Macro synthetic fibre reinforced concrete: Influence of the matrix mix design on interfacial bond behavior

C Del Prete, N Buratti, S Manzi and C Mazzotti
University of Bologna, ITALY

E-mail: clementina.delprete2@unibo.it

Abstract. Since the composite nature of Fibre Reinforced Concrete materials, their performance is strictly dependent on the mechanical properties of their components, matrix and fibres, but, above all, on their interaction. The collaboration of the two materials is directly responsible of the force transferring mechanism from concrete to fibres that reflects their contribute in the residual flexural strength performance. This paper aims at understanding how the concrete admixture components might affect the bond of polypropylene crimped fibres, and presents the preliminary results of an experimental campaign consisting of pull-out and compression tests. Four water cement ratios and three cement-sand ratios were considered. The experimental analysis is also supported by the calibration of a numerical model that simulates the pull-out behaviour of a single fibre.

1. Introduction
The design of concrete structures requires particular attention to the cracking problem. The cracked state of plain concrete might be controlled adding fibres to the matrix [1]. The advantage in using fibres is the possibility of gaining a residual tensile strength: the progressive crack opening activates the action of fibres which connect the sides of cracks. The mechanical performance of FRC during the cracked state is controlled by the crack bridging phenomenon which depends on the bond between fibres and matrix. On one hand, a weak bond can cause the slippage of fibres at low stress levels, and, on the other hand, a very strong bond might lead to the failure of fibres in tension. Intermediate bond values, for which most fibres pull out without breaking represent the most desirable behaviour because that will correspond to the highest apparent ductility of FRC elements [2]. There are many factors that might influence the bond of fibres to concrete: chemical adhesion, surface roughness, material properties and shape of fibres, strength and stiffness of the matrix [3].

Zaho et all studied the bond slip mechanism comparing hooked-end and straight shape of steel fibres by means of pull-out tests using acoustic emission techniques to investigate deeply the interfacial bond [4]. This research has revealed a better adhesion for hooked-end fibres due to his shape. Moreover, the strength of the matrix might play an important role in the pull-out mechanism, a higher concrete strength involves a greater pull-out force for steel fibres.

Besides, in case of micro PVA fibres, the interfacial properties of mortar designed with a lower water/cement ratio and higher strength are better than those with higher water/cement. In addition, the shape of the pull-out curve changes with decreasing of water cement ratio because the bond strength increases and so the peak of the curve is higher, while the pull-out displacement decreases [5].
Macro Synthetic (MS) fibres adoption is becoming widespread because of their benefits in terms of corrosion problems and ease in handling, despite their potential problems connected with temperature and creep [6]. These fibres are mostly produced using various blends of polypropylene that does not feature a hydrophilic nature. Therefore, chemical adhesion is weaker compared to PVA fibres.

Aside from understanding which factors influence the fibre bond in FRCs, it could be important also to analyse the behaviour of the single fibre in terms of constitutive law. In particular, in order to develop models to simulate the bending capacity of structural elements [7]. The behaviour of a single fibre subjected to an increasing pull-out load can be separated into two phases: there is a debonding phase after which the fibre starts to slip from the matrix following a softening or hardening branch. The load may tend to decrease during the slippage phase because of the Poisson effect that reduces the section of the fibre with its elongation, this effect is remarkable especially for polymeric materials [8]. The different trend of the second phase could be dependent on the fibre material and shape, and in general it is related to the different strength of the fibre.

The present work concerns the study of the bond of a MS fibre, with the main objective of analysing the effect of different concrete mix design parameters on the interfacial bond properties. In particular the effect of W/C ratio, Cement Sand ratio (C/S) and type of cement. The effect of this fibre on the flexural behaviour of FRC beams has been already analysed by Del Prete et al.[9]. The research is carried on by means of experimental direct pull-out tests, the experimental results are used for the calibration of a constitutive debonding law through a numerical one-dimensional model. The purpose of the analysis developed is also linked to an appropriate design of the FRC material, since the strictly connection of the fibre failure mechanism with the crack-bridging phenomenon and, consequently, the material performance in the cracking phase. In addition, the calibration of the numerical model makes possible a correct estimation of the mechanical parameters characterizing the bond behaviour of this fibre type and the definition a numerical constitutive law for the single fibre pull-out behaviour.

2. Materials and methods

2.1. Materials

The present work analyses the interfacial bond properties of crimped polypropylene fibres. This shape was adopted because it is associated to better bond performances than straight fibres [10]. The geometrical and mechanical properties of fibres are listed in Table 1: the aspect ratio is a parameter relating the diameter and the length and it is specific for geometrical characterization of short discontinuous fibres.

The fibre diameter was estimated weighing many groups of fibres, with a different length for each group, in order to obtain a more accurate value. The tensile strength and, consequently, the elastic secant modulus, were calculated from the results of direct tensile tests on single fibres.

| Fibre property                  | Value  |
|--------------------------------|--------|
| Fibre length [mm]              | 39     |
| Fibre diameter [mm]            | 0.92   |
| Fibre Aspect ratio [-]         | 43     |
| Fibre material                 | PP     |
| Fibre tensile strength [MPa]   | 391    |
| Elastic secant modulus [GPa]   | 2.25   |

In order to study the effect of the cementitious matrix on fibres bond, different mix designs were considered. Sand (0-4 mm) was the only aggregate used because coarse aggregates can compromise the failure mechanism when placed close to the fibre. The effect of the coarse aggregates in FRCs mix
design is reflected more on the random fibres placement in the concrete matrix [11]. Two different cements were adopted, i.e. CEM I 42.5 R and CEM I 52.5 R. Different mixes were defined by considering various values of Cement/Sand (C/S) ratio and of Water/Cement (W/C) ratio. In particular, for each cement type, four W/C ratios ranging from 0.4 to 0.6 and three C/S ratios, from 0.25 to 0.5 were used. Table 2 shows an outline the various mixes considered. A superplasticizer was used in order to obtain a similar workability for all the mixes. For each combination of cement type, W/C and C/S, three different batches of two specimens were produced, casting a total of six specimens.

Table 2. Experimental campaign outline.

| Mix code | Cement  | W/C | C/S | Mix code | Cement  | W/C | C/S |
|----------|---------|-----|-----|----------|---------|-----|-----|
| G1       | 42.5R   | 0.4 | 0.5 | H1       | 52.5R   | 0.4 | 0.5 |
| G2       | 42.5R   | 0.4 | 0.3 | H2       | 52.5R   | 0.4 | 0.3 |
| G3       | 42.5R   | 0.45| 0.5 | H3       | 52.5R   | 0.45| 0.5 |
| G4       | 42.5R   | 0.45| 0.3 | H4       | 52.5R   | 0.45| 0.3 |
| G5       | 42.5R   | 0.45| 0.25| H5       | 52.5R   | 0.45| 0.25|
| G6       | 42.5R   | 0.5 | 0.5 | H6       | 52.5R   | 0.5 | 0.5 |
| G7       | 42.5R   | 0.5 | 0.3 | H7       | 52.5R   | 0.5 | 0.3 |
| G8       | 42.5R   | 0.5 | 0.25| H8       | 52.5R   | 0.5 | 0.25|
| G9       | 42.5R   | 0.6 | 0.5 | H9       | 52.5R   | 0.6 | 0.5 |
| G10      | 42.5R   | 0.6 | 0.3 | H10      | 52.5R   | 0.6 | 0.3 |
| G11      | 42.5R   | 0.6 | 0.25| H11      | 52.5R   | 0.6 | 0.25|

2.2. Specimens casting

The experimental campaign performed consists of pull-out and compression tests; the specimens used for the tests are 100 mm x 100 mm x 100 mm cubes with a single fibre inserted at the middle of one of their faces for a depth 25 mm. All the specimens were produced using a planetary mixer (Figure 1a), according to UNI EN 197-1 that indicates also the mixing time. Workability was controlled measuring the slump with a 60 mm high cone. The dosage of superplasticizer was adjusted in order to obtain values ranging from 20 to 50 mm (Figure 1b).

![Figure 1](image_url)

Figure 1. Casting procedure: (a) Specimens preparation; (b) Slump test; (c) Fibres tested.
After mixing, concrete was cast in cubic polyurethane moulds and then vibrated (Figure 2). Fibres were positioned at the centre of the upper face of the moulds using aluminium supports screwed to their walls (Figure 2). Specimens were vibrated in order to remove entrapped air, in particular in the surroundings of the fibre. Moulds were then wrapped with plastic sheet. After two days, the specimens were carefully demoulded and aged in water, to limit shrinkage, for 26 days at a constant temperature of 20 °C (Figure 3). Each specimen was then used for pull out tests and then tested in compression. The choice of using the same specimen for both tests is justified by the low values of pull-out forces that do not influence the compressive strength of concrete.

2.3. Pull-out tests
Pull-out tests were performed using a servo-hydraulic MTS Landmark loading frame, controlled by a MTS Flextest 40 controller. Specimens were placed between two square steel plates and blocked by four threaded bars at their corners (Figure 4). These bars were tensioned at the beginning to each test. A threaded bar was attached to the centre of the bottom plated and was connected to the testing machine using its hydraulic grips. The upper plate had a 60 mm diameter circular opening at the top in order to grip fibres. Two aluminium plates with sand paper glued to their surface were used to this aim. These plates were tightened by the hydraulic grips of the testing machine. The test was carried in displacement control at a rate of 0.06 mm/sec. During the tests the force applied and the actuator displacement were measured. In some preliminary tests the fibre pull-out was measured using two LVDTs but their measurements were very consistent with the displacement of the actuator and therefore they were removed in order to simplify the test setup.
2.4. Porosity tests
A Mercury Intrusion Porosimetry (MIP) test was used on samples obtained by some of the specimens used for the pull-out tests. Porosity tests are a good way to investigate the different interfacial state due to the different mix design, being a good predictor of the concrete state [12]. These tests use the properties of mercury (Hg), i.e. it penetrates inside the voids of the matrix samples with pressure that increases as soon as the pores size decreases. Since the failure type is expected to be connected to the microstructure of concrete, porosity tests were carried out in order to investigate if concrete porosity can influence the pull-out behaviour of fibres. MIP tests need samples of about 1 cm$^3$ representative of the microstructure (Figure 3b). They were extracted from the undamaged core of cubes after compression tests.

3. Experimental results

3.1. Pull-out tests
In general, two failure modes could be observed in the tests; either fibre pull-out or fibre tensile failure. The typical pull-out curve observed is reported in Figure 5a. It has a quasi-linear first branch up to the peak strength, corresponding to the deboning phase. After the peak strength there is a sudden strength decrease followed by a decreasing undulating branch until complete pull-out. This last part of the curves is dominated by the friction and the mechanical interlock between the fibre and concrete. In particular the undulating behaviour is related to the shape of the fibres tested. When the pull-out strength is higher than the tensile strength of the fibre, this latter will fail in tension, as in Figure 5b. When a fibre breaks in tension it will fibrillate, the steps in the descending branch are associated to the failure of the various fibrils (Figure 5b). Table 3 lists the mean experimental results in terms of peak forces for pulled-out and ruptured fibres and number of fibres for each failure mode.

Figure 4. Test set-up used to perform the (a) pull-out tests and (b) compression tests.
The results reported in Table 3 point out that the peak forces measured on pulled out and broken fibres are very similar. Therefore for this embedment length (25 mm) it is not easy to clearly understand the effects of W/C, C/S and cement type on the bond properties. Nevertheless, analysing the possible relations between the bond strength in terms of peak forces and the variables involved in the debonding
process, a common trend among the experimental results can be found. The charts in Figure 6 show the relationship between the peak force measured during the test and the W/C – C/S ratios. It is possible to notice a strength decrement that appears more pronounced with the increment of water-cement ratio rather than with the cement-sand ratio. This decrement is more visible for the specimens with CEM I 42.5 R (Figure 6a) rather than for those with CEM I 52.5 R (Figure 6b). It is worth noticing that the cement strength can influence the type of failure, specimens with higher strength cement feature more broken fibres, in particular for matrix designed with a low water cement ratio.

Figure 7 and Figure 8 propose a two dimensional view of the same relationship considering only pull-out failure in order to better understand the relationship between concrete mix parameters and pull-out strength. This representation agrees with the previous conclusion: for specimens with higher cement strength, the scatter seems to increase and, the trend for the second group is less evident. The presence of more water and less cement and, consequently, the rearrangement of aggregates in the matrix, leads to a lower bond strength of the single fibre. Besides, the decrement in peak pull-out force is more pronounced with C/S ratio of 0.51, it seems that a greater sand amount in the mix design determines a different internal organization and, consequently, an higher scatter of results in terms of peak forces.

![Figure 6](image6.png)

**Figure 6.** Correlation of peak forces for pulled-out and ruptured fibres with C/S and W/C ratios for specimens with (a) CEM I 42.5R and (b) CEM I 52.5R.

![Figure 7](image7.png)

**Figure 7.** 2D representation of peak forces mean value relation with (a) w/c and (b) c/s ratio for specimens with CemI 42.5R.
3.2. Compressive tests
The matrix mix design, W/C, C/S ratios and cement strength, defines certainly its strength. For this reason, compressive tests results are considered for a more detailed analysis of the cement strength effect. The plot in Figure 9a, relating the peak pull-out force to the mean value of mortar compressive strength for each batch, makes possible to conclude that a higher matrix strength, associated mostly with a lower W/C ratio in the mix design, implies a higher pull-out force. On the other hand, for the specimens with CEM 52.5R (Figure 9b) the trend is less clear but in this case the number of pulled-out fibres is much lower and the regression line is not very reliable.

Taking into consideration the batches exhibiting more pulled out fibres in both groups, G9, G10, G11 and H9, H10, H11, designed with W/C ratio 0.6 and progressive C/S ratio, and respectively CEM I 42.5 R and 52.5 R, have different compressive strength. With equal mix design, the first group is placed in a range of variability between 27 – 35 MPa while the second covers a range of 40 – 45 MPa. Thus, it is directly perceptible that, a higher cement strength assures a high bond strength indeed the same compressive strength (i.e. 40 MPa) is achieved with a W/C ratio of 0.5 by the first group while the second gains the same compressive strength with a W/C ratio of 0.6.
3.3. Porosity tests

The output of these tests is the relation between the volume of mercury intruded in the pores and their size. Table 4 reports the amount of Hg inside the pores according to the IUPAC pore size classification but considering only the maximum value of this quantity. Figure 10 shows the correlation between the peak forces measured from the tests on the Specific Intruded Hg volume where the linear regression reported is evaluated only on the pull-out force results. As expected, with the increment of mercury amount and, therefore the increment of porosity, the bond strength decreases.

Table 4. Maximum values of intruded Hg volume according to the IUPAC classification pore size.

| ID sample | Macropores | Mesopores | Micropores | ID sample | Macropores | Mesopores | Micropores |
|-----------|------------|-----------|------------|-----------|------------|-----------|------------|
| G1A_P1    | 0.82       | 26.06     | 102.48     | G7C       | 0.99       | 17.61     | 79.01      |
| G1B_P1    | 0.69       | 5.29      | 67.16      | G7C       | 0.69       | 6.73      | 68.91      |
| G2B_P1    | 0.71       | 75.92     | 82.44      | G8C       | 0.65       | 35.14     | 108.79     |
| G2B_P2    | 0.59       | 29.16     | 84.81      | G9C       | 0.84       | 9.16      | 85.90      |
| G3C_P1    | 0.66       | 6.23      | 84.81      | G10C      | 0.82       | 3.65      | 84.47      |
| G4C_P2    | 0.67       | 46.38     | 108.76     | G11C      | 0.66       | 25.94     | 96.98      |
| G5C       | 0.61       | 7.74      | 74.70      | G11C      | 0.64       | 26.06     | 102.48     |
| G6C       | 0.8        | 9.55      | 85.80      |           |            |           |            |

Figure 10. Relation between peak forces of pulled out fibres with volume intruded in micropores.

4. NUMERICAL BOND SLIP MODEL

A 1D FEM model was used in order to simulate the experimental results. The embedded portion of a general fibre was modelled by means of a series of truss elements (each of them 1 mm long) with nonlinear springs at their ends in order to simulate the bond-slip behaviour. The constitutive law of these springs (Figure 11a) is based on a modified version of the Cosenza et al.[13] model, first proposed for FRP bars in concrete. This model describes the bond-slip behaviour with two different equations corresponding to the debonding and pull-out phases, respectively. The relationship between bond strength (τ) and slip (s) in the debonding stage is described by the following power-law:

\[ \tau = \tau_m \left( \frac{s}{s_m} \right)^\alpha \]  \hspace{1cm} (1)

where \( \tau_m \) represents the maximum bond strength, \( s_m \) the corresponding slip and \( \alpha \) is a shape parameter.
After the peak bond-strength $\tau_m$ the Cosenza et al. model was modified in order to consider a sudden stress drop followed by a friction-dominated behaviour. This second part of the constitutive relationship is bilinear and is defined by the parameters $\tau_f$, $s_f$ and $s_0$, as shown in Figure 11a. Therefore the adopted bond-slip model has a total of six unknown parameters. Their values were identified by means of an inverse analysis procedure, applied on all the experimental results corresponding to pulled-out fibres.

This procedure made use of the Matlab™ Pattern Search algorithm that was used to minimize a cost function defined as a linear combination of the differences between experimental and numerical results at a set of reference points. Figure 11b shows a comparison of the results given by the numerical model against the experimental curve used as input of the inverse analysis. It is possible notice that there is a very good agreement between the two curves. Of course the numerical model is not able to reproduce the undulating shape of the last branch of the experimental curves being based on a purely frictional behaviour. Figure 12 shows the relationship between the $\tau_m$ values obtained from the inverse analyses based on the experimental results for specimens with CEM I 42.5 R against the W/C ratio. The trend that can be observed follows that of the experimental results, a decrement of the peak force with the increment of water cement ratio.

![Figure 11](image1.png)

**Figure 11.** (a) Local bond behaviour characterizing the single spring and (b) global behaviour of the pull-out failure mechanism for the entire fibre.

![Figure 12](image2.png)

**Figure 12.** Relation between the maximum bond strength obtained from inverse analysis and W/C ratio, for specimens with CEM I 42.5R.
5. CONCLUSIONS
This paper presented the preliminary results of an experimental campaign aimed at investigating the effect of mix design parameters, namely Water/Cement and Water/Sand ratios and cement strength, on the pull-out behaviour of a macro-synthetic fibre. Results for different concrete mixes and a single fibre embedment length were discussed. It was found that increasing the W/C the fibre bond strength decreases while higher C/S ratio values have a positive effect on the bond properties. Also the cement type, affects the interfacial behaviour enhancing the bond strength.

It is important to notice that in the present work only one fibre embedment length was considered and for this length a significant number of fibres failed in tension without pulling-out. Therefore a better understanding of the bond behaviour will be possible after analysing different embedment lengths.

Acknowledgments
The support of the staff of the Interdepartmental Center for Industrial Research (CIRI) Building and Construction, University of Bologna, is gratefully acknowledged.

References
[1] ACI 544.5R 2010 Report on the Physical Properties and Durability of Fibre-Reinforced Concrete
[2] Jewell RB, Mahboub KC, Robl TL and Bathke AC 2015 Interfacial bond between reinforcing fibres and calcium sulfoaluminate cements: Fibre pullout characteristics ACI Mater J 112 pp 39-48
[3] Zhao G, Verstrynge E, Prisco M and Vandewalle L 2012 Investigation on Single Fibre Pullout and Interfacial Debonding Mechanisms With Acoustic Emission Techniques 8th RILEM Int Symp Fibre Reinf Concr challenges Oppor (BEFIB 2012) pp 1-11
[4] Markovich I, Van Mier JGM, Walraven JC and Microlab W, Structures C 2001 Single fibre pullout from hybrid fibre reinforced concrete Heron 46 pp 191-200
[5] Liu J, Li C, Liu J, Yang Z and Cui G 2012 Pullout behavior of polyvinyl alcohol fibre from cementitious matrix during plastic state 8th RILEM Int Symp Fibre Reinf Concr challenges Oppor (BEFIB 2012) pp 480-488
[6] Buratti N and Mazzotti C 2015 Experimental tests on the effect of temperature on the long-term behaviour of macroscopic Fibre Reinforced Concretes Constr Build Mater 95 pp 133-142
[7] Manca M, Ciancio D and Dight P 2017. Fibre reinforced concrete in flexure and single fibre pull-out test: A correlation IOP Conf Ser Mater Sci Eng. 246
[8] Redon C, Li VC, Wu C, Hoshiro H, Saito T and Ogawa A 2001 Measuring and Modifying Interface Properties of PVA Fibres in ECC Matrix J Mater Civ Eng. 13 pp 399-406
[9] Del Prete C, Tilocca A, Buratti N and Mazzotti C 2018 Effect of fibre dosage and matrix compressive strenght on msfrc performance 3rd FRC International Workshop Fibre Reinforced Concrete: from Design to Structural Applications pp 174-175
[10] Tang CS, Li J, Wang DY and Shi B 2016 Investigation on the interfacial mechanical behavior of wave-shaped fibre reinforced soil by pullout test Geotext Geomembranes 44 pp 872-883
[11] Ostrowski K et al. 2018 The Effect of the Morphology of Coarse Aggregate on the Properties of Self-Compacting High-Performance Fibre-Reinforced Concrete Materials (Basel) 11 p 1372
[12] Claisse PA, Cabrera JG and Hunt DN 2001. Measurement of porosity as a predictor of the durability performance of concrete with and without condensed silica fume Adv Cem Res. 001 13 pp 165-174
[13] Cosenza E, Manfredi G and Realfonzo R 2002. Development length of FRP straight rebars Compos Part B Eng 33 pp 493-504