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Bonding strength of stainless steel rebars in concretes exposed to marine environments

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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.

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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.

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

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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% and 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 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.

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 180°, 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

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