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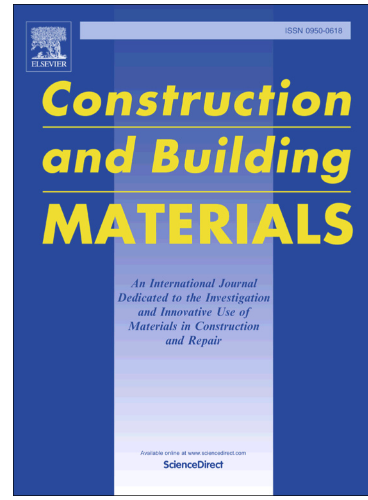

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BONDING STRENGTH OF STAINLESS STEEL REBARS IN CONCRETES EXPOSED TO MARINE ENVIRONMENTS

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Abstract

Many studies have corroborated the use of Stainless Steel Reinforcements (SSR) for structures in corrosive environments. However, even though the conditions for their employment are specified in different standards, their use is always tied to the same requirements for standard carbon steel rebars (B500SD), among which an equivalent carbon content for weldability that is inappropriate for SSR. Further studies are therefore needed to develop suitable standards that will focus on addressing not only the content, but also the technical advantages of SSR for structural engineering under specific conditions. The results of this study show improvements in the maximum bond strength behaviour of different SSRs in simulated marine environments, in comparison with B500SD, in terms of several variables: Bond index, curing time, w/c ratio, and corrosion. Specifically, the test results showed that: (a) the Bond index was not a suitable parameter for the evaluation of the bonding strength of SSR; (b) the curing time increased the bonding strength of Lean Duplex Stainless Steel (LDSS); (c) a higher w/c

ratio tended to decrease bond strength, although less so in LDSS; and, (d) corrosion reduced bond strength, especially in B500SD.

Keywords: Bond Strength, Corrosion, Stainless Steel Rebar, Chlorides.

Highlights

- Rebar-concrete adherence studied in simulated marine environments.
- Influence of stainless steel rebars: 304, 316, 2001, 2205, 2304.
- Influence of rebar diameter: 12 and 25 mm
- Effects of cement content and w/c ratio related to alkalinity and porosity
- Adherence loss due to of corrosion over time

1. Introduction

Structures are designed to withstand the loadings in their construction plans. In a structure made of reinforced concrete, the concrete is capable of withstanding compressive stress, while the steel is capable of withstanding the tensile stresses that a concrete structure alone could not otherwise withstand. Good bonding strength between rebars and concrete is essential to ensure the reliable performance of reinforced concrete. Different mechanisms are responsible for bonding strength: chemical adhesion between steel and concrete, friction between concrete and the rebar surface and, finally, and most importantly, mechanical interaction between the rebar rib of corrugated steel rebars and the concrete, [1,2]. The Bond index is defined by the rib surface geometry of a rebar, in terms of the relative area of the rib over the nominal size of the bar [3]; a parameter that implies a similar bond strength for rebars with similar values. Nevertheless, concrete-rebar interaction depends not only on the Bond index, but also on concrete compressive strength, curing time, the concrete mixture, the number of brackets, braces, and stirrups, and the environment of the structure [2,4-8].

The corrosion of rebars embedded in concrete is very common in structures exposed to aggressive environments. The behaviour of the rust layer that can form around the reinforcement is twofold. In a first stage, the bond strength increases slightly due to the radial pressure caused by the expansive corrosion products and the increased roughness of the rebar. However, in a second stage, as the corrosion process continues, these products reduce the relative size of the ribbing, decreasing the bond strength [4,9,10].

Many solutions have been developed to correct problems of corrosion, some of which add components that improve the behaviour of concretes exposed to corrosive environments. Other solutions include coating structural elements to prevent the access of corrosive electrolytes, such as chloride in marine environments. Additionally, there are other treatments that can be applied to the steel such as coating, epoxy, and hot-dip galvanizing systems [11-19]. Epoxy coatings enhance the corrosion performance of rebars. Nevertheless, once coated and subjected to loadings, the reinforcements can in some cases show weaker corrosion resistance than the uncoated reinforcements [20]. However, the main weak point is bond strength, as epoxy will usually reduce adherence by between 6.5% to 20-25%, and even by up to 42% [21-25], accompanied by a 10% reduction in bond strength. The epoxy solution only delays corrosion activation of the substrate steel in hot-dip zinc galvanized reinforcements. This delay is because the chloride concentration needed for acute corrosion in poorly alkaline carbonated concrete is quite low (0.29 wt.%) [21,26-29] and expansive compounds, such as insoluble zinc, formed on the bar-concrete interface can cause concrete spalling, even before the appearance of red rust stains [30].

Therefore, in view of the weakened bond strengths that alter the performance of the reinforced structures when coatings are applied to reinforcements, the use of stainless steel as a reinforcing steel has become a promising alternative solution over recent years. Many investigations have provided evidence in support of these alloys and their good performance in marine environments [31-35]. However, stainless steel can be more expensive than carbon steel, due to the higher costs of the alloys that improve its performance. Nevertheless, if considering the whole Life-Cycle Costs (LCC) coupled with an intelligent strategy towards the use of stainless steel, not only could the excess cost be reduced, but the retrofitting costs could also be cut back by 20-25%, making stainless steel rebars a cost-effective solution [36,37]. In the initial tests, austenitic stainless steel -AISI 304 and AISI 316- was used. However, modern duplex stainless steel has been developed (2205 DSS) to optimize nickel content and thereby reduce costs while improving yield stress, resistance to localized corrosion and SCC performance [38-41]. Current research has been studying the behaviour of Lean Duplex Stainless Steel, such as 2001 LDSS, with even lower nickel percentages than DSS that is well balanced with manganese content to maintain good mechanical properties [42-46].

As previously stated, a good bond strength is required for the acceptable performance of reinforced concrete and corrosive processes weaken that strength and the behaviour of the reinforcement inside the concrete. Abundant research has been focused on the behaviour of corroded carbon reinforcement. A similar performance is noted which can be divided into two stages [9,10]: firstly, the bond strength increases, due to the pressure that rusting products apply to concrete when bulking. Then, when the corrosion level exceeds a critical value, the bond strength decreases exponentially within a range of between 0.5% and 4% [4]. Nevertheless, the bond strength of stainless steel rebars has not been widely studied [47]. Following a commitment to research this under-investigated field, the bond behaviour of different stainless steel rebars following their

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exposure to simulated tidal environments is analysed in the present paper. Various specimens with different concrete dosages were cast, to study the importance of alkalinity and rebar passivation, diffusion, and porosity.

2. Experimental procedure

2.1 Materials

Different concrete mixtures with dosages designed for different environments were studied [48,49]: XS1 (on shore, atmospheric exposure), XS3 (tidal zone), and XC3 (interior standard). The water-to-cement (w/c) ratio affects the bond strength of the reinforced concrete, the diffusion of chlorides, and concrete porosity [8,50-52]. Cement content and the w/c ratio for each concrete are summarized in Table 1. These values are related with concrete porosity and alkalinity and therefore affect the corrosion dynamics, while other relevant parameters such as aggregate amount and proportion, cement type, etc. are important to predict bond strength, but not only to compare bond strength behaviour, provided they are kept constant: XS3 shows the lowest w/c ratio (0.45) while XC3 has the highest (0.55), the value of XS1 was 0.5. Six different steels were studied as reinforcements: standard carbon steel rebars (B500SD) were used as the reference specimens, the others were stainless steel (SS) rebars, two austenitic SS (304 ASS and 316 ASS), one duplex SS (2205DSS), and two types of lean duplex SS (2304 LDSS and 2001 LDSS) bars. Table 2 summarizes the chemical composition of the different steel rebars in weight %, according to the procedures detailed in EN 10080:2005 and EN 10088-1:2006 [53,54]. The low nickel content of LDSS may be seen that has 55%-70% less nickel when compared with austenitic stainless steel and 46%-15% less nickel than duplex stainless steel. 2001 LDSS has the lowest nickel content making it the most suitable from an economic point of view.

Table 1 properties of concrete mixtures.

	XC3	XS1	XS3
w/c	0.55	0.5	0.45
Cement [kg/m^3]	300	300	350
Concrete Class	C30/37	C30/37	C35/45
f_{ck} [MPa]	30	30	35
f_{ctk} [MPa]	2	2	2.2

Table 2 Chemical composition of stainless steel reinforcements (weight %).

Steel	Yield Stress [MPa]	C	Si	Mn	Pmax	S	Cr	Ni	Mo	N	Cu
B500SD	500	0.22	0.22	0.72	0.01	0.022	0.13	0.13	--	--	0.18
304 ASS	380	≤0.07	≤0.075	≤2	0.04	0.02-0.03	18-19	8-9	--	--	--
316 ASS	380	≤0.07	≤0.075	≤2	0.04	0.02-0.03	16.5-18	10-12	2-2.5	--	--
2205 DSS	450	≤0.03	≤1	≤2	0.035	≤0.015	21-23	4.5-6.5	2.5 - 3.5	0.1-0.22	--
2304 LDSS	400	≤0.03	≤1	≤2	0.035	≤0.015	22-24	3.5-5.5	0.1-0.6	0.05-0.25	0.1-0.6
2001 LDSS	500	≤0,03	≤1	4.0-6.0	0.035	≤0.03	19.5-21.5	1.5-3.5	0.1 - 0.6	0.05 - 0.25	≤1

2.2 Test details

Specimens for pull-out tests were taken to test the design specifications in EN 10080:2006 [54]. The bond length in the test has to be 5 times the nominal diameter, which implies 125 mm, in the case of a 25 mm diameter reinforcing bar, and 60 mm in the case of a 12 mm diameter reinforcing bar. The sides of each specimen have to be 10 times the nominal diameter and never less than 200 mm.

A schematic diagram is shown in Fig. 1a of the dimensions of the test setup and Table 3 summarizes the dimensions of each specimen. A schematic diagram is shown in Fig. 1a of the dimensions of the test setup and Table 3 summarizes the dimensions of each specimen. The free adherence length, shown in Fig. 1b, is required to prevent any compression lines from clamping the rebar. Fig. 1b also shows the same specimen detailed in Fig. 1a, but rotated 180º, so as to view the test position, with the displacement reader at the bottom of the rebar and the pull exerted by the hydraulic piston. Finally, a photograph of the actual test set-up is shown in Fig. 1c. The specimen was placed on a tripod, then a rubber sheet and a steel plate disk with a central opening was placed on top of the specimen to distribute the load. Subsequently, a hydraulic piston and a second steel plate disk was placed above it, also for load distribution, in contact with the pressure cell, and a third steel plate disk above the cell, for added stiffness. Finally, a nut+wedge system secured the rebar in place. Besides, an LDTV system was placed at the opposite end of the rebar to measure displacement.

Before the pull-out test, some of the specimens had been exposed to simulated tidal marine environments, for 9 months, in order to analyse the effect of corrosion on bond strength. The seawater chloride content surrounding a structure in a tidal zone was assumed to be 3.5% [55]. The specimens were equally divided and placed in two PVC tubs. Then, using automated pumping equipment and a timer; one tub was filled with water for 6 hours while the other was left empty, exposed only to the atmosphere in the laboratory at 20ºC. After 6 hours, the water was pumped into the empty tub, thereby simulating the conditions of a structure in a tidal zone. Fig. 2 shows the experimental setup of the corrosive environment.

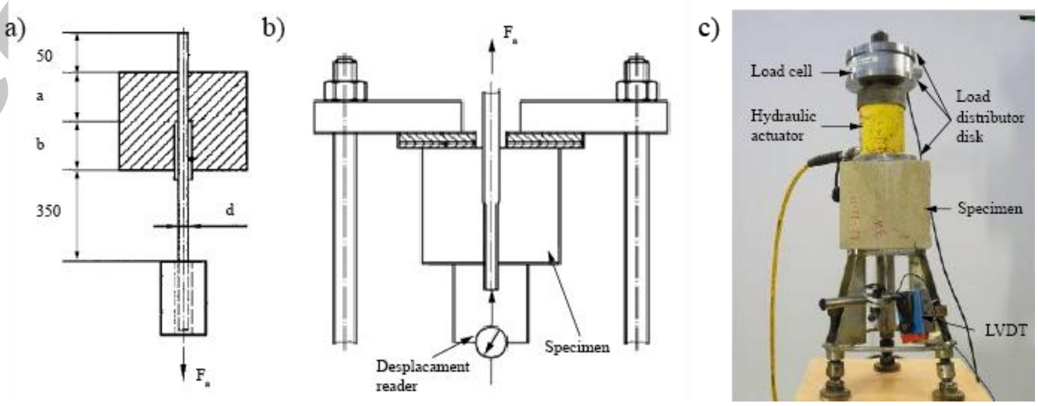

Fig. 1. Sketches and photo of the pull-out test.
a) Test setup dimensions; b) Loading system; c) Loading device.

Table 3 Specimen dimensions

d (mm)	a (mm)	b (mm)
12	60	140
25	125	125

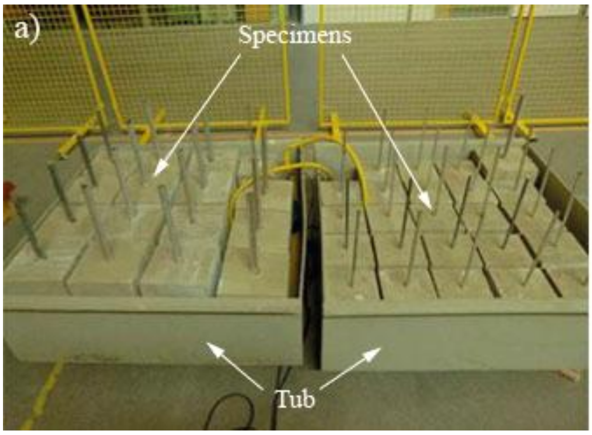

Fig. 2. a) PVC tubs filled with specimens. b) pumping equipment.

Once the corrosion tests had ended, pull-out tests of all specimens were performed. These tests consisted of applying a tensile load (F_a, kN) at one end of the reinforcing bar that increased throughout the test up until failure, due to debonding, concrete cracking, and even rebar breaking. Eq. (1) bond stress was defined on the basis of both the recorded displacement and the applied load. The load rate (ν, N/s) depends on the diameter of reinforcement, as defined by Eq. (2):

$$\tau_{dm} = \frac{1}{5\pi} \cdot \frac{F_a}{d^2} \cdot \frac{f_{cm}}{f_c} \quad (1)$$

$$\nu_p = 0.56 \cdot d^2 \quad (2)$$

where, τ_{dm} is the bond stress, MPa; d is the steel rebar diameter, mm; f_{cm} is the concrete design compression strength, 25MPa; and f_c is the mean concrete compression resistance, in MPa. After each test, τ_{max} is derived as the maximum recorded τ_{dm} value of the whole test.

Portable equipment (Fig. 1c) was used to apply the load, due to the weight of the specimens. A 200 kN capacity load cell and a linear variable differential transformer

(LVDT), with a measurement range of 10 mm and an accuracy of 0.001 were used to measure the applied load and the displacement of the rebar.

3. Results and discussion

In this section, the results of the pull-out test of reinforced concrete specimens in a corrosive marine environment are reported. First of all, the corrosion results are shown and then the bond behaviour is analysed considering the effect of the following parameters: Bond index, curing time, w/c ratio, and corrosion.

3.1 Corrosion study

Fig. 3 shows the i_{corr} values for the different rebars embedded in a concrete mixture with w/c of 0.5 under simulated tidal zone conditions for 6 months. The values obtained for the specimens that had not been exposed to a corrosive environment are plotted as reference values. The overall result shown in this figure clearly shows the superior behaviour of the stainless steel rebars compared to the B500SD rebars with an i_{corr} mean value of 0.245 $\mu A/cm^2$. The specific chemistry of the austenitic and the duplex types of stainless steel grades presented in this manuscript, shown in Table 2, and their microstructures, make them especially suitable for reinforced concrete structures in marine environments.

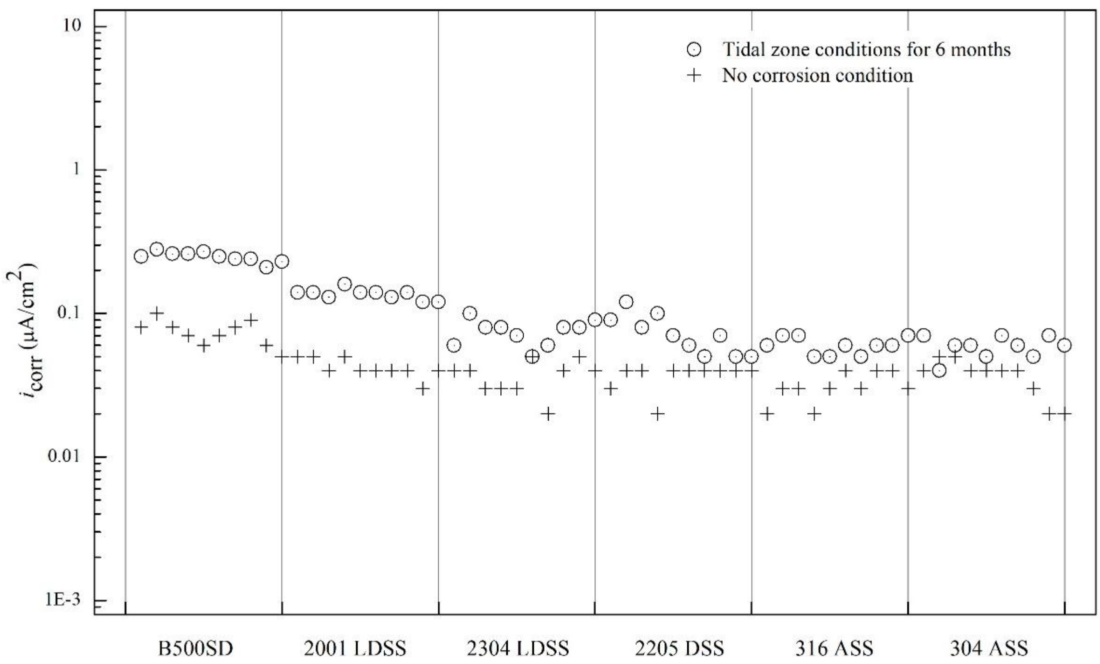

Fig. 3. i_{corr} values for different rebars after 6 months exposure to tidal zone conditions at a w/c ratio of 0.5 and in a non-corrosive environment.

European standard EN-206 [49] limits the maximum w/c value in accordance with each particular environment, such that the maximum w/c is fixed at 0.45 for tidal zones. However, the use of stainless steel as a reinforcement may reduce the required concrete strength and inspection during installation. Likewise, i_{corr} was measured in specimens with different concrete mixtures but in the same corrosive environment, simulating a tidal zone. Fig. 4 shows the corrosion current density at different w/c ratios, where each point represents the averaged value of 2 corroded specimens for greater clarity, after taking 5 corrosion measurements, each for a total of 100 measurements; the higher the w/c ratio of the concrete mixture, the higher the corrosion current density, an observation that was all the more remarkable for B500SD, in which a value of 0.12 μA/cm^2 was measured at a w/c value of 0.45. Taking those values as a baseline, when the w/c ratio was increased to 0.5 and then to 0.55, the i_{corr} values were respectively, 2 times and 3.5 times higher. While the B500SD had an almost negligible-very low corrosion limit at a w/c ratio of 0.45, the carbon steel reinforcement had low-near moderate corrosion levels at a w/c ratio of 0.55. The effects of the w/c ratios reported here are similar to those in Rivera-Corral et al [30].

With regard to the 2205 DSS rebars, the w/c ratio hardly affected i_{corr}, and although the w/c ratio was of the same proportions for B500SD, 2304 LDSS, and 2001 LDSS, the most affected was 2001 LDSS, for which the i_{corr} (0.135 μA/cm^2) value was 4 times higher at a w/c ratio of 0.5 than at one of 0.45. However, when comparing B500SD and 2001 LDSS, the i_{corr} value obtained for 2001 LDSS at a w/c ratio of 0.5 was similar to the i_{corr} value of B500SD, at a w/c of 0.45.

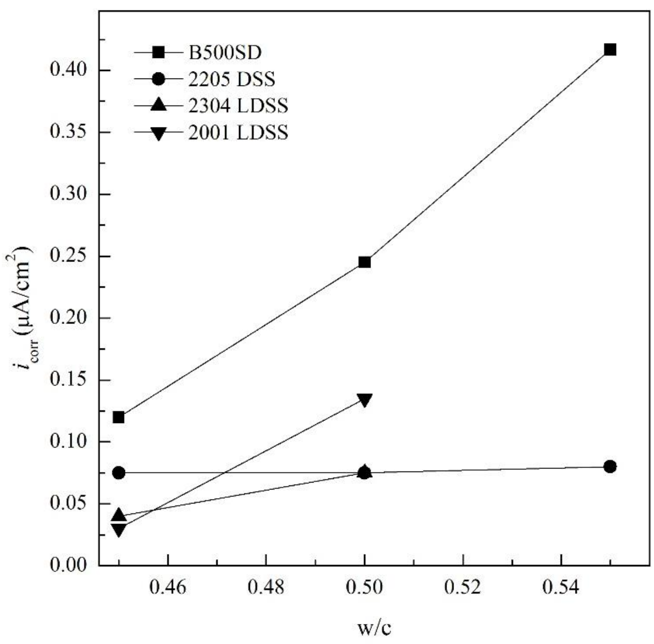

Fig. 4. Corrosion current density for different concrete mixture.

So, in view of the effect of the w/c ratio on the i_{corr} values, the use of stainless steel rebars will reduce inspection costs and concrete requirements.

3.2 Adherence assessment

As already stated in the introduction, bond strength depends on many factors: confinement, compressive strength of concrete, w/c ratio, corrosion level, embedded lengths.[4-7]. Therefore, the effects of the bond index (f_r), curing time, and the concrete mixture on bond strength were all analysed in this paper before studying the corrosive effects of different stainless-steel reinforcements on bond strength.

The Bond index is used to compare reinforced concrete bond strength; the higher the index, the higher the theoretical bond strength. Thus, the average strength values of the Bond index for each reinforcement allow us to assume that the Bond index of the stainless-steel rebars are far lower than those of the carbon steel B500SD rebars. Moreover, it can be seen that a higher f_r value in the case of B500SD yields a higher bond strength, while there is no relation between f_r and τ_{max} for the stainless-steel rebars, see Fig. 5. The scatter results obtained for stainless steel demonstrates that f_r defined in UNE-EN ISO 15630-1:2011 [3] is not a valid parameter to estimate bond strength in the case of SSR and that a new one should be defined. In fact, the specimens used in Fig. 5 are characterized by different concrete mixtures, and hence some other parameter may have much more influence than the Bond index.

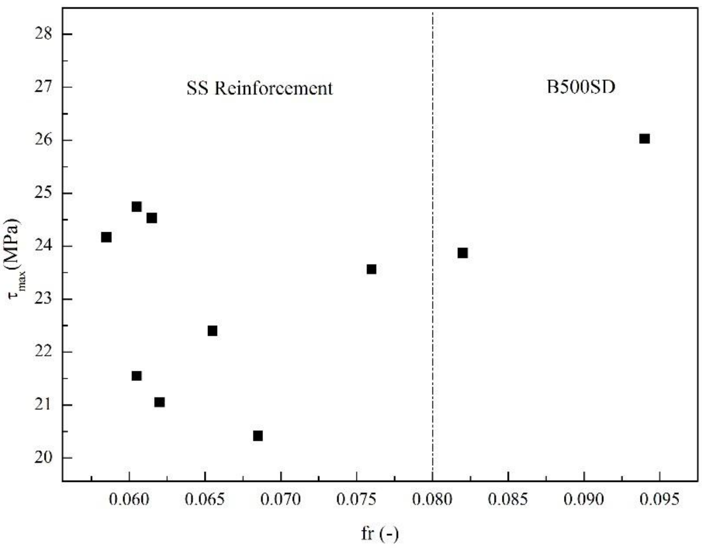

Fig. 5. Bond strength corresponding to different bond indexes.

A further variable that must be taken into account is the curing time that can also modify the maximum bond strength; the qualitative results of this effect on the bond strength of various 12 mm rebar steels are summarized in Fig. 6, after curing times of 3 and 9 months in a XS1 concrete, taking only the average values of 3 tests performed at 3 months and 2 tests performed at 9 months. The bond strength of B500SD decreased by 11.6% as the curing time lengthened and the same was true of 304 ASS where it decreased by 18.6%. The bond strength was not altered by the curing time in the case of 2205 DSS. The reinforcement bond strength was higher for the other specimens when cured over nine months. The maximum bond strength values were obtained for 2001 LDSS after 9 months curing time, for which a value of 27.43 MPa was recorded, showing an increase of 11.8%. In some cases, the resulting bond strength decreased with time, which happens because bond stress is not really uniform on the rebar surface-concrete interface. The bond stress is in fact higher in the rebar parts that are closer to the surface rather than deeper in the specimen. The higher the concrete stiffness, the lower the load distribution on the rebar surface. In this sense, other than simply increasing its strength, a longer curing time has additional effects on the concrete that include shrinkage, cracking, changing the strain-stress diagram, and stiffening. On the one hand, it means higher concrete strength, but on the other hand, less load redistribution on the rebar surface and progressive concrete failure that starts from the exterior. Thus, the final result, expressed only in terms of bond strength, depends on a balance between both concrete stiffness and curing time.

Another parameter under analysis was the concrete mixture. Fig. 7 summarizes the bond strength for different w/c ratios. The data plotted in the figure are the averaged values for 3 specimens, with different concrete w/c ratios after 3 months curing, with 12 mm rebar diameter, corresponding to a total of 18 pull out tests. In the B500SD reinforcements, the reduction of bond strength as the w/c ratio increased was notorious [56,57]: the τ_{max} of B500SD decreased by 28%, while 2205 DSS almost maintained its bond strength when w/c increased from 0.45 to 0.5, however τ_{max} decreased by 11% when the w/c ratio was increased to 0.55; a tendency that was also noted in [5] when testing GFRP bars in different types of concrete.

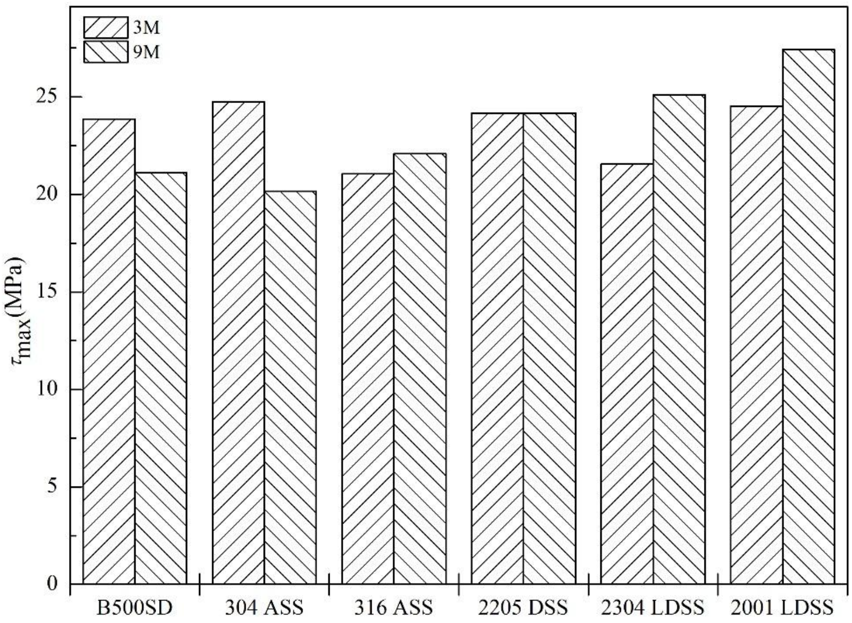

Fig. 6. Bond strength for different curing times.

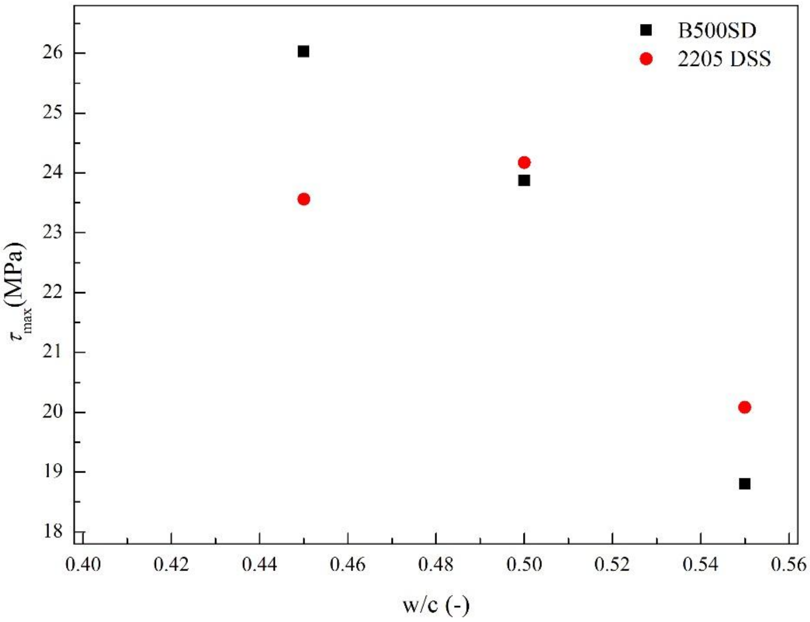

Fig. 7. Bond strengths of different concrete mixture.

Many research projects have studied the corrosive effects of bond strength, most of which studied the behaviour of B500SD. They all showed the same tendency; bond strength increased in the first stages of corrosion due to the tensile strength created by rust in the concrete; but, once the critical corrosion level had been reached, the bonding strength started to decrease [4,9,10].

Fig. 8 shows the i_{corr} values in relation to τ_{max}. It summarizes the pull-out test results of specimens that were not exposed to tidal environments and after 6 months in a tidal environment at a w/c ratio of 0.5. Examining the results of B500SD during the corrosion test, the i_{corr} values increased by 226%, moving from a zone of negligible corrosion to one of almost moderate corrosion. There was no increase in $\tau_{max,}$ despite the increased corrosion level; in fact, the bond strength decreased by 13%, suggesting that following a six-month period of exposure, the critical threshold value beyond which τ_{max} starts to decrease had been exceeded. The corrosion risk was evaluated in accordance with UNE 112072 [58] that assigns a corrosion risk in a concrete rebar depending on corrosion potential measurements based on ASTM Standard G102 [59], in this case taken by means of a Gecor8 Corrosimeter from GEOCISA. The state of corrosion was then derived from those measurements and the results are summarized in Table 4.

Table 4. Corrosion criteria for concrete rebars based on ASTM C876-91 and UNE 112072.

Resistivity [kΩ·cm]	Corrosion current density [μA/cm^2]	Associated Risk	Corrosion State
> 50	< 0.1	low	Passive
20 to 50	0,1 to 0,5	medium	Transition
< 20	0,5 to 1	High	Active
	> 1	Very High	Very Active

Apart from 304 ASS, the τ_{max} and the i_{corr} values of which increased by 53% and by 71%, respectively, the results obtained for the SS reinforcements were similar to those of B500SD. After 6 months exposure, the lowest reductions were obtained for 2205 DSS, while 2001 LDSS had an i_{corr} value that was three times higher, causing a decrease of 12% in τ_{max}. In the case of 2304 LDSS, a twofold increase in the i_{corr} values caused a reduction of 7.5% in τ_{max}.

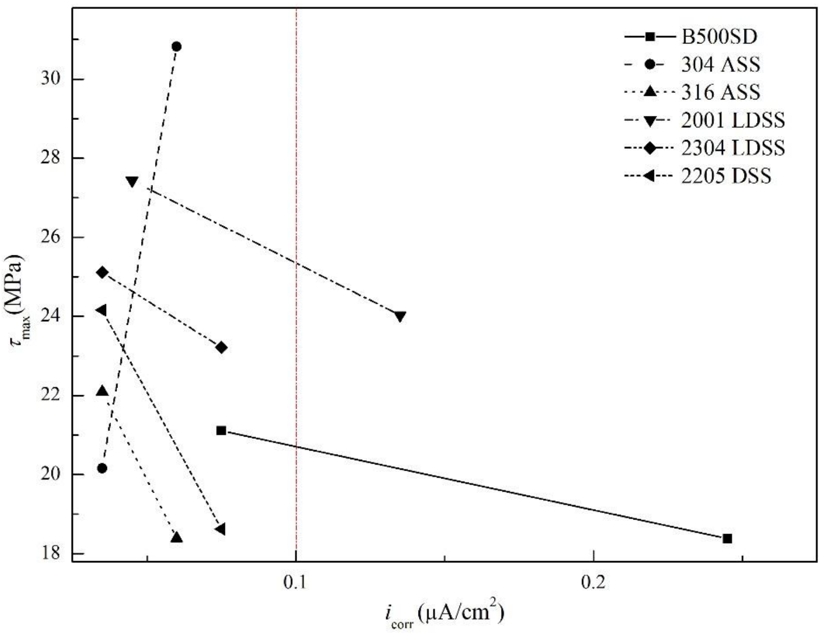

Fig. 8. Relation between bond strength and corrosion current density.

Bond failure can be due to three different mechanisms: rebar fracture (reinforcement fracture outside concrete), concrete splitting failure, and bar pull-out failure. The first failure mechanism is most likely to happen with high l_e/d_b values [47]. Besides, no specimen developed rebar fracture failure mode, which might be because l_e/d_b, anchorage length divided by rebar diameter, was quite low (l_e/d_b=5), although additional variables might be related with the absence of this failure mode. As observed in other studies [5,60], most specimens failed in the rebar pull-out tests (Fig. 9a). However, concrete splitting failure mode was detected in some specimens (Fig. 9b). It occurred in some of the first reference tests with 25 mm rebars, i.e. the 3 specimens of carbon steel rebars, 1 specimen of 2001 LDSS and 1 specimen of 2205 DSS. Besides, after 9 months of marine exposure, splitting also occurred in the 2 specimens of carbon steel and one of 2001 LDSS. The volume of this reinforcement rib was greater than the others and a higher bond strength that the concrete cannot support might have developed, causing concrete splitting. As observed in [47], some of the 25mm diameter stainless steel specimens failed due to concrete splitting.

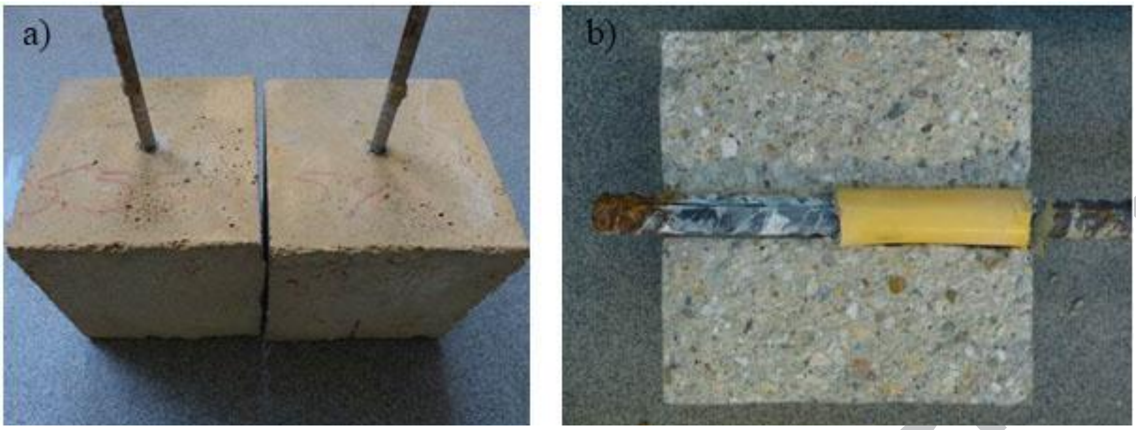

Fig. 9. a) Bar pull-out failure of two 2001 LDSS specimens after 3 months of exposure. b) A piece of the concrete specimen following splitting failure after the pull-out test on a 25mm diameter B500SD rebar.

4. Conclusions

The results of the pull-out tests have been presented, in a comparative analysis of the behaviour of various stainless steel rebars and standard B500SD rebars, having left the concrete specimens periodically in water with a chloride content of 3.5%, in a simulation of a tidal zone. The influence of curing time, concrete mixture (w/c ratio and cement content), rebar geometry, and different stainless-steel compositions have been considered in this study to assess their effects on bond strength.

1. Analysing the f_r factor, no relationship between f_r and τ_{max} was obtained for SS reinforcements. Although τ_{max} is assumed to increase with f_r, the results have shown that f_r is not a suitable test for SS reinforcement and that a new one should be developed. It appears to be defined as leverage for the use of carbon steel rebars and is not necessarily supported by a corresponding increase in τ_{max} during the service life of the structure.
2. The corrosion test results showed weaker improvements in the performance of 2001 LDSS when compared with the other SSR with higher nickel contents. However, the almost negligible i_{corr} values were within low corrosion limits,

demonstrating the suitability of 2001 LDSS as a reinforcement in marine environments.

3. When comparing the effects of curing time on τ_{max}, the latter parameter following longer curing times rose in LDSS, showing increases of 11.8% and of 16% in the respective cases of 2001 LDSS and 2304 LDSS
4. The analysis of the w/c ratio showed that an increased w/c ratio weakened the bond strengths of both B500SD and SSR. Compared with SSR, the strength of B500SD was twice as weak, showing a much worse behaviour throughout its service life.
5. Apart from 304 ASS which increased its τ_{max} after the corrosion test, probably in an initial stage of corrosion, corrosion decreased τ_{max} in the rest of specimens. Among the SSR specimens, the bond strength of 2001 and 2304 LDSS was weaker, even at higher i_{corr} values. This result suggests a better performance during service life in terms of bond strength, although all the SSR showed a τ_{max} over the required value.
6. Rebar pull-out failure was the main fracture mode observed in the tested specimens. However, concrete splitting failure mode was also detected in some specimens. It occurred in some of the first reference tests with 25 mm rebars, i.e. the 3 specimens of carbon steel rebars, 1 specimen of 2001 LDSS and 1 specimen of 2205 DSS. Besides, after 9 months of marine exposure, splitting also occurred in the 2 carbon steel specimens and one of the 2001 LDSS specimens.

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Islands) research project, in receipt of funding from the Centre for the Development of Industrial Technology (CDTI) and the Technological Fund, part of the Spanish Ministry of Industry, through the INNPRONTA research programme. The final goal of the project is to research different technologies for building off-shore island-cities, involving construction, energy and smart technologies with leading companies and research centres focused on each field. In the field of construction, the challenge is to develop modular construction and special marine reinforced concrete for the construction of islands that are capable of withstanding corrosive marine environments. In this context, most pathologies linked to reinforced concrete in marine environments are caused by rebar deterioration within the concrete and especially by chloride attack. The use of stainless steels is a very promising way to solve this problem, as has been demonstrated in several tests, among which those presented in this paper.

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References

[1] Jalili MM, Moradian S, Hosseinpour D. The use of inorganic conversion coatings to enhance the corrosion resistance of reinforcement and the bond strength at the rebar/concrete. Construction and Building Materials 2009;23:233-8 https://doi.org/10.1016/j.conbuildmat.2007.12.011.

[2] Model Code for Concrete Structures 2010. Bond and anchorage of embedded reinforcement. fib Bulletin 2010;72.

[3] UNE-EN ISO 15630. Steel for the reinforcement and prestressing of concrete - Test methods - Part 1: Reinforcing bars, wire rod and wire. European Standard 2011.

[4] Lin H, Zhao Y. Effects of confinements on the bond strength between concrete and corroded steel bars. Construction and Building Materials 2016;118:127-38 https://doi.org/10.1016/j.conbuildmat.2016.05.040.

[5] Bazli M, Ashrafi H, Oskouei AV. Experiments and probabilistic models of bond strength between GFRP bar and different types of concrete under aggressive environments. Construction and Building Materials 2017;148:429-43 https://doi.org/10.1016/j.conbuildmat.2017.05.046.

[6] Shen D, Shi X, Zhang H, Duan X, Jiang G. Experimental study of early-age bond behavior between high strength concrete and steel bars using a pull-out test. Construction and Building Materials 2016;113:653-63https://doi.org/10.1016/j.conbuildmat.2016.03.094.

[7] Yalciner H, Eren O, Sensoy S. An experimental study on the bond strength between reinforcement bars and concrete as a function of concrete cover, strength and corrosion level. Cement and Concrete Research 2012;42:643-55 https://doi.org/10.1016/j.cemconres.2012.01.003.

[8] Faleschini F, Santamaria A, Zanini MA, San Jose J, Pellegrino C. Bond between steel reinforcement bars and Electric Arc Furnace slag concrete. Mater Struct 2017;50:170-83 https://doi.org/10.1617/s11527-017-1038-2.

[9] Almusallam AA, Al-Gahtani AS, Aziz AR, Rasheeduzzafar,. Effect of reinforcement corrosion on bond strength. Construction and Building Materials 1996;10:123-9 https://doi.org/10.1016/0950-0618(95)00077-1.

[10] Fu X, Chung DDL. Effect of corrosion on the bond between concrete and steel rebar. Cement and Concrete Research 1997;27:1811-5 https://doi.org/10.1016/S0008-8846(97)00172-5.

[11] Cramer SD, Covino BS, Bullard SJ, Holcomb GR, Russell JH, Nelson FJ et al. Corrosion prevention and remediation strategies for reinforced concrete coastal bridges. Cement and Concrete Composites 2002;24:101-17 https://doi.org/10.1016/S0958-9465(01)00031-2.

[12] Aperador W, Mejía de Gutiérrez R, Bastidas DM. Steel corrosion behaviour in carbonated alkali-activated slag concrete. Corrosion Science 2009;51:2027-33 https://doi.org/10.1016/j.corsci.2009.05.033.

[13] Al-Mehthel M, Al-Dulaijan S, Al-Idi SH, Shameem M, Ali MR, Maslehuddin M. Performance of generic and proprietary corrosion inhibitors in chloride-contaminated silica fume cement concrete. Construction and Building Materials 2009;23:1768-74 https://doi.org/10.1016/j.conbuildmat.2008.10.010.

[14] Refait P, Jeannin M, Sabot R, Antony H, Pineau S. Corrosion and cathodic protection of carbon steel in the tidal zone: Products, mechanisms and kinetics. Corrosion Science 2015;90:375-82 https://doi.org/10.1016/j.corsci.2014.10.035.

[15] Konečný P, Lehner P. Durability assessment of concrete bridge deck considering waterproof membrane and epoxy-coated reinforcement. Perspectives in Science 2016;7:222-7 https://doi.org/10.1016/j.pisc.2015.11.036.

[16] Tang F, Chen G, Brow RK, Volz JS, Koenigstein ML. Corrosion resistance and mechanism of steel rebar coated with three types of enamel. Corrosion Science 2012;59:157-68 https://doi.org/10.1016/j.corsci.2012.02.024.

[17] Blunt J, Jen G, Ostertag CP. Enhancing corrosion resistance of reinforced concrete structures with hybrid fiber reinforced concrete. Corrosion Science 2015;92:182-91 https://doi.org/10.1016/j.corsci.2014.12.003.

[18] Li G, Yang B, Guo C, Du J, Wu X. Time dependence and service life prediction of chloride resistance of concrete coatings. Construction and Building Materials 2015;83:19-25 https://doi.org/10.1016/j.conbuildmat.2015.03.003.

[19] Bastidas DM, La Iglesia VM, Criado M, Fajardo S, La Iglesia A, Bastidas JM. A prediction study of hydroxyapatite entrapment ability in concrete. Construction and Building Materials 2010;24:2646-9 https://doi.org/10.1016/j.conbuildmat.2010.04.060.

[20] Wang X, Chen B, Gao Y, Wang J, Gao L. Influence of external loading and loading type on corrosion behavior of RC beams with epoxy-coated reinforcements. Construction and Building Materials 2015;93:746-65 https://doi.org/10.1016/j.conbuildmat.2015.05.101.

[21] Pokorný P, Tej P, Kouřil M. Evaluation of the impact of corrosion of hot-dip galvanized reinforcement on bond strength with concrete – A review. Construction and Building Materials 2017;132:271-89 https://doi.org/10.1016/j.conbuildmat.2016.11.096.

[22] Kobayashi K, Takewaka K. Experimental studies on epoxy coated reinforcing steel for corrosion protection. International Journal of Cement Composites and Lightweight Concrete 1984;6:99-116 https://doi.org/10.1016/0262-5075(84)90039-3.

[23] Assaad JJ, Issa CA. Bond strength of epoxy-coated bars in underwater concrete. Construction and Building Materials 2012;30:667-74 https://doi.org/10.1016/j.conbuildmat.2011.12.047.

[24] El-Hawary MM. Evaluation of bond strength of epoxy-coated bars in concrete exposed to marine environment. Construction and Building Materials 1999;13:357-62 https://doi.org/10.1016/S0950-0618(99)00042-2.

[25] Kayali O, Yeomans SR. Bond of ribbed galvanized reinforcing steel in concrete. Cement and Concrete Composites 2000;22:459-67 https://doi.org/10.1016/S0958-9465(00)00049-4.

[26] Pernicova R, Dobias D, Pokorny P. Problems Connected with use of Hot-dip Galvanized Reinforcement in Concrete Elements. Procedia Engineering 2017;172:859-66 https://doi.org/10.1016/j.proeng.2017.02.086.

[27] Hamad BS, Mike JA. Bond strength of hot-dip galvanized reinforcement in normal strength concrete structures. Construction and Building Materials 2005;19:275-83 https://doi.org/10.1016/j.conbuildmat.2004.07.008.

[28] Cheng A, Huang R, Wu JK, Chen CH. Effect of rebar coating on corrosion resistance and bond strength of reinforced concrete. Construction and Building Materials 2005;19:404-12 https://doi.org/10.1016/j.conbuildmat.2004.07.006.

[29] Roventi G, Bellezze T, Giuliani G, Conti C. Corrosion resistance of galvanized steel reinforcements in carbonated concrete: effect of wet–dry cycles in tap water and in chloride solution on the passivating layer. Cement and Concrete Research 2014;65:76-84 https://doi.org/10.1016/j.cemconres.2014.07.014.

[30] Rivera-Corral JO, Fajardo G, Arliguie G, Orozco-Cruz R, Deby F, Valdez P. Corrosion behavior of steel reinforcement bars embedded in concrete exposed to chlorides: Effect of surface finish. Construction and Building Materials 2017;147:815-26 https://doi.org/10.1016/j.conbuildmat.2017.04.186.

[31] Fajardo S, Bastidas DM, Criado M, Bastidas JM. Electrochemical study on the corrosion behaviour of a new low-nickel stainless steel in carbonated alkaline solution in the presence of chlorides. Electrochimica Acta 2014;129:160-70 https://doi.org/10.1016/j.electacta.2014.02.107.

[32] Bautista A, Paredes EC, Velasco F, Alvarez SM. Corrugated stainless steels embedded in mortar for 9years: Corrosion results of non-carbonated, chloride-contaminated samples. Construction and Building Materials 2015;93:350-9 https://doi.org/10.1016/j.conbuildmat.2015.04.060.

[33] Duarte RG, Castela AS, Neves R, Freire L, Montemor MF. Corrosion behavior of stainless steel rebars embedded in concrete: an electrochemical impedance spectroscopy study. Electrochimica Acta 2014;124:218-24 https://doi.org/10.1016/j.electacta.2013.11.154.

[34] Kouřil M, Novák P, Bojko M. Threshold chloride concentration for stainless steels activation in concrete pore solutions. Cement and Concrete Research 2010;40:431-6 https://doi.org/10.1016/j.cemconres.2009.11.005.

[35] Serdar M, Žulj LV, Bjegović D. Long-term corrosion behaviour of stainless reinforcing steel in mortar exposed to chloride environment. Corrosion Science 2013;69:149-57 https://doi.org/10.1016/j.corsci.2012.11.035.

[36] NACE International Institute. Maintenance and rehabilitation considerations for corrosion control of existing steel reinforced concrete structures. RP 0390-90 1990.

[37] Otero Huerta E. Corrosión y degradación de los materiales. Madrid: Síntesis, 2001.

[38] Keith CB. Duplex stainless steel in the pulp and paper industry. Anti-Corros Methods Mater 1997;44:170-4.

[39] Baddoo NR. Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research 2008;64:1199-206 https://doi.org/10.1016/j.jcsr.2008.07.011.

[40] Gedge G. Structural uses of stainless steel — buildings and civil engineering. Journal of Constructional Steel Research 2008;64:1194-8 https://doi.org/10.1016/j.jcsr.2008.05.006.

[41] King F. Corrosion Resistance of Austenitic and Duplex Stainless Steels in Environments Related to UK Geological Disposal. NDA RWMD 2009;v 1.2.

[42] Zanotto F, Grassi V, Balbo A, Monticelli C, Zucchi F. Stress corrosion cracking of LDX 2101® duplex stainless steel in chloride solutions in the presence of thiosulphate. Corrosion Science 2014;80:205-12 https://doi.org/10.1016/j.corsci.2013.11.028.

[43] Fajardo S, Bastidas DM, Criado M, Romero M, Bastidas JM. Corrosion behaviour of a new low-nickel stainless steel in saturated calcium hydroxide solution. Construction and Building Materials 2011;25:4190-6https://doi.org/10.1016/j.conbuildmat.2011.04.056.

[44] Fajardo S, Bastidas DM, Ryan MP, Criado M, McPhail DS, Bastidas JM. Low-nickel stainless steel passive film in simulated concrete pore solution: A SIMS study. Applied Surface Science 2010;256:6139-43 https://doi.org/10.1016/j.apsusc.2010.03.140.

[45] Briz Blanco E. Evaluation of 2205 duplex stainless steel and 2001 lean duplex stainless steel reinforcements behaviour under stress corrosion cracking in chloride contained simulated concrete pore solution. Ph D Thesis 2016.

[46] Knudsen A, Jensen FM, Klinghoffer O, Skovsgaard T. Cost-effective enhancement of durability of concrete structures by intelligent use of stainless steel reinforcement. 1999:15.

[47] Zhou Y, Ou Y, Lee GC. Bond-slip responses of stainless reinforcing bars in grouted ducts. Engineering Structures 2017;141:651-65 https://doi.org/10.1016/j.engstruct.2017.03.049.

[48] Eurocode 2. Design of concrete structures - Part 1-1: General rules and rules for buildings. European Standard 2015.

[49] UNE-EN 206-1. Concrete - Part 1: Specification, performance, production and conformity. European Standard 2008.

[50] Orangun CO, Jirsa JO, Breen JE. A reevaluation of test data on development length and splices. ACI Journal 1977;77:114-22.

[51] Kemp EL. Bond in reinforced concrete: behavior and design criteria. ACI Journal Proceedings 1986;83:50-7.

[52] Chapman RA, Shah SP. Early-age Bond Strength in Reinforced Concrete. ACI Materials Journal 1987;84:501-10.

[53] UNE-EN 10088-1:2006. Stainless steels - Part 1: List of stainless steels. European Standard 2006.

[54] UNE-EN 10080. Steel for the reinforcement of concrete - Weldable reinforcing steel - General. European Standard 2006.

[55] UNE-EN ISO 11130. Corrosion of metals and alloys - Alternate immersion test in salt solution . European Standard 2011.

[56] Ergün A, Kürklü G, Başpınar MS. The effects of material properties on bond strength between reinforcing bar and concrete exposed to high temperature. Construction and Building Materials 2016;112:691-8 https://doi.org/10.1016/j.conbuildmat.2016.02.213.

[57] Bilek V, Bonczková S, Hurta J, Pytlík D, Mrovec M. Bond Strength Between Reinforcing Steel and Different Types of Concrete. Procedia Engineering 2017;190:243-7 https://doi.org/10.1016/j.proeng.2017.05.333.

[58] UNE 112072. Laboratory measurement of corrosion speed using the polarization resistance technique. European Standard 2011.

[59] ASTM-G102-89. Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements. American Society for Testing and Materials 2015.

[60] Hou L, Liu H, Xu S, Zhuang N, Chen D. Effect of corrosion on bond behaviors of rebar embedded in ultra-high toughness cementitious composite. Construction and Building Materials 2017;138:141-50 https://doi.org/10.1016/j.conbuildmat.2017.02.008.