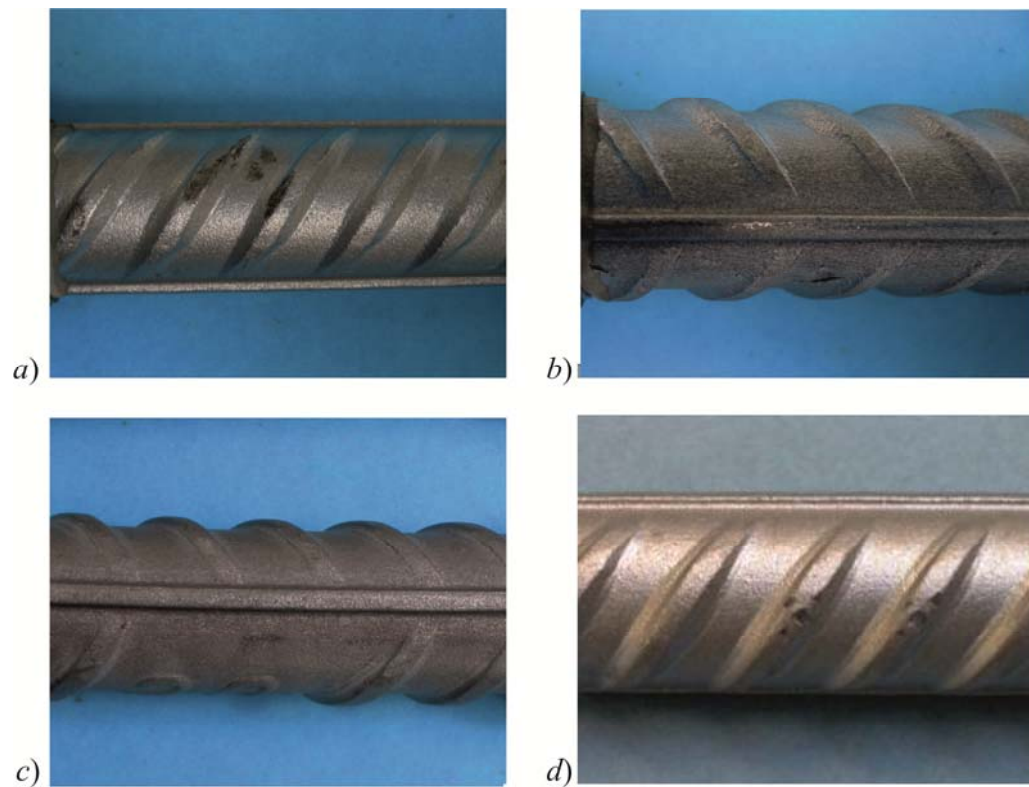


Figure 1. Examples of imperfection detected on the surface of the bars after decreasing with acetone (*a*) = rust spot; *b*) = presence of scale; *c*) = presence of dark areas; *d*) = presence of scratch).

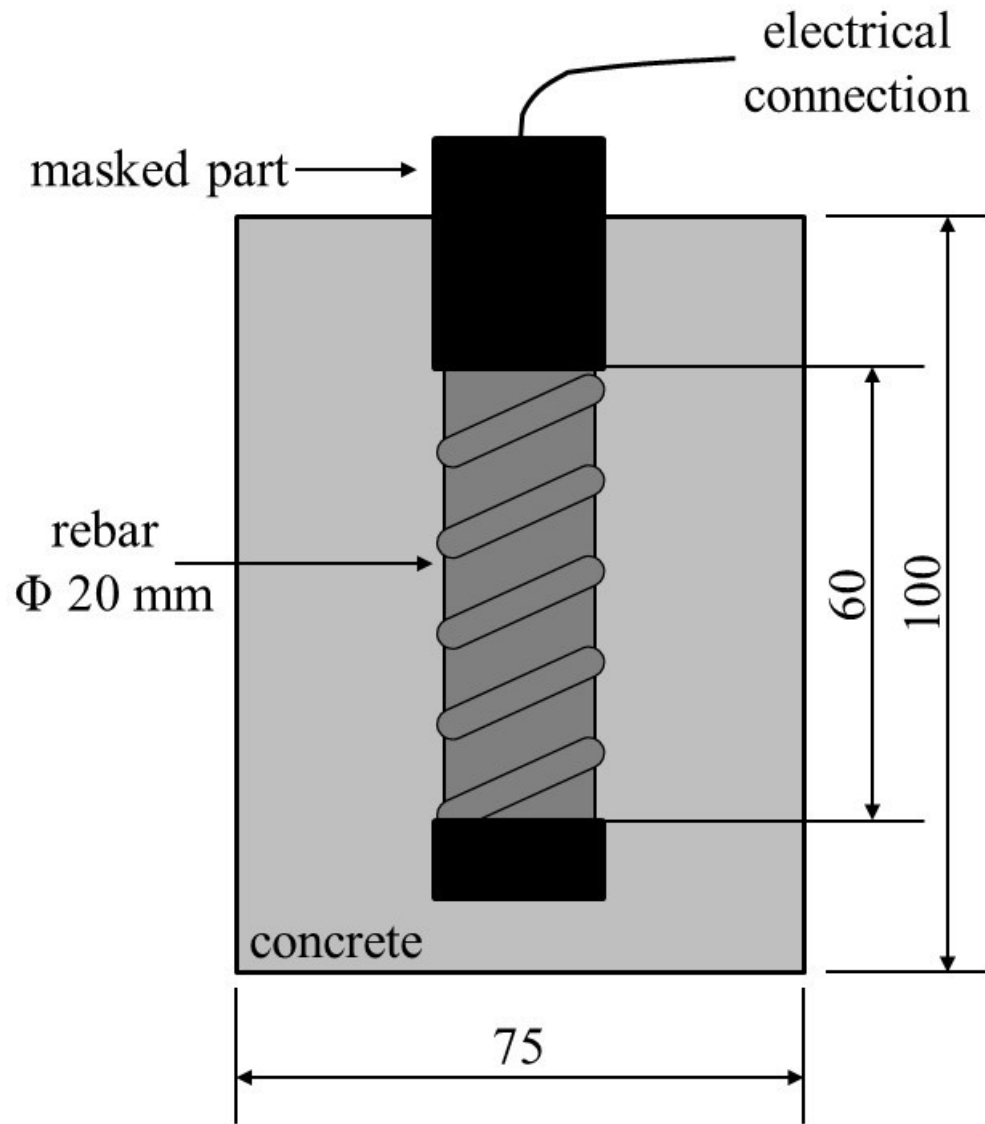


Figure 2. Schematic representation of the concrete specimen (dimensions are in mm).

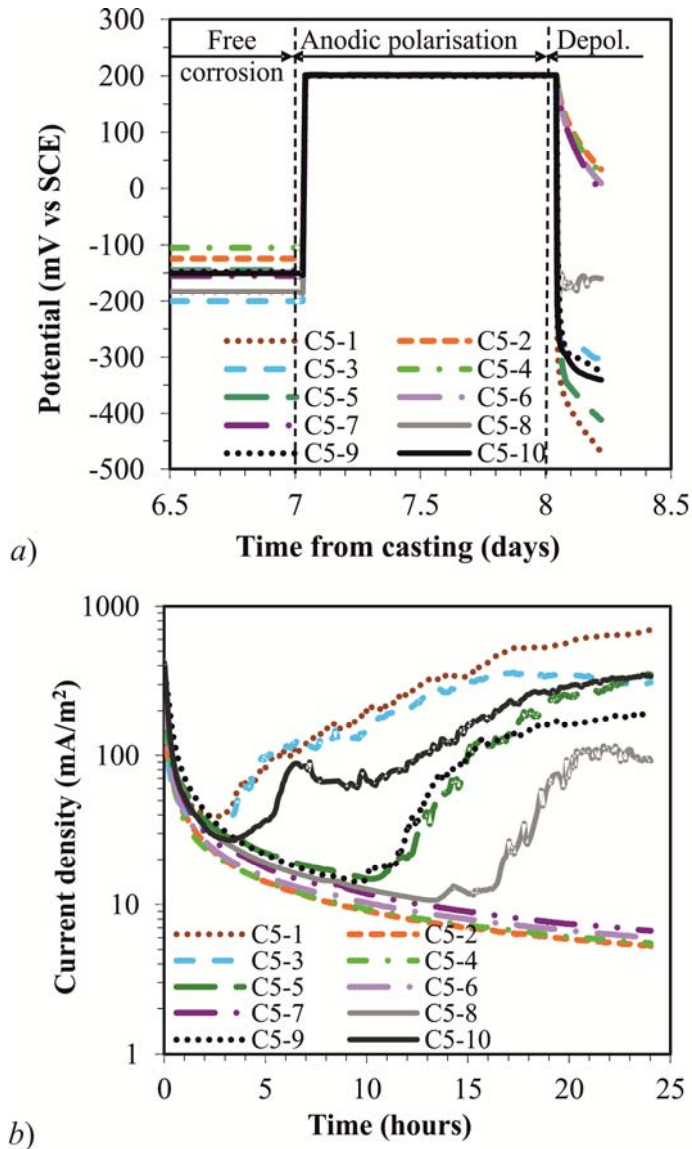


Figure 3. Corrosion potential (a) and polarisation current density (b) of bars of 1.4362 stainless steel in concrete specimens with 5% Cl<sup>-</sup> by cement mass, before, during and after polarisation at +200 mV vs SCE.

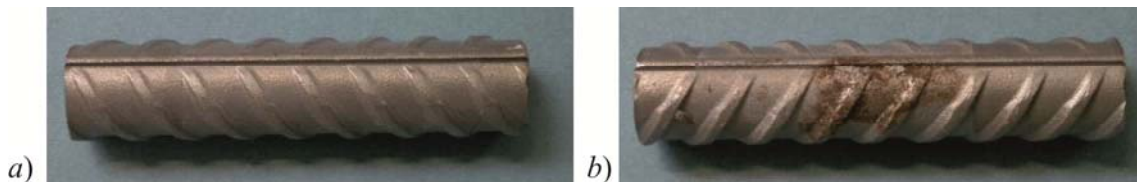


Figure 4. Example of a reinforcing bar in passive condition (a, specimen C5-4) and one with corrosion attacks (b, specimen C5-5) after tests in concrete with 5% of chloride by cement mass.

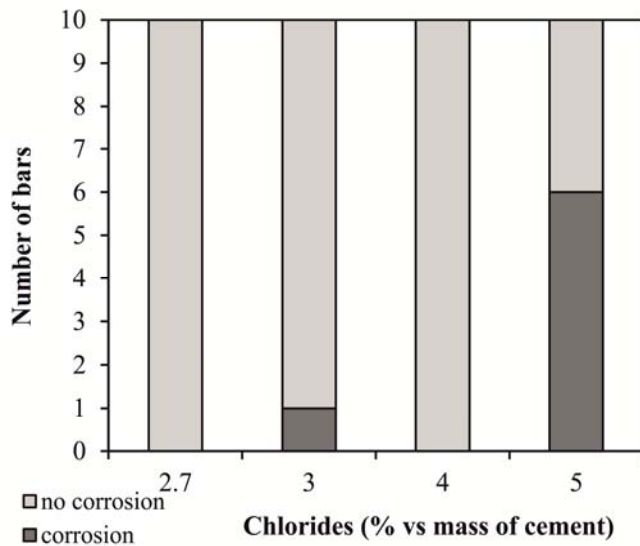


Figure 5. Number of bars, in specimens with different amount of mixed-in chlorides, where corrosion occurred (in dark grey) during the 24-hour polarisation tests at 23°C and +200 mV vs SCE.

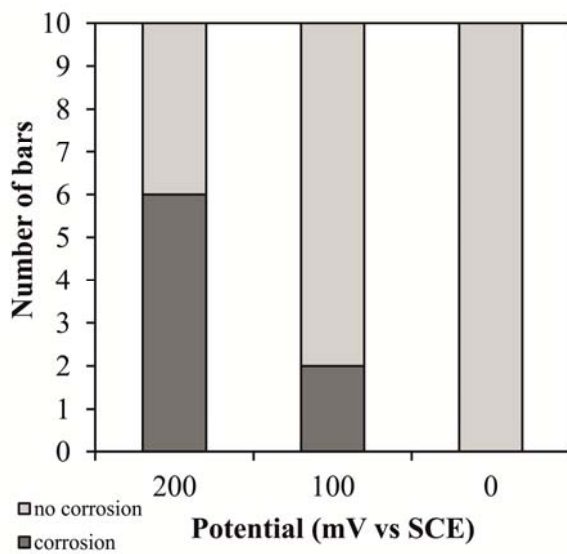


Figure 6. Number of bars, in specimens with 5% Cl<sup>-</sup> in mass of cement, where corrosion occurred (in dark grey) during the 24-hour polarisation tests at 23°C at different potentials.

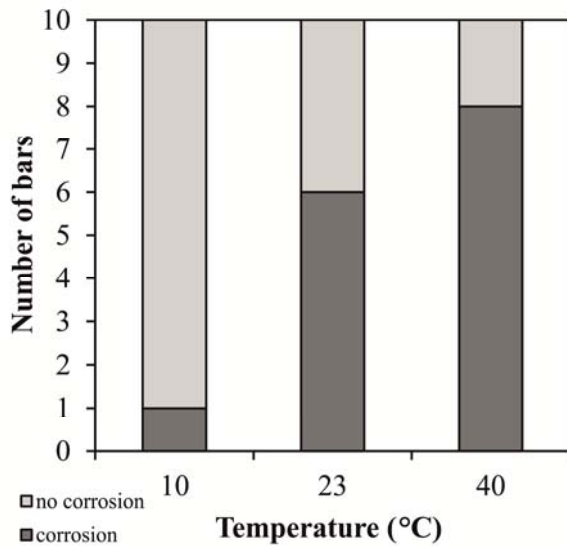


Figure 7. Number of bars, in specimens with 5% Cl<sup>-</sup> in mass of cement, where corrosion occurred (in dark grey) during the 24-hour polarisation tests at +200 mV vs SCE at different temperatures.

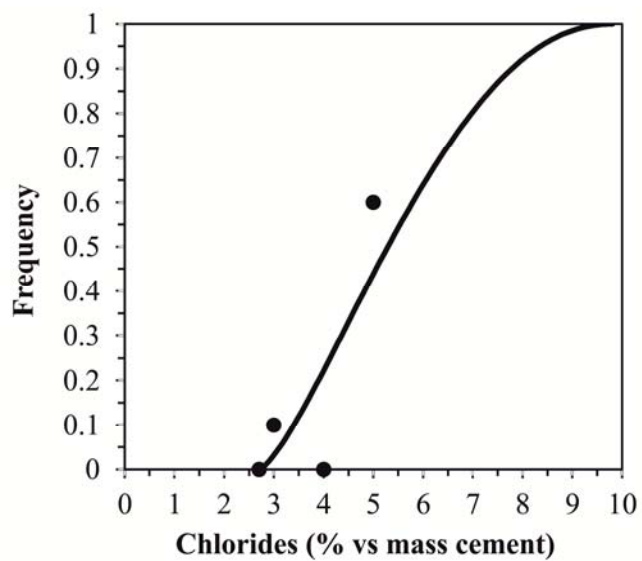


Figure 8. Cumulative distribution function (obtained considering a Beta distribution) of the critical chloride threshold of the stainless steel of types 1.4362 determined from the results of the polarisation tests at +200 mV vs SCE.

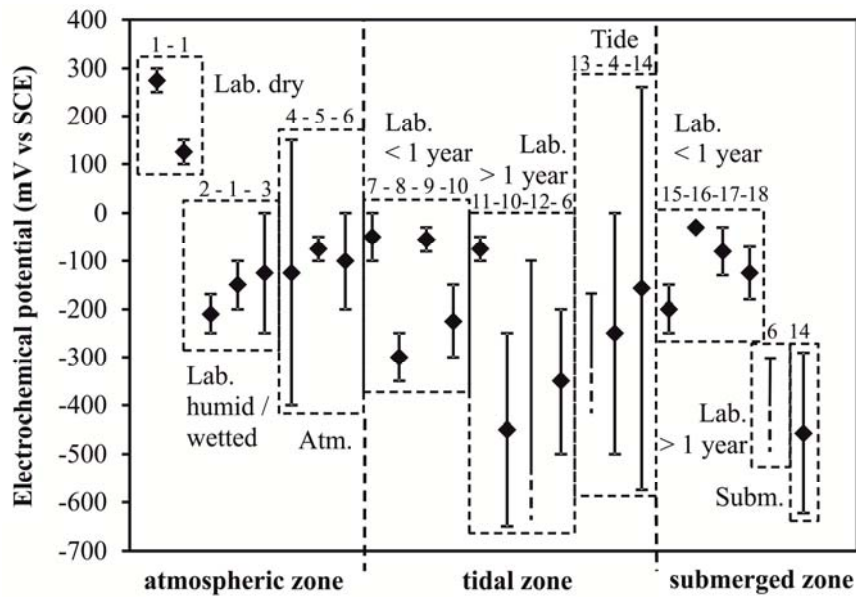


Figure 9. Relationship between the corrosion potential of passive steel and the exposure environmental zone: average values and interval of variation of the results (1: Gonzales, Miranda, & Feliu, 2004; 2: Alhozaimy, Hussain, Al-Zaid, & Al-Negheimish, 2012; 3: Montemor, Cunha, Ferreira, & Simoes, 2002; 4: Frølund, Klinghoffer, & Sørensen, 2003; 5: Pech-Canul & Castro, 2002; 6: Sosa et al., 2011; 7: Pacheco, Fajardo, & Valdez, 2010; 8: Dong, Lin, Hu, Li, & Du, 2011; 9: Xu, Jiang, Wang, Xu, & Jiang, 2011; 10: Akira, Iwanami, Yamaji, Shimazaki, & Ishinaka, 2010; 11: Pradhan & Bhattacharjee, 2009; 12: Bouteiller et al., 2012; 13: Poupard, L'Hostis, Catinaud, & Petre-Lazar, 2006; 14: Lau, Sagues, & Yao, 2005; 15: Choi, Kim, & Lee, 2006; 16: Pakshir & Esmaili, 1998; 17: Loto & Odumbo, 1989; 18: Topcu & Boga, 2010).