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COMPOSITES THEORY AND PRACTICE

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ALTERNATIVE WAYS OF REINFORCING CEMENT COMPOSITES

This paper presents the results of laboratory research on concrete beams with alternative types of reinforcement, assuming a constant volume of fibers. As the reinforcement of the cement matrix, two types of macro-fibres, namely steel and polypropylene fibres, were used. In addition, traditional beam reinforcement in the form of aligned, smooth, and ribbed steel rods were tested. In the case of the long fibers-the steel bars were assumed to force the long fibers to adopt a certain position - four rods at the corners of the cross section, two of which were in the tension zone and two in the compression zone. By introducing a slip sleeve in three stirrups to stabilize the transverse bars in the desired position, efforts were made to ensure the independent operation of each of the four rods. It was shown that the highest load-carrying capacity and the toughness of the composite, was obtained for concrete beams reinforced with ribbed steel rods. Unexpectedly, the beams with the polypropylene fibers and smooth steel rods showed substantial susceptibility to deflection. In both cases good interaction between the reinforcement and cement matrix was observed. The fracture toughness of the reinforced concrete and steel synthetic macrofibres in the share volume was comparable to 1.65% as documented by an equivalent flexural strength.

Keywords: **fibres reinforced concrete, short steel fibres, short polypropylene fibres, steel rods, the mechanical properties, the load-carrying ability**

ALTERNATYWNE SPOSOBY WZMACNIANIA KOMPOZYTÓW CEMENTOWYCH

Przedstawiono wyniki badań belek betonowych z alternatywnymi formami zbrojenia, przyjmując stały poziom objętościowy włókien. Jako wzmocnienie matrycy cementowej zastosowano dwa rodzaje krótkich włókien, włókna stalowe i włókna polipropylenowe rozproszone równomiernie w matrycy cementowej. Dodatkowo zastosowano tradycyjne zbrojenie belek w formie długich prętów stalowych gładkich i żebrowanych. W przypadku włókien długich - prętów stalowych przyjęto wymuszone położenie długich włókien - 4 pręty w narożach przekroju poprzecznego, z których dwa znalazły się w strefie rozciąganej i dwa w strefie ściskanej. Poprzez wprowadzenie tulei poślizgowych w 3 strzemionach poprzecznych, utrzymujących pręty w wymaganym położeniu, starano się zapewnić niezależną pracę każdego z czterech prętów. W wyniku przeprowadzonych badań stwierdzono, że najwyższą nośność i odporność na pękanie kompozytu wykazywały belki betonowe wzmacniane żebrowanymi prętami stalowymi. Nieoczekiwanie, belki modyfikowane włóknami polipropylenowymi i gładkimi prętami stalowymi wykazały znaczną podatność na odkształcenie. W obu przypadkach obserwowano bardzo dobre współdziałanie zbrojenia z matrycą cementową. Z kolei odporność na pękanie betonów wzmacnianych makrowłóknami syntetycznymi i stalowymi w udziale objętościowym 1,65% była porównywalna, co potwierdziły wyniki równoważnej wytrzymałości na zginanie.

Słowa kluczowe: **beton wzmacniany włóknami, krótkie włókna stalowe, krótkie włókna polipropylenowe, pręty stalowe, właściwości mechaniczne, nośność**

INTRODUCTION

Despite the increasing interest in cement composites modified with dispersed fibres by the end of the 20^{th}century (70.), only steel fibres reinforced concrete, mainly industrial ground floors, have been extensively developed [1-6]. However, the variety of research focused on brittle matrix composites with fibre reinforcement, functioning under different external and climatic conditions, contributed to creating universal investigative procedures, which have been described in American, Japanese, and European standards [7]. On the other hand, environmental interactions, such as concrete aging processes and the necessity to guarantee increasing requirements for construction safety (fires, explosions, impacts, and corrosion processes) have led to the growing interest in non-metallic fibres. Unlike steel fibres, non-metallic ones, such as polymer-based fibres [8-10], exhibit good resistance to environmental factors, durability of their own structure in the alkaline environment of the cement paste and good mechanical properties, especially in relation to their low bulk density. Our previous research showed that polypropylene fibres added to the cement matrix in the amount above 0.5 vol.% improved the flexural toughness of the composites as well as steel fibres do. However, the positive influence of synthetic fibre reinforcement was observed only at the initial time of hardening. In longer periods better flexural parameters were obtained for cement composites modified with steel fibres [11].

The main aim of this paper was to compare traditional steel rods reinforcement of concrete beams with randomly dispersed steel and polypropylene macro-fibres introduced to the cement matrix in a constant volume fraction. Contrary to the former research, fibrillated polypropylene fibres characterised by a higher modulus of elasticity and higher tensile strength, as well as hooked steel fibres, were applied.

EXPERIMENTAL PROCEDURE

The cement matrix was produced using Portland cement CEM I 52.5 R (350 kg/m^3), a fine aggregates fraction 0/2 (664 kg/m^3), and coarse aggregates fraction 2/16 (1234 kg/m^3). To achieve approximately the same workability of fresh mix, a superplasticizer in the amount of 2 wt.% was used. The water to cement ratio was assumed at the level of 0.43. The examination of the cement matrix composites distinguishes concrete elements reinforced with steel rods, and separately those reinforced with randomly dispersed steel and polypropylene fibres in a constant volume fraction. In the presented research, the following 5 series of cement composites were examined:

1. without reinforcement
2. with polypropylene fibres with diameter 0.069 mm and length 54 mm (aspect ratio 782)
3. with hooked steel fibres with diameter 1 mm and length 50 mm (aspect ratio 50)
4. with ordinary smooth steel rods with diameter 6 mm and length 390 mm (aspect ratio 65)
5. with finned higher performance steel rods with diameter 6 mm and length 390 mm (aspect ratio 65)

One of the main purposes of the presented research was to compare the traditional steel rods reinforcement with randomly dispersed macro-fibres. Therefore, in the research procedure, the same volume fraction of steel rods as well as polypropylene and steel macro-fibres was assumed (1.65 vol.%). Moreover, in the presented research it was proposed that the steel rods are movable. The four steel rods were placed in the corners of the cross section in a constant orientation. To ensure the independent interaction of each steel rod with the cement matrix, joining slip sleeves in three lateral stirrups were applied. As a result of such a solution, one-direction steel rods reinforcement was changed partially to three-dimensional. The analogy concerning the uniform distribution of macro-fibres and steel rods is presented in Figure 1. Figure 2 shows the stirrup with the slip sleeves.

In the case of the short fibres reinforced concrete, the fibres were uniformly distributed throughout the cement matrix, and; furthermore, they were randomly oriented. The physico-mechanical properties of the steel and polypropylene macro-fibres are presented in Table 1.

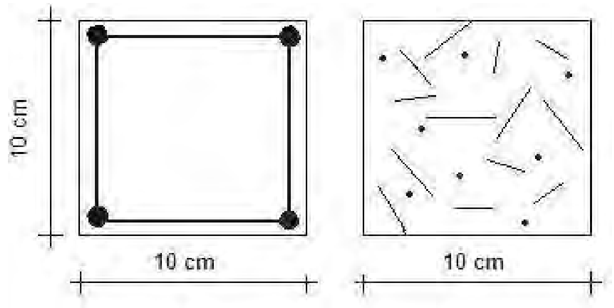

Fig. 1. Cross-section of concrete beams with aligned and short reinforcement distributed in volume unit

Rys. 1. Przekrój poprzeczny belki betonowej ukazujący charakter rozłożenia długich i krótkich włókien na jednostkę objętości

Fig. 2. Stirrup with slip sleeves in corners to enable proper interaction between steel rods and cement matrix

Rys. 2. Strzemię z tulejami w narożach dla zdystansowania prętów podłużnych i umożliwienia ich poślizgu w matrycy cementowej

TABLE 1. **Physico-mechanical properties of steel and polymer macro-fibres**

TABELA 1. **Fizykomechaniczne właściwości krótkich stalowych i polimerowych włókien**

	Steel fibres	Polypropylene fibres
Length [mm]	50	54
Diameter [mm]	1	0.069
Aspect ratio	50	782
Density [kg/dm^3]	7.85	0.91
Elongation at break [%]	< 4	>20
Tensile strength [N/mm^2]	1225÷1345	620÷758
Young's modulus [N/mm^2]	±210 000	aprox. 4900

There are several methods of determining the flexural toughness of composite elements with fibre reinforcement. According to American standards C 1018, the flexural toughness of fibre reinforced concrete is defined as the ratio of the area under the load-deflection curve out to a specified deflection to the area under the curve out to the point of the first crack, as can be seen in Figure 3. Based on the load-deflection curve, toughness indices I_5, I_{10} and I_{20}can be specified. Moreover, in this method, the residual strengths in definite deflections $R_{5,10}$ and $R_{10,20}$ can be calculated.

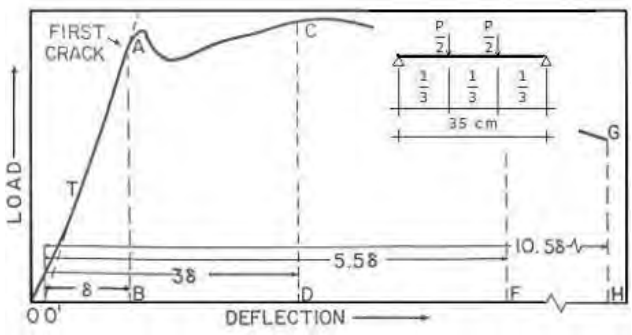

Fig. 3. Load-deflection curve according to standard [ASTM C1018]

Rys. 3. Schemat obciążeń i zależności obciążenie-ugięcie zgodnie z normą [ASTM C1018]

Alternatively to the American standards, the load-carrying capacity of fibres reinforced concrete can be determined by measuring the average residual strength, which corresponds to the equivalent flexural strength. In this case, the toughness factor is defined as the total area under the load-deflection curve out to deflection L/150 (Japanese standards JSCE SF-4).

In the presented research, the concrete beams with the proposed aligned and short reinforcement were examined according to the procedure described in the ASTM C1018 standard. The flexural tests were performed on beams with dimensions of 100×100×400 mm in the four-point bending method, while the compressive tests were conducted on specimens with dimensions of 100×100×100 mm. All the mechanical tests were carried out by means of the press machine Instron-SATEC as shown in Figure 4.The flexural behaviour of fibres reinforced concrete was characterized by the following parameters: maximum load, ultimate flexural strength, deflection at maximum load, energies at maximum load and at maximum deflection.

Fig. 4. Stand for testing beams

Rys. 4. Stanowisko do badań belek

RESULTS AND DISCUSSION

Figures 5 to 9 show the load-deflection curves obtained from a four-point bending test for specimens made with plain concrete (Fig. 5), concrete with the polypropylene (Fig. 6) and steel fibres (Fig. 7), as well as concrete with aligned smooth and ribbed steel rods (Figs. 8 and 9, respectively). Moreover, the values of maximum strength, stress, and deflection as well as the values of energy required for the maximum flexural strength and deflection were presented in Table 2.

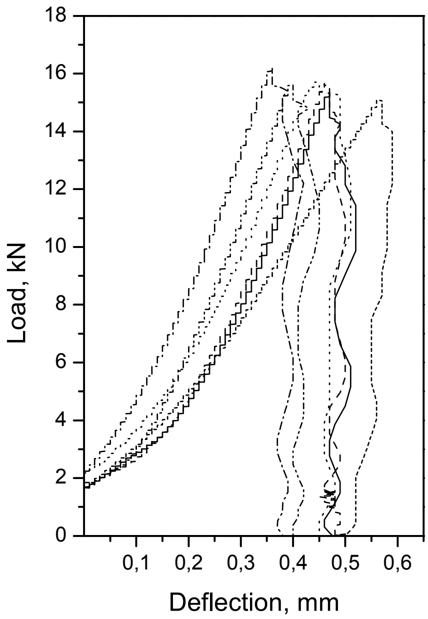

Fig. 5. Beams without reinforcement

Rys. 5. Belki bez zbrojenia

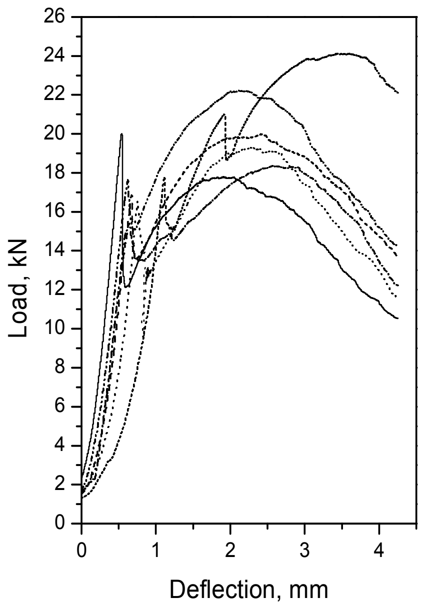

Fig. 6. Beams with polypropylene fibres

Rys. 6. Belki z włóknami polipropylenowymi

The data presented in Figures 5-9 show that there is a considerable difference in the post-cracking behaviour of concrete beams reinforced with the proposed reinforcement. It was observed that beams without reinforcement demonstrated the lowest load-carrying capacity, defined as the ability of an element to carry an external load over a specific deflection interval.

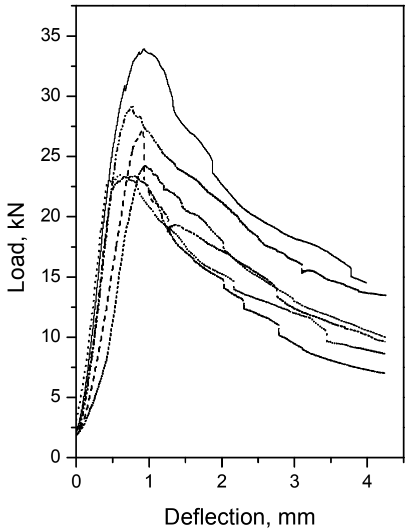

Fig. 7. Beams with steel fibres

Rys. 7. Belki z włóknami stalowymi

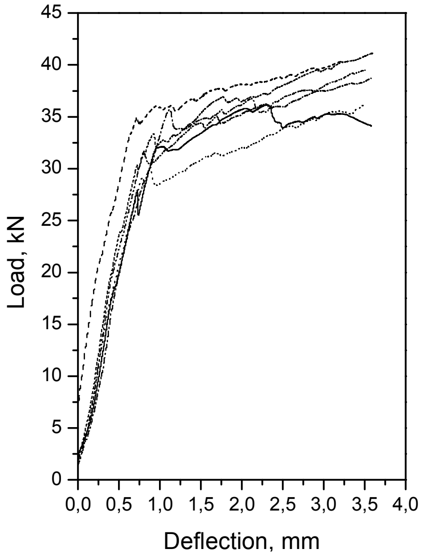

Fig. 8. Beams with smooth steel rods

Rys. 8. Belki z prętami gładkimi

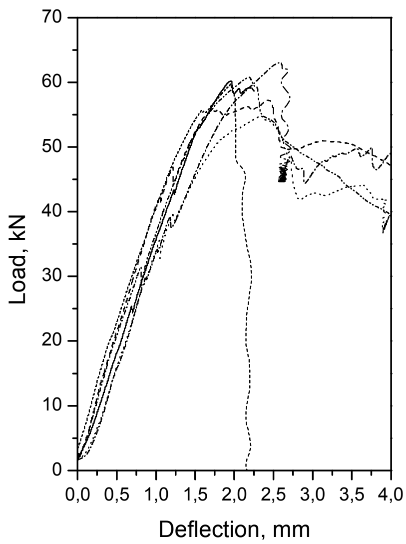

Fig. 9. Beams with ribbed steel rods

Rys. 9. Belki z prętami żebrowanymi

TABLE 2. **Comparison of mechanical parameters for concrete beams obtained during bending tests**

TABELA 2. **Porównanie parametrów wytrzymałościowych dla betonowych belek otrzymanych podczas zginania**

	Concrete beams				
	without fibres	with PP fibres	with steel fibres	with smooth steel rods	with ribbed steel rods
Maximum load [kN]	15.59 ±0.38	20.68 ±2.12	26.89 ±4.14	38.68 ±2.10	59.30 ±2.90
Ultimate flexural strength [MPa]	5.46 ±0.13	7.24 ±0.74	9.42 ±1.45	13.54 ±0.73	20.76 ±1.02
Maximum deflection [mm]	1.50 ±0.18	3.01 ±0.99	1.62 ±0.20	4.79 ±0.52	3.26 ±0.29
Energy at maximum load [J]	4.50 ±0.61	34.34 ±17.6	13.89 ±3.75	104.17 ±20.09	83.31 ±12.63
Energy at maximum deflection [J]	5.17 ±0.57	67.88 ±6.20	69.29 ±12.05	111.67 ±5.78	139.4 ±42.70

The highest load-carrying capacity and toughness of the composites were observed for the concrete beams reinforced with ribbed steel rods, followed by smooth steel rods, steel fibres, and the polypropylene had the lowest. However, this dependence was not noticed for the deflection and the energy at maximum load. In the concrete beams without fibre additives, the ultimate strength caused a one-point crack and a violent fracture at the deflection of 1.5 mm. The beams with steel fibres cracked in the same way (at deflection of 1.62 mm); in spite of this, in the post-cracking zone, the specimen showed a high load carrying capacity. Beams with ribbed steel rods exhibited relatively low flexibility to bending. In this situation, the beams deflection was blocked by the ribbed texture of the steel rods due to the flexural and shear interaction. Unexpectedly, the beams with polypropylene and smooth steel rods showed substantial susceptibility to deflection. In both cases, a good interaction between the reinforcement and cement matrix was observed. In the post-cracking zone, the beams with polypropylene fibres and smooth steel rods were characterised by a higher load-carrying ability of the composites as well.

The dependence of crack morphology in relation to the different types of reinforcement is presented in Figure 10. In beams 1 and 3, one distinct crack occurred - approximately in the central part of the beam. In beams 2 and 4 - despite the different types of reinforcement, there are two narrower cracks in two places, which is very advantageous taking into account bending and the relatively slow loss of load capacity of the cracked cross-section. Beam 5 must be treated independently. In this case, the initial propagation of numerous tiny cracks were observed and the next crack was caused by shearing (from lower to upper support) appeared.

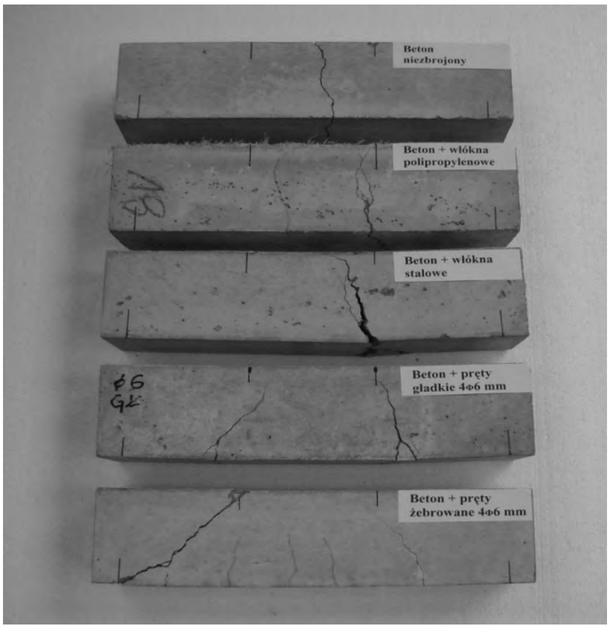

Fig. 10. Morphology of cracks in relation to different types of reinforcement

Rys. 10. Morfologia rys dla różnych rodzajów zbrojenia

In Table 3 the values of compressive strength obtained for the concrete beams with short polypropylene and steel fibres are presented. It was shown that unlike steel fibres, the polymer ones added to the cement matrix in a high volume fraction deteriorated the compressive strength of the composite. In addition, the polymer fibres negatively influenced the workability of the fresh concrete mix.

TABLE 3. **Comparison of compressive strength for concrete specimens**

TABELA 3. **Porównanie wytrzymałości na ściskanie dla kostek betonowych**

	Volume density [kg/dm^3]	Compressive strength [MPa]
Plain concrete	2.43	69.5
Concrete with polypropylene fibres	2.37	55.3
Concrete with steel fibres	2.44	69.0

The examples of load-deflection dependances recorded for the concretes reinforced with steel and polypropylene macro-fibres are shown in Figure 11. The comparison of the post-cracking zone for the studied composite clearly indicates that in the case of synthetic fibres, the flexural toughess of the composite is similar to the flexural toughness obtained for the cement matrix reinforced with steel fibers. Confirmation of the above assumption are the values of equivalent flexural strength calculated using the following equation:

$$f_{eq} = \frac{T_b L}{\delta_b b h^2}$$

where: T_b - area under load-deflection curve, to deflection value δ_b equal to 1/150 beam span, Nmm; L - beam span, mm; b - beam width, mm; h - beam hight, mm.

The values of particular flexural strengths and equivalent flexural strengths for concrete samples with polypropylene and steel fibres are presented in Table 4.

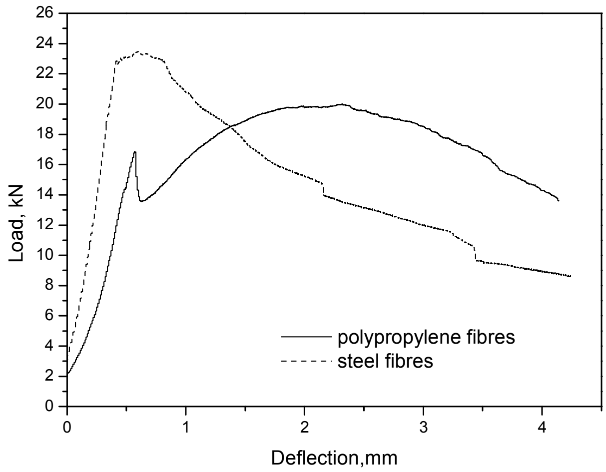

Fig. 11. Comparison of load-deflection curves for concrete beams reinforced with steel and polypropylene macro-fibres

Fig. 11. Porównanie krzywych obciążenie - ugięcie dla belek betonowych wzmacnianych makrowłóknami stalowymi i polipropylenowymi

TABLE 4. **Comparison of flexural strength and equivalent flexural strength of macro-fibres reinforced concrete**

TABELA 4. **Porównanie wytrzymałości na zginanie i wytrzymałości równoważnej dla betonów wzmacnianych makrowłóknami**

No.	1	2	3	4	5	6	average
Concrete with polypropylene fibres							
f_{fl} [MPa]	7.00	7.00	6.76	6.43	7.79	8.45	7.24±0.74
f_{eq} [MPa]	9.19	10.17	9.27	9.30	11.18	11.14	10.04±0.94
Concrete with steel fibres							
f_{fl} [MPa]	11.88	9.51	8.22	8.19	10.20	8.49	9.42±1.45
f_{eq} [MPa]	13.00	9.43	9.24	8.47	11.93	9.44	10.25±1.78

f_{fl} - flexural strength, f_{eq} - equivalent flexural strength

CONCLUSIONS

The flexural behaviour of concrete beams modified with short and aligned reinforcement have been studied in this research. The achieved results clearly showed that there was a considerable difference in the post-cracking zone depending on the type of concrete reinforcement. Among the four types of reinforcement, the beams with the ribbed steel rods were the most effective in carrying a load over a specific deflection interval after cement matrix cracking. Furthermore, it has been demonstrated that the beams with polypropylene and smooth steel rods showed substantial susceptibility to deflection. In both cases, good interaction between the reinforcement and cement matrix was observed. In addition, in the post-cracking zone, the beams were characterised by a high load-carrying ability of the composites. Depite the lower flexural strength, the composites modified with polypropylene macro-fibres exhibited a similar flexural toughness to those composites reinforced by steel fibres. The comparison of the equivalent flexural strength confirmed this statement.

REFERENCES

[1] Tatnall P.C., Kuitenbrouwer L., Steel fiber reinforced concrete in industrial floors, Concrete Int. 1992, 12, 43-47.

[2] Altoubat S.A., Roesler J.R., Lange D.A., Rieder K.-A., Simplified method for concrete pavement design with discrete structural fibers, Constr. Build. Mat. 2008, 22, 384-393.

[3] Jasiczak J., Posadzki przemysłowe, Addiment Polska Sp. z o.o., Poznań 2001.

[4] Jamroży Z., Betony ze zbrojeniem rozproszonym, Materiały XVII Ogólnopolskiej Konferencji, Warsztaty Pracy Projektanta Konstrukcji, Tom I, Ustroń 2002.

[5] Glinicki M.A., Testing of macro-fibres reinforced concrete for industrial floors, Cement Wapno Beton 2008, 4, 184--195.

[6] Zollo R.F., Fiber-reinforced concrete: an overview after 30 years of development, Cem. Concr. Comp. 1997, 19, 107--122.

[7] Bentur A., Mindess S., Fibre reinforced cementitious composites, Taylor & Francis, London and New York 2007.

[8] Zheng Z., Feldman D., Synthetic fibre-reinforced concrete, Prog. Polym. Sci. 1995, 20, 185-210.

[9] Pichór W., Dyczek W., Interfacial bond strength between cement paste and synthetic fibres, Cement Wapno Beton 1999, 1, 18-21.

[10] Lee S. M., Handbook of Composites Reinforcement, VCH Publisher, New York 1993.

[11] Ślosarczyk A., The influence of non-metallic and metallic fibres on the mechanical properties of cement mortars, Brittle Matrix Composites 10, Proceedings of the 10 International Symposium, Cambridge-Warsaw 2012, 167--176.

