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Evaluation of High Strength Self-Compacting Cementitious Composite Made with Different Types of Steel Fiber

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ABSTRACT: This paper presents mechanical and impact properties of steel fiber-reinforced self-compacting cementitious composite (SFRSCCC) made with straight and hooked-end fibers. Each of these fibers with the content of 30kg was used for SFRSCCC. The mechanical properties were evaluated by compression, flexural and splitting tensile tests, as well as abrasion resistance test, in accordance with the corresponding standards. Yet, the drop-weight impact loading test was used for determination of impact properties. The experimental results showed that compressive strength of SFRSCCC with straight fibers was slightly higher than that with hooked-end fibers, though both of them achieved high strength class of 60MPa. While, flexural and splitting tensile strength of SFRSCCC with hooked-end fibers were 19% and 17% respectively higher than that of the one with straight fibers. In addition, abrasion resistance of SFRSCCC with straight and hooked-end fibers was almost identical. The slab specimens of SFRSCCC with the fibers only failed after three drops of mass 33kg, this means that these materials are much tougher than the composite without fiber inclusion. Also, the maximum loading capacity of the slab specimens made of SFRSCCC with hooked-end fibers is 14% higher than that of the one with straight fibers.

KEYWORDS: Compression strength; Flexural and splitting tensile strength; Abrasion resistance; Impact resistance; Straight fiber; Hooked-end fiber.

INTRODUCTION

Fibers in cementitious materials can have a very positive influence on the mechanical properties of the composite in its hardened state. It was however shown that addition of fibers decreases the workability of the material. This effect increases with the volume fraction and aspect ratio of the fibers [1-2]. On the other hand, the synergy between self-compacting cementitious composite and fiber-reinforced composite combines the benefits of the former's superior fresh state behavior with the enhanced performance of the latter in the hardened state [2]. In fact, steel fiber reinforced self-compacting cementitious composite (SFRSCCC) can be defined as a material that can flow under its own weight and fill formwork without the need for any type of internal or external vibration. This kind of cementitious composite mix can mitigate two current cementitious composite weaknesses: low workability in fiber reinforced cementitious composites and reduced cracking resistance in plain cementitious composite. The enhanced properties of SFRSCCC enable to step up both the constructive process and the material mechanical properties. By the utilization of SFRSCCC, bleeding and segregation, which may exist due to improper vibration and may reduce the fiber/matrix bond strength, can be avoided [3]. The addition of fibers to a cementitious matrix may contribute to improve the energy absorption and ductility, load transfer capacity, residual load bearing capacity, durability, fire and impact resistance, e.g. [4]. The post-cracking strength is dependent not only on the fiber properties (their tensile and bond strength, stiffness and geometry), but also on their types and distribution within the cementitious composite bulk. The number of effective fibers at the fracture surface influences mostly the tensile residual stress in the post-cracking phase. Moreover, the scatter commonly observed on the residual strength of fiber reinforced composites can be ascribed to the random nature of the fiber dispersion, in particular, to the variation of the fiber density and orientation at the crack surface [5].

As previously stated, the contribution of fibers to bridge stresses across a crack depends not only on the uniformity of the fiber dispersion, but also on their types. Several researchers have observed that fiber types and dispersion are a consequence of a multiplicity of factors, namely fresh-state properties, casting conditions into the formwork, flowability characteristics, vibration and wall-effect introduced by the formwork 0. Among these factors, the most important ones for SFRSCCC are the wall effects introduced by the formwork, the fresh state properties (flowability) of self-compacting cementitious composite (SCCC) and casting process [6]. Previous works have shown that in SCCC there is a preferential fiber alignment according the cementitious composite's flow in the fresh state [7]. Thus, in order to potentiate the high flowability of SCCC, it would be desirable that the cementitious composite flow direction and, therefore, the alignment of fibers should be as close as possible to the directions of the principal tensile stresses, in order to increase the number of effective fibers to face up these stresses when cracks are forming.

In order to deepen the research on the use of steel fiber for construction, in this paper, mechanical and impact properties of SFRSCCC with two types of steel fiber such as straight and hooked-end, as shown in Figure 1, are examined. To perform this study, two SFRSCCC mixes involving with two types of fibers were proportioned. A series of cube, prism and slab specimens were prepared in order to determine compression strength, flexural strength, splitting tensile strength, abrasion resistance and impact resistance of SFRSCCC with those two types of steel fibers at hardened state.

a)

b)

Figure 1. Steel fibers used in this study: a) straight type; b) hooked-end type

MATERIAL AND METHODS

Constituent materials

Portland blended cement PCB40 with commercial band Chinfon, which is conforming to the European cement standard EN 197-1, was used in this study. Physical and mechanical characteristic of cement are given in Table 1. While silica fume with commercial brand Elkem Microsilica® 940 was used as supplementary cementitious material.

Table 1. Physical and mechanical characteristic of cement

Parameters	Units	Test results
Specific density	g/cm^3	3.12
Bulk density	g/cm^3	1.31
Blaine fineness	cm^2/g	3150
Consistency	%	28.2
Initial setting time	min.	102
Final setting time	min.	285
Soundness of cement	Mm	2.1
3 days compressive strength	N/mm^2	30.1
28 days compressive strength	N/mm^2	41.5

River sand and crushed stone were used as fine and coarse aggregates respectively for SFRSCCC mixes. Their characteristic are given in Table 2. Besides, in order to obtain grading of aggregates, sieve analysis was also carried out, hence the results are shown in Table 3.

Two types of steel fibers were considered. The straight type is made of high strength steel, and it is copper-coated to enhance tensile performance, as it can be observed in Figure 1. While the hooked-end type is longer and thicker than the straight, but both of them have the same aspect ratio. Besides, the hooked-end fibers are glued in bundles, as shown in Figure 1b, to avoid fiber-balling during mixing and ensure that the fibers are evenly spread throughout the SFRSCCC mix. The characteristic of steel fibers can be seen in Table 4.

Table 2. Characteristic of coarse and fine aggregates

Parameters	Units	Crushed stone	Sand
Specific density	g/cm^3	2.65	2.61
Bulk density	g/cm^3	1.47	1.53
Water absorption	%	1.1	3.5
Clay, silt and dust content	%	1.4	0,9
Fineness modulus	-	-	2.34

Table 3. Gradation of aggregates by sieve analysis

Sieve size	Crushes stone	River sand
70	0.0	
40	2.5	
20	47.5	
10	81.3	
5	98.0	0.0
2.5		9.2
1.25		20.8
0.63		37.6
0.315		70.2
0.14		95.3
Pan	100	100

Table 4. Characteristic of steel fibers

Steel fiber conforming EN14889-1	Units	Straight type	Hooked-end type
Diameter	mm	0.2	0.55
Length	mm	13	35
Aspect ratio	-	65	65
Tensile strength	MPa	2850	1350

Superplasticizer (SP) is a high-range water reducer admixture, which is a third generation polycarboxylate superplasticizer. Besides, in order to improve segregation resistance and cohesiveness of fresh cementitious composite, viscosity modifying agent (VMA) is also used to produce SCSFRC mix. Water used in this study is tap water.

Table 5. Characteristic of superplasticizer, viscosity modifying agent and water

Parameter	Units	Superplasticizer	Viscosity modifying agent	Water
Specific density	g/cm^3	1,075 ÷1,095	1,05	1
pH value	-	4÷ 6	7÷ 8	7

Mix proportion, specimen preparation and test procedure

In this study, SFRSCCC mix corresponding to strength class of 60MPa at the age of 28 days was designed. The "combined-type SCC" mix design method was considered, apart from the increase of powder content and reduction of coarse aggregate content [8]. Silica fume dosage was 10% of cement content. The water to powder ratio was 0.37, besides the coarse to fine aggregate volume ratio was 1.25. Meanwhile, the content of fibers was specified as a percentage over the bulk volume of cementitious composite, yet the fiber contribution was included into the grading of the solid fraction [9][9]. Steel fiber content was 30 kg per cubic meter. Some "trial-and-error" were involved, the final mix proportion of SFRSCCC is given in Table 6.

The fresh properties of SFRSCCC are provided in Table 7. It can be observed that the slump-flow value, T_{500}, J-ring and V-funnel values of SFRSCCC mix in this study are in agreement with the guideline for SCCC mix [10]. This implies that SFRSCCC mixes were properly proportioned.

Table 6. Mix proportion of SFRSCCC with two types of steel fiber

	Cement	Silica fume	Sand	Stone	Straight fiber	Hook-end fiber	SP	VMA	Water
	kg	Kg	kg	kg	kg	kg	L	L	L
M1	450	45	895	716	30	-	6.5	5.0	185
M2	450	45	895	716	-	30	6.5	5.0	185

Figure 2. Slump-flow test on SFRSCCC mixes with two types of steel fiber at fresh state

Table 7. Fresh properties of SFRSCCC mixes with two types of steel fiber

	Slump value, mm	T_{500}, s	J-ring, mm	V-funnel, s
M1	700	4	9	11
M2	680	3.5	7	9

After a relevant mixing procedure, for each mix, three standard cube specimens (150x150x150 mm^3), three prism specimens (100x100x400 mm^3), and three cylindrical specimens (diameter 150 mm and height 300 mm) were prepared in order to determine compressive strength, flexural strength and splitting tensile strength respectively at the ages of 28 days. Besides, regarding determination of abrasion resistance and impact resistance at hardened state, three cube specimens (70.7x70.7x70.7 mm^3) and slab specimens (600x600x60 mm^3) respectively were cast.

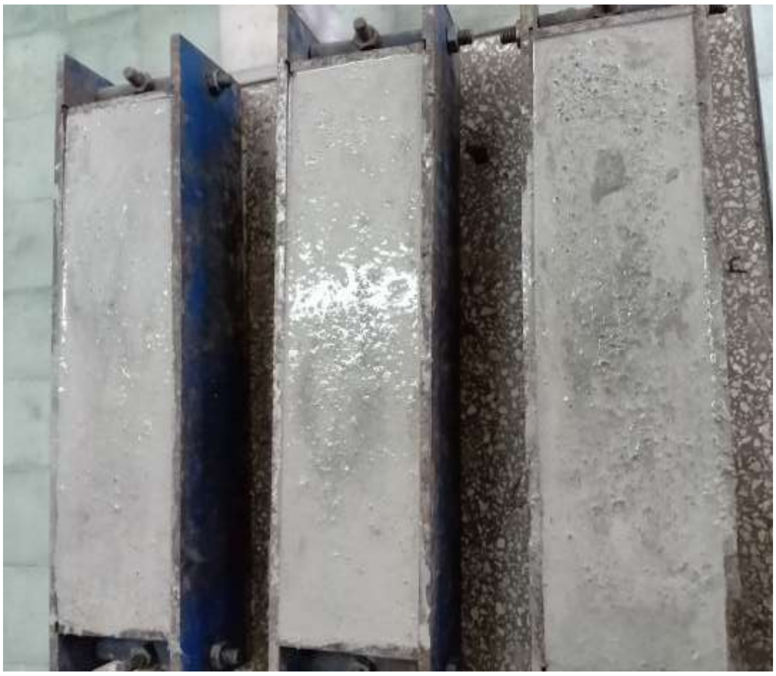

Figure 3. Preparation of prism specimens

Compression test, flexural test and splitting tensile test were carried out in accordance with the corresponding standards. The tests were conducted by using the universal testing machine with a maximum load of 200kN. While, abrasion resistance of SFRSCCC was determined at 28 days according to the ASTM D4060. A dried specimen was held in contact with a cast iron disc with a pressure of 0.6 daN/cm^2. The disc rotates at 30 ± 1 rpm. For each specimen, the disc ran 140 revolutions. During the process, the specimen was progressively rotated through 90^o, and sand with maximum particle size of 2 mm was spread on the disc. The abrasion index (g/mm^2) was calculated by dividing the mass loss of each specimen by its abraded area.

On the other hand, the impact test was performed when the specimens reach the age of 28 days. The instrumented drop-weight impact tower was used for testing. The test procedure is the following one: all slabs are placed onto the steel support in an as-cast direction and are struck at the mid-span of their top face by the weight from the maximum height (1030 mm). Since the bearing guiding rods are almost frictionless, this gave an impact velocity of approximately 4 m/s and strain rate was in the range of 10^0-10^{-2} s^{-1}. During each single drop weight the impact load (P_i) versus time (t) response is the only data recorded.

RESULTS AND DISCUSSION

Mechanical properties

The results of mechanical tests including compression, flexural, splitting tensile and abrasion on SFRSCCC with two types of steel fiber, such as straight and hooked-end, are included in Table 8. The value in this table is an average one of three samples.

Regarding compressive strength, both of SFRSCCC with straight and hooked-end fibers comply with the strength class of 60MPa. The latter one yields a bit lower compressive strength than the former. Since hooked-end fibers are longer and thicker than the straight ones, thus they intervene coarse aggregate, which in turn form cementitious matrix with slightly higher porosity than in case of straight one [5]. Therefore, compressive strength of SFRSCCC with straight fibers is higher than that with hooked-end ones.

In relation to flexural and splitting tensile strength, the tendency is quite clear that SFRSCCC with hooked-end fibers bring moderately higher strength in comparison with that with straight ones. The discrepancy is about 19% and 17% higher in case of flexural and splitting tensile strength respectively. The straight and smooth fibers do not develop sufficient bond with the cementitious matrix; while hooked-end fibers are intended to improve the bond [11]. The latter is able to interlock into the coarse aggregate that intensifies the bridge effect [12]. Hence, the hooked-end fibers help to bring higher flexural and splitting tensile strength in comparison with straight ones.

With respect to the abrasion resistance, both of SFRSCCC with straight and hooked-end fibers produce a quite similar outcome.

Table 8. Mechanical properties of SFRSCCC with two types of steel fiber

Properties	Units	Straight fiber (M1)	Hooked-end fiber (M2)
Compressive strength	MPa	62.5	61.4
Flexural strength	MPa	7.0	8.3
Splitting tensile strength	MPa	4.8	5.6
Abrasion resistance	g/mm^2	14.1	14.2

Impact properties

It has been said that fiber-reinforced composite in general and SFRSCCC in particular has much better properties under impact loading than does the cementitious composite without fibers, in terms of both strength and fracture energy [11]. This can also be observed in this study, the impact properties SFRSCCC with two types of steel fiber are provided in Table 9. In fact, the slab specimens of SFRSCCC with two types of steel fiber only failed after three drops of mass 33kg. While if the slab specimens were made of the composite without fibers, it would be failed abruptly after a single drop due to the brittleness of the matrix [13].

Looking into Table 9, the maximum loading capacity of the slab specimens made of SFRSCCC with hooked-end fibers is 14% higher than that of the one with straight fibers. This mean that although the role of the fibers is, essentially, the control of cracking by bridging across the cracks as they develop in the matrix [12-13], the hooked-end ones are more user-effective than the straight ones in terms of impact loading.

Table 9. Impact properties of SFRSCCC with two types of steel fiber

Properties	Units	Straight fiber (M1)	Hooked-end fiber (M2)
Maximum loading capacity	kN	63.5	72.4
Number of impact up to failure	-	3	3
Drop-weight mass	kg	33	33

CONCLUSION

Mechanical and impact properties of high strength self-compacting cementitious composite made with two types of steel fiber such as straight and hooked-end were studied in this paper.

Compressive strength of SFRSCCC with straight fibers was slightly higher than that with hooked-end ones, even though both of them have reached high strength class of 60MPa. While, flexural and splitting tensile strength of SFRSCCC with hooked-end fibers were 19% and 17% respectively higher than that of the one with straight fibers. Besides, the abrasion resistance of SFRSCCC with straight and hooked-end fibers was practically similar. The slab specimens of SFRSCCC with two types of steel fiber only failed after three drops of mass 33kg, this means that these materials are much tougher than the cementitious composite without fiber inclusion. Yet, the maximum loading capacity of the slab specimens made of SFRSCCC with hooked-end fibers was 14% higher than that of the one with straight fibers. For the future research, the outcome would be more appealing if mechanical and impact behavior of these materials served for the main objective.

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