ADHERENCE BETWEEN STAINLESS STEEL REBARS AND LOW BINDER CONCRETE

Emanuel Rocha Freitas

ABSTRACT

To ensure the sustainability of the construction sector, it is mandatory to reduce the Portland cement content in concrete mixtures, although ensuring the required design compressive strength, giving rise to the herein called ‘low binder concrete’ (LBC).

One of the expressions that have to be analyzed first refers to the rebar-to-LBC bond strength, since this stands as the main pillar of the reinforced concrete concept. For this reason, it was decided to settle it as the main goal of the study herein presented.

The bonding characterization was assessed by means of 60 pull-out tests using specimens prepared according to Annex D of EN 10080:2005. The reference specimens were produced with C25/30 concrete and S500NR SD steel rebars with 12 and 16 mm of diameter.

Results are discussed and conclusions are presented, as well as a new design expression based on the one adopted by *fib* Model Code 2010, aiming at better predict the rebar-to-LBC bonding strength.

KEYWORDS: Sustainability, low binder concrete, stainless steel rebars, bond

1. INTRODUCTION

1.1. Scope

The environmental impact of concrete has always been pointed out as a disadvantage for this structural material. In fact, Portland cement is the second most consumed product worldwide, immediately after water, and each ton produced is responsible for an emission of almost the same amount in mass of CO_2. Nowadays, with an increasing environment awareness, it is important to find new solutions to minimize this impact. The most direct approach is to develop an eco-efficient concrete by reducing its cement content but keeping the required mechanical and durability properties. In the present paper, this Low Binder Concrete (LBC) concept is explored. This name has been attributed since the cement content of all the mixtures herein presented are below the minimum prescribed in EN 206-1:2007, which is 260 kg/m^3 or higher, depending on the exposure class of concrete elements. Lastly, it should be stated that, since durability tests were out of the scope of the present study, to cope with this requirement, stainless steel reinforcing bars (rebars) were adopted.

1.2. Goals and Methodology

The main goal of the study herein described was to characterize the bond between stainless steel and LBC, which depends on both characteristics of the rebars and the mechanical properties of concrete.

Sixty pull-out tests were performed using specimens prepared according to Annex D of EN 10080:2005. All results were compared with those obtained with reference specimens produced with current materials, namely C25/30 concrete and S500NR SD steel rebars with 12 and 16 mm of diameter.

2. STATE OF ART

2.1. Low binder concrete mixtures

Packing density is strongly linked to the concrete mixtures. Fennis et al. (2009) state that aggregates should be chosen to fit in the voids of the bigger ones. In another study [Fennis et al. (2012)], the same authors claim that the fillers chosen to replace part of Portland cement should increase the packing density value because, otherwise, they will increase the water demand and, consequently, concrete will have lower properties. Proske et al. (2014) also state that adding fillers to a concrete mixture provides an ideal binder paste.

The quantity of water present in a mixture is also related to the packing density, being important to separate the water demand to fulfill the voids between particles and the water demand to provide workability. According to Fennis and Walraven (2012), if a concrete mixture is optimized to have a higher packing density, less water is required to fulfill the voids between particles. Therefore, it is possible to develop concrete mixtures with the same workability and lower water/cement ratio.

Coutinho (1988) state that a mixture with the highest compressive strength is obtained with the highest packing density and the lowest quantity of water.

Proske et al. (2014) concluded that the loss of compressive strength, as a result of cement reduction, can be compensated with less water or with the use of higher class cements.

According to Fennis (2011), the compressive strength can also be used to classify LBC, because the relationships between cube compressive strength, tensile splitting strength, and Young’s modulus correspond to those for normal concrete.

2.2. Bond between rebar-concrete

As described in *fib* Model Code 2010, bond is the term used to denote the interaction and transfer of force between reinforcing and concrete, which influences performance of concrete structures. At the serviceability limit state, it influences width and spacing of transverse cracks, tension stiffening and curvature and at the ultimate limit state, it is responsible for strength of end anchorages and lapped joints of reinforcing bars, and influences rotation capacity of plastic hinge regions.

2.2.1. Parameters influencing bond

Bond between steel rebars and concrete depends on the characteristics of both materials, such as rebars' diameter, ribs' geometry, and concrete's strength. The influence of concrete's cover [Gavilán et al. (2014) and Muttoni e Ruiz (2012)] and rebars' corrosion [Cairns et al. (2007), Fischer and Ožbolt (2012)] has been also studied.

The rib's geometry has a major influence in bond strength, because the mechanical interlocking between rebars and concrete is achieved by means of transversal ribs. André and Pipa (2010) refer that, according to CEB-FIP Model Code 90, there are 10 parameters that influence the bond strength, including roughening and rib's geometry. These authors concluded that a local change in ribs' geometry, namely due to the brand's name graving ('ARCER'), has a negative influence in bond strength.

Some authors [Lorrain et al. (2010) and Filho et al. (2012)] studied the influence of rebars' geometry, such as height, inclination of ribs' face, and ribs' spacing, on the bond strength through pull-out tests on rebars with 12 mm of diameter. The main conclusion is that ribs' geometry is essential to the adherence between both materials and have obtained a linear relationship between maximum bond stress and maximum height of ribs.

Concrete strength also has an important role in bond behavior, because concrete between ribs is subjected to high stresses leading to splitting and crushing. According to Louro (2014), Eligehausen et al. (1983) concluded that there is an inverse relationship between concrete's compressive strength and slipping and a direct relationship between concrete's compressive strength and bond strength. Also according to *fib* MC2010, the maximum bond stress depends on concrete's compressive strength, given by Equation (2.1):

$$\tau_{máx} = 2{,}5 \times \sqrt{f_{cm}} \qquad (2.1)$$

3. EXPERIMENTAL PROGRAM

3.1. Concrete mixtures

The materials used in all concrete mixtures were the followings: Portland cement CEM I 52.5 R, limestone filler, fly ash, superplasticizer BASF Glenium Sky 526, three sands (0/3, 0/4_I and 4/8) and one gravel1 6/14.

The adopted mixture design method is reported in Lourenço et al. (2004). For mixtures LBC, Faury and Funk and Dinger curves were used. With the first one, the quantity of gravel presented in the mixture was higher than for Funk and Dinger curve. Thus, to compensate this result, it would have been necessary to consider a larger quantity of binder, which would go against the purpose of LBC mixtures. For this reason, the Faury curve was used only for the reference mixtures, while Funk and Dinger curve was used for LBC mixtures, being all compositions presented in Table 3.1. The packing density of LBC mixture is higher than the reference mixture, with 0.86 and 0.81 respectively.

Table 3.1 – Mix design of all concrete mixtures

		C250 (Faury)	LBC125	LBC75
CEM I – 52.5 R	(kg/m^3)	250.00	125.00	75.00
Limestone filler	(kg/m^3)	100.00	125.00	75.00
Fly ash	(kg/m^3)	-	-	100.00
***Basf Glenium Sky* 526 [% kg/kg CEM I]**	(%)	0.40	2.00	3.00
Sand 0/3	(kg/m^3)	492.00	44.00	43.50
Sand 0/4_I	(kg/m^3)	427.40	1080.10	1067.60
Sand 4/8	(kg/m^3)	116.40	287.20	283.90
Gravel1 6/14	(kg/m^3)	795.40	630.60	623.30
Water	(kg/m^3)	169.10	117.64	117.90
Water/cement ratio	(-)	0.68	0.94	1.57
Water/binder ratio	(-)	0.48	0.47	0.47
Packing Density	(-)	0.81	0.86	0.86
Air	(%)	2.00	2.00	2.00

3.2. Reinforcing bars

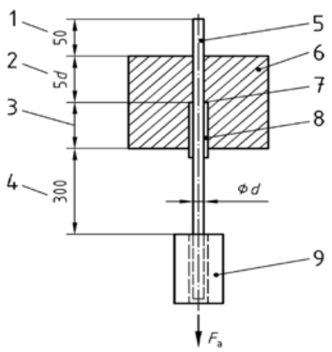
Stainless steel rebars AISI304 with 12 mm diameter and AISI316 with 16 mm diameter were used, as well as current steel rebars S500NR SD with 12 and 16 mm diameter to serve as reference.

3.3. Bond between rebars and concrete

For bond characterization between stainless steel rebars and LBC mixtures, pull-out test were performed. The pull-out specimens and the testing procedure were based on the method described in annex D of EN 10080:2005, which follows the recommendations of RILEM/CEB/FIP – Bond test for reinforcement steel (1983). The pull-out specimen is illustrated in Figure 3.1.

Pull-out tests were conducted with 60 specimens combining the following three influencing variables: concrete type (C250, LBC125 and LBC75), rebar's diameter (12 and 16 mm), and steel type (S500 NR SD and AISI). Five identical specimens were considered for each situation.

Tests were performed with a constant slipping speed of 0.03 mm/s, thus ensuring conservative results of bond stress, and were ended when a 20 mm slip was reached.



1. part of the bar up to the point of application of the displacement measuring device
2. bond length
3. free pre-length 5Ø, min. 200 mm -5Ø
4. part of the bar to the point of application of the tension force
5. reinforcing bar
6. concrete
7. lugging
8. plastic sleeve
9. grip of the testing machine

Figure 3.1 – Illustration of the pull-out test principle (EN 10080:2005 – annex D)

The bond stress was obtained from measured values using Equaton (3.1):

$$\tau_{dm} = \frac{F_a}{5 \times \pi \times Ø^2} \frac{f_{cm}}{f_j} \quad (3.1)$$

where

- F_a is the tension force (kN);
- Ø is the rebar diameter;
- f_{cm} is concrete strength at 28 days;
- f_j is the concrete strength at the day test.

Note that f_j is estimated from measured values of the compressive strength obtained with two cubes tested at 3, 7, 14, 56 and 84 days and three cubes tested at 28 days and taking into account the EC2 (2010) hardening curve.

4. RESULTS DISCUSSION

4.1. Fresh and hardened concrete properties

The workability was first measured with the slump test, according to EN 12350-2:2002, but for LBC mixes this test is not suitable. According to the standard test, if two consecutive tests show a portion of the concrete shearing off from the mass of the test specimen, the concrete lacks the necessary plasticity and cohesiveness for the slump test to be suitable. Therefore, the workability evaluation was tested by Alves (2016) and was measured according to EN 12350-4:2002 - degree of compactability.

Results of fresh and hardened concrete properties of the three mixes are detailed in Table 4.1. The workability of C250 was S2/S3 whereas both LBC mixtures presented a C2 compactability class.

Table 4.1 - Fresh and hardened concrete properties

	C250	**LBC125**	**LBC75**
Rheological properties			
Slump (mm)	60 e 110	140* e 160*	-
Degree of compactability [Alves (2016)]	-	1.23	1.21
Mechanical properties			
3-days cube compressive strength (MPa)	27.7	22.7	-
4-days cube compressive strength (MPa)	-	-	10.6
7-days cube compressive strength (MPa)	32.3	26.0	14.5
14-days cube compressive strength (MPa)	35.7	29.4	17.4
28-days cube compressive strength (MPa)	38.4	31.9	20.9
56-days cube compressive strength (MPa)	40.0	32.9	24.4
84-days cube compressive strength (MPa)	40.8	33.8	24.6

*Do not represent a real slump

4.2. Reinforcing bars

Rebars properties are detailed in Table 4.2, including maximum rib's height ($a_{1/2}$), free length between ribs (c_{free}), relative ribs' area (f_R) and the minimum values of f_R according to EC2 (2010) and LNEC E460 (2010). Each value correspond to the average of three tests of identical specimens. All the f_R values obtained with the rebars used in this study are higher than the standard minimums. The highest value corresponds to the 12 mm diameter rebar of S500NR SD class. For this reason, the latter was expected to lead to the highest bond strength.

Table 4.2 - Ribs geometry of tested rebars

Diameter (mm)	Class	$a_{1/2}$ (mm)	C_{free} (mm)	f_R	Minimum standard values	
					EC2 (2010)	LNEC E460 (2010)
12	S500NR SD	1.07	7.8	0.082	0.056	0.040
	AISI304	0.67	6.7	0.058		
16	S500NR SD	1.18	10.8	0.066	0.056	0.056
	AISI316	1.06	10.2	0.066		

4.3. Characterization of rebar-concrete bond

The maximum bond stress values (τ_{dm}) were calculated according to Equation (3.1). Average bond stress values ($\tau_{d,average}$) were also evaluated according to Equation (4.1), presented in Annex C of EC2 (2010).

$$\tau_{d,average} = \frac{\tau_{0.01} + \tau_{0.1} + \tau_{1.0}}{3} \tag{4.1}$$

where, $\tau_{0.01}$, $\tau_{0.1}$ and $\tau_{1.0}$ represent the bond stress at 0.01, 0.1 and 1 mm slip, respectively.

Table 4.3 – Maximum and average bond stress values, after statistical analysis

	Average values (MPa)	
	$\tau_{d,average}$	$\tau_{d,maximum}$
C250_A12	9.50	21.13
C250_i12	6.79	15.68
C250_A16	7.68	19.19
C250_i16	7.35	17.63
LBC125_A12	11.21	24.76
LBC125_i12	9.80	21.84
LBC125_A16	10.77	22.59
LBC125_i16	10.68	21.73
LBC75_A12	9.23	22.49
LBC75_i12	6.55	15.89
LBC75_A16	8.81	18.93
LBC75_i16	7.42	16.69

According to ISO 3534:1993 (Burke, 2005), extreme values, i.e., values quite different from the remainders, suggesting belonging to a different population or the result of an error in measurement, must be eliminated. Burke (2005) suggests the use of the median instead of the average, because robust statistics are the ones that remain unaffected by the presence of extreme values, and this is achieved with the former. In the present study, a t-student distribution with 99 % confidence interval was used. The results that were outside the outliers were eliminated and average bond stress values are detailed in Table 4.3.

The influence of each parameter, such as relative ribs area, maximum ribs height, compressive concrete strength and packing density of the mixtures, were individually analysed. From this point onwards, the symbols presented in Figure 4.1 apply; the type of concrete is represented by a triangle, a full square, or an empty square; to the S500NR SD steel corresponds the letter ‘A’; to the stainless steel corresponds the letter ‘I’; finally, the diameter is represented by the number ‘12’ or ‘16’.

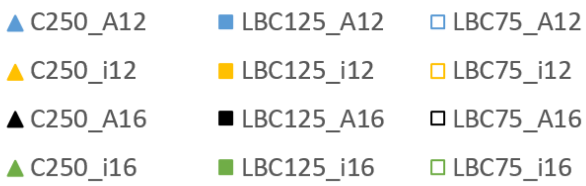


Figure 4.1 – Symbols for each situation tested (type of concrete, type of steel, and diameter)

4.3.1. Relative ribs area

For rebars with 12 mm diameter, the increase of the bond strength with the increase of f_R is clear. Regarding rebars with 16 mm diameter, both types of steel have the same f_R value and thus results should be identical. Nevertheless, there is difference in bond strength that reaches 2.2 MPa for LBC75 mixture. This might be related with the fact that, although having the same f_R value, the rib geometry is different, being the maximum rib height of S500NR SD higher than that of AISI316.

4.3.2. Compressive strength of concrete

Three different concrete mixtures with different compressive strength were tested with the purpose of studying the influence of the latter on bond strength. Figure 4.2 shows an unexpected behavior between mixtures LBC125 and C250, since the increase in compressive strength is not followed by an increase in bond strength. It is believed that packing density assumes a relevant role on bond strength behavior.

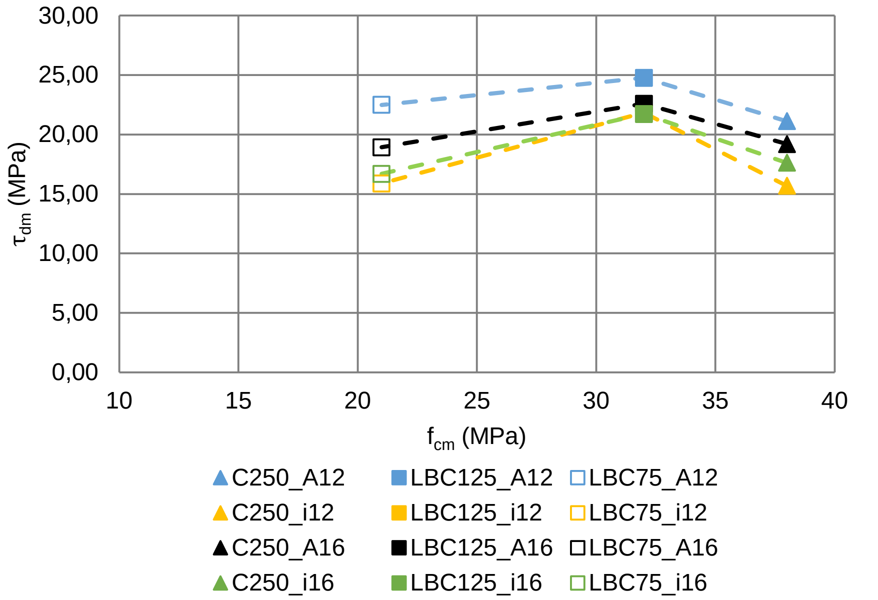


Figure 4.2 – Influence of concrete compressive strength on bond stress results

4.3.3. Bond strength prediction according to *fib* Model Code 2010

In this section, experimental results are compared with those predicted by *fib* MC2010, being the resulting curve plotted in Figure 4.3 with a red layer. Comparing the experimental results of bond stress-slip relationship with *fib* MC2010 curve (Figure 4.3), it is clear that there is a very significant difference between them. For all mixtures, the maximum bond strength predicted by *fib* MC2010 is quite below the corresponding experimental value.

The *fib* MC2010 prediction of the bond strength only takes into account the compressive strength of concrete mixtures. In order to improve the prediction, and taking into account the conclusions referred to in previous sections, it is herein proposed to modify the *fib* MC2010 equation in order to consider the concrete compressive strength combined with the concrete packing density and the relative ribs area of rebars.

Regarding f_R, section 6 of *fib* MC2010 states that the curve adopted applies for $f_R > f_{R,min}$, which according to EC2 (2010) takes the value of 0.056. Herein, it is proposed a corrective factor $k_{f_R} = \frac{f_{R,j}}{0.056}$ calibrated with the results obtained with C250 and LBC mixtures. The packing density also showed a significant influence in bond strength and, thus, a second corrective factor $k_\sigma = \sigma_j[\%] - 0.81$ is proposed, calibrated with the results also obtained with C250 and LBC mixtures.

Taking everything into account, it is suggested that the bond strength be predicted according to Equation (4.2):

$$\tau_{máx} = 2.5 \times \sqrt{f_{cm}} \times k_{f_R} + k_\sigma \qquad (4.2)$$

A good match between values predicted using Equation (4.2) and experimental results can be checked both in Table 4.4 and Figure 4.3.

Table 4.4 - Comparison of (4.2) expression values with experimental results

	f_R	Packing density, σ	f_{cm} (MPa)	$\tau_{d,maximum}$ (Mpa)	Eq. (4.2) (MPa)	Δ (%)
C250_A12	0.0823	0.81	38.4	21.13	22.78	8
C250_i12	0.058		38.4	15.68	16.05	2
C250_A16	0.066		38.4	19.19	18.27	-5
C250_i16	0.066		38.4	17.63	18.27	4
LBC125_A12	0.0823	0.86	31.9	24.76	25.72	4
LBC125_i12	0.058		31.9	21.84	19.60	-10
LBC125_A16	0.066		31.9	22.59	21.62	-4
LBC125_i16	0.066		31.9	21.73	21.62	-1
LBC75_A12	0.0823	0.86	20.9	22.49	21.75	-3
LBC75_i12	0.058		20.9	15.89	16.81	6
LBC75_A16	0.066		20.9	18.93	18.44	-3
LBC75_i16	0.066		20.9	16.69	18.44	10

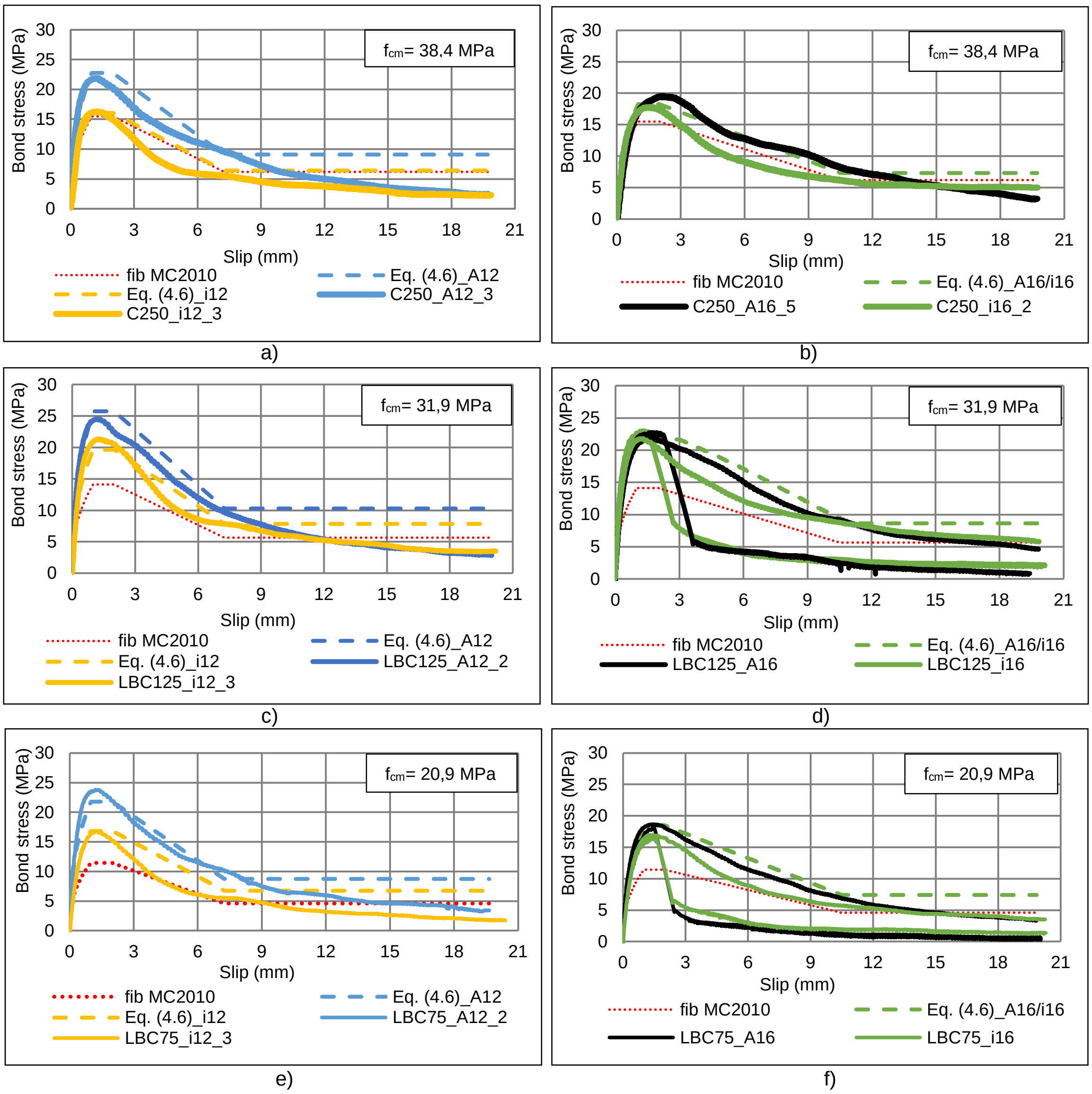


Figure 4.3 - Comparison of bond stress-slip relationships between *fib* MC2010, Equation (4.2) and experimental results

5. CONCLUSIONS

Bond between rebar and concrete is one of the most relevant parameters for reinforcing concrete structures. For this reason, to check the validity of the corresponding predictive equation of *fib* MC2010 defined for current concretes before widening the scope to include other concrete types, such as LBC, is absolutely mandatory. This was the main goal of the study herein described and the main conclusions drawn from the latter are the following:

- The effect of f_R was evident, and this parameters continue to be a fundamental parameter in adherence value. Bond value increase with the increase of f_R;
- The influence of compressive strength on bond value is evident when the results of LBC75 and LBC125 are compared. It is believe that compressive strength is not the only parameters related to the concrete properties that influence directly bond value. Comparing the results between LBC125 and C250, where there is an increase of compressive strength from 32 to 38 MPa, the value of bond strength decrease. Even more, the reached bond value between LBC75 and C250, which have 21 and 38 MPa respectively, are identical;
- Packing density might be responsible by the increase of bond stress;
- There is not a good relationship between *fib* Model Code 2010 theoretical curve and the experimental results;
- Two corrective factors are proposed and showed a good relationship between (4.2) values and experimental results, where:

$$\tau_{máx} = 2.5 \times \sqrt{f_{cm}} \times k_{f_R} + k_\sigma \tag{4.2}$$

where,

$$k_{f_R} = \frac{f_{R,j}}{0.056}$$

$$k_\sigma = \sigma_j[\%] - 0.81$$

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