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Mechanical properties of synthetic fibers applied to concrete reinforcement

Механические свойства синтетических волокон для армирования бетона

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Abstract. Short synthetic fibers are increasingly used for reinforcing of cement-based composites along with metallic and inorganic fibers. In this work, the mechanical properties of short polypropylene fibers with different structures were investigated. The main characteristics, including tensile strength, Young's modulus, strain at maximum load, and work of rupture were determined. In addition, fiber samples were examined for creep at various loading levels up to 50 % of the tensile strength. Relationship between the creep strain rate and applied stress for the fiber samples was determined. The results obtained can be used for selection the synthetic fibers for the reinforcement of cement-based composites.

Аннотация. Короткие синтетические волокна приобретают всё большое распространение для армирования бетона наряду с металлическими и неорганическими волокнами. В данной работе исследованы механические свойства коротких полипропиленовых волокон различного строения. Определены основные характеристики, включая прочность при растяжении, удлинение при максимальной нагрузке, работа разрыва и модуль упругости. Кроме того, образцы волокон исследованы на ползучесть при различных уровнях нагружения до 50 % от прочности при растяжении. Для образцов волокна была выведена зависимость между скоростью ползучести и приложенной нагрузкой. Полученные результаты могут быть использованы при выборе армирующих волокон для бетона.

1. Introduction

The development of structural cement composites reinforced with short fibers has been the focus of many studies in the last three decades [1–9]. This is mainly due to a significant improvement in the mechanical properties of concrete composites. The combination of short fiber reinforcement and the concrete matrix has led to the formation of fiber-reinforced concrete (FRC). FRC finds different applications in civil engineering, ranging from architectural elements to precast structural elements. Synthetic fibers may replace the conventional steel bar reinforcement, or along with it. The main advantage of FRC is the control of concrete cracking, the weight reduction of the building structure and the consumption of conventional steel reinforcement. It also significantly minimized the need for concrete, improves ductility, impact resistance, and increases the durability, which helps to reduce the amount of harmful emissions during its manufacture.

Various short fibers made of different raw materials have been employed for concrete composites. These short fibers include metal fibers, glass fiber, natural fibers and synthetic fibers [10]. Metal fibers are usually made of steel [11]. Their main undoubted advantage is the high Young's modulus of around 210 GPa. The main disadvantage is their low corrosion resistance, as well as for traditional steel reinforcement. Inorganic fibers mainly include glass and basalt fibers containing in their structure special additives (for example, zirconium dioxide ZrO_2), which leads to a significant increase in resistance to aggressive environment [12]. In practice, some manufacturers produce special types of alkali-resistant fibers (AR glass fibers), designed specially for reinforcing concrete. Natural fibers include sisal, jute, hemp, etc. [13]. Their main advantage is low cost. However, the main drawback is high water absorption

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and low biological stability. Another type of fiber used in reinforcing concrete is synthetic fibers. The variety of properties of the synthetic polymers makes it possible to obtain fibers with different properties. Many types of synthetic fibers, such as polypropylene (PP), polyethylene (PE), polyvinylalcohol (PVA), etc., are used to reinforce concrete. The mechanical properties of fibers depend on the material, density, length, length-to-diameter ratio, fiber shape, etc.

The reinforcing mechanism of a fiber in a concrete matrix is very different from a polymer matrix because of the brittleness of the concrete. In polymer composites, the matrix is usually more ductile than fiber. Therefore, in concrete composites, the matrix is destroyed before the strength properties of the fiber can be realized. Thus, fiber reinforcement becomes effective mainly after the crack of the matrix. The main characteristics influenced by the addition of short fibers to concrete are impact strength, fracture toughness, fatigue strength, dynamic strength, tensile strength [14–16]. In addition, short fibers are used as a supplement to conventional steel reinforcement to prevent cracking and improve resistance to degradation of properties resulting from fatigue, impact, shrinkage and thermal stress [17, 18]. To increase the work of rupture or toughness of concrete structures, metal fibers are used, while synthetic fibers are more often used to reduce crack opening during shrinkage [3, 19]. However, the equal amount of steel and synthetic fibers did not lead to the same results in toughness. In [3], the influence of steel and synthetic fibres on the flexural and compressive performance of FRC was investigated. It was found that that the steel fibres reinforcement increased the compressive strength by about 4 and 5 MPa while the synthetic fibres increased it only by 2–3 MPa. According to other studies, the effect of synthetic fibers on the toughness is comparable to steel fibers [4]. Cifuentes et al found that synthetic PP fibers in FRC slightly increased the mechanical properties, but greatly increased its fracture behaviour and ductility [20]. Freitas et al found that the presence of a short randomly oriented polypropylene fiber (1.7 % by volume) leads to a decrease in compressive strength and modulus of elasticity by 20 % and 15 %, respectively [21]. In [22], fiber-reinforced concrete samples with addition of steel, polypropylene, polyolefin fibers were investigated. The addition of fibers had no any considerable effect on compressive strength of the FRC. However, the properties of fibers affected on reducing the cracking width. The steel fibers showed the best performance due to their hook-shaped tail compared to PP fibers.

Considering the properties of fibers, one should especially highlight their viscoelastic behavior, which is common for polymer materials [23–25]. Since synthetic fibers are a polymer material, creep deformation is observed when constant load is applied to the samples. This phenomenon has been extensively studied in fiber-reinforced concrete samples by many authors [26–31]. The viscoelastic properties of the fibers and their effect on structural properties of FRC have been only investigated in a small number of works [32–35]. However, the viscoelastic properties of the fibers used for reinforcing concrete can have a significant effect on the mechanical performance of FRC. Vrijdaghs et al [32] evaluated the creep of two types of PP fibers with a length of 45 mm and diameter of 0.90 and 0.95 mm. To determine the Young's modulus and the maximum tensile load, tensile tests were carried out. In creep test, the load levels of 22, 36, 43, 53, 63 % of the maximum tensile strength were applied to the samples. It was shown that the load level influences the time to failure. They also concluded that creep deformation can play an important role in the total crack width growth in FRC elements. In [33], viscoelastic properties of concrete reinforced with synthetic PP macrofiber were considered. The individual fiber was tested for creep. For a four-day period, a constant load of 30 % of the average tensile strength of fibers was applied to the sample. It was found that synthetic fibres showed significant tensile creep at the load level of 30% and higher. The crack widening in FRC under loading has two mechanisms: time-dependent fibre pull-out and time-dependent fibre creep. Zhao et al [36] studied the effect of the fiber type (Steel, PP, PVA, basalt) on the creep of FRC. It was concluded that the Young’s modulus of the added fiber exerts the greatest influence on the creep of the samples: if it is higher than the Young’s modulus of the concrete, then creep resistance decreases, if lower then increases.

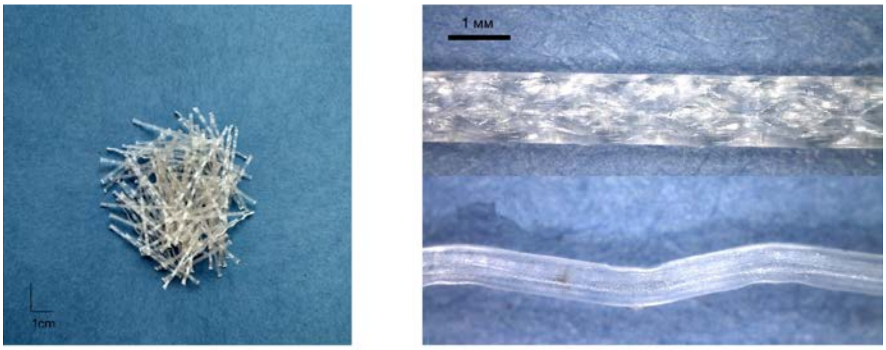
This work aims to study the mechanical and creep properties of macro PP fibers applied to concrete reinforcement. The objective of this work included:

1. evaluate mechanical properties of PP synthetic fibers with different configurations;
2. study the creep of PP fibers at different load levels;
3. establish the relationship between the fiber configuration and their mechanical properties.

2. Methods and materials

2.1. Materials

In this work, macro PP fibers with different configuration (fiber geometries) were studied. Generally, two types of fiber configurations including crimped (wave shaped) and surface intended geometries were selected for this study. This modification along the fiber length significantly improves the bond characteristics. Synthetic fibers for concrete reinforcement is shown in Figure 1a. Close view with magnification of 45× of two different types of synthetic fibers with different configurations is shown in Figure 1b. The upper picture denotes the fiber with surface intended geometry and the lower picture denotes the fiber with crimped geometry. Both considered fiber types had elliptical cross-sectional geometry. The characteristic of the investigated PP fiber samples are listed in Table 1. These two types of PP fibers are dominated in the market of FRC.



(a) (b)

Figure 1. Synthetic fibers for concrete reinforcement (a) and view with magnification of 45× (b)

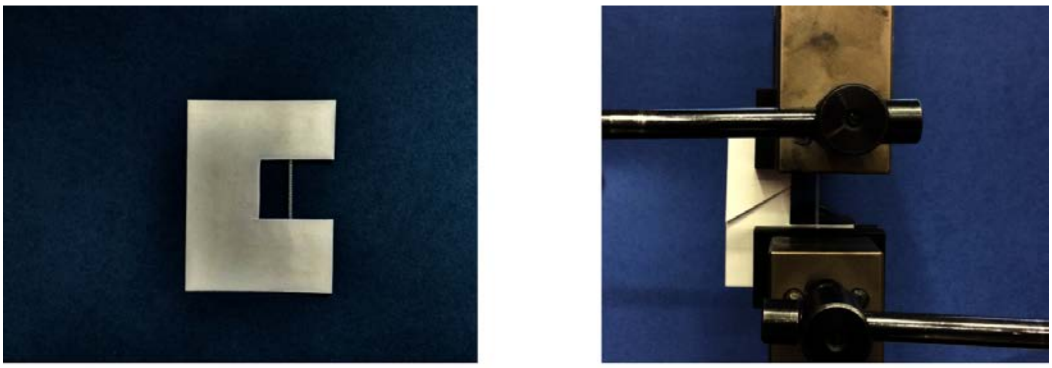
Table 1. Properties of PP fibres

Sample designation	Fibres Length, mm	Cross-sectional area, mm2	Linear density, tex	Fiber configuration
#1	53	0.8	610	surface intended
#2	37	0.72	590	crimped
#3	46	0.54	510	surface intended
#4	37	0.66	600	crimped

2.2. Methods

2.2.1. Tensile test

Computer controlled electronic universal testing machine Instron 5965 was used in this work. This machine enables for conducting tension, bending, and compression testing of various materials. The short PP fibers were tested in uniaxial tensile test. Samples of short fibers for tensile testing were prepared according to following method. The free ends of the fiber specimen were clamped to a special paper frame as shown in Figure 2. The fixing of the fiber end was ensured by applying glue. Then, specimens were left until tensile testing. Five specimens were tested for each type of PP fiber. The fiber specimens were tested with a test speed of 10 mm/min and a gauge length of 20 mm. The tensile strength (σ_{max}), strain at maximum load, Young's modulus and work of rupture (also called *toughness)* were determined from the stress-strain curves.



(a) (b)

Figure 2. Fiber in a paper frame for tensile testing (a) and uni-axial tensile test (b)

2.2.2. Creep test

The creep test was performed on an Instron 5965 tensile machine. The creep behaviour of fibre samples was performed at different levels of loading up to 50 % of the tensile strength with the step of 10 %. Preparation of specimens for creep test was done similar as for tensile tests described above.

3. Results and Discussion

3.1. Tensile properties of the fiber samples

The stress-strain curves obtained from all the studied fiber samples are shown in Figure 3. As can be seen from these curves, the fiber samples have a different curve type. Mechanical behavior differs significantly for different fiber types. The tensile characteristics of fiber samples were determined from the stress-strain curves. These characteristics were plotted as histograms and are shown in Figure 4.

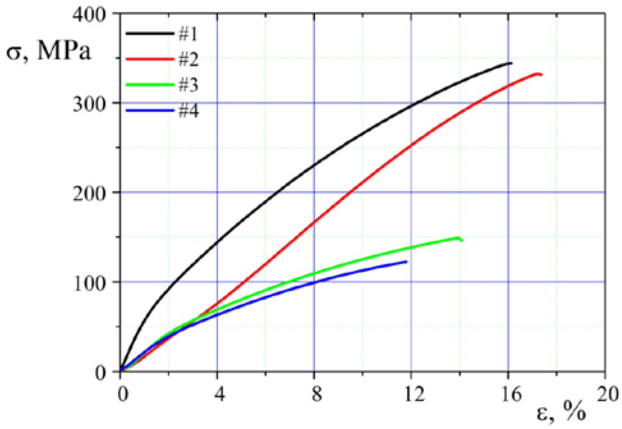


Figure 3. Stress-strain curves of PP fiber samples

The tensile strength of fibers differs more than twice and does not depend on the fiber type. The fiber samples of the first group, both with an intended surface (#1) and crimped surface (#2), showed a maximum tensile strength of about 350 MPa. However, the Young's modulus for these two fiber samples varies substantially, i.e. it differs by a factor of ~ 3. This is clearly demonstrated by the slope of the initial part of the stress-strain curve. The lower values of the Young's modulus of fiber sample #2 are affected by the structure of the fiber geometry. The fiber with crimped geometry shows a lower value of the Young's modulus; since to remove the crimp some additional work is necessary. The fibers of the second group #3 and #4 have a lower strength compared to values of fiber samples #1 and #2. In this case, the tensile strength and Young's modulus values were similar for both fiber samples.

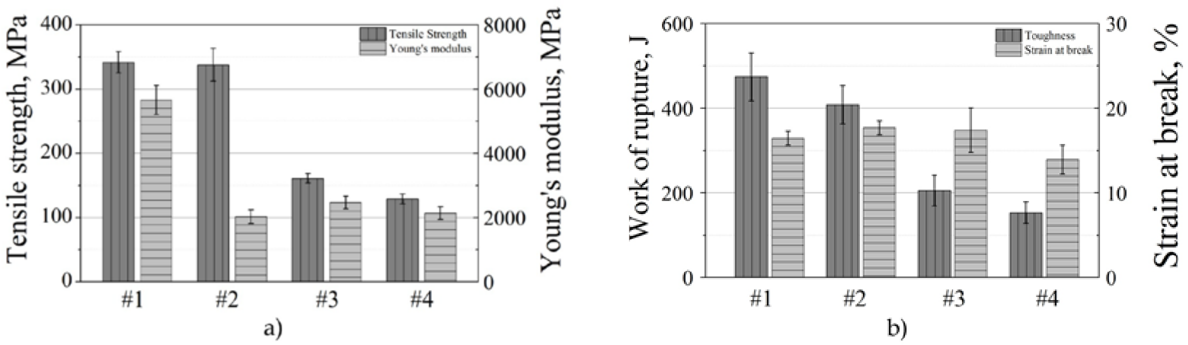


Figure 4. Tensile properties of PP fiber sample, including 95% confidence interval

Analyzing the obtained data on mechanical characteristics, it should be noted that the characteristics of the fibers are in similar ranges obtained by other authors. According to [37], tensile strength of the PP fiber varies from 310 to 760 MPa and Young's modulus – from 3.5 to 4.9 GPa. In [20], studied PP fibers with different properties have the tensile strength in the range from 288 to 450 MPa. In work [4] tensile strength and Young's modulus values of selected PP fibers were 640 MPa and 10 GPa, respectively. Another important mechanical characteristic of fibers for reinforcing concrete is plastic deformation and work of rupture. These characteristics determine the ability of the PP fibers and, consequently, of concrete to resist prolonged plastic deformation. This also provides a large residual load-bearing capacity of the concrete elements. Analyzing the data presented in Figure 4b, we can conclude that the obtained values of the characteristics of plasticity strongly depend on the work factor of the tensile diagram and values of the tensile strength. For the first group of fibers #1 and #2 with higher characteristics, the plasticity are higher in comparison to that of the samples #3 and #4. This fact will ensure a longer work of the fiber in concrete and, as a consequence, its plasticity. The magnitude of the work of rupture decreases proportionally with decreasing their tensile strength.

To conclude, the mechanical characteristics of synthetic fibers used for concrete reinforcement differ significantly. The fibers studied in this paper represent the optimal sample for a range of properties in terms of tensile strength, Young's modulus, strain at break and work of rupture among all typical reinforcing short fibers for concrete.

3.2. Creep behaviour of the fiber samples

When performing creep tests, the loading levels of the PP fibers are of particular interest. Creep tests are generally performed at the load levels up to 50% of the maximum tensile strength. If we compare loading levels with other researchers, then we can note that they lie approximately in the same range. Only the load step is varied. For example, in [32] the load levels were chosen at 22, 36, 43, 53 and 63 % of σ_{max}, then in [35] these steps were equal to 25, 40, 50, 60 and 75% of σ_{max}. The load levels, which are more than half of the tensile strength, lead to a sharp increase in the creep rate, which does not quite objectively reflect the real properties of the synthetic fibers for creep. Load levels from 60 to 90% are usually used in creep rupture test. Therefore, when planning the experiment, loads of up to 50% of the maximum load were applied with the step of 10 %. This approach makes it possible to perform comparative analysis for different fibers at the same relative loading levels.

The creep curves obtained for PP fiber samples #1, #2, #3, #4 are shown in Figure 5a, b, c, d, respectively. As can be seen from the presented curves, all the samples have exceptional viscoelastic properties, which manifest themselves in a significant increase in the creep strain with an increase in the level of the applied load. This behavior is typical for all synthetic fibers, including PP fibers for reinforcing concrete [32, 35]. The slope of the creep curve determines the creep rate. As can be seen for all the curves, the creep strain rate starts to grow already at a level of 20–30 % of σ_{max}. At a load level of 50 % of σ_{max}, the creep rate increases significantly. In practice, this means that the fiber does not exist for an arbitrarily long time to sustain such deformation. In order to compare the different fiber samples, the values of strain rate were plotted against the applied load as shown in Figure 6. These curves show a change in the creep rate with increasing applied load. A greater slope of the curve indicates a worse creep resistance of the PP fiber.

Relationship between the creep strain rate and applied stress for the fiber samples #1 #4 are given in equations 1-4 respectively.

$$\dot{\varepsilon} = \left(-42.59 + 7.23\sigma_{\max}^{\%}\right)\cdot 10^{-8} \quad (1)$$

$$\dot{\varepsilon} = \left(28.20 + 5.75\sigma_{\max}^{\%}\right)\cdot 10^{-8} \quad (2)$$

$$\dot{\varepsilon} = \left(-116.16 + 13.03\sigma_{\max}^{\%}\right)\cdot 10^{-8} \quad (3)$$

$$\dot{\varepsilon} = \left(-91.50 + 8.59\sigma_{\max}^{\%}\right)\cdot 10^{-8} \quad (4)$$

As can be seen from Figure 6, the curves of fiber samples #1 and #2 have the smallest slope as expected. However, fiber sample #2 demonstrates less stability in creep rate than sample #1. Although the slope of its curve is the lowest, the initial creep at a level of 10 of σ_{max} here is much higher than for the other three samples. Thus, the positive effect of a smaller angle of slope here is not determined by greater initial creep. At the structural level, this can be explained by crimp removal behavior of the fiber.

The practical application of the equations has two aspects. First, the comparative analysis of short reinforcing fibers of different structures can be made from the obtained coefficient. The selected fiber type based on this comparison will show a more stable behavior to load resistance already directly in the fiber reinforced concrete. This is very important, for example, with the ability of the stretched fiber to maintain the concrete when broken. Secondly, these equations allow us to determine the allowable stresses applied to the PP fiber.

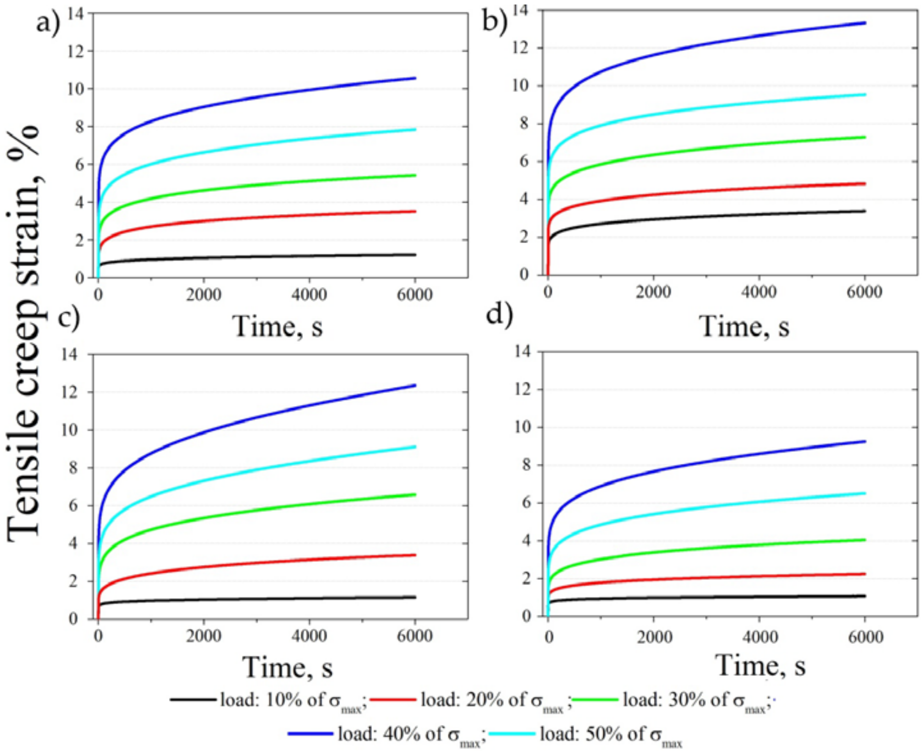


Figure 5. Creep curves of PP fiber samples at the temperature 20 ºC and the indicated assigned loads

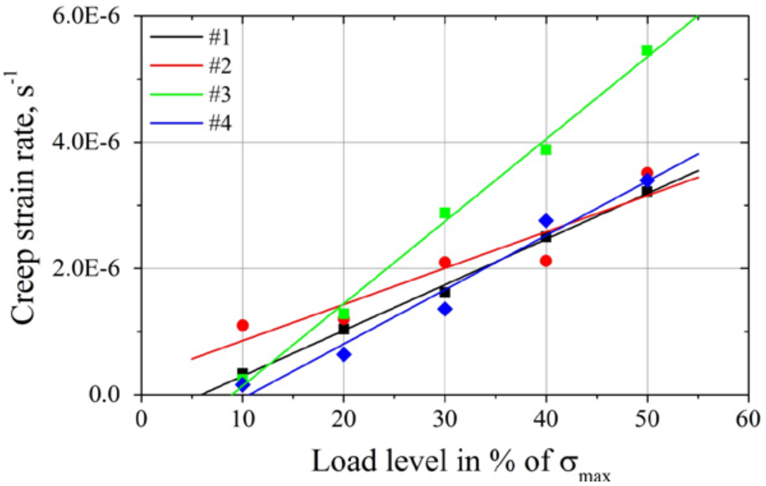


Figure 6. Creep strain rate vs. load level of PP fiber samples

4. Conclusions

In this paper, four different types of PP short fibers having different configurations and mechanical characteristics were investigated. The mechanical characteristics including tensile strength, Young's modulus, strain at maximum load and rupture work were determined. The results showed that the mechanical characteristics of the reinforcing PP fibers are dependent on their structure and the fiber geometry. According to the results obtained, the fiber samples can be divided into two groups, including PP fibers with a minimum tensile strength range (~150 MPa) and an average tensile strength range (~350–400 MPa). Moreover, it was shown that configuration of the fiber is not a key factor in determining the tensile strength parameters of the fiber. The characteristics of the fibers in the creep tests were also examined at different load levels up to 50 % of σ_{max}. It was shown that the creep rate increases substantially with increasing level of the applied load. For fibers with higher strength, the creep rate is not as high as for fibers with lower strength. Summarizing the results, the relationship between configuration of the fibers and their mechanical properties was established.

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