Construction and Building Materials 147 (2017) 286–295

Contents lists available at ScienceDirect

Construction and Building Materials

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

On the mechanical response of Hybrid Fiber Reinforced Concrete with Recycled and Industrial Steel Fibers

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HIGHLIGHTS

- The paper reports experimental results on FRC with industrial/recycled steel fibers.
- Recycled fibers from waste tires were employed in substitution/addition of the industrial ones.
- Concrete mixtures including different amount of industrial/recycled steel fibers were analyzed.
- The results demonstrate that industrial fibers can be replaced by the recycled ones.
- No significant decay was observed if the recycled fibers present adequate characteristics.

ARTICLE INFO

Article history:
Received 1 February 2017
Received in revised form 14 April 2017
Accepted 17 April 2017

Keywords:
FRC
Waste tires
Recycling
Sustainable concrete
Hybrid industrial-recycled FRC
Post-cracking toughness

ABSTRACT

This paper summarizes the results of an experimental research on "sustainable" cementitious composites internally reinforced with industrial and recycled steel fibers, the latter being recovered from waste tires and employed in substitution and/or addition of the industrial steel ones. Specifically, six concrete mixtures including different amount of industrial/recycled steel fibers were produced and tested both in compression and bending. The obtained results confirm the promising prospects already observed by the authors in a previous study on concrete reinforced with recycled steel fibers obtained from waste tires. Furthermore, they clearly demonstrate that industrial fibers can be replaced by an equal amount of recycled ones without a significant decay in the relevant mechanical properties, provided that the recycled fibers present adequate geometrical characteristics.

1. Introduction

Plenty of researches aim at characterizing the mechanical behavior of cementitious composite with short fibers randomly dispersed throughout the matrix [1]. Relevant applications in this field are based on employing metallic [2], synthetic [3,4], glass [5], natural [6,7] and recycled [8] fibers. More recently, short reinforcing fibers modified with nanotechnologies have been also considered [9]. In principle, fibers can play a significant role in enhancing the post-cracking response and toughness of the so-called Fiber Reinforced Concrete (FRC). From both experimental and theoretical standpoints, several studies have been performed with the aim of investigating the mechanical properties of FRC [10,11]. Nevertheless, for many years the lack of international codes, standards and guidelines for designing FRCs limited their actual use in structural applications. As a matter of fact, in the past, FRC was mainly employed for controlling non-structural aspects, such as cracking control, durability enhancements, etc. Incorporating fibers as reinforcement in partial substitution of classical steel rebars has increasingly been considered in the last two decades, as a result of the publication of many design guidelines and codes [12]. Among various codes and standards, the very recent fib new Model Code [13] represents one of the worldwide reference for the design of FRC.

Moreover, in recent years, a significant research effort focused on the suitability and efficiency of using various recycled materials and industrial by-products as sustainable concrete constituents [14–16]. In this regards, one of the most promising solution from both environmental and technical point of view is to reuse waste

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http://dx.doi.org/10.1016/j.conbuildmat.2017.04.160
0950-0618/

tires whom two main constituents can be potentially obtained from recycling. As a matter of fact, approximately 1.4 billion tons vehicle pneumatics are sold annually in the world and, consequently, many of them can be categorized as "end of life" tires [17]. Therefore, there are strong motivations for investigating solutions capable to reduce the negative environmental impacts of waste tires during their service life (from the acquisition of raw materials through to the recycling processes of the exhausted tire) [18,19]. Specifically, several studies propose a Life Cycle Assessment (LCA) for quantifying the material and energy flows in the different life stages of tires [20,21]. LCA for unutilized scrap tires is commonly used to determine the most cost-effective waste conversion or reusing option [22,23]. From the technical point of view, the internal steel reinforcement of tires can be reused in partial to total replacement of industrial steel fibers commonly use in FRC [24,25], meanwhile, rubber particles can be employed as partial or total replacement of natural aggregates for obtaining a cementitious composite often referred to as "rubberized concrete" [26–28].

In the recent years, several researches focused on the possible employment of Recycled Steel Fibers (RSFs) derived from waste tires for structural concrete production [29–40]. As a matter of principle, these studies demonstrated that the geometrical characterization of the RSFs can be highly variable: they are generally characterized by a nominal diameter ranging between 0.1 and 2 mm with a corresponding average aspect ratio (i.e., length-to-diameter ratio) ranging between 20 and 150. These variations mainly depend on both the original source (i.e., tires typology) and recycling processes. However, based on the results available in the scientific literature [25,31], RSFs and Industrial Steel Fibers (ISFs) exhibited similar mechanical response, both in terms of tensile strength and matrix-to-fiber bond. Consequently, the resulting Recycled FRC post-cracking behavior can be highly influenced by the intrinsic geometrical characteristics of RSFs.

On the other hand, innovative studies on fiber-reinforced cementitious composites addressed the possible combination of different types of fibers (leading to the so-called Hybrid FRC, HyFRC) which can play a synergistic role in enhancing the post-cracking response of structural members [41].

In this context, the present study reports the results of an experimental research carried out at the STRuctural ENGineering Testing Hall (STR.ENG.T.H) of the University of Salerno (Italy), that aims at investigating the post-cracking behavior of concrete reinforced with both industrial and recycled fibers obtained from waste tires (i.e., HyFRCs). First of all, a detailed geometrical characterization of the RSFs is executed. Then, several HyFRC mixtures were produced beyond three reference mixtures: plain concrete and FRCs with 100% of ISFs and RSFs, respectively. On these mixtures, the mechanical characterization of the pre and post cracking behavior of FRC was performed through four-point bending tests [42,43].

One of the main original aspects addressed in this paper is the investigation of the mechanical response of the aforementioned HyFRCs aimed at quantifying the effect of replacing industrial fibers with an equal amount (in weight) of recycled ones. As a matter of fact, in the authors' best knowledge only few experimental studies have been carried out so far on these kinds of FRCs since most of the studies mainly referred to the two "extreme" cases of FRC (i.e, 100% of ISFs or 100% of RSFs) considered in this paper.

2. Materials and methods

2.1. Materials

2.1.1. Recycled steel fibers from waste tires

The RSFs employed in the experimental campaign reported in this work were supplied by an Italian company that collects and recycles exhausted waste tires. Around 20 kg of RSFs were received at the laboratory: they present highly variable diameters and lengths and, moreover, they generally have irregular shapes (Fig. 1).

First, fibers were cleaned and selected by separating some thicker pieces of steel, which were deemed not suitable for being used as spread reinforcement, and rubber particles (Fig. 1). No further cleaning operations were performed as the supplied RSFs did not present oil or other substances that could affect bond with the cementitious matrix. Then, a detailed geometric characterization was performed on a sample of 2000 fibers. Specifically, the geometric characterization was performed by measuring (for each fiber) the following parameters:

- *Fiber diameter (d_f):* expressed in mm and measured by means of a micrometer (Fig. 2); three diameters were measured (at the two ends and in the middle of the fiber) and an average value was determined for each RSF;
- *Fiber length (l_f):* expressed in mm and conventionally defined, in accordance with the CNR-204/2006 specifications [12], as the distance between the outer ends of a fiber;
- *Developed length of the fiber (l_d):* expressed in mm and conventionally defined, in accordance with the CNR-204/2006 specifications [12], as the total ("developed") length of the fiber along its axis;
- *Curvature Index (CI):* representing a shape index aimed at evaluating the curvatures (somehow a tortuosity index) of the fiber. It is expressed in percentage and can be calculated through the following expression:

Fig. 1. Recycled steel fibers derived from waste tires.