Construction and Building Materials 94 (2015) 290–298

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

An experimental study on the post-cracking behaviour of Hybrid Industrial/Recycled Steel Fibre-Reinforced Concrete

Enzo Martinelli [a,*], Antonio Caggiano [b,c], Hernan Xargay [c]

[a] *Department of Civil Engineering, University of Salerno, Italy*
[b] *National Scientific and Technical Research Council (CONICET), Argentina*
[c] *LMNI, FIUBA, Laboratory of Materials and Structures, Faculty of Engineering, University of Buenos Aires, Argentina*

HIGHLIGHTS

- Recycled Steel Fibres can be obtained from end-of-life tyres.
- They can partially-to-totally replace Industrial Steel Fibres.
- Fibre replacement aims at enhancing sustainability of cementitious composites.
- A decay in the post-cracking behaviour is expected in FRC with recycled fibres.
- This paper is intended at investigating and quantifying such a decay.

ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form 22 May 2015
Accepted 5 July 2015

Keywords:
Waste tyres
Concrete
FRC
Recycled Steel Fibre
Hybrid
Post-cracking behaviour

ABSTRACT

This paper investigates the mechanical behaviour of FRC made with both Industrial and Recycled Steel Fibres recovered from waste tyres. Specimens of various mixtures, characterised by the same volume fraction of fibres, but different proportions of industrial and recycled reinforcement were tested both in compression and bending. The results highlighted a fairly negligible influence of fibres in terms of compressive strength, whereas a significant decay in the post-cracking behaviour was observed in specimens with higher fractions of recycled fibres. However, a significant enhancement in the bending response was observed with respect to the case of plain concrete, even for specimens reinforced by recycled fibres only.

1. Introduction

In recent years the disposal of exhaust tyres has emerged as a big issue in waste management [1] and the increasing amount of these waste actually constitutes a serious threat for both environment and human health [2]. Moreover, based on the "Council Directive 1999/31/EC" of the European Commission on the Landfill of Waste, as of 2003 post-consumer "whole tyres" could no longer be landfilled and, since July 2006, such regulations must be applied to both "whole" and "shredded" tyres [3].

Therefore, there are strong motivations for recycling such waste that can easily be turned into a eco-friendly source of secondary raw materials [4]. In fact, recycling processes of waste tyres mainly consist of separating the internal steel reinforcement from the rubber covering. Hence, rubber scraps and short steel fibres are generally obtained by these processes and can be utilised in several valuable applications. Particularly, they can be used as concrete components in partial-to-total replacement of the ordinary constituents (e.g., natural aggregates and industrial fibres, respectively). On the one hand, rubber scraps find an interesting field of application as a partial replacement of ordinary stone aggregates for obtaining the so-called "rubberised concrete" which is characterised by enhanced damping and toughness properties [5,6]; on the other hand, recycled fibres can be potentially used in substitution of the industrial ones commonly employed for producing Fibre Reinforced Cementitious Composites (FRCCs) [7,8].

As a matter of fact, adding a small fraction (usually in the order of 0.5–1.0% in volume) of short fibres during mixing results in enhancing the toughness in the post-cracking response of cementitious materials as those fibres have a bridging effect across the opening cracks and, then, a positive influence on their propagation [9].

---

[*] Corresponding author.

E-mail addresses: e.martinelli@unisa.it (E. Martinelli), acaggiano@fi.uba.ar (A. Caggiano), hxargay@fi.uba.ar (H. Xargay).

http://dx.doi.org/10.1016/j.conbuildmat.2015.07.007

However, the fibres employed in FRCC need to have good mechanical properties, be easy to spread in concrete mixtures and durable when embedded into cementitious matrices [10]. Many types of fibres (i.e., made of steel, glass, natural cellulose, carbon, nylon, polypropylene, etc.) have been used in FRCC and are widely available for commercial applications [11]. A total of 60 million tonnes of these kinds of fibres are currently employed every year around the world, and, then, their production requires a huge amount of raw materials [12]. Therefore, Recycled Steel Fibres (RSFs) obtained from waste tyres could contribute to reducing this demand. Particularly, they can directly be utilised as a dispersed reinforcement in concrete to obtain a material that could be designated as Recycled Steel-FRC. In this regards, some pioneer researches already demonstrated the feasibility of these applications [13–15].

Innovative researches on FRC also have addressed the possible use of mixed fibres made of different material and/or geometry which can, in principle, play a synergistic role in enhancing the post-cracking response of structural members. These kinds of fibre-reinforced cement-based composites are often referred to as Hybrid FRC (HyFRC). Experimental tests aimed at investigating the HyFRC failure behaviour in direct tension have been performed, among others, by Sorelli et al. [16] and Park et al. [17]. The mechanical behaviour measured by means of indirect tensile tests have been proposed on Hy-Polypropylene FRC [18], Hy-Steel FRC [19] or combining several fibres: i.e., Carbon/Steel/Polypropylene FRC [20] or Steel/Palm/Synthetic FRC [21]. Other relevant contributions regarding HyFRC with lightweight aggregates [22], high-volume coarse fly ash [23], HyFRC exposed to high temperatures [24] or self compacting HyFRC [25] have also been proposed within the scientific community.

This paper investigates the mechanical behaviour of FRC with both industrial fibres and RSFs obtained from waste tyres, as mentioned above. In fact, it is mainly based on the results of an experimental campaign carried out at the Laboratory of Materials testing and Structures (LMS) of the University of Salerno (Italy). Starting from a FRC mixture with 0.5% (in volume), that is to say 40 kg/m^3, of Industrial Steel Fibres (ISFs), three more mixtures were prepared by replacing 25%, 50% and 100% in weight of such fibres with an equal amount of RSFs. Therefore, the mechanical behaviour of conventional Steel Fibre-Reinforced Concrete (SFRC) was observed in comparison with the one of both Hybrid Industrial/Recycled Steel Fibre-Reinforced Concrete (HIRSFRC) and RSFRC. The experimental campaign was mainly aimed at observing the key aspects of both cubic samples tested in compression and notched beam specimens tested in four-point bending (4PB) according to UNI-11039-1 [26] and UNI-11039-2 [27].

Investigating the mechanical response of the aforementioned HIRSFRC and, particularly, quantifying the effect of replacing industrial fibres with an equal amount (in weight) of recycled ones is the main original aspect addressed in this paper. In the authors' best knowledge no experimental investigation was carried out so far for comparing the mechanical response of FRC characterised by an invariant volume fraction of fibres and variable proportion of industrial and recycled ones; in fact, the results currently available in the literature are always referred to the two "extreme" cases of FRC with either industrial or recycled fibres. Therefore, the results presented in this paper might be useful to readers interested in calibrating theoretical models and numerical procedures intended at simulating the effect induced by partially replacing ISFs with RSFs.

Finally, the paper is organised as follows. Section 2 preliminarily describes the key geometric properties of the RSF employed in this research, whereas the complete definition of the adopted "materials and methods" is reported in Section 3. Then, Section 4 reports the results of both compression and bending tests and Section 5 proposes a systematic analysis based upon well-established standard parameters describing the post-cracking response of FRC. In conclusion, the key findings of the present study are outlined in Section 6 along with some comments about their conceptual significance and insights on the future developments of this research.

2. Recycled Steel Fibres from waste tyres

The Recycled Steel Fibres (Fig. 1) employed in this study were supplied by a company whose main business consists in collecting and recycling exhausted tyres. Particularly, 15 kg of RSFs were received at LMS and sampled to obtain a comprehensive description of their variable geometry, being the mechanical characterisation not covered in this paper and specifically addressed in dedicated experimental campaign [28].

First of all, the fibres were cleaned and separated from some thicker pieces of steel, which were not clearly suited for being used as a spread reinforcement for FRC. Fig. 2 reports two Scanning Electron Microscope (SEM) images revealing that residual rubber impurities, no wider than 20–25 μm, were still attached to the fibre surface.

Then, a detailed geometric characterisation was carried out on a bunch of about 2000 RSFs randomly sampled from the available amount of RSFs. The diameter (d_f) was measured by means of a micrometer: particularly, three measures were taken (i.e., at the two ends and at the mid-point) and an average value was determined for each fibre. According to such measurements, the average fibre diameter was ranging between 0.11 and 1.64 mm: Fig. 3 highlights its apparently multimodal distribution (probably due to the mixing of different types of tyres in the recycling process) characterised by a mean value of 0.27 mm. However, more than one third (35.7%) of the sampled fibres exhibited an average diameter between 0.22 and 0.24 mm.

The geometric characterisation of RSFs was completed by determining the fibre length l_f which was conventionally defined, according to the CNR-204/2006 [29] specifications, as the distance between the outer ends of a fibre. Fig. 4 shows the frequency distribution of measured fibre lengths: in this case, a unimodal distribution was observed (probably resulting from the identical cutting process underwent during the recycling process): the mean value

Fig. 1. Recycled Steel Fibres employed for the HIRSFRC.

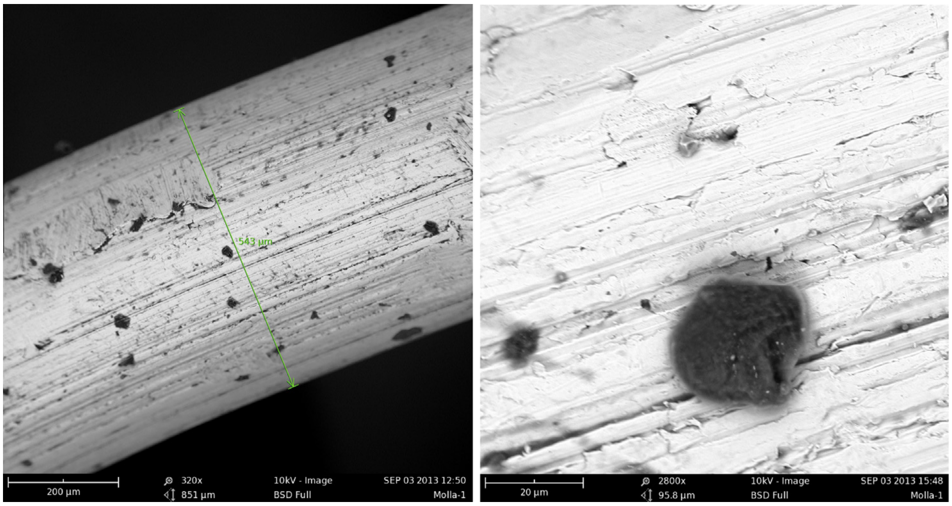


Fig. 2. SEM analysis of RSF.

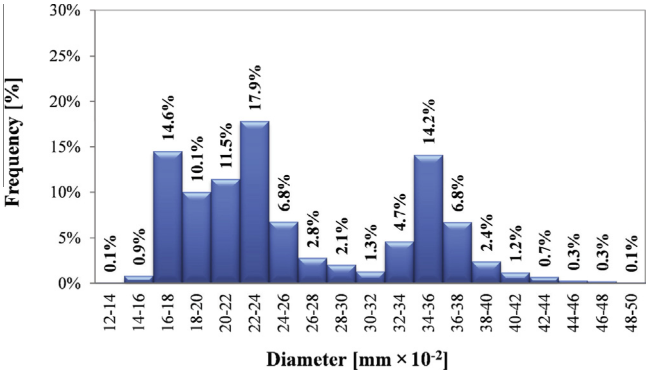


Fig. 3. Frequency distribution of diameter measurements.

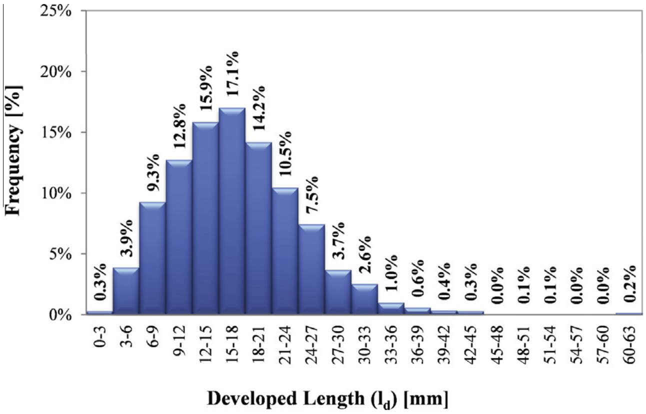


Fig. 5. Frequency distribution of measured fibre developed lengths.

was about 12 mm and almost one half of measured fibre lengths (47.1% of the total amount) was found ranging between 9–15 mm, whereas the 10%, 50% and 90% percentiles were of 18, 24 and 37 mm, respectively.

Furthermore, the total "developed length" l_d [29] was also measured for the same sample of fibres: Fig. 5 shows the resulting unimodal frequency distribution of l_d. Moreover the l_f/l_d ratio was also determined for describing the shape of the same fibres (Fig. 6): values of this ratio closer to unit corresponds to fairly straight fibres, whereas the lower this ratio the more curled and twisted the fibre.

Finally, the aspect ratio (l_f/d_f) of fibres was analysed, as it is a key parameter controlling their mechanical performance in FRC. Fig. 7 highlights a unimodal distribution of the aspect ratio, with a mean value of about 47 and more than one half (57%) of fibres exhibited a value within the range 30–60: in fact these values

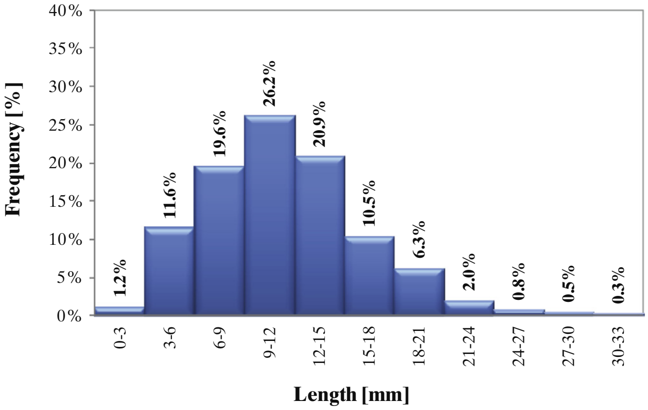


Fig. 4. Frequency distribution of fibre length measurements.

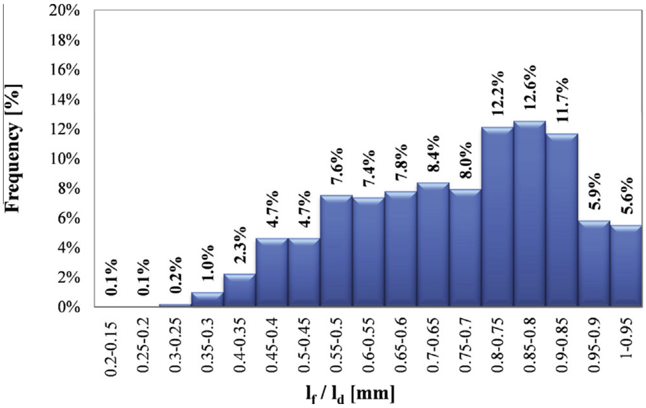


Fig. 6. Frequency distribution of l_f/l_d ratio.

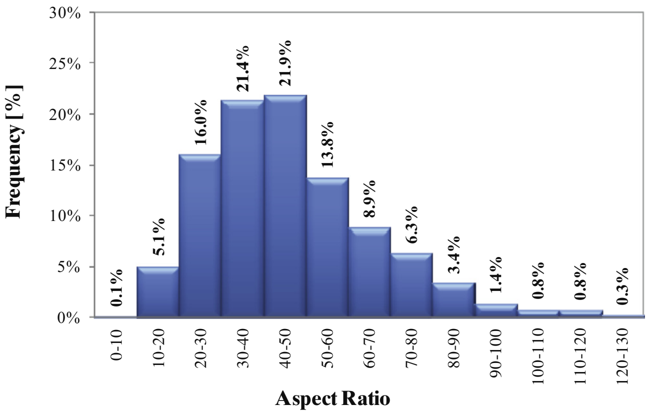


Fig. 7. Frequency of the aspect ratio.

Table 1
Mixture design per cubic metre of the reference concrete.

Material	Dosage[kg/m^3]
Sand	1012
Coarse agg. N1	134
Coarse agg. N2	764
Cement 42.5R	320
Free water	163
Water absorption	17
Superplasticizer	2.75

Table 2
Specific weight and absorption of aggregates and sand.

Material	Specific weight [kg/m^3]	Absorption (%)
Sand	2690	1.20
Coarse agg. N1	2690	0.70
Coarse agg. N2	2690	0.50

are rather close to the aspect ratios commonly characterising Industrial Steel Fibres [11].

3. Experimental campaign

The results reported in this section were obtained from experimental tests performed according to UNI-11039-1 [26] for definitions, classification and designation and UNI-11039-2 [27] for the test method.

3.1. Materials

The FRCs specimens tested in this study were prepared by adopting a unique mixture for the concrete matrix which was also employed for preparing the plain concrete specimens considered as a reference (labelled as REF). This mixture was designed for a target 28 days mean cubic compressive strength of 40 MPa and prepared by using crushed limestone aggregates with a maximum aggregate size of 20 mm according to EN-12620 [30] and UNI-11039-1 [26], a constant cement content of 320 kg/m^3 and a free water to-cement-ratio w/c of 0.51. Table 1 describes the mixture composition: coarse natural aggregates with grain size ranging between 2 and 10 mm were denoted as $N1$, whereas $N2$ corresponds to grain size from 10 to 20 mm. Moreover, fine aggregates (namely "sand") were characterised by a maximum equivalent size equal to 2 mm. Table 2 reports the specific weight and water absorption capacity of the aforementioned aggregates and sand. The aggregate grading of the reference concrete is represented in Fig. 8 in comparison with the well-known Fuller grain size distribution.

Wirand Fibres type FS7 Fig. 9, already considered by the authors in a previous experimental campaign [31] and generally referred to as "Industrial Steel Fibres" (ISFs) in the following, were considered in this study along with the RSFs already described in details in Section 2 (Fig. 1). The key geometric and mechanical properties of ISFs are listed in the following [32]: $l_f = 33$ mm (fibre length), $d_f = 0.55$ mm (fibre diameter), $AR = 60$ (aspect ratio), number of fibres per kg = 16,100, $f_t > 1200$ MPa (failure strength in tension) and $\varepsilon_u \leqslant 2\%$ (ultimate strain).

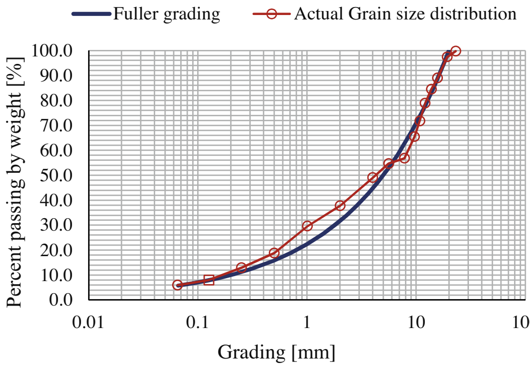


Fig. 8. Grain size distribution of the "REF" mixture.

Fig. 9. Industrial fibre types FS7 [32] employed for the HIRSFRC.

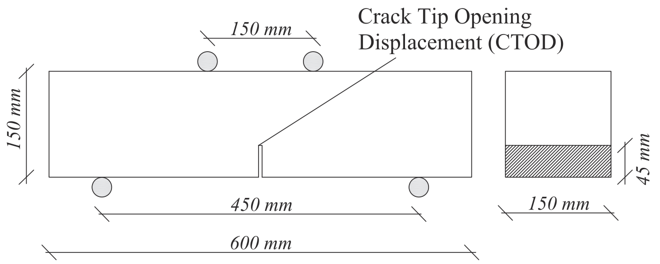


Fig. 10. Geometry of the notched beam tested in four-point bending.

Four FRC mixtures were prepared, always using 0.5% of fibres in volume of matrix, and also combining the aforementioned ISFs and RSFs:

- RSFRC 0-05: with only ISFs (RSFs = 0%).
- RSFRC 25-05: with 25% of ISFs replaced by an equal amount of RSFs.
- RSFRC 50-05: with 50% of ISFs replaced by an equal amount of RSFs.
- RSFRC 100-05: with all RSFs.

3.2. Methods

The concrete mixtures described in the previous section were prepared by using a laboratory mixer. Both coarse and fine aggregates were saturated and mixed; subsequently, cement, fibres and, finally, a super-plasticizer were added. The REF mixture, whose composition is described in Table 1, was designed for a target slump value of 150–180 mm; a value of 175 mm was actually measured at fresh state. Moreover, the cementitious matrix composition of all FRC specimens was kept fairly unchanged; only the super-plasticizer was slightly adjusted for controlling the influence of fibres on the resulting workability.

Three cube samples of $150 \times 150 \times 150$ mm^3 and beam specimens of $150 \times 150 \times 600$ mm^3 (Fig. 10) were cast in polyurethane moulds and duly vibrated. One of the cubic samples (labelled as "white") was extracted from each mixture before fibre mixing: it was tested in compression and compared with the corresponding FRC samples with the aim to observe the actual contribution of fibres on the compressive strength in each different mixture. After 36 h the concrete samples were removed from the moulds. Then, the hardened beam samples were notched (through a 2.0 mm wide-slit) of 45 mm depth and starting from the bottom surface of the sample (Fig. 11(b)). Moreover, all concrete specimens were cured in a water bath (100% humidity) at a constant temperature of 22 °C, up to reach the 28 days of curing. All the aforementioned preparation procedures were carried out according to UNI-11039-2 [27].

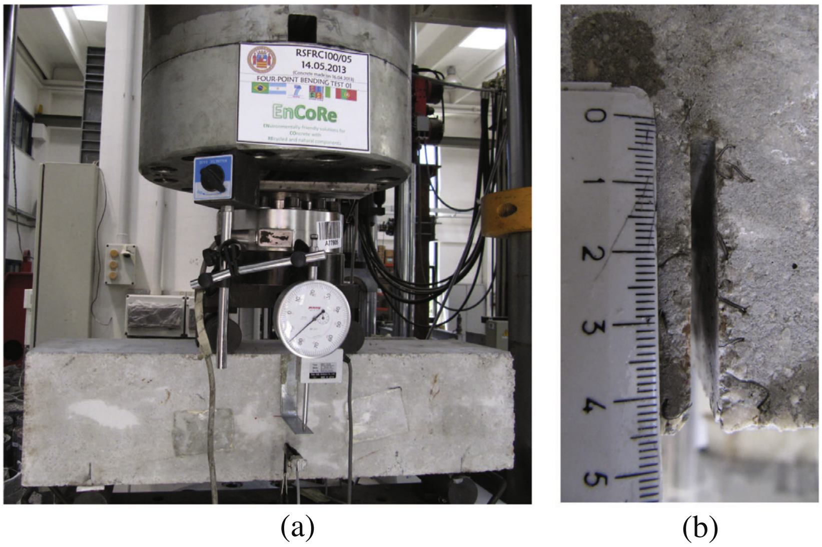


Fig. 11. Four-point bending test: (a) experimental set-up and (b) the vertical notch at the bottom surface of the specimen.

Table 3
Considered mixture types of the experimental programme.

Mixtures	Compression tests (28 days)	Four-point bending beams (28 days)
“REF”	3	3
RSFRC 0-05	3	3
RSFRC 25-05	3	3
RSFRC 50-05	3	3
RSFRC 100-05	3	3

Fig. 12. Disposition of the instrumentation for the four-point bending tests.

Table 3 outlines the experimental programme reported in this paper. Experimental tests were carried out according to the procedures described in the UNI-11039-2 [27]. Four-point bending tests of notched beams, as shown in Fig. 11(a), were performed in displacement control (having displacement rate of 0.005 mm/s). Relevant load and displacement quantities were measured and recorded during all tests. Particularly, the crack-tip opening displacement were measured by means of dedicated transducers that monitored the relative displacements of the two sides of the notch tip (Fig. 12). Furthermore, compressive tests were performed according to EN-12390-3 [33] for measuring the cubic compressive strength of the SFRCs at the time of testing.

4. Experimental results

4.1. Compression tests

Table 4
Densities and cube compressive strengths measured in each mixture.

Mixture label	Specific weight [kg/m^3]		$f_{c,cube}$ at 28 days [Mpa]	
	White	SFRC	White	SFRC (mean of two)
REF	2371		42.59	(mean of three)
RSFRC 0-05	2376	2413	40.57	39.01
RSFRC 25-05	2428	2435	36.42	36.52
RSFRC 50-05	2459	2450	36.89	36.74
RSFRC 100-05	2446	2491	36.69	37.37

The results of compression tests are summarised in Table 4 reporting the average values of compressive strengths obtained from cubic samples of the plain concrete and FRC mixtures considered in this study. The same table also reports the average values of specific weight measured in hardened samples of the same concrete mixtures. As widely documented in the scientific literature [31], no significant difference was observed in terms of compressive strengths of both the so-called “white” and SFRC specimens.

This means that, at least for the volume fraction considered in this study, the resulting compressive strength of FRC is mainly controlled by the matrix properties. Conversely, fibres only play a role in the post-cracking regime. The observed $\sigma-\epsilon$ curves are omitted herein for the sake of brevity and the influence of fibres on the post-cracking response of FRC is discussed into details for the case of bending tests.

4.2. Four-point bending tests

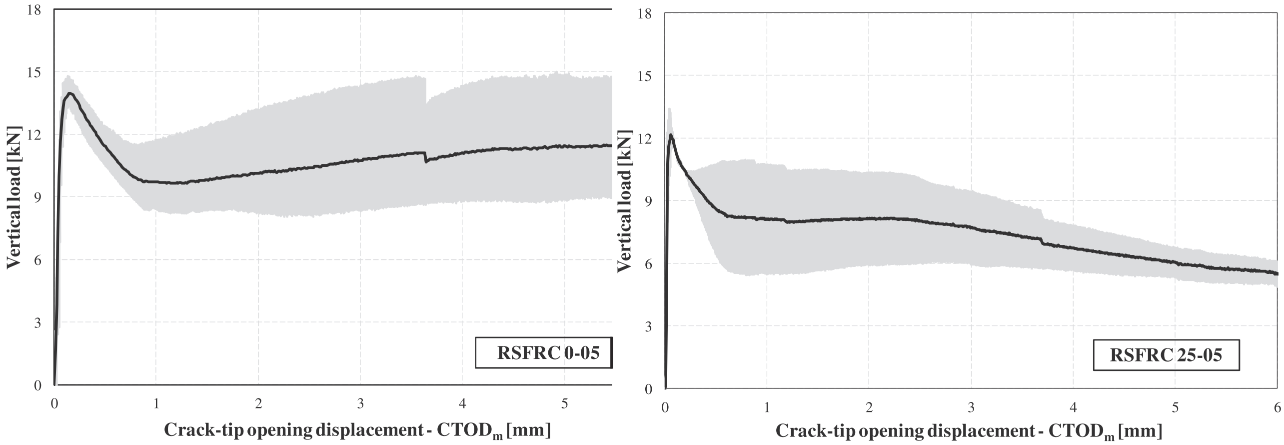
Four-point bending tests were performed with the aim of characterising the post-cracking flexural behaviour of HIRSFRC samples (Fig. 13): UNI-11039-1 [26] and UNI-11039-2 [27] provisions were taken into account for this purpose.

Fig. 14 reports the experimental curves of the vertical load, P, versus the corresponding Crack Tip Opening Displacement (*CTODm*) curves, obtained in the tests: *CTODm* represents the mean of the two opposite *CTODs*.

Based on the experimental evidence, the post-cracking response in bending of FRC specimens reinforced with only ISFs was characterised by a significant toughness (Fig. 14(a)), which is due to the bridging action of fibres and cannot be obtained in plain concrete [31].

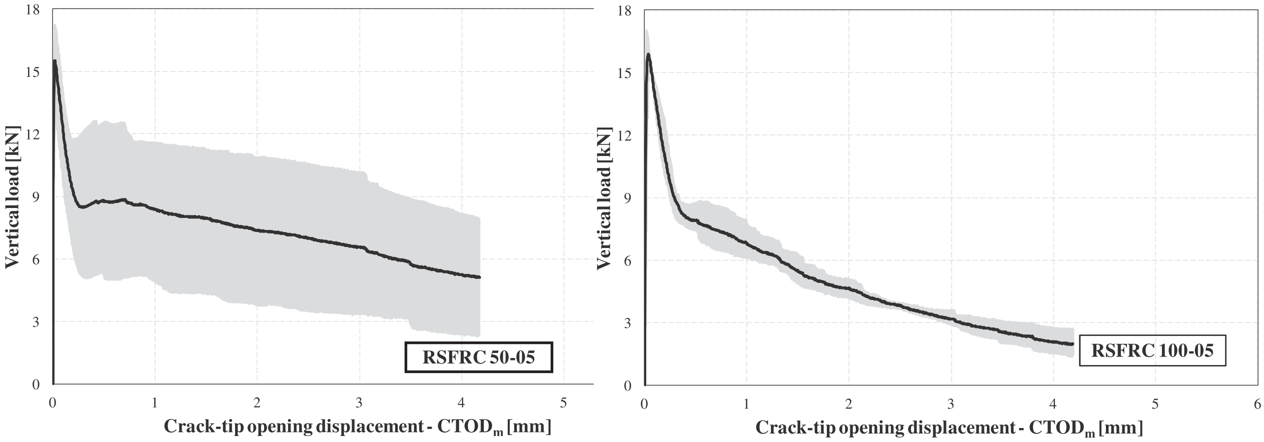
The effect of replacing increasing amount of ISFs with an equal quantity of RSFs can be easily understood by analysing the curves depicted in Fig. 14. The post-cracking behaviour of FRC is generally characterised by a more pronounced softening range in specimens characterised by a greater quantity of RSFs in substitution of ISFs.

Fig. 13. Cracked configuration after the 4 PB test of HIRSFRC notched beams.



(a) RSFRC 0-05 mixture

(b) RSFRC 25-05 mixture

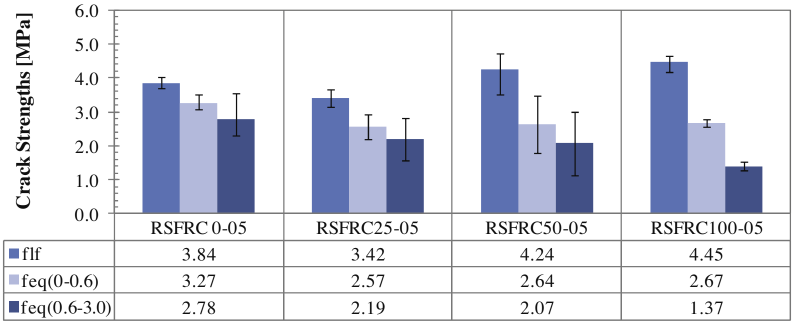


(c) RSFRC 50-05 mixture

(d) RSFRC 100-05 mixture

Fig. 14. Vertical force – *CTODm* curves.

Fig. 15. Observed distribution of fibres at crack section for one of the specimens (mixture RSFRC 100-05).



	RSFRC 0-05	RSFRC25-05	RSFRC50-05	RSFRC100-05
■ flf	3.84	3.42	4.24	4.45
■ feq(0-0.6)	3.27	2.57	2.64	2.67
■ feq(0.6-3.0)	2.78	2.19	2.07	1.37

Fig. 16. Comparisons between the first crack strength, f_{lf}, with the equivalent crack resistances, $f_{eq(0-0.6)}$ and $f_{eq(0.6-3.0)}$ [27]. The vertical segments represent the range between the minimum and the maximum value.

This is a result of the lower efficiency of the recycled fibres with respect to the industrial ones, which are specifically designed to exhibit a good interaction with the concrete matrix. Particularly, recycled fibres are not straight, have no hooks and have (generally) lower aspect ratios: these are the main reasons explaining the (expected) decay resulting from replacing part (to total) of industrial fibres with an equal amount (in weight) of recycled ones.

The steeper slope of the post-peak response observed for RSFRC 25-05 (Fig. 14(b)) is clearly due to the fact that the recycled fibres employed in those specimens need a wider crack opening for mobilising their bridging effect. The post-peak slope is even steeper for RSFRC 50-05 (Fig. 14(c)) and RSFRC 100-05 (Fig. 14(d)) where the actual volume fraction of RSF is even higher.

Nevertheless, a significant increase in toughness can be observed for all FRC specimens with respect to the significantly brittle behaviour characterising the post-cracking response of plain concrete.

Finally, it is worth highlighting that a fairly uniform distribution of fibres throughout the cracked surface was observed in all tested specimens: Fig. 15 shows the fracture surface obtained for one of the specimen made of RSFRC 100-05.

5. Analysis of results

Three representative parameters, defined by UNI-11039-2 [27], can be evaluated and compared for the FRC mixtures under investigation, with the aim of identifying and describing their post-cracking response. They are defined as the first crack strength (f_{lf}) and two equivalent post-cracking strengths: the first flexural strength ($f_{eq(0-0.6)}$) corresponds to a CTOD ranging between $CTOD0$ and $CTOD0 + 0.6$ mm and is supposed to be relevant significant for the Serviceability Limit State, whereas the second one ($f_{eq(0.6-3.0)}$) refers to a $CTOD$ ranging between $CTOD0 + 0.6$ and $CTOD0 + 3$ mm which is rather relevant for the Ultimate Limit State [34].

According to UNI-11039-2 [27], the first crack strength values, f_{lf}, defining the post-cracking response of HIRSFRC, was evaluated in each sample as

$$f_{lf} = \frac{P_{lf} \cdot l}{b(h-a_0)^2} \tag{1}$$

where P_{lf} represents the first crack load [N], b, h and l are the width [mm], height [mm] and length [mm] of the beam, respectively, and a_0 [mm] represents the notch depth.

Fig. 16 shows the comparisons of the mean values of first crack strength and the two equivalent crack resistances, defined in standard $CTODm$ ranges, i.e. $[CTODm_0; CTODm_0 + 0.6\text{ mm}]$ and $[CTODm_0 + 0.6; CTODm_0 + 3.0\text{ mm}]$. $CTODm_0$ is the Crack Tip Opening Displacement (mean value) corresponding to the peak load of the reference specimen.

The following quantities, known as “equivalent crack resistances” $f_{eq(0-0.6)}$ and $f_{eq(0.6-3.0)}$, are defined as follows

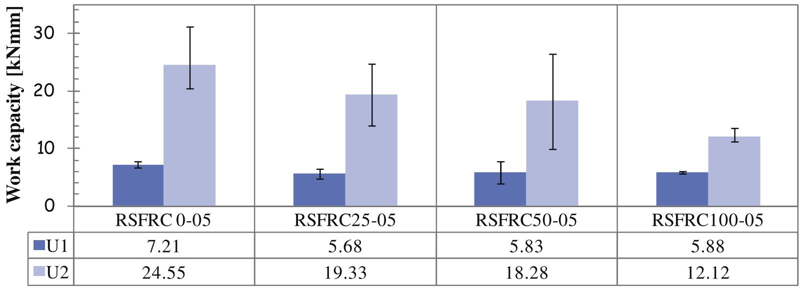
$$\begin{aligned} f_{eq(0-0.6)} &= \frac{l}{b(h-a_0)^2}\,\frac{U_1}{0.6} \\ f_{eq(0.6-3.0)} &= \frac{l}{b(h-a_0)^2}\,\frac{U_2}{2.4} \end{aligned} \tag{2}$$

being U_1 and U_2 work capacity measures derived by means of the following relations

$$\begin{aligned} U_1 &= \int_{CTODm_0}^{CTODm_0+0.6} P(CTODm)\,dCTODm \\ U_2 &= \int_{CTODm_0+0.6}^{CTODm_0+3.0} P(CTODm)\,dCTODm \end{aligned} \tag{3}$$

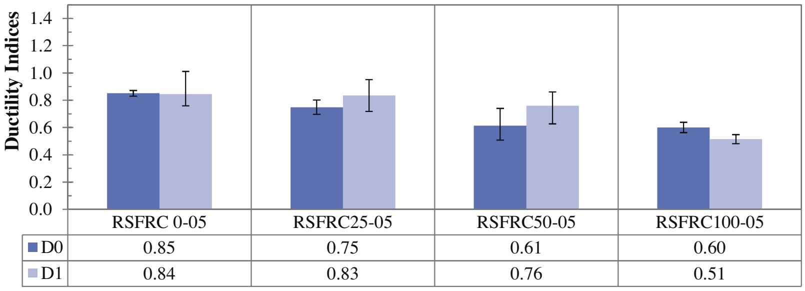
calculated on the HIRSFRC test data.

As a matter of principle, the quantities described by Eq. (3) represent the enclosed area (toughness measure) under the $P - CTODm$ curves between the range $[CTODm_0;\ CTODm_0 + 0.6\text{ mm}]$ and $[CTODm_0 + 0.6; CTODm_0 + 3.0\text{ mm}]$ for U_1 and U_2,



	RSFRC 0-05	RSFRC25-05	RSFRC50-05	RSFRC100-05
■U1	7.21	5.68	5.83	5.88
■U2	24.55	19.33	18.28	12.12

Fig. 17. Energy absorption measures U_1 and U_2 according to UNI-11039-2 [27]. The vertical segments represent the range between the minimum and the maximum value.



	RSFRC 0-05	RSFRC25-05	RSFRC50-05	RSFRC100-05
■D0	0.85	0.75	0.61	0.60
■D1	0.84	0.83	0.76	0.51

Fig. 18. Indices of the ductility according to UNI-11039-2 [27]. The vertical segments represent the range between the minimum and the maximum value.

respectively. Fig. 17 shows such energy absorption values of each sample and calculated by means of Eq. (3). Keeping in mind the mechanical meaning of those parameters, these results show that, as expected, all specimens, reinforced with a total amount of 40 kg/m^3 of steel fibres (equivalent to 0.5% in fibre volume fraction), mainly exhibit a softening behaviour in the post-cracking regime.

Moreover, ductility indices can be considered as further objective "measures" of the fibre bridging mechanisms and the following ductility measures were calculated [27]

$$D_0 = f_{eq(0-0.6)}/f_{lf} \tag{4}$$

and

$$D_1 = f_{eq(0.6-3.0)}/f_{eq}(0-0.6). \tag{5}$$

Fig. 18 reports the values of ductility indices (defined by Eqs. (4) and (5)) for the various tested beams. According to the classification of the UNI-11039-1 [26], all the cementitious composites, tested in this experimental campaign, can be classified as "crack-softening" media, as both D_0 and $D_1 < 1$.

Finally, it is worth highlighting that UNI-11039-1 [26] states that the D_0 index should not be lower than 0.5 for a FRC to be used in structural applications. Based on this criterion, Fig. 18 shows that all SFRC mixtures, even the one reinforced with only RSFs, can be considered as a structural fibre reinforced cementitious material.

6. Conclusions

This experimental research was intended at investigating the mechanical behaviour of concrete reinforced with both Recycled and Industrial Steel Fibres. Based on the obtained results the following observations can be highlighted:

- as expected, the observed compressive strength is almost unaffected by the presence of fibres and, then, no significant difference was detected between the FRC specimens with only industrial fibres and the ones made with an increasing proportion of recycled fibres;
- on the contrary, as it was also expected, the bending behaviour observed in the experimental tests was significantly influenced by the fibre contribution;
- in this regard, a significant decay in the post-peak cracking behaviour was observed as a result of the partial to total replacement of industrial fibres with an equal amount of recycled ones;
- particularly, the higher is the amount of recycled fibres, the more significant is the reduction in the post-cracking toughness (in terms of equivalent post-cracking strengths and/or ductility indices) observed in the four-point bending tests;
- nevertheless, it is worth highlighting that, in spite of the low amount of fibres (0.5% in volume), a significant increase in the equivalent fracture energy was observed for FRC specimens with respect to the reference ("white") ones, even in the case of a total replacement of ISFs with RSFs.

Finally, the presented results confirmed the promising application of concrete reinforced with Recycled Steel Fibres derived from waste tyres. However, the proposed results clearly demonstrate that industrial fibres cannot be replaced by an equal amount of (unprocessed) recycled ones without a significant decay in the relevant mechanical properties. In fact, the definition of an "equivalent" (and higher) amount of recycled fibres which might be substituted to a certain amount of industrial ones, without significant loss in terms of mechanical properties, is a further possible prospect for the use of HIRSFRCs in structural applications. However, further investigations are still necessary to completely understand this and the other relevant aspects of the mechanical response of these materials.

Acknowledgements

The authors are grateful to "Calcestruzzi Irpini S.p.A" and "General Admixtures S.p.A." for their important support to the experimental investigation. "RPN Tyres S.r.l" is also acknowledged for having supplied the Recycled Steel Fibres for the experimental campaign.

Finally, it has to be outlined that this study is part of the activities carried out by the authors within the "EnCoRe" project (www.encore-fp7.unisa.it), funded by the European Union within the Seventh Framework Programme (FP7-PEOPLE-2011-IRSES, n. 295283).

References

[1] G. Tchobanoglous, F. Kreith, Handbook of Solid Waste Management, McGraw-Hill, New York, 2002.
[2] M. Sienkiewicz, J. Kucinska-Lipka, H. Janik, A. Balas, Progress in used tyres management in the European Union: a review, Waste Manage. 32 (10) (2012) 1742–1751.
[3] EU-Directive1999/31/EC of the council of 26 April 1999 on the landfill of waste, Off. J. Eur. Union L182 (1999) 1–19.
[4] V. Sharma, F. Fortuna, M. Mincarini, M. Berillo, G. Cornacchia, Disposal of waste tyres for energy recovery and safe environment, Appl. Energy 65 (1) (2000) 381–394.
[5] E. Ganjian, M. Khorami, A.A. Maghsoudi, Scrap-tyre-rubber replacement for aggregate and filler in concrete, Constr. Build. Mater. 23 (5) (2009) 1828–1836.
[6] G. Centonze, M. Leone, M. Aiello, Steel fibers from waste tires as reinforcement in concrete: a mechanical characterization, Constr. Build. Mater. 36 (2012) 46–57.
[7] A.G. Graeff, K. Pilakoutas, K. Neocleous, M.V.N. Peres, Fatigue resistance and cracking mechanism of concrete pavements reinforced with recycled steel fibres recovered from post-consumer tyres, Eng. Struct. 45 (2012) 385–395.
[8] W.H. Yung, L.C. Yung, L.H. Hua, A study of the durability properties of waste tire rubber applied to self-compacting concrete, Constr. Build. Mater. 41 (2013) 665–672.
[9] A. Naaman, H. Reinhardt, Proposed classification of HPFRC composites based on their tensile response, Mater. Struct. 39 (2006) 547–555.
[10] X. Qian, X. Zhou, B. Mu, Z. Li, Fiber alignment and property direction dependency of FRC extrudate, Cem. Concr. Res. 33 (10) (2003) 1575–1581.
[11] ACI-544.1-96, State-of-the-art report on fiber reinforced concrete. Reported by ACI Committee 544, American Concrete Institute, 1996.
[12] A. Bartl, A. Hackl, B. Mihalyi, M. Wistuba, I. Marini, Recycling of fibre materials, Process Saf. Environ. Prot. 83 (B4) (2005) 351–358.
[13] H. Tlemat, K. Pilakoutas, K. Neocleous, Stress-strain characteristic of SFRC using recycled fibres, Mater. Struct. 39 (3) (2006) 365–377.
[14] K. Neocleous, H. Tlemat, K. Pilakoutas, Design issues for concrete reinforced with steel fibers, including fibers recovered from used tires, J. Mater. Civil Eng. 18 (5) (2006) 677–685.
[15] M.A. Aiello, F. Leuzzi, G. Centonze, A. Maffezzoli, Use of steel fibres recovered from waste tyres as reinforcement in concrete: pull-out behaviour, compressive and flexural strength, Waste Manage. 29 (6) (2009) 1960–1970.
[16] L. Sorelli, A. Meda, G. Plizzari, Bending and uni-axial tensile tests on concrete reinforced with hybrid steel fibers, ASCE – J. Mater. Civil Eng. 17 (5) (2005) 519–527.
[17] S. Park, D. Kim, G. Ryu, K. Koh, Tensile behavior of ultra high performance hybrid fiber reinforced concrete, Cem. Concr. Compos. 34 (2) (2012) 172–184.
[18] M. Hsie, C. Tu, P. Song, Mechanical properties of polypropylene hybrid fiber-reinforced concrete, Mater. Sci. Eng.: A 494 (12) (2008) 153–157.
[19] D. Kim, S. Park, G. Ryu, K. Koh, Comparative flexural behavior of hybrid ultra high performance fiber reinforced concrete with different macro fibers, Constr. Build. Mater. 25 (11) (2011) 4144–4155.
[20] W. Yao, J. Li, K. Wu, Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction, Cem. Concr. Res. 33 (1) (2003) 27–30.
[21] E. Dawood, M. Ramli, Mechanical properties of high strength flowing concrete with hybrid fibers, Const. Build. Mater. 28 (1) (2012) 193–200.
[22] N. Libre, M. Shekarchi, M. Mahoutian, P. Soroushian, Mechanical properties of hybrid fiber reinforced lightweight aggregate concrete made with natural pumice, Constr. Build. Mater. 25 (5) (2011) 2458–2464.
[23] M. Sahmaran, I. Yaman, Hybrid fiber reinforced self-compacting concrete with a high-volume coarse fly ash, Constr. Build. Mater. 21 (1) (2007) 150–156.
[24] Y. Ding, C. Azevedo, J. Aguiar, S. Jalali, Study on residual behaviour and flexural toughness of fibre cocktail reinforced self compacting high performance concrete after exposure to high temperature, Constr. Build. Mater. 26 (1) (2012) 21–31.
[25] B. Akcay, M. Tasdemir, Mechanical behaviour and fibre dispersion of hybrid steel fibre reinforced self-compacting concrete, Constr. Build. Mater. 28 (1) (2012) 287–293.
[26] UNI-11039-1Steel Fibre Reinforced Concrete –Definitions, Classification and Designation, UNI Editions, Milan, Italy, 2003.
[27] UNI-11039-2Steel Fibre Reinforced Concrete – Test Method to Determine the First Crack Strength and Ductility Indexes, UNI Editions, Milan, Italy, 2003.
[28] A. Caggiano, H. Xargay, P. Folino, E. Martinelli, Experimental and numerical characterization of the bond behavior of steel fibers recovered from waste tires embedded in cementitious matrices, Cement and Concrete Composites 62 (2015) 146–155.
[29] CNR-204/2006, CNR Consiglio Nazionale delle Ricerche: Istruzioni per la progettazione, lesecuzione ed il controllo di strutture di calcestruzzo fibrorinforzato, 2006 [in Italian].
[30] UNI-EN-12620, Aggregates for concrete, volume Ref. No. EN 12620:2002 E. Europ. Committee for Standardization, Brussels, 2002.
[31] A. Caggiano, M. Cremona, C. Faella, C. Lima, E. Martinelli, Fracture behavior of concrete beams reinforced with mixed long/short steel fibers, Constr. Build. Mater. 37 (2012) 832–840.
[32] Officine-Maccaferri, Cold drawn steel wire fibre, for concrete reinforcement. TECHNICAL DATA SHEET, WIRAND FIBRE FS7, 2010.
[33] EN-12390-3, Testing hardened concrete. Part 3: compressive strength of test specimens. BSI, 2009.
[34] M. di Prisco, G. Plizzari, L. Vandewalle, Fibre reinforced concrete: new design perspectives, Mater. Struct. 42 (9) (2009) 1261–1281.