INTERFACE ANALYSIS BETWEEN STEEL BARS AND RECYCLED STEEL FIBER REINFORCED CONCRETE

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Abstract: The positive effect of fibers on the bond of reinforcing bars in concrete is widely recognized and supported in literature; on the contrary information are not available on recycled steel fiber reinforced concrete. The experimental work discussed in this paper represents a part of a wider analysis, performed by the authors, on the mechanical performance of RSFRC. In particular the main objective is to investigate the bond behavior between steel bar and recycled steel fiber (from waste tires) reinforced concrete. To this aim eccentric pull-out test on prismatic samples were designed varying the type of fiber (recycled and industrial steel fibers) and the concrete cover-bar diameter ratio; in addition similar tests were carried out on plain concrete for comparison purpose. The experimental data in terms of peak bond stress, mode of failure and bond stress-slip curves are analyzed and discussed evidencing the good bond performance of specimens realized with recycled steel fiber reinforced concrete compared with both those realized with plain and industrial fiber reinforced concrete.

1 INTRODUCTION

As well know, the 2008/98/Ce European Directive [1] expands in Europe the “end of waste” concept, previously introduced by the Italian legislature [2]. The concrete obtained by adding recycled steel fibers from scrap tires showed a good improvement of the mechanical properties of the material such as tensile strength, energy absorption and toughness as well as fatigue strength [3], [4]; as a consequence this material appears to be a promising candidate for both structural and no-structural applications.

The presence of fibers in concrete has also a positive effect on the bond between reinforcing steel bars and concrete. In fact, even if the bond behavior of steel bars in concrete is controlled by several phenomena (such as chemical adhesion, frictional resistance, mechanical interlock), the presence of fibers improves the bond properties thanks to the their bridging action at cracks arising at the bar ribs. Thus, at the onset of cracking the presence of fibers prevents further cracks opening and resists additional tensile forces which the concrete itself cannot sustain [5].

In [6[7] it is shown that the addition of fibers to concrete improves the bond-slip behavior of the reinforcing steel bars after the development of splitting cracks leading to more ductile failures. In these works the authors observed two main types of failure: pull-out and splitting. The first failure mode (pull-out) was characterized by the presence of cracks on the bottom loaded face only; while the splitting mode was characterized by the development of bottom and side longitudinal cracks.

Many authors concluded that fibers improve bond capacity in terms of ductility [8[11] while their effect on the bond strength could be appreciated when the loss of bond is due to splitting [12[13]. The present work is focused on evaluating the influence of recycled steel fibers (RSF) on the bond-slip behavior of steel bars into concrete. Splitting bond failures were investigated: the bridging effect of steel fibers generally improves the bond behavior enhancing the evolution of the cracking phenomenon; a similar benefit is expected when recycled steel fibers are used.

Pull-out tests have been performed varying two parameters: the concrete cover thickness and the type of fiber. In particular, the bond behavior of steel bars in concrete reinforced with RSF was compared with that of the same bars embedded into concrete reinforced with industrial steel fibers (ISF).

The work is a part of a wider research aimed to evaluate the effectiveness of RSF when used in concrete structural applications.

2 EXPERIMENTAL PROGRAM

The experimental program comprises a series of eccentric pull-out tests on prismatic samples for evaluating the influence of the fiber type and concrete cover-bar diameter ratio (c/d). The experimental tests were carried out on cubes made of plain concrete (PC), reinforced concrete with both 0.3% by volume of industrial steel fibers (ISFRC) and 0.3% by volume of recycled steel fibers (RSFRC).

2.1 Materials

Portland cement, water, limestone aggregates and locally available sand were used for the experimental program. All the mixtures were realized using a planetary vertical concrete mixer. Three different mixes were cast with a strength target of 30 MPa: a control mix without fibers (PC), a mix reinforced with recycled fibers (RSF) and a mix reinforced with industrial steel fibers (ISF), with an aspect ratio l/d=50. The utilized mix design is listed in the Table 1.

Table 1: Mix design

Material		PC	RSF	ISF
Portland CEM 32.5R II-A/LL	[kg/m^3]	350	350	350
Water	[l/m^3]	188	188	188
Aggregate I (8-20 mm)	[kg/m^3]	513.00	510.70	510.70
Aggregate II (4-10 mm)	[kg/m^3]	227.60	226.60	226.60
Sand (0-4 mm)	[kg/m^3]	1025.20	1020.70	1020.70
Fibres	[%v]	0	0.30	0.30
	[kg/m^3]	---	16	23.45
Super Plasticizer	[%v]	0.70	0.80	0.53
	[kg/m^3]	2.45	2.80	1.86

The basic properties of both fresh and hardened concrete were determined according to the related standards [14[16].

According to the requirement of the standards [15], cubic specimens with a 150 mm side and cylindrical specimens with 150 mm diameter and 300 mm height were used for concrete characterization. Both cubic and cylindrical specimens were cast using iron moulds, were left to cure under a polyethylene covering at room temperature for 24 hours and then demoulded and placed under water until testing, thus reproducing the environmental condition corresponding to RH 95% and 20°C.

The steel bars used for pull-out test were supplied by “Acciaierie di Sicilia S.p.A”. Their mechanical properties were determined on the basis of tensile and rebend test [17] on at least three specimens.

2.1 Bond test: specimens and experimental set-up

Taking into account the lack of standards for this kind of test, the realized set-up was specifically designed for the proposed experimental work, (Figure 1).

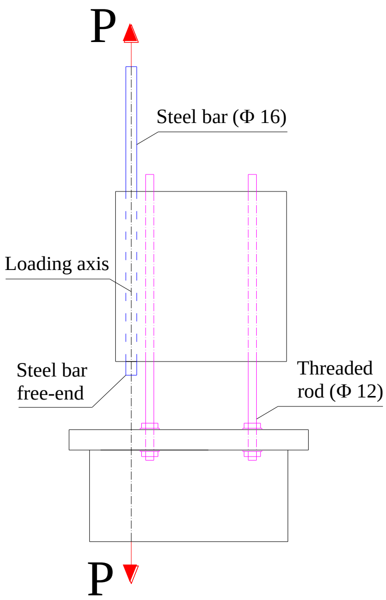

Figure 1: Bond test set-up.

The test set up was designed to avoid compression on concrete and to have the possibility of varying the cover thickness using the same test apparatus: to this scope the bar position was designed to be eccentric with respect to the concrete block.

This aspect (the eccentric position) has been the main critical issue to be solved in order to have a perfectly working set-up and, consequently, reliable experimental data. For this reason, an appropriate steel frame as well as wooden moulds has been designed.

The dimensions of the specimens and the embedded length of the steel bar were defined according to [18[19] for the pull-out test:

- the total length of the specimen should be ten times the nominal diameter of the reinforcing bar but not less than 200 mm. In the present research the nominal diameter of the bar is 16 mm and the side of the cubic specimen is 250 mm;
- the total embedded length should be five times the nominal diameter of the reinforcing bar. In the present research the nominal diameter is 16 mm, thus the embedded length is 80 mm (Figure 2), while the total length of the bar inside the wooden mould is 250 mm. The position of the bonded length was chosen at the bottom of the specimens according to experimental works available in the literature [20].


Figure 2: Bonded length

A view of the specimens before the test is reported in the Figure 3.


Figure 3: Specimen before the test

Three different configurations with the same nominal diameter of the steel bar and three different concrete cover were realized. The main parameters considered in this experimental study are reported in Table 2.

Table 2: Variable parameters

Fibers type	Industrial fibres	
	Recycled fibres	
Nominal diameter of the bars	16 mm	
Concrete cover	A) 15 mm	c/d = 0.94
	B) 25 mm	c/d = 1.56
	C) 35 mm	c/d = 2.19

The experimental program consists of 30 pull-out tests with three different configurations, obtained varying the concrete cover - bar diameter ratio (c/d). In Table 3 the total number of the tested specimens for each configuration is summarized.

Three displacement transducers were used during the test (Figure 4): one transducer was applied at the free end of the steel bar, at the bottom of the cubic sample (Figure 4b), while the other two transducers were applied at the loaded end (Figure 4a).

a) b)

Figure 4: Positions of the displacement transducers: a) loaded end, b) free end

Table 3: Experimental program

	Bond Specimens		
	Conf. A c/d=0.94	Conf. B c/d=1.56	Conf. C c/d=2.19
PC	3	3	3
RSF	4	4	4
ISF	3	3	3

The tests were carried out after 28 days of curing under displacement control (constant displacement rate of 0.2 mm/min) by means of an electro-mechanic machine with a load cell of 200 kN. During the test, the applied load, the corresponding displacement as well as the slips at the free and loaded ends of the specimens were recorded by the data acquisition system.

3 EXPERIMENTAL RESULTS

3.1 Materials characterization

All the tests results of fresh and hardened concrete are summarized in Table 4. The presence of both industrial and recycled fibers did not affect the workability of the concrete as well as adding fibers to the concrete matrix did not significantly improve its compressive strength.

As regards steel bars, it was found that the average experimental values of the ultimate and yielding strength, together with the coefficient f variation (C.O.V.) were f_t=669.7 MPa (C.O.V.=0.34%) and f_y=567.3 MPa (C.O.V.=0.79%) respectively, while the ultimate elongation was A=14.3% (C.O.V.=10.67%). Finally, the rebend test was successful as the specimens after the test were characterized by the absence of visible cracks.

3.2 Bond test results and discussion

The results of pull-out test are reported in Table 5 in terms of ultimate load (F_U), maximum bond strength (τmax) and corresponding slip at both loaded (s_L) and free (s_F) end. The letter “P” refers to specimens without fibers, “R” refers to specimens reinforced with recycled fibers and the “I“ refers to specimens reinforced with industrial fibers. Furthermore A, B and C indicates the type of configuration used (Table 2).

As a short bond length was utilized, a uniform bond stress distribution along the embedded length of the bar was assumed.

Table 4: Fresh and hardened properties

	Slump [mm]	Class of consistency	Air [%]	Density [kg/m^3]	Compressive strength R_c [MPa]	C.O.V. [%]	Tensile splitting f_{ct} [MPa]	C.O.V. [%]
PC	225	S5	2.8	2252	34.03	2.64	4.55	5.80
RSF	205	S4	2.7	2279	35.71	3.08	4.73	10.60
ISF	200	S4	3.0	2219	34.32	0.97	4.56	8.61

S4: measured slump in the range 160 mm – 210 mm [16]

S5: measured slump ≥ 220 mm [16]

In this hypothesis the bond stress values (τ) was calculated on the basis of the measured applied load, with the following equation :

$$\tau = P/(\pi DL) \tag{1}$$

where: P is the applied load, D is the nominal diameter of the embedded bar and L is the embedded length of the steel bar.

Table 5 Bond tests experimental results

	F_U (kN)	τ_{max} (Mpa)	s_F (mm)	s_L (mm)
PA_1	37.20	9.25	0.45	1.84
PA_2	35.37	8.79	1.28	1.06
PA_3	35.24	8.76	0.55	1.04
PB_1	47.70	11.87	0.43	0.79
PB_2	51.75	12.87	0.18	0.79
PB_3	54.20	13.48	0.25	0.92
PC_1	76.70	19.07	0.31	1.05
PC_2	68.51	17.04	0.21	1.04
PC_3	68.63	17.07	0.20	0.96
RA_1	34.39	8.55	0.44	0.76
RA_2	36.10	8.98	0.57	0.72
RA_3	46.13	11.47	0.54	1.10
RA_4	44.54	11.07	0.25	0.58
RB_1	54.81	13.63	0.35	--
RB_2	52.61	13.08	0.20	1.18
RB_3	40.26	10.01	0.65	1.57
RB_4	45.88	11.41	0.70	1.15
RC_1	55.54	13.81	0.43	1.13
RC_2	57.49	14.42	0.34	0.90
RC_3	52.98	13.17	1.11	1.71
RC_4	48.09	11.96	1.30	1.34
IA_1	30.35	7.55	0.49	1.00
IA_2	30.47	7.58	0.29	0.40
IA_3	35.86	8.92	0.33	0.57
IB_1	31.94	7.94	1.69	2.41
IB_2	36.22	9.01	1.40	1.62
IB_3	35.86	8.92	1.10	1.49
IC_1	34.88	8.67	1.22	1.89
IC_2	44.05	10.95	1.01	1.29
IC_3	43.93	10.92	0.87	0.88

Analyzing the maximum bond strength values, it is possible to note that, in the case of plain concrete specimens the τ_{max} increases with increasing c/d ratios. In fact, the average value of τ_{max} is 8.93 MPa (C.O.V. 3.07%) in the case of configuration A, 12.74 MPa (C.O.V. 6.38%) for configuration B and 17.73 MPa (C.O.V. 6.56%) for configuration C. A different behavior is observed in the case of FRC specimens. For the specimens with recycled steel fibers similar τ_{max} values were obtained for the configurations B and C (average value equal to 12.03 MPa and 13.34 MPa, respectively) while a lower value was recorded in the case of specimens with geometric configuration A (average value of 10.02 MPa). In the case of specimens reinforced with industrial steel fibers similar τmax values were obtained for the configurations A and B (average value equal to 8.02 MPa and 8.62 MPa, respectively) while an higher value was recorded in the case of specimens with geometric configuration C. (average value of 10.18 MPa). In Figure 5 the τ_{max} values for each type of concrete are summarized.

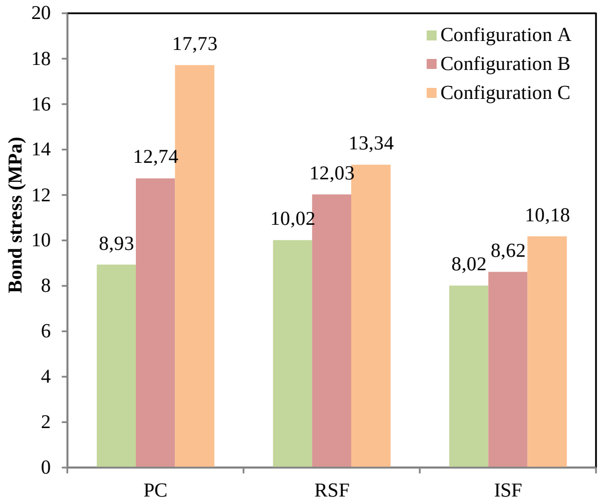

Figure 5: Bond stress values comparison

Comparing the bond strength values for the same configuration while varying the type of concrete it can be noted that for the configuration A, the values of τ_{max} are comparable. However, a different behaviour can be observed referring to the other configurations: for the configuration B the bond strength for plain and recycled steel fibers reinforced concrete is quite similar, while is lower for industrial steel fibers reinforced concrete; for the configuration C, a high value of the bond strength is obtained for plain concrete with respect to those registered for fibers reinforced concrete. In general the scatters don't appear relevant varying the type of concrete even if the worst behavior in terms of τ_{max} was that of concrete reinforced with industrial steel fibers. It is in the opinion of the authors that this aspect could be related to a poor dispersion of industrial fibers near the steel bars (Figure 6e and Figure 6f).

In Figure 6 the bonding surface between steel rebar and concrete matrix at the end of test is shown for some specimens. Figure 6a-d are related to unreinforced specimens: in particular in Figure 6b it can be noted a longitudinal crack generated, as expected, at the interface bar/concrete, while in the Figure 6d it is shown the specimen PC1. broken exactly at the half.

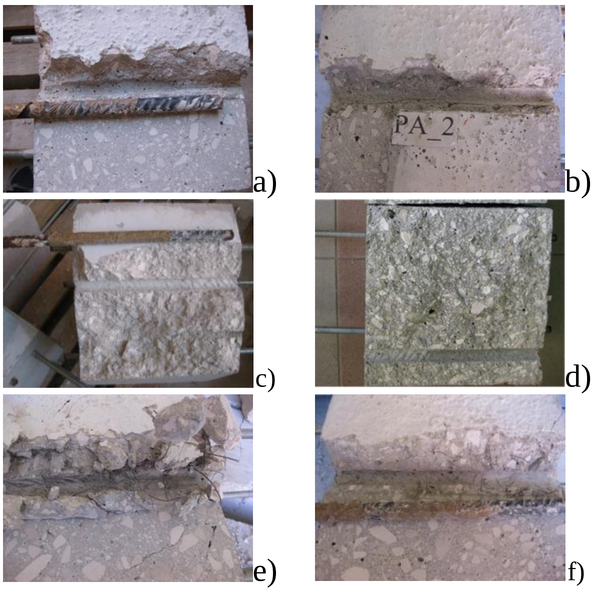

Figure 6: Bonding interface between steel rebar and concrete matrix for the specimens: a)PA1; b)PA2; c) PB2; d)PC1; e)RA3; f)IB3

Analysing the fibres reinforced specimens it can be observed a consistent presence of recycled fibers (Figure 6e), bundled around the bar, while in the case of industrial steel fibres (Figure 6f) there were few fibres distributed at the interface. This would justify, as already mentioned, results reported in Table 6, where the RSFRC samples (RA, RB and RC series) show maximum bond strength values always higher than those registered when using industrial fibres (IA, IB and IC series). In the Figure 7-Figure 8 bond stress versus slip curves are reported, referring to both slip at the loaded and free ends, for specimens realized with plain concrete (Figure 7) and recycled steel fibre reinforced concrete (Figure 8).

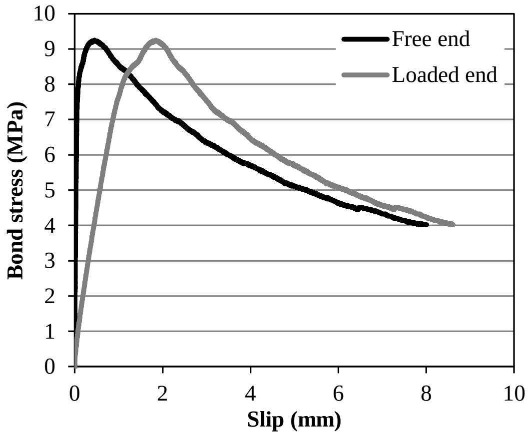

Figure 7: Bond stress versus slip behaviour: plain concrete (PA_1)

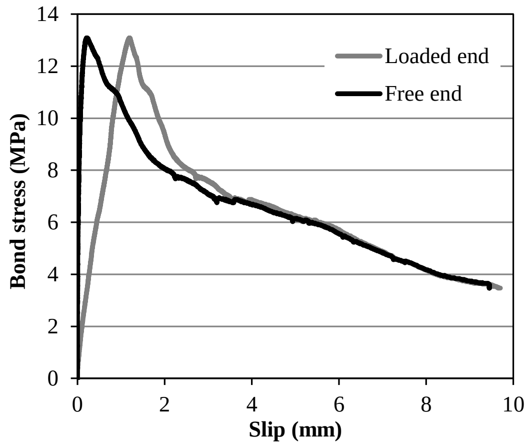

Figure 8: Bond stress versus slip behaviour: RSF concrete (RB_2)

The plotted loaded end slip is the average value of the two measurements. As expected the slip recorded at the loaded end is higher than that recorded at the free end as consequence of the component of the slip due to the deformation of the un-bonded bar read by the displacement transducers at the loaded end. Analyzing the curves, three stages can be clearly identified for both plain and fiber reinforced concrete. At the first stage of the ascending branch of the curve (almost linear at the loaded end) the bond is guaranteed only by chemical adhesion, the slip is negligible and the localized stress arises very fast. In the second stage the curves lose the linearity as the chemical adhesion breaks down for higher bond stress values and transverse micro-cracks originate at the tip of the lugs. Increasing the applied load, longitudinal cracks spread radially from the bar, a loss of bond occurs evidenced by the sharp drop of the curve. In the last stage it can be noted a further decrease of the bond stress with a final descending branch of the curve due to the friction between bar and concrete.

In Figure 9÷Figure 11 the bond stress-slip curves are reported for specimens reinforced with recycled steel fibers in configuration A, B, and C.

As shown in Table 6, even if an increase in bond strength with the increase of the concrete cover was recorded, this was lower than that recorded for the plain concrete, being approximately 20% for the configuration B and 33% for the configuration C.

Table 6: Average bond results for recycled steel fibres specimens

	τ_{max} [MPa]	C.O.V. [%]	Δ [%]
RA	10.02	14.63%	---
RB	12.03	13.68%	20.11%
RC	13.34	7.89%	33.17%

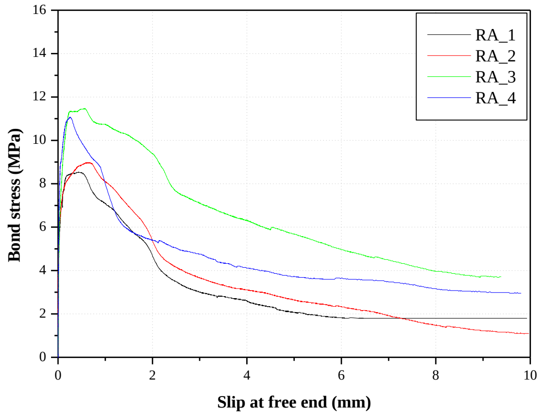

Figure 9: Bond stress versus free end slip for RSFRC - configuration "A"

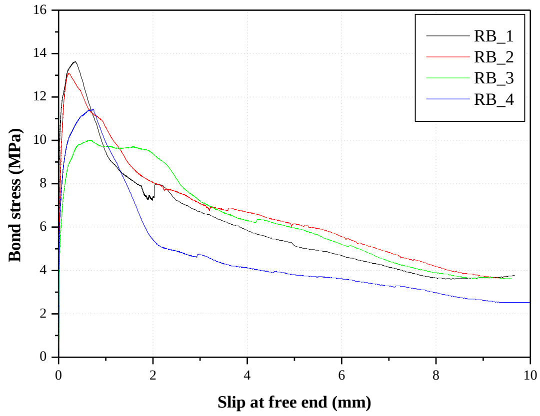

Figure 10: Bond stress versus free end slip for RSFRC - configuration "B"

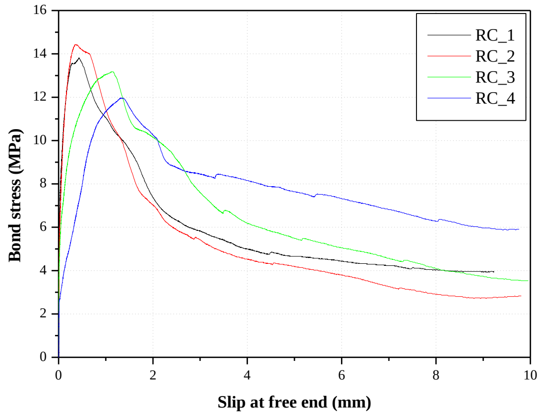

Figure 11: Bond stress versus free end slip for RSFRC - configuration "C"

3.2.1 Failure mode

All the tested specimens showed splitting failure. In fact, the specimens after the tests clearly evidence the presence of splitting cracks, generally expected when the radial component of the bond force causes a circumferential stress exceeding the tensile strength of the concrete [12[21].

In the Figure 12 plain concrete specimens after the test are shown. Analysing the figure it is possible to observe the typical splitting longitudinal crack from the loaded to the free end. In the case of PC_1 and PC_2 specimens the formation of a unique crack (Figure 12a) induced a more brittle failure of the specimens with their final separation into two blocks. Otherwise in the other reference tested specimens more longitudinal cracks formed (Figure 12b) avoiding the sudden crash of the specimens.

Similar kinds of failure were observed for the specimens realized with recycled steel fibres concrete mix even if in this case all tested specimens showed always more than one splitting cracks around the steel bar (Figure 13). Probably in this case the presence of the fibres in the concrete mix promotes the formation of the new cracks while the further widening of the existing ones is inhibited by the bridge effect of fibres.

Even if the specimens realized with industrial steel fibres failed in splitting mode, the presence of the longitudinal cracks corresponding to the position of the steel reinforcing bar was clear visible only for the configuration C (Figure 14c), while for the other two configurations (i.e. A and B) the splitting cracks were better identified by using a digital microscope. Similar to the other specimens there were inclined cracks starting from the steel reinforcing bar (Figure 14b).

From the Table 7 it is possible to observe that, as expected, for the entire tested configurations (i.e. A, B and C) the average values of the crack width in the case of the reinforced samples decreases if compared to the values of the plain concrete specimens belonging to the same configuration.

Table 7: Average value of the crack width

	Width (mm)		
	A	B	C
PLAIN	0.556	0.739	0.821
RECYCLED	0.393	0.316	0.362
INDUSTRIAL	0.165	0.052	0.200

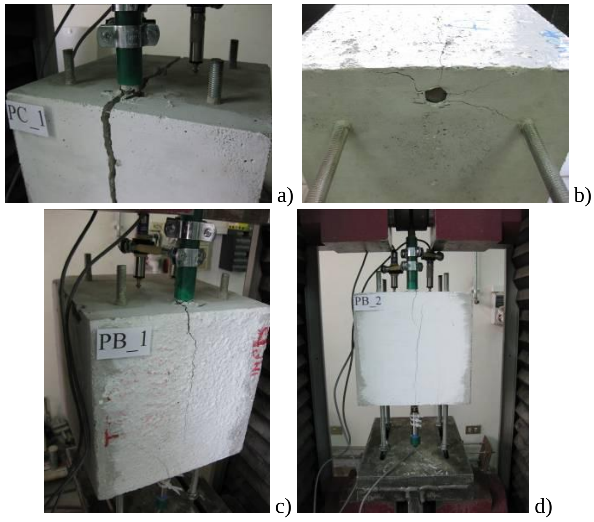

Figure 12: Failure of specimens realized with plain concrete: a) loaded end of PC_1; b) free end of PA_1; c) overall view of PB_1; d) overall view of PB_2

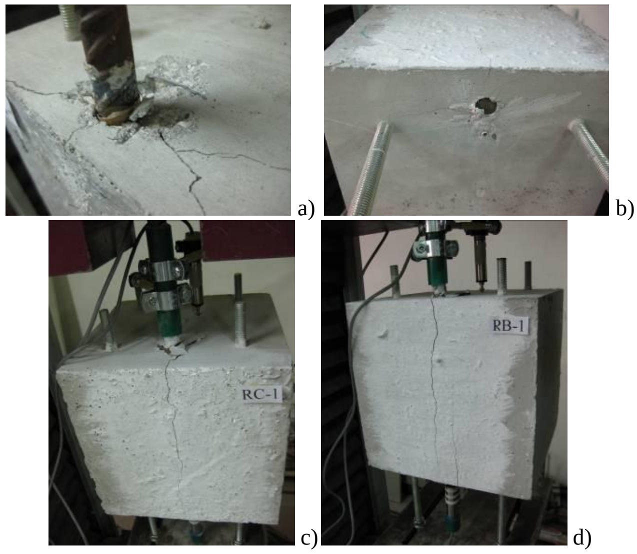

Figure 13: Failure of specimens realized with RSF: a) loaded end of RA_1; b) free end of RB_2; c) overall view of RC_1; d) overall view of RB_1.

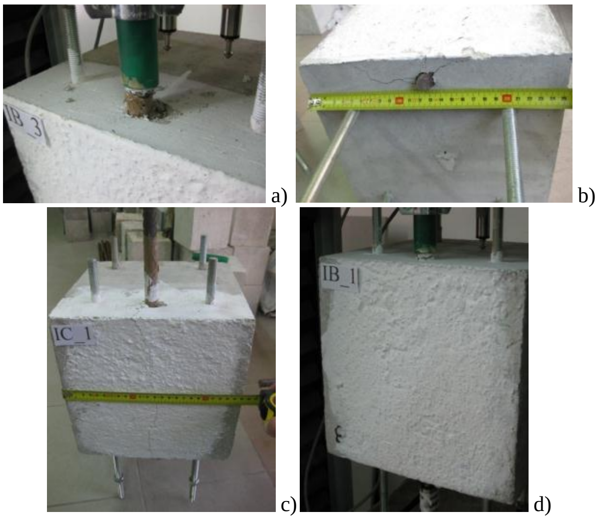

Figure 14: Failure of specimens realized with ISF: a) loaded end of IB_3; b) free end of IA_1; c) overall view of IC_1; d) overall view of IB_1.

3.1.3 Experimental comparison

Furthermore, a comparison in terms of bond stress-slip curve for the three different configurations was performed and illustrated in Figure 15÷Figure 17. Because of the different maximum slips recorded during the tests, in this analysis it was established to plot all the experimental curves up to a maximum slip set equal to 8 mm, in order to have a conventional limit for the calculation of the ultimate residual strength.

Analysing the comparison shown in Figure 15 between the specimens realized with the three different mixtures in configuration A, it is possible to note as the maximum bond strength is almost similar, except for two recycled steel fibres specimens which exhibits a slightly higher bond stress.

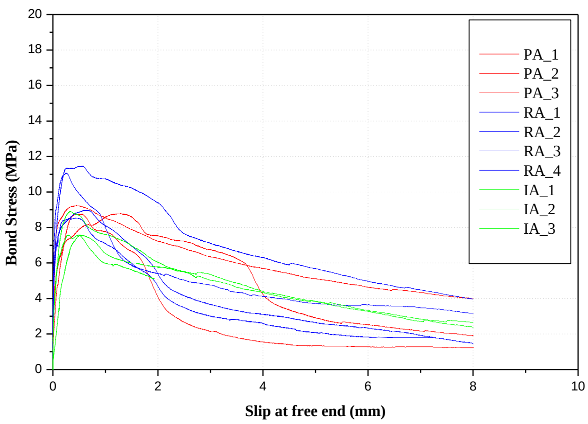

Figure 15: Experimental comparison – configuration A

Then the descending branch is almost similar for all the curves with a low value (1-4 MPa) of residual bond strength.

Analyzing the comparison between specimens in configuration B (Figure 16), it is possible to note as the maximum bond strength is almost similar for plain and recycled steel fibers concrete (between 10-14 MPa) while it is lower for industrial steel fibers concrete (<9 MPa). A different behavior was recorded in the descending branch. In fact, the specimens realized with plain concrete showed a more brittle behavior with a steeper descending branch respect to the FRC specimens; in the last case the loss of bond takes place more gradually. In addition, the friction contribution of the specimens with both type of reinforced concrete is higher than that of plain concrete ones.

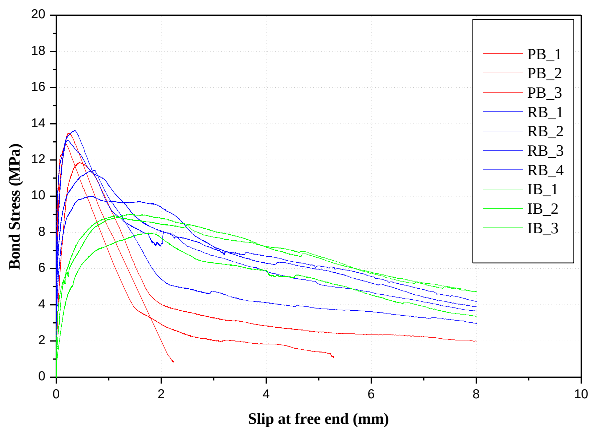

Figure 16: Experimental comparison – configuration B

The presence of fibers seems to improve the bond in the post peak phase due to their bridging effect at cracks. This effect is more evident comparing the specimens with geometric configuration C (Figure 17). In fact the brittle behavior of the plain concrete specimens is compared with the softening behaviour of the reinforced concrete samples which is characterized by a high friction component in the last stage. In this last case the maximum bond strength of plain specimens is higher than that realized with FRC concrete mix.

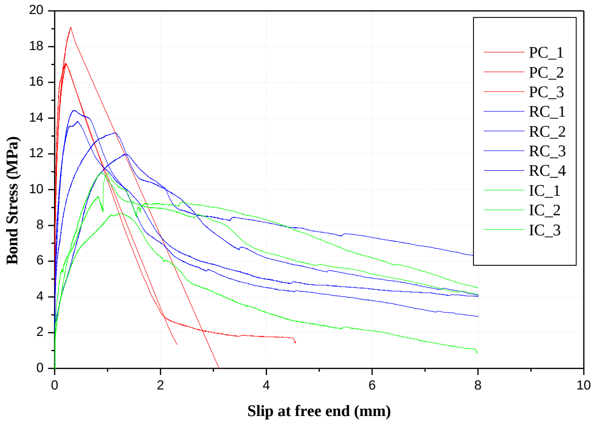

Figure 17: Experimental comparison – configuration C

4 CONCLUSIONS

The experimental tests reported in this section are part of a wider research aimed at analyzing the effectiveness of recycled steel fibers from waste tires as reinforcement in concrete for structural e no-structural applications. In this section the analysis of the bond mechanisms between steel bars and FRC concrete was analyzed. In particular, eccentric pullout tests were performed varying the ratio between the concrete cover and the bar diameter (c/d) and the types of reinforcement (recycled and industrial steel fibers). Similar tests were executed on plain concrete for comparison in order to better understand how the presence of fibers influences the bond performance.

On the basis of these first results the following considerations can be drawn:

– By the bond tests carried out in this experimental work it was found that the bond failure for all tested specimens (plain and reinforced concrete) occurred by splitting; it was also found that the crack width of the reinforced samples decreases if compared to the values referred to the plain concrete;
– The bond mechanisms do not change when recycled steel fibres are added to the concrete mix. In fact, for all tested specimens three different stage can be distinguished, related to chemical adhesion, mechanical interlocking and friction between bar and concrete.
– The presence of fibre in the concrete mix does not affect the maximum bond strength but it seems to be able to improve the bond performance after the peak bond stress is attained, mostly when thicker concrete cover are utilized.

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