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Original Research Paper

Influence of polyolefin fibers on the strength and deformability properties of road pavement concrete

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HIGHLIGHTS

- New type of fibers was investigated in road pavement concrete.
- Fibers introduction method was shown as a way to improve fibers uniform distribution.
- Strength and deformation properties with W/C ratio within 0.31–0.55 were investigated.
- Maximum abrasion decrease was observed in concrete with W/C ratio within 0.44–0.55.
- Results can contribute to the rational use of fibers in road pavement concrete.

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ABSTRACT

Influence of the type and quantity of polyolefin fibers on the strength properties (compression strength, tensile strength in bending, strength in uniaxial tension), the deformation properties (elastic modulus, Poisson's coefficient) and the abrasion resistance of cement concrete with water-to-cement ratio within 0.31–0.55 were stated in the paper. The ways of fibers introduction into fresh concrete were investigated. It was shown that the fibers introduction method and procedure of mixing are the ways to improve the fibers uniform distribution in fresh concrete. The increase of the bending tensile strength and the uniaxial tensile strength of concrete with fibers reinforcement in comparison with the reference concrete was observed with the water-to-cement ratio decrease. The increase of uniaxial tensile strength at age of 28 days for concrete with macrofibers in amount of 4.5 kg/m^3 was 23% and 29%; for macrofibers in quantity of 3 kg/m^3 was 19% and 26% with water-cement ratio equal to 0.49 and 0.31, respectively. The maximum reduction of abrasion in the range of 7.5%–10% was observed in concrete with water-to-cement ratio within 0.44–0.55 for all investigated types of fibers. The influence of fibers on the concrete abrasion with lower W/C ratio was negligible. The results can contribute to the rational use of modified polyolefin fibers in road pavement concrete.

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1. Introduction

Normative characteristics of road cement concrete (hereinafter "concrete") are a tensile in bending strength class, compressive strength class; modulus of elasticity; frost resistance; coefficient of linear thermal deformation; Poisson's ratio (Guidelines for the design of rigid pavements, 2003).

The following design layers are distinguished in road pavements: covering - upper part of the pavement perceiving stress from the car wheels and exposing the direct influence of atmospheric factors; base (foundation) - part of the pavement providing together with the coating redistribution and reduction of pressure on the underlying supporting layers or soil subgrade; additional layers of base – layers between the base and the soil subgrade. Additional layers of base perform frost resistance, drainage and heat insulation functions.

The foundations made of fiber reinforced concrete are arranged for structures with asphalt covering as well as for structures with cement concrete covering. Cement concrete covering can also be made of fiber reinforced concrete. Road fiber reinforced concrete in Russia are designed with the following requirements: compressive strength class: B20–B60; tensile in bending strength class: $B_{tb}1.2$-$B_{tb}4.4$; frost resistance: F25–F200. In accordance with the requirements of the Russian normative documents the service life of pavements with the cement concrete covering must be at least 25 years, for pavements with asphalt covering on a concrete base must be at least 20 years. However, the issue of increasing the service life of pavement is very serious.

It is required to design pavements for the long term based on technical and economic considerations, with a lifespan of 35–50 years. Significant increase in durability can be accomplished through the use of high-strength concrete with increasing the tensile in bending strength class up to $B_{tb} = 5.2–6.4$ or increasing the thickness of the structures up to 28–30 cm. However, any increase in the basic characteristics should be ensured the increase of the coating service life. On the above mentioned, the relevant issue is the tensile in bending strength increase through the use of modern polymeric fibers. This application requires extensive research.

Major studies have been conducted in the field of the development of road pavement fiber reinforced concrete to improve the mechanical properties such as compressive strength, tensile strength, frost resistance with polypropylene-based fibers (Nobili et al., 2013), with steel fibers (Achilleos et al., 2011; Graeff et al., 2012). Steel fibers contribute to the significant improvement of deformation performance of concrete whereas steel fibers have such disadvantage as corrosion. There is a need for the application of fiber reinforced concrete on the basis of synthetic fibers in road construction.

For the critical structures different types of fibers can be used such as fibers based on steel, organic and inorganic materials (Kharitonov and Shangina, 2012; Alberti et al., 2017). Fibers vary by shape, length, superficial roughness, etc. Polyolefin fibers have a higher impact/static strength ratio and toughness factor in comparison with steel fibers (Banthia et al., 1999a; b). Alberti et al. (2016) stated that the pull-out work and load of polyolefin fibers were similar to steel fibers.

Scanning electron microscopy analysis shows that the bond between polyolefin fiber and hardened cement paste is mainly mechanical (Yan et al., 1998, 2000). In the study done by Tagnit-Hamou et al. (2005) the microstructural observations show the bond evolution between cement matrix and polyolefin fibers because of the exothermic nature of the hydration reaction generates a partial penetration of hydrates into the fiber and bond quality increases according to hydration time. In the study done by Enfedaque et al. (2017) the bond improver admixture increased the interfacial properties of the fiber-matrix interface that became the reason of increase of the post-cracking loads.

Polyolefin fiber is a new commercial synthetic product. It provides an opportunity to produce cement composites without fibers' clots. Modern co-extrusion processes make the production of sheath/core type fibers possible. Such so-called bi-component fibers consist of two different polymers namely the core which is covered by the sheath of specific thickness. This leads to the optimization of surface and core material. Furthermore, expensive components may be used at a reduced volume either in the sheath or in the core only (Cho et al., 2000; Kaufmann et al., 2007; Zhao and Wadsworth, 2003).

The polyolefin fibers are hydrophobic since they do not absorb water and have the surface which cannot be wetted (Chatterji et al., 2001; Pyle, 2001). So the friction between fibers and cement matrix can be enhanced by the increase of density of hardened cement paste and accordingly decrease of the water-to-cement ratio or adding supplementary cementitious materials.

The bond strength between the fiber and cement matrix as well the associated interfacial friction are the main sources hindering fiber movement (Yan et al., 1998). The stress versus strain curves indicate that specimens containing polyolefin fibers and silica fume have higher direct tensile strength. The area under the tensile loading-strain curves of concrete represents the strain capacity and toughness. When water-to-cement ratio (W/C) equals to 0.55 the strain capacity of specimens increased up to 260%. When a lower W/C ratio equals to 0.35, the strain capacity of specimens increased up to 493% (Han et al., 2012). The composites with high strain capacity and toughness demonstrated a greater ability to arrest cracking.

Relatively low bond strength less than about 1 MPa was obtained between different polyolefin fibers and cement matrix with pull-out tests in paper (Kaufmann et al., 2007). The compositions of six kinds of fibers and their properties were

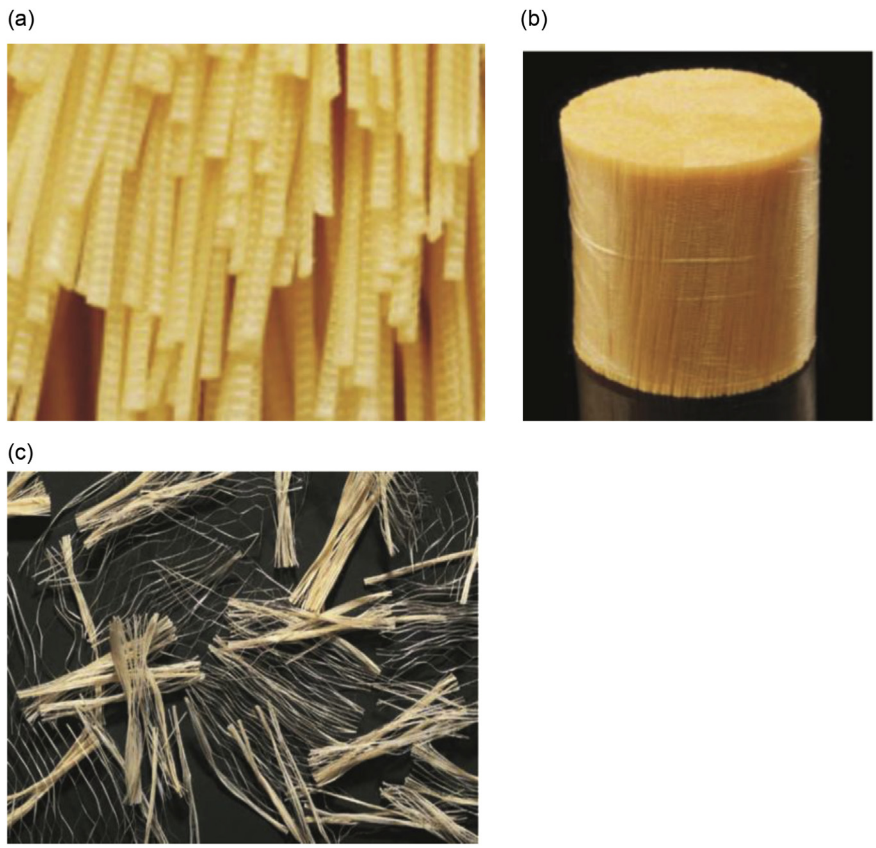

Fig. 1 — Fibers. (a) The appearance of macrofibers. (b) Convenient packing of macrofibers using the water-soluble film. (c) Fibrillated microfibers.

studied. The fibers contained either of polypropylene (PP) or high density polyethylene (HDPE) as the base polymer. For some fibers mineral fillers were added to increase the modulus of elasticity and the hardness of the surface. A chemical bond by hydration reaction of these mineral fillers with the cement matrix was not expected as the fillers generally were covered by a thin non-reactive polymer film. Fiber surface was generally very smooth with the exception of fiber B (core = 100% PP/sheath = PP + microglass) with rough surface. Best peak values were found for fiber B with a rough surface (Kaufmann et al., 2007). This confirms once again that the bond mechanism between different polyolefin fibers and cement matrix is mechanical. One can assume that the densification of the hardened cement paste must increase this mechanical bond. The hydration of cement paste can be a factor in the densification.

Thus, according to the published results on testing the concrete with polyolefin fibers it is complicated to do the definitive conclusions about their influence on the properties of concrete. Often published results vary among different authors as the results were obtained by using only one type of concrete composition or a fiber mode of introduction. The properties of road pavement concrete of B22.5-B50 strength classes (compression strength, tensile strength in bending, strength in uniaxial tension, elastic modulus, Poisson's coefficient, the abrasion resistance) depending on water-to-cement ratio, type and quantity of polyolefin fibers as well the ways of fibers introduction into fresh concrete were investigated in the paper. The results make it possible to establish the new dependencies of the influence of polyolefin fibers and water-to-cement ratio on the main properties of road pavement concrete.

2. Materials and methods

Currently the new synthetic fibers are developed. The use of these fibers in road pavement concrete requires further investigation. Synthetic bicomponent polyolefin-based macrofibers Concrix ES (Brugg Contec AG) were used in the research and named as macrofibers in the paper (Fig. 1). The technological process of production has physical and chemical modification of this macrofibers with the purpose of giving mechanical strength to the fibers and chemical reaction activity of the fibers surface to the products of cement hydration. The core and shell of macrofibers consist of different synthetic polymers. The fiber core material has high strength characteristics, high modulus of elasticity. The fiber shell material has higher adhesion to the cement matrix. The surface roughness of macrofibres can also increase the fiber adhesion with cement stone.

Fibrillated polyolefin-based microfibers Fibrofor High Grade (Brugg Contec AG) were also used and named as microfibers in the paper (Fig. 1(c)). The macrofibers and microfibers had the following characteristics according to Table 1 (Bruggcontec, 2017). Fibers are certificated according to EN-14889.

Portland cement CEM I 42.5 was used as a binder for concretes of bases and coverings for road pavements. Crushed granite of fractions 5–10 (33%) and 10–20 (67%), river sand were used.

The workability of all mixtures was within 10–14 cm (slump) and was adjusted with polycarboxylate-based superplasticizer in quantity of 0.6%–0.8%. Coarse or fine-grained concretes should be used for coverings and bases of pavements according to requirements, which are presented in the Table 2 (Guidelines for the design of rigid pavements, 2003).

The minimum frost resistance should be taken according to the requirements of Table 3.

Investigation of the effect of selected fibers on concrete characteristics was carried out for the B22.5-B55 concrete strength classes, water-to-cement ratio in the range from 0.55 to 0.31 (Table 4). Three samples were tested for each composition.

Table 2 – Requirements to coverings and bases of pavements.

The structural layer of the pavement	Minimum strength classes	
	Tensile in bending strength class, B_{tb}	Compressive strength class, B
Monolithic coating	4.0	30.0
Monolithic base	1.2	7.5
Precast coating (base)	3.6	25.0

Table 3 – Requirements to frost resistance of coverings and bases.

The structural layer of the pavement	The minimum frost resistance of concrete for areas with an average temperature of the coldest month		
	from 0 °C to −5 °C	from − 5 °C to −15 °C	under −15 °C
Coating	100	150	200
Base	25	50	50

3. Results and discussions

3.1. *Workability of fresh concrete*

The method of fibers introduction in the fresh concrete has a great influence on its workability and on the formation of fibers clumps. Several ways of introducing polypropylene microfibers are described in the literature (Ramezanianpour et al., 2013; Zhang and Li, 2013). The authors suggested preventing the ball-shaped formation of microfibers in concrete mixture due to mixing the microfibers with water at first and then adding to fresh concrete (Ramezanianpour et al., 2013). The investigated polypropylene microfibers had the diameter of 18 μm, the length of 12 mm. The authors stated that in order to distribute the polypropylene microfibers (length equal to 10–20 mm) uniformly the forced mixing machine was needed as well as the following mixing procedure should be used (Zhang and Li, 2013): the coarse and fine aggregates were mixed initially for 1 min and the binder and polypropylene fibers were mixed for another 1 min; finally the superplasticizer and water were added and mixed for 3 min.

Two ways to introduce fibers were investigated in this paper. With the first method fibers were introduced into the ready fresh concrete. Then the fresh concrete was stirred for 5 min. In the second method fibers were introduced into the dry mixture of cement and aggregates then stirred for 2.5 min. Then water was added and the fresh concrete was stirred for another 5 min. Forced action mixer was used.

Slump test was conducted on mixtures with slump within 10–14 cm. The introduction of macrofibers in the amount of 3–4.5 kg/m^3 (volume of the fibers 0.31%–0.47%) by first method leaded to slump loss. The decrease in strength characteristics was observed due to poor distribution and fibers clumping in the concrete structure. The purpose of improving the properties of hardened concrete has not been achieved with this method of fiber introducing.

The second method of macrofibers introducing appeared to be more suitable. According to slump tests the introduction of macrofibers in volume of 0.31%–0.47% did not lead to slump loss. The use of the second method of the macrofibers introduction leaded to eliminating the fibers clumps formations as well as keeping the workability.

The introduction by both methods of microfibers in the amount greater than 1.1 kg/m^3 (volume of the microfibers 0.12%) has reduced workability of fresh concrete and showed poor microfibers distribution in hardened concrete. In order to ensure fresh concrete workability and uniform distribution of the microfibers the maximum microfibers quantity was determined as 1.0 kg/m^3 (volume of the fibers 0.11%) in the case of the second method of fiber introduction.

Thus, development of the fiber introduction method and procedure of mixing are the ways to improve the fibers uniform distribution in fresh concrete.

Table 1 – Properties of fibers.

Fiber	Macrofiber	Microfiber
Average diameter (mm)	0.50	0.02
Length (mm)	50	19
Density (g/cm^3)	0.95	0.91
Tensile strength (MPa)	600	400
Tensile modulus of elasticity (MPa)	11,000	4900
Melting temperature (°C)	150	150

3.2. *Specimen molding*

As shown in Sarmiento et al. (2016) and Ferrara et al. (2011), the casting process must be designed to make the flow direction of fresh concrete in which fibers may be aligned as close as possible to the direction of the principal tensile stress. The molding of the specimens tested in the present study was done to create anisotropy of the mechanical properties due to the fiber alignment as governed by the flow molding and the placement of fresh concrete. The

Table 4 – The compositions of the tested concrete mixtures.

W/C	Macrofibers (kg/m^3)	Microfibers (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)
0.31	0.0	0	475	800	1000
0.31	3.0	0	475	800	1000
0.31	4.5	0	475	800	1000
0.31	0.0	1	475	800	1000
0.35	0.0	0	465	790	985
0.35	3.0	0	465	790	985
0.35	4.5	0	465	790	985
0.35	0.0	1	465	790	985
0.39	0.0	0	455	785	970
0.39	3.0	0	455	785	970
0.39	4.5	0	455	785	970
0.39	0.0	1	455	785	970
0.42	0.0	0	450	770	955
0.42	3.0	0	450	770	955
0.42	4.5	0	450	770	955
0.44	0.0	0	410	790	965
0.44	3.0	0	410	790	965
0.44	4.5	0	410	790	965
0.49	0.0	0	340	835	970
0.49	3.0	0	340	835	970
0.49	4.5	0	340	835	970
0.49	0.0	1	340	835	970
0.55	0.0	0	320	760	1010
0.55	0.0	1	320	760	1010

effects of vibration and the method of fresh concrete laying on reorientation of macrofibers in concrete were investigated through comparisons between the measured fiber numbers per unit cross-sectional area.

The fractured samples were examined after the uniaxial tensile test. Approximately twice the number of the pulled out macrofibers per unit area was observed in the samples which were laid using direction of laying. An increase of the microfiber numbers plucked per unit area was observed in samples subjected to vibration. However, it depended on the duration of vibration and additional tests are required. Overall, the increase of tensile strength in the range of 10% was observed in samples that molded with the stacking direction. This provides experimental evidence that the molding process can be effectively tailored to orient the fibers along the direction of the tensile stresses.

The influence of the stacking direction to enhance the strength is not observed at small percent of the fiber reinforcement. It is possible to be explained by a small number of fibers and their random arrangement in which the orientation does not coincide with the action of tensile stresses. The number of fibers, which oriented along the action of tensile stresses, increases with the total number of fibers in the concrete mix. As a result the increase of tensile strength with the increase of fiber content should be observed.

Thus, increasing the strength characteristics of concrete with fibers is a complex task that requires selection of concrete composition, fibers with specific properties, the method of fibers introducing, and the method of the fresh concrete molding. The direction and uniformity of distribution of fibers in concrete enhance further its operational reliability. Concrete resists the current load in the best way if fibers are distributed evenly and aligned in the direction of major stress.

3.3. *Strength properties*

Fiber reinforcement of the concrete compensates the major drawbacks of cement concrete – low tensile strength and fragility fracture. Properties of fiber-reinforced concrete depend on the properties of reinforcing components. To obtain fiber-reinforced concrete with high strength characteristics it is necessary to know the influence of the main parameters of fibers on the properties of concrete.

The average value of compressive strength, tensile bending and uniaxial tensile strength of concrete specimens at age 28 and 90 days is shown in Figs. 2–6. The decrease of the compressive strength of the samples with fibers was not observed. However, the certain dependencies were not established.

The increase of tensile strength in bending of concrete with fibers in comparison with the reference concrete (without

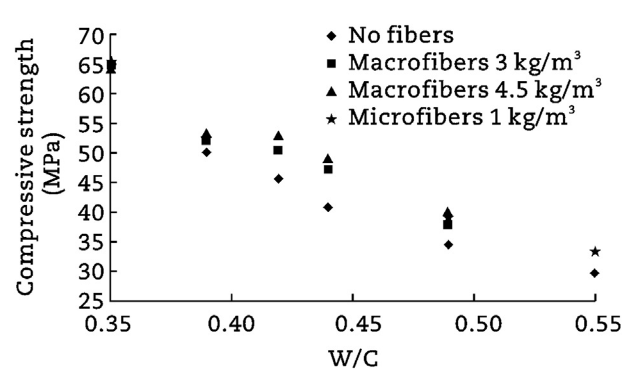

Fig. 2 – Concrete compressive strength at the age of 28 days.

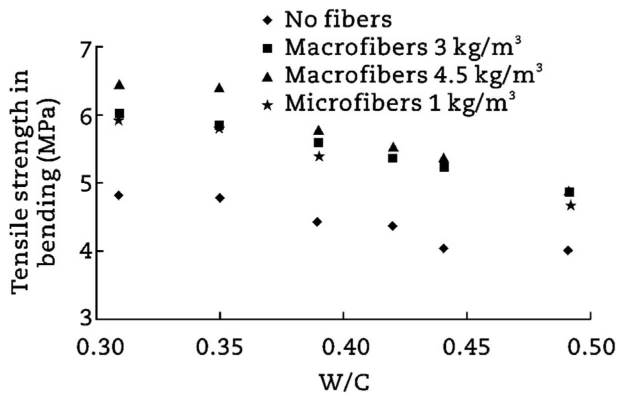

Fig. 3 – Concrete tensile strength in bending at the age of 28 days.

fibers) was observed with the water-to-cement ratio decrease. The reason can be the hardened cement paste density increase. This increase for macrofibers in quantity of 4.5 kg/m^3 was 21% and 32%; for macrofibers in quantity of 3 kg/m^3 was 19% and 23%; for microfibers in quantity of 1 kg/m^3 was 15% and 22% with water-cement ratio equal to 0.49 and 0.31, respectively.

With a sufficient degree of accuracy (correlation coefficient $R = 0.97$) the dependence of the tensile strength in bending from water-to-cement ratio (for concrete with microfibres in the amount of 4.5 kg/m^3) can be described by the equation

$$\sigma_{tb} = -9.1587W/C + 9.3968$$

The use of fibers in bending reinforced concrete elements is feasible only in the stretched area. This leads to the increase of the stress of first microcracks formation and the reduction of the microcracks width under their disclosure.

Typically, the first cracks under the bending test are formed at the surface pores. The analysis of the samples after loading showed that more cracks appeared with the load increase on the surface of samples with a lower water-to-cement ratio. These microcracks were united at the ultimate stage in solid cracks with a step of 4–8 mm if water-to-cement was equal to 0.31 and with a step of 20–30 mm if water-to-cement was equal to 0.50.

The increase of uniaxial tensile strength for concrete with fibers reinforcement in comparison with the reference concrete was also observed with water-to-cement ratio decrease. This increase at age of 28 days for macrofibers in amount of 4.5 kg/m^3 was 23% and 29%; for macrofibers in quantity of 3 kg/m^3 was 19% and 26% with water-cement ratio equal to 0.49 and 0.31, respectively; for microfibers in quantity of 1 kg/m^3 was 15% and 24% with water-to-cement ratio equal to 0.55 and 0.31, respectively.

The hardened cement paste densification increases the mechanical bond between fiber and cement matrix. The cement paste hydration can be a factor in this densification and accordingly in the mechanical bond growth. For this reason the uniaxial tension strength of the concrete with fiber reinforcement in comparison with the reference concrete was determined at the age of 90 days.

The increase of concrete uniaxial tensile strength at age of 90 days for macrofibers in quantity of 4.5 kg/m^3 was 18% and 36%; for macrofibers in quantity of 3 kg/m^3 was 15% and 30% with water-to-cement ratio equal to 0.49 and 0.31, respectively; for microfibers in quantity of 1 kg/m^3 was 15% and 26% with water-to-cement ratio equal to 0.55 and 0.31, respectively.

Complex microscopic processes of damage accumulation precede the macro-fracture of materials. Concretes are materials with so-called "imperfect" structure since they have a large number of pores, inclusions, cracks, various phases. It detects a wide range of manifestations of the physical essence of the creep and fracture processes. The main feature for concrete with good adhesion between the components is the appearance and development of microcracks.

Forces of internal friction of concrete under compression play a significant role at the stage of transformation of microcracks into the main crack. They, like armature, hold the local transverse deformation, distribute them more evenly over the entire cross section of the model and do not allow the avalanche development of the first crack. Many micro-cracks are formed instead of a single crack. It is manifested in the form of plastic deformation of concrete. Under the uniaxial tension or bending of unreinforced concrete, limiting and distributing forces are not available, therefore the bearing capacity of the concrete underutilized due to the early development of cracks in any one section.

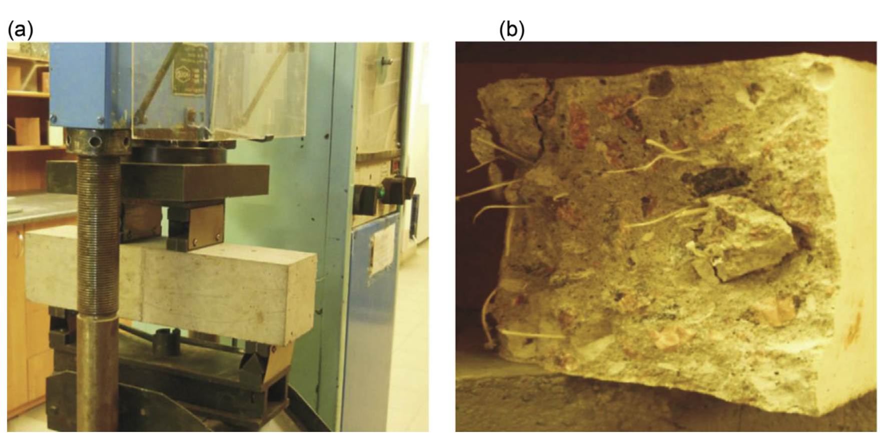

Fig. 4 – Concrete tensile strength in bending test. (a) The prism-samples 10 cm × 10 cm × 40 cm under testing. (b) Sample after testing.

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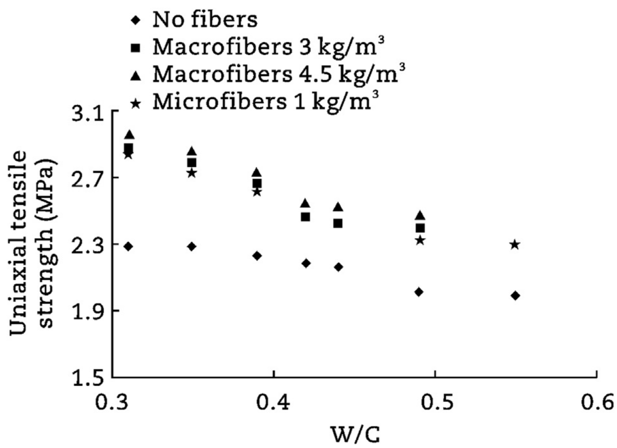

Fig. 5 – Uniaxial tensile strength at the age of 28 days.

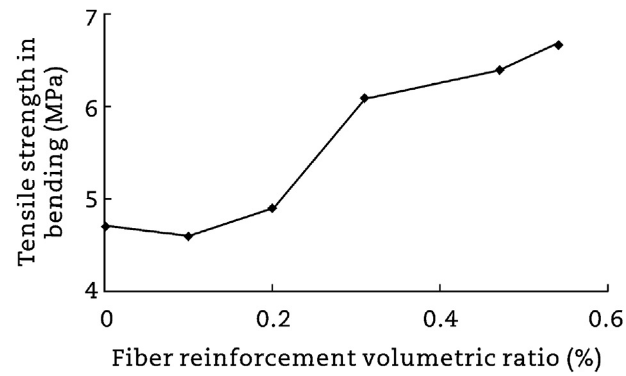

Fig. 7 – Dependence of the concrete tensile strength in bending on fiber reinforcement volumetric ratio.

Optimization of fiber quantity is one of the main objectives in the development of compositions of fiber reinforced concrete. The effectiveness of the fiber reinforcement and the degree of application of fiber capacity depend largely on the interaction between fibers and cement matrix at the interphase boundary. Adhesion strength determines the fracture behavior of fiber reinforced concrete. Failure can occur as a result of fibers rupture under the maximum stresses or pulling out fibers from the matrix after breaking the bond between fiber and matrix. Fracture of fiber reinforced concrete (for example, based on polypropylene or steel fibers) often occurs due to pulling out fibers because of lack of bond on the interphase boundary “fiber-cement matrix”.

Method for determination of optimal fiber quantity taking into account the nature of the fiber work in the cement matrix can be proposed according to the above-mentioned results. The method consists in finding empirically the minimum reinforcement volumetric ratio. Fibers with quantity equal to the minimum reinforcement volumetric ratio have no effect on the strength characteristics and fibers with quantity bigger than the minimum reinforcement volumetric ratio contribute to a significant increase of tensile strength.

Mortar mixture with the water-cement ratio corresponding to the water-cement ratio of the concrete mixture can be selected as the initial mixture for the experiment. The minimum fiber reinforcement volumetric ratio is determined by using the mortar mixture. Samples with fiber reinforcement and without fibers are made. The graph of “tensile strength at bending – volume content of fibers (fiber reinforcement volumetric ratio)” is based on the test results. The position of the point which corresponds to the minimum fiber reinforcement volumetric ratio is determined from the chart. A steady increase in tensile strength is observed at values greater than the minimum fiber reinforcement volumetric ratio.

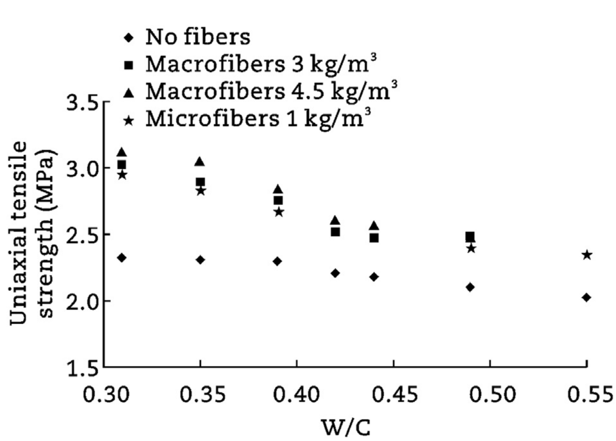

Fig. 6 – Uniaxial tensile strength at the age of 90 days.

The mortar mixture with the water-cement ratio equal to 0.3 was chosen as the initial mixture for the experiment. The minimum fiber reinforcement volumetric ratio was determined using the mortar mixture. The dependence of “tensile strength at bending – volume content of fibers (reinforcement volumetric ratio)” is presented in Fig. 7.

The position of the point which corresponds to the minimum fiber reinforcement volumetric ratio is determined from the chart in Fig. 7. A steady increase in tensile strength was observed at values greater than the minimum fiber reinforcement volumetric ratio, which was equal to 0.31% for the mixture with the water-to-cement ratio equal to 0.3.

3.4. *Deformation properties*

The purpose of the deformation properties test was the determination of the prism strength, elasticity modulus and Poisson's coefficient of concrete samples according to Fig. 8. The test is done by stages loading of prism-specimens with compressive axial load till failure to determine the prism strength. Loading is done to the level of 30% of the failure load with measuring of sample deformation to determine of the elasticity modulus and Poisson's coefficient. The sensors were attached to the sample. The measurement accuracy of the sensors was 0.001 mm. The sensor base to determine the longitudinal deformation was 150 mm and to determine the Poisson's coefficient – 70 mm.

The highest concrete prism strength of the B35 strength class was 45 MPa, so the loading was performed from 50 kN to 350 kN with steps of 50 kN. The results of elasticity modulus,

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Fig. 8 – Test of determination of elasticity modulus and Poisson's coefficient.

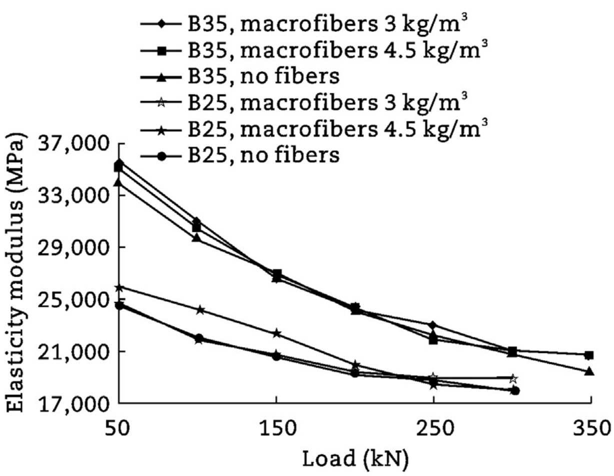

Fig. 9 – Determination of elasticity modulus.

prism strength and Poisson's coefficient are shown in Fig. 9 and Table 5.

The studied fibers one can relate to low modulus fiber reinforcement (modulus of elasticity $E = 11{,}000$ MPa). However the increase of elasticity modulus of fiber reinforced concrete and the reduction of the Poisson's coefficient are observed. Such influence on the concrete properties is characterized by using high modulus fibers, wherein the elastic modulus is more than $(0.2–0.25) \times 10^5$ MPa (Tagnit-Hamou et al., 2005), for example, steel fibers ($E = 2 \times 10^5$ MPa). Use of the polypropylene fiber ($E = (0.04–0.08) \times 10^5$ MPa) is associated with the elasticity modulus decrease with the reinforcement degree increase. However, due to a strong anchoring in the cement matrix the polyolefin fibers can increase the prism strength and concrete rigidity. The prism strength increase of concrete with fibers can indicate on the fracture toughness increase.

3.5. *Abrasion resistance*

As it was established above, a significant increase of tensile strength in concrete with fiber was obtained in samples with the lowest water-to-cement ratio. Concretes with lower water-to-cement ratio are expedient for use as coatings in the road pavements. Cover-upper part of the pavement perceives stress from the car wheels and exposes to direct weathering. Thus, the abrasion of fiber reinforced concrete in dry and hydrated state is important characteristic of concrete coverings.

Abrasive resistance of concrete depends on different parameters such as: aggregate properties, concrete component proportion, concrete strength, cement type and quantity, fiber properties, molding and hardening conditions, surface treatment etc. (Cavdar and Yetgin, 2010; Grdic et al., 2012). Many previous studies demonstrated that the concrete abrasive resistance mostly depends on the concrete compressive strength. The abrasion resistance increase of 6%–7% was observed in Cavdar and Yetgin (2010) when using fibrillated polypropylene microfibers of 12 mm length and the abrasion resistance increase of 13%–16% - using a monofilament microfibers of 12 mm length for concrete with compressive strength in the range of 18–38 MPa (W/C was changed from 0.7 to 0.5).

The influence of polyolefin fibers on the abrasion of concrete with W/C ratio in the range of 0.55 to 0.31 is stated in this paper (Figs. 10 and 11). Cube samples of size 70 mm × 70 mm × 70 mm in the dry and wet state were tested using the abrasion wheel.

Abrasion resistance of concrete with fibers was higher than that of the reference samples. However, the influence of macro- and microfibers on abrasion resistance reduces with the decrease of water-to-cement ratio (with the increase of the concrete compressive strength) and was in the range of 7%–9%.

It is known that the concrete strength under water saturation decreases. This can be explained by the fact that microcracking is facilitated by adsorption of polar liquids. This is true for the concrete used in the road pavement.

Exposure to moisture in the presence of various salts activates the physico-chemical interaction of the phase components of material. Such conditions accelerate the processes of internal mass transfer and facilitate the migration of substances in the concrete structure, causing the change in the composition of the pore fluid and the decrease in the

Table 5 – Prism strength, elasticity modulus, Poisson's coefficient at the 30% failure load.

N	Concrete	Elasticity modulus at 30% failure load (MPa)	Prism strength (MPa)	Poisson's coefficient
1	B35, no fibers	27,446	40.9	0.181
2	B35, macrofibers 3 kg/m^3	28,362	43.0	0.102
3	B35, macrofibers 4.5 kg/m^3	28,114	43.7	0.144
4	B25, no fibers	21,988	33.6	0.219
5	B25, macrofibers 3 kg/m^3	22,249	35.6	0.182
6	B25, macrofibers 4.5 kg/m^3	22,448	36.4	0.152

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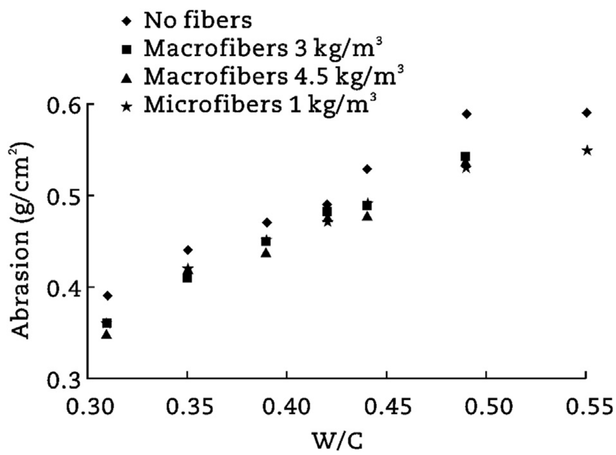

Fig. 10 – Abrasion depending on the water-to-cement ratio in the dry state.

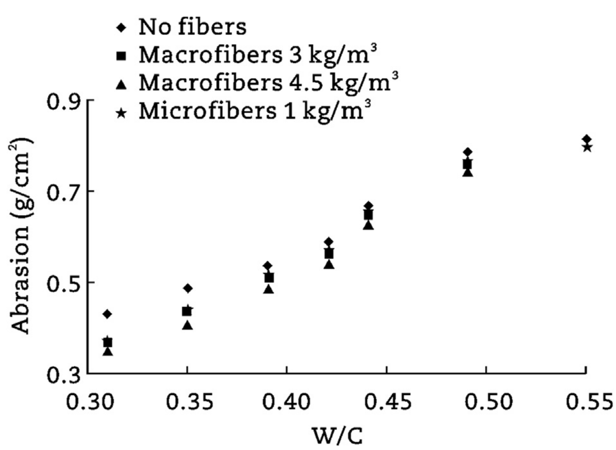

Fig. 11 – Abrasion depending on the water-to-cement ratio in the wet state.

concentration of water soluble alkalis. This leads to an increase in the concentration of migrating substances in some areas. The existence of such active areas leads to the uneven development of stresses in concrete and the development of large cracks, the mouths of which are active areas. The process of crack formation in this case is characterized by rapid destruction of the concrete. The growth of micro-defects at the initial stage can be prevented or stopped in case of using the fiber. Thus, the use of fiber reinforcement allows to reduce stress concentration, to prevent the development of counter-cracks and hinder the cracking process. The results of these studies support the possibility of using of fiber reinforced concrete with polymer fiber reinforcement in road pavements as bases and coverings.

4. Conclusions

It has been shown that the fibers introduction method and procedure of mixing are the ways to improve the fibers uniform distribution in fresh concrete. Two ways to introduce fibers were investigated. In the first method, fibers were introduced into the ready fresh concrete. Then the fresh concrete was stirred for 5 min. In the second method fibers were introduced into the dry mixture of cement and aggregates, stirred for 2.5 min. Then water was added and the fresh concrete was stirred for another 5 min. Forced action mixer was used. The second method of fiber introducing appeared to be more suitable and it did not lead to slump loss.

From the condition of ensuring the fresh concrete workability and fiber uniform distribution the maximum quantity of microfibers was determined in the amount of 1.0 kg/m^3 and macrofibers - in the amount of 3–4.5 kg/m^3. The tensile strength increase up to 10% was observed in samples that were molded with the stacking direction. The increase of the bending tensile strength and the uniaxial tensile strength for concrete with fibers reinforcement in comparison with the reference concrete was observed with the water-cement ratio decrease, because the hardened cement paste density is increased. The results of uniaxial tensile test at the age of 90 days also confirmed this statement. The abrasion resistance of concrete with fibers was more than the reference samples. However, the influence of macro- and microfibers on abrasion resistance reduces with the decrease of water-to-cement ratio (with the increase of the concrete compressive strength) and it was in the range of 7%–9%.

Method for determination of optimal fiber quantity taking into account the nature of the fiber work in the cement matrix was proposed according to the above-mentioned results. The method consists in finding empirically the minimum reinforcement volumetric ratio. Fibers with quantity equal to the minimum reinforcement volumetric ratio have no effect on the tensile strength characteristics and fibers with quantity bigger than the minimum reinforcement volumetric ratio contribute to a significant increase of tensile strength.

Conflicts of interest

The authors do not have any conflict of interest with other entities or researchers.

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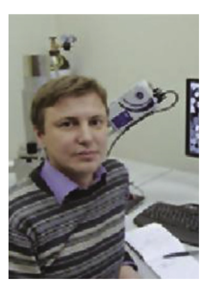

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