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UFRG – UNIDIRECTIONAL FIBRE REINFORCED GROUT AS STRENGTHENING MATERIAL FOR REINFORCED CONCRETE STRUCTURES

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Summary: *The present study is part of an extensive research project, where the main objective is to evaluate a strengthening solution for reinforced concrete structures using a small thickness jacketing in the compression side of the RC element with unidirectional fibre reinforced grout - UFRG.*

For this purpose a high performance cementitious grout reinforced with continuous and unidirectional non-woven fibremat has been developed. It was expected that the use of these type of fibres allowed an optimization of its percentage and orientation. Besides, for continuous fibres (with an aspect ratio, defined as the length-to-diameter ratio, l/d=∞), the composite should attain higher tensile strength since the fibre embedment length is enough to prevent fibre pullout.

The experimental campaign included a set of preliminary tests that allowed the design of the fibre reinforced grout, sustained with rheological parameters [7] and mechanical characterization tests of the materials.

Finally, an experimental campaign was carried out in order to proceed to the mechanical characterization of the unidirectional fibre reinforced grout. Compressive tests were conducted in small thickness tubular specimens that enable the determination of the compressive strength and the static modulus of elasticity of the material. The tensile strength of the material was obtained using splitting tests of cubic specimens (according the standard DIN 1048-5). The experimental results are presented and analysed.

1 INTRODUCTION

In the last decades, research efforts have been made in order to improve the performance of conventional concrete that have promote a technological development and an improvement of its mechanical behaviour.

For instance, the use of superplasticizers, among other additives, that allow the production of a more compact concrete with optimized water/cement ratio (w/c); the careful choice of materials, as the use of fine-grained aggregates that leads to a more compact and dense matrix (with a more reduced w/c ratio); the addition of fillers to reduce the voids, leading to an improvement of the overall performance of the concrete in terms of strength, workability and durability. The materials that exhibit these properties belong to the class of high performance concretes (HPC). However, in general, a compact mixture, with a high compressive strength, exhibits a brittle behaviour. The incorporation of fibres can prevent or delay this failure behaviour. These materials are designated by High Performance Fibre Reinforced Concrete (HPFRC), such as BSI/CERACEM [1]; DUCTAL [2]; CEMTEC multiscale [3]; CARDIFRC [4]; ECC (Engineered Cementitious Composite) [5], among others.

In general, HPFRC contain dispersed and randomly oriented fibres. The fibres can be distinguished by the nature (metal, glass, polymer, natural, etc.), cross section and shape (smooth, end hooks, deformed, indented, twisted, etc.) and aspect ratio (length-to-diameter ratio - l/d).

The mechanical performance of FRC is strongly dependent on the properties of the matrix, fibres and fibre-matrix interface. The main difficulties lie in ensuring the homogeneity of the mixture (without segregation of fibres), the workability of FRC for a high fibre volume and in assuring an adequate bond between fibre-matrix. These aspects can be controlled through the optimization of the cementitious matrix microstructure and the choice of the fibres.

As mentioned, the mechanical properties of FRC are influenced by various parameters, such as the type of fibre, aspect ratio, the amount of fibre, the strength of the matrix [6]. Hereby, the compressive strength of the FRC is strongly influenced by the resistance of the matrix; the fibres affect specially the tensile strength of the FRC. The failure mode of the composite can be associated to tensile strength of the fibres or debonding on the interface between fibre and matrix [8]. In order to increase the tensile strength of the FRC, failure mode should occur, preferentially, by demanding the fibre strength. For this purpose, it can be use high-strength fibres. Alternatively, the use of fibres with a high aspect ratio or improving the bond fibre-matrix may prevent premature debonding between fibre and matrix, enhancing the requested fibre strength. On the other hand, the failure mode through debonding leads to an increase of the ductility.

Naaman (2007) [9] suggests a classification for fibre reinforced cementitious composites based on the tensile strength response, differentiating two types of behaviour: strain-softening or strain-hardening after the appearance of first crack.

It should also be noted that the addition of two or more types of fibres can improve the behaviour of the material, called a Hybrid Fibre Reinforced Concrete. Marković (2006) [10] present a hybrid solution using short and long steel fibres. The author observed an increase in tensile strength due to short fibres crossing the microcracks and a post-cracking behaviour, conferred by the long fibres crossing the macrocracks, associated to an increase of ductility.

Considering the high fibre reinforced concrete properties, several research studies have been developed and presented. Among others, focusing the application of these materials at strategic points of a structure such as the beam-column joints [5], [15]; as an alternative strengthening technique [16], specially, in seismic retrofitting [13], [14].

2 SCOPE

The main objective of the study was to evaluate a strengthening solution for reinforced concrete structures with fibre reinforced grout jacketing. It is expected an improvement of the confinement of the section with a small thickness jacketing, delaying concrete crushing and buckling of longitudinal reinforcement in the compression side of the RC element.

For this purpose a high performance cementitious composite reinforced with unidirectional nonwoven fibremat - UFRG - was developed. In order to improve the compression behaviour of the RC, the required mechanical properties of the composite material were high compressive and tensile strength (rather than ductility). Knowing that the behaviour of a composite is influenced by the properties of the cementitious matrix and fibres, continuous and unidirectional steel fibres (set in the form of a mat) exhibited the appropriate features in order to achieve the required mechanical properties. It was expected that the steadiness provided by the use of a preplaced fibremat (into the mould) poured with a high performance grout, reducing the tendency of segregation of the fibres, allowed an optimization of its percentage and orientation. Besides, for continuous fibres ($l/d = \infty$), the composite should attain higher tensile strength since the fibre embedment length is enough to prevent fibre pullout. Thus, the expected failure is associated to the rupture of the fibre. This argument is valid for one fibre, but, in principle, the effect in a group of fibres enhances this phenomenon. In fact, the pullout of a fibre introduces compression in the matrix surrounding the closer fibres and vice versa. However, the excessive amount of fibres can be prejudicial because the amount of matrix between them may not be sufficient, compromising a good bond between fibre-matrix.

A reference should be made to the efforts developed in this domain, namely the attempt to increase significantly the mechanical properties of a steel reinforced concrete, obtained with SIFCON (slurry infiltrated fibre concrete) [11] and SIMCON (slurry infiltrated mat concrete) [12]. These materials belong to the category of high performance concrete and their production process allows the incorporation of a high volume fraction of steel fibre. This process consists in preplacing the discrete fibres volume - SIFCON - or a fibremat - SIMCON - into the form, followed by the infiltration of the slurry. This way, production problems, such as, difficulty of mixing, can be avoided, allowing a higher volume of fibre.

Observing the high strength and dissipation of energy capacity of HPFRC, and, in particular, of SIFCON and SIMCON, Dogan Krstulovic-Opara (2003) [13] proposed a strengthening solution using these materials. The research work presented included the development and evaluation of the strengthening solution in beam-column connection with inadequate detailing, such as, insufficient confinement of the columns, the lack of shear reinforcement on the beam-column joints and discontinuities in the beam bottom reinforcement.

The main difference between those materials and the one used in the present research project is the fibremat. In the present case, the fibremat is made of unidirectional and continuous fibres.

3 STEEL FIBREMAT

The steel fibremat used in this study was provided by *Favir.* The fibremat was produced from a steel wire (with a 3.1mm diameter). The production process consists in a lamination procedure of the steel wire, resulting in a non-woven mat formed by steel filaments.

Table 1 presents the values of the tensile strength determined from the experimental results.

Table 1 – Main mechanical characteristics of steel wire used in the production of fibremat

Ø (mm)	Specimen	A (mm^2)	f_{su} (MPa)	f_{sum} (MPa)	ε_{su}(%)	ε_{sum}(%)	ε_{sr}(%)	ε_{srm}(%)
3.1	1	7.1	892.68	908.2	1.6	1.8	2.7	3.2
	2		847.41		1.7		3.5	
	3		984.64		2.0		3.3	

Where

Ø - wire diameter

A - wire cross section

f_{su} - experimental value of the tensile strength

f_{sum} - experimental mean value of the tensile strength

ε_{su}- strain experimental value at maximum load

ε_{sum} - strain experimental mean value at maximum load

ε_{sr} - ultimate strain experimental value

ε_{srm} - ultimate strain experimental mean value

4 CHARACTERIZATION TESTS OF THE FIBRE REINFORCED GROUT

4.1 Preliminary tests

A set of preliminary test were carried out to assess the maximum volume fraction of fibre in the composite. At this early stage, the aim was to evaluate the penetrability of the matrix from a 1% up to a 5% volume fraction of fibre, without compromising the quality and the mechanical properties of the specimens. In order to produce the test specimens, a cementitious matrix was used, assuming two mixtures: a water/cement ratio (w/c) of 0.40 and 0.28, adding 3% of superplasticizers (to increase the workability of the mixture).

In the fresh state, it was observed the workability of the mixture, penetrability of the cementitious matrix, quality of the specimens and presence of voids. At the hardened state, in order to evaluate the mechanical properties of the composite at an age of 1, 7 and 28 days, flexure and compressive strength test were conducted in 160x40x40 (mm) specimens. Two specimens for each age were produced.

The cementitious matrix with a water/cement ratio of 0.40 was able to infiltrate in a volume of fibre up to 4%. However, it was observed segregation of the cementitious matrix - Figure 1.

Figure 1: Deficiencies in a specimen (5% fibre vol.; w/c = 0.40)

For the cementitious mixture with a water/cement ratio of 0.28, it was observed that the matrix was not able to infiltrate in a volume fraction of fibre greater than 3%, leading to deficient specimens. It could be observed the presence of voids in the hardened specimens - Figure 2.

Figure 2: Deficiencies in a specimen (4% fibre vol.; w/c = 0.28)

At this point, it could be concluded that the mixture of the cementitious matrix should be optimized. Nevertheless, the specimens were subject to flexure and compressive strength test. For the mixture with water/cement ratio of 0.40, there were produced 30 specimens (related to 0, 1, 2, 3 and 4% fibre volume; with 1, 7 and 28 days and two for each age). For the mixture with water/cement ratio of 0.28, there were made 24 specimens (with 0, 1, 2 and 3% fibre volume; for 1, 7 and 28 days and two for each age). In the overall, there were performance 54 bending tests and 108 compressive tests. The acceptable results are presented in the following tables and diagrams. The stresses were calculated as if the specimens are of a homogenous material, neglecting the existence of fibres and the different modulus of elasticity.

Table 2 - Flexure test results, at 7 and 28 days of age

w/c	t (days)	% fibre vol.	$f_{ct,fl}$ (MPa)
0.28	7	0	10.0
		1	12.6
		2	26.0
		3	41.6
	28	1	12.9
		2	30.2
		2	26.4
0.40	7	1	13.1
		2	26.5
		2	27.4
		3	34.6
		3	30.3
		4	43.6
		4	41.3
	28	1	17.8
		2	26.2
		2	32.7
		3	43.4
		3	37.1

$f_{ct,fl}$ (MPa) - Flexure tensile strength

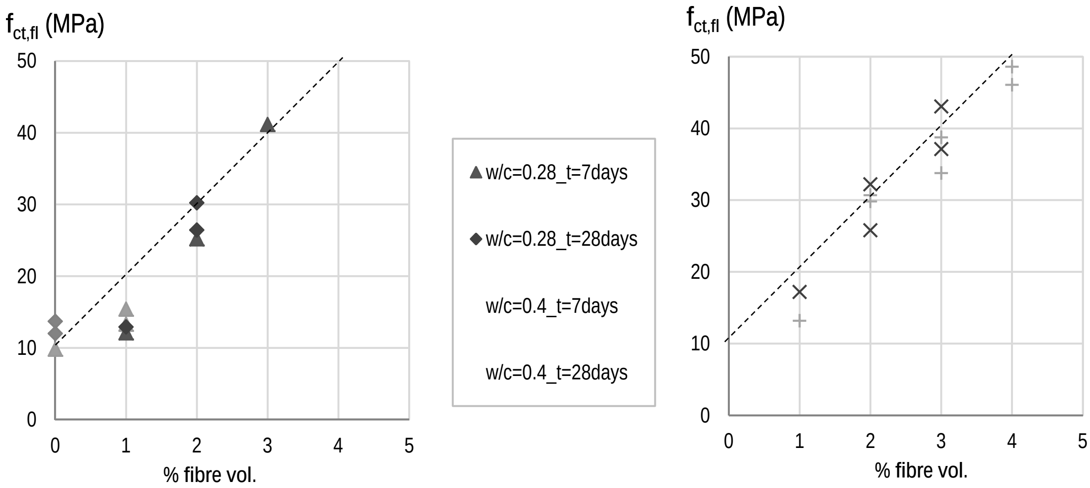

Figure 3: Diagram flexure tensile strength versus % fibre volume

The experimental results indicate that the composite material has a high flexure tensile strength which is proportional to the volume fraction of fibre - Figure 3.

Table 3 - Compression test results, at 28 days of age

w/c	% fibre vol.	$f_{ct,fl}$ (MPa)
0.28	0	84.8
	1	87.7
	1	86.4
	2	76.3
	2	84.5
	3	86.8
	3	89.1
0.4	1	80.0
	1	79.4
	2	69.9
	2	69.8
	3	64.9
	3	69.0
	4	73.5
	4	64.9

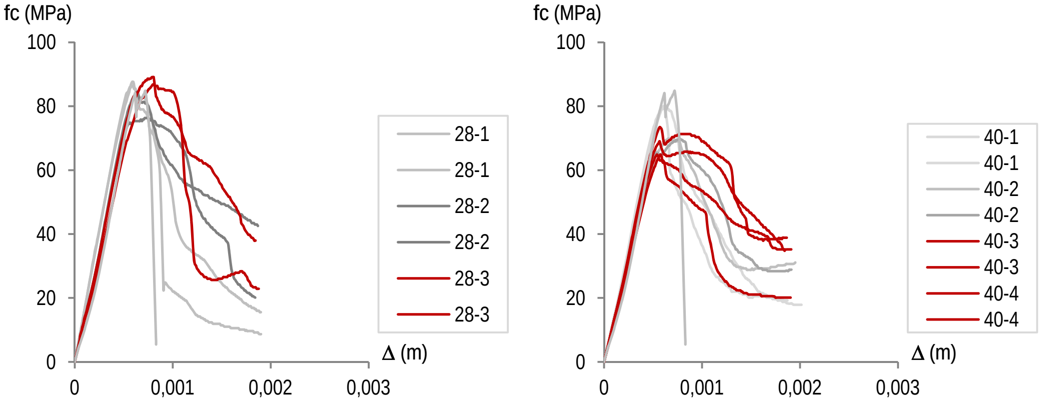

Figure 4: Diagram compression strength versus displacement between plates of the press

The analysis of the experimental results indicates that the optimum volume fraction of fibre in the composite is 3%. From the observation of the compressive test results, it can be also pointed out that the composite material has a high compressive strength (essentially dependent on the matrix compressive strength). The composite exhibited a brittle mode failure. However, the increase of the fibre volume percentage led to a less brittle behaviour - Figure 4.

In the following step, an experimental campaign was carried out in order to optimize the cementitious matrix from the rheologic point of view. The conducted procedure of the rheological mix design is presented in [7]. In this study was assumed a water/cement ratio equal to 0.3. It should be pointed out that it was assess the influence of the superplasticizer (SP) and silica fume (SF) dosage in the mechanical strength of the matrix. It was concluded that the optimum superplasticizer dosage, of 0.5%, corresponds also to the best fresh grout behaviour. In fact, an optimization of the grout composition in the fresh state leads to the best compacity and to a robust grout microstructure. Concerning the influence of silica fume in compressive strength, it could be detected that there are no main changes if SF dosage increases from 0% to 2%. However, for values higher than 2% the mechanical strength tends to decrease.

The grout cumulative shrinkage (autogenous and drying shrinkage) was measured, at a temperature of 20-25ºC and 50-60% relative humidity, for the a composition with: w/b=0.3; SP=0.5% and SF=0 - 2%.Figure 5shows the evolution of grout cumulative shrinkage, from day 1 to 70, for those compositions.

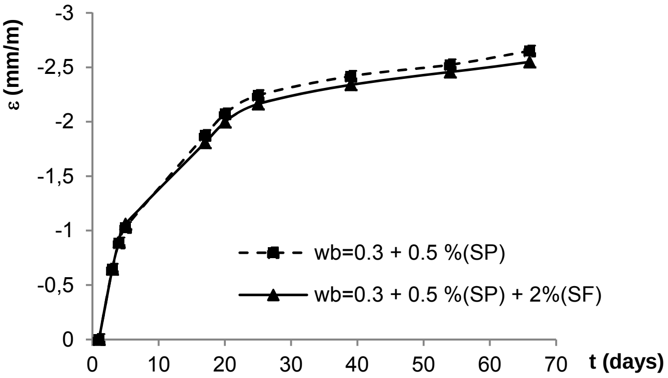

Figure 5: Cumulative shrinkage of the cementitious grout with CEMI 42.5R+SF=2%+SP=0.5% and CEMI 42.5R+SP=0.5% (w/b=0.30) from day 1 to 70.

The importance of this parameter is related with the influence of the shrinkage cracks in the long-term behaviour of the fibre reinforced composite. The experimental results show that the shrinkage values are similar for the two compositions. However, it can be observed that the shrinkage is smaller for the grout with silica fume.

The cementitious matrix was design as shown in Table 4.

Table 4 - Fibre reinforced grout composition

Matrix Composition		
Cement *SECIL Type I Class 42.5R*	-	1536 Kg/m^3
Silica Fume	2%	31 Kg/m^3
Water-binder ratio	0.30	470 Kg/m^3
Superplasticizers: Modified polycarboxylates (PCE) *SikaViscocrete 3005*	0.5%	8 Kg/m^3
Steel fibre vol. (%)		3%

4.2 Compressive tests on tubular specimens with a circular cross-section

As mentioned above, the strengthening solution consists in a small thickness jacketing in the compression side of the RC beam. In order to characterize mechanically the use of a small thickness composite, compressive tests were conducted in small thickness tubular specimens that enable the determination of the static modulus of elasticity.

For the preparation of tubular specimens with circular cross-section, a metal mould (with a 150mm diameter and a height of 300mm) was used. In order to accomplish the 2 cm thickness, a PVC pipe with a 110mm outside diameter, properly positioned and fixed, was used as a negative. The 3% volume fraction of unidirectional fibremat was preplaced around the negative. Finally, the cementitious grout was poured onto the fibremat with external vibration. Six tubular specimens were produced, three for each fibre volume percentage - 0% and 3%. In Figure 6, the specimens' preparation is illustrated.

Figure 6: Execution of fibre reinforced grout tubular specimens of circular cross-section

The tests were performed according to DIN 1048-5 (1991)[17], which recommends that the length measuring instruments should be placed symmetrically and parallel to the axis of the specimen in such way that the gauge points are away from the ends of the specimen. The length measuring has proceeded on the central zone of the cylindrical specimen through displacement transducers placed and fixed by metal rings. The tests were performed at an age of 28 days.

As mentioned, the compressive test, (including the determination of the modulus of elasticity) was conducted in accordance with DIN 1048-5 (1991) [17]. The standard recommends a test procedure in force control, which includes the imposition of two loading-unloading cycles between an initial tension (0.5 MPa to 1.0 MPa) and 1/3 of the compressive strength.

Table 5 shows the values of the modulus of elasticity determined from the experimental results, where $E_{c,i}$ (MPa) is the experimental value of the elasticity modulus at 28 days of specimen i, and E_{cm} (MPa) is the mean value.

Table 5 : Values of the static modulus of elasticity of the grout and the fibre reinforced grout

% fibre vol.	Specimen	$E_{c,i}$ (GPa)	E_{cm} (GPa)
0	1	25.03	25.06
	2	23.58	
	3	26.56	
3	1	22.65	23.13
	2	23.17	
	3	23.58	

An analysis of the results indicated that the modulus of elasticity of the matrix is about 25 GPa. However, the experimental value for the modulus of elasticity of the composite is lower than the matrix. Probably, this fact occurs due to the porosity associated to the specimen casting (through pouring the grout into the fibremat). However, it can be concluded that the composite modulus of elasticity is of the same order of magnitude as that of the matrix.

Finally, the specimens were loaded until failure through displacement control at a rate of 0.02mm/s. Figure7 illustrates the stress-displacement curves related to the compressive tests and Table 6 shows the compressive strength values of the specimens, where $f_{c,i}$ (MPa) is the experimental value of the compressive strength at 28 days of specimen i.

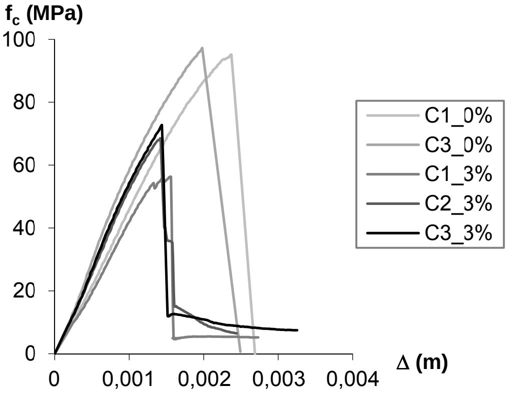

Figure 7: Stress-displacement diagram of the compressive testing of the tubular specimens

Table 6 : Compressive strength values of the grout and the fibre reinforced grout

% fibre vol.	Specimen	$f_{c,i}$ (MPa)
0	1	95.08
	2	*
	3	97.20
3	1	56.22
	2	68.49
	3	72.64

(*) During compressive test of Specimen 2 was observed a premature failure of the specimen.

The cementitious matrixes exhibit a brittle failure mode, presenting a compressive strength of approximately 96 MPa. In the case of composite fibre specimens, it was observed a failure mode located approximately at one third of the height. This failure mode was associated to transverse tensile stresses that caused a radial delamination and led to failure.

Figure 8: Compressive failure mode of fibre reinforced grout tubular specimens

The dispersion in the results could also be due to eventual irregularities on the contact surface of the specimen or insufficient impregnation of the fibres.

It should be pointed out that, compared to the specimens without fibres, the fibre reinforced grout specimens preserved geometric integrity after failure (see Figure 7).

4.3 Tensile splitting tests of cubic composite specimens

The tensile strength of the material was obtained using splitting tests. According to DIN 1048-5 (1991) [17], the specimens used in this test may be cylindrical, prismatic or cubic. The preference for a cubic specimen is related to a more suitable disposition for the placement of the unidirectional fibre.

The preparation of the cubic specimens included the placement of the unidirectional fibres, equivalent to a 3% volume fraction and pouring the cement based grout with external vibration - Figure 9.

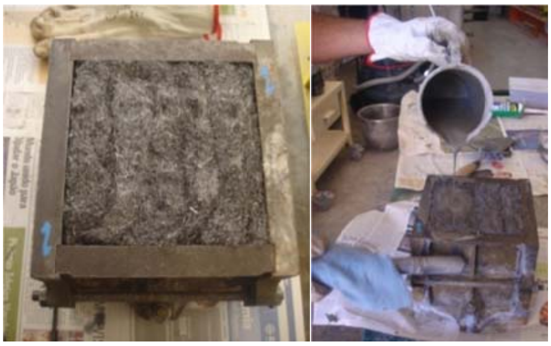

Figure 9: Execution of fibre reinforced grout cubic specimens

The splitting test consisted on the imposition of a linearly distributed load, along the width of the cube, by means of wood packing strips, placed on top of a metal plate with the same size. The test was carried out through force control, at a rate of 1.75 kN/s.

The tensile splitting strength, shown in Table 7, can be obtained from the following expression:

$$f_{ct,sp}=\frac{2\cdot F}{\pi\cdot b\cdot h} \tag{1}$$

Where

$f_{ct,\,sp}$ - tensile splitting strength
F - maximum load test
b - width of the specimen
h - height of specimen

According to Eurocode 2 [18], the approximate mean value of axial tensile strength of the material (f_{ctm}) is equal to:

$$f_{ctm}=0,9\cdot f_{ct,sp} \tag{2}$$

Table 7 : Splitting test - Values of tensile strength

% fibre vol.	Specimen	Q (kN)	$f_{ct,sp}$ (MPa)	f_{ct} (MPa)
0	1	53	1.50	1.35
	2	61	1.73	1.56
	3	52	1.47	1.32
3	1	474	13.41	12.07
	2	489	13.84	12.46
	3	*		

(*) Specimen 3 presented deficiencies that conducted to a premature failure therefore this value was neglected.

The following figures illustrate the failure mode of the specimens. It should be pointed out that, in the case of composite specimens, Specimen 1 exhibited an unexpected failure mode. Specimen 3 presented deficiencies that conducted to an unacceptable failure mode - Figure 10.

Figure 10: Splitting Test - Failure mode of fibre reinforced grout cubic specimens

From the analysis of experimental results it can be observed that the tensile strength values of the fibre reinforced grout are about 9 times higher than ones of the cementitious grout. However, it should be noted that, given the dispersion of values, it would be necessary to carry out more tests.

5 CONCLUSIONS

From the characterization tests of the UFRG, taking into consideration the difficulties associated to development of a new material, such as the production of the specimens, and despite the small number of tests performed, it can be pointed out that:

- The composite modulus of elasticity of the UFRG is of the same order of magnitude as that of the matrix (23 GPa and 25 GPa, respectively);
- The compressive strength of the composite is mainly dependent on the matrix compressive strength that was approximately 96 MPa for the matrix and 66 MPa for the UFRG;
- The addition of fibres increased substantially the tensile strength (12.3 MPa for the UFRG);
- The reduction of some mechanical properties of the UFRG in relation to the matrix ones may be associated to a natural higher porosity of the UFRG due to the injection process.

The main goal of this work was to develop a high performance fibre reinforced cementitious grout with the adequate characteristics in order to use it as a jacketing material for strengthening RC elements. From the analysis of the experimental results, it can be observed that UFRG exhibit high compression and tensile strength. Those are the required mechanical properties for a confining material in the stress state imposed on the compression side of the RC beam. Thus it is expected an improvement of the confinement of the section with a small thickness jacketing, delaying the concrete crushing and the buckling of the longitudinal reinforcement in the compression side of the RC element.

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