THIN PANELS OF CEMENT COMPOSITES REINFORCED WITH RECYCLED FIBRES FOR THE SHEAR STRENGTHENING OF REINFORCED CONCRETE ELEMENTS

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Abstract

A new technique was developed for producing thin panels of a cement based material reinforced with relatively high content of steel fibres originated from the industry of tyre recycling. Flexural tests with notched and un-notched specimens were carried out to characterize the mechanical properties of this Fibre Reinforced Cement Composite (FRCC) and the results are presented and discussed. The values of the fracture mode I parameters of the developed FRCC were determined by performing inverse analysis with test results obtained in three point notched beam bending tests. To appraise the potentialities of these FRCC panels for the increase of the shear capacity of reinforced (RC) beams, numerical research was performed on the use of developed FRCC panel for shear reinforcement by applying the panels in the lateral faces of RC beams deficiently reinforced in shear.

Keywords: Recycled steel fibre; fracture mode I parameters; inverse analysis; shear reinforcement

1. Introduction

Concrete is the most frequently used construction material in the world. However, it has low tensile strength, low ductility, and low energy absorption. An intrinsic cause of the low tensile strength of concrete is its low toughness and the presence of mentioned defects. Therefore, improving concrete toughness and reducing the size and amount of defects in concrete would lead to better concrete performance. An effective way to improve the toughness of concrete is the addiction of discontinuous fibres [1]. One of the main effects of the fibres is to control the crack propagation and maintain the crack width in the limits. The fibre reinforcement provides a residual strength in the post-cracking stage of FRCC, which is much higher than in the corresponding mortar of the same strength class but without any reinforcement, resulting in a significant improvement of the material

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toughness. Recent research is showing that the addition of Recycled Steel Fibres (RSF) from wasted tyres (Fig.1) can decrease significantly the brittle behaviour of cement based materials, by improving its toughness and post-cracking resistance [2]. In this sense, Recycled Steel Fibre Reinforced Concrete (RSFRC) seems to have the potential to constitute a sustainable material for structural and non-structural applications [2]. The use of RSF as a reinforcement system of concrete elements has also beneficial environmental and economic impacts, since an added commercial value is given to a sub-product of the tyre recycling industry that, in general, is considered a waste product [3,4]

Fig. 1: Recycled steel fibres extracted from wasted tires

In the present work a new technique was developed for producing thin panels of cement based composite reinforced with relatively high content of RSF for shear strengthening of Reinforced Concrete (RC) beams.

Flexural tests with 30 specimens reinforced with six different recycled steel fibre dosages (0%; 1.5%; 2.5%; 3.0%; 3.5% and 3.8% by volume) were carried out to characterize the mechanical properties of FRCC under flexural. In this context, three point bending test using unnotched specimens were performed to evaluate the cracking moment and the corresponding deflection. To determine the contribution of the fibres for the post-crack residual strength of the specimens, three point (centre-point) flexural tests on notched specimens were also carried out.

The values of the fracture mode I parameters of the developed RSFRC were determined by performing inverse analysis with test results obtained in three point bending tests on notched specimens. In order to have an evaluation for the potentiality of using the developed FRCC as prefabricated panel for shear reinforcement in Reinforced Concrete (RC) beams, material nonlinear simulations were performed on the I cross shape beams strengthened by attaching FRCC panels on the web panel of the beams.

2. Specimens details and preparation

The mix composition is composed of cement, fly ash, fine sand, super-plasticizer and viscosity modifying admixture (Tab. 1). Considering the direct influence of the fibres on the mix design methodology, in order to accommodate properly 1.5%, 2.5%, 3.0%, 3.5% and 3.8% of RSF by volume, the mix composition was optimized. Firstly, the fibres were distributed inside the mould; then the cementitious mortar was poured (Fig.2). An external vibration was applied to fill all the fibres by mortar.

Fig. 2: Specimens preparation

Tab.1: Mix proportions per mortar cubic meter

Mix	C [kg]	FA [kg]	FS [kg]	VMA [kg]	SP [kg]	W [l]	W/C
M	546	669	437	1.710	11	318	0.58

C = Cement; FA = Fly Ash; FS = Fine Sand; VMA = Viscosity modifying admixture; SP = Superplasticizer; W = Water; W/C = Water/Cement ratio.

After casting and curing during two days the panel specimens were removed from the moulds. The specimens were cured in the laboratory natural environmental conditions. All the specimens were tested at the age of 14 days.

Specific weight and fibre percentage of the tested specimens and number of specimens are depicted in Tab.2. The labels M_j were used to differentiate the series of the tested specimens, where label "j" identifies the fibre volume percentage. The label M_jn identifies the notched specimens. Fig.3 shows the geometry of the specimens. Considering the existence of relatively high amount of rubber particles mixed with the steel fibres in the RSF that was supplied by a Portuguese company, in order to evaluate the effect of these particles in mechanical properties of developed composite, for the mixes M_2.5, M_3, M_3.8 and M_3.8n an attempt was made to separate and take out the rubber particles as much as possible. However in the mix M_3r the used RSF were intact.

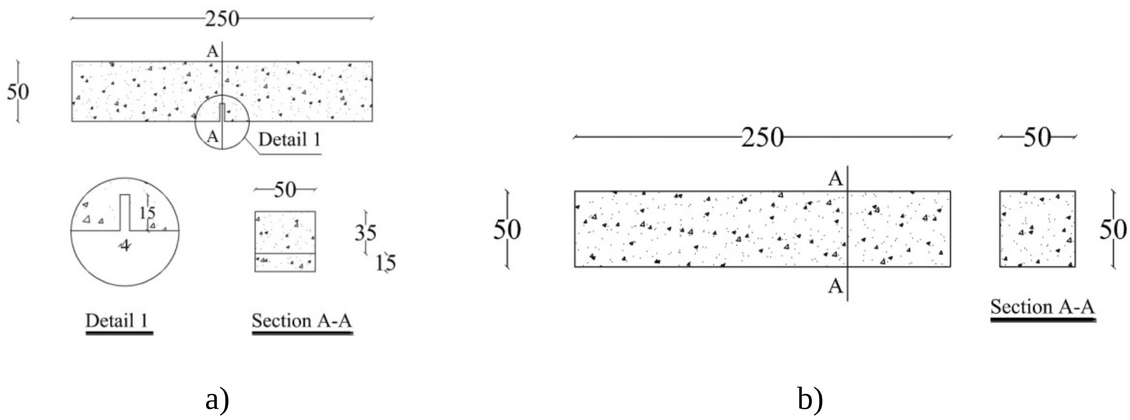


Fig. 3: Geometry of specimens for flexural test: a) Notched beams b) un-notched beams

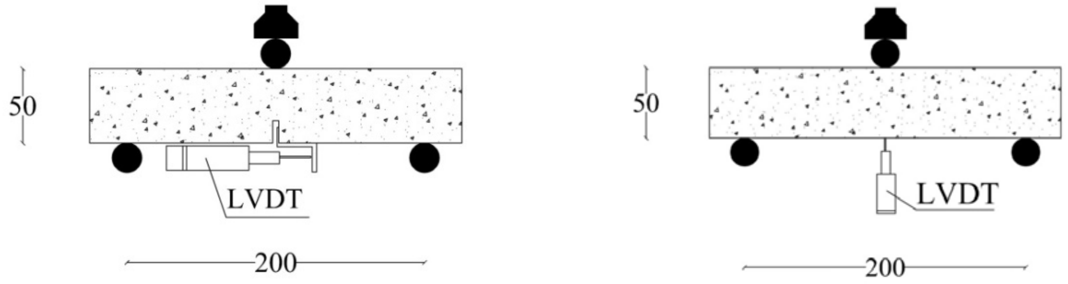
Tab.2: Fibre dosage, specific weight and number of specimens

Specimen	Fibre percentage (%)	Specific weight (KN/m^3)	Number of specimens
M_3r	3.0	19.99	5
M_2.5	2.5	20.03	4
M_3	3.0	20.22	5
M_3.8	3.8	20.49	8
M_3.8n	3.8	20.49	5

3. Flexural test procedures

Flexural tests were carried out to assess the mechanical properties of FRCC specimens under three-point bending test. To evaluate cracking moment and the corresponding deflection and also the maximum flexural stress, 25 un-notched specimens were tested under three point loads. A displacement transducer (LVDT) was used in the bottom of each specimen to measure the vertical deflection during testing (Fig.4.b).

The remaining five specimens were used to evaluate the contribution of the fibres for the post-crack residual strength of the specimens by performing three-point bending tests with notched specimens. A notch of 10 mm depth and 4 mm width was made in the middle span of the five specimens (Fig.4.a). An LVDT was installed at the lateral face of the specimen, close to the notch tip in order to measure the crack mouth opening displacement (CMOD).



a) b)

Fig. 4: Test setup for three-point bending test: a) Notched specimens; b) Un-notched specimens(dimensions in mm)

The results of these tests were also used to estimate the fracture energy of the composite material (energy to propagate a crack of unit area), which is designated as mode I fracture energy (also an indicator of the ductility of the material).

4. Experimental results

4.1 Three-point bending test with un-notched specimens

As expected, the failure in flexure for all specimens was due to fibres pull-out, since fibre rupture occurrence avoids the mobilization of the potential benefits of fibre addition in terms of energy absorption and residual strength. The results of three-point bending tests with unnotched prisms are used to estimate the stress at crack initiation. The cracking moment, M_{cr}, is obtained from:

$$M_{cr} = \frac{F_{cr} \times L}{4} \quad (1)$$

where F_{cr} is the cracking load, L is ... having been assumed as the load when a reduction of 10% in initial secant stiffness occurred. The stress at crack initiation is obtained from:

$$\sigma_{cr} = \frac{6 \times M_{cr}}{b \times h^2} \quad (2)$$

Where b and h are the width and height of the specimen.

Fig.5 shows the average flexural stress-mid span deflection curves of three-point bending tests for all the un-notched specimens. The calculated values for M_{cr} and σ_{cr} are presented in Tab. 3. Increase of fibre content leads to increase maximum flexural stress, $\sigma_{\max}$; however, this tendency was not seen in term of σ_{cr}.

Comparing the average value of the experimental results obtained for M_3r specimens and M_3 specimens, it was verified that, in terms of σ_{cr} and $\sigma_{\max}$, taking out rubber particles from RSF, provides an increase of 53% and 12% respectively. In other words, flexural results showed that specimens with 3% intact RSF have similar performance as those with 2.5% RSF with removed rubber particle.

Tab.3: Results of three-point bending tests with un-notched specimens

Specimen	M_{cr} [kN.mm]	σ_{cr} [MPa]	$\sigma_{\max}$ [MPa]
M_0	83.91	5.04	5.04
M_3r	69.91	4.14	6.60
M_2.5	88.31	5.21	6.33
M_3	114.56	6.35	7.42
M_3.8	121.15	6.18	9.51

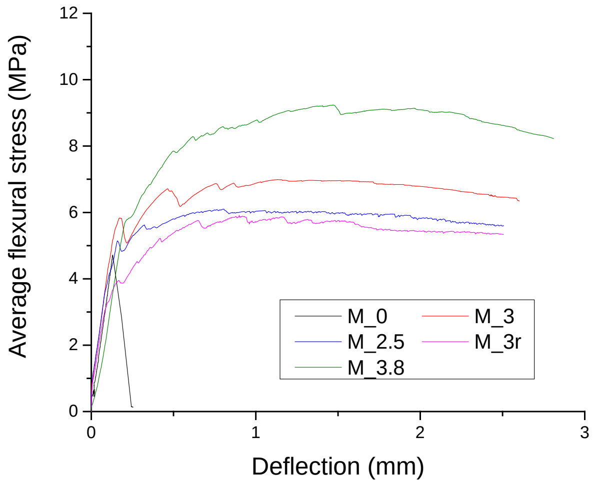


Fig. 5: Average flexural stress-mid span deflection curves of three-point bending tests

4.2 Three-point bending test with notched specimens

In Fig. 6 curves of flexural stress vs CMOD are presented for M_3.8n specimens. Almost constant load carrying capacity was obtained up to a CMOD = 2.5mm. The results of three point bending tests are analysed in term of equivalent and residual flexural tensile strength parameters and corresponding coefficient of variation (COV) for M_3.8n series (Tab. 4). Based on the force values for the $CMOD_j$ (j = 1 to 3, see Fig.6), the corresponding force values, F_j, are obtained, and the derived residual flexural tensile strength parameters are determined from the following equation:

$$f_{R,j} = \frac{3F_j L}{2bh_{sp}^2} \quad (3)$$

Where $f_{R,j}$ [N/mm^2] and F_j [N] are, respectively, the residual flexural tensile strength and the load corresponding to CMOD = $CMOD_j$ [mm] and h_{sp} is the distance between the tip of the notch and the top of the cross section.

Load at the limit of proportionality (F_L) is the highest value of the load recorded up to a deflection (or CMOD) of 0.05 mm.

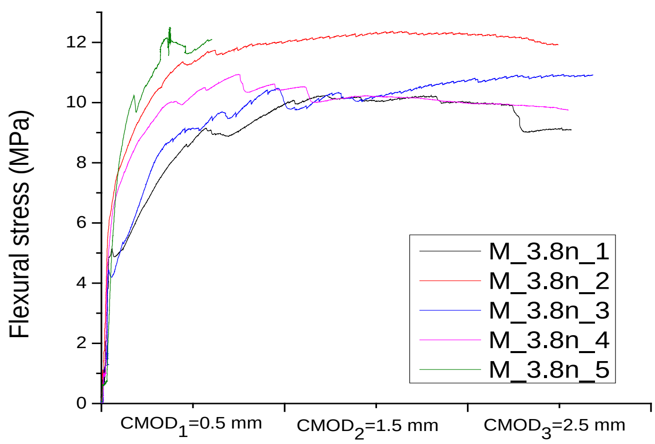


Fig. 6: Flexural behaviour in three point notched specimen bending tests

Tab.4: Equivalent and residual flexural tensile strength parameters for M_3.8n series

M_3.8n series	$f_{fct,L}$ [MPa]	$f_{R,1}$ [MPa]	$f_{R,2}$ [MPa]	$f_{R,3}$ [MPa]	$f_{eq,2}$ [MPa]	$f_{eq,3}$ [MPa]
Average	5.12	10.23	11.14	11.20	10.54	10.34
STD	0.949	1.385	1.241	1.283	1.883	1.048
COV (%)	18.53	13.53	11.14	11.45	17.84	10.12

5. Numerical study

Previous research [5] has indicated that fracture mode I propagation of FRCC can be simulated by the trilinear softening diagram represented in fig.7, whose parameters (mode I fracture energy, G_f^I, and values of $\varepsilon_{n,i}^{cr}$ and $\sigma_{n,i}^{cr}$ that define the shape of the softening diagram) can be obtained performing inverse analysis with the force-CMOD data (or force-vertical deflection data) registered in three-point notched beam bending tests. In fig.7, G_f^I / l_b corresponds to the area defined by the trilinear stress-strain normal to the crack plane (σ_n^{cr} - ε_n^{cr}), where l_b is the crack band width that assures the results of the numerical simulations with a smeared crack approach are not dependent on the refinement of the finite element mesh [5]. The objective of the analysis is to evaluate the values of the $\sigma_{n,i}^{cr}$, $\varepsilon_{n,i}^{cr}$ and G_f^I of the $\sigma_n^{cr} - \varepsilon_n^{cr}$ diagram (Fig.7) based on the minimization of the error parameter:

$$err = \frac{\left| A_{F-CMOD}^{\exp} - A_{F-CMOD}^{num} \right|}{A_{F-CMOD}^{\exp}} \quad (4)$$

where $A_{F-CMOD}^{\exp}$ and A_{F-CMOD}^{num} are the areas below the experimental and the numerical $F - CMOD$ curves respectively [6].

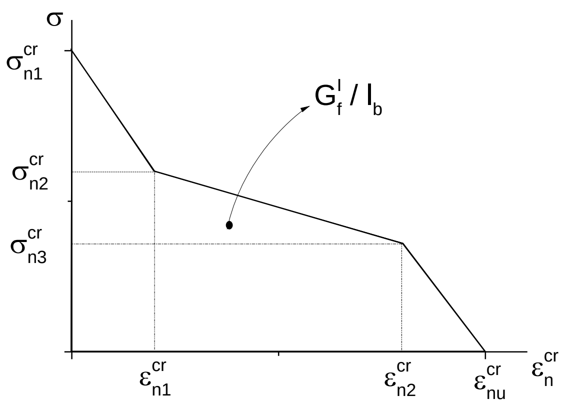


Fig. 7: Trilinear stress strain diagram to simulate the fracture mode I crack propagation

In this context, the specimen was modelled with a mesh of 8 node serendipity plane stress finite elements. The Gauss-Legendre integration scheme with 2×2 integration points was used in all elements, with the exception of the elements at the specimen symmetry axis, where 1×2 integration points were used in order to assure that the crack progresses along the symmetry axis of the specimen. Fig.8 shows the finite element mesh used in the inverse analysis [7]. An average value of E_c = 19 GPa was considered for the concrete Young's Modulus. The numerical simulations were carried out with the FEM software FEMIX V4.0 [8].

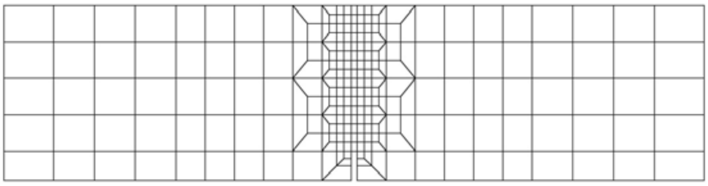


Fig. 8: Finite element mesh adopted in the inverse analysis

The values defining the $\sigma_n^{cr} - \varepsilon_n^{cr}$ diagram obtained from inverse analysis are presented in Tab.5. The comparison between the average experimental load vs CMOD and numerical load vs CMOD notched specimens is shown in Fig.9, revealing that using the values shown in Tab.5, the load vs CMOD curve, predicted by FEM software FEMIX v.4.0 is in good agreement with the average curve of the experimental results.

Tab.5: Values defining the tensile softening diagram, obtained from inverse analysis

Series	$\sigma_{n,1}^{cr}$ (N/mm^2)	$\varepsilon_{n,1}^{cr}/\varepsilon_{n,u}^{cr}$	$\sigma_{n,2}^{cr}/\sigma_{n,1}^{cr}$	$\varepsilon_{n,2}^{cr}/\varepsilon_{n,u}^{cr}$	$\sigma_{n,3}^{cr}/\sigma_{n,1}^{cr}$	G_f^I (N/mm)
M_3.8n	3.0	0.07	1.2	0.6	1.13	12.000

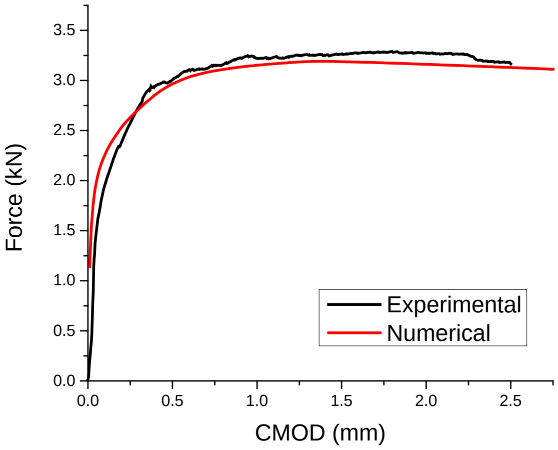


Fig. 9: Average experimental and numerical load vs deflection relationships

6. Evaluation of the potentiality of the developed FRCC for shear reinforcement

In order to have an evaluation on the effectiveness of the developed FRCC for the shear strengthening of the RC beams, the previous numerical model for the simulation of the beams failing in shear [9] was used for the prediction of the shear capacity of the I cross shape beams strengthened by attaching FRCC panels on the web faces of the beams. Fig.10 shows the geometry of the beams in this numerical simulation.

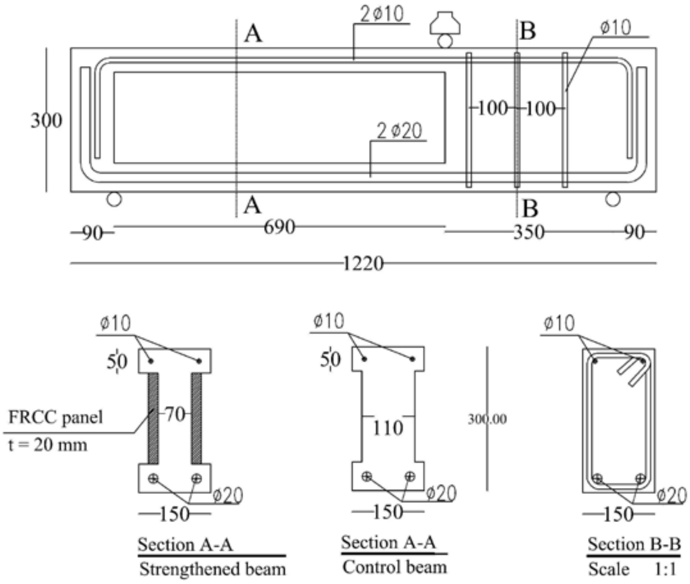


Fig. 10: Geometry of the beams in numerical prediction

The comparison of the numerical load-mid-span deflection obtained for the beam strengthened with conventional concrete panel as control beam and the beam strengthened with FRCC panel is depicted in Fig.11. It was verified that attaching two FRCC panel with thickness of 20 mm provided an increase of 33% in terms of shear capacity of the beam with a web's thickness of 70 when the shear capacity of the reference beam (plain concrete with web's thickness of 110 and the same flexural reinforcing ratio) is considered for comparison purpose.

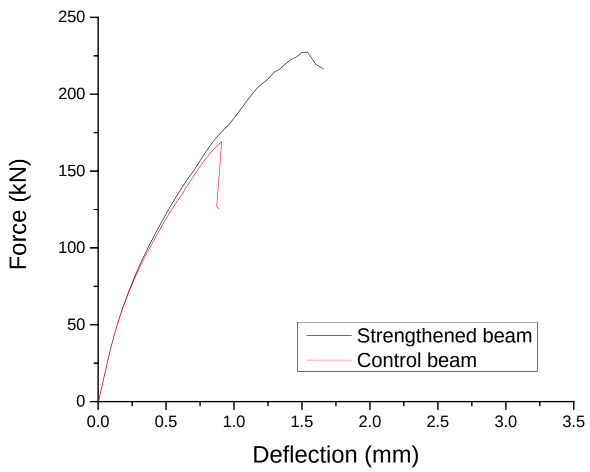


Fig. 11: Average experimental load vs deflection and numerical load vs deflection

7. Conclusion

In the present work an effort to develop recycled steel fibre reinforced cement based composite for the manufacture of thin panels has being done. On the basis of results obtained by three point bending tests and numerical simulations the following concluding remarks can be made:

- Since fibre rupture occurrence avoids the mobilization of the potential benefits of fibre addition in terms of energy absorption and residual strength, the failure in flexure for all the tested specimens was due to fibres pull-out;
- Flexural results presented in this paper showed that the increase of fibre content leads to the increase of maximum flexural stress and the flexural strength of FRCC specimens is almost constant and of the same order of the flexural tensile strength up to the ultimate crack width recorded in the executed tests (2.5 mm). On the other hand it was verified that taking out rubber particles from RSF provides an increase of 53% and 12% in terms of σ_{cr} and $\sigma_{\max}$, respectively;
- By using a previous numerical model [9] for the simulation of the beams failing in shear, an increase of 33% in terms of shear capacity of the beam with a web's thickness of 70 mm strengthened with two FRCC panel (20 mm thickness) was obtained in comparison with the shear capacity of the reference beam (plain concrete with web's thickness of 110 and the same flexural reinforcing ratio).

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