Assessment of the potentialities of recycled steel fibres for the reinforcement of cement based materials

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ABSTRACT: Recent research is evidencing that adding steel fibres recycled from wasted tires can improve the post-cracking behaviour of cement based materials, enhancing the ductility, energy dissipation and impact resistance of elements made by this type of composites. As a consequence, Recycled Steel Fibre Reinforced Concrete (RSFRC) appears as a promising candidate for both structural and non-structural applications. To contribute for the assessment of the potentialities of RSFRC, an experimental program composed of three series of notched beam bending tests with concrete reinforced with 45, 60 and 90 kg/m^3 of recycled steel fibres (RSF) was carried out by determining the post-cracking residual strength parameters, $f_{R,,j}$, defined according to the recommendations of the CEB-FIP Model Code 2010. Based on the obtained $f_{R,,j}$, the constitutive laws characterizing these three RSFRC were determined and used to estimate the reinforcement potentialities of RSFRC for structural applications. A data base with $f_{R,,j}$ corresponding to industrial steel fibres (ISF) was built in order to compare the post-cracking performance of RSFRC and concrete reinforced with Industrial steel fibres (ISF). This paper describes the experimental program, and presents and discusses the obtained results.

1 INSTRUCTION

1.1 Overview

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 deficient tensile behaviour 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 a relatively small fraction (usually 0.5–2.0% by volume) of short fibres to the concrete during mixing.

In the fracture process of fibre reinforced concrete (FRC), fibres bridging the cracks in the matrix can provide resistance to crack propagation and crack opening before being pulled out or stressed to rupture. After extensive studies it is widely reported that such fibre reinforcement can significantly improve the tensile properties of concrete (ACI 1996), (Bentur et al. 1990) and (Wang et al. 2000).

Fibre reinforcement is also used for the reduction of shrinkage cracking of concrete associated with hardening and curing processes. Other benefits of FRC include improved fatigue strength, wear resistance, and durability. By using FRC instead of conventional concrete, section thickness can be reduced and cracking can be effectively controlled,

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resulting in lighter structures with a longer life expectancy. FRC is currently being used in many applications, including buildings, highway overlays, bridges, airport runways, precast concrete industry and tunneling (ACI 1996), (Bentur et al. 1990) and (Wang et al. 2000).

1.2 Concrete reinforced with recycled steel fibres

Recent research is showing that adding to cement based materials recycled steel fibres (RSF) from wasted tires can decrease significantly the brittle behaviour of these materials, by improving its toughness and post-cracking resistance. As a consequence Recycled Steel Fibre Reinforced Concrete (RSFRC) appears as a promising candidate for both structural and non-structural applications (Aiello et al. 2009). The use of Recycled Steel Fibre (RSF) as reinforcement in concrete will benefit the environment, since the fibres are currently a waste arising from the recycling of tires. However, the lack of a general design framework and simple design guidelines for concrete reinforced with RSF is perceived as one of the main barriers to the use of RSF in concrete construction. Although the flexural behaviour of RSFRC is similar to that of conventional SFRC (Tlemat et al. 2004) it is not certain whether existing design guidelines, developed specifically for SFRC, can be successfully applied for the flexural design of RSFRC. Therefore, the authors deemed necessary to examine these guidelines in order to assess their suitability for RSFRC and, if necessary, to propose appropriate modifications to the guidelines.

2 EXTRACTION OF FIBRES FROM WASTE TIRE PROCESS

Tire shredding and the cryogenic process can be used to mechanically obtain RSF from used tires. In addition, steel fibres can be obtained by utilizing anaerobic thermal degradation, such as conventional pyrolysis and microwave-induced (AMAT 2003). The RSF adopted in the present experimental work was supplied by RECIPNEU company, and the cryogenic process of waste tires is the one adopted by this company, which is composed by the four following stages (Figure 1): 1) whole tire size is reduced by various means; 2) tires are then fed into cryo-chamber and frozen with liquid nitrogen to -184º C (-300º F); 3) hammer mill reduces crumb to particles of various sizes; 4) steel is removed magnetically throughout process. The RSF obtained from this process (Figure 2) are characterized by different diameters, lengths and shapes, and present irregular wrinkles.

3 EXPERIMENTAL WORK

To assess the potentialities of recycled fibres for the reinforcement of concrete elements, the test program indicated in Table 1 was carried out. Four specimens for each mixture were prepared. Note that for all the specimens, mixes of similar concrete strength class were used in order to perform a reliable comparison of the mechanical properties. The specimens with recycled steel fibres were tested at 14 days, while the specimens with industrial steel fibres were tested at 28 days.

Table 1. Designation of the series of tests of the experimental program

Mix	Reinforced with recycled fibres	Reinforced with industrial steel fibres	Content of steel fibres [kg/m^3]
M_45	M45_RSF	M45_ISF	45
M_60	M60_RSF	M60_ISF	60
M_90	M90_RSF	M90_ISF	90

(a) (b)

(c) (d)

(e) (f)

Figure 1. Overview of the industrial process to transform tires in fibers for using in concrete: a) Tires to be recycled, b) Tires transformed in pieces of rubber, c) Stock of pieces of rubber, d) Cryogenic tunnel to put the pieces of tire in the glassy state, e) Tunnel hammers to break the pieces of rubber in glassy state and f) The fibres are separated by magnetic and collected in a container

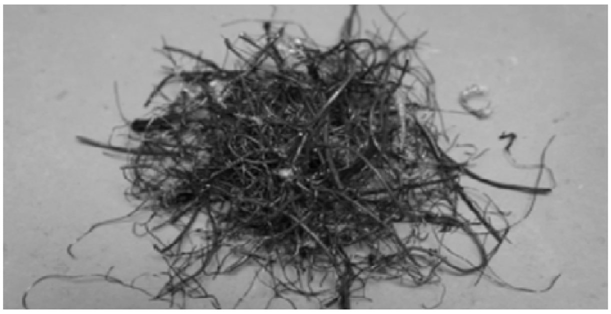


Figure 2. Recycled steel fibers extracted from rubber tires

During the execution of the concrete mixes, the recycled steel fibres were gradually added to the mixture to get, as much as possible, a homogenous fibre distribution into the concrete. Table 2 shows the three mix proportions used.

Table 2. Mix proportions per concrete cubic meter

Mix	C [kg]	LF [kg]	W [kg]	SP [kg]	FRS [kg]	CRS [kg]	CA [kg]	FA [kg]	SF [kg]
M_45	380.5	326.2	126.8	6.09	362.6	574.6	510.1	-	45
M_60	380.5	353.0	140.0	7.83	237.0	710.0	590.0	-	60
M_90	408.0	395.0	150.0	6.26	263.0	658.0	446.0	73.0	90

C=Cement; LF=Limestone Filler; W=Water; SP=Superplasticizer; FRS=Fine River Sand; CRS=Coarse River Sand; CA=Crushed Aggregates; FA=Fly Ash; SF=Steel fibres

3.1 Test setup and methodology

The specimen geometry (Figure 3), the position and dimensions of the notch sawn into the specimen, the loading and specimen support conditions, the characteristics for both the equipment and measuring devices, and the test procedures to characterize the flexural behaviour of RSFRC (Figure 4) are all given elsewhere (CEB-FIP 2011) and (RILEM 2000).

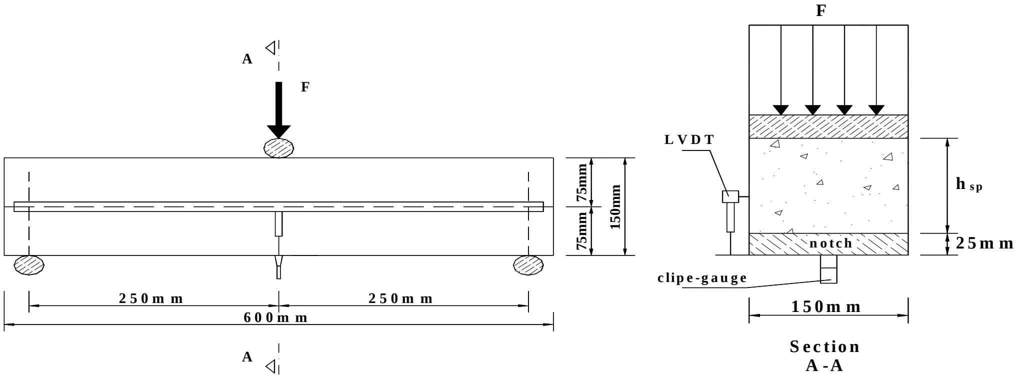


Figure 3. Three point beam bending test setup

Figure 4. Test setup

Figure 5 presents a typical relationship between the applied load and the crack mouth opening displacement (CMOD) obtained from a three-point beam-bending test. Using this type of relationships, the load at the limit of proportionality (F_L) and the residual flexural tensile strength parameters ($f_{R,j}$) can be obtained. F_L is the highest value of the load recorded up to a deflection (or CMOD) of 0.05 mm.

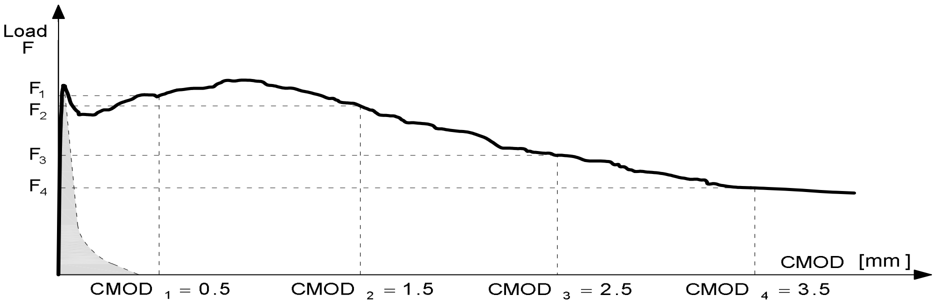


Figure 5. Typical load F – CMOD curve of FRC (CEB-FIP 2011)

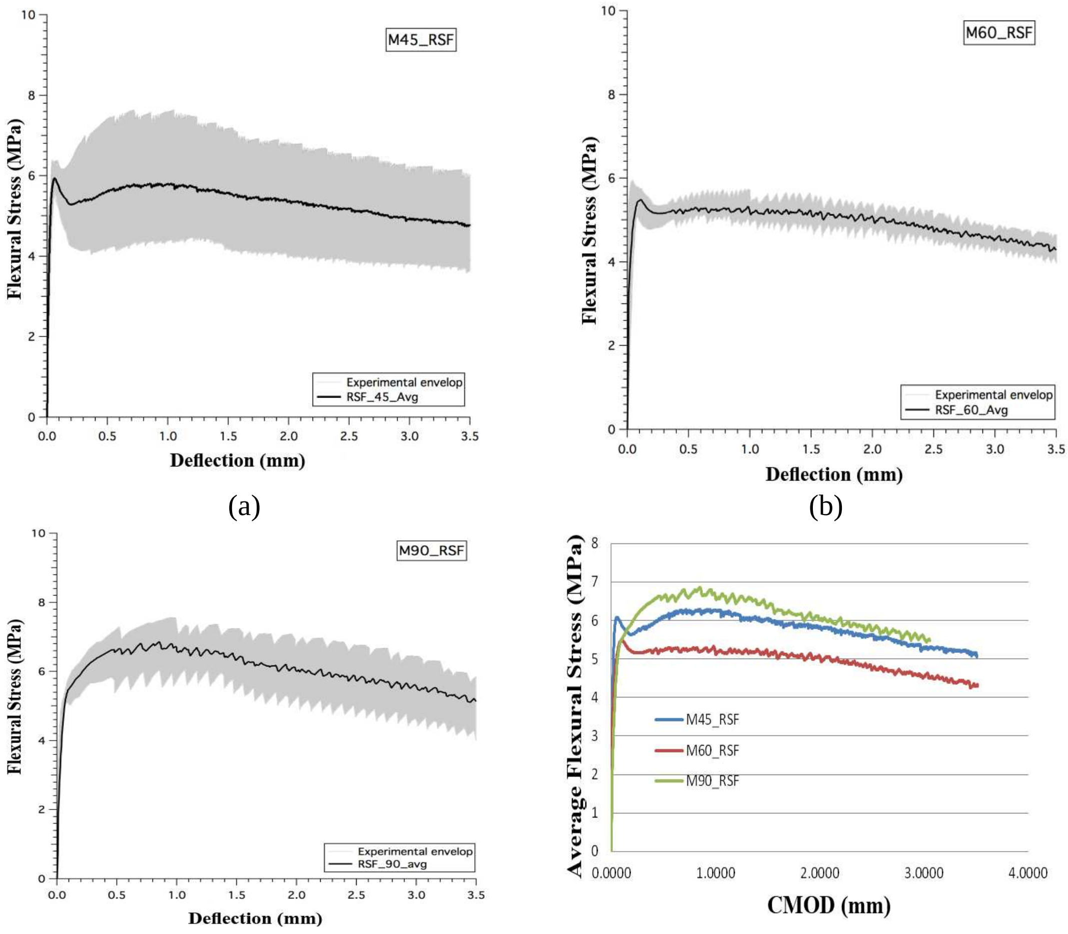
Based on the force values for the $CMOD_j$ (j= 1 to 4, see figure 5), the corresponding force values, F_j, are obtained, and the derived residual flexural tensile strength parameters are determined from the following equation:

$$f_{R,j} = \frac{3F_jL}{2bh_{sp}^2} \tag{1}$$

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], b (=150 mm) and L (=500 mm) are the width and the span of the specimen, and h_{sp} (=125 mm) is the distance between the tip of the notch and the top of the cross section.

3.2 Experimental results

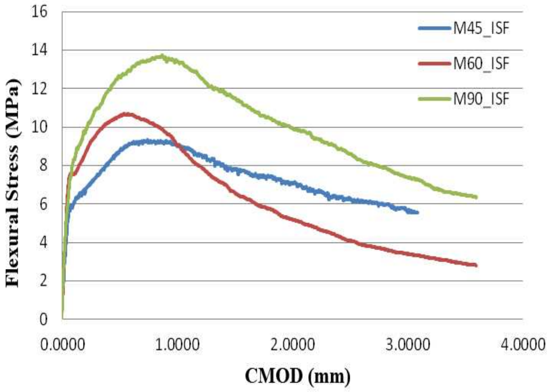
As reported in the literature (Pilakoutas et al. 2004) the main effect of the fibres is to control the crack propagation, maintaining the crack width in the limits according to the exigencies of the application of FRC; as a consequence, the flexural behaviour is characterized by a residual strength in the post-cracking stage that is much higher than its corresponding plain concrete, resulting a significant improvement of the material toughness. 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. In Figure 6 the curves flexural stress versus deflection are presented for all the tested specimens. In the M45_RSF specimens (45kg/m^3 of fibres) a larger dispersion of the results was obtained, which indicates difficulties of assuring a suitable distribution of the fibres. The average curves for the RSF series are depicted in Figure 6d. It is verified that the post-cracking flexural strength was smaller in the M60_RSF than in the M45_RSF, which can be justified by extra difficulties on assuring proper fibre distribution in the M60_RSF specimens. Taking this into account, the mix composition for the M90_RSF was tailored by increasing the content of cement, limestone filler and fine river sand, and adding fly ash in order to improve the conditions for a better fibre distribution. The flexural behaviour recorded in the three point bending tests with beams of Industrial steel fibre reinforced concrete (ISFRC) is illustrated in Figure 7, and the comparison of RSFRC and ISFRC curves are depicted in Figure 8. Table 3 and Table 4 include the average values for the equivalent and residual flexural tensile strength parameters for tested RSFRC and ISFRC specimens, respectively. Due to the reasons already pointed out, the equivalent and residual flexural tensile parameters were the lowest in the M60_ISF series. The graphical representation of the equivalent and residual flexural strength parameters for all the tested series is represented in Figure 9. From the comparison it is verified that the deflection hardening phase registered in the ISFRC specimens (from crack initiation up to flexural tensile strength) was not developed in the RSFRC specimens. This indicates that the fiber reinforcement mechanisms for relatively small crack width levels are not effective in the RSF due to the geometry and surface characteristics of these fibers. However, the flexural strength of RSFRC 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 (3.5 mm).



(a) (b)

(c) (d)

Figure 6. Flexural stress versus deflection curves for the: a) M45_RSF, b) M60_RSF, c) M90_RSF



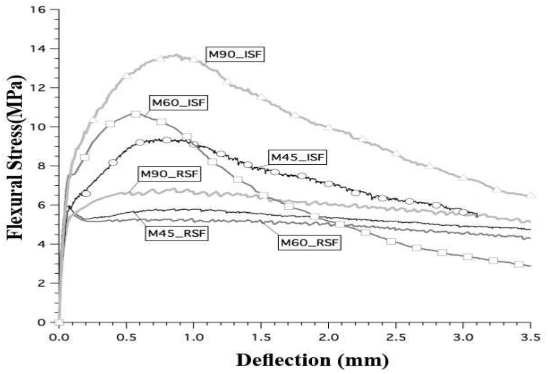


Figure 7. Flexural behaviour of ISFRC in three point notched beam bending tests.

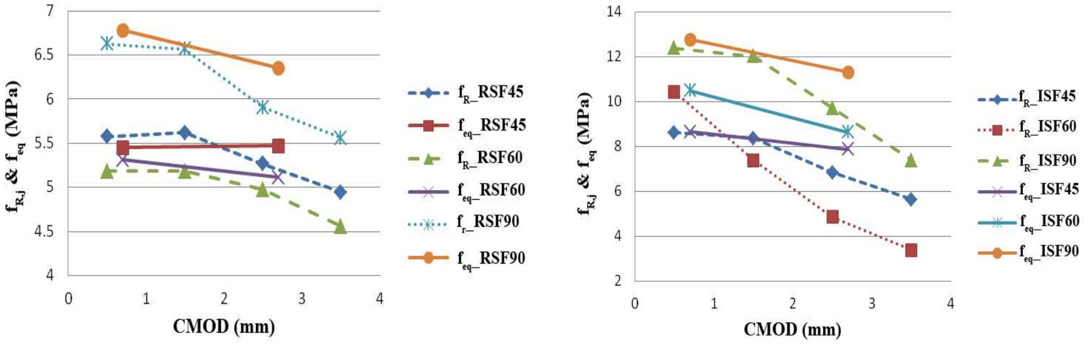
Figure 8. Comparison of the flexural behaviour of ISFRC and RSFRC.

Table 3. Equivalent and residual flexural tensile strength parameters for RSFRC

Series	$f_{fct,L}$ [MPa]	$f_{eq,2}$ [MPa]	$f_{eq,3}$ [MPa]	$f_{R,1}$ [MPa]	$f_{R,2}$ [MPa]	$f_{R,3}$ [MPa]	$f_{R,4}$ [MPa]
M45_RSF	5.866	5.449	5.471	5.576	5.622	5.270	4.947
M60_RSF	5.045	5.311	5.113	5.184	5.182	4.976	4.560
M90_RSF	4.562	6.783	6.354	6.627	6.565	5.906	5.560

Table 4. Equivalent and residual flexural tensile strength parameters for ISFRC

Series	$f_{fct,L}$ [MPa]	$f_{eq,2}$ [MPa]	$f_{eq,3}$ [MPa]	$f_{R,1}$ [MPa]	$f_{R,2}$ [MPa]	$f_{R,3}$ [MPa]	$f_{R,4}$ [MPa]
M45_ISF	5.148	8.661	7.872	8.613	8,369	6.834	5.641
M60_ISF	6.620	10.493	8.643	10.431	7,395	4.868	3.400
M90_ISF	5.991	12.755	11.311	12.376	12,009	9.713	7.385



(a) (b)

Figure 9. Representation of the f_{eq} and $f_{R,i}$ parameters for the series: a) RSFRC, b) ISFRC

Figure 10 shows the relationship between $f_{eq,2}$ and $f_{eq,3}$ obtained in the tested RSFRC specimens. It is verified a clear linear relationship between these two parameters, which is in agreement to previous research with SFRC specimens (Barros et al. 2005).

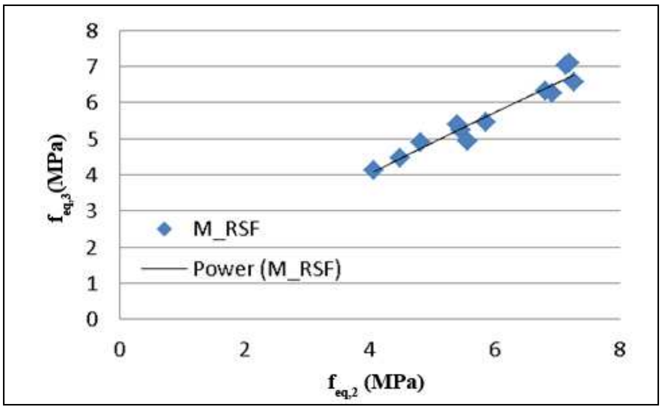
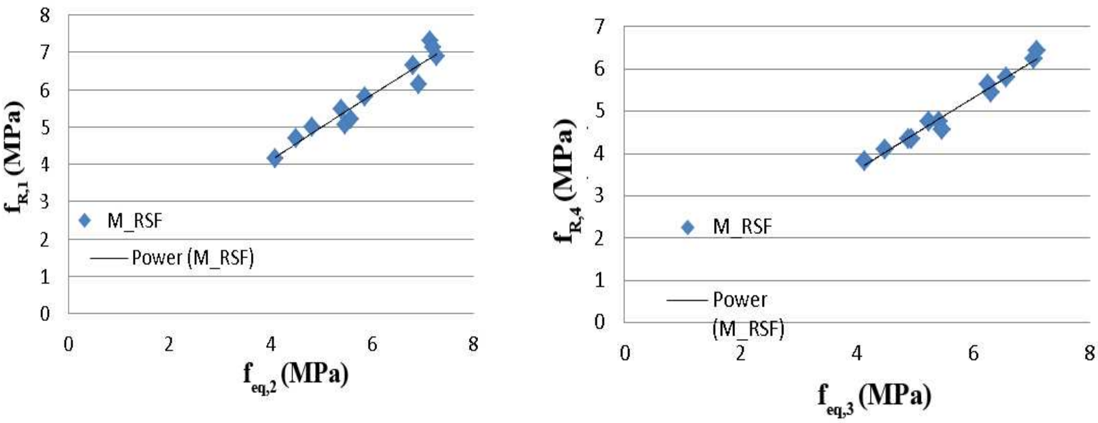


Figure 10. Relationship between $f_{eq,2}$ and $f_{eq,3}$

The relationships between $f_{eq,2}$ and $f_{R,1}$, and between $f_{eq,3}$ and $f_{R,4}$ are represented in Figure 11. It is also verified a linear trend between these parameters.



(a) (b)

Figure 11. Relationship between: a) $f_{eq,2}$ and $f_{R,1}$, b) $f_{eq,3}$ and $f_{R,4}$ for RSFRC

For a more enlarged comparison, the database (DB) collected by Moraes Neto (2013) in terms of f_{Ri} values in concrete reinforced with hooked ends ISF was used in the present work. Since the fibre volume percentage, V_f, and fibre aspect ratio, (l_f/d_f), (quotient between fibre length, l_f, and fibre diameter, d_f) are practically the unique common information available in the works forming the DB, the statistical analysis performed with the collected data for the characterization of the post-cracking behaviour of SFRC was governed by the criterion of deriving equations for the f_{Ri} dependent on the V_f and l_f/d_f. The authors are aware that this is a quite simple approach to simulate the fibre reinforcement mechanisms, since other variables like the fibre-matrix bond strength, fibre inclination and fibre embedment length influence the values of f_{Ri} (Cunha et al. 2010), but this information is not available in those works. Therefore, a relatively large scatter of results is naturally expected for the relationships f_{Ri}-(V_f, l_f/d_f). Preliminary statistical analysis by considering also the bond strength was also carried out (Moraes Neto 2013), but the obtained results have revealed that by also adopting these parameters, the dispersion of the results increase significantly, since a large scatter of bond strength values exists in the bibliography. Taking this into account, the statistical analysis was carried out and the following equations were determined:

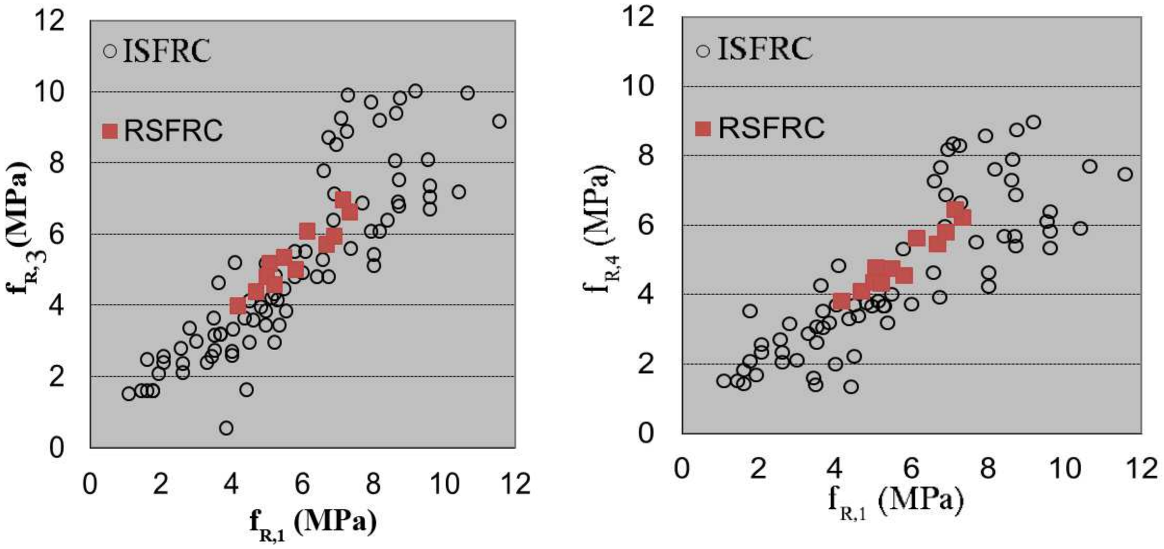
$$f_{R1} = k_1 \cdot \left(V_f \cdot \frac{l_f}{d_f} \right)^{c1} = 7.5 \cdot \left(V_f \cdot \frac{l_f}{d_f} \right)^{0.8} \quad \text{[MPa]} \tag{2}$$

$$f_{R3} = k_2 \cdot \left(V_f \cdot \frac{l_f}{d_f} \right)^{c2} = 6.0 \cdot \left(V_f \cdot \frac{l_f}{d_f} \right)^{0.7} \quad \text{[MPa]} \tag{3}$$

$$f_{R3} = k_3 \cdot f_{R1} = 0.85 \cdot f_{R1} \tag{4}$$

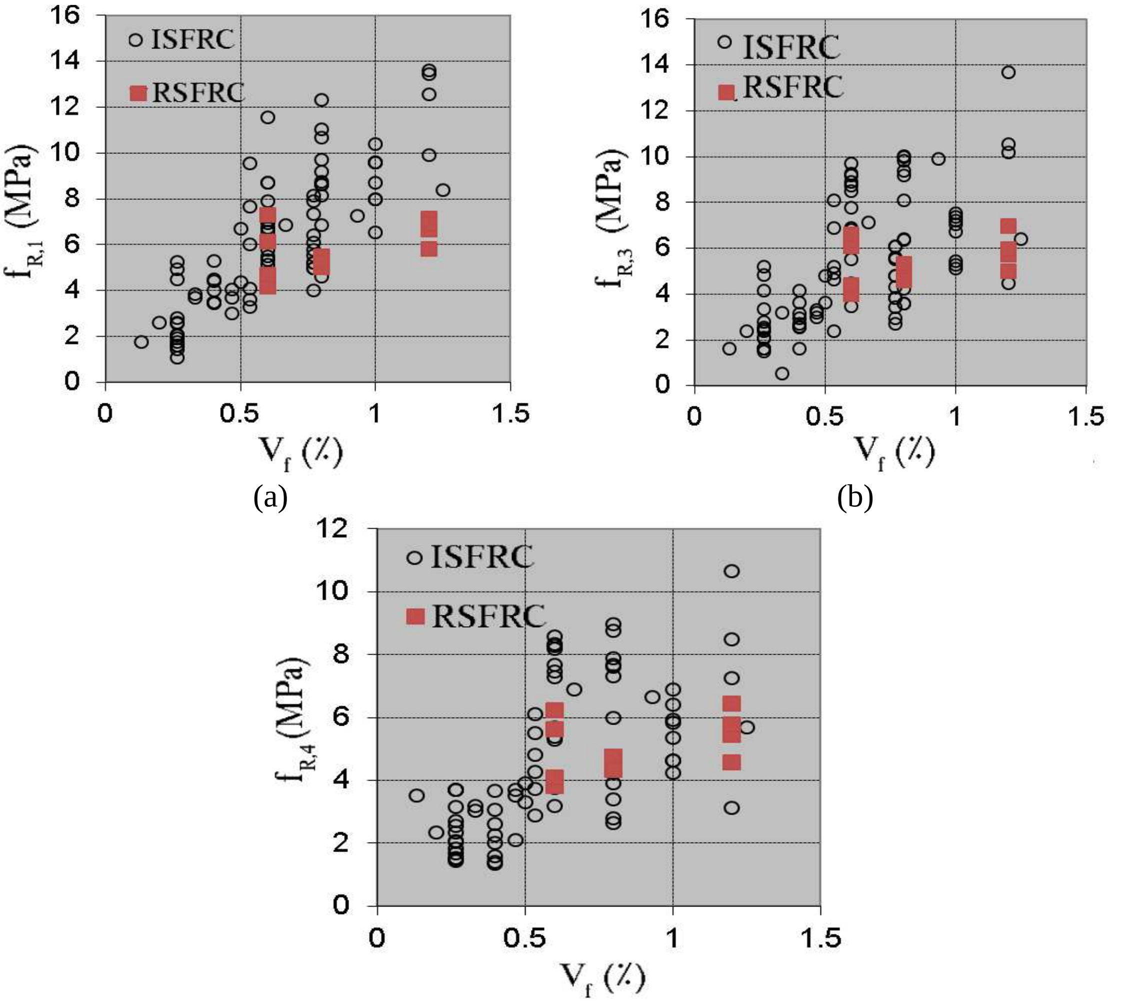
Figure 12 compares f_{R1} and f_{R3}, and f_{R1}-f_{R4} from the experimental results of this database with those obtained from the RSFRC specimens. In these figures different markers were adopted for the results of the database with ISF (IFRSCC) and RSF (RSFRC). It is verified that in ISF and RSF similar trend was obtained for the f_{R1}-f_{R3} and f_{R1}-f_{R4}.

Figure 13 compares $f_{R,i}$ and V_f from the experimental results of the database with those obtained from the RSFRC specimens. In these figures different markers were adopted for the results of the database with ISF (SFRSCC) and RSF (RSFRC). It is verified that the f_{Ri}-V_f relationship for the RSF is close to the lower bound of the f_{Ri}-V_f results for the ISF.



(a) (b)

Figure 12. Relationship between: a) $f_{R,1}$ and $f_{R,3}$ and b) $f_{R,1}$ and $f_{R,4}$ for RSFRC and SFRSCC



(a) (b)

(c)

Figure 13. Relationship between: a) f_{R1} and V_f, b) f_{R3} and V_f, and b) f_{R4} and V_f, for RSFRC and SFRSCC

4 CONCLUSIONS AND DISCUSSION

In this paper, the experimental work was carried out to evaluate the mechanical properties of recycled fibre reinforced concrete. On the basis of results obtained by three point bending tests, 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.

- From the comparison of the equivalent and residual flexural strength parameters for all the tested series it is verified that the deflection hardening phase registered in the ISFRC specimens (from crack initiation up to flexural tensile strength) was not developed in the RSFRC specimens. This indicates that the fiber reinforcement mechanisms for relatively small crack width levels are not effective in the RSF due to the geometry and surface characteristics of these fibers. However, the flexural strength of RSFRC 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 (3.5 mm).

- It is revealed that up to a deflection of δ_3, the energy absorption capacity of the RSFRC designed is linearly dependent on the deflection. Therefore, it is enough to analyze the evolution of the $f_{eq,2}$, because the comments can be also applied to $f_{eq,3}$.

- It is verified that, for steel fibre reinforced concrete with recycled fibres, there is almost linear relationship between $F_{R,1}$ and $F_{R,3}$ and a similar tendency was observed between the $F_{R,1}$ and $F_{R,4}$.

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