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Characterization and optimization of hardened properties of self-consolidating concrete incorporating recycled steel, industrial steel, polypropylene and hybrid fibers

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ABSTRACT

This paper presents an experimental/analytical investigation to examine the feasibility of hybrid fibers in self-consolidating concrete containing different fiber types (industrial steel fiber, recycled steel fibers, and Polypropylene fiber), contents (0.5%, 0.75%, 1%, 1.5% in Vol.), and combinations (as single and blended fibers). Fresh and hardened properties of the fiber reinforced self-consolidating concrete were assessed, considering total fiber volume fraction of 1.5%. The fresh state properties were assessed in terms of flow slump diameter and T_{500}. Moreover, the hardened state properties of specimens were characterized by using the ultrasonic pulse velocity, the compressive strength, the splitting tensile strength, the flexural strength, and the impact resistance. Then, a statistical method based two-parameter Weibull and an optimization procedure were executed on the collected experimental results.

The results showed an enhancement of mechanical properties and impact resistance in self-consolidating concrete by the addition of fiber, which was significantly governed by fiber type, content, and combination. Moreover, the optimization procedure revealed that the best performance in terms of maximum mechanical properties and impact resistance, as well as the minimum cost, was achieved in the mixture reinforced with 1.5% recycled steel fiber (Rst1.5) as mono-fiber and the mixture reinforced with 1% industrial steel fiber and 0.5% recycled steel fiber (St1Rst0.5) as hybrid fiber. In addition, the statistical study showed that the two-parameter Weibull could be adopted to analyze the distribution of the first crack (FC) and ultimate crack (UC) impact resistance.

1. Introduction

During the last three decades, the feasibility of using fiber reinforced concrete (FRC) to enhance the structural performance of reinforced concrete (RC) structures has been approved experimentally and numerically. FRC significantly improves load carrying capacity and energy absorption capability as compared to the plain concrete. Various industrial types of fibers such as steel, carbon, glass, polypropylene, nylon, etc. have been used to reinforce the plain concrete. Averagely, a total of 60 million tons of different fibers is used to reinforce plain cement-based composites every year around the world, production of which requires a huge amount of raw materials. Therefore, using recycled fibers from waste sources could be an alternative solution, which decreases negative environmental impacts and construction costs. Various studies have been executed to assess the feasibility of using waste materials obtained from different sources in concrete [1–8]. In this regard, among various recycled fibers, recycled steel fibers (RSFs) indicated a remarkable improvement in mechanical properties and impact resistance of reinforced mix compositions due to re-hardening capacity in tension and bending [9–11]. Particularly, this enhancement is intensified in terms of the post-cracking behavior of reinforced fiber composites [9–11]. RSFs are mainly recovered from waste tyres. In 2009, the Rubber Manufacturer's Association estimated that 292 million tyres were generated in the United States. However, 42 states have restricted tyre landfill and only 8 states have no restrictions on placing scrap tyres in landfills. In 2004, the Tyre Recovery Association (TRA) members fully agreed to appropriately collect, recycle and reuse all tyres [12]. Now, this program is ongoing in many U.S. states and around 110 million tyres are annually recycled. Using this huge amount of recycled tyres creates a substantially smaller carbon footprint and

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helps the rubber recycling industry to generate more than $1.6 billion in economic activity annually in the U.S. and account for nearly 8000 jobs [13]. Thus, using recycled steel fibers recovered from tyres in reinforcing concrete not only reduces both construction cost and negative environmental impacts, but also significantly improves mechanical properties and impact resistance of the plain concrete.

Martinelli et al. in Ref. [11] 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. Thus, some innovative solutions were proposed to overcome this deficiency such as using different industrial fibers as the hybrid. Using hybrid fibers provides a synergistic action on the resulting pre- and post-crack behavior of fiber reinforced specimens [11].

Mechanical properties of fiber concrete reinforced containing both industrial and recycled steel fibers were reported in Ref. [11]. The results revealed that fibers had a negligible impact on increasing or decreasing trend of the compressive strength, while the addition of recycled steel fiber had a significant effect on the deterioration of the post-cracking behavior.

With respect to literature, no extensive experimental, statistical and optimization studies have yet been reported on the effect of using only one type of fibers (steel, recycled steel, polypropylene (PP)) and a blend of fibers (steel/PP, steel/recycled steel, and recycled steel/PP) on the impact resistance and mechanical properties of the fiber reinforced self-consolidating concrete.

To the best knowledge of the authors, one study has been carried out on the impact resistance and mechanical characterizations of the reinforced self-consolidating concrete with hybrid-recycled steel and PP fibers [17]. However, some investigations have been conducted on mechanical properties of normal concrete reinforced with hybrid steel-PP fiber [10,14,15]. Moreover, an investigation was executed on the mechanical behavior of self-consolidating concrete incorporating hybrid short and long steel fibers [16]. Yet, no experimental, statistical, and optimization studies have been observed on the hardened state properties of the reinforced self-consolidating concrete by using single (steel, recycled steel, PP) and blended fibers (steel/PP, steel/recycled steel, and recycled steel/PP). Therefore, this study established to investigate the synergistic action of hybrid fibers on the resulting pre- and post-crack behavior of fiber-reinforced specimens.

2. Experimental program

2.1. Materials and design of mix composition

The ingredients of mix composition used in this study were composed of Ordinary Portland cement (OPC) 42.5R, fly ash, aggregates, water and superplasticizer (SP). Table 1 lists the chemical composition and physical properties of OPC and fly ash. To adjust the workability of mix composition a water reducer was used, which reduce 10–15% water consumption at the small dosage and up to 30% at high dosage. A grain size distribution was obtained for sand grains based on the ASTM D6913 recommendation [18], which sand grains were distributed between the minimum and maximum grain sizes of 0.2 mm and 4.76 mm, respectively. The used fly ash in mix composition was classified in class F regarding the ASTM C618 recommendation [19]. The proportions of mix composition were listed in Table 2, which these proportions were obtained based on the minimum slump flow diameter of 650 mm and the compressive strength equal or greater than 50 MPa for the plain self-consolidating concrete. In this study, various fibers (recycled steel fiber, industrial steel fiber and polypropylene fiber) with different contents and combinations were used to reinforce mixtures with constant fiber volume fraction of 1.5%. Considering different fiber combinations, contents and types, totally thirteen different mix compositions were prepared. Table 3 indicates the designated mix compositions, contents and combinations of fibers.

Regarding the irregular geometry of recycled steel fibers, the lengths and diameters of fibers had great variabilities. Therefore, a statistical analysis was used to define the geometric properties of recycled fibers in this study by using 150 fibers. Concerning this analysis, an average length over 50 mm and the diameter of 0.15 ± 0.05 mm were measured for recycled steel fibers. More details can be obtained in Refs. [9–11,20]. The mechanical properties of industrial steel and polypropylene fibers were listed in Table 4. Moreover, the used fibers in this study are shown in Fig. 1.

In the batching process, the cement, fly ash and aggregates were initially mixed for 1 min in a mixer. Then, superplasticizer (SP) and water were added to the mixture and then, the mix composition was stirred for a further 4 min. Finally, to avoid unfavorable effects of adding fibers like balling, fibers were gradually added to the mix compositions and then mixed for a further 2 min. Afterward, fresh self-

Table 1
Chemical composition and physical properties of OPC and fly ash.

Composition	OPC (%)	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	0.10
TiO2	–	1.40
SO3	–	≤ 0.10
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

Table 2
The proportions of mix composition (kg).

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

Table 3
The nomenclature of mixtures, dosage and type of fibers.

	Dosage and type of fiber (in Vol. %)		
	Industrial steel fiber	Polypropylene fiber	Recycled steel fiber
Reference	0.00	0.00	0.00
St0.5PP1	0.50	1.00	0.00
St1PP0.5	1.00	0.50	0.00
St1.5	1.50	0.00	0.00
PP1.5	0.00	1.50	0.00
St0.75PP0.75	0.75	0.75	0.00
Rst1.5	0.00	0.00	1.50
St0.5Rst1	0.50	0.00	1.00
St0.75Rst0.75	0.75	0.00	0.75
St1Rst0.5	1.00	0.00	0.50
PP0.5Rst1	0.00	0.50	1.00
PP0.75Rst0.75	0.00	0.75	0.75
PP1Rst0.5	0.00	1.00	0.50

Table 4
Mechanical properties of polypropylene and industrial steel fibers.

Fiber name	Length/Diameter (mm/mm)	Young's modulus (GPa)	Tensile strength (MPa)
Industrial steel	47	200	1300
Polypropylene	461	5	600