Chapter 9

Application of Polypropylene Fibrillated Fibres for Reinforcement of Concrete and Cement Mortars

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Additional information is available at the end of the chapter

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Abstract

Polypropylene fibres have been applied for reinforcement of cement mortars and concrete for many years. The fibres restrict crack propagation and positively affect several concrete parameters. To improve the adhesion of polypropylene to cement matrix, geometrically deformed or modified fibres are commonly used. Good results are obtained by application of fibrillated fibres with the net-like structure obtained from the polypropylene types. The fibrillated polypropylene fibres were produced. The fibres were chopped to specified lengths and used for the reinforcement of concrete and cement mortars. The parameters of fresh concrete and mechanical parameters of reinforced concrete and mortar were determined. It was stated that the fibres do not affect the compressive strength of the reinforced concrete and mortar. The beneficial effect of fibres on the compressive strength of concrete is revealed after freezing and thawing cycles. The fibres influence the bending strength of the mortars. For mortars reinforced with fibrillated fibres a significant increase in the bending strength is observed. The increase in the bending strength results from enhanced interfacial adhesion and mechanical anchoring, which results from opening of the network structure and splitting of fibrillated fibres.

Keywords: polypropylene fibrillated fibres, concrete, mortar, adhesion, compressive and bending strength

1. Introduction

The application of fibres in improving the mechanical properties of construction materials has been known for a long time. In the ancient times the primitive mud huts were built of clay doped with straw. In the next centuries bricks baked from clay with straw and later lime and cement mortars with horse bristle were used. In the nineteenth century the concrete with addition of asbestos fibres became very popular. In the beginning of the twentieth century the first attempts of reinforcing the concrete with steel fibres were undertaken. Few decades later natural and chemical fibres for reinforcement of concrete came into use. The literature on the subject describes the successful attempts of applying various natural, as well as glass, carbon, polyaramide and other typical synthetic fibres [1–7].

From the group of synthetic fibres the polypropylene fibres are the most frequently applied [8, 9]. The great interest in polypropylene fibres results from their relatively low price, abundant availability and several valuable properties [10, 11]. The fibres are safe and easy to use and compatible with all concrete chemical admixtures. The fibres are chemically inert and possess high chemical and biological resistance, including very good resistance in concrete's alkaline environment [12]. Thanks to high resistance the fibres are rust free and do not corrode during the utilisation of concrete. The fibres are hydrophobic, show practically no wet absorption and do not absorb water during the mixing of cement paste. Due to low density of fibres, much lower than the density of steel, the reinforcement is light and does not load the constructions additionally.

Short polypropylene fibres distributed uniformly in the whole capacity of concrete sew lips of cracks and restrict their propagation [13–15]. The reduction of cracking is of great importance especially in the first hours after pouring, when the concrete possesses low tenacity and low Young's modulus, and the stresses arising as a result of shrinkage exceed its strength [16].

Fibres effectively restrict the propagation of contraction cracks through dispersing the internal stresses. In the moment when the crack is formed some fibres break, some, after the breaking of bonds connecting them with the concrete, are partially pulled out and some bridge the widening cracking [17]. All these processes lead to dissipating stresses occurring at the ends of the crack. Although the ability of single fibres to dissipate the stresses is not high, with greater amount of fibres the accumulation of the effect is observed and effective restriction of spreading the cracks occurs.

Apart from reducing crack propagation, the addition of fibres positively affects other concrete parameters. Concrete reinforced with polypropylene fibres possesses high strength and high resistance to cracking at bending, high resistance to dynamic loads, improved fatigue resistance and lower grindability comparing to the classical concrete [18–22]. Fibres improve the fire resistance of the concrete and its thermal resistance to sudden temperature changes. In higher temperatures fibres are melted and partially absorbed by the cement matrix. The fibres generate a permeable network that allows the outward gas migration, decreasing the pore pressure in the material and, consequently, eliminating the possibility of explosive spalling occurrence [23, 24]. Adding fibres improves also the freeze resistance of concrete. In this way fibres prolong significantly the concrete durability [25, 26].

In recent years fibre-reinforced concrete is getting widely used for the construction of roads and highways, airport pavements, watersides and many other engineering objects [27–29].

The performance of the fibre-reinforced concrete depends on interaction between the cement matrix and the fibres, which depends on the adhesion and the friction forces [30–33]. By weak

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stresses the adhesion forces ensure the cohesion of interfacial area. In this circumstance, the internal stresses are transferred by both composite ingredients, and the displacements of the fibres and the matrix at the phase border are compatible. At larger stresses, in a view of significant difference of fibres' and matrix' elastic moduli, breaking of adhesive bonds between the fibres and the matrix occurs. After the break of such bond the process of pulling the fibres out begins, during which the friction forces play the main role [34–36].

Polypropylene fibres, due to their chemical structure and low surface energy, show extremely low wettability and poor adhesion to cementitious matrix. The literature describes various methods for modification of fibres, aimed at increasing the wettability and improving their adhesion capacity. One method consists in introducing polar groups on the surface of the fibres through reactions occurring during the plasma treatment or other reactions initiated by UV or γ radiation [37–42]. The second method of improving the adhesive properties consists in the increase of roughness of fibres' surface by chemical and physical treatment [43]. This method includes chemical etching, flame treatment, corona discharge or microwave radiation [44]. The significant improvement of adhesive capacity is obtained by the deformation of the fibres by crimping or twisting [45, 46]. Other interesting option is application of fibrillated fibres with the net-like structure obtained from the polypropylene types [47–49].

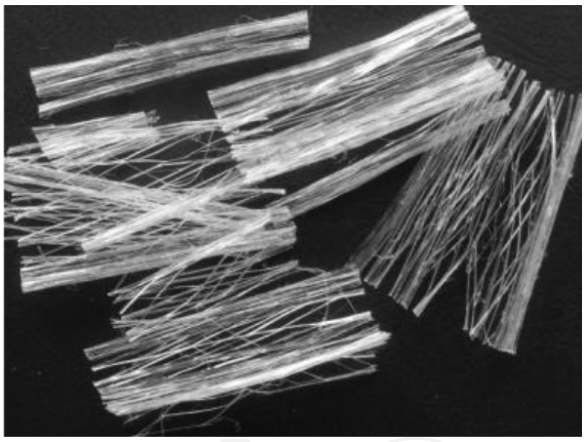


Figure 1. The network structure of polypropylene fibrillated fibres.

The fibrillated polypropylene fibres are produced since the early 1960s [50]. Because of relatively simple and inexpensive procedure as well as good mechanical properties, the production of such fibres became quickly a reasonable alternative for classical melt spinning. In next years, the technology was often used in the industrial practice and the fibres found a broad application on a large-scale production of sack cloth, ropes and carpet backing fabrics as well as agro-, geo- and different technical textiles.

The production of the fibrillated fibres is a multistage process. The process starts from the extrusion of the polypropylene melt through a flat die. The film is solidified by water quenching and then uniaxially drawn and thermally stabilised. Efficient quenching in liquid media allows higher stretching in subsequent proceedings steps. After stabilisation the film is cut into narrow tapes of width in the range of 1–20 mm and then split into fibrous material by needle roller fibrillation unit. Finally, the fibres are taken-up on the winding device. By cutting and splitting of fibres regular network-like structure is achieved (**Figure 1**). The particular operations and processing conditions have a considerable influence on the structure and final properties of the fibres [51]. By the change of the formation parameters fibres with various mechanical and thermal parameters can be obtained [52].

For the reinforcement of concrete the fibrillated fibres chopped to the specific length between few mm and tens mm are used. The thickness of commercially available fibres corresponding to the thickness of the film ranges from 15 to 100 μm. For fibres the width of the individual fibrils equals 100–600 μm. The fibres have the specific surface area in the range of 80–600 mm^2/mm^3. The Young's modulus of fibres is in the range of 3–5 GPa, what is many times lower than the modulus of cementitious materials (15–40 GPa). The tensile strength of used fibres is about 140–690 MPa [8].

2. Experimental study

2.1. Samples

Two series of polypropylene fibrillated fibres were obtained. Fibres were produced in industrial conditions in Bezalin SA (Bielsko-Biala, Poland). For the production DPM and Starlinger StarEx 1500 production lines were used. The fibres were formed from the commercial polypropylene resin Moplen HP 456 J (Orlen Polyolefins, Poland) characterised by melt flow index 3.4 g/10 min with addition (2%) of polyethylene Bralen FB 2-30 (Slovnaft Petrochemicals, Slovakia).

Polypropylene films were extruded through a flat die into water and then were cut into narrow strips. After drawing and heat stabilisation, the strips were locally cut with a needle roller and split with the final stretching unit. The fibres with the linear density of 1000 tex were produced.

For the first series produced on DPM line two draw ratios: 8.66 and 9.83 and three velocities of the needle roller: 150, 180 and 200 [m/min] were applied. For the second series produced on Starlinger StarEx 1500 line, two draw ratios: 10 and 12 and four velocities of the needle roller: 155, 175, 195 and 215 m/min were used.

Selected fibres from the first series characterised by the best mechanical parameters: the highest tenacity and the highest Young's modulus were cut into segments with the length of 19 mm and were used for the preparation of samples of reinforced of concrete. The standard cubic samples with dimensions 150 mm × 150 mm × 150 mm were prepared. The fibres were mixed with the concrete in proportion 0.9 kg of fibres per cubic metre of concrete. After formation the samples were cured for 28 days.

The fibrillated fibres selected from the second series were chopped to specified lengths of 5, 10 and 15 mm and were mixed with the cement mortar. The cement mortars were prepared using Portland cement CEM I 42,5 R, sand and tap water in accordance to EN 197-1:2002 and EN 197-2:2002 standards. The mixtures with different content of fibres: 0.25, 0.5, 0.75 and 1%

by weight were obtained. The components were mixed with the laboratory mixer Multiserw. Wet mortars were poured into the rectangular prism moulds with dimensions 40 mm × 40 × 160 mm and allowed to harden in the open space. Then the samples were cured in water for 28 days.

2.2. Methods

The morphology of fibres and their mechanical properties were investigated. The morphology of fibres was studied using a scanning electron microscope JEOL JSM 5500 LV. Observations were carried out for the fibres sputtered with gold in JEOL 1200 ionic sputter.

The mechanical parameters of the fibrillated fibres: tenacity, elongation at break and Young's modulus were determined according to PN-EN ISO 5079 standard. The measurements were performed using a tensile machine INSTRON 1026.

Workability of the fresh concrete, density and air content were investigated according to the Polish standards PN-EN 12350-2:2001, PN-EN 12350-6:2001 and 12350-7:2001, respectively. According to the Polish norm PN-EN 12390-3-2002, the compressive strength of concrete before and after 150 freeze-thaw cycles was measured. According to the Polish norm PN-88/B the investigations of water absorbability were performed.

Basic mechanical parameters of mortars: the compressive and bending strength were determined according to the norm EN 196-1:2006. The measurements were carried out by the TECNOTEST KE 200/A tensile machine. For comparison the plain mortar specimen without fibres was tested.

After mechanical tests the morphology of the interfacial area of broken samples was analysed. The studies were performed with scanning electron microscope JEOL JSM 5500 LV.

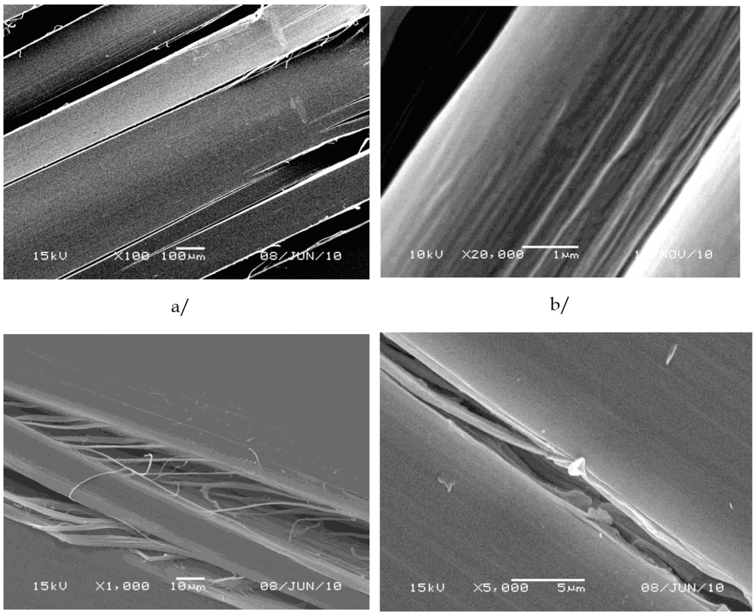
3. Results

3.1. The morphology, supermolecular structure and properties of fibrillated fibres

Figure 2 presents SEM microphotographs of the surface of the fibres. **Figure 2a** presents longitudinal cuttings on the polypropylene strips produced by the needle roller mounted before the final drawing unit. At higher magnifications on the surface of the strips the fibrillar structure is clearly visible (**Figure 2b**). Fibrils are closed packed and well oriented along the strips. The diameter of the fibrils equals ca. 0.1 μm.

After cutting the strips with the needle roller and drawing, the splitting of the fibrils is observed. Due to weak intermolecular forces in polypropylene the cuttings propagate easily. As a result, strips partially disintegrate into fibres connected together in a network-like structure formed from flat fibres with the rectangular cross section and the diameter approximately of 500 μm. Between the adjacent fibres many links are still observed (**Figure 2c**). By intense drawing the number of links between the fibres decreases (**Figure 2d**).

For the fibres drawn at ratio 9.83 the tenacity is slightly higher. For both series of fibres, drawn at 8.66 and 9.83, the largest tenacity exhibit the fibres produced at the smallest needle roller velocity 150 m/min. With the increase in roller velocity the tenacity of fibres slightly decreases. In comparison to the fibres drawn at 8.66, elongation at break for the fibres drawn at 9.83 is higher. For both series of fibres elongation at break does not change with the change in the needle roller velocity. Fibres drawn at lower ratio 8.66 possess lower value of the Young's modulus, which is independent of the needle roller velocity. For the fibres drawn at ratio 9.83 the value of Young's modulus is higher. The fibres produced at low needle roller velocity possess the highest value. With the increase in the roller velocity the Young's modulus decreases.



a/ b/ c/ d/

Figure 2. Surface morphology of fibrillated fibres: **(a)** longitudinal cuttings of polypropylene strips, **(b)** fibrillar structure of the strips, **(c)** links between adjacent fibres, and **(d)** splitting of fibres.

Table 1. presents mechanical parameters determined for the first series of investigated fibres.

Draw ratio	Needle roller velocity [m/min]	Tenacity [cN/tex]	Elongation at break [%]	Young's modulus [cN/tex]
8.66	150	37.5	32	1.92
	180	36.9	28	1.95
	200	34.7	30	1.89
9.83	150	38.0	21	3.2
	180	37.0	23	2.9
	200	37.0	23	2.7

Table 1. Mechanical parameters of fibrillated fibres produced on DPM line.

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Table 2. presents mechanical parameters determined for the second series of fibres produced on Starlinger StarEx 1500 line.

Draw ratio	Needle roller velocity [m/min]	Tenacity [cN/tex]	Elongation at break [%]	Young's modulus [cN/tex]
10	155	42.3	24.7	2.61
	175	41.7	24.9	2.55
	195	41.4	25.0	2.70
	215	39.0	25.3	2.40
12	155	49.0	22.8	3.55
	175	47.7	23.1	3.20
	195	42.5	21.6	3.40
	215	41.0	21.5	2.95

Table 2. Mechanical parameters of fibrillated fibres produced on Starlinger StarEx 1500 line.

For this series larger tenacity exhibits fibres drawn at ratio 12. The largest tenacity possesses fibres fibrillated at 155 m/min. With the increase in the needle roller velocity the tenacity of fibres decreases. The elongation at break for fibres drawn at the higher ratio 12 is minimally lower in comparison to fibres drawn at the ratio 10. The elongation at break does not significantly change with the change in the needle roller velocity. The Young's modulus of fibres drawn at the ratio 12 is higher than the modulus of fibres drawn at the ratio 10. By the increase in the needle roller velocity the Young's modulus decreases.

3.2. Reinforcement of concrete

Table 3 presents parameters determined for the fresh concrete.

Sample	Workability [cm]	Density [kg/m^3]	Air content [%]
Without fibres	13	2329	1.9
With fibres	10	2315	2.3

Table 3. Parameters of fresh concrete for samples prepared with and without fibres.

The workability of the fresh concrete with fibres is lower in comparison to the sample without fibres. Addition of fibres results in a decrease in the concrete density and an increase in the air content.

Table 4 presents parameters determined for the unreinforced concrete and concrete reinforced with fibres.

Sample	Compressive strength [MPa]		Strength decrement [%]	Water absorbability
	Before freezing	**After 150 freeze-thaw cycles**		
Without fibres	45.4	33.3	26.7	6.5
With fibres	43.7	35.7	18.3	4.7

Table 4. Parameters of concrete for samples unreinforced and reinforced with fibrillated fibres.

For the concrete reinforced with fibres the compressive strength is minimally lower.

The influence of fibres on concrete compressive strength was repeatedly investigated. It was revealed that the compressive properties of fibre-reinforced concrete are relatively less affected by the presence of fibres as compared to the properties under tension and bending [53]. Studies of Naaman et al. [54] showed that with the addition of fibres there is an almost negligible increase in strength for mortar mixes. Richardson [55] stated that the compressive strength of concrete containing polypropylene fibres is significantly reduced. Mindess [56] reported that the compressive strength of concrete reinforced with fibrillated fibres is increased by 25%. Parveen and Sharma [57] observed the increase in the compressive strength of concrete at low fibres dosage up to 0.2% and the reduction in compressive strength above 0.2%. Alhozaimy et al. [18] suggested that polypropylene fibres have no statistically significant effect on compressive strength of concrete. Similarly, Aulia [58] revealed that the use of a certain amount of fibres in the concrete does not influence detrimentally its main mechanical parameters.

After freeze-thaw treatment the compressive strength of the concrete decreases significantly. For the reinforced concrete the decrement of the compressive strength is much lower. After 150 cycles the compressive strength of reinforced concrete becomes higher in comparison to the unreinforced concrete. Simultaneously, after freezing and thawing cycles the water absorbability of the reinforced concrete becomes considerably lower. On the surface of the unreinforced concrete many cracks are observed. In contrast, on the surface of the fibre-reinforced concrete microcrackings are not visible.

The obtained results clearly show that addition of fibres delays the concrete deterioration caused by repetitive freeze/thaw cycles.

It is known that freezing is harmful to porous and brittle materials as concrete. The influence of freezing on the concrete was repeatedly investigated and some freezing and thawing theories of concrete were proposed [59]. In investigations the positive effect of polypropylene fibres on the concrete compressive strength after freeze/thaw action was documented [55, 60, 61].

The resistance of fibre-reinforced concrete to freeze/thaw cycles is explained by the formation of air void system. The fresh concrete, which contains fibres, reveals lower density and higher air content. When the paste dries out, due to retained water, or low bleed characteristics, in the concrete small water voids are created. Formation of fibres' water voids provides an air entrained system, which ensures subsequent freeze/thaw protection. Additionally in comparison to the surrounding concrete the fibres exhibit lower modulus of elasticity and lower density. When subject to freeze/thaw action the polypropylene yields under hydrostatic pressure before the concrete, thus providing further pressure relief. Richardson stated that fibres assist in blocking capillaries [60]. In this way fibres reduce water ingress, which contributes to lower water absorption of fibre-reinforced concretes.

3.3. Reinforcement of cement mortar

Table 5 shows the determined values of compressive and bending strength of cement mortars with fibres by different fibres' length and different fibres' dosage. For all fibres, regardless of the length of the fibres and their content, the compressive strength does not significantly change. The determined values are close to the compressive strength of the plain mortar [62].

Similarly as for reinforced concrete the influence of fibres on the compressive strength of mortars is less visible.

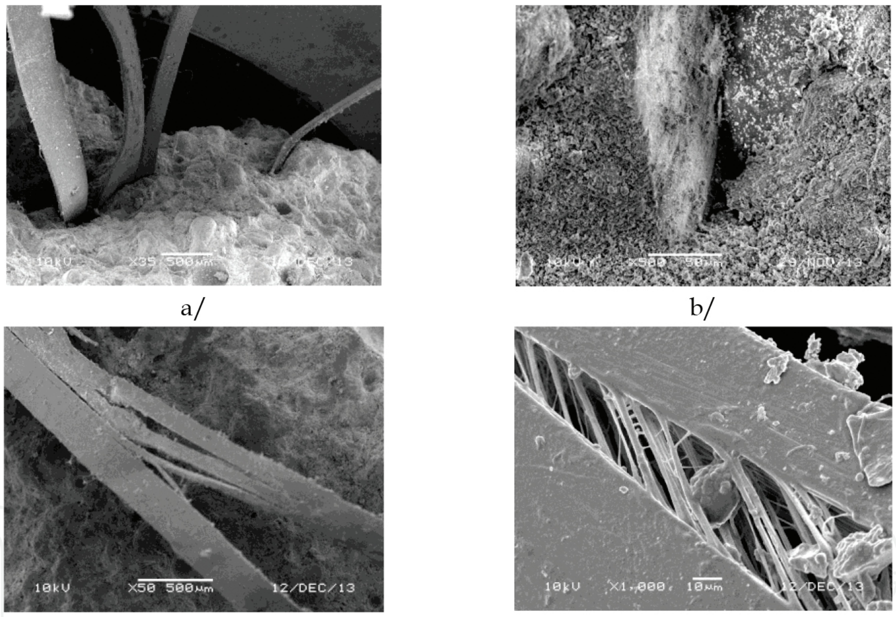

Figure 3. The SEM microphotographs of the fracture of mortars reinforced with fibrillated fibres. **(a)** Fibres anchored in the matrix, **(b)** the hole in the cement matrix after pulling out the fibres, **(c)** splitting of fibres, and **(d)** fibrillation of fibres.

The effect of fibres is more pronounced in the case of the bending strength. For mortars reinforced with the short and medium length fibres the bending strength is higher than the strength of the plain mortar. For these fibres with the increase in the fibre content till 0.75% the bending strength increases and then at the highest content decreases. For the longest fibres the bending strength is comparable with the strength of the plain mortar. At the lowest dosage the bending strength is the highest. At medium dosages the bending strength is lower and then at the highest dosage is higher again.

In **Figure 3**, SEM microphotographs of fractures of samples after the mechanical tests are presented. In the pictures, the fibres' ends with different lengths, which protrude in different directions from the cement matrix, are visible (**Figure 3a**). Particular fibres 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. In the second microphotograph the hole in the matrix, which remains after pulling out of fibres, is visible (**Figure 3b**).

One can observe that in the concrete the network structure of the fibrillated fibres is partially opened. Simultaneously further splitting into smaller particular fibrils is observed (**Figure 3c**). As a result of these processes the specific surface area of fibres increases, what significantly enhances their adhesion ability.

Length [mm]	Content [%]	Compressive strength [MPa]	Bending strength [MPa]
No fibres	–	16.3	5.5
5.0	0.25	16.5	5.8
	0.50	16.3	6.0
	0.75	16.4	5.6
	1.00	16.0	5.4
10.0	0.25	16.2	5.2
	0.50	16.3	6.0
	0.75	16.1	6.2
	1.00	16.3	5.8
15.0	0.25	16.2	5.9
	0.50	16.1	5.5
	0.75	16.1	5.3
	1.00	16.2	5.6

Table 5. The compressive and bending strength of reinforced mortars by different fibres' content and lengths.

Moreover, it is seen that the mortar ingredients can penetrate in the mesh between the individual fibrils and create additional mechanical bonds between fibres and matrix (**Figure 3d**).

In previous investigations it was revealed that the opening of the network structure and splitting contribute to the fibres matrix interaction and support mechanical anchoring of fibres in the matrix [63]. Bentur et al. stated that by the use of fibrillated fibres two effects contribute to the fibre-matrix interaction: interfacial adhesion and mechanical anchoring. The first is

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apparently due to the intimate contact at the interface and the dense matrix developed in the transition zone. The second is associated with a combination of filamentising, where the fibres separate into multifilament strands, branching of fibrils and forming tiny fibrillations on the fibres' surface [64].

On the basis of obtained results one can conclude that during bending the pulling out of fibres' ends occurs. At the beginning of bending the interfacial zone is deformed. Due to the high difference in Young's modulus, 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 (**Figure 4**).

The highest bending strength was registered for fibre length of 10 mm and the fibre 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% ensures the sufficient number of connections sewing lips of the crack.

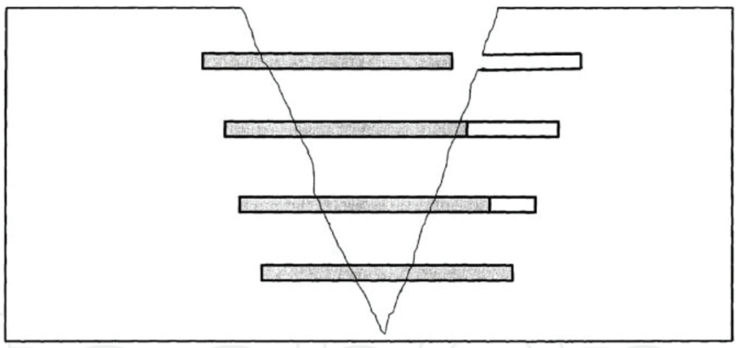

Figure 4. The mechanism of fibres/matrix interaction during bending.

4. Conclusions

The mechanical parameters of fibrillated polypropylene fibres are strongly influenced by the formation parameters. High draw ratio and low needle roller velocity promote formation of fibres with high tenacity and high Young's modulus. By optimizing the formation parameters, the appropriate fibres for the reinforcement of concrete can be produced.

Fibres added to the concrete improve the parameters of a fresh concrete. Fibres have a relatively little effect on the compressive strength of concrete before freezing. The beneficial effect of fibres is revealed after freezing and thawing cycles. After multiple freeze/thaw cycles the compressive strength of reinforced concrete exceeds the strength of plain concrete. Simultaneously, the reinforced concrete exhibits lower water absorbability.

The fibrillated fibres do not affect the compressive strength of the reinforced cement mortars. Independently on the fibres' length 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 increase in the bending strength results from enhanced interfacial adhesion and mechanical anchoring, which results from opening of the network structure and splitting of fibrillated fibres.

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