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Development of eco-efficient and cost-effective reinforced self-consolidation concretes with hybrid industrial/recycled steel fibers

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HIGHLIGHTS

- Mechanical properties and impact resistance were examined experimentally.
- Economic aspects and carbon emission studied for recycled/industrial steel fiber combinations.
- A multi-criteria ranking method used to obtain eco-efficient and cost-effective solution.
- Using a recycled fiber content over 1.2% results in the most promising results.

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ABSTRACT

This paper presents the results of an experimental/analytical investigation on the development of eco-efficient and cost-effective self-consolidation concretes reinforced with hybrid steel industrial and recycled fibers. Particularly, eleven mixtures containing different combinations of the hybrid industrial/recycled steel fibers were cast and examined under the compressive, tensile, flexural, and the repeated drop weight impact tests. Then, the mechanical properties were correlated to the resistance to impact actions. The effects of fiber combinations on the cost and the released carbon emission into the atmosphere were studied. Finally, a simplified optimization approach was used to obtain the eco-efficiency and cost-effectiveness of the fiber-reinforced self-consolidation concrete.

The results showed that the greatest impact of replacing industrial steel fibers by recycled steel fibers was observed in the residual flexural strength, in ultimate impact resistance, and in the compactness. Moreover, recycled/industrial steel fiber combinations had the greater impact on increasing the cost than the released carbon emission.

1. Introduction

The use of discrete fibers is one effective solution to reinforce the matrix for improving the tensile and flexural performances of the plain concrete. Among the fibers, steel fiber was one of the earliest and it is one of the most effective materials for improving the mechanical properties and impact resistance of concrete [1]. Over the years, hundreds of types of steel fibers have been used in concrete, distinguished by their shape, length, diameter, and surface area [2,3]. Three hundred thousand tons of steel fibers are sold each year worldwide, and this amount is increasing by 20% per year [4]. Over 90% of the steel fiber available on the market is concerned to the industrial steel fiber with deformed ends, treated surfaces, and twisted, crimped, and hooked [5]. Production this huge amount of steel fiber requires a huge amount of the raw materials and releases extremely large amount of CO_2 into the atmosphere. Due to high cost and negative environmental impacts of production, the use of recycled steel fibers has attracted increased attention in the past fifteen years [6].

Furthermore, over the past fifteen years, scrap tires have become a key concern for many environmental bodies and agencies. The European Union prohibited the disposal of tires and their by-products in landfills in 2003 and 2006, respectively [7]. In 2009, the Rubber Manufacturer's Association estimated that 292 million tires were generated in the United States. However, 42 states have restricted the deposit of end life tires in landfills and only 8 states have no restrictions on placing the scrap tires in landfills. In 2004, the Tire Recovery Association (TRA) members fully agreed to appropriately collect, recycle, and reuse all scrap tires [8]. Now,

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Table 1
Chemical composition and physical properties of ordinary Portland cement and fly ash.

Composition	Ordinary Portland cement (%)	Fly ash (%)
SiO_2	21.10	72.10
Al_2O_3	4.37	24.70
Fe_2O_3	3.88	1.20
MgO	1.56	0.18
K_2O	0.52	0.50
Na_2O	0.39	0.10
CaO	63.33	0.1
TiO_2	–	1.40
SO_3	–	≤0.1
C_3S	51.00	–
C_2S	22.70	–
C_3A	5.10	–
C_4AF	11.90	–
Physical properties		
Specific gravity	3.11	2.30
Specific surface (cm^2/g)	3000	3430
Loss on ignition (%)	1.10	0.90

this program is ongoing in many states in the United States and around 110 million tires are recycled annually. Reusing these recycled tires reduces carbon emissions. Furthermore, it is a part of the reason that the rubber recycling industry generates more than $1.6 billion annual economic activity in the U.S. and accounts for nearly 8000 jobs [9]. Therefore, using recycled steel fibers recovered from tires to reinforce concrete not only reduces construction costs and negative environmental impacts, but also improves mechanical properties of the plain concrete.

Martinelli et al. [10] reported that industrial steel fibers could not be replaced by an equal amount of recycled ones without a significant decay in the relevant mechanical properties. Some innovative solutions were proposed to overcome this deficiency, such as mixing recycled fibers with different industrial fibers to create a hybrid. Using hybrid fibers provides synergistic actions on the resulting pre- and post-crack behavior of fiber-reinforced specimens [10]. The mechanical properties of fiber-reinforced concrete (FRC) containing both industrial and recycled steel fibers have also been examined [10]. It was found that the fibers had a negligible impact on the compressive strength, while the addition of recycled steel fibers led to a significant deterioration in the post-cracking behavior.

Caggiano et al. also investigated the mechanical response of concrete reinforced with hybrid industrial and recycled steel fibers [11]. The compressive strength and flexural strength of the mixtures were measured and compared. This study concluded that industrial fibers could be replaced by an equal amount of recycled ones without a significant decay in the relevant mechanical properties [11].

So far, no extensive experimental and analytical studies have attempted to clarify the effects of using mono-FRC (recycled and industrial steel fibers) and hybrid FRC (steel/recycled steel fibers) on the cost, carbon footprint, and mechanical properties (compressive strength, tensile strength, flexural strength), and impact resistance. To the best knowledge of the authors, only two studies [10,11] have investigated the influences of using hybrid recycled/industrial steel fibers on the compressive and flexural strengths of concrete. However, no experimental, statistical, or optimization studies have compared the hardened properties of reinforced self-consolidation concrete made with mono-FRC (steel and recycled steel) and hybrid FRC (industrial/recycled steel). Therefore, this study will investigate the synergistic actions of hybrid fibers on the resulting pre- and post-crack behavior of fiber-reinforced specimens.

2. Experimental program

2.1. Material properties and mix designs

The mixtures were composed of Portland cement, fly ash, aggregate, water, and polycarboxylate-based superplasticizer (SP). The chemical and physical properties of cement and fly ash are listed in Table 1. Polycarboxylate-based superplasticizer is a water reduction agent. At a relatively low dosage (0.15% of cement weight), it can reduce the water content of concrete by up to 40%. Sand particles (with a minimum diameter of 0.2 mm and a maximum diameter of 4.76 mm) were distributed throughout the mixtures used in this study. According to the ASTM C618 recommendation, fly ash is a class F (low calcium content) ingredient [12]. The content of mixture obtained regarding the minimum slump flow diameter of 600 mm and the compressive strength equal or greater than 50 MPa for the plain self-consolidation concrete [42,43]; the ingredients are shown in Table 2. Different combinations of recycled and industrial steel fibers (mono-fiber and hybrid-fiber) were used to reinforce the mixtures. The total fiber volume percentage and mass in each of the reinforced mixtures was constant and equal to 1.5% (117 kg/m^3). Thirteen different mixtures were tested in this study; their contents and combinations are shown in Table 3. The combinations of recycled/industrial steel fiber outlined in Table 3 were based on the results of previous experiments [10], in which it was found that replacing industrial fibers by an equal amount of recycled steel fibers resulted in a significant decrease in the flexural performance of fiber-reinforced concrete.

The average ratio of length to diameter for the industrial steel fibers was 47. The fibers' average elastic modulus was 200 GPa, and the average tensile strength was 1300 MPa. The lengths and diameters of recycled steel fibers are irregular, so a statistical analysis was used to define the physical properties of the scrap tire fibers used in this study. Several previous studies explain this in more details [10,11,40]. One hundred and fifty-six fibers were used as statistical samples for the analysis of the fibers' physical properties. The fibers used in this study had an average length of over 50 mm (Frequency distribution of the measured fiber lengths was 11% ≤ 15 mm, 15 mm < 26% ≤ 50 mm, 63% ≥ 50 mm) and an average diameter of 0.15 ± 0.05 mm (Frequency distribution of the measured fiber diameters was 2% < 0.1 mm, 0.1 mm ≤ 69% ≤ 0.2 mm, 0.2 mm < 15% ≤ 0.3 mm, 0.3 mm < 14% ≤ 0.45 mm). Fiber length was considered as the average of straight distance between the two ends. A slide caliper was also used to measure the external diameters of fibers.

Fig. 1 represents the morphology (using a scanning electron microscope (SEM) and topography (using an Atomic Force Microscope (AFM)) and of industrial and recycled steel fiber surfaces. Fig. 1a shows surface topography images of industrial steel fibers. The corrugations in industrial fibers have an average height of 35 nm, while the corrugations in recycled steel fibers have an average height of 580 nm

Table 3
Designation of mixtures, dosage and type of the used fibers.

Mixture identification	Industrial steel	Recycled steel
	In vol% (kg/m^3)	
Reference	0.00	0.00
St1.5	1.50 (117.0)	0.00
St1.35Rst0.15	1.35 (105.3)	0.15 (11.7)
St1.2Rst0.3	1.20 (93.6)	0.30 (23.4)
St1.05Rst0.45	1.05 (81.9)	0.45 (35.1)
St0.9Rst0.6	0.90 (70.2)	0.60 (46.8)
St0.75Rst0.75	0.75 (58.5)	0.75 (58.5)
St0.6Rst0.9	0.60 (46.8)	0.90 (70.2)
St0.45Rst1.05	0.45 (35.1)	1.05 (81.9)
St0.3Rst1.2	0.30 (23.4)	1.20 (93.6)
St0.15Rst1.35	0.15 (11.7)	1.35 (105.3)
Rst1.5	0.00	1.50 (117.0)

Table 2
The proportions of mix compositions (kg/m^3).

Cement	Fly ash	Aggregate	Superplasticizer (SP)	Water
457.00	457.00	457.00	2.74	347.00