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NEW VIEWS ON THE STUDY OF VARIABLES AFFECTING BOND OF REINFORCING BARS TO STEEL FIBER REINFORCED CONCRETE

Emili García Taengua*, Leticia Mas*, José R. Martí Vargas*, and Pedro Serna Ros*

* ICITECH – Institute of Concrete Science and Technology, Universitat Politècnica de València
Camí de Vera, s/n – 46022 València, Spain
e-mail: emgartae@upvnet.upv.es, lemagis@gmail.com, jrmarti@cst.upv.es, pserna@cst.upv.es

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Summary: Fibers have a positive effect on bond of rebars to concrete since they clearly improve bond capacity in terms of ductility although their influence on bond strength, i.e. peak bond stress, is of relatively little importance. This paper reports the results of two series of pullout tests carried out on prismatic specimens made with two different SFRCs (required compressive strengths of 25 MPa and 45 MPa respectively) and comprehensively analyses the effect of four factors (fiber geometry and content, concrete cover, and rebar diameter) upon bond performance. In order to come to conclusions that can be considered as statistically reliable, all results have been analyzed by means of statistical inference based on multiple linear regression models. Furthermore, having some specimens where concrete splitted before the rebar was pulled out, the effect of the aforementioned factors on the probability of splitting has been analyzed by means of logistic regression. It has been shown that the role fibers play in bond of rebars to concrete is of the same importance as that of concrete cover. It is especially remarkable that the mere fact of adding fibers, no matter the amount, decreases the probability of splitting and increases the ductility of bond failure considerably, this underlining the role of fibers in bond performance as passive confinement.

1 INTRODUCTION

Fibers are widely recognized to have a positive effect on bond of steel reinforcing bars in concrete. Such a positive effect is observed even with low fiber contents [1] and is being gradually assumed by codes. The most recent version of the Spanish code for structural concrete [2] recognizes that fibers improve bond conditions and states that this may be taken into account. A very similar statement is found in ACI 408R-03 [3] with respect to the expressions provided by ACI 318-11 [4] for determining development lengths.

Fibers improve concrete bond capacity by confining the bars (their role being similar to that of stirrups) and by widening the range of crack widths within which this confinement remains active [1,5]. Although their influence on bond strength (peak bond stress) is of relatively little importance, several authors have agreed that fibers improve bond capacity mainly in terms of ductility. This is the reason why the authors have introduced [6] bond parameters which are representative of bond performance in terms of ductility, such as areas under the bond stress-slip curve.

Some investigations state that the positive effect of fibers on bond is not significant when the mode of failure is due to pullout but it is when there is splitting. As a matter of fact, when there is splitting the effect of fibers is important [7,8]. In addition, some authors state that adding fibers does not significantly affect the bond strength in normal- and middle- strength concretes [5,9] (compressive strength values up to 50 MPa).

Studies on bond of rebars in SFRC have usually considered only one or two variables and have analyzed their effect on bond behaviour in a 1-to-1 fashion rather than in a thorough, multivariate, comprehensive context. Furthermore, bond behaviour is usually understood in terms of only bond strength instead of considering other parameters which are equally or perhaps more significant when it comes to describe the reponse of bars being anchored.

The objective of this research was to comprehensively study the effect of four different factors (fiber type, fiber content, concrete cover, and reinforcing bar diameter) in addition to compressive strength upon SFRC bond capacity and ductility in order to come to reliable and statistically supported conclusions.

2 EXPERIMENTAL PROGRAM

2.1 Materials

Two mix designs, named A and B, have been considered in this research. Their specified compressive strengths were 25 MPa and 45 MPa respectively. Since these values can be regarded as typical in most applications, they center the research in the background of normal or middle strength concretes.

As a consequence of fiber content and fiber type being considered as variables in this research, a variety of different mixes based on these base mix designs were to be produced. High-range water-reducing admixture and limestone filler have also been used and adjusted in each particular case, depending on the fiber type and content, to have very fluid mixes though securing no segregation would happen. This was decided so in order not to vibrate concrete. Vibration was thought unconvenient as a consequence of using fibers and the moulds being of reduced size: vibration could have led to reorientation of fibers, which might interfere with bond performance.

Table 1 summarizes the composition of base mix designs, A and B. Both the cement type and the water / cement ratio fit within the ranges that are usual in regular construction. In the case of A mixes, the coarse aggregate / sand ratio is nearly 1 to have good levels of cohesion to work with different levels of fibers and admixture and not risk segregation. In the case of B mixes, the strategy was a bit different: by adjusting both admixture and filler content. Cement content was also slightly varied depending on the amount of fibers considered (+/-20 kg/m^3), though water was always varied accordingly in order not to have water / cement ratio modified.

Table 1 : Definition of base mix designs considered.

	Type A mixes	Type B mixes
Specified compressive strength	25 MPa	45 MPa
Cement type	CEM II/B-M 42.5 R	
Water / cement ratio	0.60	0.45
Cement content	325 kg/m^3	440 kg/m^3
Coarse aggregate / sand ratio	0.90	0.70
Sand type	River limestone	Crushed limestone
Coarse aggregate type	Crushed limestone 7/12 and 12/20	Crushed limestone 7/12

2.2 Variables Considered

The variables considered as factors in this study as well as their different values are summarized in Table 2. The levels these factors have been considered at are not exactly the same for type A mixes and type B mixes. This was decided in order to have the variables tested at as many levels as possible at the same time the door is open to complete the experiment and analyze each group of mixes separately in the future.

Compressive strength of concrete is indirectly defined as a variable by having two groups of mixes: those that are derived from base mix design A (type A mixes hereafter), and those from base mix design B (type B mixes hereafter). It is true that the effect of compressive strength on bond strength is well known [5]. However, it is introduced as a variable in this research for two reasons: a) its effect upon other bond parameters is not so very well known, and b) it may interact with the other variables considered and have a synergic effect.

Cold drawn hooked-end steel fibers which are different in terms of slenderness and length have been used. With respect to fiber content, it has been kept in all cases not greater than 70 kg/m^3. This maximum content was chosen bearing in mind that fiber contents in typical applications are rarely greater than 1% in volume (78 kg/m^3). It has also been considered as reference a virtual fiber content of 0 kg/m^3.

Nominal diameters chosen for reinforcing bars are all of them usual both in common buildings and in the precast concrete industry. The nominal yield strength of reinforcement has not been considered as one more variable, using reinforcing bars with a yield strength of 500 MPa in all cases.

Concrete cover as a variable in the context of this research is defined as shown in Figure 1, where it is named C. Three different levels have been considered for the concrete cover:

- C1 = 30 mm is the minimum value required by the Spanish code [2] for reinforcing bars in a precast element with a compressive strength of 25 MPa. In the case of type B mixes C1 was not 30 mm but 2.5 times the rebar diameter, D, to widen the number of different concrete cover values finally considered in the experiment.
- C2 is the average of C1 and C3.
- C3 is five times the nominal diameter of the reinforcing bar, D, which corresponds to a good confinement according to Model Code [10].

Table 2 : Variables considered and their values.

	Type A mixes	Type B mixes
Type of fibers (slenderness / length)	65 / 60 80 / 50	45 / 50 80 / 50 80 / 35
Fiber content	(0 kg/m^3) 40 kg/m^3 70 kg/m^3	(0 kg/m^3) 40 kg/m^3 60 kg/m^3
Rebar diameter (D)	8 mm 16 mm 20 mm	8 mm 12 mm 16 mm
Concrete cover (C)	C1 = 30 mm	C1 = 2.5 x D
	C2 is average C3 = 5 x D	

2.3 Design of Specimens for the Pull Out Test

Prismatic pullout specimens have been produced and tested, their cross-section following the general pattern shown in Figure 1. Dimensions were different in each particular case, depending on the reinforcing bar diameter and the concrete cover value. However, cross-section is never less than 150 x 150 mm^2 and in all cases the distance between the rebar and the most distant surface is not less than five times the diameter, to guarantee a good confinement in 2 out of the 4 semi-axes centered in the rebar.

The longitudinal dimensions (total length, and embedded length) were defined according to the RILEM recommendations in relation to the pull out test [11,12]. According to these recommendations, the embedded length is to be five times the nominal diameter of the reinforcing bar, and the total length of the specimen no less than 200 mm. Figure 1 (right) and Table 3 together summarize the longitudinal dimensions of all pullout specimens produced and tested for this research, the position (and therefore height) of the reinforcing bar varying as a result of the concrete cover being a variable.

Table 3 : Longitudinal dimensions.

Rebar nominal diameter D, mm	Total length L_T, mm	Embedded length L_E, mm
8	200	40
12	200	60
16	200	80

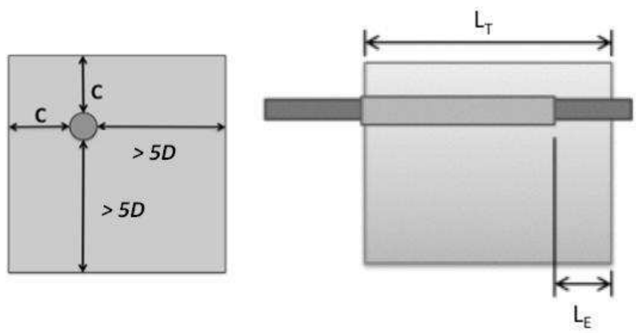

Figure 1: Cross-section (left) and longitudinal section (right) of specimens for pull out test.

2.4 Definition of Cases to Be Tested

Not all possible combinations of the levels considered for the variables in this research (Table 2) have been tested. The combinations tested are listed in Table 4 and were selected with the help of orthogonal arrays and derived factorial plans [13,14]. As a consequence, the number of combinations to be tested becomes affordable without affecting the reliability of conclusions to be drawn from the results. As the research reported herein was still in progress at the time of writing, three out of nine combinations concerning type B mixes that have not yet been tested are not included, whose results will complete this study in the near future.

To make conclusions more reliable, each test was not carried out only once: three specimens from each combination were produced and tested. As a consequence, values for the bond parameters considered as outputs for each one of the combinations tested are well defined, analyses are carried out on a set of reliable data and the quality of statistical inference to come to conclusions is highly assured.

2.5 Mixing, Production, and Testing of Specimens

Mixing, production, and testing of all specimens for the pull out test were carried out in the same, controlled way (including timing) in all cases in order to avoid any possible uncontrolled interference that might affect the results. Components were poured into the mixer following this sequence: aggregates and filler, cement, water, fibers, and high-range water-reducing admixture.

Sleeves were used to control the embedded length (L_E in Figure 1, right). In addition to prismatic specimens for the pull out test, compressive strength was controlled in all mixes. 24 hours after casting specimens were demolded and stored in a moist room. Both the pullout specimens and the control specimens were tested 28 days after casting.

During the pull out tests (see Figure 2), relative displacements (slip values) were measured at the unloaded end of the bar by means of a linear variable differential transformer (LVDT). Further details concerning the experimental procedures can be found in [6].

Table 4 : Pullout specimens produced and tested.

Base mix design	Fiber type	Fiber content, kg/m^3	Reinforcing bar diameter, mm	Concrete cover, mm
A	65 / 60	40	16	C1 (30)
A	--	0	8	C2 (35)
A	65 / 60	70	20	C3 (100)
A	65 / 60	40	8	C3 (40)
A	--	0	20	C1 (30)
A	65 / 60	70	16	C2 (55)
A	80 / 50	40	20	C2 (65)
A	--	0	16	C3 (80)
A	80 / 50	70	8	C1 (30)
B	--	0	8	C1 (20)
B	80 / 35	60	8	C2 (28)
B	45 / 50	40	8	C3 (40)
B	45 / 50	60	12	C1 (30)
B	80 / 50	40	12	C2 (42)
B	--	0	12	C3 (60)

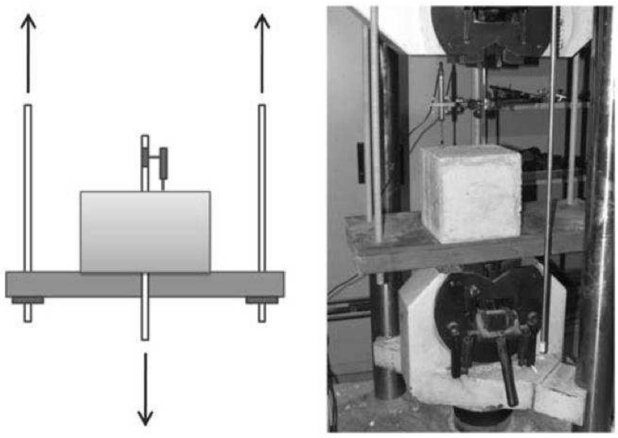

Figure 2: Scheme and picture of the pull out test.

3 RESULTS, ANALYSIS, AND DISCUSSION

3.1 Results

Average compressive strength values obtained were 32 MPa for type A mixes (specified 25 MPa) and 52 MPa for type B mixes (specified 45 MPa).

The result of each pull out test was a bond stress - slip curve, as shown in Figure 3. The following parameters are related to bond capacity and ductility and have been calculated from bond stress - slip curves according to their definition:

- τ_{max}: bond strength or peak bond stress, in MPa.
- τ_{av}: average bond stress in MPa, as defined for the beam test by EN 10080 [15], in MPa, i.e. the average of bond stress values corresponding to slips of 0.01, 0.1, and 1.0 mm.
- s_{max}: slip that corresponds to the peak bond stress, in mm.
- A_{80}: area under the curve in mmMPa, measured up to the slip value (in the postpeak

region) that corresponds to the 80% of the peak bond stress.

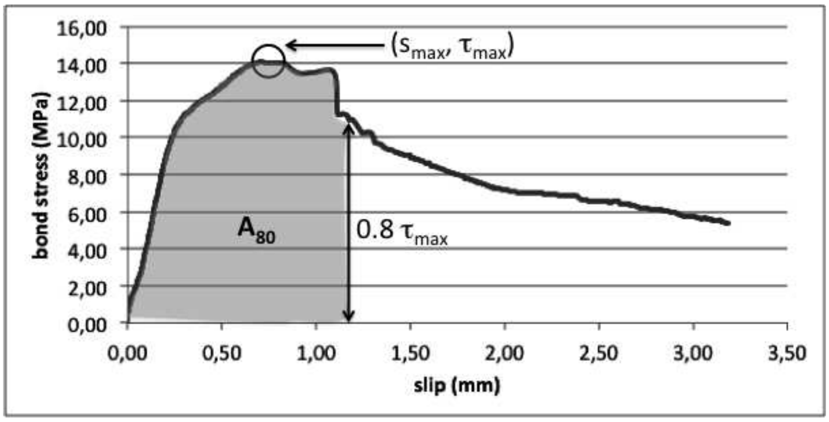

Figure 3: An example of bond stress - slip curve.

Results are all summarized in Table 5. The column 'Splitted specs.' informs about the mode of failure observed, showing the proportion of specimens that have experienced splitting in each case. With respect to the other columns showing results, since 3 specimens were produced in each case, values shown are averaged results (splitted specimens have not been considered to calculate averaged results, since parameters such as τ_{max}, s_{max}, and A_{80} are not defined in such case).

Table 5 : Summary of results from pull out tests.

					Results				
Mix design	Fiber type	Fibers, kg/m^3	Diameter D, mm	Cover C, mm	Splitted specs.	τ_{max}, MPa	τ_{av}, MPa	s_{max}, mm	A_{80}, mmMPa
A	65 / 60	40	16	30	-	6.24	3.46	1.34	13.24
A	--	0	8	35	-	8.36	4.78	1.01	20.27
A	65 / 60	70	20	100	-	18.44	8.99	1.67	86.93
A	65 / 60	40	8	40	-	7.78	3.59	1.64	20.27
A	--	0	20	30	3/3	-	-	-	-
A	65 / 60	70	16	55	-	6.83	4.10	1.92	24.50
A	80 / 50	40	20	65	-	11.79	4.03	2.60	52.00
A	--	0	16	80	-	5.76	2.48	1.71	16.27
A	80 / 50	70	8	30	-	5.62	1.76	2.3	24.20
B	--	0	8	20	1/3	15.83	7.73	3.27	13.30
B	80 / 35	60	8	28	-	22.33	12.82	1.07	56.20
B	45 / 50	40	8	40	-	21.77	10.71	1.44	117.00
B	45 / 50	60	12	30	3/3	-	-	-	-
B	80 / 50	40	12	42	2/3	24.36	14.92	0.47	24.20
B	--	0	12	60	-	25.29	14.23	1.36	90.07

3.2 Analysis of results: methodology

As shown in Table 5, there were some of the pullout specimens tested which experienced splitting of the concrete cover. In such cases the bond stress-slip curve obtained is not a complete one like that shown in Figure 3. No numerical results could be obtained, but logistic binary regression has been applied to take advantage of the information regarding the mode of failure observed to try to predict under what circumstances a pullout specimen is likely to experience splitting when the rebar is pulled out.

After that, combinations where splitting occured were discarded, and numerical results have been analyzed by applying multiple linear regression (MLR hereafter). The core of this methodology is finding models which relate each one of the bond parameters measured to the variables considered. But there is much more than simply a predictive equation to be obtained for each bond parameter, because variables that have a statistically significant effect upon a certain parameter can be identified. Regarding such points, statistical inference has been made by means of significance tests associated to the coefficients estimated in the construction of each linear model. This way it is possible to assess what variables have a really important effect on most bond parameters, what variables affect bond ductility but not bond capacity, or vice versa, and other similar questions can be answered which are more general and valuable conclusions than the predictive equations themselves.

3.3 Variables determining the mode of failure

Logistic binary regression [16] has been applied to test results concerning mode of failure (column 'Splitted specs.' in Table 5) to relate the probability that a specimen experiences splitting (p) instead of having the bar pulled out to the variables considered in this research. Since cover/diameter ratio is usually assumed to determine mode of failure, a model where the effect of such ratio is affected by other variables is initially proposed. Once estimates for the coefficients in the model have been calculated on the basis of maximum likelihood, the following expression is obtained:

$$\frac{p}{1-p} = \exp\left[43.61 + \left(-42.81 + 0.57\, f_C + 8.82\Gamma - 0.10 C_F\right)\frac{C}{D}\right] \tag{1}$$

where f_c is the specified compressive strength of concrete, expressed in MPa; Γ is a boolean variable which equals 1 when there are fibers in the mix, and 0 when there are not; and C_F is the fiber content, expressed in kg/m^3.

The accuracy of the model cannot be significantly improved by any other model (p-value for residuals 1.00 >> 0.05). According to the significance tests on the coefficient estimates, all effects considered are significant (p-values 0.0000 for C/D and f_cC/D; 0.0092 for ΓC/D) with the clear exception of fiber content, C_FC/D, which is not (p-value 1.0000).

Accordingly, the model (1) is simplified and its coefficients re-estimated, and the following expression is obtained:

$$\frac{p}{1-p} = \exp\left[134.96 + \left(-131.63 + 1.72\, f_C + 15.45\Gamma\right)\frac{C}{D}\right] \tag{2}$$

The accuracy of the model (2) is the same as that of model (1) (p-value for residuals 1.00 >> 0.05), which is a highly satisfactory result, and all effects of the variables and interactions considered are significant (p-values 0.0000 for C/D and f_cC/D; 0.0058 for ΓC/D). One of the consequences of the high accuracy of this model is shown in Figure 4 for illustration purposes. Figure 4 shows the probability of splitting evaluated by means of expression (2) vs C/D ratio for two compressive strength values, without fibers: 25 MPa and 45 MPa. Figure 4 clearly shows how the model very clearly distinguishes between cases in which splitting is to be expected and cases in which no splitting occurs: such threshold is C/D = 1.5 if compressive strength of concrete is 25 MPa, with no fibers, and C/D = 2.5 if compressive strength of concrete is 45 MPa, no fibers either.

The signs of the estimated coefficients in expression (2) are also informative. The coefficient associated to C/D ratio is negative, which is coherent with the fact that the probability of splitting decreases when this ratio is increased. But the coefficients associated to its interactions with compressive strength and Γ are positive, which means that they modify the way C/D ratio controls the probability of splitting in the opposite way: when a higher compressive strength is considered or fibers are used, the minimum C/D value required to avoid splitting is increased, independently of what the fiber content is.

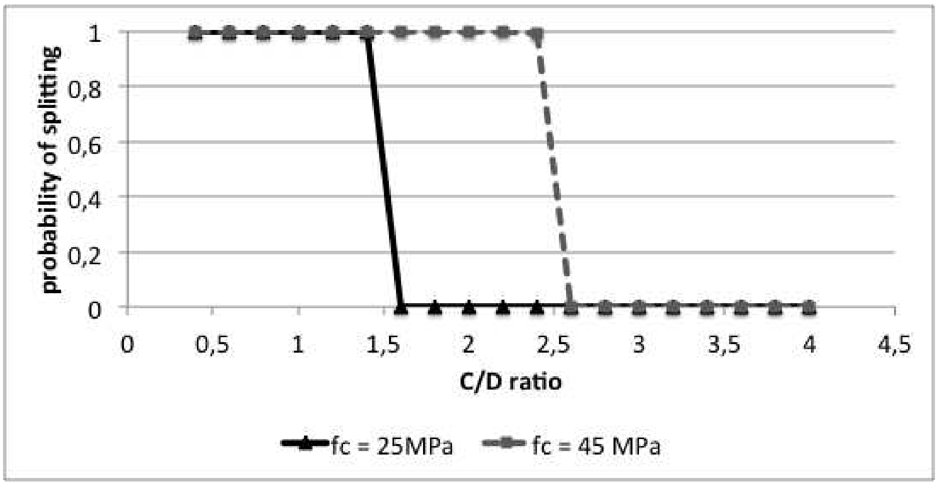

Figure 4: Probability of splitting vs C/D ratio calculated for two compressive strengths.

This is clearly explained by Table 6, showing the minimum C/D value required to assure no splitting will occur (threshold assumed is p=0.5) for different values of compressive strength in concretes with and without fibers. Such tendency can be interpreted as follows: the higher compressive strength is, the more it takes for the concrete between ribs of the rebar to be crushed, hence higher tensile stresses (the so-called hoop stresses) can develop, this meaning that the probability that concrete cover splits increases. The role played by the presence of fibers can be understood in a similar way, improving the properties of the matrix rather than contributing in a structural way.

Table 6 : Minimum C/D values for mode of failure not to be splitting.

Compressive strength of concrete, MPa	Without fibers ($\Gamma = 0$)	With fibers ($\Gamma = 1$)
25	1.50	1.84
30	1.68	2.09
35	1.89	2.41
40	2.15	2.85
45	2.50	3.48

3.4 Effects on bond strength

A MLR has been performed on bond strength values in order to model the effects that the variables considered have on these parameter. Compressive strength of concrete has been retained as independent variable instead of removing it by normalizing bond strength. Only simple effects (no transformations, no interactions) have been considered, with the exception of fiber slenderness and length, which are considered only interacting with fiber content. The reason is that these variables are only defined when fiber content is different than zero and, as a consequence, they cannot be treated as standalone variables.

Table 7 shows estimates for the coefficients and their p-values for the model developed for each bond parameter, together with the R-squared of each model and its p-value. In the case of bond strength, only concrete cover (p-value 0.0893) and compressive strength (p-value 0.0010) significantly affect bond strength. The model as a whole is also significant (p-value 0.0080) and its accuracy is very good (R-squared = 90,25%). However, rather than the predictive equation, the really important part is the information regarding influence of the variables considered on bond strength, more general than an equation found for a particular set of data. Fibers are detected not to have a significant effect on bond strength, though it is worth noting that the set of data these analyses are based upon does not contain any case of partial or thorough splitting: only those specimens with pull out as mode of failure are being considered in this and following sections.

Table 7 : Output of the MLRs on bond parameters:
only significant effects shown (p-values in brackets).

	BOND PARAMETERS			
	τ_{max}	τ_{av}	s_{max}	A_{80}
(constant)	-32.19	-17.60		-1.78
Concrete cover	0.14 (0.0893)	0.067 (0.0339)		0.76 (0.0670)
Diameter				
Compressive strength	1.066 (0.0010)	0.60 (0.0000)		
Fiber Content				7.88 (0.0109)
Fiber Content x Length				-0.067 (0.0248)
Fiber Content x Slenderness				-0.058 (0.0186)
Model, R-squared	90.25% (0.0080)	83.94% (0.0001)		63.23% (0.0645)

3.5 Effects on average bond stress

As shown in Table 7, concrete cover (p-value 0.0339) and compressive strength (p-value 0.0000) are once again the only variables determining average bond stress values, in coincidence with findings for bond strength. The model as a whole is also significant (p-value 0.0001) and accurate (R-squared 83.94%).

3.6 Effects on the slip corresponding to bond strength

None of the variables considered in this research has been found to have a statistically significant effect on slip values corresponding to bond strength. This is probably due to the nature of the parameter itself: as it can be observed in Figure 3, the position of the peak is not clear and the error which is inherent to evaluating this parameter is very serious. As a consequence, position of the peak is not a reliable parameter to take into account when analyzing bond behaviour (ductility, rather).

3.7 Effects on the area A_{80} under the curve

The area A_{80} under the bond stress-slip curve informs about ductility of bond failure, and has been found to be very stable: when several repetitions of the same specimen are tested, the position of the peak in the curve is highly variable, but A_{80} shows very little variation (data not shown).

As shown in Table 7, concrete cover (p-value 0.0670) and fiber content (p-values 0.0109, 0.0248, and 0.0186) have a statistically significant effect on A_{80} values. This, together with the fact that both coefficients are positive, proves that concrete cover and fibers are of capital importance concerning ductility of bond failure, i.e. the energy associated to the material's fracture. Furthermore, the authors have already observed that areas under the curve increase linearly with respect to fiber content, and that this linear tendency observed in areas vs fiber content is very similar to that of areas vs concrete cover [6]. Such coincidence points out the role of fibers as passive confinement and opens the door to the possibility of reducing requirements in relation to development length for reinforcing bars when SFRC is used.

Furthermore, the effect that fiber content has on A_{80} is affected by fiber length and slenderness, i.e. by fiber length and diameter. By looking at the sign of the coefficient estimates for these interactions (both negative), it is concluded that increasing fiber length or decreasing fiber diameter will soften the effect that increasing fiber content has on A_{80}.

The model as a whole is significant (p-value 0.0645) and reasonably accurate (R-squared 63.23%).

4 CONCLUSIONS

Cover/diameter ratio is the variable which determines the probability that concrete cover splits when the reinforcing bar is being pulled out of concrete. Compressive strength of concrete and the presence of fibers have been found to significantly modify the way cover/diameter ratio affects such probability. Regarding fibers, what is significant is whether they are present or not, no matter what the amount is.

Only concrete cover and compressive strength have been detected to have a statistically significant effect on bond strength. Fibers effect on bond strength is not significant probably because no results corresponding to specimens with partial splitting have been considered. The same conclusions have been obtained concrening average bond strength.

No variable among those considered in this research has been found to determine slip values corresponding to peak bond stress. This, together with the high variability observed in this parameter among repetitions of the same test, suggests this parameter is not a good option when it comes to single out significant differences among the combinations tested in this research.

Concrete cover and fiber content are of capital importance concerning ductility of bond failure, i.e. the area under the bond stress-slip curve. This confirms the role of fibers as passive confinement and points the direction towards the reduction of required development lengths for reinforcing bars when SFRC is used.

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