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Effects of different deformed steel-fibers on preparation and fundamental properties of self-compacting SFRC

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HIGHLIGHTS

- Effects of four deformed steel fibers are investigated for self-compacting SFRC.
- The fiber length mainly impacts the passing ability and dynamic stability.
- Evaluation method of static segregation resistance of steel fibers is presented.
- Predictive models of axial compressive and tensile strengths are proposed.

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ABSTRACT

Effects of different deformed steel fibers on the preparation and fundamental properties of self-compacting SFRC were experimentally studied. Four types and three volume fractions of steel fiber were considered as the influence parameters. Evaluation method of static segregation resistance of steel fibers is presented using the distribution uniformity of steel fibers in matrix. Several suggestions are proposed to improve the test methods for characterizing workability and to evaluate the efficiency of steel fiber in enhancing strengths of self-compacting SFRC. The predictive models for axial compressive and splitting tensile strengths are proposed in relation with the effective distribution of steel fiber.

1. Introduction

Self-compacting SFRC has attracted widespread attention due to the benefits of self-compacting behavior in construction process, and the hardened peculiarities of more ductile and higher residual tensile strength comparing with vibratory compacting concrete (VCC). It has been applied in construction of various components and structures of civil engineering, such as slabs on grade [1] and overlay [2], precast beams [3,4], and tunnel segment [5].

Commonly, the workability of self-compacting concrete is mainly investigated under three aspects as filling ability, passing ability and segregation resistance. An ideal mix proportion of self-compacting SFRC should has a balanced filling ability and segregation resistance in fresh state [6], and a suitable mechanical behavior in hardened state. Investigations [7–9] exhibited that except the influences of matrix materials such as the type and content of binders, and the type, particle size and content of aggregates, the physical properties of geometry and surface morphology, volume fraction and tensile strength of steel fibers have essential influences on the preparation and fundamental mechanical properties of self-compacting SFRC.

The elongated shape and large surface area of steel fibers increased the difficulty of self-compacting performance [9,10]. When the mix proportion of matrix was constant, the plastic viscosity and yield stress of fresh self-compacting SFRC increased with the fiber factor λ_f, i.e. the product of the volume fraction (ρ_f) and the aspect ratio (l_f/d_f) of steel fiber [11,12]. However, the increase in fiber factor will decrease slump-flow, increase flow time and decrease passing ability of self-compacting SFRC [13-15]. Due to the different influence of fiber types, there was no

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unique relationship between λ_f of steel fiber and plastic viscosity or yield stress of fresh self-compacting SFRC [16].

There were debatable results of the influence of steel fiber on fundamental mechanical properties for hardened self-compacting SFRC. Chen [17] reported that adding hook-end steel fiber of RC-65/35-BN in 1.0% volume fraction into the self-compacting SFRC with water to binder ratio $w/b = 0.3$, the cubic compressive strength and the axial compressive strength increased 33% and 34% in average, respectively. Zhao et al. [14] discovered that the cubic compressive strength slightly increased with ρ_f ranged from 0 to 0.6% for the self-compacting SFRC with $w/b = 0.37$, 0.33 and 0.31. Akcay et al. [15] added three different types of steel fibers with and/or without hook-ends into self-compacting concrete, $w/b = 0.19$, to evaluate the enhancement of hybrid steel fibers on the mechanical performance. The results showed that type and tensile strength of steel fibers had no obvious influence on the axial compressive strength, the splitting tensile strength and the modulus of elasticity, but high-strength, long steel fiber with hooked-ends had more enhancement on the toughness and ductility. Ghanbarpour [18] added micro wire and crimped steel fibers into self-compacting concrete of $w/b = 0.4$ with the ρ_f = 0.5%, 0.75% and 1.0% respectively. Compared to those of VCC calculated by the formulas specified in ACI 318, the self-compacting SFRC had a similar growth rate between cubic compressive strengths at curing ages of 7 days and 28 days, a higher ratio of modulus of elasticity to cubic compressive strength and a lower ratio of splitting tensile strength to cubic compressive strength. Irki [10] added crimped steel fibers with three different length into self-compacting concrete, w/b = 0.4, with ρ_f ranged from 0.3% to 1.2%. The results showed that fiber length had sensible influence on the fundamental mechanical properties of self-compacting SFRC, the cubic compressive strength had a higher decrease rate while the modulus of elasticity had a higher increase rate with the increasing fiber length.

At present, most of literatures have detailed discussed properties of self-compacting SFRC with single type of steel fiber. Few study [18] focused on the effects of variable shapes and quantities of steel fibers on the properties of self-compacting SFRC. In this paper, seven series of self-compacting SFRC with different types of steel fiber were prepared and systematic studied. The static segregation of steel fibers in fresh self-compacting SFRC and the effect of different types of steel fibers on the fundamental properties are analyzed combining with the fiber distribution observed. Predictive models of the axial compressive strength and the splitting tensile strength of self-compacting SFRC are proposed in relation with the effective distribution of steel fiber.

2. Materials and methods

2.1. Raw materials

Binder materials: the ordinary Portland cement, class II fly ash and ground granulated blast furnace slag (GGBS) of S95 were used in this test. The basic properties of cement are listed in Table 1. The densities of fly ash and GGBS are 2349 kg/m^3 and 2941 kg/m^3, respectively. All the properties of binder materials met the requirements of Chinese codes GB 175 [19] and GB/T51003 [20].

Aggregates: natural sand (0–5 mm) and crushed limestone with maximum particle sizes (MPS) of 20 mm were used as fine aggregate and coarse aggregate, respectively. The physical and mechanical properties, which were tested in accordance with the specification of Chinese code JGJ 52 [21], are listed in Table 2.

Table 1
Physical and mechanical properties of cement.

Fineness (%,45 μm)	Density (kg/m^3)	Setting time (min)		Compressive strength (MPa)		Flexural strength (MPa)	
		initial	final	3d	28d	3d	28d
8.6	3195	176	222	34.9	57.8	6.23	8.83

Table 2
Physical properties of aggregates.

Physical properties		Natural sand (0–5 mm)	Crushed stone (5–20 mm)
Apparent density (kg/m^3)		2693	2713
Bulk density (kg/m^3)	Loose	1495	1543
	Close	1625	1647
Crushed index (%)		–	9.0
Mud content (%, by mass)		1.5	0.3
Content of needle-pieces (%)		–	6.0
Fineness module		1.9	–

Steel fiber: as shown in Fig. 1, four different types of deformed steel fiber were used, the basic properties are listed in Table 3. Where l_f and d_f are the length and equivalent diameter of steel fiber, l_f/d_f is the aspect ratio of steel fiber, C is the cross-sectional circumference of steel fiber, N is the amount of steel fibers per kilogram, E is the elastic modulus of steel fiber [22].

Others: tap water was used. PCA-I Polycarboxylate superplasticizer with the water-reducing ratio up to 30% and the solid content of 35%, and air-entraining agent with solid content of 1% were used. Both of them were produced by Jiangsu Sobute New Materials Co. Ltd. in China.

2.2. Mix proportions of self-compacting SFRC

Seven series of self-compacting SFRC were designed on the basis of the absolute volume method of SFRC [22]. Four types of deformed steel fibers identified in Table 3 with volume fraction ρ_f=1.0% and CF also with volume fraction ρ_f = 0.5% and 1.5% were added to the concrete mixture, respectively. Considering the influence of steel fiber on the workability of fresh concrete [11] and the relationship between sand ratio and optimal volume fraction of steel fiber [23], the sand ratio increased about 4% with every 0.5% increment of ρ_f, the dosage of water increased from 180 kg/m^3 to 187 kg/m^3 with ρ_f ranged from 0 to 1.5%. The detailed mix proportion are listed in Table 4. Where C0 is a reference trial of self-compacting concrete without steel fiber, which is a common mixture proportion that easy to achieve the self-compacting performance with normal chemical admixture [14,17]. The identifiers of mixtures CF, IF, HF, LF correspond to the type of steel fiber, the digit followed-by represents different volume fractions of steel fiber.

2.3. Tests design and methods

The workability of fresh self-compacting concrete was evaluated in accordance with the specifications of Chinese Standard JGJ/T 283-2012 [24] and ASTM C1611/C1611M-2009a [25]. The slump-flow and slump-flow time T_{500} (termed as T_{50} in ASTM C1611/C1611M-2009a) were measured by using the slump cone to evaluate the filling ability (Fig. 2(a)), the difference between slump-flow diameters with and without J-ring were measured to evaluate the passing ability (Fig. 2(b)). Similar to GTM method