Jan Broda,
Waclaw Brachaczek

Influence of Polypropylene Fibre Geometry on the Mechanical Properties of Cement Mortars

Institute of Textile Engineering and Polymer Materials, University of Bielsko-Biala,
ul. Willowa 2, 43-309 Bielsko-Biala, Poland,
E-mail: jbroda@ath.bielsko.pl

Abstract
In this study, fibrillated polypropylene fibres and fibres with a round and five-arm star cross section were produced. The fibres were chopped to specified lengths and used for the reinforcement of cement mortars. Mortars containing different dosages of fibres were prepared. The compression and bending strength of the mortars were determined and it was noted that the fibres do not affect the compressive strength of the mortars. For reinforced mortars, regardless of the fibre geometry and dosage, the compressive strength is comparable with that of plain mortar. The fibres influence the bending strength of the mortars. For mortars reinforced with fibrillated fibres a significant increase in the bending strength was observed. For mortars which contained other fibres, the effect of the reinforcement on the bending strength was less visible. The increase in the bending strength was explained by the fibre/matrix interaction.

Key words: *mortar, fibre reinforcement, compressive strength, bending strength, SEM.*

Introduction

Polypropylene fibres have been applied for the reinforcement of concrete for many years [1, 2]. The particular interest in polypropylene fibres results from their relatively low price and several valuable properties [3, 4]. The fibres possess high chemical and biological resistance, including very good resistance in concrete's alkaline environment [5]. Thanks to high resistance the fibres do not corrode during the utilisation of concrete. They are hydrophobic, show practically no wet absorption and do not absorb water during the mixing of cement paste. Due to the low density of fibres, many times lower than that of steel, the reinforcement is light and does not additionally load the constructions.

Short polypropylene fibres distributed uniformly in the whole capacity of concrete sew lips of cracks and restrict their propagation [6]. The reduction of cracking is of great importance, especially in the first hours after pouring before concrete reaches its initial strength [7]. Apart from reducing crack propagation, the addition of fibres positively affects other concrete parameters. Concrete reinforced with fibres possess high strength and resistance to cracking at bending, high resistance to dynamic loads, improved fatigue resistance, better thermal resistance to sudden temperature changes and lower grindability comparing to classical concrete [8 - 12].

A crucial aspect governing the performance of reinforced concrete is adhesion between the matrix and fibres [14 - 17]. Due to chemical inertness and low surface energy, polypropylene fibres reveal poor adhesion to cementitious matrix. To improve the adhesion, for concrete reinforcement deformed or surface modified fibres are used. The fibres deformed by fibrillation, crimping or twisting posses a rough surface, higher specific surface area and, consequently, greater adhesion to the cement matrix [18]. The surface modified fibres contain polar groups, which ensure higher wettability and better interfacial strength between fibres and the cement matrix [19 - 22].

Fibres modification affects the mechanism of fibre/matrix interaction, which is revealed in the macroscopic behaviour of concrete [23 - 25]. The change in cracking sensitivity and other concrete properties dependant on the polypropylene fibre geometry and properties has been observed many times. In literature on the subject, the problem has been repeatedly discussed, however contradictory test results and conclusions have been reported. Contradictions between the results obtained concern even the basic concrete parameters as well as compressive and bending strength. Richardson [26] stated that the compressive strength of concrete containing polypropylene fibres was significantly reduced. Mindness and Vondran [27] reported that the compressive strength of concrete reinforced with fibrillated fibres was increased by 25%. Parveen and Sharma [28] observed an increase in the compressive strength of concrete at low fibre dosage up to 0.2% and a reduction in compressive strength at a percentage above 0.2%. Alhozaimy [29] suggested that polypropylene fibres have no statistically significant effect on the compressive strength of concrete. Similarly Aulia [30] revealed that the use of a certain amount of fibres in concrete did not influence its main mechanical parameters detrimentally.

The varying results of previous investigations led to the undertaking of subsequent studies on the dependence between polypropylene fibre characteristics and concrete parameters. In these investigations fibrillated fibres and fibres of different cross-section geometry were used. Fibrillated polypropylene fibres as well as fibres with a round and five-arm star profile were produced and applied for the reinforcement of cement mortars. Mechanical parameters of the mortars were determined and the effect of the fibre length, shape and dosage was analysed.
The majority of papers published present the reinforcement of concrete with polypropylene fibres from the point of view of the construction engineer, for whom concrete parameters play the most important role. This paper presents the issue from the point of view of fibre science, where fibre characteristics and their behaviour in the cement matrix are the main object of interest.

Experimental

Samples

Multifilaments with a round and five-arm star cross-section were produced at the Institute VÚCHV, a.s. (Research Institute for Man-Made Fibres, a.s.) in Svit (Slovakia). Commercial isotactic polypropylene TATREN HT1810 (Slovnaft Company, Slovakia) with MFI = 18 g/10 min was used. Fibres were formed using the

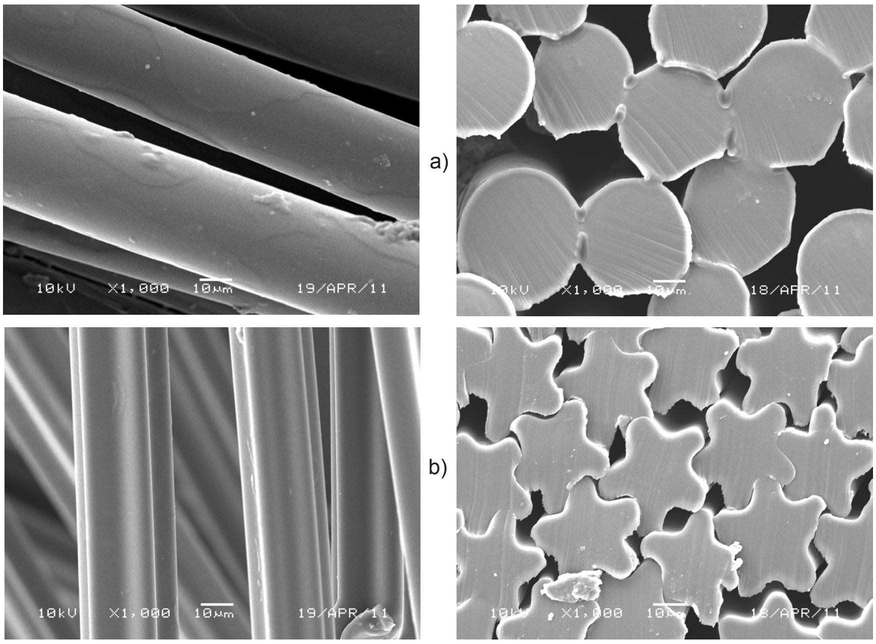

***Figure 1.** SEM microphotographs of the multifilament; a/ round profile; b/ five-arms star profile.*

classical continual process of spinning and drawing at a spinning temperature of 260 °C and draw ratio λ = 3.0.

The fibrillated fibres were produced using the production line StarEx 1500 in Bezalin (Bielsko – Biala, Poland). During formation the polypropylene films were cut into strips and then split by a needle roller installed ahead of the stretching unit. Commercial isotactic polypropylene resin Moplen HP 456J (Orlen Polyolefins, Poland) characterised by a melt flow index of 3.4 g/10 min, with the addition (2%) of polyethylene Bralen FB 2-30 (Slovnaft Petrochemicals), was used. Fibres with a linear density of 1000 tex were obtained.

The multifilaments and fibrillated fibres were chopped to specified lengths of 5, 10 and 15 mm and mixed with cement mortar.

Mortars were prepared using Portland cement CEM I 42,5 R, sand and tap water in accordance with the EN 197-1:2002 and EN 197-2:2002 standards. Mixtures with different contents of fibres: 0.25, 0.5, 0.75 and 1% by weight were obtained. The components were mixed with a laboratory mixer - Multiserw (Poland). Wet mortars were poured into rectangular prism moulds with dimensions of 40 × 40 × 160 mm and allowed to harden in the open. Then the samples were cured in water for 28 days.

Methods

Before the mixing of fibres with cement mortars, the morphology of fibrillated fibres and multifilaments was studied. After mechanical tests the morphology of fractures of the fibre-reinforced mortars was investigated. The investigations were performed with a scanning electron microscope - Jeol JSM 5500 LV (Japan) for samples sputtered with gold by a Jeol JFC 1200 ionic sputter (Japan).

Of the mortars' basic mechanical parameters, the compressive and bending strength were determined. The measurements were carried out using a TECNOTEST KE 200/A tensile machine (Italy) according to the norm EN 196-1:2006. For comparison a plain mortar specimen without fibres was tested.

The results determined were analysed by statistical methods using the regression function and Multi-Factor ANOVA test.

Results

During microscopic studies of the fibres, their surface and cross section was observed. SEM microphotographs of the surface and cross section of the multifilaments are presented on ***Figure 1***.

The multifilaments have regular round or five-star arm cross section. The fibres are uniform and their diameter equals 40 μm. For round profile fibres the specific surface area, determining the contact area to the cement matrix, is relatively small. The surface of fibres is smooth, without any specific elements. Lack of surface irregularities prevents mechanical anchoring of fibre in the matrix and enables their easily pulling out of the matrix.

Thanks to the change of the cross section profile, the star shaped fibres exhibit greater specific area. With the fibres thickness of 40 μm the increase of the surface area is of the order of 5%. Such enhancement of specific surface area leads to the increase of the number of adhesive connections. On the surface of the fibres the regular longitudinal groves are observed. The higher specific surface area and grooves ensure better anchoring of fibres in the matrix, but still, do not prevent their pulling out from the matrix.

Figure 2 presents photographs of the fibrillated fibres. The fibres are obtained

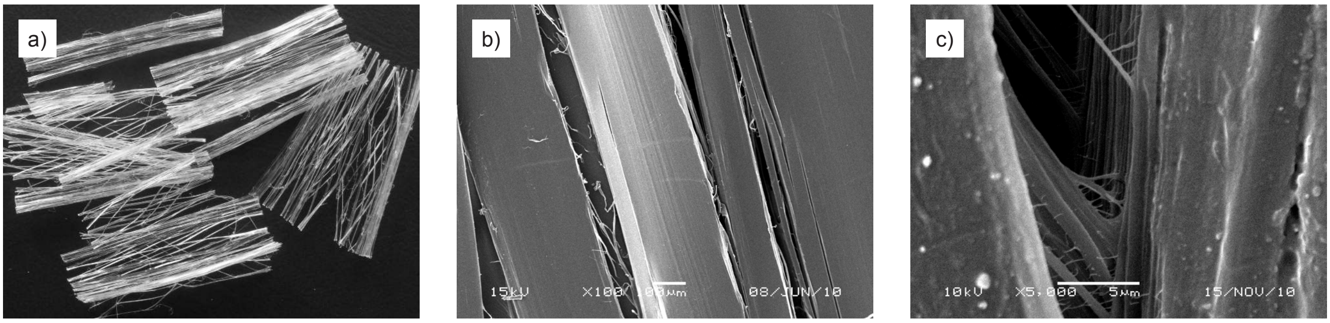

***Figure 2.** Polypropylene fibrillated fibres; a) the network-like structure of fibres; b) splitting of polypropylene strips; c) splitting area.*

by local longitudinal cutting and drawing of narrow strips. Due to weak intermolecular forces in polypropylene the cuttings propagate easily. As a result, the strips partially disintegrate into a network-like structure formed from flat fibres with the rectangular cross section and the diameter of 500 μm. Thanks to the specific structure the fibrillated fibres posses high specific surface area. The network-like structure of fibres partially opens during mixing of the mortar [31]. The cement matrix can penetrate in the mesh between the individual fibrils and create additional mechanical bonds between fibres and matrix. Moreover, during mixing a combination of filamentising, where the fibres separate into multifilament strands, branching of fibrils and forming of tiny fibrillations on the fibres surface occur [32]. All those processes support mechanical anchoring of fibres in the matrix.

Table 1 shows the determined values of compressive strength measured for different fibres content for fibrillated fibres as well as round and star cross section shaped fibres. For all fibres, regardless of the length of the fibres and their content, the compressive strength does not significantly change. For mortars containing all those fibres, independently on the fibres length and dosage, the determined values are close to the compressive strength of the plain mortar 16.3 MPa.

The compressive strength for different fibres content with marked confidence intervals are presented on ***Figure 3***.

In order to verify whether the simultaneous changes in the shape and length of the fibres as well as their interaction affect the compressive strength of reinforcement mortars the Multi-Factor ANOVA test was performed [33]. The results of the test are presented in ***Table 2***.

Analyzing data presented in ***Table 2*** one can conclude that the compressive strength is dependent solely on the change in length of the fibres used for reinforcement of mortar. The analysis indicates the lack of interaction between input variables.

To assess the simultaneous effect of the fibres content and fibres length (for different shapes of cross-sections of the fibres) the multiple regression was used. The analyses was carried out using a posteriori method [33, 34]. The values of summary statistics are summarized in ***Tables 3, 4*** and ***5***.

Analyzing values summarized in ***Tables 3 - 5*** one can conclude that from all regression functions describing the correlation between the compressive strength of the mortars and fibres content u (%) and the fibres length l (mm) the substitute characteristics was found only for mortar reinforced with fibres with star cross-section. Then the regression functions is written (1):

$$\sigma_{comp.} = 16.967 - 1.247 \cdot u + - 0.060 \cdot l - 0.133 \cdot u^2 - 1.687 \cdot l^2 + 5.822 \cdot u \cdot l \quad (1)$$

Because of the low value of a statistic $t_{11} = -0.217$ in accordance with the *a posteriori* procedure variable u^2 was eliminated. As the result a significant increase in the computational F-Snedecor's statistics $F_7^4 = 22.58$ was achieved. After eliminating the variable u^2 the regression function takes the form (2):

$$\sigma_{comp.} = 17.008 - 1.413 \cdot u + - 0.060 \cdot l - 0.006 \cdot l^2 + 0.196 \cdot u \cdot l \quad (1)$$

Table 1. *The compressive strength of reinforced mortars by different fibres content and lengths.*

Content u, %	Length l, mm	Compressive strength, MPa		
		Shape of fibres		
		fibryl	round	star
0.25	5.0	16.5	16.3	16.4
0.50		16.3	15.8	16.3
0.75		16.4	16.5	16.3
1.00		16.0	16.0	16.2
0.25	10.0	16.2	16.2	16.2
0.50		16.3	16.3	16.1
0.75		16.1	16.3	16.2
1.00		16.3	15.4	16.3
0.25	15.0	16.2	15.5	15.1
0.50		16.1	15.8	15.7
0.75		16.1	15.8	16.1
1.00		16.2	16.1	16.4

Figure 4 presents the surface and layer graph of the regression function described by the ***Equation 2***.

Analyzing the graph one can see that from both factors the change of the fibres length has greater impact on the mortars compressive strength. This effect is par-

Table 2. *Two-factor Anova test for factorial systems for the compressive strength of reinforced mortars.*

Effect	Sum of squares	Degree of freedom	Mean square	F	Significance p
Absolute term	9344.4	1	9344.4	114421.8	0.000
Length of fibres l, mm	0.674	2	0.337	**4.1**	**0.0273**
Shape of fibres	0.304	2	0.152	1.9	0.175
Length × shape	0.133	4	0.033	0.4	0.802
Error	2.205	27	0.082		

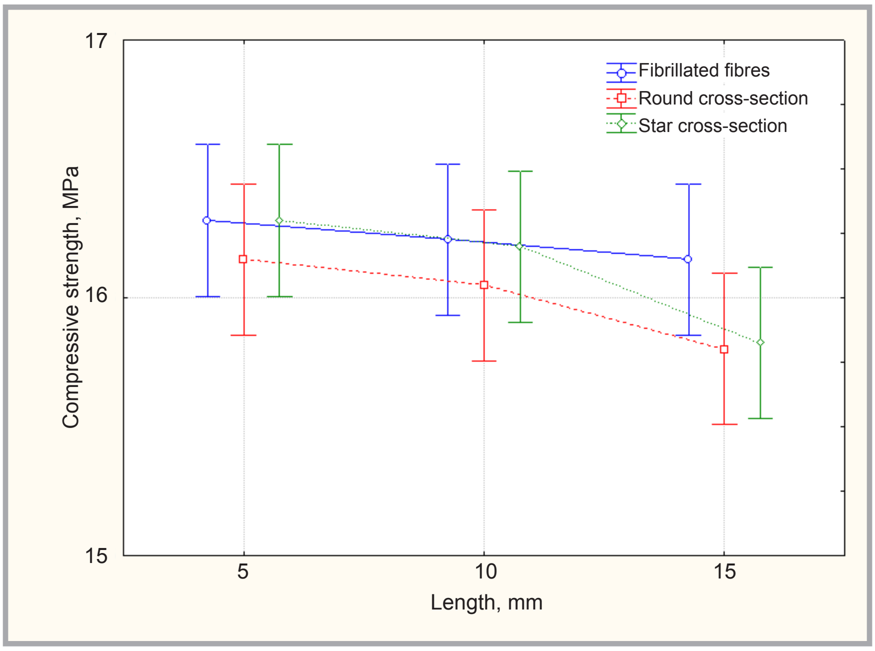

Figure 3. *Compressive strength of reinforced mortars versus lengths of the fibres.*

***Table 3.** Values of summary statistics of regression function for compressive strength determined for fibrillated fibres and fibres with round cross-section.*

Analysed parameter	**Statistical parameters of regression function**			
	R^2	R	F_6^5	$F_{crit.\ 6}^{\ 5}$
Compressive strength (fibrillated fibres)	0.552	0.743	1.48	4.39
Compressive strength (round fibres)	0.349	0.590	0.64	4.39

***Table 4.** The values of summary statistics of regression function for compressive strength determined for fibres with star cross-section*

Compressive strength (star fibres) $\sigma_{compr.} = f(u; l)$						
The coefficients of the regression function						**Partial test**
B_0	B_1	B_2	B_{11}	B_{22}	B_{12}	$t_{crit.} = t_{0.05;\,6}$
16.967	-1.247	-0.060	-0.133	-0.006	0.196	
The values of the partial Student-t test						
t_0	t_1	t_2	t_{11}	t_{22}	t_{12}	
40.832	-1.467	-0.868	-0.217	-1.687	5.822	2.447
Correlation coefficients				Degree of freedom	F-Snedecor's statistics	
R^2	R			K; N – K – 1	F_6^5	$F_{crit.}$
0.928	0.963			5; 6	**15.62**	4.39

***Table 5.** The values of summary statistics of regression function for compressive strength determined for fibres with star cross-section after elimination of B_{11} coefficient by u^2 variable.*

Compressive strength (star fibres) $\sigma_{compr.} = f(u; l)$						
The coefficients of the regression function						**Partial test**
B_0	B_1	B_2	B_{11}	B_{22}	B_{12}	$t_{crit.} = t_{0.05\,;\,7}$
17.008	-1.413	-0.060	–	-0.006	0.196	
The values of the partial Student-t test						
t_0	t_1	t_2	t_{11}	t_{22}	t_{12}	
49.665	-4.182	-0.934	–	-1.815	6.264	2.365
Correlation coefficients				Degree of freedom	F-Snedecor's statistics	
R^2	R			K; N – K – 1	F_7^4	$F_{crit.}$
0.928	0.963			4; 7	**22.58**	4.12

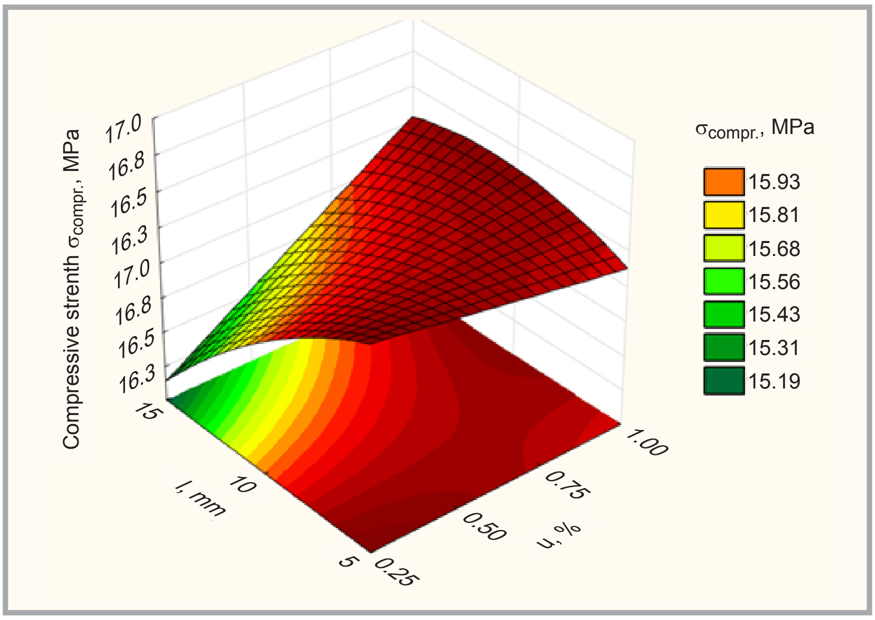

***Figure 4.** Surface and layer graph of the regression function $\sigma_{compr.} = f(u; l)$.*

ticularly noticeable in a range of fibres lengths 10 – 15 mm. With the decrease of the length of the fibres and increase their content the compressive mortar increases. The most preferred combination of both factors is obtained at the content u = 0.5% and a fibre length l = 5 mm. The use of longer fibres 15 mm and lower content 0.25% results in lowering of the compressive strength.

Table 6 presents the bending strength for different fibres content for fibrillated fibres and multifilaments with round and star cross section. For mortars reinforced with fibrillated fibres, for low and medium lengths the bending strength is higher than the strength of the plain mortar 5.5 MPa. For the greatest fibres length the bending strength is comparable with the strength of the plain mortar. For fibres with the star profile, at the lowest fibres content the bending strength is lower than the strength of non-reinforced mortar. At higher content the bending strength is comparable to the strength of the plain mortar. For multifilaments with round cross section the bending strength is slightly lower compared to the plain mortar.

Figure 5 presents the relation between bending strength of mortars and fibres length for different geometry of fibres with marked confidence intervals.

Table 7 presents the results of the Anova test for values of the bending strength of mortars reinforced with different fibres.

Similarly as for results of the compressive strength one can state that the bending strength is dependent solely on the change in length of the fibres used for reinforcement of mortar. The analysis indicates the lack of interaction between input variables.

Table 8 (see page 128) presents the values of summary statistics of regression function for bending strength determined for all investigated fibres. The values show that for all fibres the regression function is insignificant and further analyses is purposeless.

For mortars reinforced with fibrillated fibres, for low and medium lengths the bending strength is higher than the strength of the plain mortar 5.5 MPa. For the greatest fibres length the bending strength is comparable with the strength of the plain mortar. For fibres with the star profile, at the lowest fibres content the bending strength is lower than the strength of non-reinforced mortar. At higher content the bending strength is comparable to the strength of the plain mortar. For multifilaments with round

Table 6. *The bending strength of reinforced mortars by different fibres content and lengths.*

Content u, %	Length l, mm	Bending strength, MPa		
		Shape of fibres		
		fibryl	round	star
0.25	5.0	5.8	4.9	4.8
0.50		6.0	5.7	5.6
0.75		5.6	5.3	5.3
1.00		5.4	5.2	5.3
0.25	10.0	5.2	5.5	5.3
0.50		6.0	4.9	5.5
0.75		6.2	5.4	5.9
1.00		5.8	5.2	4.8
0.25	15.0	5.9	5.8	5.1
0.50		5.5	5.2	5.4
0.75		5.3	4.8	5.7
1.00		5.6	5.9	5.7

cross section the bending strength is slightly lower compared to the plain mortar.

It can be clearly seen that for short and medium length the bending strength of mortars containing fibrillated fibres is greater than the strength of the samples reinforced with multifilament fibres.

For the longest fibres, the samples reinforced with fibrillated fibres have higher strength at low fibre contents of 0.25% and 0.5%. For higher content the bending strength containing fibrillated fibres is lower.

The highest bending strength, about 12% higher in the comparison to the plain mortar, is observed for mortar reinforced with fibrillated fibres of 10 mm length and fibres content of 0.75%.

On ***Figures 6*** and *7* SEM microphotographs of fractures of samples after the mechanical tests are presented. On the pictures the fibres ends with different lengths, which protrude from the cement matrix are visible. Particular fibres, independently on their geometry, are well separated and evenly distributed throughout the volume of the sample. The protruding ends are well anchored and cannot be manually pulled out from the mortar.

For fibrillated fibres it is clearly seen that fibres are split into smaller particular fibrils with the diameter of few μm.

Table 7. *Two-factor Anova test for factorial systems for the bending strength of reinforced mortars.*

Effect	Sum of squares	Degree of freedom	Mean square	F	Significance p
Absolute term	1072.6	1	1072.6	8279.9	0.000
Length of fibres l, mm	0.990	2	0.490	**3.81**	**0.034**
Shape of fibres	0.047	2	0.023	0.18	0.838
Length × shape	0.228	4	0.057	0.44	0.778
Error	3.498	27	0.130	-	-

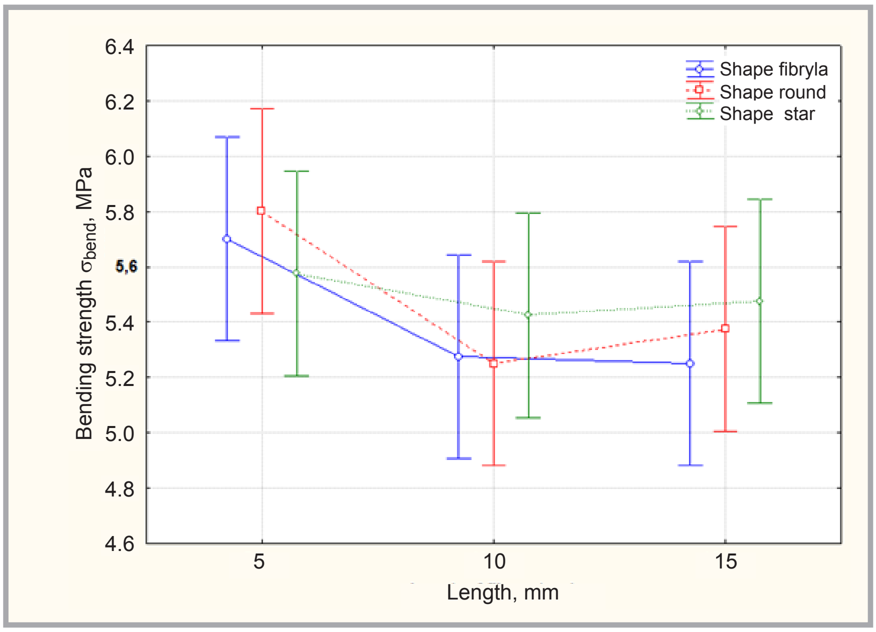

Figure 5. *The bending strength of reinforced mortars versus fibres length.*

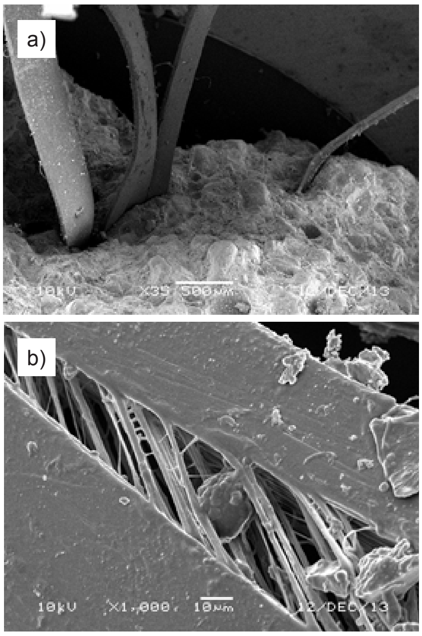

Figure 6. *The SEM microphotographs of the fracture of mortars reinforced with fibrillated fibres. a) fibres anchored in the matrix; b) fibrillation of fibres.*

Simultaneously, one can observe mortar ingredients, which penetrate into the network of split fibres.

For fibre-reinforced concrete several types of interactions, such as fibres sliding, fibres bridging, fibres rupture and fibres/matrix debonding, are known [35]. On the basis of the microscopic studies one can conclude that during bending tests the dominating interaction is fibres slidings (***Figure 8***).

At the beginning of bending the deformation of the interfacial zone occurs. Due to the high difference in Young's modules, deformations of the fibres and the surrounding cement matrix are not compatible. As a result, the adhesive connections linking fibres with cement mortar are disrupted. By further bending one end of a fibre stays firmly anchored in the mortar, while the other is pulled out from the cement matrix. During pulling out the friction forces play an important role.

The mechanical tests have revealed that mortars containing fibrillated fibres posses the highest bending strength, higher than the strength of plain mortar and mortars containing other fibres. The higher bending strength results from the interaction between the fibrillated fibres and mortar components. According to the previous statements, thanks to the network structure, the fibrillated fibres ex-

Table 8. *The values of summary statistics of regression function for bending strength determined for fibrillated fibres and fibres with round and star cross-section.*

Analysed parameter	R^2	R	F_6^5	$F_{crit.\,6}^5$
Bending strength (fibrillated fibres)	0.175	0.418	0.25	4.39
Bending strength (round fibres)	0.141	0.376	0.19	4.39
Bending strength (star fibres)	0.522	0.722	1.31	4.39

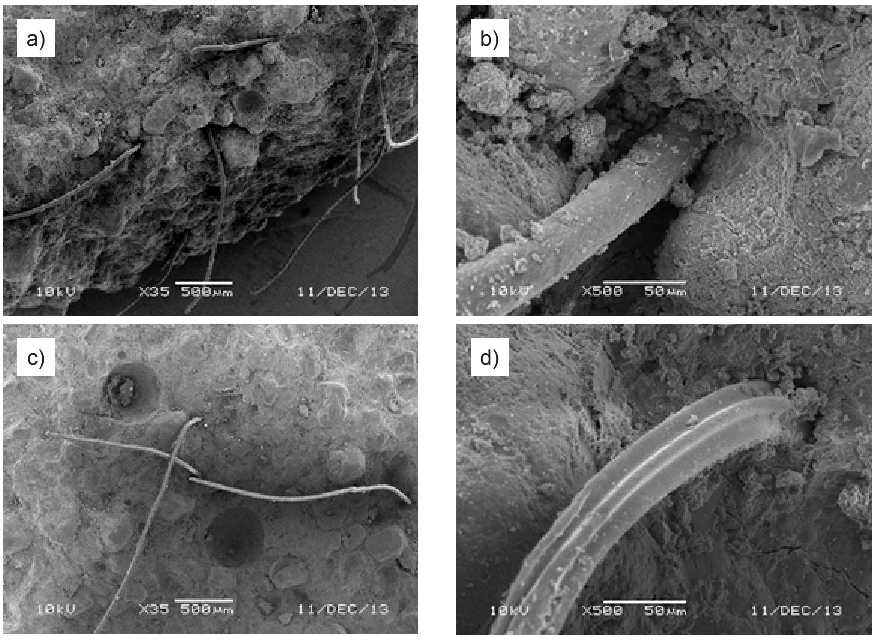

Figure 7. *The SEM microphotographs of the fracture of mortars reinforced with polypropylene multifilaments; a) and b) round fibres; c) and d) fibres with star cross section.*

hibit the greatest adhesion to the matrix and the highest friction during pulling of fibres ends out of the matrix. Stronger adhesive connections delay the release of fibres ends, while higher friction hinders pulling the fibres out of the cement matrix.

In case of multifilament fibres the adhesive connections are much weaker and friction forces during pulling fibres ends out of the cement matrix are smaller. As a result, the bending strength is lower, especially for fibres with round cross section.

The highest bending strength for fibrillated fibres was registered for fibre length of 10 mm and the fibres content of 0.75%. By this length, during mixing of the mortar, the fibres remain straight and do not bend or tangle. Fibres of this length have relatively large contact surface to form a sufficient number of adhesive connections with the mortar components and to provide high friction forces during pulling fibres ends out of the matrix. For shorter fibres the contact area is smaller, what consequently leads to the lower number of adhesive connections and lower friction. Fibres longer than 10 mm exhibit greater contact surface, but have a tendency to bend and tangle. Such tendencies reduce efficiency of reinforcement and leads to the decrease in the bending strength of the mortar. The fibre content of 0.75% ensure the sufficient number of connections sewing lips of the crack.

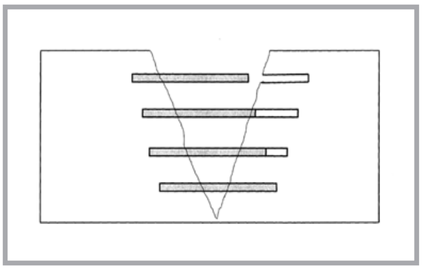

Figure 8. *The mechanism of fibres/matrix interaction during bending.*

Conclusions

On the basis of the performed investigations one can conclude that polypropylene fibres do not affect the compressive strength of the reinforced cement mortars. Independently on the fibres geometry and their dosage the compressive strength of the reinforced mortar does not change and is equal to the strength of the plain mortar. The fibres cause the change of the mortar bending strength. The significant increase of the bending strength is observed for mortars reinforced with fibrillated fibres. For the fibres with star cross section the bending strength is comparable with the strength of the plain mortar. For the fibres with round shape the bending strength is slightly smaller.
The increase of the bending strength of reinforced mortar results from the strong interaction of the fibrillated fibres with the cement matrix.

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