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Review

Flexural behavior of self-compacting concrete reinforced with different types of steel fibers

M. Pająk [a,*], T. Ponikiewski [b]

[a] The Silesian University of Technology, Faculty of Civil Engineering, Department of Structural Engineering, Akademicka 5, 44-100 Gliwice, Poland
[b] The Silesian University of Technology, Faculty of Civil Engineering, Department of Building Materials and Processes Engineering , Akademicka 5, 44-100 Gliwice, Poland

HIGHLIGHTS

- The load-deflection curve depends on properties of fibers in SFR-SCC as for SFRC.
- The flexural tensile strength of SFR-SCC can be predicted as for SFRC.
- The relationship between the post-peak parameters of SFR-SCC was analyzed.
- The equation to predict deflection-CMOD relationship for SFR-SCC was proposed.
- The G_F of SFR-SCC was investigated and the formula to describe it was presented.

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ABSTRACT

The aim of the present work is to investigate the flexural behavior of self-compacting concrete reinforced with straight and hooked end steel fibers at levels of 0.5%, 1.0% and 1.5% and compare it to normally vibrated concrete (NVC). The laboratory tests were determined according to RILEM TC 162-TDF recommendation. The flexural behavior of SCC appeared to be comparable to NCV, where the increase of fibers volume ratio cause the increase in prepeak and post-peak parameters of SCC. Nevertheless, the type of steel fibers influences much this dependency. Based on the performed analysis, the flexural tensile strength of SFR-SCC can be described with the formulas used for SFRC. The equation proposed to predict the deflection-CMOD relationship of SCC fits into the coefficient of variation of the formula for NVC. However, the SCC achieves the maximum crack mouth displacement for lower deflections than NVC. The article contains also the analysis of the fracture energy of SCC with a formula to describe it.

Contents

* Corresponding author. Tel./fax: +48 32 237 22 88.
E-mail address: malgorzata.pajak@polsl.pl (M. Pająk).

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1. Introduction

Self-compacting concrete (SCC) was defined by Okamura [1] as concrete that is able to flow in the interior of the formwork, filling it in a natural manner and passing through the reinforcing bars and other obstacles, flowing and consolidating under the action of its own weight. These properties enable the SCC to be an excellent material for constructions with complicated shapes and congested reinforcement. One of the main advantages in using SCC is the minimization of skilled labor needed for placing and finishing the concrete. All these benefits decrease the costs and reduce the time of the building process over constructions made from traditionally vibrated concrete [2]. However, hardened self-compacting concrete is still as brittle as normal concrete and has a poor resistance to crack growth. To improve the post-peak parameters of SCC the steel fibers are added.

As generally known, steel fibers continue to carry stresses after matrix failure. The addition of steel fibers does not change considerably the compressive strength and the modulus of elasticity of concrete but has noteworthy effects on the residual tensile strength and flexural strength . Therefore, in case of SFRC analyzing the post-peak behavior of tested specimens is crucial [3–7]. The main recommendations to analyze post-peak bending behavior of steel fiber reinforced concrete are: JSCE method [8], RILEM TC 162-TDF recommendation [9] and based on it EN 14651 [10], and (withdrawn in 2006) ASTM C1018 [11]. The detailed information about the post-peak behavior of SFRC can be found in [4].

The mechanical properties and post-peak behavior of FRC depend mainly on the characteristics of the concrete matrix but also on the type, geometry, content and orientation of fibers [12–14]. However, effective work in concrete matrix is only one factor that has the influence on the efficiency of the currently produced fibers. Efficiency is also based on the simplicity of its production which in turn has a significant influence on its price. The five most popular types of steel fibers are: traditional straight, hooked, crimped, with deformed ends (coned, with end paddles or end buttons) and with deformed wire (indented, etched or with roughened surface) [15]. A statistical analysis of the assortment offered by the largest fiber producers allows to claim that around 67% of sold fiber consist of the hooked type. Other most popular fiber types are: straight fiber (around 9%), fiber with deformed wire (around 9%) and crimped fiber (around 8%) [16]. Aspect ratio of all steel fiber types offered by main producers are from 20.4 to 152. Fifty percent of the population of all types offered by producers has aspect ratio from 45 to 63.5 [15].

The aim of this article is to investigate the tensile behavior of SCC reinforced with two different types of steel fibers and compare it to traditionally vibrated concrete. It is widely recognized that the determination of tensile strength in the test in direct tensile is troublesome. Thus, the authors choose the bending tests on notched beams according to [9,10], which is the best candidate to be a standard test method for analyzing the FRC [17]. Among the most popular types of fibers authors choose two types with the comparable aspect ratio but different shape: hooked end and straight. The articles usually deal with the fibers with aspect ratio higher than 40. Authors choose steel fibers with smaller aspect ratio, because that kind of reinforcement is not widely investigated.

2. Experimental program

2.1. Materials and mix design

The studies were performed on the self-compacting concrete reinforced with two types of steel fibers (SFR-SCC). The experimental investigation of SFR-SCC, conducted by authors, allows to properly adjust the ingredients of the mix in order to obtain the required workability and stability.

The composition of the mix, where the proportions of the ingredients of the matrix are maintained and only the fiber content changes, is presented in Table 1. The concretes were prepared using water/cement ratios of all tested mixes equal 0.42. To obtain comparable rheological and mechanical parameters of SFR-SCC, the cement containing 25% of silica fly ash was employed. The use of mixed cement eliminates the effect of different composition of Supplementary Cementing Materials (SCM) which causes variation of physical and chemical parameters of SFR-SCC. The authors applied high content of the cement (490 kg/m^3), which is widely investigated by other researchers [18,19]. The physical and chemical properties of cement CEM II/B-V 32.5R, are presented in Table 2. The aggregate used in the mix was: natural sand and coarse aggregate, with a maximum size of respectively: 2 mm and 8 mm. The Glenium SKY 592 Superplasicizer and Stabilizer RheoMATRIX were applied in the mix in the amount of respectively: 3.5%, 0.4% of the mass of cement.

The authors used mix proportioning system proposed by Okamura and Ozawa [20] which assumes general supply from ready-mixed concrete plants. The coarse and fine aggregate contents are fixed so that self-compatibility is achieved easily by adjusting only the water-powder ratio and superplasticizer dosage [21]. The detailed mixing procedure and mixing time is illustrated in Fig. 1.

The investigations were carried out on straight and two times bigger hooked steel fibers. The geometry and parameters of steel fibers are presented in Table 3. Three different volume fractions of steel fibers were developed to cover the majority of practically used fractions range: 0.5%, 1.0%, 1.5%, which is the dosage of respectively: 40, 80, 120 kg/m^3.

2.2. Tests

The bending tests were carried out on 550 mm beams with 150 × 150 mm cross section. The span of the beams was 500 mm. The bottom side of each specimen was notched with 25 mm depth using 2 mm diamond saw.

Table 1
Composition of SFR-SCC mix.

Cement CEM II/B-V 32,5R (kg/m^3)	Sand (0–2 mm) (kg/m^3)	Fine aggregate (2–8 mm) (kg/m^3)	Water (l/m^3)	Steel fibers (kg/m^3) (% by volume)	Superplasicizer (kg/m^3)	Stabilizer (kg/m^3)	W/C
C	S	FA	W	F	SP	ST	–
490	808	808	201	40; 80; 120 (0.5; 1.0; 1.5)	17	2	0.42

Table 2
Chemical and physical properties of cement CEM II/B-V 32, 5R.

Chemical properties										Physical properties						
Cement composition (%)									Cement specific surface (m^2/kg)	Fineness (cm^2/g)	Specific gravity	Setting (h: min)		Compressive strength (MPa) after days		
SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O	SO_3	K_2O	Cl^-				Initial set	Final set	2	7	28
26.4	47.9	10.8	3.7	1.6	0.43	2.2	1.42	0.007	370	3300	3.15	04:15	06:00	13 ± 2	28 ± 2	38 ± 3