STATISTICAL APPROACH TO THE EFFECT OF FACTORS INVOLVED IN BOND PERFORMANCE OF SFRC

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ABSTRACT

The positive effect of fibers on bond of rebars in concrete is widely recognised. However, different authors come to different conclusions regarding particular points.

This research analyses the results of a series of pullout tests in order to obtain statistically supported conclusions regarding bond performance of a normal strength SFRC. To do so, the experimental program has been conceived by observing statistical criteria (DOE techniques) and the results have been analysed by means of analysis of variance (ANOVA).

It has been shown that the role fibers play in bond of rebars in concrete is of the same importance as that of concrete cover or rebar diameter. It is especially remarkable that the mere fact of adding fibers, no matter the amount, increases the ductility of the bond failure considerably, thus underlining the role of fibers in bond performance as passive confinement.

Keywords: bond, SFRC, pullout test, statistical approach.

INTRODUCTION

The fact that fibers have a positive effect on bond of steel reinforcing bars in concrete is widely recognised and supported by literature. Such positive effect is observed even with low fiber contents[1] and is being gradually assumed by codes. The new Spanish code for structural concrete, EHE-08[2], recognises that fibers improve bond conditions and states that it may be taken into account when determining development lengths (or 'anchorage lengths' in the terminology of Eurocode 2[3]). A very similar statement is found in the last ACI Committee 408 Report[4] with respect to the expressions provided by ACI 318-08[5] for determining development lengths.

Fibers improve concrete bond capacity by confining the bars, their role being similar to that of stirrups, and also by widening the range of crack widths within which this confinement remains active[1]. Besides, improvement in terms of bond capacity can be regarded as a consequence of the betterment of matrix properties due to the fibers[6].

There are relatively few studies available that deal with bond of rebars in steel fiber reinforced concrete (SFRC). Several authors[1,6,7] agree that fibers improve bond capacity mainly in terms of ductility, while their influence on bond strength (peak bond stress) is of little importance when compared to that.

However, different authors come to different conclusions regarding particular points. To begin with, while some investigations conclude that the effect of fibers on bond strength is not significant[8], some others state this is true only when the mode of failure is by pullout but not when there is splitting. As a matter of fact, when there is splitting, the effect of fibers is pretty important[9,10]. In addition to that, some authors state that adding fibers does not significantly affect bond strength in normal strength concretes[6,11] (compressive strength values up to 40-50 MPa). And when it comes to compressive strength values of 90-100 MPa, some authors relativize the effect of fibers and conclude that they do increase bond strength but no more than 15%[6]. This raises the question whether it would be really useful to take the effect of fibers on bond into account when determining development lengths or lap splice lengths.

Several studies on bond of rebars in SFRC consider no more than two factors among these ones: fiber content, compressive strength, concrete cover, and rebar diameter. It is quite rare to find all combinations of different values of these factors tested, and conclusions are usually obtained by comparing bond strength values or bond stress–slip curves in a one-to-one manner. In consequence, any disagreement between the conclusions of different studies may be considered taking into account the difficulty of their being generalised.

As a consequence, the aim of this research was to study in a comprehensive fashion the effect of four different factors on SFRC bond capacity and ductility. According to that purpose, the experimental program was conceived to obtain reliable and statistically supported conclusions at the same time laboratory work was minimised.

RESEARCH SIGNIFICANCE

The significance of this research concerns the bond performance of reinforcement in SFRC and the ductility of bond failure by means of a statistically reliable approach.

This research comprises a series of pullout tests carried out on SFRC prismatic specimens and it studies in a comprehensive fashion the effect of several factors (fiber type and content, concrete cover, and rebar diameter) upon bond capacity and allow conclusions to be statistically reliable, which is not frequent among studies dealing with bond of reinforcement in concrete.

EXPERIMENTAL INVESTIGATION

Mix design

One composition of the concrete matrix was considered through all the research, whose required average compressive strength was 30 MPa [4350 psi]. This centered the research upon a normal strength concrete which may be regarded as typical in most of the applications. The concrete composition was the same for all specimens produced and tested in this research, only the fiber content varied. Accordingly, the superplasticizer content was adjusted in each case, depending on the fiber type and content, to keep the slump values in the range of 10-15 cm [4-6 in]. Contents of all other components were kept constant.

Table 1 summarises the composition of the concrete matrix. Both the cement type and the water/cement ratio place may be considered as usual in regular construction. The coarse aggregate/sand ratio is close to one to have good levels of cohesion in order to work with different levels of admixture and no risk of segregation. This was necessary because different fiber contents would require variations in the admixture content, as workability was required to be always the same.

Factors and Levels Considered

Table 2 shows the situations or parameters considered by three different codes (ACI 318-08[5], Eurocode 2[3] and Spanish code EHE-08[2]) in the expressions for determining the development length of rebars. They were taken into account when deciding the factors to be considered in this research.

With respect to compressive strength, it has been already said that it was fixed to a required average value of 30 MPa [4350 psi]. The reason why it has not been considered as a factor is because its effect upon bond is very well known and quantified[4].

The nominal yield strength of reinforcement was not a factor either since steel rebars having a yielding strength of 500 MPa [72500 psi] were used in all cases, being that the usual type of steel used nowadays.

Lightweight concretes, epoxy-coated bars or the application of transverse pressure were not situations to be covered by this research according to its objectives. Consequently, no factors were considered regarding them.

The parameters considered (factors) in the present research study as well as their different values (levels) are summarized in **Table 3**.

Two different types of cold drawn hooked-end steel fibers were used, characterized by different slenderness and length. In relation to fiber contents, three different values were considered, with a maximum value of 70 kg/m^3 [4.37 lb/ft^3] (0.89% in volume); this maximum content was chosen bearing in mind that fiber contents in usual applications are rarely greater than 1% in volume.

Three different nominal rebar diameters were used, all of them usual in normal buildings, and in the precast concrete industry.

Concrete cover, C, in the pullout specimens was defined as shown in **Fig. 1;** the unsymmetrical concrete cover reflects the most common situation of rebars in real concrete elements. The distance between the bar and the opposite surface was not less than 125 mm [4.94 in] in any case, which corresponds to a situation of good confinement for a 25 mm [0.99 in] rebar according to the Model Code MC-90[13]. This choice was due in prevision of the possibility of extending the research to 25 mm [0.99 in] rebars in the future.

Three different values were considered for the concrete cover:

- C1 = 30 mm [1.2 in], which is the minimum value required by the Spanish code[2] for rebars in a precast element with a compressive strength of 30 MPa [4350 psi].
- C2 is the average of C1 and C3.
- C3 is five times the nominal diameter of the rebar, which corresponds to a good confinement according to the Model Code MC-90[13].

Design of the Specimens

Prismatic pullout specimens were produced and tested in this study whose cross-section is shown in **Fig. 1**. Its dimensions are variable and depend upon the rebar diameter and the concrete cover value. The cross-section dimensions of all specimens are summarised in **Table 4**.

The longitudinal dimensions, total length and embedded length, were defined according to the RILEM recommendations for the pullout test[14,15]. According to these recommendations:

- Total length of the specimen should be ten times the nominal diameter of the rebar, but never less than 200 mm [7.9 in]. As the largest diameter considered was 20 mm [0.79 in], all specimens had a length of 200 mm [7.9 in].

- Embedded length should be five times the nominal diameter of the rebar.

Table 5 and **Fig. 2** show the longitudinal dimensions of the pullout specimens for the three different rebar diameters considered, where rebar position is variable as a result of the concrete cover being a factor.

Design of the Experiment: Statistical Approach

Researches whose aim is to analyse how different factors affect bond capacity usually proceed by varying only one factor at a time and by comparing results. However, these approaches are not the best ones because they do not take into account that the effect of a factor on bond capacity can vary depending on the values of other factors[16,17]. The techniques globally known as Design of Experiments (DOE)[17,18,19] allow the amount of labour to be optimised and the conclusions to be reliable on a statistical basis. Therefore, DOE-based experiments make it possible to study the effect of several factors on one (or more) parameters on the basis of the analysis of variance (ANOVA)[18,19]. Considering all that, this experiment was planned by applyinng DOE techniques and statistical considerations.

If all possible combinations of the different factors and levels considered (see **Table 3**) had to be analysed, it would have implied 54 different specimens to be produced and tested. By using orthogonal arrays and derived factorial plans[17,18,19] the number of specimens to be tested would be affordable and statistical inference in relation to the effect of the factors considered on the response variables would be totally reliable. As a result, this research comprised nine different combinations, summarised in **Table 6**.

In order to have more experimental results and, as a consequence, to make conclusions more reliable, each one of the tests was not carried out only once: three specimens of each combination were produced and tested.

In addition, four cube specimens (side = 100 mm [3.94 in]) and four prismatic notched specimens (in agreement with the standard EN 14651[20]) were produced in each case to control both compressive strength and residual flexural strength.

Consequently, 27 pullout specimens, 36 cube specimens, and 36 prismatic notched specimens were produced and tested in total.

Mixing, Specimens Production and Testing

Mixing, production and testing of specimens were carried out in all cases by following exactly the same sequence and by controlling the time for all operations. Components were added to the mix by following this sequence: aggregates, cement, water, fibers, and superplasticizer. Moisture in aggregates was also strictly controlled in order to pour the exact amount of total water required. All this was done this way in order to avoid any possible uncontrolled interference affecting the results.

Right after mixing, workability was monitored and controlled by means of the slump test (following EN 12350-2[21]).

Specific moulds for the pullout specimens were designed and produced on purpose because both the position of the bar and the dimensions of the specimen were different in each case. Sleeves were used in order to control the embedded length, as **Fig. 3** shows.

Concrete was poured into the mould in two stages. First, concrete was poured until it filled half the mould and then it was vibrated no more than 4-5 seconds by using an internal vibrator. After that, the mould was filled and vibration was repeated. In order to minimise the possibility of fibers orientation, the vibrator was immersed in concrete far enough from the rebar. 24 hours after casting, the specimens were demoulded and stored in a moist room.

Both the pullout specimens and the control specimens were tested 28 days after casting. During the pullout tests (**Fig. 4**), relative displacements (slip values) were measured at the unloaded end by means of a LVDT displacement transducer. Every test was carried out by keeping the load/time ratio between 2-4 kN/min [450-900 lbf/min] before the peak load was reached, and by keeping the slip/time ratio between 0.4-0.6 mm/min [0.016-0.024 in/min] after the peak load in all cases. The test was finished when slip reached values of 14-15 mm [0.5-0.6 in].

Response Variables: Parameters Measured and Analysed

Response variables are the results related to bond capacity and ductility determined from the bond stress-slip curves as shown in **Fig. 5**. They are the following:

- τ_{max}: bond strength or peak bond stress, in MPa [psi].
- τ_{av}: average bond stress, in MPa [psi], as defined for the beam-test by the standard UNE-EN 10080[22], that is: the average of the values of bond stress that correspond to slip values of 0.01 mm, 0.1 mm and 1 mm [0.0004 in, 0.004 in and 0.04 in].
- s_{max}: slip that corresponds to the peak bond stress, in mm [in].
- A_{80}: area under the curve, in mmMPa [inpsi], measured up to the slip value (in the postpeak region) that corresponds to 80% of the peak bond stress.
- A_{50}: area under the curve, in mmMPa [inpsi], measured up to the slip value (in the postpeak region) that corresponds to 50% of the peak bond stress.

Bond stress (either τ_{max} or τ_{av}) values are defined upon the assumption of a uniform stress distribution and are determined as follows:

$$\tau = \frac{P}{\pi DL} \tag{1}$$

where: P is the load (either peak or average load), D is the nominal rebar diameter, and L is the embedded length.

The aforementioned parameters, and particularly areas A_{80} and A_{50}, were first defined for bond stress-slip curves that correspond to pullout failures. When specimens experienced splitting, the bond stress values after failure were taken as zero.

CONTROL TESTS RESULTS

The average compressive strength determined from cubes was 33 MPa [4785 psi], which is in agreement with the required average compressive strength.

In relation to the bending test results, **Table 7** shows the average values of all of them (each value is the average of four individual values), determined according to the standard EN 14651[20]:

$f_{ct,L}$ is the limit of proportionality.

f_{R1}, f_{R2}, f_{R3}, and f_{R4} are the residual flexural tensile strengths corresponding to CMOD (crack mouth opening displacement) values of 0.5 mm, 1.5 mm, 2.5 mm, and 3.5 mm [0.02 in, 0.06 in, 0.10 in, and 0.14 in] respectively.

f_{Rmax} is the maximum residual flexural tensile strength in the postcrack region.

These results were taken as informative. The more fibers added to concrete, the greater residual flexural strength values are. It should be noticed that, in concretes with 40 kg/m^3 [2.50 lb/ft^3] of fibers, residual flexural strength values are significantly improved when 80/50 fibers are used instead of 65/60 fibers. These results detect differences in the properties of the matrix and, consequently, fiber type is expected to be an influent factor upon bond capacity.

PULLOUT TESTS RESULTS AND DISCUSSION

Fig. 6 shows a typical bond stress-slip curve, as obtained from one of the L3 specimens. **Table 8** shows average values of all pullout tests results (each one is the average of three values corresponding to three different specimens).

All results were analysed by means of analysis of variance (ANOVA), which detects factors that have a statistically significant influence on the response variables of the experiment.

Table 9 summarises the effects of the factors considered upon all response variables of the pullout tests. The following criterion has been followed:

- Effects corresponding to confidence levels of 95% (p-values up to 0.05) were ticked as "very significant" and marked with XX.
- Effects corresponding to confidence levels of 90% (p-values between 0.05 and 0.10) were ticked as "significant" and marked with X.

As **Table 9** shows, all the factors considered are very influential on bond capacity, one way or another. Although the influence that concrete cover and bar diameter have on bond is well known, these parameters were considered in order to give the research a more comprehensive approach and to better evidence the fibers contribution. Bearing that in mind, these results show that the role that fibers play in bond is not less important than that of concrete cover or bar diameter.

Results of the analysis of variance carried out for each one of the response variables are reliable because of the following reasons[17,18,19]:

- Orthogonal arrays were used to design the experiment so that no interferences between different effects exist.
- The total number of results (3 x 9) minus the total number of levels considered is a value large enough (greater than 4) so as to consider the ANOVA as robust; and
- All circumstances not considered as factors were controlled and kept constant: if any of them had been influential, it would have equally affected all the results and, as a consequence, not the results of the ANOVA.

Results obtained from these analyses are valid for the concrete, factors, and levels considered in this research. However, these results would have to be complemented with those of other experiments to be completely valid in general (different mix designs or different levels of variation).

The analysis of variance is just a first step. After that, graphical analysis by means of the calculation and interpretation of LSD (Least Significance Difference) intervals makes it possible to detect general tendencies in the effect of the factors considered on the response variables of the experiment[18,19].

Furthermore, in order to quantify the effect of fibers on the different parameters of the pullout test, regression analyses in multifactor scenarios have been carried out based on the experimental data obtained and summarized in **Table 8**, which has led to correlation expressions whose R^2 values are between 55% and 75%. They have been used to determine the effect that the addition of fibers has on bond parameters when concrete cover is 2.5 times the rebar diameter. This information is summarized in **Table 10**, where each percentage is the expected average increase of a bond parameter (τ_{max}, s_{max}, τ_{av}, A_{80}, A_{50}) under different circumstances (fiber content, fiber type, and rebar diameter).

The following lines show and discuss the LSD intervals plots for the factors considered in this research as well as the information summarized in **Table 10**. LSD intervals for the average bond stress are not shown in any case because they follow the same tendency as the peak bond stress.

Effect of Concrete Cover

As seen in **Table 9**, the effect of concrete cover on bond is very strong and affects all response variables. **Fig. 7** shows the LSD intervals plots related to the values of concrete cover. The tendency with respect to concrete cover values is increasing and practically linear for all response variables: the more concrete cover, the more bond capacity and ductility.

Effect of Rebar Diameter

Rebar diameter affects all response variables except the slip that corresponds to the peak bond stress (see **Table 9**). **Fig. 8** shows the LSD intervals plots related to the values of rebar diameter. Although this factor has a strong influence on bond capacity and ductility, the difference with respect to the effect of concrete cover is that tendencies are no longer linear. It seems that the difference between small and medium diameters is of no importance. However, it is indeed between medium and large diameters.

Effect of Fiber Type

Fiber type affects bond capacity (bond peak stress, the slip that corresponds to the peak stress and average bond stress) but not at all ductility parameters (areas) (see **Table 9**).

Fig. 9 shows the LSD intervals plots related to the fibers types. By using 65/60 fibers the bond strength achieved is greater than by using 80/50 fibers, in particular, a greater peak bond stress (and also average bond stress values) was observed at smaller slip values. In relation to the fact that the improvement of ductility when fibers are added is not sensitive to the fiber type, **Table 10** gives an interesting explanation if the percentages that compare the concrete with 40 kg/m^3 [2.50 lb/ft^3] of fibers to its unreinforced counterpart are observed. When 65/60 fibers are used, the peak stress is increased between 21.0% and 47.8% but the s_{max} is increased no more than 10.3%. When 80/50 fibers are used there is the reverse situation: the peak stress is increased no more than 5.7% but s_{max} is increased between 78.6% and 86.5%. That is: 65/60 fibers affect mainly the peak stress while 80/50 affect its position, but both parameters are balanced in approximately the same way, this explaining why the areas are not differently affected when different fibers are used. As a matter of fact, this confirms the importance of previous testing when choosing which fibers are more adequate.

Effect of Fiber Content

As seen in **Table 9**, the effect of fiber content on bond is pretty strong and affects all response variables. **Fig. 10** shows the LSD intervals plots related to the fiber contents considered.

LSD intervals for the peak bond stress reveal a tendency which is noticeably similar to that observed in the plots related to concrete cover values. However, it seems that rather large fiber contents (close to 1% in volume) are required to strongly affect these parameters.

The effect of fibers on the slip value that corresponds to the peak bond stress is definitely important. The mere fact of adding fibers, no matter the amount, increases this value, that is: adding the fibers displaces the position of the peak bond stress. It is quantified in **Table 10** that most of the effect of fibers on s_{max} is achieved when 40 kg/m^3 [2.50 lb/ft^3] of fibers are added, being the difference between 40 kg/m^3 [2.50 lb/ft^3] and 70 kg/m^3 [4.37 lb/ft^3] of relatively little importance, especially with 65/60 fibers. This might be interesting when trying to reduce development lengths by taking into account the fibers contribution.

Fiber content has a strong effect on areas as well. Bearing in mind that areas someway quantify the energy associated to the material's fracture, these areas increasing linearly with respect to fiber contents is a consequence of the positive effect that fiber content has on both peak bond stress and its position. And, as a matter of fact, the tendency observed in areas related to the fiber content is very similar to that of areas related to concrete cover. This underlines the role of fibers as passive confinement, just like concrete cover or stirrups, and foreshadows the possibility of reducing the development length for rebars when normal strength SFRC is used.

CONCLUSIONS

The following conclusions can be drawn based on the results of this research:

1. The effect of fibers type and content, concrete cover and rebar diameter on bond of rebars in SFRC has been analysed in a comprehensive fashion by applying the statistical procedures and criteria globally known as Design of Experiments (DOE).
2. The effect of concrete cover on both bond capacity and ductility is very strong, being the tendency observed in all bond parameters with respect to concrete cover increasing and practically linear.
3. The effect of rebar diameter on bond performance is also very important but no linear at all. Differences between medium and large diameters are very important, while there is practically no difference between small and medium diameters.
4. Although fiber type has been shown not to affect the ductility of the failure, it indeed affects bond capacity as well as the slip corresponding to the peak bond stress. 65/60 fibers affect mainly the peak and average bond stress while 80/50 affects mainly the position of the peak. This confirms the importance of previous testing when choosing which fibers are more adequate.
5. The effect of fiber content on bond is very important. Although it seems that rather large fiber contents (close to 1% in volume) are required to strongly affect peak and average bond stresses, the mere presence of fibers increases the ductility of the failure, the tendency being linear. This underlines the role of fibers in bond performance as passive confinement.
6. Considering how fibers improve bond performance of normal strength concrete, further research is needed to survey the possibility of modifying the expressions for determining development lengths in SFRC.

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Table 1–Composition of the concrete matrix

Cement type	CEM II/B-M 42,5 R (*)
Water/cement ratio	0.60
Cement content	325 kg/m^3 (20.29 lb/ft^3)
Coarse aggr./sand ratio	0.90
Sand type	river limestone (0/4)
Coarse aggregate type	crushed limestone (7/12 and 12/20)

* Cement type designation according to EN 197-1:2000[12].

Table 2–Parameters influencing the development length in selected building codes

	ACI 318-08	Eurocode 2	EHE (Spain)
Compressive strength of concrete	X	X	X
Nominal diameter of bar	X	X	X
Yield strength of reinforcement	X	X	X
Position of the reinforcement	X	X	X
Lightweight / normal concrete	X	X	X
Epoxy-coated / Non-epoxy-coated bars	X		
Concrete cover	X	X	
Confinement by transverse reinforcement	X	X	
Confinement by transverse pressure		X	

Table 3–Parameters considered (factors) and their values (levels)

Type of fibers	Type A (slenderness/length = 65/60) Type B (slenderness/length = 80/50)
Fibers content	0 kg/m^3 (0 lb/ft^3) 40 kg/m^3 (2.50 lb/ft^3) 70kg/m^3 (4.37 lb/ft^3)
Nominal diameter of bar	8mm (0.31 in) 16mm (0.63 in) 20mm (0.79 in)
Concrete cover	C1 = 30mm (1.18 in) C2 (average) C3 = 5 x diameter

Table 4–Dimensions of specimens cross-section for different rebar diameters

Diameter, D mm (in)	Factor level	Cover, C mm (in)	D + C + 125 mm (in)	Side, S mm (in)
8 (0.31)	C1	30 (1.18)	163 (6.42)	180 (7.09)
	C2	35 (1.38)	168 (6.61)	
	C3	40 (1.57)	173 (6.81)	
16 (0.63)	C1	30 (1.18)	171 (6.73)	230 (9.06)
	C2	55 (2.17)	196 (7.72)	
	C3	80 (3.15)	221 (8.70)	
20 (0.79)	C1	30 (1.18)	175 (6.89)	250 (9.84)
	C2	65 (2.56)	210 (8.27)	
	C3	100 (3.94)	245 (9.64)	

Table 5–Longitudinal dimensions

Rebar nominal diameter mm (in)	Total length, L_T mm (in)	Embedded length, L_E mm (in)
8 (0.31)	200 (7.87)	40 (1.57)
16 (0.63)	200 (7.87)	80 (3.15)
20 (0.79)	200 (7.87)	100 (3.94)

Table 6–Pullout specimens produced and tested

Id.	Fiber Type	Fiber Content kg/m^3 (lb/ft^3)	Rebar Diameter mm (in)	Concrete Cover
L1	65/60	40 (2.50)	16 (0.63)	C1
L2	--	0 (0)	8 (0.31)	C2
L3	65/60	70 (4.37)	20 (0.79)	C3
L4	65/60	40 (2.50)	8 (0.31)	C3
L5	--	0 (0)	20 (0.79)	C1
L6	65/60	70 (4.37)	16 (0.63)	C2
L7	80/50	40 (2.50)	20 (0.79)	C2
L8	--	0 (0)	16 (0.63)	C3
L9	80/50	70 (4.37)	8 (0.31)	C1

Table 7–Results of the 4-point bending tests

Concrete	$f_{ct,L}$	f_{R1}	f_{R2}	f_{R3}	f_{R4}	f_{Rmax}
No fibers	4.13 (598.85)	--	--	--	--	--
Type 65/60 40kg/m^3	3.51 (508.95)	2.95 (427.75)	3.78 (548.1)	4.01 (581.45)	4.00 (580)	4.14 (600.3)
Type 65/60 70kg/m^3	3.72 (539.40)	4.68 (678.60)	5.76 (835.20)	6.03 (874.35)	5.93 (859.85)	6.22 (901.90)
Type 80/50 40kg/m^3	3.47 (503.15)	3.62 (524.90)	5.15 (746.75)	4.70 (681.50)	4.73 (685.85)	5.33 (772.85)
Type 80/50 70kg/m^3	3.52 (510.40)	6.17 (894.65)	6.44 (933.80)	6.03 (874.35)	5.61 (813.45)	6.55 (949.75)

units: MPa (psi)

Table 8–Results of pullout tests: average values

Id.	τ_{max}	s_{max}	τ_{av}	A_{80}	A_{50}
	MPa (psi)	mm (in)	MPa (psi)	MPa x mm (inpsi)	MPa x mm (inpsi)
L1	6.24 (904.8)	1.34 (0.05)	3.46 (501.7)	13.24 (75.6)	25.37 (144.8)
L2	8.36 (1212.2)	1.01 (0.04)	4.78 (693.1)	20.27 (115.7)	39.77 (227.0)
L3	18.44 (2673.8)	1.67 (0.07)	8.99 (1303.5)	86.93 (496.3)	159.00 (907.7)
L4	7.78 (1128.1)	1.64 (0.06)	3.59 (520.6)	20.27 (115.7)	35.30 (201.5)
L5*	10.17 (1474.6)	0.26 (0.01)	3.54 (513.3)	2.08 (11.9)	2.08 (11.9)
L6	6.83 (990.4)	1.92 (0.08)	4.10 (594.5)	24.50 (139.9)	34.40 (196.4)
L7	11.79 (1709.6)	2.60 (0.10)	4.03 (584.4)	52.00 (296.9)	95.27 (543.9)
L8	5.76 (835.2)	1.71 (0.07)	2.48 (359.6)	16.27 (92.9)	25.32 (144.5)
L9	5.62 (814.9)	2.30 (0.09)	1.76 (255.2)	24.20 (138.2)	35.38 (202.0)

* Mode of failure is pullout in all cases except L5 (splitting).

Table 9–Analysis of variance: summary of the results

	Concrete cover	Bar diameter	Fiber type	Fiber content
τ_{max}	XX	XX	XX	X
s_{max}	XX		XX	XX
τ_{av}	XX	XX	XX	X
A_{80}	XX	XX		XX
A_{50}	XX	XX		XX

X: significant effects (p-values between 0.05 and 0.10)

XX: very significant effects (p-values up to 0.05)

Table 10–Quantification of the effect of fibers on bond parameters

		Fiber type: 65/60		Fiber type: 80/50	
	Rebar diameter mm (in)	0→40kg/m³ (0→2.50lb/ft³)	40→70kg/m³ (2.50→4.37lb/ft³)	0→40kg/m³ (0→2.50lb/ft³)	40→70kg/m³ (2.50→4.37lb/ft³)
τ_{max}	8 (0.31)	47.8%	13.6%	5.7%	18.9%
	16 (0.63)	27.7%	9.1%	3.3%	11.2%
	20 (0.79)	21.0%	7.3%	2.5%	8.6%
s_{max}	8 (0.31)	9.4%	30.1%	78.6%	18.5%
	16 (0.63)	10.0%	31.9%	83.7%	19.1%
	20 (0.79)	10.3%	32.9%	86.5%	19.5%
τ_{av}	8 (0.31)	84.1%	14.6%	69.1%	30.6%
	16 (0.63)	52.8%	11.0%	32.2%	18.3%
	20 (0.79)	94.1%	9.8%	25.4%	15.2%
A_{80}	8 (0.31)	--	82.5%	--	70.1%
	16 (0.63)	--	47.3%	--	42.9%
	20 (0.79)	--	32.3%	--	30.2%
A_{50}	8 (0.31)	--	83.9%	--	76.5%
	16 (0.63)	--	45.0%	--	42.8%
	20 (0.79)	--	29.9%	--	28.9%

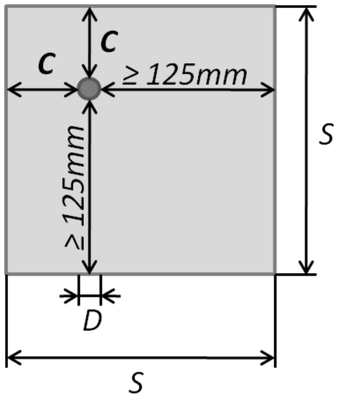

Fig. 1–Definition of 'concrete cover'.

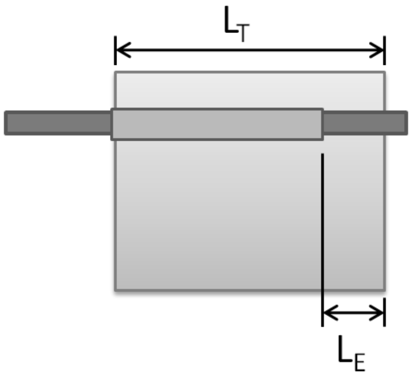

Fig. 2–Longitudinal section of a generic pullout specimen.

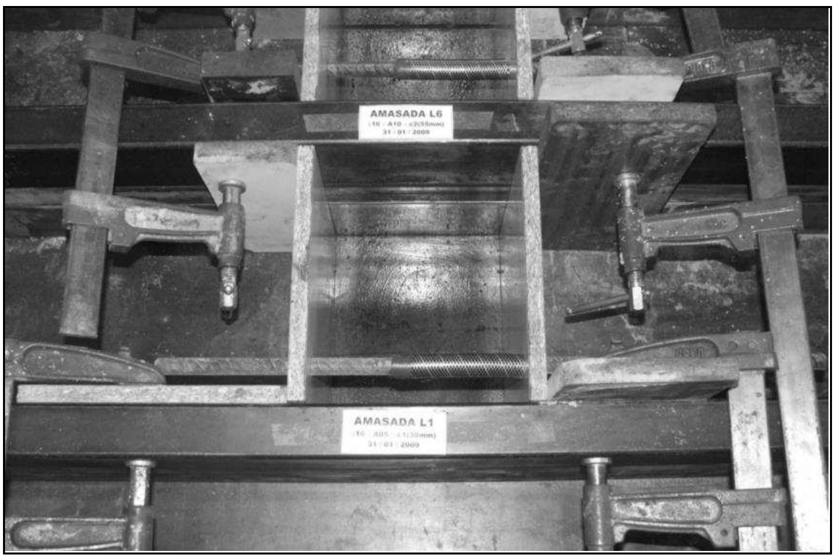

Fig. 3–Detail of a wooden mould for a pullout specimen.

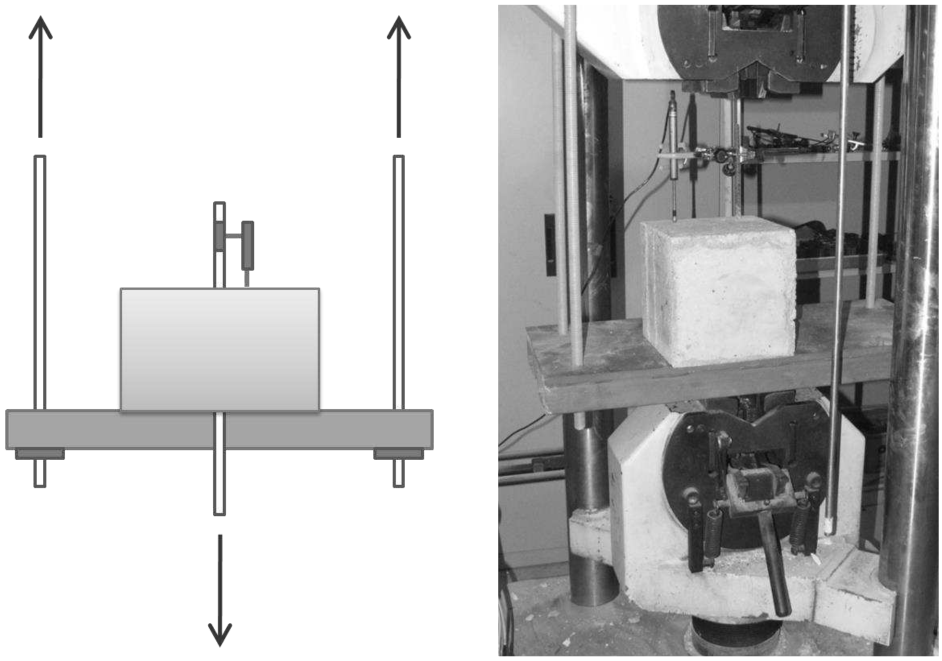

Fig. 4–Pullout test.

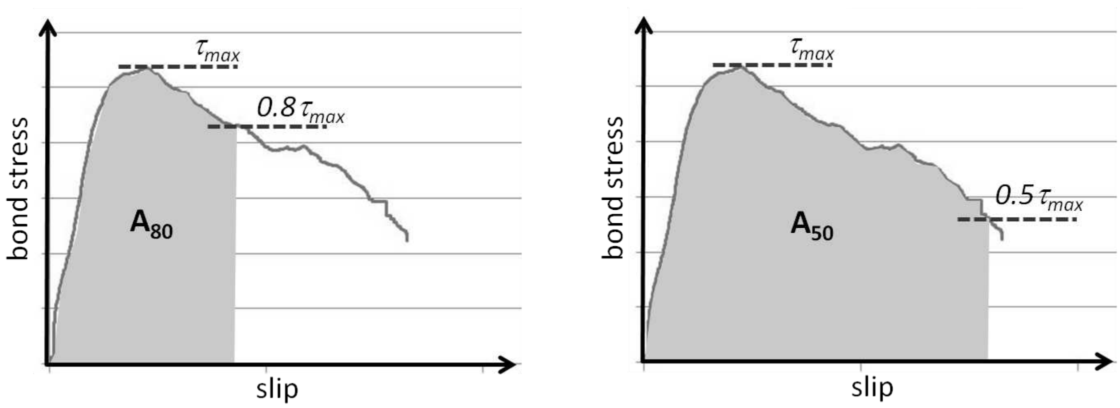

Fig. 5–Definition of parameters for ductility, A_{80} and A_{50}.

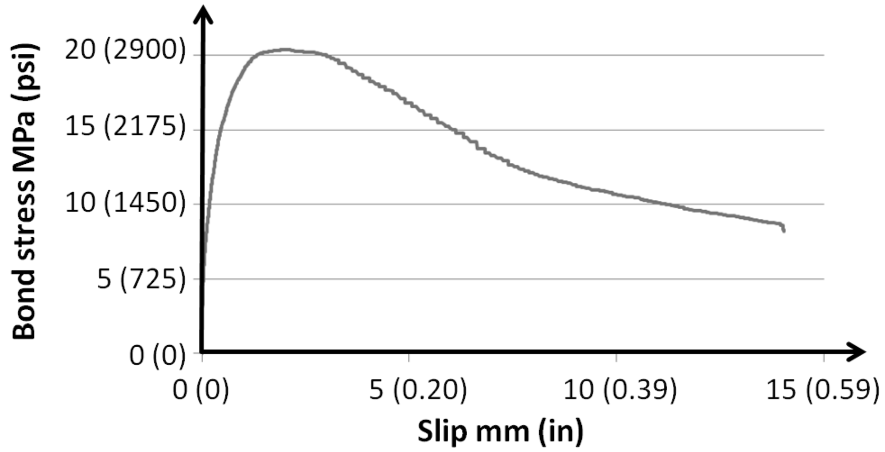

Fig. 6–Bond stress-slip curve corresponding to one of the L3 specimens.

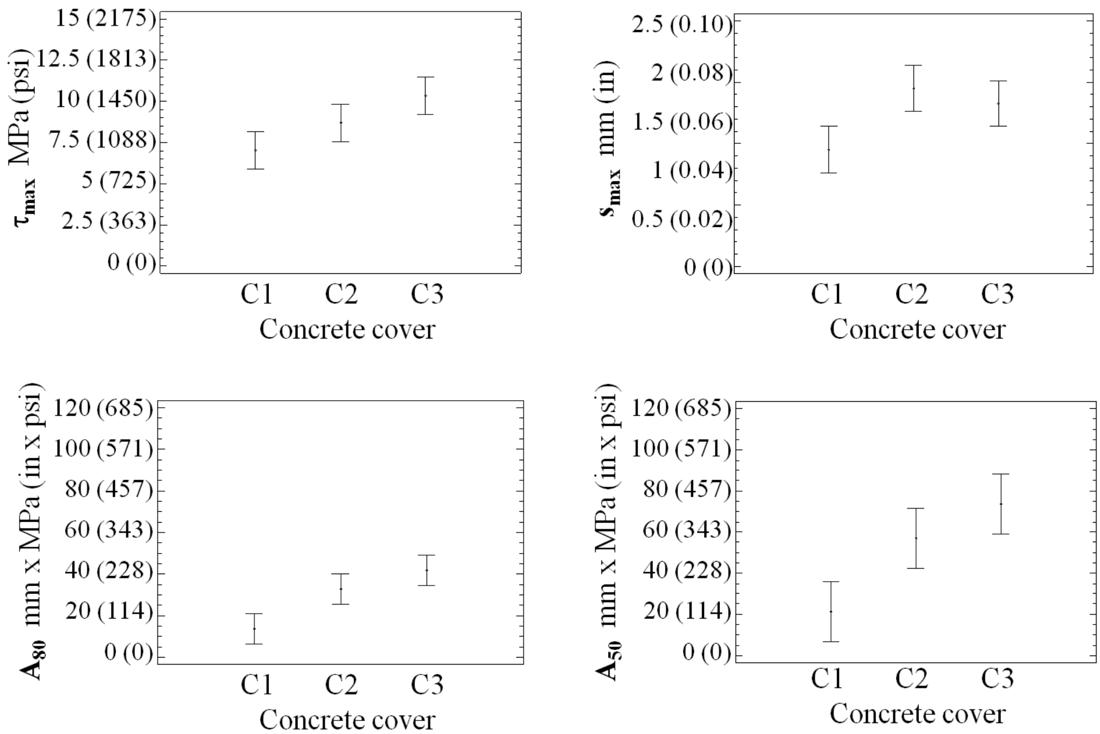

Fig. 7–LSD intervals plots related to concrete cover.

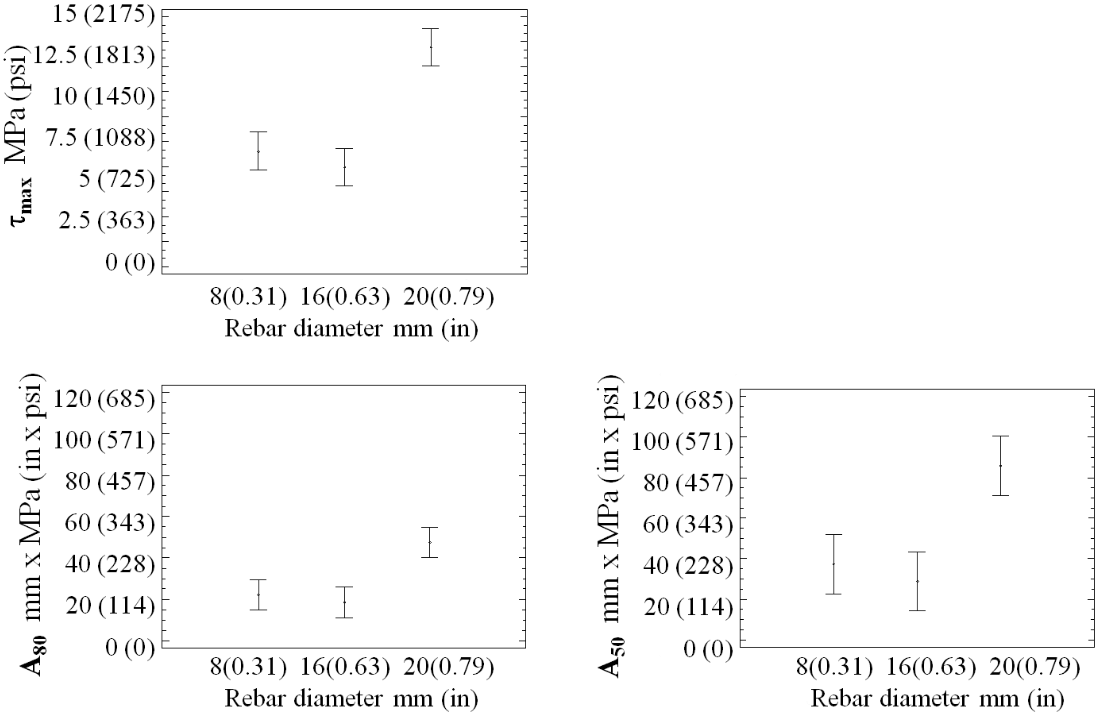

Fig. 8–LSD intervals plots related to rebar diameter.

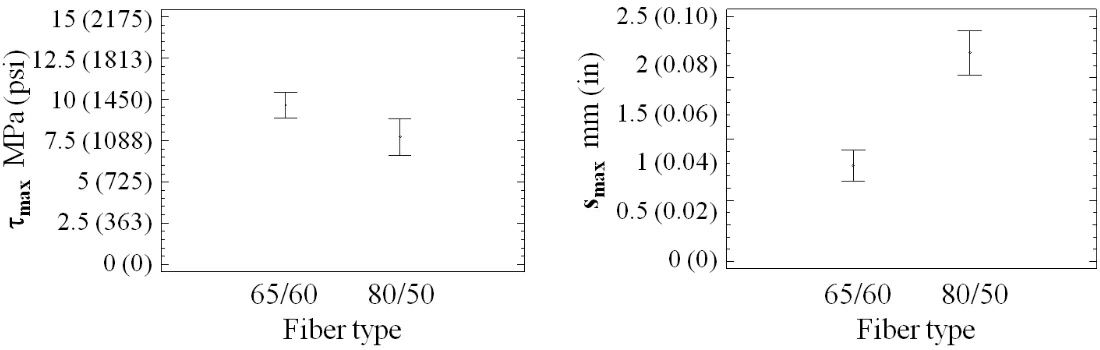

Fig. 9–LSD intervals plots related to fiber type.

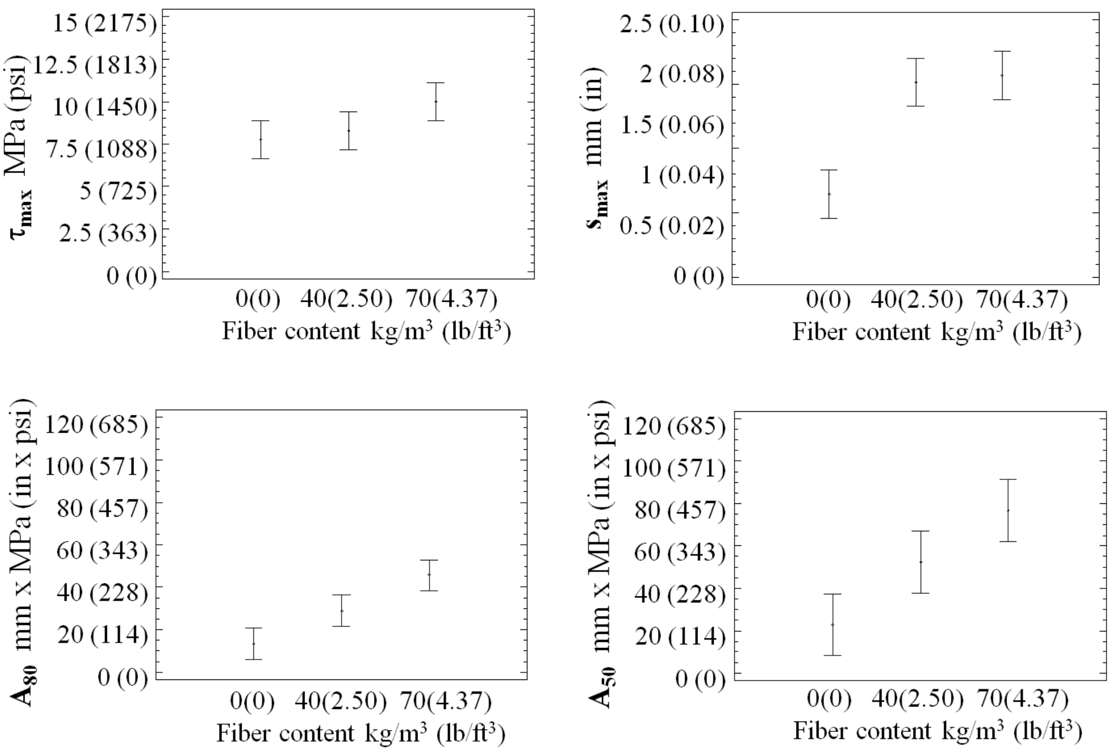

Fig. 10–LSD intervals plots related to fiber content.