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Strengthening Polymer Concrete with Carbon and Basalt Fibres

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Abstract: To date, composite materials, such as polymer concrete, have found wide application in various industries due to their unique properties combining high strength, resistance to aggressive media and durability. Improving the performance characteristics of polymer concrete is an important task aimed at expanding the areas of its application. One of the promising methods of increasing the strength of this material is the use of various fillers. In this paper, the effect of fillers, based on carbon and basalt fibres, on the mechanical properties of polymer concrete was investigated. The polymer concrete was made of the following components: rubble stone, sand, quartz flour and polyester resin. During the experimental work, the amount of carbon and basalt fibres in the polymer concrete mixture varied from 0 to 6%. Bending and compressive strength tests showed that the addition of carbon and basalt fibres increased these properties. The highest bending and compressive strengths were achieved when carbon fibre contents were up to 1.5%, while basalt fibres provided the highest strengths in the case of around 2%. These results confirmed that carbon fibres had a higher efficiency in strengthening polymer concrete compared to that of basalt fibres. This could be explained by the fact that carbon fibres had a higher tensile strength and modulus of elasticity, which allowed them to better redistribute loads within the composite material. The fibre length for carbon fibre, which gave the maximum increase in properties, was 10–15 mm. For basalt fibre, the maximum bending strength was reached at 20 mm and compressive strength at 10 mm. Increasing the content of carbon fibre above 2% and basalt fibre above 1.5% did not give further increase in mechanical properties. In conclusion, it could be stated that the use of carbon fibres as fillers offered significant advantages in strengthening polymer concrete, opening up opportunities for its use in more demanding conditions and in a wider range of industrial applications.

Keywords: fibre concrete; concrete strengthening; basalt fibre; carbon fibre; polymer concrete

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1. Introduction

Modern composite materials, including polymer concrete and fibre concrete, are gaining popularity in various industries due to their high-performance characteristics, which are in many ways comparable to traditional metals, such as cast iron and aluminium alloys.

The use of reinforced polymer concrete provides significant economic benefits. In some cases, replacing metal materials with polymer concretes reduces the cost of both the material and production processes. This is especially relevant in conditions that require resistance to aggressive environment, high loads and extreme temperatures.

Polymer concretes demonstrate high resistance to aggressive influences. A key factor that stimulates the growth of their popularity is reinforcement with various types of fibre.

In recent decades, the scientific community has been actively exploring the potential of reinforcing the concretes with fibres to increase their strength and durability. In particular, studies on the efficiency of reinforcing the polymer concretes with carbon and basalt fibre have shown promising results. This opens prospects for using reinforced polymer concretes in mechanical engineering and construction technologies.

Further research can lead to significant innovations in the production of polymer concretes and the expansion of their application beyond the construction industry. This will provide new opportunities for mechanical engineering and other industries, contributing to the creation of lighter, stronger and more cost-effective components. Such achievements will contribute to the sustainable development of industry and economy, ensuring the growth of technological efficiency and the reduction of operating costs.

Scientific and applied research in the field of reinforcing polymer concretes with carbon and basalt fibres has high scientific and practical significance. These works can contribute significantly to the development of new technologies and methods of using polymer concretes, which will ultimately have a positive influence on various industries.

A sufficiently large number of works are devoted to the study of the influence of various reinforcing admixtures on the performance properties of concrete [1–4]. One of the promising materials used for fillers is basalt fibres and carbon fibres [5,6]. New studies show that in some cases these fibres, used as fillers, can replace the reinforcement with metal rods and provide a comparable increase in strength.

The authors of [7] investigated in their work the reinforcement with different types of materials. They used reinforcing rods, made of steel, basalt and glass. The results of their work showed that steel rods allowed obtaining a maximum strength gain of 57%. However, when basalt rods were used, the strength gain was 32%, and when glass rods were used, it was 27%. In [8], studying the concrete reinforcement with basalt fibre and glass fibre additives in the concrete mixture, positive results were also obtained. The compressive and bending strengths of concrete increased during compression and bending tests. The maximum increase in compressive strength was achieved when adding basalt fibre, which was 25%. Basalt fibres are used to enhance the mechanical properties of concrete when gravel is used as a filler [9]. The addition of basalt fibres 12 mm long in the amount of 0.4% increased its compressive strength by more than 44%. In this work, concrete with a gravel filler was used. Basalt fibre is often used as a filler in combination with other fillers. The combination of basalt fibre with cellulose granules allowed the authors of [10] to increase the compressive strength of concrete by more than 20%. Reference [11] is devoted to determining the optimum amount of basalt fibre to be added. Basalt fibre was introduced into the concrete composition in the amount of 0, 0.1, 0.3 and 0.5%. The studies showed that the best strength properties were obtained using concrete containing 0.5% of basalt fibre. A similar work on the basalt fibre addition shows that the optimum reinforcement percentage in terms of increasing compressive strength is 1%. This basalt fibre content not only improves strength properties, but also reduces drying shrinkage by 31.6% [12]. A large work performed by the authors on the analysis of the influence of basalt fillers on the properties of concrete and polymer concretes shows the main trends and opportunities in improving the performance properties by means of basalt fibres. According to [13], adding basalt fibres to any type of concrete increases its bending strength and tensile strength. However, the addition of basalt fibres does not always result in an increase in compressive strength. The optimum percentage in terms of increasing the compressive strength of ordinary concrete by the basalt fibre reinforcement is between 0.05 and 0.15%. The maximum increase in bending and tensile strengths of ordinary concrete occurs when basalt fibres are added in the amount of 0.5–1%. This review shows that the effect of adding reinforcing fibres depends significantly on the concrete composition and the shape and size of the fibres themselves. In some cases, the maximum increase in properties (bending and tensile strengths) is achieved when adding 2–4% of basalt fibres. The optimum length of basalt fibres used for the reinforcement is usually 10–20 mm. The combination of different types of fillers also shows good results. In addition to basalt fibres, carbon fibres are a promising filler.

These conclusions are largely confirmed by the authors of [14,15]. At the same time, they say that an optimum ratio between an aggregate and a binder is often chosen experimentally. At the same time, the aggregate of such granulometric composition is used, which provides the minimum hollowness of the aggregate mixture. For each specific type of the aggregate, there is a different optimum ratio between the amount of the binder, aggregates and a reinforcing agent.

Most of the works on the use of reinforcing admixtures based on basalt fibre are devoted to the reinforcement of conventional concretes. But the works, devoted to geopolymer concretes [16–19], show similar results. The conclusions on the results of the works largely repeat the conclusions presented earlier in [13].

A further increase in polymer concrete properties can be achieved by using carbon fibre. In comparison with basalt fibre, carbon fibre is more expensive; however, some works show that it is possible to obtain a greater increase in compressive strength when using it [20–22].

In this research work, the authors focused on studying the strengthening mechanisms of polymer concrete by integrating basalt and carbon fibres of various lengths. The aim of the study is to identify an optimum configuration and properties of fibres that can significantly increase the strength properties of the composite material.

Based on previous scientific data and theoretical assumptions, we assumed that the inclusion of carbon and basalt fibres in the structure of polymer concrete improves its strength and deformation parameters, enhances the bond between the matrix and reinforcing elements, and increases resistance to mechanical loads and environmental impacts. In particular, the strengthening process can be realised due to the enhancement of cohesive and adhesive forces at the fibre–matrix interface. At the same time, the analysis of previous works shows that the optimal percentage of reinforcement with carbon and basalt fibres can vary from 0.3 to 2.5%. In a small number of works, a positive effect is given by the addition of 3–4% of fibre. The amount of added fibre and its effect largely depends on the composition of polymer concrete. Therefore, in many ways, to determine the optimal amount of reinforcing additive for each composition, it is necessary to conduct their own studies. In previous works of the authors [10,23,24], an attempt was made to replace the metal material of the pump body with polymer concrete. In this paper, we continued this work. Studies were conducted aimed at increasing the strength properties of polymer concrete from previous works due to reinforcement with fibres. The main emphasis in the study is on the analysis of the effect of the amount of added fibres and their length on the mechanical properties of the composite. Different sizes and types of fibres can change the structure and micromechanics of polymer concrete, which, in turn, will affect its macroscopic properties. By analysing the influence of fibre length, the authors seek to determine the boundary conditions under which the maximum increase in strength is observed.

2. Methods and Materials

The general plan of the research works included several stages, each of which was performed sequentially and systematically. At the first stage, polymer concrete samples were obtained. The control group of samples was made without using fibre fillers, which allowed the creation of a basis for comparison with other groups. Then, two experimental groups of the samples were formed. The first group contained additives of basalt fibres, and the second one had carbon fibres. In both groups, both the number and the length of the added fibres varied, which allowed studying the influence of these parameters on the properties of polymer concrete. After obtaining the samples, mechanical tests were conducted and the failure pattern of the tested samples was studied.

2.1. Experimental Design and Research Programme

All compression and bending test samples were measured and weighed prior to the work. The samples were left in the laboratory building for 10–20 h before testing. The temperature in the testing building was 20 ± 2 °C. To test the bending and compressive strengths of the samples, a Liangong WAW-4106-E high-accuracy class hydraulic universal testing machine (Liangong Group, Jinan, China) with a maximum load of 1000 kN was used.

Ten samples were mechanically tested for each selected composition. The statistical processing of the results of the experimental studies was performed using the software product Statistica 12.0. The samples with two types of reinforcing additives (basalt fibre and carbon fibre) were taken for testing. The control group of the samples without reinforcing additives was also tested. When choosing the percentage of reinforcement with carbon and basalt fibres, we based the choice on the data obtained from literature sources. Our analysis, provided in the introduction, showed that the optimum reinforcement percentage could vary from 0.3 to 2.5%. In a small number of works, the addition of 3–4% of fibres had a positive effect. The amount of the added fibre and its effect depended largely on the composition of the polymer concrete. Based on this, the following percentages of reinforcement were used in this work: 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6%. The analysis of previous works also showed that the greatest influence on the properties is the percentage of reinforcement. The length of reinforcing fibres can be chosen as the next factor in terms of the strength of influence on mechanical properties. There are few works devoted to the study of the influence of the length of reinforcing fibres. The available works most often show that for basalt and carbon fibres the optimum length is 10–24 mm. For carbon fibres, a value of 10–15 mm is more common, for basalt fibres 15–24 mm. Based on this we chose a fibre length of 10 mm for carbon fibres and 20 mm for basalt fibres. For these fibre lengths we tested specimens with different percentage of reinforcement. Then, for the percentage of reinforcement where maximum strengthening was achieved, we investigated the effect of the length of the reinforcing fibres. Fibre lengths of 5, 10, 15, 20, 25 mm were used.

2.2. Sample Preparation for Tests

As a result of testing the samples at the previous stage, a rational composition of polymer concrete was selected [5,23]. This experimental composition was selected taking into account the previous experimental works carried out by the authors. Polymer concretes can be used not only in industry, but also as a possible replacement of some hull parts. In [5,23,24], the authors showed that certain compositions of polymer concretes can meet the requirements for the manufacture of housing parts of gearboxes. With minimum consumption of components, samples of polymer concrete of the exhausted composition have high compressive and bending strengths, which guarantees a long-term operation of housing parts under severe working conditions.

We used rubble with the size of fractions of 2–3 mm as an aggregate for the polymer concrete mixture. Quartz sand with a fraction size of 0.5–1 mm and mineral flour with a fraction size of 0.05–0.01 mm were used as fillers. For the separation of rubble into fractions, a sieve with a mesh size not exceeding 1.8 mm was used, which allowed sifting out of the largest fraction with a size ranging from 2 mm and separating smaller particles and powdery components. Then, for the selection of fractions of the required size (2–3 mm), a sieve was used. The use of silica sand as a filler also helped to improve the mechanical properties of the material due to its high hardness and stable structure. Mineral flour, due to its fine fraction, contributes to the denser filling of voids in the matrix, which reduces the number of pores and improves the overall quality of the obtained material.

The crushed rubble, used to make the samples, was dried. In this case, drying was carried out in the drying SHS-200 SPU (Smolenskoye Sktb, Smolensk, Russia) unit at a temperature of 80 °C for 120 min. A similar temperature regime was used for drying quartz sand and mineral flour. These measures are necessary to reduce the moisture content of the components, thus avoiding undesirable reactions during the mixing and polymerisation process.

The composition of the polymer concrete mixture included the following proportions: 50% of rubble of a 2–3 mm fraction, 25% of quartz sand of a 0.5–1 mm fraction and 15% of mineral flour of a 0.05–0.01 mm fraction from the total mass of the sample. To improve the mechanical properties of the mixture, the reinforcing filler (carbon fibre or basalt fibre) was added in an appropriate amount. The dry components were mixed for 3 min. Polyester, which is the main component of polymer concrete, consists of alcohols, acids and anhydrides. In our case, ethylene glycol is used as alcohol; fumaric acid acts as acid, and phthalic anhydride is used as anhydride. To achieve the required strength of polymer concrete products, the epoxy resin was heated to a temperature of 60 °C.

The analysis of the obtained results [5] showed that achieving a necessary strength requires the rational drying temperature in the range of 120–130 °C. This temperature range provides consistently high strength of polymer concrete products. A polyester resin hardener was added to the polyester resin heated to a temperature of 120 °C to act as a catalyst for the chemical curing reaction of the polymer concrete mixture. Its addition and subsequent stirring for 2 min provided a uniform distribution of the catalyst throughout the volume of the resin, which is a critical step for subsequent uniform curing. The polyester resin with the uniformly distributed hardener was then added to the vessel with the pre-prepared dry mix. The obtained mixture was stirred for 6 min to achieve a homogeneous mass.

After the thorough mixing, the polymer concrete mixture was evenly distributed into matrices, each of which had 3 cells. A vibration table was used for a denser distribution of the mixture in the matrix cells. Vibrating the samples for 10 min allowed the removal of possible air inclusions and ensuring a tight adherence of the mixture to the walls of the matrix. This is important to prevent micropores, which can reduce the strength characteristics of the finished products. Immediately after vibration processing, the samples were left in the matrix at room temperature for 7 h for initial curing. This process gives the products sufficient initial strength and allows one to complete the polymerisation process as required. After this initial stage, the samples were removed from the matrices (Figure 1) and placed in the drying SHS-200 SPU cabinet, where they underwent further drying at a temperature of 70 °C for 2 h. The fibre concrete mix sample for the production of control samples was taken from the middle part of the mix. The fibre concrete mix for samples was prepared in strict accordance with the requirements of the standard [25].

Figure 1. The mould for manufacturing control samples (square section prisms).

After complying with all the technological stages, ready-made fibre concrete samples with the dimensions of the working cross-section of 40 × 40 × 160 mm were obtained. Such dimensions were chosen for the convenience of testing for strength, resistance to loads and other mechanical properties, allowing a full analysis of the quality and suitability of the material for further use in construction and engineering tasks.

The samples were obtained which underwent a series of mechanical tests aimed at determining their strength characteristics. The tests allowed evaluation of such parameters as compressive strength and bending strength.

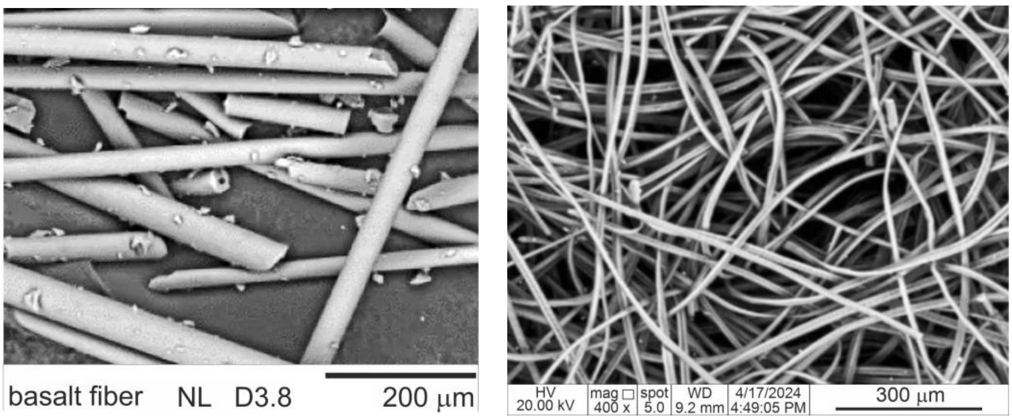
2.3. The Used Materials of Reinforcement Fibres

Carbon fibre and basalt fibre were used as reinforcing additives. Characteristics of the used additives are given in Table 1. The characteristics of the fibres were obtained from the manufacturers of these fibres. In case of the carbon fibre, this was the "OOO Dipchel" company (Saratov, Russia); for the basalt fibre, the company was "OOO Kamenny Vek" (Dubna, Russia).

Table 1. Material characteristics of used reinforcement fibres.

Comparative Parameters	Fibre Materials	
	Basalt	Carbon
Density, kg/m^3	2900	1900
Fibre thickness, μm	100	20
Fibre length, mm	15–20	15–20
Tensile strength, MPa	2600	2000
Modulus of elasticity, GPa	95	245
Resistance to the alkaline environment of cement	High	High

The carbon fibre, obtained from "OOO Dipchel" (Saratov, Russia) and used to form the composite, is shown in Figure 2a. The basalt fibre, obtained from "OOO Kamenny Vek" (Dubna, Russia), is shown in Figure 2b.



(**a**) (**b**)

Figure 2. Fibres used to modify polymer concrete: (**a**) basalt fibres; (**b**) carbon fibres.

2.4. Mechanical Tests

2.4.1. The Bending Test for Samples

Studies were carried out using control samples (L = 160 mm); the cross-section in the middle part was 40 × 40 mm. Before testing, burrs were ground to improve the dimensional accuracy of the samples. The height and the width of the sample in its middle part were determined using a calliper whose accuracy was 0.05 mm. The samples were tested on a manual hydraulic press Liangong WAW-4106-E (Liangong Group, Jinan, China) with a maximum load of 1000 kN. To carry out the studies, an attachment to the press was developed (Figure 3), consisting of a steel disc, on which two stops, made of bar (d = 10 mm), were fixed. To control the loading parameters of the samples, the press standard pressure gauge was used. And to calculate P, we measured the diameter of the press piston d_{pist} [26].

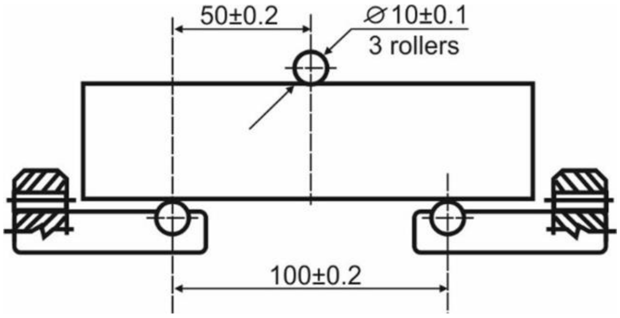


Figure 3. The calculation diagram for bending strength determination.

P was calculated according to the following formula:

$$P = d_{pist} \cdot p, \quad (1)$$

where p is pressure in the working cavity of the press, Pa $(N/cm)^2$.

The bending strength was calculated using the formula below:

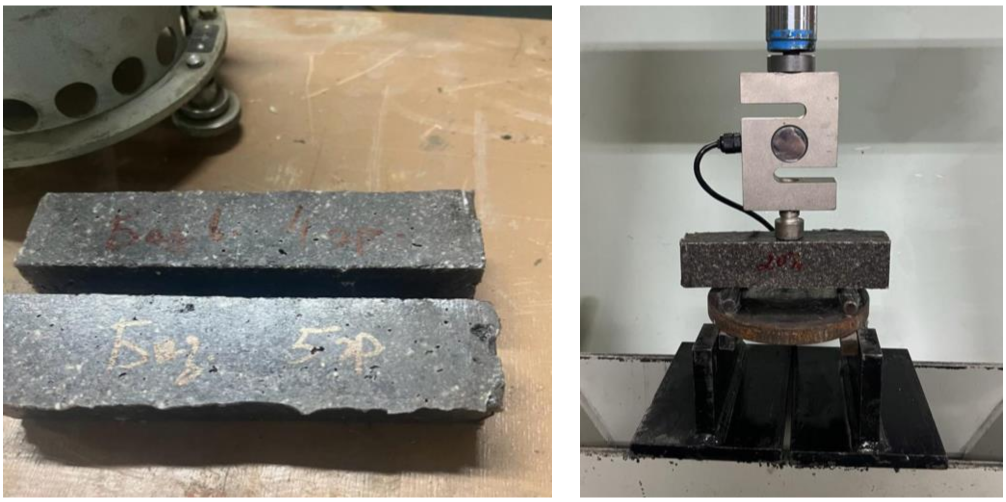
$$\sigma = \frac{M}{\frac{c \cdot h^2}{6}}, \quad (2)$$

where σ is bending strength, Pa;

c—width of the sample at the point of fracture, m;
h—height of the sample at the fracture point, m;
P—load in the middle part of the sample, N;

2.4.2. The Compression Test for Samples

The sample together with the plates was centred on the base plate of the press (Figure 4). The average rate of load growth during the tests was (2.0 ± 0.5) MPa/s. The calculation of the compressive strength was carried out in the same way as the calculation of the bending strength.

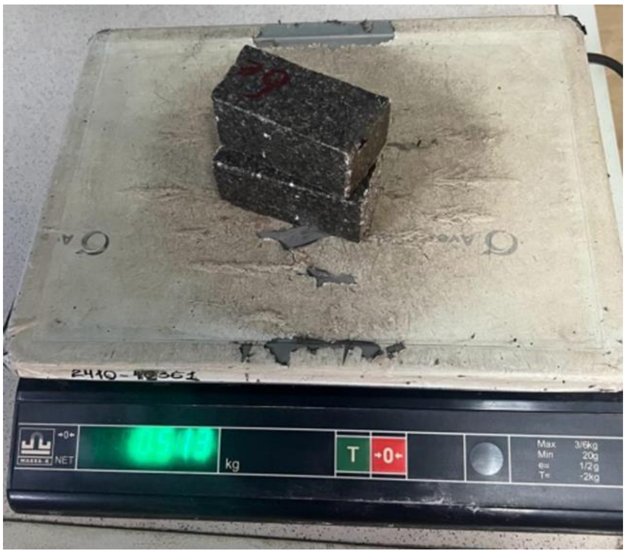


(**a**) (**b**)

Figure 4. The external view of (**a**) test samples made for testing; (**b**) bending tests of specimens.

The compressive strength of an individual sample (Figure 5) was calculated as the quotient of the failure load (kN) divided by the working area of the plate S_{pl} (cm^2), i.e., 2.0 cm^2 as the arithmetic mean of the four highest test results of six samples.

(a)



(b)

Figure 5. The failure sample after compression tests: (**a**) samples after compression testing; (**b**) samples after bending strength testing.

P_{comp} was calculated according to the formula below:

$$\sigma_{comp} = \frac{P_{comp}}{S_{pl}},$$

where S_{pl} is the support area of the pressure plates.

2.5. Study of the Fracture Surface of the Samples

The microstructure of the material was studied by scanning electron microscopy using Carl Zeiss EVO 50 XVP (Jena, Germany). The operating modes of the equipment in low vacuum using secondary and backscattered electron detectors were as follows: the accelerating voltage was 0.2–30 kV, ensuring a maximum resolution of 3 nm.

3. Results and Discussion

Experimental studies have shown that the percentage of the reinforcement is the main factor affecting the bending and compressive strengths of reinforced polymer concrete samples. The parameters and the test methodology of the samples for strength studies are described in Section 2. Special attention was paid to the analysis of the influence of different reinforcement parameters on the behaviour of the samples. During the experiments, we found that increasing the percentage of the reinforcement up to a certain limit significantly increases the strength. This is because the larger area of the reinforcement allows better absorption and a uniform distribution of stresses arising from external loads. The dispersed reinforcement distributed over the cross-section of the sample contributes to the stiffness and resistance of concrete to cracking and deformation. The optimum concentration of the reinforcing admixture provides an increase in the load-bearing capacity of the structure and improves its performance characteristics. The conducted experiments confirmed the significance of the percentage of the reinforcement in improving the bending and compressive strengths of the polymer concrete samples. These results provide a foundation for further research and optimisation of reinforced concrete structures, which is important for producing the most durable and reliable structures.

3.1. Mechanical Tests of the Samples for Bending Strength

Based on the experimental work, graphs were made showing the functional dependence of the bending moment and compressive strength on the percentage of the basalt and carbon fibre reinforcement. Figure 6 shows the graph of the dependence of the failure bending moment on the percentage of the fibre reinforcement in polymer concrete beams.

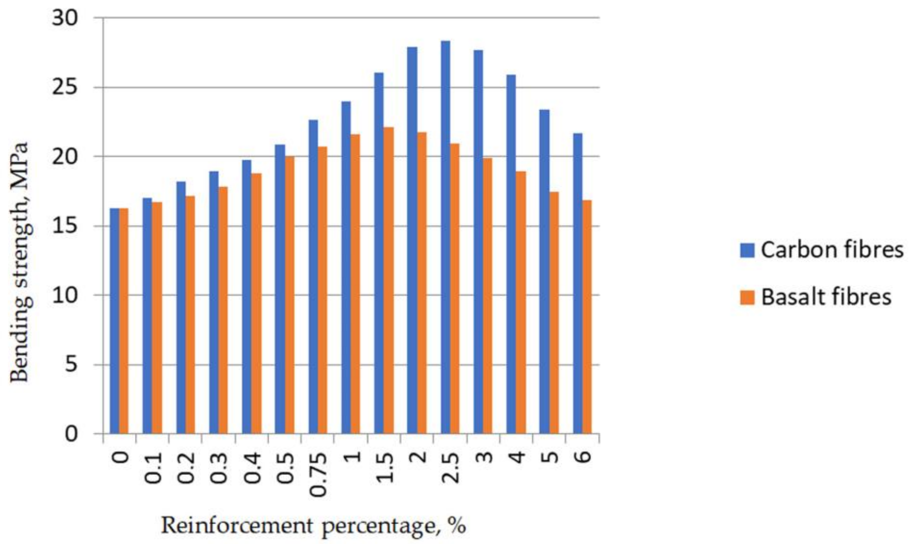


Figure 6. The graph of the dependence of the ultimate bending strength on the reinforcement percentage.

The results of the analysis of the graph presented in Figure 6 show that, in the range of reinforcement percentage values from 0.1 to 2.0%, a linear dependence of bending strength on the reinforcement percentage is observed for carbon fibre. For basalt fibre, a linear dependence is observed in the range of 0.1 to 1.5% of the reinforcement. Further increase in the reinforcement percentage leads to failure of samples mainly in the compression zone. For samples with the percentage of the carbon fibre reinforcement in the range from 0.1 to 2.0%, failure starts from the tensile zone, indicating that the reinforcement has reached its yield strength [27]. A similar pattern is observed for samples with basalt fibre. When the fibre content ranges from 0.1 to 1.5%, failure starts in the tensile zone. At the same time, in samples with a higher percentage of the fibre reinforcement, failure occurs already in the compression zone. The difference in the fibre content, during a transition of fracture from the tensile zone to the compressive zone, is explained by different properties of basalt and carbon fibres. Carbon fibres have a much higher modulus of elasticity. This allows the fibres to stretch longer without collapsing. Therefore, the maximum hardening for carbon fibre is 73.6% and 35.6% for basalt fibre. For polymer concrete samples, where the percentage of the fibre reinforcement exceeded 4.5–5.0%, brittle failure in the compression zone is observed.

3.2. Mechanical Tests of the Samples for Compression

In addition to examining the bending strength of the reinforced concrete samples, compressive tests were performed using the samples. Figure 7 shows a plot of the compressive strength of the samples as a function of the percentage of the fibre reinforcement in the polymer concrete beams.

The results of the analysis of the graph, presented in Figure 7, allow one to conclude that, in the range of reinforcement percentage values ranging from 0.1 to 1.0%, a linear dependence of bending strength on the reinforcement percentage is observed for carbon fibre. For basalt fibre, the linear dependence is observed in the range of 0.1 to 1.5% of the reinforcement. Maximum strengthening is achieved for the carbon fibre reinforcement of 1.0% and for the basalt fibre reinforcement of 1.5%. During such strengthening with basalt fibres, an increase in compressive strength by 15.4% is observed. During the reinforcement with carbon fibres, the increase in compressive strength is 10.1%.

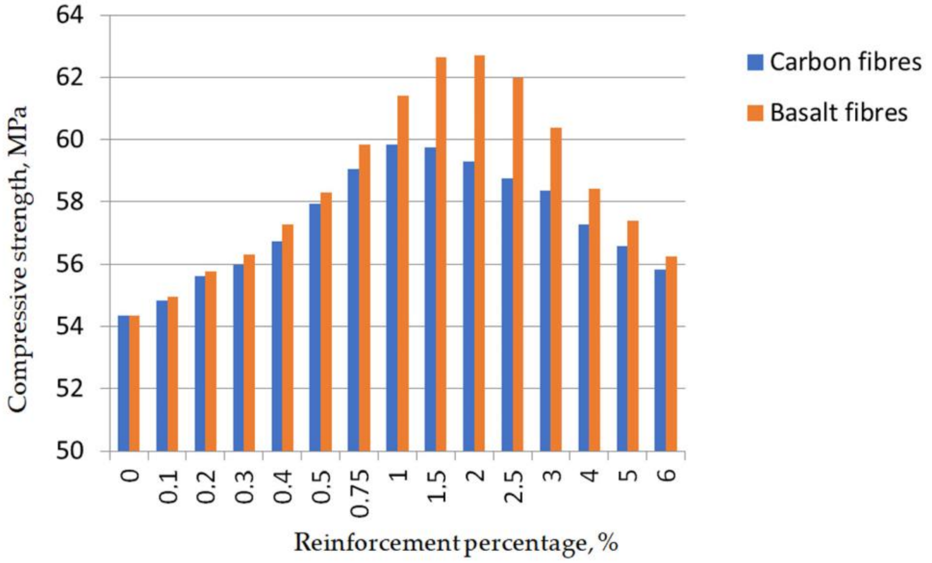


Figure 7. The graph of the dependence of the compressive strength on the reinforcement percentage.

3.3. Diagrams "σ–ε" of Material Deformation

In order to analyse in detail the stress–strain state of bending element cross-sections, functional relationships between stresses and relative strains in polymer concrete samples with reinforcing additives were constructed. The methodology of the tests, as well as their geometrical parameters and schemes of measuring devices arrangement, is described in Section 2. As a result of conducting compression tests for the samples, graphs of the relationship between stresses and relative strains were plotted for polymer concrete without the reinforcement, as well as for concrete reinforced with carbon fibres (1%) and basalt fibres (2%). These graphs are presented in Figure 8. This graph shows that fibre reinforcement allows for a significant increase in the sample deformation value before failure. Reinforcing fibres continue to work and prevent the material from failing for much longer. At the same time, the use of basalt fibres provides the maximum increase in relative elongation before failure of 55%. When reinforcing with carbon fibres, this value is 27%.

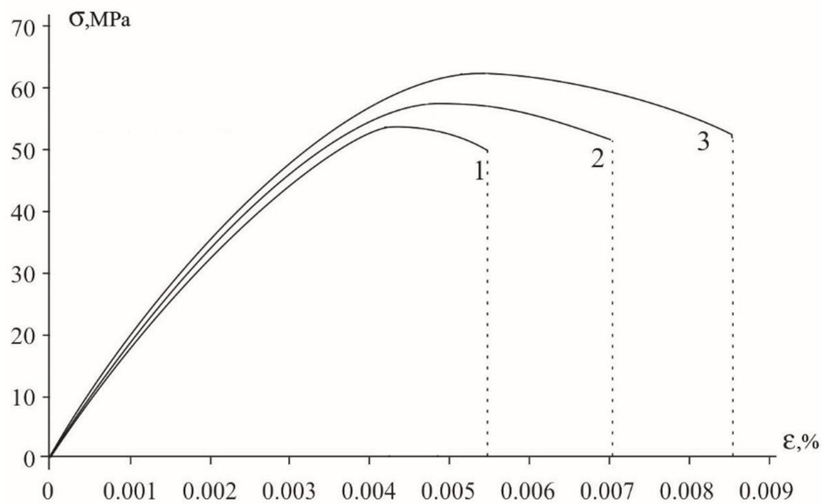
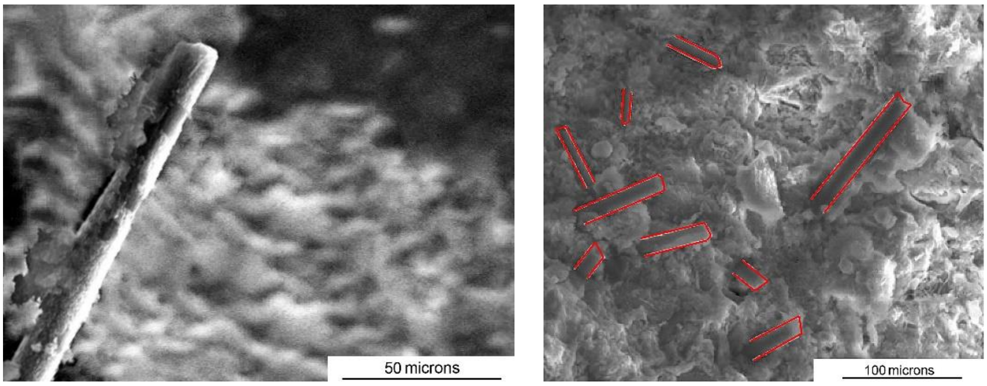


Figure 8. Stress–strain diagram for testing specimens for bending strength: 1—specimen without reinforcing fibres; 2—specimen with 1% carbon fibres; 3—specimen with 2% basalt fibres.

3.4. Analysis of the Fracture Surface of the Tested Samples

In order to investigate the reasons for the change in strength characteristics with the increasing percentage of the dispersed reinforcement and to study the peculiarities of fracture of carbon fibre concrete, we analysed the microstructure of the fracture surface of the experimental samples. The obtained data allowed us to establish that the reinforcement in the range from 0 to 1.0% leads to a uniform distribution of carbon fibres (Figure 9b), while increasing the concentration up to 1.5% and above, clusters of fibres of different density are observed. These clusters disturb the homogeneity of the fibre concrete structure, which negatively influences its force structure, promotes the appearance of stress concentration zones and cracks, which ultimately reduces the strength properties of the material.



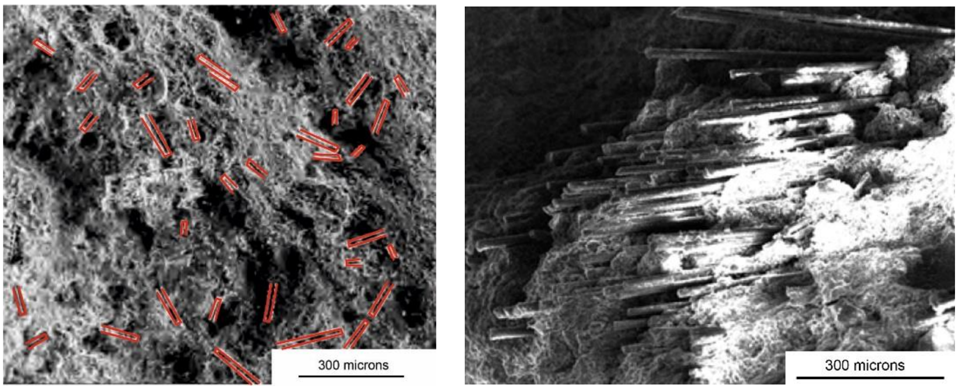
(**a**) (**b**)

Figure 9. The fracture surface of carbon fibre-reinforced polymer concrete: (**a**) formations on the surface of carbon fibre; (**b**) broken fibres and voids of torn out fibres.

The analysis of the contact zone between the carbon fibres and the cement matrix showed that deposits of newly formed cement hydration products are formed on the surface of the fibres, which helps to improve the adhesion between the surface of the fibres and the matrix, as well as their anchoring in the sample material (Figure 9a). These results are in line with the findings of other researchers [28], confirming the significance of these phenomena in the context of strengthening the strength characteristics of the composite material.

The concentration of reinforcing fibres has a significant influence on the mechanical properties of polymer concrete. This applies to both the carbon fibre reinforcement and the basalt fibre reinforcement. A uniform distribution of fibres at low concentrations contributes to a better strength behaviour of the material, as it ensures a uniform distribution of loads (Figure 10a). However, the increase in defect areas due to fibre clustering at higher concentrations reduces the strength of the composite (Figure 10b). The formation of such clusters disrupts the continuity of the matrix, resulting in insufficient bonding and sites for the initiation of microcracks. Under mechanical load, these microcracks can coalesce and propagate, especially if stress concentrations from agglomerates are present. The development of microcracks in the course of time significantly reduces the durability and reliability of the material. Continuous loading exacerbates this problem, leading to premature failure.

It is known that the failure mechanism of carbon fibre concrete with an arbitrary fibre orientation depends on their physical and mechanical properties and sizes. This process can be accompanied by the rupture of a certain number of fibres with the subsequent pulling out of the rest or the complete pulling out of all fibres from the concrete composition. During the investigation of the fracture surface of the carbon fibre concrete, we found that failure occurred with partial rupture of some fibres followed by the pulling out of the rest. Some fibres showed signs of rupture while others were pulled out of the concrete matrix. This fact was confirmed by the observed signs of rupture and craters in the concrete body (Figure 9b).



(a) (b)

Figure 10. The fracture surface of polymer concrete reinforced with basalt fibres: (**a**) uniform distribution of fibres during the 1.5% reinforcement; (**b**) non-uniform distribution with clotted fibres during the 5% reinforcement.

The adhesion between the polymer matrix and the reinforcing fibres is of fundamental importance for the material performance. A good adhesion ensures an effective stress transfer from the matrix to the fibres, allowing the composite material to withstand higher stresses without failure.

Based on the obtained test results and microstructure photographs, one can state that when a crack appears in the polymer concrete matrix, the fibres continue to function and resist its further development. This leads to an increase in the plastic properties of such concrete. In particular, a significant increase in relative elongation is observed for fibre-reinforced samples, which indicates an increased deformation capacity of the material. The fibres resist not only the formation of cracks, but also their propagation, even when a crack has already been initiated in the main matrix. They act as bridges across the cracks. This phenomenon allows the material between the cracks to contribute to the overall load-bearing capacity. This bridging action delays the propagation of cracks and distributes loads more uniformly, increasing both the bending and compressive strengths. Our studies demonstrated an increase in the bending and compressive strengths. According to the data, presented by other authors, an increase in the hardness of fibre-modified concrete was also observed, although this increase was not significant [29]. Therefore, an increase in all the above-mentioned strength characteristics also entails an increase in the rigidity of the material. These findings emphasize an important role of fibres in improving the mechanical properties of polymer concrete and indicate the potential for their use in creating more reliable composite materials. The study of fracture mechanisms of carbon fibre concrete with a volumetrically random fibre orientation is key to understanding its strength properties. The analysis of the fracture microstructure can provide valuable data on the interaction of carbon fibres with the concrete matrix and reveal the peculiarities of the fracture processes.

The research shows that reinforcement with both carbon and basalt fibres improves the strength properties of concrete. However, the cost of these fibres varies significantly. Basalt fibre practically does not increase the cost of concrete since its price is relatively low and the required amount is only 1–2%. While carbon fibre, whose cost is almost 10 times higher than that of basalt fibre, significantly increases the costs of the production process. The economic feasibility for using carbon fibre is justified in cases when it is necessary to ensure maximum bending strength of the material. At the same time, the use of basalt fibre is more appropriate in terms of cost and efficiency for a wide range of construction applications. In view of this, the choice of the type of reinforcing fibre should be based on a balance between the required performance characteristics and financial considerations.

3.5. Mechanical Tests (Flexure, Compression) of the Samples with Additions of Fibres of Different Lengths

The uneven distribution of fibres throughout the volume of polymer concrete significantly affects its properties. In addition, the strength is largely influenced by the bonding force between the fibres and the polymer concrete matrix. Figures 11–14 show the data on the effect of the length of reinforcing carbon and basalt fibres on the strength of the polymer concrete specimens under study (bending and compressive strengths).

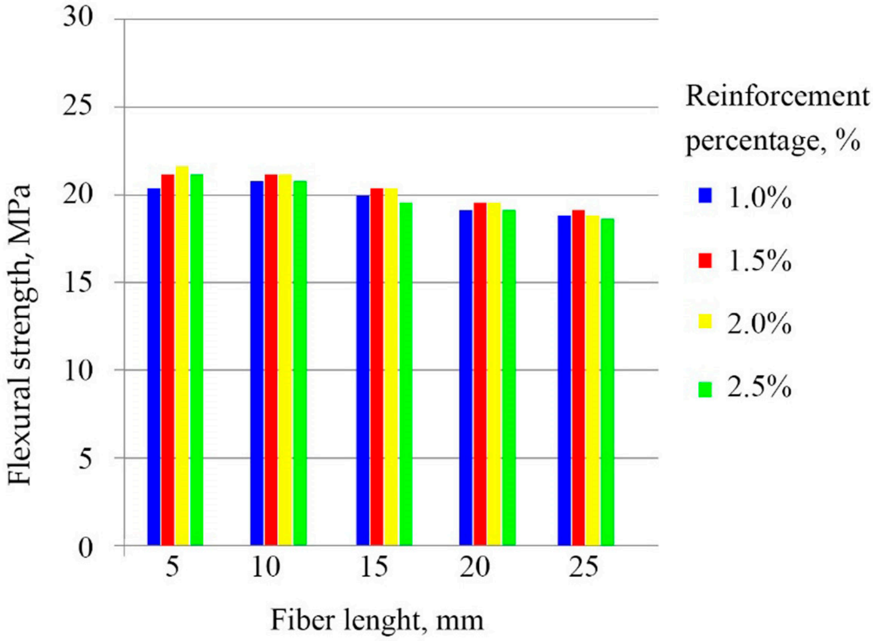


Figure 11. Bending strength for the samples made of polymer concrete reinforced with basalt fibres of different lengths.

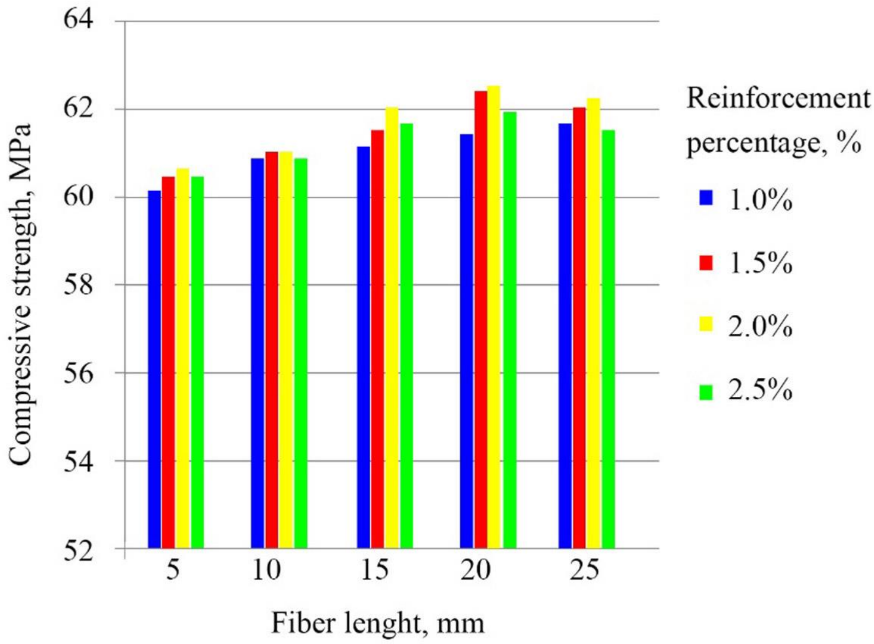


Figure 12. Compressive strength for the samples of polymer concrete reinforced with basalt fibres of different lengths.

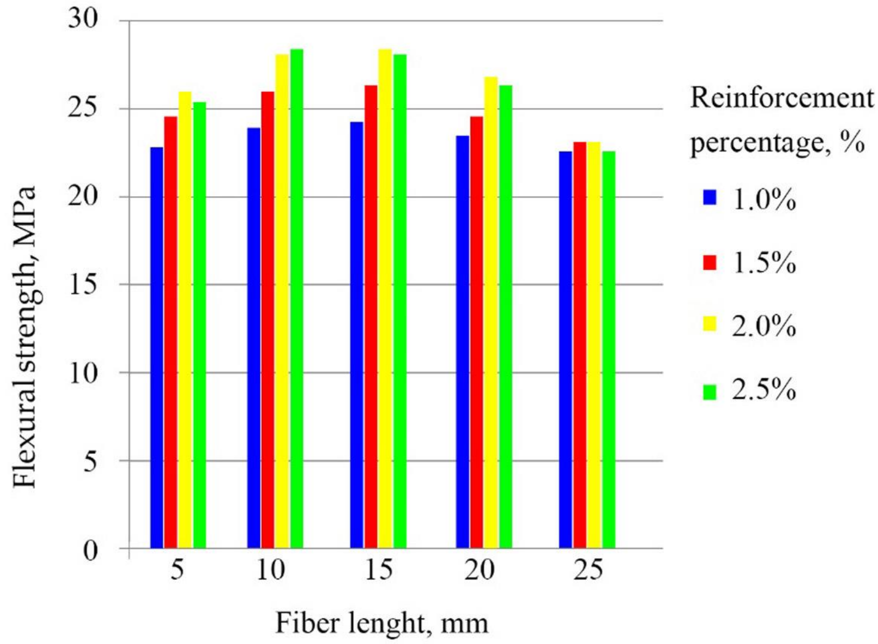


Figure 13. Bending strength for the samples of polymer concrete reinforced with carbon fibres of different lengths.

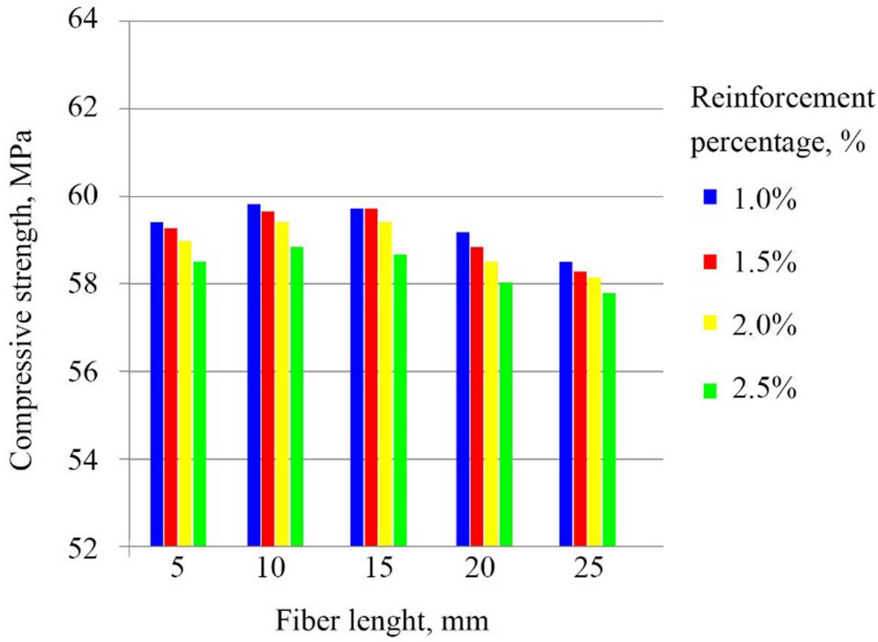


Figure 14. Compressive strength for the samples of polymer concrete reinforced with carbon fibres of different lengths.

Analysis of Figures 13 and 14 shows that for carbon fibre reinforcement the optimum fibre length is 10–15 mm. Further increase in fibre length leads to a decrease in both bending and compressive strengths. This is due to the fact that with longer lengths it is more difficult to ensure a uniform distribution of fibres throughout the specimen. A longer length promotes the formation of fibre clusters. Also with longer lengths, the total number of fibres in the specimen decreases for the same percentage of reinforcement. A shorter fibre length increases the total number of fibres in the sample. However, the fibres have a shorter length and a smaller bonding surface to the matrix. Therefore, such fibres are more easily torn out of the matrix and are less able to withstand the load. A similar picture is observed when reinforcing with basalt fibres. But when reinforcing with basalt fibres, the maximum bending strength is achieved at a fibre length of 10 mm, and the maximum compressive strength at a fibre length of 20 mm. The difference in the optimum fibre length in terms of improving properties for basalt and carbon fibres can be explained by the different properties of these fibres. Also, basalt fibres and carbon fibres have different diameters. Basalt fibres have a larger diameter and this also influences the results obtained.

Further research in this area will improve the strength properties of the composite material and optimise its structure for better use in relevant industries.

The following conclusions can be drawn as a result of the conducted experiments:

1. Bending test strength for reinforced polymer concrete samples:

For the elements with the percentage of the carbon fibre reinforcement of 2.0%, the increase in bending strength compared to that of unreinforced samples is 73.6% (the length of fibres is 10 mm).

For the elements with the basalt fibre reinforcement percentage of 1.5%, the increase in bending strength compared to that of unreinforced samples is 35.6% (the length of fibres is 20 mm).

2. Tensile strength during the compression test for reinforced polymer concrete samples:

For the elements with the percentage of the carbon fibre reinforcement of 1.0%, the increase in bending strength compared to that of unreinforced samples is 10.1%.

For the elements with the basalt fibre reinforcement percentage of 1.5%, the increase in bending strength compared to that of unreinforced samples is 15.4%.

In general, the mechanical properties of flexural elements with the fibre reinforcement are superior to those of similar elements without the reinforcement [30]. This is due to the higher anchorage value of the reinforcement in fibre-reinforced concrete structures, which ensures a reliable coordination between the reinforcement and polymer concrete, preventing the abrupt development of plastic deformations in the reinforcement. The fibre reinforcement also helps to increase the duration of joint operation between the reinforcement and polymer concrete in the tensile zone, which allows a more efficient redistribution of stresses over the reinforcement bar even when cracks are formed.

Studies show that fibres continue to work and retain cracks at the moment of polymer concrete delamination, which significantly increases the overall mechanical performance of the structure, guaranteeing its durability and resistance to loads [29,30]. The use of the fibre reinforcement throughout the entire section height contributes to the improvement of stiffness of bending elements, which is associated with a uniform distribution of stresses throughout the entire section height and a reduction in the probability of sudden failure [31–33].

The fibre reinforcement makes it possible to create more reliable and durable structures and engineering products capable of withstanding high loads in harsh operating conditions. The load-bearing capacity of reinforced polymer concrete flexural elements is superior to that of the elements made of conventional concrete and polymer concrete. This can be explained by a number of key factors:

1. Resistance to deformation in the tensile zone. Polymer concrete in the tensile zone contributes to the strengthening of normal sections, so that even in the event of initial fractures in the material, its ability to absorb stresses is maintained.
2. High adhesion between the reinforcement and structural material. Improved adhesion between reinforcement bars and polymer concrete slows down the development of plastic deformations in the reinforcement, which increases the stability of flexural elements.
3. Compression zone material strength. High material strength in the compression zone of structures increases their load-bearing capacity, as the central part of the element remains less susceptible to collapse.

Due to the above parameters, reinforced polymer concrete elements demonstrate improved mechanical properties and increased durability, which makes them particularly relevant for use in critical construction and engineering structures.

4. Conclusions

The characteristics of polymer concrete, reinforced with carbon and basalt fibres, are determined by the interaction of the fibre content, fibre length and matrix–fibre interactions. The optimum fibre content (up to 2% for carbon and up to 1% for basalt) ensures a good fibre distribution, effective crack bridging and stress transfer. In case of such percentage contents of fibres, for basalt fibre the maximum bending strength is achieved when the length is 10 mm and compressive strength is reached at 20 mm in length. As for carbon fibre, the maximum compressive and bending strengths are achieved when its length is 10–15 mm. Beyond these optimal values, such negative effects as fibre agglomeration and poor adhesion reduce the benefits, resulting in reduced mechanical properties and fractured structural integrity. Understanding these micromechanisms allows fine-tuning the polymer concrete compositions to achieve the desired balance of strength, durability and reliability.

When the carbon fibre content exceeds 2% or the basalt fibre content exceeds 1.5%, fibre agglomeration occurs. These agglomerates act as weak points in the material. Instead of a uniform distribution of fibres, the agglomerates create localised microregions of high stiffness and low strength, which leads to stress concentration. An excessive fibre content can prevent the fibres from mixing and bonding properly with the matrix. A poor adhesion results in an ineffective stress transfer, which leads to the formation of microcracks under mechanical loads. Over time, these microcracks widen, which compromises the structural integrity and durability of the material.

In addition, in the case of the excessive fibre content, the combination of components and adhesion between fibres and the matrix deteriorate. This leads to the appearance of microcracks, which increase in the course of time under mechanical loads. This phenomenon significantly influences the durability and reliability of the material.

The results of the work also showed that the reinforcement with carbon fibre provided a greater increase in bending strength than the reinforcement with basalt fibre did. In case of compressive strength, an opposite situation was observed. At the same time, the cost of basalt fibre is significantly lower, and if maximum strength characteristics under bending are not required, it is more economically feasible to use reinforcement with basalt fibre.

Therefore, optimisation of the percentage of the fibre content in composites is a key factor for achieving maximum strength and durability of finished products. This fact, in turn, is directly related to the practical aspects of production and allows, based on the experimental data, the development of new materials with specified characteristics to meet the requirements of various industries. In particular, polymer concrete reinforced with basalt or carbon fibres can be used as a material for a number of industrial parts. Examples of such parts include gearbox housings, pump casings and other parts where the strength requirements are not high.

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