

HORMIGON REFORZADO CON FIBRAS DE ACERO INDUSTRIALES Y RECICLADAS: ANALISIS EXPERIMENTAL DEL COMPORTAMIENTO MECÁNICO

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RESUMEN

El uso de fibras recicladas como refuerzo en una clase de materiales generalmente denominados Compuesto Cementicio Reforzado con Fibras (FRCCs) es una tendencia relativamente nueva en la Ingeniería de Materiales. Las fibras recicladas, caracterizadas por un impacto económico menor con respecto a las “comunes” industriales, pueden ser empleadas en FRCCs de alta performance, conllevando a mejores características de sustentabilidad. Este trabajo presentará los resultados de la investigación del comportamiento mecánico de fibras de acero recicladas de cubiertas vehiculares, aptas para la producción de hormigón eco-sustentable reforzado con fibras para uso estructural. Se mostrarán y discutirán los resultados de una campaña experimental centrada en el entendimiento de la respuesta a tracción de las fibras antes mencionadas, la adherencia presentada cuando son embebidas en matrices cementicias y se estudiará el comportamiento mecánico de hormigones híbridos realizados con fibras industriales y recicladas.

ABSTRACT

The use of Recycled Steel Fibers (RSFs) as a dispersed reinforcement in a class of materials referred to as Fiber-Reinforced Cementitious Composites (FRCCs) is a relatively new trend. RSFs, characterized by a lower economic impact with respect to the Industrial ones (ISFs), can be employed in High-Performance FRCCs, leading to enhanced sustainability features. Therefore, this work presents the results of a research investigating the mechanical behavior of RSFs recovered from waste tires and, then, suitable to produce eco-friendly fiber-reinforced concrete for structural applications. Particularly, the results of an experimental investigation aimed at understanding the tensile response of the aforementioned steel fibers and their bond behavior when embedded in cementitious matrices are reported and discussed. Furthermore, the mechanical behavior of FRC made with both ISFs and RSFs.

INTRODUCCIÓN

In recent years the disposal of exhaust tires 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 tires” could no longer be landfilled and, since July 2006, such regulations must be applied to both “whole” and “shredded” tires ^[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 tires mainly consist of separating the internal steel reinforcement from the rubber covering. Hence, rubber scraps and short steel fibers are generally obtained by these processes and can be utilized 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 fibers, 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 “rubberized concrete” which is characterized by enhanced damping and toughness properties ^[5]; on the other hand, recycled fibers can be potentially used in substitution of the industrial ones commonly employed for producing Fiber Reinforced Cementitious Composites (FRCCs) ^[6].

As a matter of fact, adding a small fraction (usually in the order of 0.5–1.0% in volume) of short fibers during mixing results in enhancing the toughness in the post-cracking response of cementitious materials as those fibers have a bridging effect across the opening cracks and, then, a positive influence on their propagation ^[7].

However, the fibers, employed in FRCC, need to have good mechanical properties, be easy to spread in concrete mixtures and durable when embedded into cementitious matrices ^[8]. Many types of fibers (i.e., made of steel, glass, natural cellulose, carbon, nylon, polypropylene, etc.) have been used in FRCC and are widely available for commercial applications ^[9]. A total of 60 million tons of these kinds of fibers are currently employed every year around the world, and, then, their production requires a huge amount of raw materials ^[10]. Therefore, Recycled Steel Fibers (RSFs) obtained from waste tires could contribute to reducing this demand. Particularly, they can directly be utilized 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 ^[11].

This paper investigates the mechanical behavior of FRC with both industrial fibers and RSFs obtained from waste tires, as mentioned above. The work preliminarily describes the key geometric and mechanical properties of the Recycled Steel Fibers (RSFs) employed in this research. Then, starting from a FRC mixture with 0.5% (in volume), that is to say 40 kg/m³, of Industrial Steel Fibers (ISFs), three more mixtures

were prepared by replacing 25%, 50% and 100% in weight of such fibers with an equal amount of RSFs. Therefore, the mechanical behavior of conventional Steel Fiber-Reinforced Concrete (SFRC) was observed in comparison with the one of both Hybrid Industrial/Recycled Steel Fiber-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 ^[12] and UNI-11039-2 ^[13].

RECYCLED STEEL FIBERS FROM WASTE TIRES

A quantity of 15 kg of RSFs was examined to obtain a comprehensive description of both their geometry and mechanical characterization (Figure 1). It is worth mentioning that, due to the possibility that fibers could derive from different recycling plants and/or countries, it is largely accepted in the literature that a specific identification is necessary to investigate the expected variability of both geometrical and mechanical properties for the employed RSF.

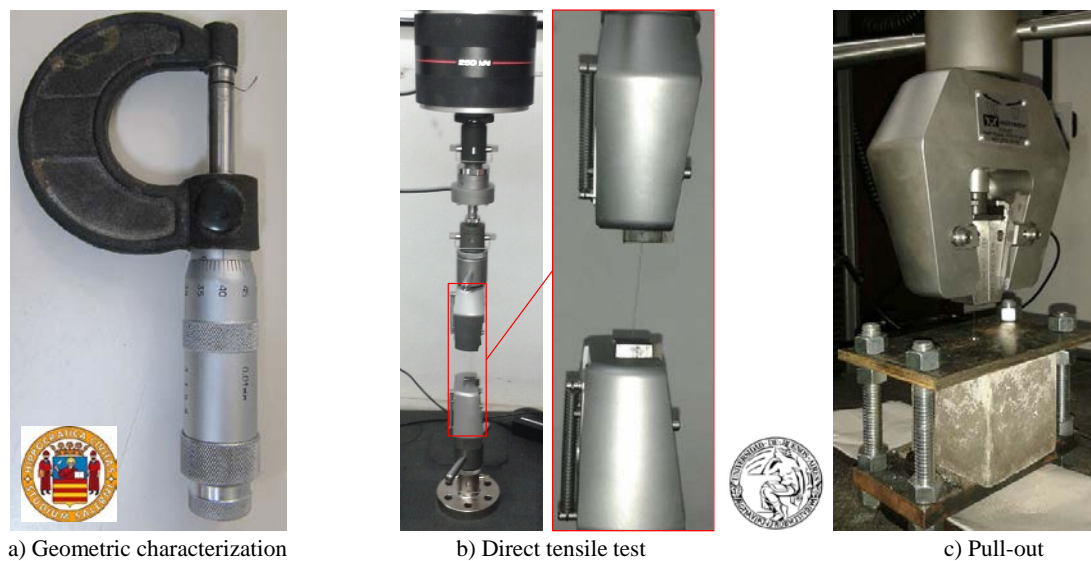


Figure 1 – Geometric and mechanical characterization of RSF ^[14].

As a result of the shredding and separation process, the RSFs under consideration have variable diameters and lengths, and often are characterized by irregular shapes with curls and twists. Therefore, the description of the main geometric parameters of these fibers deserves a dedicated investigation. Moreover, mechanical characterization tests on RSF through tensile and pull-out tests were carried out at the Laboratory of Materials and Structures (LAME) of the University of Buenos Aires (Argentina). For the sake of brevity these results are omitted in this work, however the complete discussion is outlined in the work by Caggiano et al. ^[14].

EXPERIMENTAL CAMPAIGN

The results reported in this section were obtained from experimental tests performed according to UNI-11039-1^[12] for definitions, classification and designation and UNI-11039-2^[13] for the test method.

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^[15] and UNI-11039-1^[12], a constant cement content of 320 kg/m³ and a free water to-cement-ratio w/c of 0.51^[16].

Wirand Fibers type FS7, generally referred to as “Industrial Steel Fibers” (ISFs) in the following, were considered in this study along with the RSFs. The key geometric and mechanical properties of ISFs are listed in the following^[17]: $l_f = 33$ mm (fiber length), $d_f = 0.55$ mm (fiber diameter), AR = 60 (aspect ratio), number of fibers per kg = 16100, $f_t > 1200$ MPa (failure strength in tension) and $\varepsilon_u \leq 2\%$ (ultimate strain).

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, fibers and, finally, a super-plasticizer were added. The REF mixture, 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 fibers on the resulting workability.

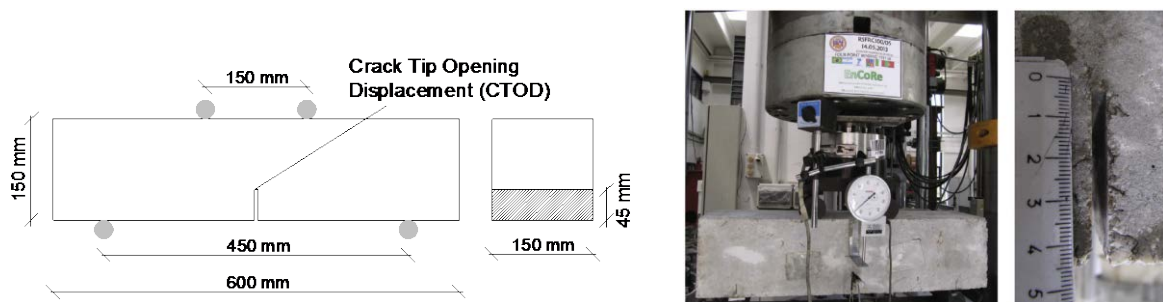


Figure 2 – Four-point bending test: geometry of the notched beam and experimental set-up^[16].

Three cube samples of 150×150×150 mm³ and beam specimens of 150×150×600 mm³ (Figure 2) were cast in polyurethane molds and duly vibrated. One of the cubic samples (labelled as “white”) was extracted from each mixture before fiber mixing: it was tested in compression and compared with the corresponding FRC samples with the aim to observe the actual contribution of fibers on the compressive strength in each different mixture. After 36 h the concrete samples were removed from the

molds. 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 (Figure 2). 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.

Mix Label	Compression (28 days)	Four-point bending test (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

Table 1 – *Considered mixture types of the experimental programme.*

Four FRC mixtures were prepared, always using 0.5% of fibers 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. Table 1 outlines the experimental programme reported in this paper. Experimental tests were carried out according to the procedures described in the UNI-11039-2 ^[13]. Four-point bending tests of notched beams, as shown in (Figure 2), 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 displacements were measured by means of dedicated transducers that monitored the relative displacements of the two sides of the notch tip. Furthermore, compressive tests were performed according to EN-12390-3 ^[18] for measuring the cubic compressive strength of the SFRCs at the time of testing.

EXPERIMENTAL RESULTS

The results of **compression** tests are summarized in Table 2 reporting the average values of 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, 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, fibers only play a role in the post-cracking regime.

Mix 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

Table 2 – Densities and cube compressive strengths measured in each mixture.

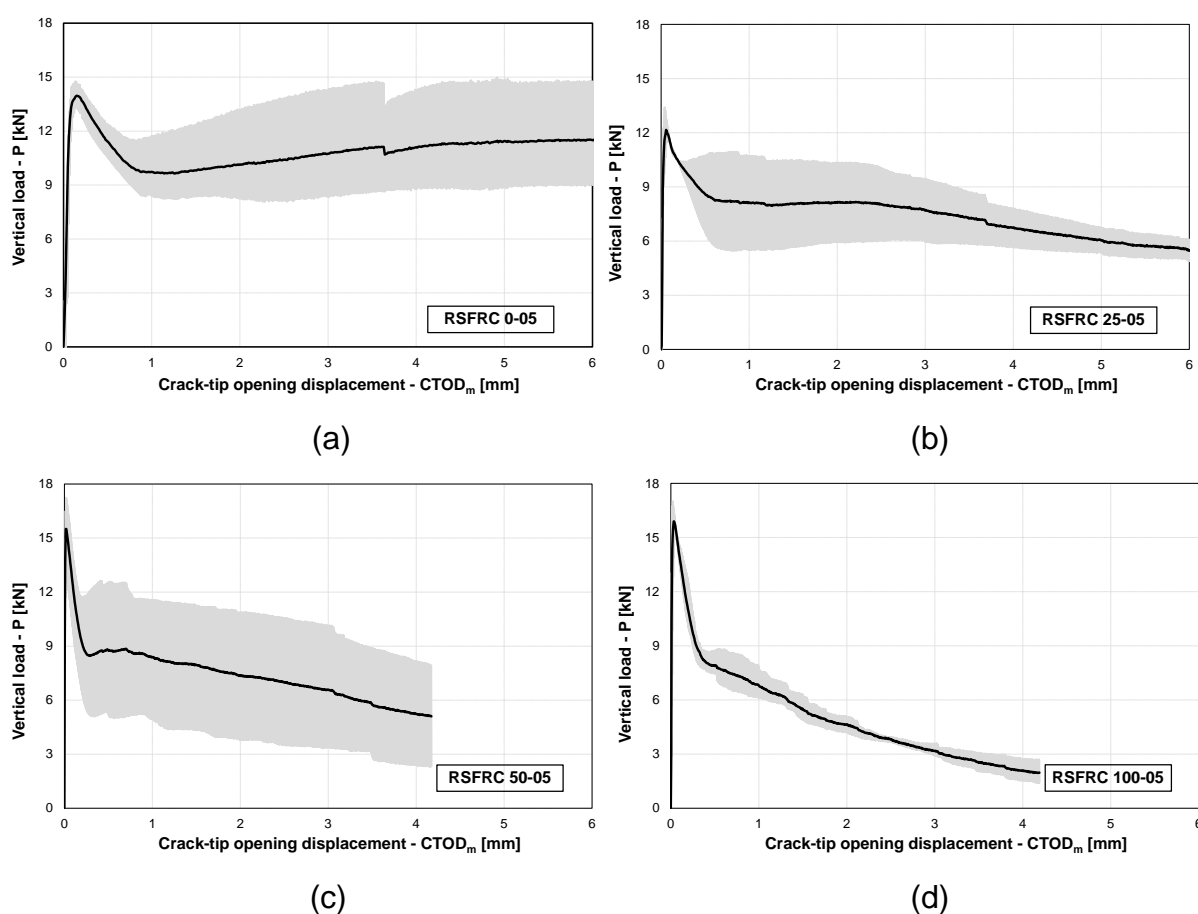


Figure 3 – Vertical force vs. $CTOD_m$ curves.

Four-point bending tests were performed with the aim of characterizing the post-cracking flexural behavior of HIRSFRC samples: UNI-11039-1^[12] and UNI-11039-2^[13] provisions were taken into account for this purpose.

Figure 3 reports the experimental curves of the vertical load, P , versus the corresponding Crack Tip Opening Displacement ($CTOD_m$) curves, obtained in the tests: $CTOD_m$ 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 characterized by a significant toughness (Figure 3 (a)), which is due to the bridging action of fibers and cannot be obtained in plain concrete.

The effect of replacing increasing amount of ISFs with an equal quantity of RSFs can be easily understood by analyzing the curves depicted in Figure 3. The post-cracking behavior of FRC is generally characterized by a more pronounced softening range in specimens with a greater quantity of RSFs in substitution of ISFs. This is a result of the lower efficiency of the recycled fibers with respect to the industrial ones, which are specifically designed to exhibit a good interaction with the concrete matrix. Particularly, recycled fibers 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 fibers with an equal amount (in weight) of recycled ones.

The steeper slope of the post-peak response observed for RSFRC 25-05 (Figure 3 (b)) is clearly due to the fact that the recycled fibers employed in those specimens need a wider crack opening for mobilizing their bridging effect. The post-peak slope is even steeper for RSFRC 50-05 (Figure 3 (c)) and RSFRC 100-05 (Figure 3 (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 behavior characterizing the post-cracking response of plain concrete.

ANALYSIS OF RESULTS

Three representative parameters, defined by UNI-11039-2 ^[13], 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_{ff}) and two equivalent post-cracking strengths: the first flexural strength ($f_{eq(0-0.6)}$) corresponds to a $CTOD$ ranging between $CTOD_0$ and $CTOD_0+0.6$ 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 $CTOD_0+0.6$ and $CTOD_0+3.0$ mm which is rather relevant for the Ultimate Limit State ^[19].

According to UNI-11039-2 ^[13], the first crack strength values, f_{ff} , defining the post-cracking response of HIRSFRC, was evaluated in each sample as

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

where P_{ff} 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.

Figure 4 shows the comparisons of the mean values of first crack strength and the two equivalent crack resistances, defined in standard $CTOD_m$ ranges: i.e. [$CTOD_{m0}$, $CTOD_{m0}+0.6$ mm] and [$CTOD_{m0}+0.6$, $CTOD_0+3.0$ mm]. $CTOD_{m0}$ 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

$$f_{eq(0-0.6)} = \frac{l}{b \cdot (h - a_0)^2} \cdot \frac{U_1}{0.6} \quad (2)$$

$$f_{eq(0.6-3.0)} = \frac{l}{b \cdot (h - a_0)^2} \cdot \frac{U_2}{2.4} \quad (3)$$

being U_1 and U_2 work capacity measures derived by means of the following relations, calculated on the HIRSFRC test data,

$$U_1 = \int_{CTOD_0}^{CTOD_0+0.6} P(CTOD_m) \cdot dCTOD_m \quad (4)$$

$$U_2 = \int_{CTOD_0+0.6}^{CTOD_0+3.0} P(CTOD_m) \cdot dCTOD_m \quad (5)$$

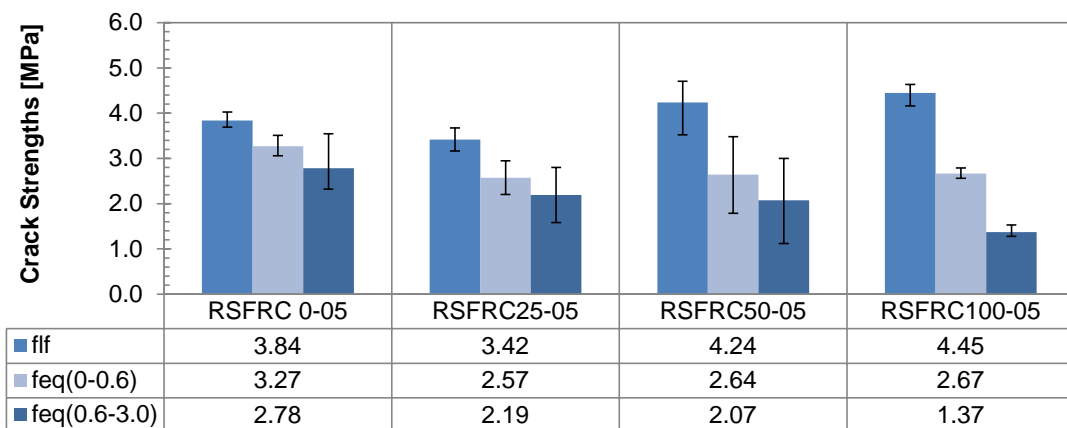


Figure 4 – Comparisons between the first crack strength, f_{lf} , with the equivalent crack resistances, $f_{eq(0-0.6)}$ and $f_{eq(0.6-3.0)}$. The vertical segments represent the range between the minimum and the maximum value.

As a matter of principle, the quantities described by Eqs. (4-5) represent the enclosed area (toughness measure) under the P - $CTOD_m$ curves between the range $[CTOD_{m0}, CTOD_{m0}+0.6 \text{ mm}]$ and $[CTOD_{m0}+0.6, CTOD_0+3.0 \text{ mm}]$ for U_1 and U_2 , respectively. Figure 5 shows such energy absorption values of each sample and calculated by means of Eqs. (4-5). 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 fibers (equivalent to 0.5% in fiber volume fraction), mainly exhibit a softening behavior in the post-cracking regime.

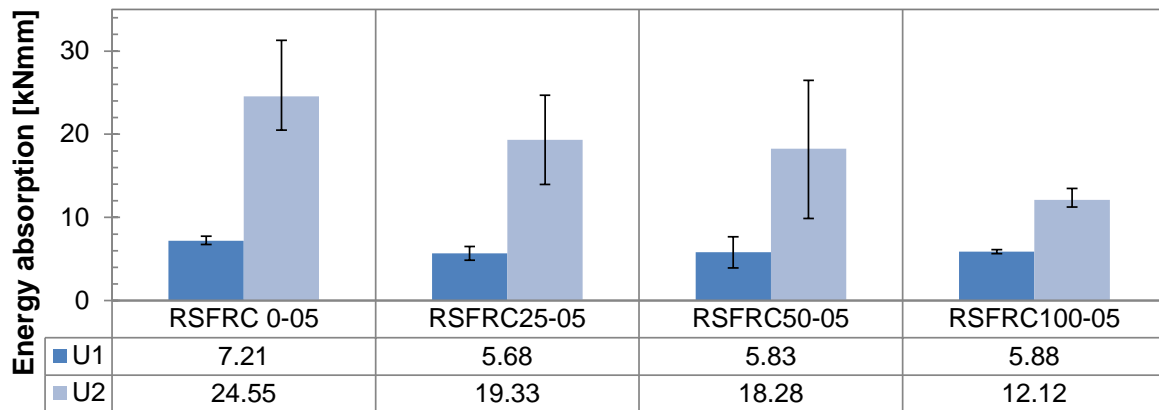


Figure 5 – Energy absorption measures U_1 and U_2 according to UNI-11039-2^[13]. The vertical segments represent the range between the minimum and the maximum value.

Moreover, ductility indices can be considered as further objective “measures” of the fiber bridging mechanisms and the following ductility measures were calculated^[13]

$$D_0 = \frac{f_{eq(0-0.6)}}{f_{ff}} \quad (6)$$

$$D_1 = \frac{f_{eq(0.6-3.0)}}{f_{eq(0-0.6)}} \quad (7)$$

Figure 6 reports the values of ductility indices (defined by Eqs. (6) and (7)) for the various tested beams. According to the classification of the UNI-11039-1^[12], 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^[12] 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, Figure 6 shows that all SFRC mixtures, even the one reinforced with only RSFs, can be considered as a structural fiber reinforced cementitious material.

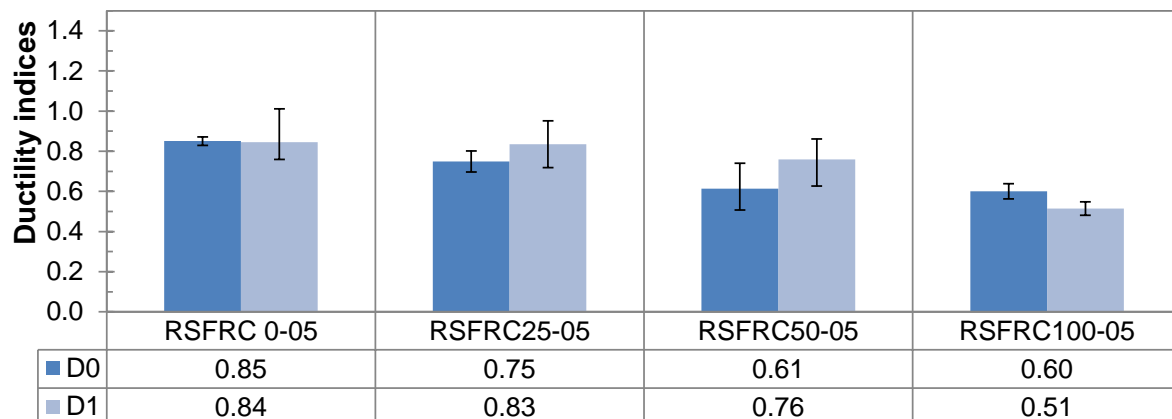


Figure 6 – Indices of the ductility according to UNI-11039-2^[13]. The vertical segments represent the range between the minimum and the maximum value.

CONCLUDING REMARKS

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

- as expected, the observed compressive strength is almost unaffected by the presence of fibers and, then, no significant difference was detected between the FRC specimens with only industrial fibers and the ones made with an increasing proportion of recycled fibers;
- on the contrary, as it was also expected, the bending behavior observed in the experimental tests was significantly influenced by the fiber contribution;
- in this regard, a significant decay in the post-peak cracking behavior was observed as a result of the partial to total replacement of industrial fibers with an equal amount of recycled ones;
- particularly, the higher is the amount of recycled fibers, 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 fibers (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 Fibers derived from waste tires. However, the proposed results clearly demonstrate that industrial fibers 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 fibers 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.

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