International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 20 (2017) pp. 9397-9404

Strength and Deformability Properties of Polyolefin Macrofibers Reinforced Concrete

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Abstract

Mechanical properties of fiber reinforced concrete from the type and quantity of polyolefin macrofibers were investigated in the paper. The dependence of fresh concrete workability from the macrofibers quantity and technique of macrofibers introduction into fresh concrete was determined. Dependences of cement matrix properties on mechanical properties of polyolefin fiber reinforced concrete (compression strength, tensile strength in bending, strength in uniaxial tension, elastic modulus, Poisson's coefficient) were stated. The increase of the bending tensile strength and the uniaxial tensile strength of concrete with polyolefin macrofibers reinforcement in comparison with the reference concrete was observed with the water-to-cement ratio decrease in the range of 0.50-0.30.

Keywords: Polyolefin macrofibers; fiber reinforced concrete; tensile strength in bending; elastic modulus; water-to-cement ratio

INTRODUCTION

At present the properties of fiber-matrix interface that are of primary significance in predicting the overall behavior of fiber-reinforced concrete are investigated [1-4]. Different types of fibers such as fibers based on steel, organic and inorganic materials were generally used in these studies. Major studies were conducted in the field of the development of fiber reinforced concrete (FRC) to improve the mechanical properties such as compressive strength, tensile strength, frost resistance [5-8]. Fibers vary in shape, length, superficial roughness, etc. Polyolefin fibers have a higher impact/static strength ratio and toughness factor in comparison with steel fibers [9]. In the paper [10] it was stated that the work for pulling out the polyolefin fibres was similar to the work with steel fibres.

Scanning electron microscopy analysis showed that the bond between polyolefin fiber and hardened cement paste is mainly mechanical [11,12]. In the paper [13] the microstructural observations showed the bond evolution between the cement matrix and polyolefin fibers because of the exothermic nature of the hydration reaction. The microstructural observations showed the partial penetration of hydrates into the fiber.

Polyolefin macrofibers are a new commercial synthetic product making it possible to produce the high volume of concrete without fibers' clots. Modern co-extrusion processes allow to produce the sheath/core type macrofibers. The so-called bi-component macrofibers consist of two different polymers e.g. of the core which is covered by the sheath of specific thickness. This leads to the optimization of the surface and core material. Furthermore, expensive components may be used at a reduced volume either in the sheath of the core or only in the core [14,15].

The polyolefin macrofibers are hydrophobic since they do not absorb water and their surface cannot become wetted [16,17]. The bond strength between the macrofiber and cement matrix and the interfacial friction associated with it are the main sources hindering fiber movement [18].

The low bond strength less than about 1 MPa was obtained between different polyolefin fibers and cement matrix with pull-out tests in the paper [15]. The compositions of six kinds of fibers and their properties were studied. The fibers contained either polypropylene (PP) or high density polyethylene (HDPE) as the base polymer. A number of mineral fillers were added to some fibers to increase the modulus of elasticity and the hardness of the fibers surface. The chemical bond that is usually formed by means of the hydration of these mineral fillers with the cement matrix did not take place as the fillers 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 a rough surface. The best peak values were found for fiber B with a rough surface [15]. This confirms once again that the bond mechanism between different polyolefin fibers and cement matrix is mechanical. The densification of the hardened cement paste can increase the mechanical bond. The hydration of cement paste can contribute to this densification.

Thus, according to the published test results of concrete with polyolefin fibers it is complicated to make the definite conclusions about their influence on the concrete mechanical properties. Very often the published results vary among different authors because the results were obtained by using only one type of concrete composition or a mode of fiber introduction. The aim of this paper is to define properties of FRC of B25-B55 strength classes (i.e. compression strength, tensile strength in bending, strength in uniaxial tension, elastic modulus, Poisson's coefficient) depending on water-to-cement ratio, type and quantity of polyolefin macrofibers as well as the mode of macrofibers introduction into fresh concrete. The results make it possible to establish the new dependencies of the influence of polyolefin macrofibers and water-to-cement ratio on the FRC properties.

MATERIALS

Currently the new synthetic macrofibers are being developed. The use of these macrofibers in FRC requires the further investigations. Synthetic bi-component polyolefin-based macrofibers Concrix ES (Brugg Contec AG) were used in the research and named macrofibers in the paper (Fig.1). The technological process of production has physical and chemical modification of these macrofibers with the purpose of giving mechanical strength to the macrofibers and chemical reaction activity of the macrofibers surface to the cement hydration products.

The core and shell of macrofibers consist of different synthetic polymers. The macrofiber core material has high strength characteristics and high elasticity modulus. The macrofiber shell material has higher adhesion to the cement matrix. The surface roughness of macrofibres can also increase the fiber adhesion to the cement matrix.

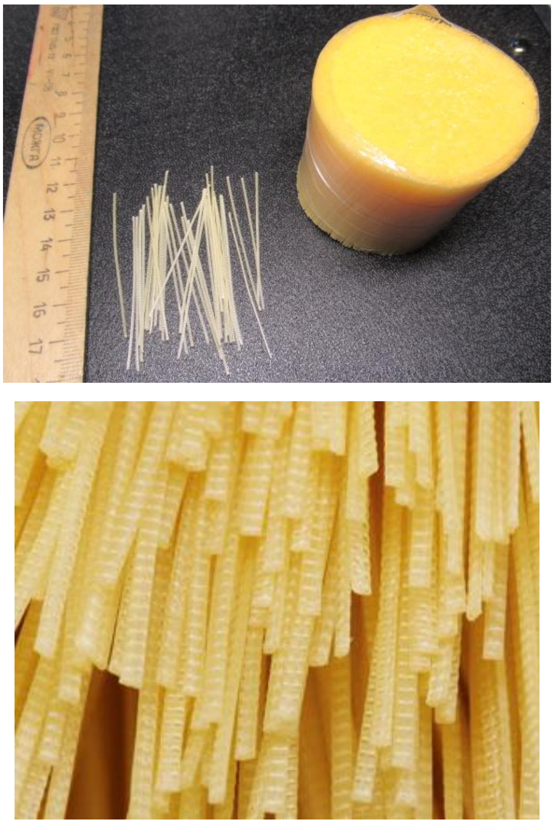

Figure 1: The appearance of macrofibers and convenient packing of macrofibers using the water-soluble film

The macrofibers had the following characteristics according to Table 1 [19]. Macrofibers are certificated according to EN-14889.

Table 1: Properties of macrofibers

Average diameter [mm]	0.5
Length [mm]	50
Density [g/cm³]	0.95
Tensile strength [MPa]	600
Tensile modulus of elasticity [MPa]	11000
Melting temperature [°C]	150

Portland cement CEM I 42.5, crushed granite of fractions 5-10, 10-20 and river sand were used as concrete components. The workability of all mixtures was within 12-14 cm (slump) and was adjusted with polycarboxylate-based superplasticizer in quantity of 0.6-0.9%.

Investigation of the effect of selected macrofibers on concrete strength characteristics was carried out for the B25-B55 concrete strength classes, the water-to-cement ratio varying in the range from 0.50 to 0.30 (table 2). Three samples (cubes with sides of 10 cm, prism- samples 10×10×40 cm) were tested for each composition.

Table 2: The concrete compositions

W/C	Macrofibers, kg/m^3	Cement, kg/m^3	Coarse aggregate, kg/m^3	Fine aggregate, kg/m^3
0.30	0	470	800	1000
0.30	3	470	800	1000
0.30	4.5	470	800	1000
0.35	0	460	790	985
0.35	3	460	790	985
0.35	4.5	460	790	985
0.40	0	450	785	970
0.40	3	450	785	970
0.40	4.5	450	785	970
0.42	0	440	770	955
0.42	3	440	770	955
0.42	4.5	440	770	955
0.45	0	410	790	965
0.45	3	410	790	965
0.45	4.5	410	790	965
0.50	0	340	835	970
0.50	3	340	835	970
0.50	4.5	340	835	970

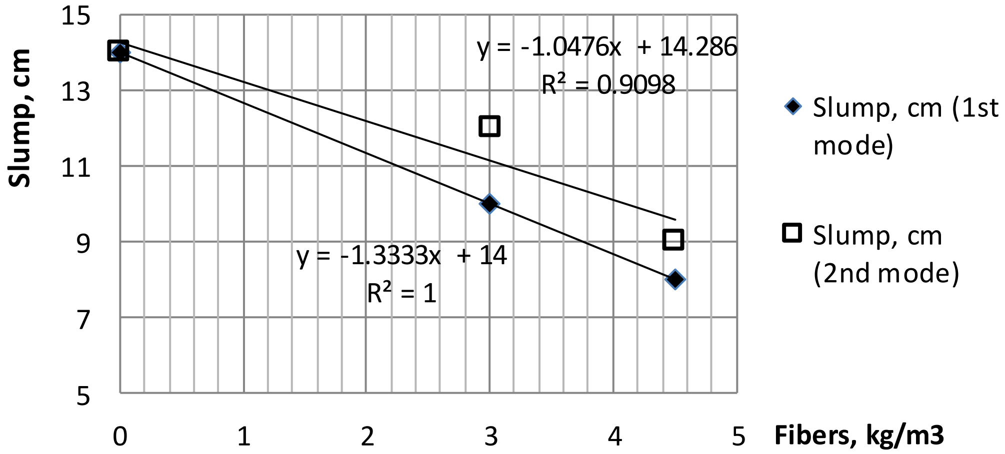

Figure 2: The dependence of fresh concrete workability from the macrofibers quantity and mode of macrofibers introduction

RESULTS AND DISCUSSIONS

Workability of fresh concrete and specimen molding

The results of the paper [20] confirm that the rheology of fresh concrete has an important influence on the fibers orientation. The flexural and tensile strengths depend on the fibre distribution and orientation and are significantly improved when the fibres are oriented in the direction of the tensile stresses in fresh concrete with good workability.

The method of macrofibers introduction into the fresh concrete has a great influence on its workability and on the formation of macrofibers clumps.

Several ways of introducing polypropylene microfibers are described in the literature [21,22]. The authors [22] stated that in order to distribute the polypropylene microfibers (with length equal to 10-20 mm) uniformly it was necessary to use the forced mixing machine and the certain mixing procedure which consisted of mixing the coarse and fine aggregates initially for 1 min and then of mixing the binder and polypropylene fibers for another minute and finally, the superplasticizer and water were added and mixed for 3 minutes.

Two ways to introduce macrofibers were investigated in this paper. In the first method macrofibers were introduced into the ready fresh concrete. Then the fresh concrete was stirred for 5 minutes. In the second method macrofibers were introduced into the dry mixture of cement and aggregates and then were stirred for 1 minute. Then water and superplasticizer were added and the fresh concrete was stirred for another 4 minutes. The forced action mixer was used.

Tensile strength should increase with increasing quantity of macrofibers. However, the introduction of macrofibers in the amount of 3-4.5 kg/m^3 (volume of the fibers 0.31-0.47%) using the first method resulted in the slump loss. The decrease of strength characteristics was observed due to poor macrofibers distribution and clumping in the concrete structure. The purpose of improving the properties of hardened concrete was not achieved with this method of macrofiber introducing.

The second method of macrofibers introduction 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 lead to eliminating the fiber lump formations as well as keeping the initial workability.

The dependence of fresh concrete workability from the macrofibers quantity and technique of macrofibers introduction into fresh concrete was determined (fig.2).

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

As shown in the papers [23,24] the casting process must be designed to make the flow direction of fresh concrete along which fibres may be aligned to match as close as possible the direction of the principal tensile stress within the structural element. The molding of the specimens tested in the present study was done to create anisotropy of the mechanical properties due to the fibre alignment as governed by the fresh concrete flow molding. The effects of fresh concrete laying on distribution of macrofibers in concrete structure were investigated by comparing the fractured samples using the measured macrofiber numbers per unit of the cross-sectional area.

The fractured samples were examined after the uniaxial tensile test. Approximately the double number of the pulled out macrofibers per unit area was observed in the samples which were laid using direction of laying. Overall, the increase of tensile strength up to 10% was observed in samples that were molded in the direction of laying.

Strength properties

The average value of compressive strength, tensile bending and uniaxial tensile strength of concrete specimens at the age of 28 and 90 days are shown in figures 3-6.

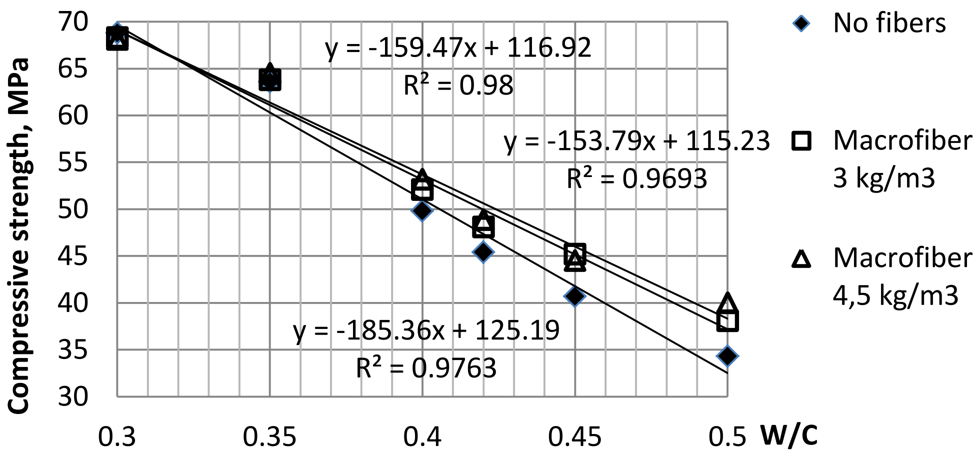

Figure 3: The concrete compressive strength at the age of 28 days

The decrease of the compressive strength of the samples with macrofibers was not observed.

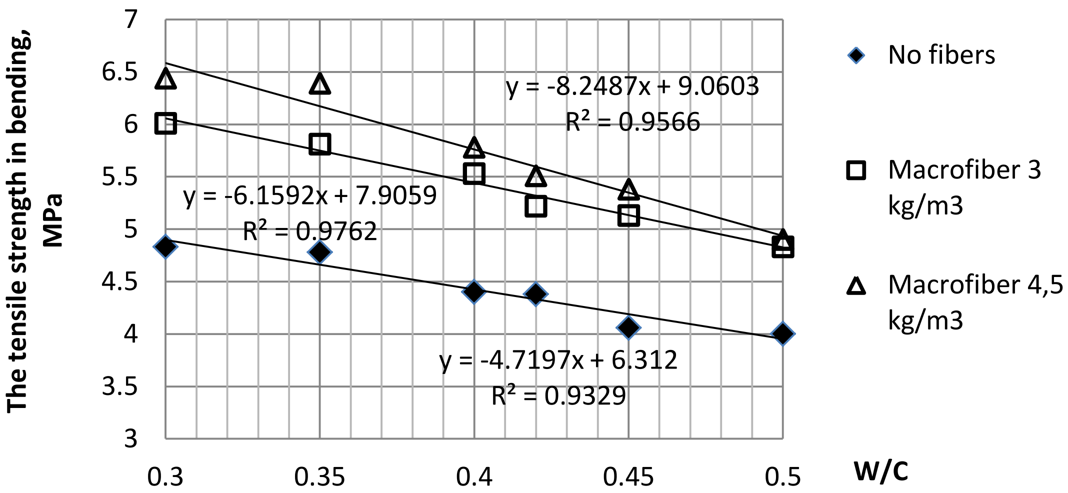

Figure 4: The concrete tensile strength in bending at the age of 28 days

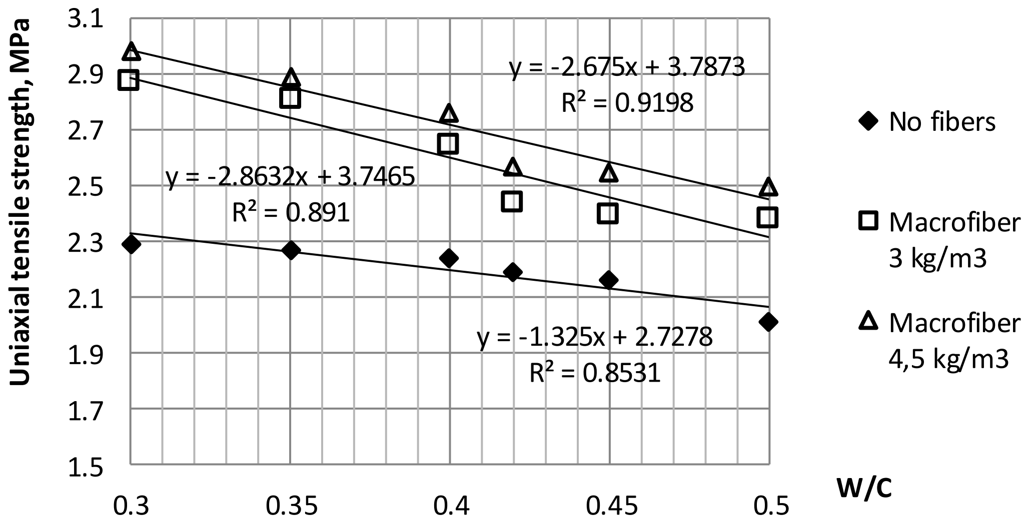

Figure 5: Uniaxial tensile strength at the age of 28 days

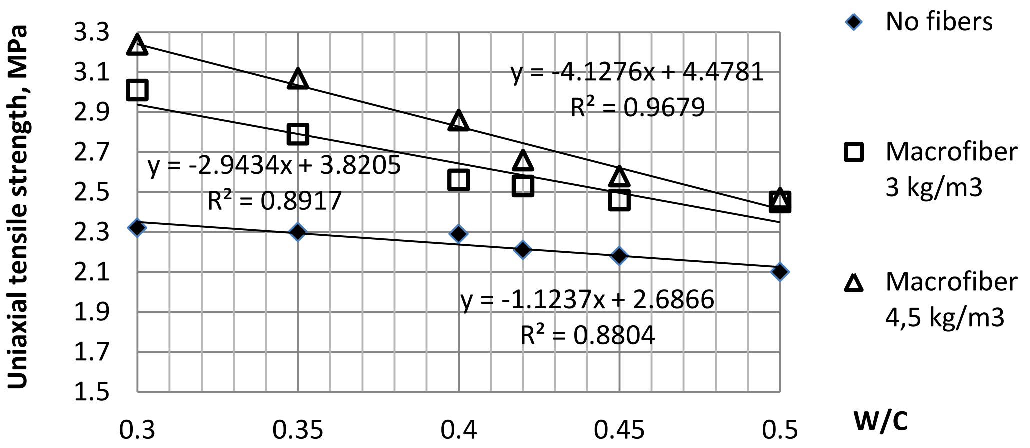

Figure 6: Uniaxial tensile strength at the age of 90 days

The increase of tensile strength in bending of concrete with macrofibers in comparison with the reference concrete (without fibers) was observed with the water-to-cement ratio decrease. This increase for macrofibers in quantity of 4.5 kg/m^3 was 22% and 33%; for macrofibers in quantity of 3 kg/m^3 was 20% and 24%, respectively. The reason can be the increase of the hardened cement paste density since water-to-cement ratio decreases.

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 the age of 28 days for macrofibers in quantity of 4.5 kg/m^3 was 24% and 30%; for macrofibers in quantity of 3 kg/m^3 was 18% and 25% with water-cement ratio equal to 0.50 and 0.30, respectively.

The density of cement matrix and accordingly the friction between polyolefin macrofibers and cement matrix can be increased by reducing the water-to-cement ratio. The hardened cement paste densification increases the mechanical bond growth between fiber and cement matrix. The cement paste hydration can be the reason for this 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 the age of 90 days for macrofibers in quantity of 4.5 kg/m^3 was 17% and 35%; for macrofibers in quantity of 3 kg/m^3 was 16% and 29% with water-to-cement ratio equal to 0.50 and 0.30, respectively.

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 figure 7. The test was made by stages loading of prism- specimens with compressive axial load till failure to determine the prism strength. Loading was made up to the level of 30% of the failure load with measuring of sample deformation to determine 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.

Figure 7: Determination of elasticity modulus and Poisson's coefficient

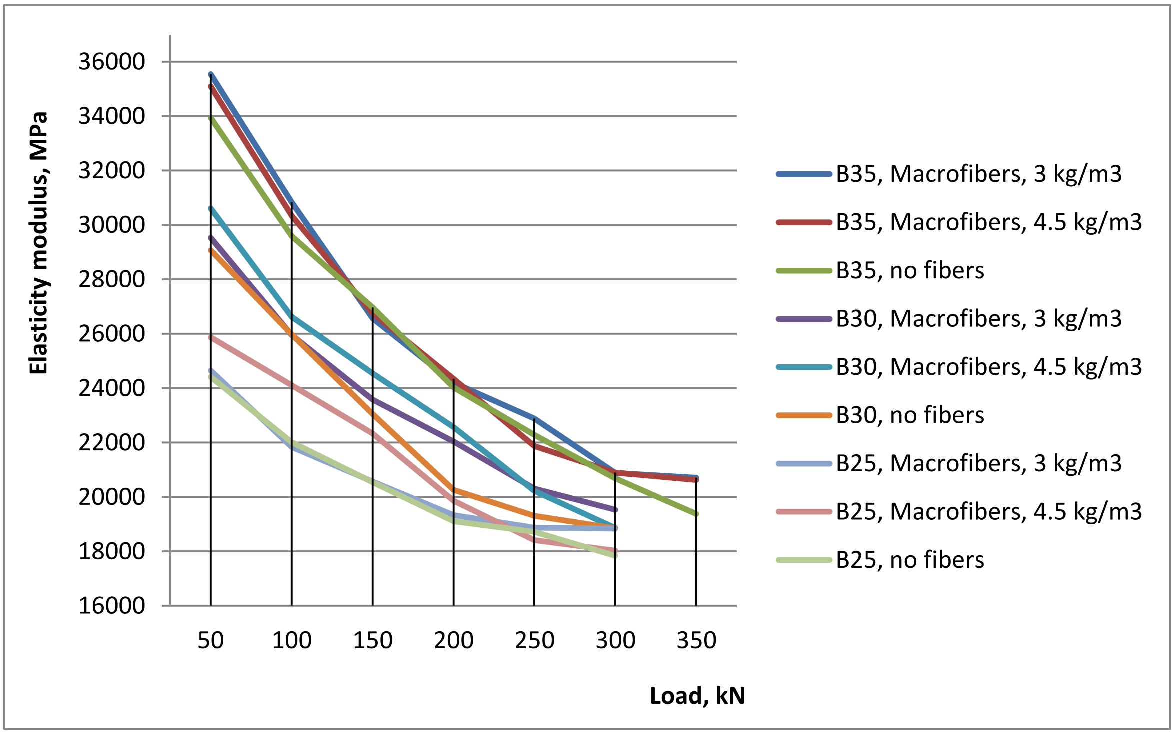

Figure 8: Determination of elasticity modulus

Table 3: 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	27446	40,9	0,181
2	B35, macrofibers 3,0 kg/m^3	28362	43,0	0,102
3	B35, macrofibers 4,5 kg/m^3	28114	43,7	0,144
4	B25, no fibers	21988	33,6	0,219
5	B25, macrofibers 3,0 kg/m^3	22249	35,6	0,182
6	B25, macrofibers 4,5 kg/m^3	22448	36,4	0,152

The highest concrete prism strength of the B35 strength class was 45MPa, so the loading was performed from 50kN to 350kN with steps of 50kN. The results of elasticity modulus, prism strength and Poisson's coefficient are shown in figure 8 and table 3.

One can relate the studied fibers to low modulus fiber reinforcement (modulus of elasticity E = 11000 MPa). However the increase of elasticity modulus of fiber-reinforced concrete and the reduction of the Poisson’s coefficient were observed. Such influence on the concrete properties is characterized by using high modulus fibers, wherein the elastic modulus is more than 0,2-0,25×10^5 MPa, for example, steel fibers (E = 2×10^5 MPa). The use of the polypropylene fiber (E = 0,04-0,08×10^5 MPa) is associated with the elasticity modulus decrease when the reinforcement degree is increased. 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 the fracture toughness increase.

The increment of values of strength and deformation properties of concrete with polyolefin macrofibers increases with the decrease of water-to-cement ratio in the range of 0.50 to 0.30. It makes the use of polyolefin macrofibers promising and requires the further research in concrete which has to meet high demands on strength and deformation properties [21,25].

CONCLUSIONS

Thus, increase of the strength characteristics of concrete with macrofibers is a complex task that requires selection of concrete composition, fibers with specific properties, the method of fibers introduction, the method of the fresh concrete molding.

It has been shown that the correct choice of the macrofibers introduction method and procedure of mixing are the ways to increase the polyolefin macrofibers volume in concrete and to improve the polyolefin macrofibers uniform distribution in fresh concrete. From the condition of ensuring the fresh concrete workability and macrofibers uniform distribution at the established method of fibers introducion, the maximum quantity of polyolefin macrofibers was 3-4.5 kg/m^3. The increment of the tensile strength in bending and the uniaxial tensile strength of FRC was observed at lower water-to-cement ratio in the range of 0.50 to 0.30. The results of uniaxial tensile test at the age of 90 days also confirmed that approval. The increase of the elasticity modulus and the reduction of Poisson's ratio were observed. Prism strength of concrete increased which may indicate the increase of the crack resistance of concrete with polyolefin macrofibers reinforcement.

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