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Experimental and numerical characterization of the bond behavior of steel fibers recovered from waste tires embedded in cementitious matrices

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A B S T R A C T

This work investigates the mechanical behavior of recycled steel fibers recovered from waste tires and, then, suitable to produce eco-friendly fiber-reinforced concrete. 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. Moreover, as a case study, a fracture-based plasticity formulation for simulating the overall pull-out behavior of fibers embedded in cementitious matrices is also employed. This formulation is based on assuming a discontinuous response between interface bond stresses and the corresponding relative displacements. Then, an extensive comparison between numerical predictions and the corresponding experimental results of the pullout behavior of recycled steel fibers embedded in concrete is presented for validating and calibrating the model. A satisfactory agreement was observed between the numerical and experimental results: it demonstrates the soundness of the interface formulation.

1. Introduction

The climate change observed in the last decades and its further evolutions expected for the coming ones are the key motivation for a tremendous effort undertaken by the international scientific community to tackle some of the supposed causes of the aforementioned phenomena, such as greenhouse gas emissions and air pollution [1]. Since CO_2 emissions (and, particularly, the whole of greenhouse gases that currently define the so-called CO_{2eq}) were detected as the main reason for the above mentioned phenomena, in the last years several actions were put in place for reducing such emissions. Particularly, in the construction sector, these actions were mainly oriented to either re-using waste materials [2,3] or employing components made with renewable ones [4].

Plenty of studies on Fiber-Reinforced Concrete (FRC) addressed the feasibility of using recycled fibers, deriving from different waste streams, which can in principle play a significant role in enhancing the post-cracking response of members made of FRC [5]. Relevant applications in this field are based on employing some recycled fibers for FRC, such as tire cords/wires [6], carpet fibers [7], waste bottles PET fibers [8], waste paper fibers [9] and natural reinforcements [10].

A large amount of experimental research available in the scientific literature deals with the mechanical characterization of FRC in post-cracking response. The investigation of the mechanical performance and post-cracking response of the most common composite materials, i.e., Steel-FRC [11,12], Polypropylene FRC [13] or Hybrid-FRC [14] had been the subject of several recently issued works. Furthermore, some experimental campaigns on “eco-friendly fiber reinforced concrete composites”, such as those made with either recycled steel fibers obtained from waste tires (RSFRC) [15] or natural fibers (NFRC) [16] are already available in literature.

Several theoretical models are also available and capable of simulating the failure behavior and post-cracking response of FRC at both material and structural levels. The main contributions on theoretical modeling of FRC range from empirical design relationships [17,18] to consider more complex proposals, typically based on the explicit meso-mechanical contributions of fibers on concrete cracks [19,20].

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As a matter of principle, a sound knowledge of fiber–matrix interaction is of key importance for simulating the effect of the embedded fibers on the resulting response of structural members made out of FRC [21]. Several factors, such as fiber length, diameter, geometric details (e.g., smooth fibers, hooked-end, flattened, twisted, etc.) and materials strongly affect the FRC material response [22]. The role of fiber length and its aspect-ratio on the cracking behavior of FRC was recently pointed out by Cunha et al. [23], whereas the pull-out response of inclined fibers was investigated in Laranjeira et al. [24].

In this paper, Section 2 preliminarily describes the key geometric properties of the Recycled Steel Fibers (RSFs) employed in this research and proposes the complete definition of materials and methods. Then, the results of both direct tensile and pull-out tests are presented. Section 3 outlines the fundamental assumptions of the unified formulation for simulating the bond behavior of fibers in cementitious materials. The model was previously published by the first and fourth author in [21] with a validation focused on the debonding response of industrial steel fibers embedded in concrete matrices. However, in that work a unique softening rule was considered. Section 3.2 briefly summarizes the fracture-based model employed in this paper for simulating the inelastic debonding phenomena in RSF anchored in cementitious material. The experimental results, reported in Section 2 and some others available in literature, are then considered in Section 4 to calibrate the bond-slip model and demonstrate its ability. The influence of relevant parameters (such as fiber anchorage and diameter) is also outlined in the same section.

2. Recycled steel fibers from waste tires

A quantity of 15 kg of Recycled Steel Fibers (RSFs), a sample of which is depicted in Fig. 1, was examined to obtain a comprehensive description of both their geometry (proposed in Section 2.1) and mechanical characterization (this latter reported in Section 2.2).

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. This is the main reason why the results of the fiber characterization obtained in the work by Aiello et al. [25] are quite different with respect to the ones obtained in this experimental campaign and discussed in the following.

Fig. 1. Recycled steel fibers employed in FRC.

2.1. Geometric characterization

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 outlined this section.

First of all, fibers were cleaned and separated by some thicker pieces of steel, which were not clearly suited for being used as a spread reinforcement of FRC. Then, a detailed geometric characterization was carried out on a bunch of 2000 RSFs, randomly sampled from the available amount of RSFs. The diameter (d_f) of each single fiber was manually measured by means of a micrometer (Fig. 2): i.e., three measures were taken (i.e., at the two ends and at the fiber mid-point) and an average value was determined for each fiber. According to such measurements, the average fiber diameter was found ranging between 0.11 and 1.64 mm and characterized by a mean value of 0.27 mm. Fig. 3 highlights its apparently multimodal distribution (probably due to the mixing of different types of tires in the recycling process). However, more than one third (35.7%) of the sampled fibers exhibited an average diameter between 0.22 and 0.24 mm.

The geometric characterization of RSFs addressed also the determination of the fiber length l_f which was conventionally defined, according to the CNR-204/2006 specifications [26], as the distance between the outer ends of a fiber. Fig. 4 shows the frequency distribution of measured fiber lengths: in this case a unimodal distribution was observed (probably resulting from the unified cutting underwent during the recycling process). The mean value was of about 12 mm and almost one half of measured fiber lengths (47.1% of the total amount) was found ranging between 9 and 15 mm.

Finally, the aspect (length-to-diameter) ratio of fibers was analyzed, as it represents a key parameter controlling their mechanical performance in FRC. Fig. 5 highlights a unimodal distribution of the aspect ratio, with a mean value of about 47 and more than one half (57%) of fibers exhibited a value within the range 30–60.

2.2. Mechanical characterization

Mechanical characterization tests were carried out on RSF through tensile and pull-out tests carried out at the Laboratory of Materials and Structures (LAME) of the University of Buenos Aires (Argentina).

2.2.1. Direct tensile test

Direct tensile tests were carried out in displacement control by means of an electromechanical dynamometer "Instron Dynamometer 4467". During the tests a proper anchorage within the grips was considered in order to avoid possible failure in this zone.

Fig. 2. Characterization of fibers: diameter measurement by a micrometer.