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Concrete with recycled polyethylene terephthalate fiber

Бетон с добавлением фибры из переработанного полиэтилентерефталата

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Ключевые слова: полиэтилентерефталат; ПЭТ; переработка ПЭТ; фибра; флекс; фибробетон

Abstract. The purpose of this study was to obtain the data on the influence of fiber from the products of recycled polyethylene terephthalate (PET) on the strength properties of fiber-reinforced concrete. In the experiments, used the direct product of industrial recycling of plastic bottles (flex), as well as specially prepared smooth and ribbed fiber from the same raw material. The influence factors were chosen fiber length from 1 to 5 cm and the amount of fiber-from 1 to 3 % by weight of cement. It has been found that the use of PET fibers provides a gain in the concrete tensile strength of up to 66 %. The compressive strength of the studied samples of fiber-reinforced concrete within the limits of the varying factors decreased by 3–25 %. The most favorable ratio of the increase in the bending tensile strength and the decrease in the compressive strength was obtained in concrete with the addition of smooth 4cm long fiber with the smallest reinforcement value. The abrasion capacity (abrasive wear) of the samples decreased with the addition of 3 % of smooth and ribbed 4 cm long fiber. The research resulted in the experimental determination of the effective fiber length (critical fiber length) providing the most reliable fastening of the fiber in the concrete matrix.

Аннотация. Целью данного исследование было получение данных о влиянии фибры из продуктов вторичной переработки полиэтилентерефталата (ПЭТ) на прочностные свойства фибробетона. В экспериментах применялись прямой продукт промышленной переработки пластиковых бутылок (флекс), а также специально подготовленная фибра гладкой и ребристой формы из того же сырья. Варьируемыми факторами, кроме типа фибры, были выбраны длина волокон от 1 до 5 см и количество вводимой фибры – от 1 до 3 % от массы цемента. Было выяснено, что применение ПЭТ фибры обеспечивает прирост прочности бетона на растяжение до 66 %. Прочность на сжатие исследуемых образцов фибробетона в границах варьируемых факторов снизилась на 3–25 %. Наиболее благоприятное соотношение увеличения показателя прочности на растяжения при изгибе и понижения показателя прочности на сжатие, получилось в бетоне с добавлением гладкой фибры длиной 4 см при наименьшей величине армирования. Истираемость (абразивный износ) образцов снизилась при добавке 3 % гладкой и ребристой фибры длинной 4 см. В результате исследований экспериментальным путем была определена эффективная длина фибры (критическая длина фибры), обеспечивающая наиболее надежное закрепление волокна в матрице бетона.

1. Introduction

The problem of a sustainable development of the civilization and the global construction complex is inextricably linked with the environmental management and the use of modern construction materials with enhanced physical and mechanical characteristics. Such materials include fiber-reinforced concrete [1–3].

Dispersed reinforcement of concrete with different types of fiber, as opposed to discrete reinforcement with reinforcement rods, grids and frameworks, has a number of advantages noted by many scientists [4–8]. Fiber-reinforced concrete also has technological advantages: labor expenditures for reinforcement of structures are significantly lowered or completely eliminated, loads on the vertical formwork are reduced [9, 10].

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There are developed regulatory documents on the design engineering and production technology for steel fiber concrete and specialized equipment allowing to use it safely [11–13]. This makes it possible to state the perspective development of the concrete technology with the addition of various types of fiber based on other materials: fiberglass, basalt, polypropylene, etc.

Recently, the use of the products of recycled polyethylene terephthalate (PET) has been studied intensively. Numerous types of water and beverage bottles and various types of containers and packaging are made of this plastic. The output of this product worldwide is many millions of tons. Waste (secondary raw materials), which is formed after the use of the products, is actively recycled [14]. However, as far as the use increases significantly throughout the world, collection and recycling efforts are insufficient. Therefore, the issue of using recycled PET containers in other industries, including construction, as a concrete reinforcing additive (fiber) has become increasingly important [15].

A number of studies dealing with this topic have already been conducted worldwide. Scientists from Japan have noted the safety of using PET fibers in concrete, as well as improving the physical and mechanical characteristics of concrete. There are two successful examples of using structures made of this material [16]. In general, there is a proven positive influence of PET fibers on the strength of concrete samples, which is shown in the works of researchers from the universities in Italy and Malta [17]. They studied various types of straight and deformed milled recycled PET fibers, alongside with different fiber lengths: 30 mm and 50 mm. They evaluated various options of percentage concrete additives and determined tensile properties and stretching characteristics of fibers. Then, they evaluated the effects of the fibers for soothing of plastic cracking and drying shrinkage, and finally, determined the compressive and bending strength of fiber-reinforced concrete. The cracking potential of thin plates of a fiber-reinforced mortar was also evaluated.

A Portuguese article reports on the strength behavior of concrete containing three types of recycled polyethylene terephthalate (PET) [18]. The results are also analyzed to determine the influence of the PET aggregate on the bending, splitting and compressive strength.

Three types of PET aggregates were used in the experiment. Samples were made with a 5 %, 10 % and 15 % content of the PET aggregate. The samples were tested after 7, 28 and 91 days. It is shown that the introduction of any type of the PET aggregate significantly reduces the compressive strength of the resulting concrete. However, the introduction of the PET aggregate improves the stiffness of the resulting concrete. This behavior depends on the shape of the PET aggregate and is maximized for concrete containing a rough, peeling PET aggregate. The tensile and bending strengths are proportional to the decrease in the compressive strength of concrete containing plastic aggregates.

Employees of the Warsaw University of Technology published an article on the use of PET in concrete. The research results have shown that the introduction of PET fibers does not worsen the mechanical strength of the concrete composite. However, the presence of polymer fibers worsens the slump of the concrete mix cone, which can cause difficulty in mixing or laying of the concrete mix [19].

Researchers from Malaysia worked with concrete containing PET fiber in the volume of 0.5 %, 1.0 % and 1.5 % of the fraction. They noted a slight increase in strength [20].

Employees of Baba Ghulam Shah Badshah University (India) also studied the behavior of various types of concrete of grades B20, B25 and B30, with the addition of a certain amount of PET fibers (2 %, 3 %, 4 % and 5 %). They noted that the environmental pollution from various non-biodegradable waste does not only pose an environment risk, but can also entail serious consequences for the human life. The use of these materials instead of a fine aggregate in concrete allows to partially solve this problem.

Then, the mechanical properties, such as compressive strength, were compared with ordinary concrete. The optimum compressive strength of concrete was achieved with the addition of 3 % of PET fibers [21].

Employees of another Indian university also noted that polyethylene terephthalate (PET) is an outstanding material, which is widely used as a raw material for the production of containers. The purpose of the research was to determine the reusability of PET as a replacement of aggregates in Portland cement. In this research, they used concrete with 0 %, 5 %, 10 %, 15 % and 20 % of PET waste.

In their conclusions they noted that a solid substance (concrete) with PET waste significantly reduces the consumption of cement, and this helps in the preparation of a concrete mix with an increased specific gravity. Concrete with the addition of PET also had an increased compressive strength and bending strength as compared to PET-free concrete [22].

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Several directions can be outlined in the latest published works dealing with the use of PET recycling waste for concrete additives:

– use of various types of PET reinforcement, for example, grids [23];

– study of the influence of the shape of PET fibers introduced into concrete, for example, ring-shaped fibers [24];

– complex use of PET fibers and other reinforcing materials (other types of plastics, rubber) also obtained by waste recycling, and additives in the form of ash and silica fume [25, 26].

Thus, till present, the overall efficiency of using polyethylene terephthalate fiber in a concrete matrix has been proven for the purpose of recycling plastic waste, facilitating concrete structures, saving cement consumption and improving the strength characteristics of concrete. In most studies, researchers use PET fiber obtained by extrusion and remelting from PET waste. Or apply PET granules heat-treated. Therefore, the question of the effectiveness of the use of industrial Flex (Flex – raw material obtained by recycling waste from PET, serving for the production of plastic bottles, containers, etc.), without additional processing as an additive to concrete remains relevant. This method would significantly reduce the cost of production of fiber concrete with PET-fiber.

But the researchers did not come to a consensus on the effective consumption of fiber in reinforcement, the influence of the shape of the fibers used on the properties of fiber concrete, as well as the areas of application of this material.

Therefore, the problem of this study is the effectiveness of the use of fiber in concrete from waste PET materials (obtained by mechanical grinding), and not subjected to heat treatment. The aim of this study is to assess the effect of PET fiber on the properties of fiber concrete.

For this purpose, it is necessary to solve a number of research problems. To check usability of industrial flex (a direct product of PET waste recycling, without any special treatment) as an additive to concrete. To assess the influence of the shape of specially produced fibers on the characteristics of fiber-reinforced concrete. To study the dependence of the strength characteristics of fiber-reinforced concrete on the amount of the added PET fiber. To obtain the value of the “critical length” of fiber, the indicator determining the degree of anchoring (fastening strength) of the fiber in the concrete matrix, which, in its turn, determines the strength of the fiber concrete structure.

2. Methods

The properties of concrete mixes with the use of fibers from the materials of recycled PET bottles were studied in several stages:

– creation and testing of PET fiber-free concrete samples;

– creation and testing of concrete samples with the addition of industrial PET fiber (flex);

– creation and testing of concrete with the addition of various amounts of smooth PET fiber;

– creation and testing of concrete with the addition of various amounts of ribbed PET fiber;

– analysis of the obtained results;

– conclusions.

The fiber was added in the amount of 1.2 and 3 % of the cement weight. In absolute values it is 4.42 kg/m^3, 8.84 kg/m^3, 13.26 kg/m^3, respectively. The fiber length was: for industrial flex – 1 cm (the standard length of this type of raw material), for the specially prepared smooth and ribbed fiber – 3.4 and 5 cm (Figure 1).

Standard methods were used for the studies (EN 12390 Testing hardened concrete). We used B30 concrete of the following composition: M400 cement – 442 kg; sand – 446 kg; 5–20 mm crushed stone – 1254 kg; water – 207 liters.

Series of samples were made for various tests. 28-day old samples were tested in a dry state.

The compressive strength was tested on 100×100×100 mm cube samples, while the bending tensile strength was determined on 100×100×400 mm samples.

The abrasion capacity of fiber concrete is studied according to the procedure of Russian State Standard GOST 13087-81 (Concretes. Methods of determination of abrasion) on the LKI-3 abrasive disc. The abrasion capacity of the 70×70×70 cube samples was estimated by the weight loss per unit area (kg/cm^2) during the abrasive wear.

a) b) c)

Figure 1. Different types of PET fiber used in the study: a) flex; b) smooth fiber; c) ribbed fiber.

The samples are placed in special sockets of the abrasive disc. A concentrated vertical force of (300±5) N is applied to each sample (center-wise), which corresponds to the pressure of (60±1) kPa (Figure 2). The total abrasion path is 600 m.

Figure 2. Testing the fiber samples for abrasive capacity (abrasive wear).

As it is known, the joint work of the fiber and the matrix under load has been the subject of numerous studies. In some of them, experimental and theoretical models of fiber-reinforced concrete systems are based on the assumptions that the fiber and the matrix have some elasticity before the destruction, and the fiber-matrix contact area is solid and uniform. At the same time, it is assumed that stresses are distributed linearly in the fiber from the zero values at the ends of the fiber to the maximum values at some distance from them, while shear stresses are considered constant at the same sections.

Let us consider the phenomenon that occurs when of the matrix interacts with short straight fibers in the process of stretching with the effort P of the fiber concrete sample. For this purpose, we will outline an elementary region consisting of a single fiber and the volume of the matrix adjacent to it from the stretchable sample.

The fiber with the length l_f and the cross section area S adheres to the matrix. Under the influence of the force P, there appear shear stresses with respect to the fiber in the contact area of the fiber-matrix system. With increasing load there is tearing of fibers of concrete or rupture of the fibers. In any event, the fiber stops working in the concrete.

Thus, we define the “critical length” of the fiber as the minimum allowable length, which provides a reliable fixation of the fiber in the concrete by the tangential stresses (reaction to the force) under the influence of the tensile force.

15 cm long fibers were cut for testing (Figure 3). We also prepared casting molds. After all the fibers were laid in the mold, we prepared a cement-sand mortar and poured it into the mold. Then, they were compacted on the platform vibrator. After the samples gained the necessary strength, they were subject to stretching (Figure 4).

Figure 3. A sample for testing the fiber adhesion strength with the concrete matrix (determination of the critical length of the fiber).

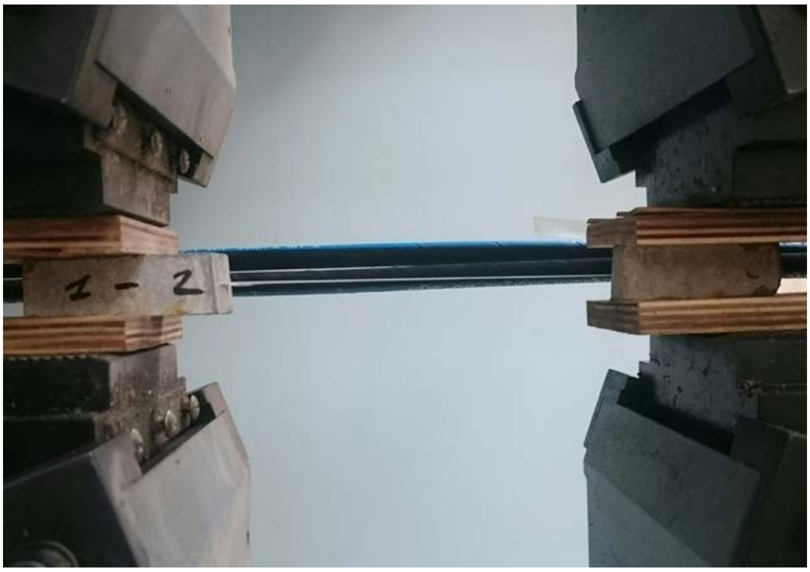

Figure 4. Testing of the fiber adhesion strength with the concrete matrix (determination of the critical length of the fiber).

The test results are as follows: the fiber broke (was destroyed) under the load P_1 = 200 N; the fiber came out of the concrete body without destruction under the load of P_2 = 110 N.

Then, we make calculations using the formulas:

$$P_1 = \sigma \cdot S, \tag{1}$$

where S is the cross-section area of the fiber, mm^2 (S = 0.1 mm^2);

$$P_2 = \tau \cdot u \cdot l, \tag{2}$$

where: τ is shear stresses, N/mm^2;

u is the perimeter of the fiber cross section, mm, (u = 11.04 mm);

l is the length of the fiber, which is in concrete, mm, (l = 23 mm).

From formula (1) we will find the rupture strength of the fiber:

$$\sigma = P_1 / S. \tag{3}$$

From formula (2) we will find the shear stresses:

$$\tau = P_2 / u \cdot l. \tag{4}$$

So that the fiber did not leave the concrete body, but broke, we will equate formulas (1) and (2) and find the critical length of a half of the fiber.

$$l = \sigma \cdot S / \tau \cdot u. \tag{5}$$

Then, the length of the whole fiber will be:

$$l_f = 2 \cdot l. \qquad (6)$$

Thus, the fiber will not be pulled out of the matrix contact area if the fiber is not shorter than 8.426 cm. The critical length of the fiber is l_f = 8.426 cm.

3. Results and Discussion

Based on the obtained experimental data, we will build diagrams of the dependence of the compressive and bending tensile strength of concrete on various factors.

As it is shown by the experiment results, if we add the PET fiber, the compressive strength of all types of samples decreases. This is consistent with a number of studies [15–17], but contradicts other publications [19, 20]. The compressive strength is 49.3 MPa for the control samples with 0 % of the PET fiber. The maximum strength loss is observed in the samples with the addition of the industrial flex. At the maximum amount of fiber added (3 %), the strength is reduced by 25 % (37.1 MPa). The maximum strength loss was 20 % (39.5 MPa) for the samples with smooth fiber. The compressive strength reduced by 15 % (42.3 MPa) for the samples with ribbed fiber. The decrease in the compressive strength can be explained by a low adhesion between the surface of the PET fiber and the concrete matrix. Therefore, when the volume of injected fiber increases, the compressive strength decreases. When using longer fibers, the strength decreases less. This is due to the larger surface area, and higher adhesion forces. As well as the effect of mechanical engagement of fiber in concrete. That allows you to resist the load when the sample is destroyed. The best effect is achieved by ribbed fiber. This material has the best strength characteristics, due to the better engagement of the fiber in the concrete matrix.

The values of the tensile strength of the studied compounds have a different nature. The addition of PET fiber to concrete provides an increase in tensile strength, which is confirmed by the work of other researchers [21–23]. The tensile strength of additive-free concrete is 3.6 MPa. The strength of the flex samples increases to 122 % (4.4 MPa) with the addition of 1 % of fiber. The strength of the samples with smooth fiber reaches 166 % (5.8 MPa), with a 1 % reinforcement with 3 cm long fiber. It is up to 153 % (5.5 MPa) in the samples with ribbed fiber. This confirms the effectiveness of the use of PET fiber

It is also worth noting that when testing prism samples with the addition of 400×100×100 mm smooth and ribbed fiber for tensile bending, it was noted that when the sample lost its strength, it almost did not lose its stability indicators and kept its shape under its own weight, after there was no load.

A generalized concrete strength indicator R was introduced in the diagrams to eliminate the ambiguity of the influence of various factors and facilitate the determination of the dependence of the strength characteristics on the parameters of the used fiber

$$R = R_{bt} / R_b, \qquad (7)$$

where R_{bt} is the tensile strength of concrete, R_b is the compressive strength of concrete.

After evaluating the influence of the type of fiber used on the strength of concrete (Figure 5), we can conclude that the most optimal is ribbed (uneven) fiber. Such a shape allows the fiber to be more firmly fixed in concrete and ensures the transfer of tensile stresses from concrete to PET fiber. This contributes to an increase in the strength characteristics.

An increase in the amount of introduced fiber also predetermines an improvement of strength characteristics (Figure 6). It should be noted that this dependence is changeable (within the experiment), but is best described by a straight line.

The strength increases with an increase in the length of the fiber used (Figure 7). This can be explained by an increase in the effective adhesion area of the fiber and the concrete matrix with an increase in the size of the PET fiber used. This effect was noted in the works of other researchers who studied PET fiber reinforcement grids.

The abrasion capacity of fiber-reinforced concrete with PET fibers increases slightly with an increasing strength. This is not typical for concrete. Usually, the wear resistance increases with an increasing strength. This property can be explained by a poor adhesion of the fiber and the concrete matrix, especially in the area of the sample wear, which leads to spalling (separation) of the fine aggregate during the test. The abrasion capacity of fiber-free concrete was 0.52 g/cm^2. The abrasion capacity of the concrete with the addition of different amounts of PET fibers of various shapes and lengths ranges from 0.44 g/cm^2

to 0.62 g/cm². In general, we can speak about a neutral influence of PET fibers on the durability of fiber-reinforced concrete. This confirms the effectiveness of the use of PET fiber (Figure 8).

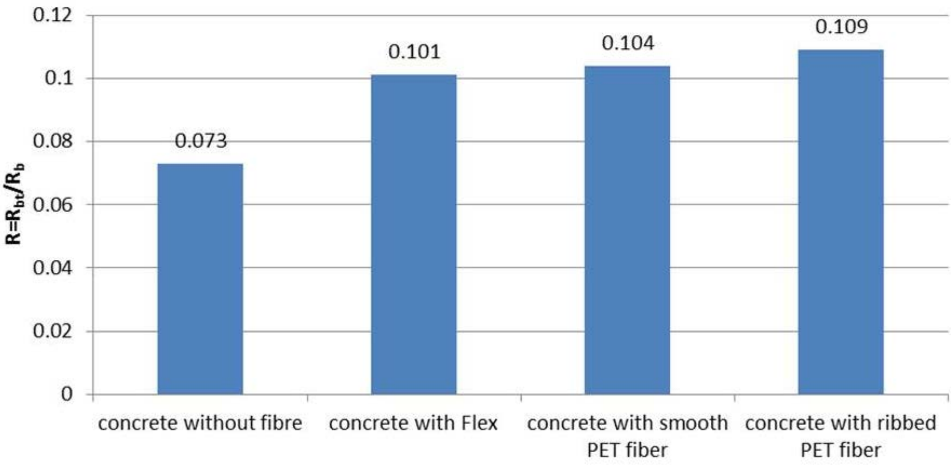

Figure 5. The dependence of the fiber concrete strength on the type of the PET fiber used.

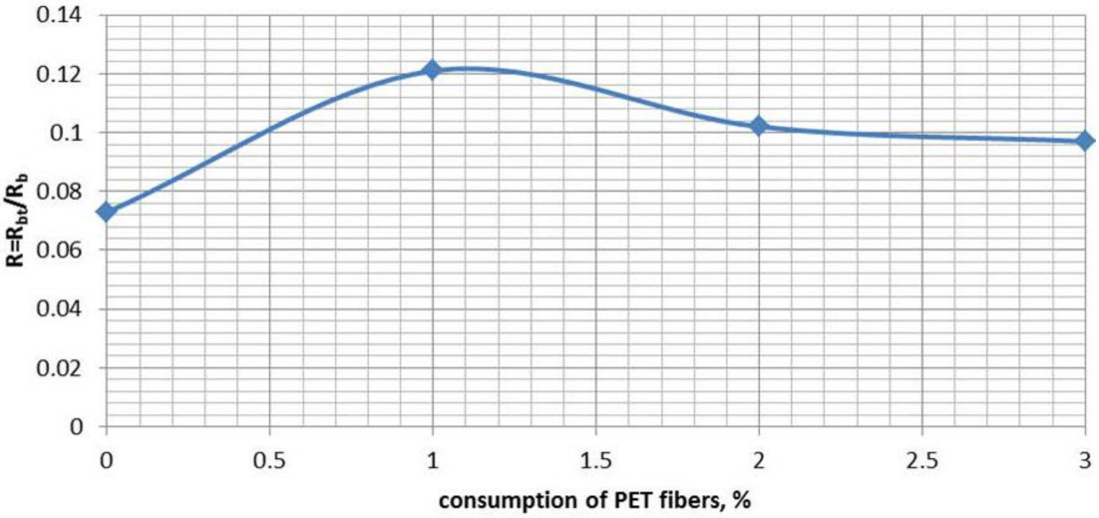

Figure 6. The dependence of the fiber concrete strength on the amount of introduced PET fibers.

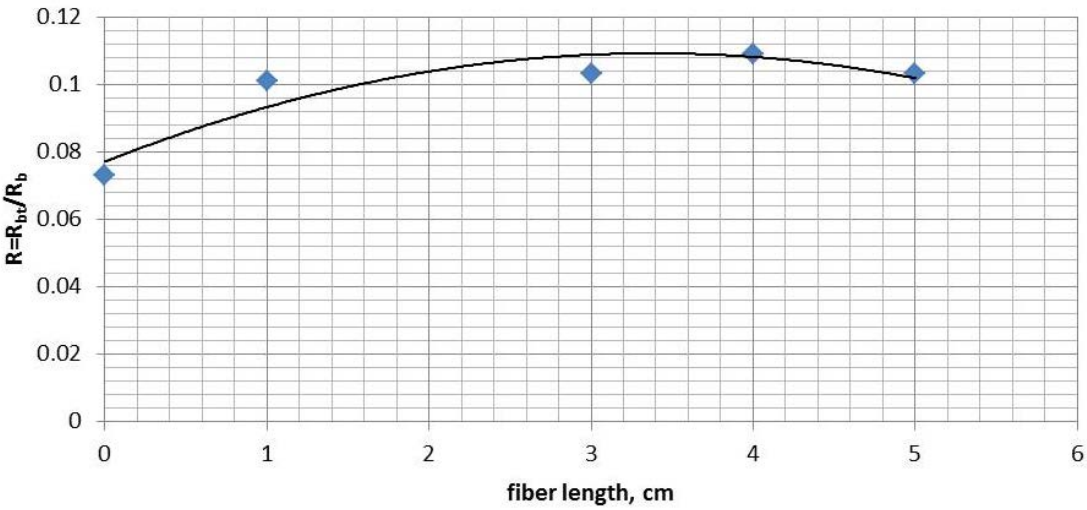

Figure 7. The dependence of the fiber concrete strength on the length of the fiber used.

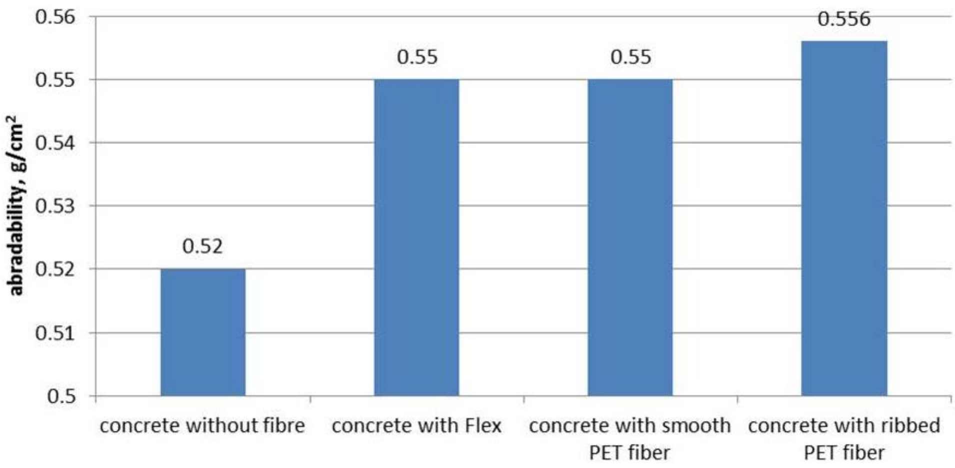

Figure 8. The dependence of fiber concrete abrasion on the type of fiber used.

4. Conclusions

With an obvious increase in the bending tensile strength indicator, which reaches 22–66 %, was obtained a decrease in the compressive strength indicator, which reaches 3–25 %. The most favorable ratio of the increase in the bending tensile strength indicator and the decrease in the compressive strength was obtained in the concrete with the addition of a smooth 4 cm long fiber with the lowest amount of reinforcement, 66 % increase in the bending tensile strength and 3 % decrease in the compressive strength. The most unfavorable ratio is in the concrete with the addition of the industrial PET flex with the highest reinforcement, where we obtained a decrease in strength in both tests, 13 % decrease in the bending tensile strength, and 25 % decrease in the compressive strength.

A decrease in the concrete abrasion capacity indicator was shown only by the samples with smooth and ribbed fiber, cut manually, with the largest value of concrete reinforcement (15 % and 7 %, respectively). The use of Flex leads to an increase in abrasion.

We calculated the critical fiber length (l_f) equal to 8.426 cm, at which the fiber would not be pulled out from the contact area of the matrix. This fiber length is in conflict with the procedure of introducing fibers into concrete, its preparation, transportation and laying in structures. Therefore, the variant of the ribbed fiber concrete, which is almost not inferior in strength to the smooth fiber concrete, is more favorable because of the possibility to reduce the fiber length due to various shapes of anchors on the lateral surface.

In general, the use of fiber in concrete from waste PET materials (obtained by mechanical grinding), and not subjected to heat treatment can increase the tensile strength. Compressive strength is reduced.

Industrial Flex is not recommended as a fiber (additive) in concrete, as it leads to a decrease in strength characteristics. Increased tensile strength is provided by the use of specially prepared PET fiber.

The study proved the possibility of using in concrete pet fiber from waste PET materials (obtained by mechanical grinding), and not subjected to heat treatment. PET fiber is recommended for use in concrete structures to increase tensile strength. This will make it possible to dispose of some plastic waste and preserve the environment.

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