THE LABORATORY INVESTIGATION ON THE INFLUENCE OF THE POLYPROPYLENE FIBRES ON SELECTED MECHANICAL PROPERTIES OF HARDENED SELF-COMPACTING CONCRETE

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Abstract

The laboratory investigation presented in the paper focuses on the influence of the polypropylene fibres on compressive and flexural strength of self-compacting concrete. The paper deals with two volume ratios 0.3% and 0.9% of 19 mm and 38 mm long PP fibres. On the basis of the tests performed, the addition of PP fibres has a minor effect on compressive strength of SCC and pronounced when analysing the flexural tensile strength of the matrix. In case of 19 mm long fibres the increase of post-peak parameters was considerable, however, not proportional to the fibres volume ratio. The 38 mm long PP fibres applied as a SCC reinforcement needs further investigations, as for a smaller amount of the fibres it doesn't meet the requirements for the composites.

Streszczenie

W pracy przeanalizowano wpływ włókien polipropylenowych na wytrzymałość na ściskanie i właściwości przy zginaniu betonu samozagęszczalnego. Badania laboratoryjne dotyczyły betonu SCC zbrojonego polipropylenowymi włóknami o długościach 19 mm i 38 mm przy ich udziale objętościowym wynoszącym 0.3% i 0.9%. Na podstawie przeprowadzonych badań stwierdzono, że zastosowane włókna mają niewielki wpływ na wytrzymałość SCC na ściskanie, a znaczący przy analizie wytrzymałości na rozciągnie przy zginaniu. Wyniki badań zginania betonu SCC zbrojonego włóknami o długości 19 mm wykazały wzrost parametrów w zakresie po-sprężystej pracy SCC. Uzyskane wyniki, nie były jednak proporcjonalne do przyrostu zawartości objętościowej włókien. Beton samozagęszczalny zbrojony dłuższymi włóknami (38 mm) wymaga dalszych badań, gdyż w przypadku zastosowania mniejszej zawartości objętościowej włókien nie zostały spełnione wymagania stawiane kompozytom w zakresie pracy po-sprężystej.

Keywords: **Compressive strength; Flexural tensile strength; Polypropylene fibres; Self-compacting concrete.**

1. INTRODUCTION

The self-compacting concrete (SCC) is a new type of a cement-based material that is able to fill under its own weight without segregation or bleeding the formwork with even very sophisticated shape and congested reinforcement. However, the SCC has a brittle nature, like all other cement-based materials, and to improve its mechanical parameters, ductility and energy absorbing capacity under impact the randomly distributed short fibres are added. Among the variety of the fibres types (metal, organic, inorganic), the organic ones starts to be commonly used. Polypropylene fibres (PP), next to polyethylene, polyolefin, acrylic and polyvinyl alcohol organic fibres are eagerly used because of low cost and qualities. Taking into account its low Young's modulus polypropylene fibres are mainly used to resist plastic and drying shrinkage at early age of concrete [1]. Considering the hardened concrete it is also applied for the concrete structures subjected to fire as it reduces the amount of spalling [2]. The current study deals with the influence of this addition of the PP fibres on the basic mechanical parameters of hardened cement-based materials, what is believed to be insignificant.

Based on the latest investigations, incorporating the PP fibres as a concrete reinforcement, it may increase the compressive strength [3,4] or rather decrease it [5]. *Alavi Nia et al*. [3], who tested concrete with the 0.2÷0.5 percentage of 48 mm long PP fibres reported the increase of fc from 1% to 12% depending on concrete strength and fibres volume ratio. Further, *Behfarnia et al*. [4] also exhibit increment of compressive strength (about 3%) for short 19 mm long fibres, which were examined in volume ratios from the range of 0.4÷0.8%. The slight decrease equal maximally 3% and occasional increase reaching 2% of f_c was showed in [5]. The investigations were performed with the use of 19mm long PP fibres for much smaller, than in case of works [3,4], fibres volume ratio (0.05÷0.2%) and taking into account mixes containing fly ash.

The flexural tensile strength of concrete was increased by the addition of polypropylene fibres in papers [4,6,7] and surprisingly in some works it was also decreased [8]. *Behfarnia et al*. [4] and *Hsie et al*. [7] investigated fibres with a length equal 48 mm and 60 mm, respectively. The applied dosages rates were high and varied from 0.33% to 1% in [7] and 0.4% to 0.8% in [4]. The enhancement of flexural tensile strength was proportional to the increment in the amount of fibres. For the highest investigated in [4,7] fibres volume ratio the flexural tensile strength was 20% higher than the f_{ts} of the matrix. The three volume fractions 0.05%, 0.1% and 0.15% of shorter (19 mm) PP fibres were tested by Sun et al. [6]. The 14 percent increase in f_{ts} was achieved, but not for the highest dosages of fibres but for the amount equal 0.1%. Further, *Alhozaimy et al*. [8], in the range of much lower fibres volume ratio (0.05%÷0.25%) of the longest fibres (75mm) noted the decrease or very slight increase of f_{ts}.

The submitted test results indicate the need of the further investigation on the mechanical properties of cement-based materials reinforced with different kinds and dosages of PP fibres. The current paper deals with the self-compacting concrete reinforced with two types of polypropylene fibres (PP).

2. EXPERIMENTAL INVESTIGATIONS

2.1. Materials, mix design and specimen preparation

The materials applied to create the self-compacting concrete was: CEM I Portland Cement 42.5R, natural sand (0-2 mm), coarse aggregate (2-8 mm and 8-16 mm), tap water, silica fume (10% of the mass of cement), superplasticizer, stabilizer and polypropylene fibres (Table 1). The mix was enriched by an addition of silica fume as a micro-filler, which influences its viscosity in the fresh state. The physical and chemical parameters of silica fume, are presented in the Table 2. The used silica fume was characterized by specific surface equal to 18000 m^2/kg and SiO_2 content equal to 92.8%. The Glenium SKY 592 Superplasticizer and Stabilizer RheoMATRIX 100 were applied in the mix in the amount of respectively: 3.5%, 0.3% of the mass of cement. The superplasticizer was based on polycarboxylate ether (concentration 20%) and characterized by density of 1.07 g/cm^3. The density of the stabilizer was equal to 1.01 g/cm^3.

Two types of polypropylene fibres were studied in the current paper: 19 mm and 38 mm long (Table 3). The applied volume ratios of fibres were equal 0.3% and 0.9%, which is the dosage of respectively: 2.7, 8.1 kg/m^3. The experimental program and the assignations of the mixes according to the fibre used are presented in the Table 4.

The self-compacting concrete was prepared according to the methodology presented by *Szwabowski et al*. [9]. All mixes were prepared in an ordinary rotary drum mixer using oven dry aggregate. Initially aggregates and cement (after 1 min) were added to the mixer. Mixing of dry components lasted 2 min, and then the first part of water with fibres were added. The second stage of mixing lasted 1 min followed by adding the second part of water with superplasticizer. The third stage of mixing lasted 2 min followed by adding the third part of water with stabilizer. The last stage of mixing process lasted 2 min (Fig. 1).

2.2. Tests

The compressive tests have been carried out with a constant strain rate in 3000kN hydraulic compression testing machine according to PN-EN 12390-3 [10]. The program involved testing of four 28-day cube specimens (150x150x150 mm) from each mix.

The four-point bending tests have been carried out on 100x100x400 mm beams according to ASTM C1609 [11]. The beam span used in the tests was

Table 1.
Composition of SFR-SCC mix

Cement CEM I 42.5R (kg/m^3)	Natural sand (0-2 mm) (kg/m^3)	Coarse aggregate (2-8 mm) / (8-16 mm) (kg/m^3)	Water (kg/m^3)	Polypropylene fibres (%) by volume	Superplasticizer (kg/m^3)	Stabilizer (kg/m^3)	Silica fume (kg/m^3)	*W/C*
C	S	CA	W	F	SP	ST	SF	-
485	749	468/468	203	0.3-0.9	17	1.6	48.7	0.42
Specific gravity, kg/dm^3								
3.14	1.65	1.88	1.00	0.91	1.07	1.08	2.21	-

Table 2.
Chemical and physical properties of silica fume

Chemical composition,%									Specific surface, m^2/kg
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	
92.8	0.60	0.30	0.70	1.32	0.76	0.30	0.50	1.90	18 000

Table 3.
Properties of polypropylene fibres

		
Designation	PP19	PP38
Length [mm]	19	38
Tensile strength [MPa]	570÷660	570÷660
Density [kg/m^3]	910	910
Acid/Alkali Resistance	Excellent	
Absorption	No	

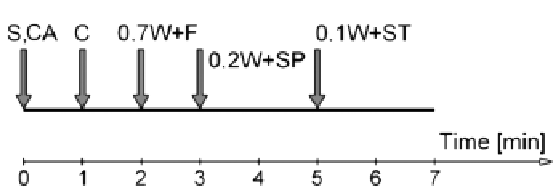

Figure 1.
Mixing procedure for polypropylene fibres reinforced concrete

equal 300 mm (Fig. 2). The tests were performed with a rate of mid-span deflection equal 0.2 mm/min, until the mid-span deflection reached 2 mm. To avoid either the settlement or twisting of the specimen in overall deflection the steel frame was used to support the pair of the LVDT.

Table 4.
Test program

Mix	V_f of PP fibres [%] (kg/m^3)	
	l=19 mm	l=38 mm
0	-	-
0.3PP19	0.3 (2.7)	-
0.9PP19	0.9 (8.1)	-
0.3PP38	-	0.3 (2.7)
0.9PP38	-	0.9 (8.1)

3. TEST RESULTS AND DISCUSSION

The laboratory investigation has been carried out on self-compacting concrete (SCC) specimens reinforced with two types (19 mm, 38 mm) and two volume ratios (0.3%, 0.9%) of polypropylene fibres according to the test program presented in the Table 4.

3.1. Test results of fresh PFR-SCC

In order to characterize the flow and workability properties of polypropylene fibres reinforced self-compacting concrete (PFR-SCC), the traditional slump-flow test was performed according to RILEM TC 145-WSM [12] (Table 5). Both methods used in the research program for workability/consistency tests of fibre reinforced SCC proved to be viable, feasible and reliable. There is no doubt that the slump flow test is the simplest and most widely used. The straight forward correlation: the higher the slump flow value, the greater its ability to fill formwork under its own weight, makes it very easy to use and

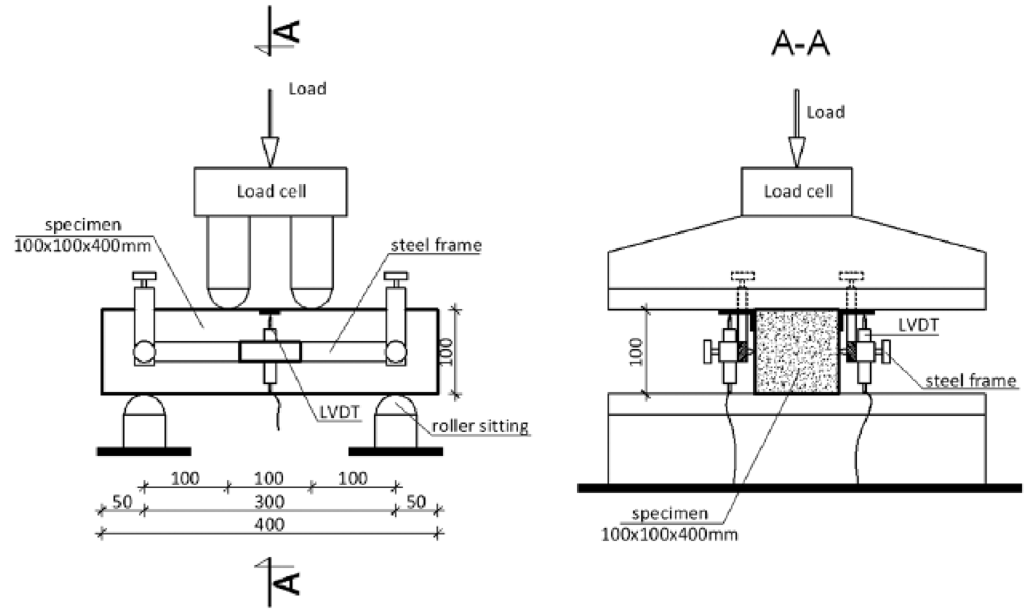

Figure 2.
Testing setup for flexural tests

interpret the results. The last mix composition allowed to add the highest volumes of PP38 fibres with almost self-compacting concrete pat diameter still reaching 525 mm in less than 4 s. All other fibre compositions gave acceptable flow diameters. The results of L-box test are presented in a form of dimensionless blocking ratio H2/H1. Achieved values of blocking ratio for unreinforced SCC matrix were equal to 1.0±0.1. The value of blocking ratio was strongly influenced by fibre dosage. In the case of composition mixes with maximum fibre addition did not pass the test (0.9PP38). The theoretical value of H2/H1 = 0 was associated with these tests. The required technological processes for this type of concrete make keeping concrete cast homogenous even more difficult. In case of pumped fibre reinforced SCC, fresh mix should be delivered directly to a cast place, with limiting horizontal relocation of mixes within formed concrete structure.

Table 5.
Properties of fresh PFR-SCC mix

Mix	Slump flow test		L-box (H_2/H_1)
	SFD [mm]	T_{50} [s]	
0	805	1.5	1
0.3PP19	795	1.5	1
0.9PP19	705	2.0	0.81
0.3PP38	755	1.5	0.94
0.9PP38	525	3.5	-

3.2. Test results of hardened PFR-SCC

The detailed mechanical parameters obtained in the compressive and flexural laboratory investigations are summarized in the Table 6, where in parenthesis the coefficient of variation is presented. The Table 6 contains also the relative value of some considered parameters, which is the ratio of the value obtained in the tests on PFR-SCC to the reference mix.

3.2.1. Compressive strength

The compressive strength of the plain SCC was equal 85.7 MPa. On the basis of the tests performed by the author, the addition of polypropylene fibres slightly decreases fc of SCC (Fig. 3a). The decrease was also independent of the fibres length and volume ratio. In all reinforced mixes the fc was in ranges of 92÷94% of the compressive strength of the SCC matrix (Fig. 3b). The reduction of compressive strength can be attributed to the redistribution of voids structures due to performance of fibres [5].

In the state-of-the-art, there can be found the results, where the PP fibres applied as a reinforcement of self-compacting concrete (PFR-SCC) causes the pronounced increase of more than 10% [13] or the decrease of fc [14]. The investigations made by Kamal at el. [13] were performed with the use of the 20 mm long fibres and the volume ratios ranging 0.22÷0.66%. *Beigi et al*. [14] applied low dosages

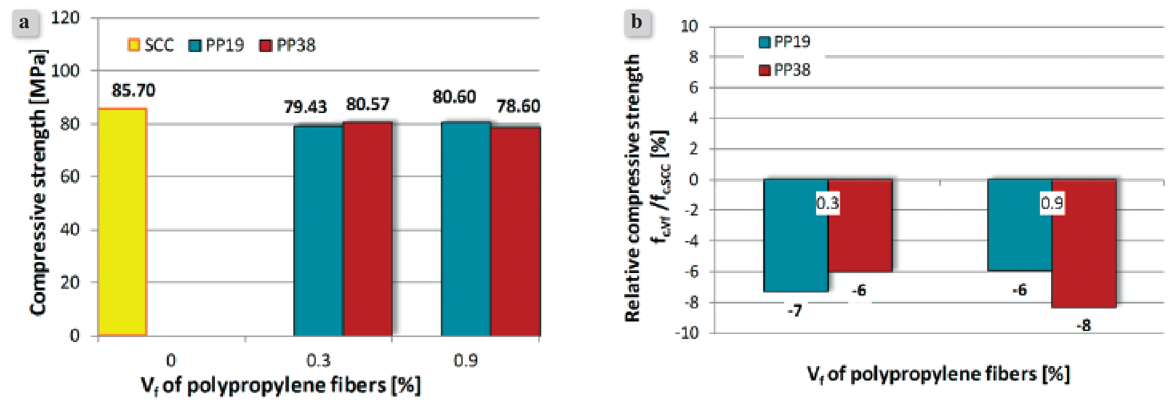

Figure 3.
(a) Compressive strength; (b) relative compressive strength of SCC reinforced with polypropylene fibres

(<0.2%) of 12 mm long fibres. However, in the majority of the works the influence of PP on f_c of SCC is rather slight and in the same tests can decrease or increase the compressive strength of the SCC matrix [2,14,15,16,17]. It can be concluded that the obtained results are comparable to the other researchers work dealing with SCC.

3.3. Flexural tensile strength

The load-deflection curves from three specimens for each mix and the average curves from flexural test are shown in Fig. 4. Figure 5 presents the collate of the average load-deflection curves from mixes with different types and volume ratios of PP fibres. The first cracking, peak and post-peak parameters from flexural tests, which according to the ASTM C 1609/C [11] should be considered, are collected in the Table 6 and depicted in Figures 6÷8. The Table 6 additionally includes the commonly used post-peak parameters to describe the flexural response of FRC, which are: the post-crack strength (PCS_m) obtained according to the concept of *Banthia and Gupta* [18] and flexural toughness factor (FT) according to *Japan Society of Civil Engineering* [19].

The equivalent flexural strength was estimated using the following equation:

$$f = \frac{PL}{bh^2} \qquad (1)$$

where L, b and h are the span, width and depth of the beam and P is the load.

The first cracking and peak parameters are graphically presented in Fig. 6. The analysed post-peak parameters are toughness and the residual strength, which are shown in the Fig. 7 and Fig. 8, respectively.

The toughness ($T_{100.2}$) at 2 mm (L/150) was determined as the area under the load-deflection curve (F-δ) up to 2 mm deflection according to the following equation:

$$T_\delta = \int_0^{\delta_u} F(\delta)d\delta \qquad (2)$$

The residual strengths were determined at 0.5 mm (L/600) and 2 mm of deflection.

Discussing Fig. 4 it can be implied, that the specimens behaviour is repeatable, so the average load-deflection curve well represents the results for each mix. Thus, the influence of the fibres type on flexural parameters is discussed on the basis of Figure 5, which presents the average load-deflection curves obtained for all mixes for deflections equal 2.0 mm (Fig. 5a) and 0.2 mm (Fig. 5b).

The flexural tensile strength (f_{ts}) of plain SCC was enhanced by polypropylene fibres (Fig. 6c). For the V_f=0.3% the increase in f_{ts} was 25% in case of 19 mm long fibres and 59% for the longer PP fibres. Providing higher amount of fibres (0.9%) increased the flexural tensile strength of the matrix of 41% and 56%, for 19 mm and 38 mm long PP fibres, respectively (Fig. 6e). Thus, only in case of 19 mm long PP fibres the increase of f_{ts} was proportional to the increase in the amount of fibres. The SCC reinforced with 38 mm PP fibres exhibit comparable f_{ts} for both tested volumes of fibres.

Polypropylene fibres did not bring any benefits in proportions between the first cracking strength and flexural tensile strength. The first cracking strength (f_1) was equal about 95% of the f_{ts} for plain SCC and

PFR-SCC (Fig. 6a). The net deflection corresponding to the peak load and the first crack load was considerably decreased by the addition of 19 mm long fibres, what can be noted in Fig. 6d and Fig. 6b, respectively. The percentage of the decreases of δ_P compared with the reference mix were: -17%, -6%, for volumes of fibres 0.3% and 0.9% respectively (Fig. 6f). The net deflection of mixes, where longer fibres were applied, was equal δ_P ±2%. However, for 38 mm long PP fibres the fact that the coefficient of variation for the δ_P was the highest from all parameter, have to be taken into account.

Analysing the proportion between the net deflection at first crack (δ_I) and δ_P, it can be seen, that 19 mm long fibres have an adverse effect. In other words, not only the net deflection is much smaller in case of SCC reinforced with 19 mm fibres comparing it to plain SCC but also the first crack occurs for smaller part of this deflection (56÷64%). The 38 mm long PP fibres considerably improve the first crack deflection, so it was noted to be about 76% of the net deflection.

Referring to Figure 7, the differences between the toughness of the mixes are not significant, except from the specimens reinforced with 0.3% of 38 mm PP fibres. The increase in $T_{200.2}$ was about 50 times the toughness of reference mix for 19 mm PP fibres and 58 times in case of 0.9% of 38 mm fibres. The smaller amount of 38 mm PP fibres resulted in obtaining the material as brittle as plain SCC, with relatively small toughness and zero values of residual strengths. The residual strengths determined for the deflection equal 0.5 mm and 2.0 mm for discussed mixes are presented in the Fig. 8.

General remarks from the tests are that the flexural behaviour of the composite made of SCC and shorter PP fibres (19 mm) is more predictable. Indeed, the mixes with this fibres exhibit smaller increase in f_{ts} than the specimens with 38 mm PP fibres, however, the increase of peak and post-peak mechanical parameter was proportional to the increase of the amount of fibres. For the 0.3% of 38 mm long PP fibres no post-peak part of the load-deflection curve (toughening effect) was observed. In this case, the practical application of small volume of this type of PP fibres may bring unexpected results with no increase of post-peak parameters. Thus, the 19 mm long PP fibres are more recommended to practical usage and especially in small amounts.

Some investigations on SCC reinforced with PP fibres can be found in the literature. The flexural tests were performed on polypropylene fibres reinforced self-compacting concrete (PFR-SCC) specimens with the same cross-section as presented in the paper (100x100 mm) and the span of the beam equal 300 mm [15], and 400 mm [13,14,16]. All lengths of the tested fibres was lower than 20 mm, apart from *Alberti et al*. [15], who investigated 60 mm long PP fibres. The tested fibres volume ratio was in the range of 0.1÷0.66%. For this amounts of fibres the f_{ts} in [13,14,16] achieved maximum 128% of the f_{ts} of the SCC matrix. In the current paper comparable increase was noted for 19mm long PP fibres (125%). For long PP fibres the increase in flexural tensile strength was outstanding and was close to 150% of the f_{ts} of the SCC matrix [15]. Comparing these results and the ones obtained by authors it can be concluded, that the effectiveness of polypropylene fibres in SCC may increases with the increase of fibres length.

The data published by some authors deals also with the splitting tensile strength of PFR-SCC. The strength obtained in this test was lower comparing to the flexural tests [14,15], or mostly higher [16]. However, apart from work of *Widodo* [17], in all cases the splitting tensile strength of reinforced specimens was also higher, than the strength of matrix.

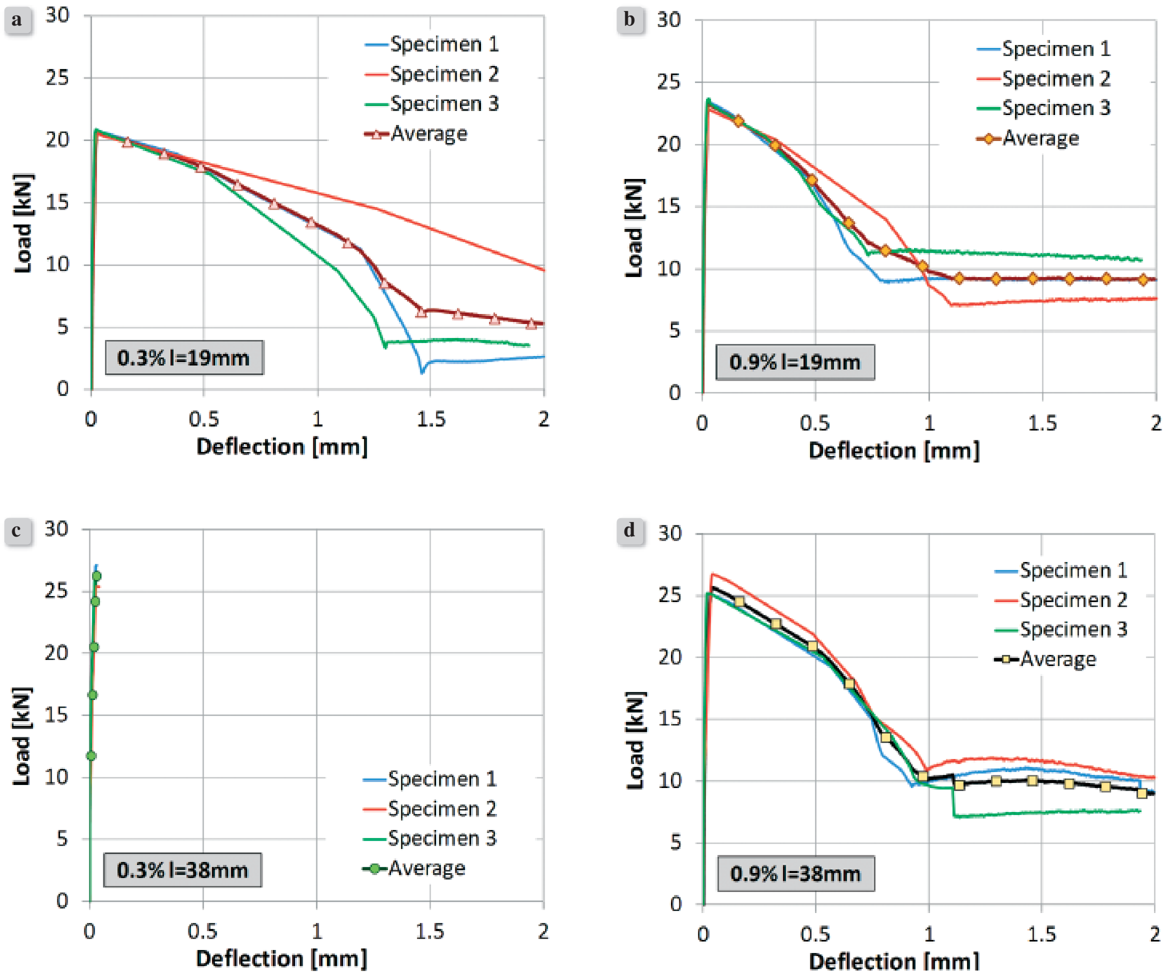

Figure 4.
Load-deflection curves of SCC reinforced with polypropylene fibres: (a) V_f = 0.3% l = 19 mm; (b) V_f = 0.9% l = 19 mm; (c) V_f = 0.3% l = 38 mm; (d) V_f = 0.9% l = 38 mm

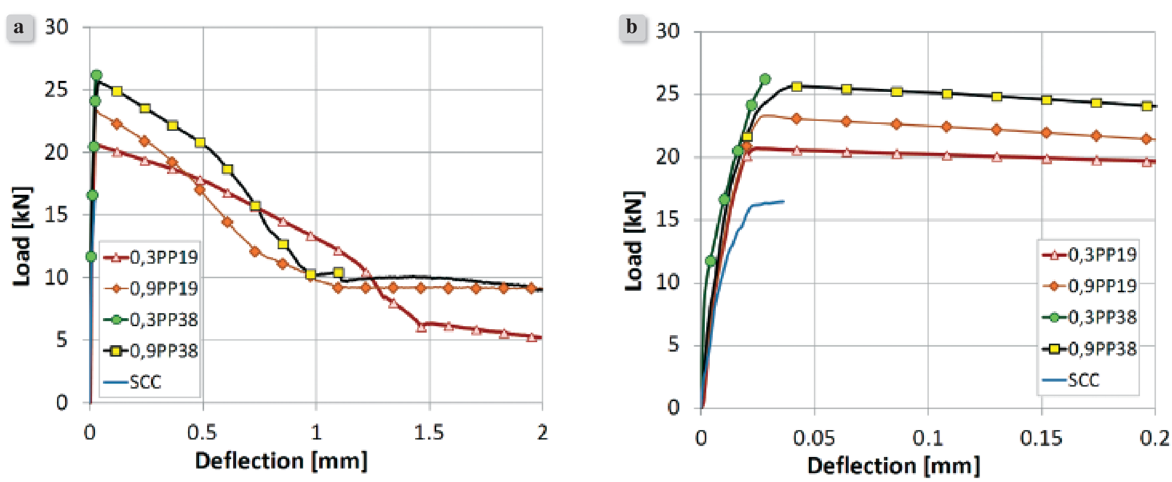

Figure 5.
Average load-deflection curves of SCC reinforced with PP fibres for defletcion equal (a) 2.0 mm, (b) 0.2 mm

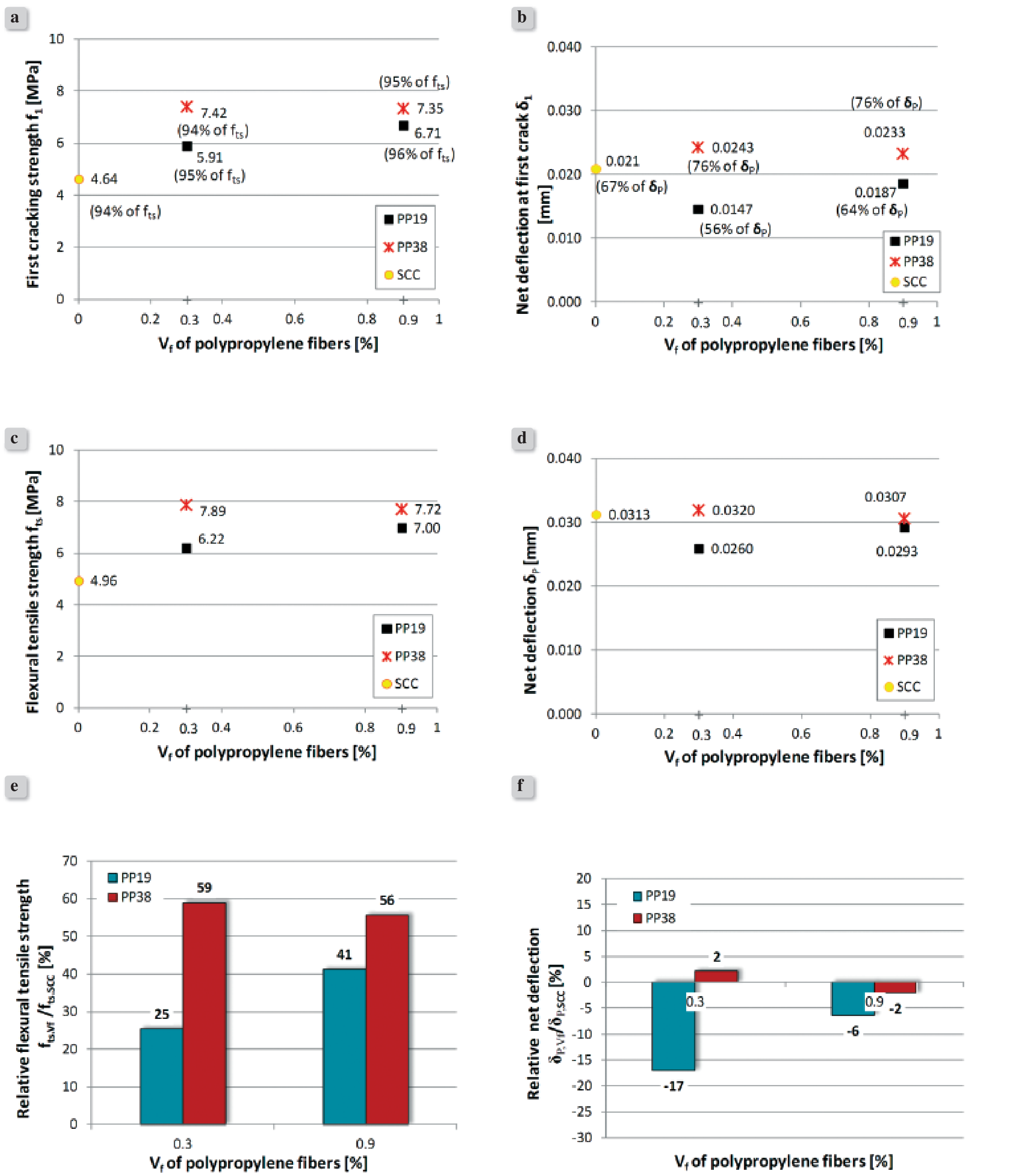

Figure 6.
(a) First cracking strength; (b) net deflection at first cracking load; (c) flexural tensile strength; (d) net deflection; (e) relative flexural tensile strength; (f) relative net deflection of SCC reinforced with polypropylene fibres

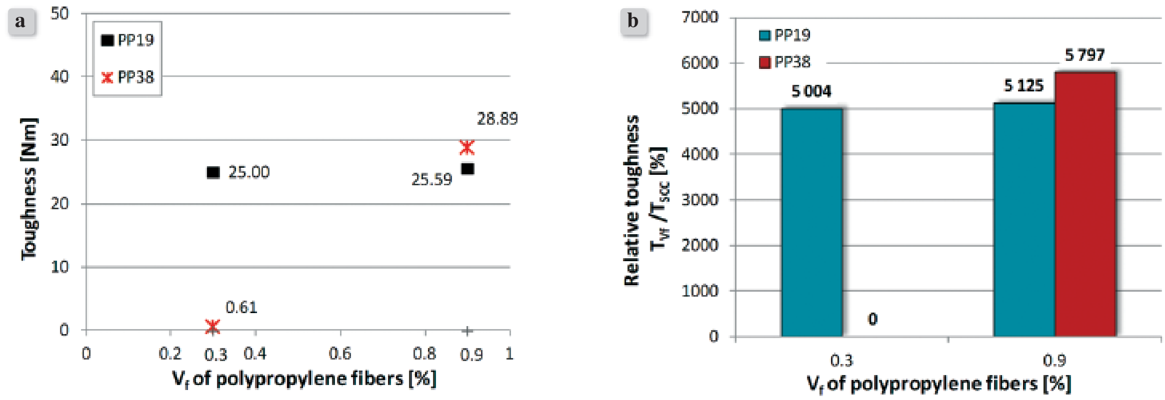

Figure7.
(a) Toughness; (b) relative toughness of SCC reinforced with polypropylene fibres

Table 6.
Properties of hardened PFR-SCC mix

Mix	Compre-ssive strength f_c (MPa)	Peak load PP (kN)	Net deflec-tion δ_P (mm)	Relative δ_P (%)	Flexural tensile strength f_{ts} (MPa)	Relative flexural tensile strength (%)	First cracking strength f_1 [MPa]	Net deflec-tion at first cracking load δ_I [kN]	Tough-ness $T_{100,2}$ (Nm)	Relative Tough-ness (%)	Residual strength at $L/600$ $f_{100,0.5}$ (MPa)	Residual strength at $L/150$ $f_{100,2}$ (MPa)	Flexural tough-ness factor [FT] (kNm)	PCSm (kNm)
0	85.7 (0)	16.5 (11)	0.0313 (21)	-	4.96 (11)	-	4.64 (18)	0.0210 (54)	0.49 (12)	-	-	-	-	-
0.3PP19	79.4 (6)	20.7 (1)	0.0260 (8)	-17	6.22 (1)	25	5.91 (4)	0.0147 (26)	25.00 (20)	5004	5.34 (2)	1.58 (72)	3.75 (20)	3.69 (21)
0.9PP19	80.6 (3)	23.3 (2)	0.0293 (10)	-6	7.00 (2)	41	6.71 (2)	0.0187 (13)	25.59 (6)	5125	5.02 (7)	2.75 (17)	3.84 (6)	3.77 (6)
0.3PP38	80.6 (3)	26.3 (3)	0.0320 (87)	2	7.89 (3)	59	7.42 (3)	0.0243 (31)	0.61 (13)	-	-	-	-	-
0.9PP38	78.6 (3)	25.7 (4)	0.0307 (40)	-2	7.72 (4)	56	7.35 (5)	0.0233 (46)	28.89 (8)	5797	6.20 (4)	2.70 (15)	4.33 (8)	4.25 (8)

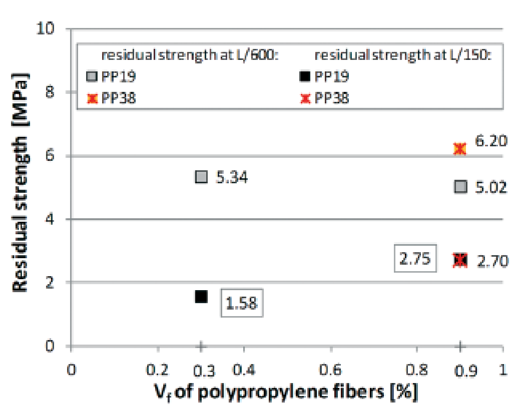

Figure 8.
Residual strength of SCC reinforced with polypropylene fibres at 0.5 mm and 2.0 mm

4. CONCLUSIONS

Based on the investigations on SCC reinforced with two types of polypropylene fibres presented in the paper the main conclusions can be drawn:

- The compressive strength of PFR-SCC was slightly decreased by the presence of PP fibres. In all cases the decrease did not reach 8% of f_c of the SCC matrix;
- In case of 19 mm long PP fibres the flexural tensile strength, net deflection and the first cracking strength increased proportionally to the fibres volume ratio. For 0.3% and 0.9% of the fibres volume ratio the f_{ts} achieved 25% and 41% of the f_{ts} of the SCC matrix, respectively;

- The toughness of SCC was enhanced by the 19 mm long polypropylene fibres and it was comparable in case of both investigated volumes of fibres;
- Usage of 38 mm long PP fibres in SCC is uncertain and needs further flexural laboratory investigation. Especially the 0.3% volume ratio of 38 mm long PP fibres, may bring unexpected results with no toughening effect as observed in the paper. The pronounced increased in f_{ts} and first cracking strength was observed for both investigated volumes of fibres, when comparing it to the test results with 19 mm long PP fibres. Admittedly, the application of volume equal 0.9% of 38 mm long PP fibres gave the best mechanical post-peak parameters from all tested in the paper, however, the post-peak mechanical parameters are unpredictable. This conclusion concerns also the parameter of the PFR-SCC mix in a fresh state.

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