Journal of Cleaner Production 158 (2017) 18–28

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Comparison of the mechanical characteristics of engineered and waste steel fiber used as reinforcement for concrete

Jacek Domski [a], Jacek Katzer [a, *], Mateusz Zakrzewski [a], Tomasz Ponikiewski [b]

[a] Faculty of Civil Engineering, Environmental and Geodetic Sciences, Koszalin University of Technology, Koszalin, Poland
[b] Faculty of Civil Engineering, Silesian University of Technology, Gliwice, Poland

ARTICLE INFO

Article history:
Received 14 November 2016
Received in revised form
26 April 2017
Accepted 28 April 2017

Keywords:
Waste
Fibre
Tyre
Concrete
SFRC
Reinforcement

ABSTRACT

Engineered steel fiber has been used for reinforcing concrete since the mid-nineteenth century. The influence of fiber reinforcement on the mechanical characteristics of concrete is commonly known and thoroughly described in literature. The fast growing and vibrant market of engineered steel fiber is increasingly disrupted by waste steel fiber obtained during recycling of tires. The lack of knowledge about properties of the waste steel fiber significantly limits its technically viable use. The main aim of the conducted research program was to test waste steel fiber and to compare its properties with most popular engineered steel fiber. Such properties as tensile strength estimated according to EN ISO 6892-1:2009, ductility tested according to EN 10218-1:1994, and tensile strength after ductility test were considered. Waste steel fiber proved to be characterized by much higher tensile strength and ductility than engineered steel fiber. Stress–strain characteristics of both the types of fiber also differ significantly. Conducted bends influence the tensile strength and modulus of elasticity of all tested waste and engineered steel fiber. The achieved knowledge would allow to create sustainable steel fiber-reinforced concretes in a much more efficient way.

1. Introduction

Fiber-reinforced construction materials have been known since ancient times. In Pharaohs' Egypt mud bricks were reinforced by straw. Romans used a whole range of different fiber of organic origin to modify brittle clay bricks and lime mortars (Maidl, 1995). When modern concrete was born at the beginning of the nineteenth century, its brittleness forced engineers to look for a new type of reinforcement (Nawy, 1996). Steel bars, stirrups, meshes, mats and fibers were the answer to this challenge. Steel fiber-reinforced concrete (SFRC) was one of the very earliest modern structural materials (Havlikova et al., 2015). In the early twentieth century, first engineered fibers for concrete reinforcement were produced in different shapes and sizes. Over the years some geometrical fiber shapes proved to be easy to produce and practical to use (Spinella, 2013). Others did not catch up and were abandoned (Katzer, 2006). Currently, there are dozens of major producers of engineered steel fiber (ESF) located all over the world (Katzer and Domski, 2012). Altogether they offer hundreds of steel fiber types differentiated by geometric shape, size, diameter, and finishing of surface (Naaman, 2003).

The global market of steel fiber is assessed at 300,000 tons of ESF sold per year and is growing very fast with a rate of 20% per year (Pająk and Ponikiewski, 2013). Over 90% of the steel fiber available on the market is ESF with deformed ends, treated surface, twisted, crimped, and hooked (see Fig. 1.) (Mohammadi et al., 2008). In the past 15 years, the ESF market has been increasingly disrupted by waste steel fiber (WSF) obtained during recycling of tires (Ghorpade and Sudarsana Rao, 2010). Worldwide, over one billion of fully exploited tires arise annually (Graeff et al., 2012). So far, majority of these tires have been disposed to landfill (Pilakoutas et al., 2004). Only a small fraction of used tires was reused in the form of energy or materials (Aiello et al., 2009). Over the past 15 years, waste management of exploited tires has become a key concern for many environmental bodies and agencies (especially in the EU where in 2003 the disposal of tires to landfill was prohibited and in 2006 the disposal of tire by-products to landfill was prohibited) (Neocleous et al., 2011). Very demanding European environmental legislation forced European states and tire industry to significantly change waste management of used tires (Achilleos et al., 2011). New facilities dedicated to recycling of exploited

* Corresponding author.
E-mail address: jacek.katzer@yahoo.com (J. Katzer).

http://dx.doi.org/10.1016/j.jclepro.2017.04.165
0959-6526/© 2017 Published by Elsevier Ltd.

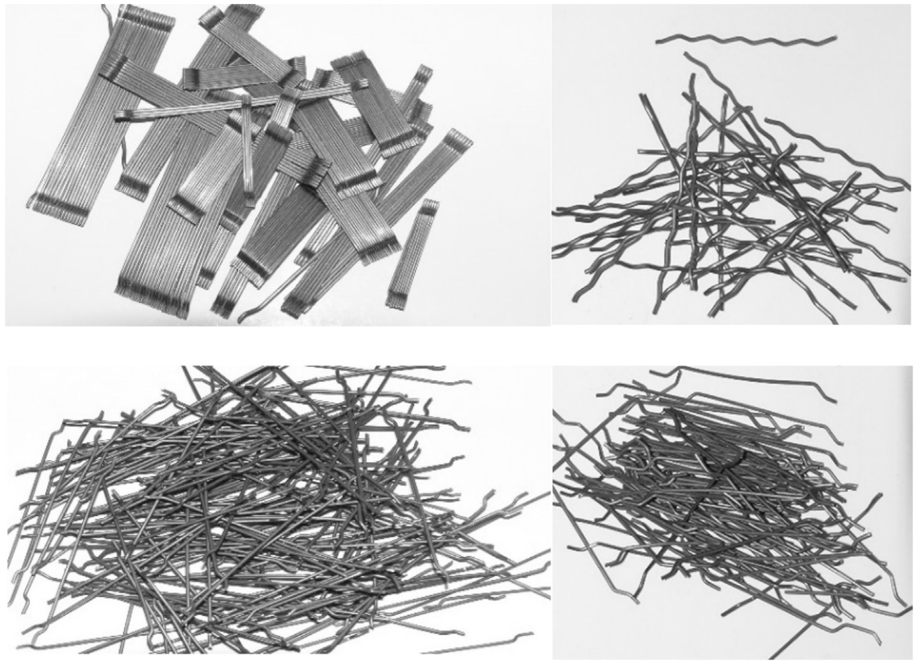

Fig. 1. Examples of geometric shapes of commonly used ESFs.

tires were created all over Europe. Initially, material recovery (rubber and steel) from used tires was done mechanically (Angelakopoulos, 2011). The steel in tires is in the form of belts running longitudinally around the perimeter of the tires. The steel belts are made of thin steel wires with high carbon content, which are woven together into thicker cords. The steel wires have different configurations, but all are brass coated (Baranowski et al., 2016). The cords are then woven again to form larger sheets of braided steel. These sheets are sandwiched between two layers of rubber (Torretta et al., 2015). Most tires contain two or three steel belts. An ordinary light vehicle tire consists of 15% of steel by weight. Average truck tires contain up to 25% of steel by weight (Graeff, 2011). This complex internal structure is difficult to recycle mechanically. Early recycling facilities utilizing mechanical material recovery were "producing" long steel wires tangled together forming a three-dimensional mesh, which could not be used as RFC apart from slurry infiltrated concrete (SIFCON) and roller compacted concrete (Graeff et al., 2012). The fibers were also significantly contaminated by rubber parts, which influenced the overall performance of achieved SFRC. Modern state-of-the-art tire recycling facilities are based on thermal degradation process. During the process, tires are reduced to steel, char, liquids, and gases (Graeff, 2011). The achieved steel fiber is clean (with no rubber contamination), and its availability grows significantly due to new recycling facilities being open all over the world. Assuming the 100% tire recycling rate, there would be more than 500 000 tons of recovered steel fiber in the EU alone (Pilakoutas et al., 2004). This amount of WSF would cover the whole current global consumption of ESF with 50% surplus margin. In a very near future, harnessing all available WSFs will become a major problem. Using WSF as concrete reinforcement is no longer limited by fiber availability or poor quality but by competition with ESF. Full knowledge about the mechanical properties of WSFs is required (Bartolac et al., 2016) to efficiently compete with ESF and eventually fully substitute them on the market. Research programs dealing with WSF and conducted in previous years were mainly focused on the properties of the achieved SFRC. The properties of fiber (both ESF and WSF), apart from some geometrical dimensions, were omitted in this research and theoretical analysis. In authors' opinion, thorough knowledge about fiber properties is essential for achieving high-performance SFRC. The more sophisticated and demanding applications found for SFRC, the more thorough knowledge about fiber properties needed. The bond between steel fiber and concrete matrix is crucial for maintaining specific mechanical properties of SFRC (Graeff et al., 2011). Fiber can be either pulled out from the matrix or destroyed if the bond with the matrix is strong enough. Therefore, fiber's geometrical properties (defining its external surface and hook efficiency) are so important for achieving high mechanical performance of SFRC. Fiber tensile strength and tensile strength after bends influence multiple SFRC properties including dynamic response and fatigue durability. Mechanical and geometrical characteristics of a steel fiber define the overall quality of the achieved SFRC (Katzer and Domski, 2012). Nevertheless, the mechanical characteristics of fiber are underestimated and neglected in ordinary SFRC designing. Keeping in mind all the above facts, the authors decided to conduct a research program focused on the mechanical characteristics of the most popular ESF and WSF. The comparison of these properties would enable efficient and technically viable use of WSF for SFRC production. Modeling and feasible SFRC mix designing are based on these data too. The most efficient utilization of both types of fiber reinforcement would also be enabled. This paper initially presents the ESF and WSF chosen for the study. It is followed by a description of testing methodology and research program. The main results are presented in the form of stress–strain relations after bends. The paper concludes with a discussion.

2. Method section

As representatives of ESF, hooked steel fibers offered by different producers in Europe were chosen. The hooked type of ESF is the most popular on the global civil and structural engineering market (Domski, 2016). This popularity is followed by a vast number of research programs focused on the properties of SFRC