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Results of Research into the Physical and Mechanical Properties of Biopolymer Gravel Composite Block Filters for Hydrogeological Wells

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Abstract. The article presents the results of a study of the physical and mechanical properties of a biopolymer gravel composite made on the basis of polylactide (PLA) and natural gravel. The developed composite is intended for filtration elements of hydrogeological wells. The biopolymer-gravel composite was tested for compressive strength.
The results showed that the biopolymer gravel composite is characterized by sufficient mechanical strength and resistance to the effects of the aquatic environment, which confirms the feasibility of its use as an environmentally safe material for filtration elements of hydrogeological wells. The obtained data can be used for further optimization of the composition of the composite material and the development of new biopolymer block gravel filters of hydrogeological wells.

Introduction

In modern conditions of intensive use of natural resources and active development of geotechnical, hydrogeological and oil production technologies, the need for highly efficient and environmentally friendly materials for drilling systems is growing [1-7]. One of the key components of such systems is filtration elements that provide purification and stabilization of water or gas flow in the well operation zone. Traditionally, inorganic materials (metals, concrete, ceramics) or polymers of petrochemical origin are used for the manufacture of such elements, which, despite satisfactory performance characteristics, have a number of significant disadvantages. In particular, they are poorly suited to biological degradation, can cause environmental pollution after the end of operation and require complex and energy-intensive disposal [8-10].

Against the backdrop of global challenges related to climate change [11,12], groundwater pollution and depletion of natural resources, there is becoming increasingly relevant the introduction of materials based on biopolymers, which are made from renewable raw materials and are characterized by the ability to naturally decompose. One of the most promising such materials is polylactide (PLA), a biodegradable thermoplastic polymer obtained from plant sugars (e.g., corn starch), which demonstrates acceptable mechanical properties, water resistance and chemical inertness in a moderately aggressive environment [13].

The integration of PLA with natural gravel in the form of a composite material opens up new possibilities for creating a new generation of filtration gravel elements - biocompatible, technologically adaptable and at the same time strong and durable. Gravel, as a natural filler, provides a stable filtration structure of the composite, and PLA performs the function of a binding component that forms a monolithic structure with controlled porosity and permeability. However, in order for such a system to be effectively applied in practical conditions of drilling and well operation, it is necessary to study its physical and mechanical properties [14-18].

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In particular, determining parameters such as compressive strength allows us to assess not only the operational reliability of a biopolymer gravel composite (BGC), but also its compliance with the requirements of specific hydrogeological conditions. Additionally, given the biodegradable nature of PLA, it is important to assess the resistance of the composite to the effects of the aquatic environment.

The study of the physical and mechanical properties of PLA-based biopolymer gravel composite is a relevant direction in the context of the development of environmentally friendly technologies for the construction and operation of hydrogeological wells. The results of such studies will serve as a basis for further improvement of the composition of the composite material, the development of new biopolymer block gravel filters and their implementation in industrial practice [19-23].

Analysis of Recent Research and Publications (Literature Review)

In the context of the global trend towards sustainable development, increased attention to environmental safety and the need to use biodegradable materials in engineering systems, there is a growing interest in polymers of natural origin, in particular PLA. PLA is characterized by high strength, biocompatibility and the ability to biodegrade in natural conditions. Thanks to these properties, it is actively studied as a basis for the manufacture of composites intended for use in technical areas [24].

In [25], it was noted that PLA has significant potential for application in engineering systems thanks to the combination of high strength and environmental friendliness. Further studies, such as [26], emphasized the ability of PLA to form stable matrices in composites with various types of fillers, which opens up wide possibilities for its use in difficult operating conditions.

To improve the characteristics of PLA as a structural material, mineral and natural fillers, in particular gravel, are increasingly used. Research [27] has shown that the addition of natural stone filler to PLA improves the stiffness, shape stability and overall strength of the composite. Similar results are presented in [28], where the authors emphasize the importance of appropriate selection of the fractional composition of gravel for the formation of optimal porosity of the material, which is critical in filtration processes.

In addition, the review [29, 30] provides a systematization of approaches to the modification of polymer composites, including the compatibility of fillers with the polymer matrix, which is key to ensuring their operation in conditions of high humidity.

Literature analysis indicates a high scientific interest in the development of biopolymer composites with the involvement of natural fillers for engineering tasks [31-35]. However, narrowly focused studies that consider biopolymer gravel composites specifically in the context of well filtration are currently limited. This creates a scientifically substantiated need to study the physical and mechanical properties of such materials to ensure their effective use in drilling and water production wells.

Previously Unresolved Aspects of the General Problem

Despite the growing attention to the development of biopolymer gravel composites, the application of such materials in the field of drilling practice is still accompanied by a number of unresolved technical and scientific problems. One of the main unresolved problems is ensuring the long-term mechanical stability of biopolymers during the descent of the filter string.

The biodegradability of PLA, on the one hand, is its advantage in an environmental context, but on the other hand, it may raise doubts about the feasibility of its use where long-term functional stability of the material is required. Mechanical degradation of PLA can begin after just a few hours of operation in an aggressive aqueous environment, which may necessitate the creation of modified composites with increased resistance to hydrolysis.

Another unsolved problem is the formation of the optimal microstructure of biopolymer gravel composites to provide the desired porosity and permeability of the filtration material. In most studies, PLA composites are studied with finely dispersed organic or mineral fillers (e.g., bamboo

fiber, cellulose, carbon nanotubes), while the use of natural gravel remains almost unexplored [36-39]. This lack of data limits the understanding of the interaction processes between the polymer matrix and gravel, as well as the influence of the fractional composition of gravel on the characteristics of permeability, capillarity and mechanical strength of the material.

Moreover, the available literature reveals a lack of systematic studies dedicated to the behavior of PLA–gravel composites under real operating conditions of drilling wells. In particular, under the influence of wetting–drying cycles, seasonal temperature fluctuations, fluid pressure, and mechanical loading from the surrounding soils. Current laboratory models often do not fully reproduce the hydrogeological loads that arise during long-term operation of filtration systems in field conditions [28].

Another important unresolved aspect is the lack of a unified methodology for evaluating the effectiveness of biopolymer composites for filtration applications. Most scientific works focus on individual material properties (e.g., strength or water absorption), but a comprehensive assessment that combines the indexes of mechanical properties, filtration, biostability, and durability is almost nonexistent. Such a fragmented approach makes it impossible to compare results and hinders the creation of universal materials for practical implementation.

Methods

The purpose of this work is to experimentally study the physical and mechanical properties of a PLA-based biopolymer gravel composite in order to assess its suitability for use in filtration elements of hydrogeological wells.

The relevance of such research is conditioned by the need to create environmentally safe, mechanically stable and water-resistant materials for use as mechanical filters for hydrogeological wells, capable of ensuring effective purification of groundwater and the stability of well structures.

To achieve this purpose, the following tasks were set:

1. To develop and manufacture an experimental sample of a PLA-based gravel composite using filler (gravel) of different fractions;
2. To conduct physical and mechanical tests of the composite, determining:

- uniaxial compression strength of BGC samples;
- strength under uniaxial compression of BHC samples after their aging in an aqueous medium;

3. To analyze the effect of the fractional composition of gravel and the percentage of PLA on the mechanical and operational properties of the material;
4. To assess the material's resistance to the aquatic environment. To substantiate the feasibility of using a biopolymer gravel composite as a biopolymer gravel filtration element in well purification systems for produced water.

Methods

To achieve the set goal, an experimental program was implemented, which included the stages of preparing composite samples, conducting physical and mechanical tests, as well as analyzing the results obtained in order to assess the suitability of the material for use in hydrogeological wells.

1. Materials

The following main components were used in the study. Polylactide (PLA LX175) is a thermoplastic, biodegradable polymer used as a binder. Gravel is a filler with a fraction of 0.25-0.5, 0.5-0.75, 1.2–2.5 mm.

2. Sample preparation

BHC composites were manufactured in cubic molds KF-50 with a sample side of 50 mm according to [40], by hot pressing. Gravel was mixed with PLA at a mass concentration of 4 to 16%. The composite was heated and mixed until homogeneous. The resulting mass was molded in molds at a temperature of 220–260 °C under pressure. After cooling, BGC samples were removed from the molds and kept at room temperature for at least 24 hours before further testing.

3. Testing of physical and mechanical properties

The research was conducted in two stages. In the first stage, there were determined the strength indicators under uniaxial compression of cubic samples of BGC with different fractional composition of gravel (0.25-0.5, 0.5-0.75, 1.2–2.5 mm) conditioned in an air environment. The mass concentration of PLA was 4%, 8%, 12%, 16%. After determining the samples with the maximum strength, they were used in the research in the second stage.

At the second stage, there were determined the strength indicators under uniaxial compression of BGC samples with a PLA mass concentration of 4%, 8%, 12%, 16%, which were kept in an aqueous environment for 30, 60, 90, and 120 minutes at a water temperature of +20 °C, after which the change in the strength indicator under compression of BGC samples was recorded.

All tests were performed in five repetitions for each series of samples. The arithmetic mean and standard deviation were calculated for each indicator. Correlation analysis was used to identify the influence of PLA content on the properties of the composite. The results made it possible to compare the behavior of the composite at different ratios of polymer and mineral phases, which helps to determine the optimal composition for further use in bench-set conditions.

Results and Discussion

After manufacturing experimental BGC samples for the first stage, homogeneous cubic samples of biopolymer gravel composite (Fig. 1) with a uniform distribution of gravel particles in the polymer matrix were obtained.



Fig. 1 Appearance of experimental BGC samples

To confirm the qualitative contact of PLA and gravel, visual and microscopic examination of experimental samples was carried out, the general appearance of which is shown in (Fig. 2). It confirmed the presence of adhesion between PLA and the mineral phase.

The experiment showed that the BGC samples are stable. During the study of BGC samples, it was found that when PLA is heated with gravel, PLA melts well, forming biopolymer structures that cover the gravel particles, and when the PLA composite cools, it provides strong adhesion of the gravel particles, connecting them into a single monolith.

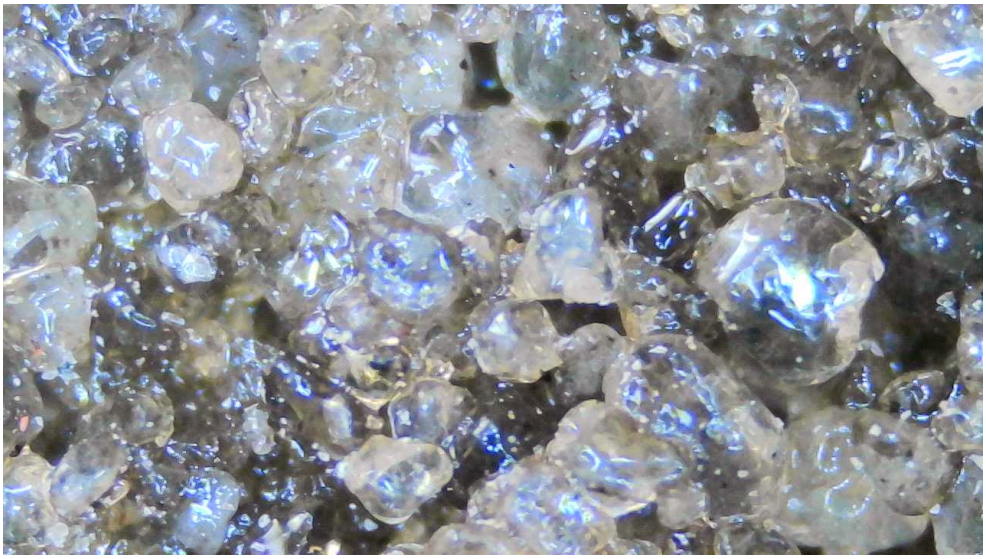


Fig. 2 Appearance of experimental BGC samples, magnified 2000 times

After conditioning the BGC samples, they were pressed (Fig. 3), the strength parameters were assessed, and the obtained results served as the basis for plotting the dependence of the strength limit (Fig. 4) on the PLA content.



Fig. 3 Appearance of the experimental BGC sample during the study

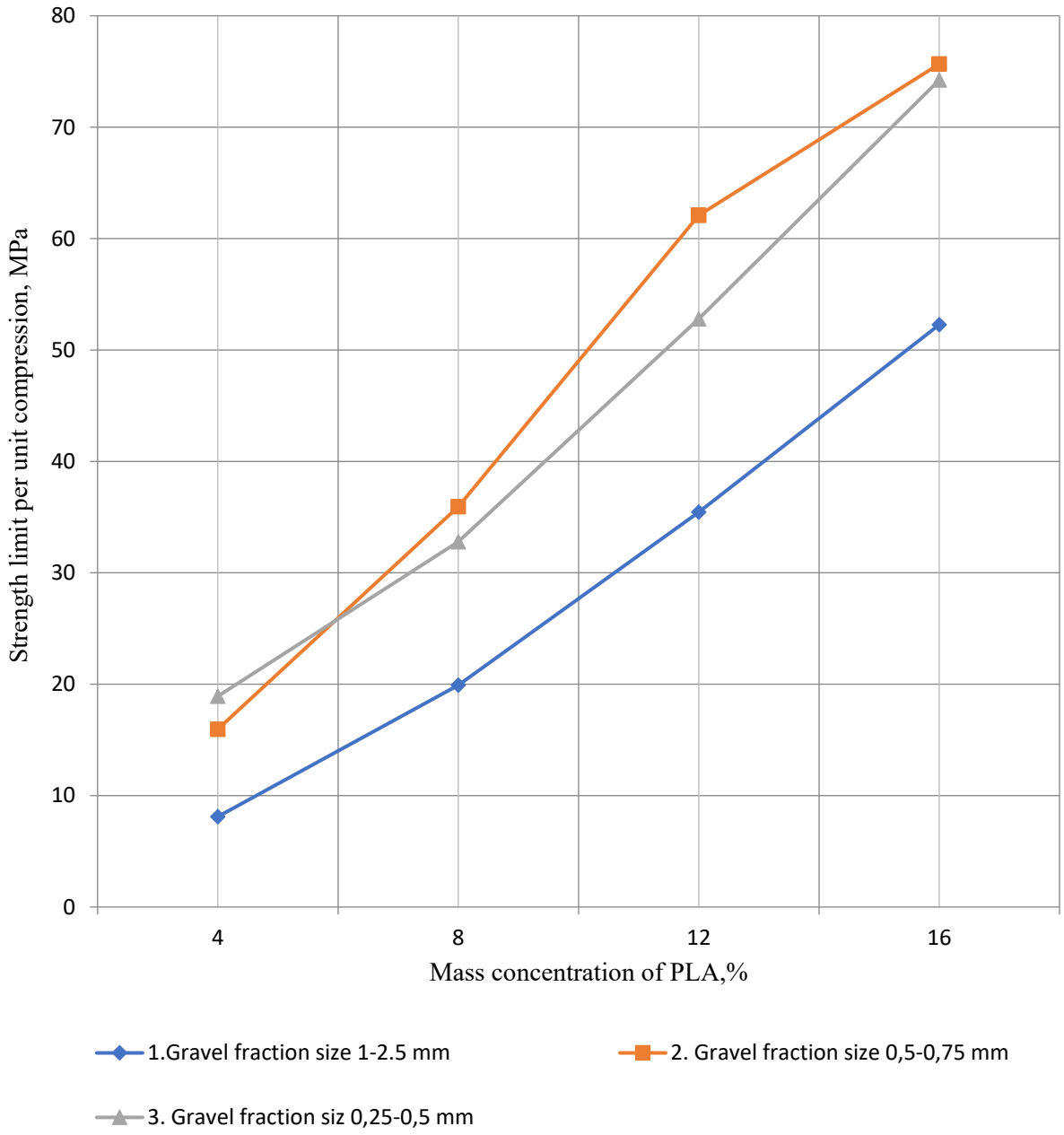


Fig. 4 Dependence of the uniaxial compressive strength of experimental BGC samples on the PLA content

It follows from (Fig. 4**)** that, despite the varying mass concentration of PLA in the comparable experimental samples of BGC (from 4% to 16%), the increase in strength characteristics in these samples — from the initial point of 4% to the final point of 16% — increased by 4.7 times. This is due to the fact that with increasing PLA content, the number of biopolymer structures that glue gravel particles increases.

According to the graph (Fig. 4), the BGC samples have sufficient strength and stiffness for the use of BGC in the preparation of a biopolymer-gravel filter, since the strength of PLA is relatively higher than other binders used previously.

In the second stage, 40 cubic samples of BGC with a gravel fraction of 0.5–0.75 mm (Fig. 5) were manufactured, which were kept in an aqueous environment (Fig. 6), after which they were pressed in a press and the decrease in the strength indicators for uniaxial compression of BGC samples was assessed. Based on the results of the study, the dependence of the tensile strength (Fig. 7) on the PLA content was plotted.



Fig. 5 Appearance of experimental BGC samples for the second stage of research



Fig. 6 Exposure of experimental BC samples in an aquatic environment

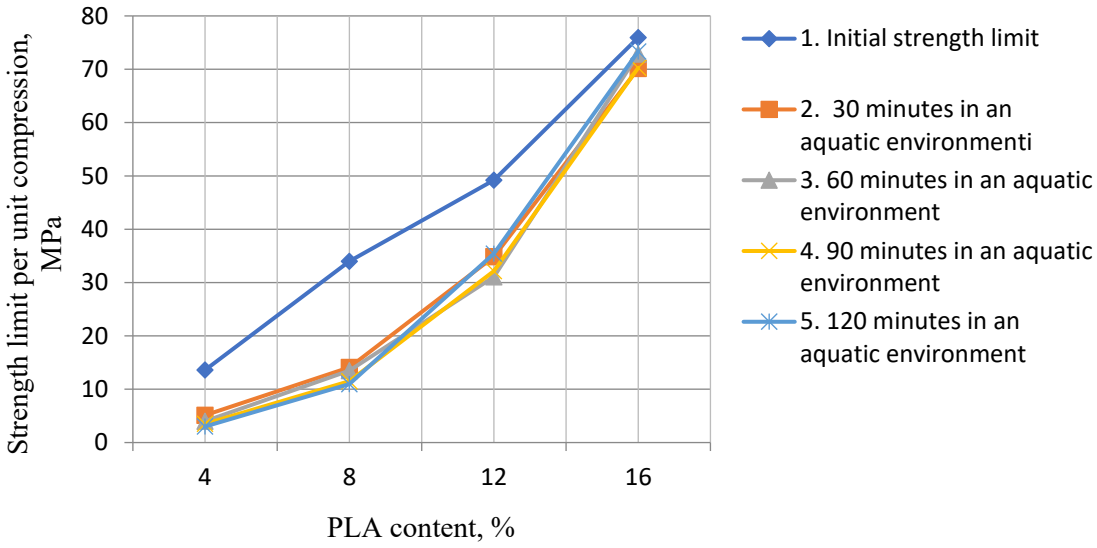


Fig. 7 Dependence of the uniaxial compressive strength of experimental BGC samples on the PLA content and exposure time in an aqueous medium at a temperature of +20°C

It follows from (Fig. 7) that the aqueous medium actively affects the experimental BGC samples in the initial period - up to 30 minutes. After analyzing the graph (Fig. 7), a comparative table was compiled (Table 1).

Table 1. Decrease in the uniaxial compression strength index (in %) of experimental BGC after their exposure in an aqueous environment

No.	PLA content, [%]	Water resistance [min]			
		30	60	90	120
1	4	62	71	74	78
2	8	59	60	66	68
3	12	29	37	35	28
4	16	7,6	4	7,4	3,5

Table 1 clearly shows that the BGC samples lose their strength immediately after their immersion in an aqueous environment. This is especially observed in samples with a PLA content of 4 - 12%. In samples with a PLA content of 16%, water partially affected the decrease in the strength index. This means that water almost does not penetrate through these samples due to the large amount of PLA in the BGC composition.

The results of the second stage of the study showed that the BGC samples are dismonolized in an aqueous environment. After saturation, the strength characteristics, within 120 minutes, change significantly and at the appropriate concentration of PLA have approximately the same results. This indicates the stability of the composite and the binder in it. It can also be confirmed that PLA can be used as a binder for the manufacture of biopolymer gravel filters. However, it is necessary to determine the optimal concentration of PLA.

Therefore, the authors of the article decided to continue studying the physical and mechanical characteristics of BGC samples in order to determine the density, water absorption, porosity, permeability, and filtration coefficients.

Conclusions

Biopolymer gravel composite based on PLA and natural gravel is a promising environmentally friendly material for the manufacture of biopolymer-gravel filters in hydrogeological wells.

Experimental samples of BGC revealed good homogeneity and uniform distribution of gravel particles in the polymer matrix, which ensures strength and stability of the structure. An increase in strength characteristics is observed with an increase in the PLA content from 4% to 16% by 4.7 times.

However, the aqueous environment significantly affects the strength of BGC samples with low PLA content, indicating a gradual degradation of the polymer matrix upon contact with water. The smallest decrease in strength was observed in samples with 16% PLA, indicating a certain waterproofing effect at high polymer saturation.

The obtained results demonstrate the need to optimize PLA content to achieve a balance between mechanical strength, moisture resistance, and effective filtration properties.

Biopolymer gravel composite has the potential for application in the production of new generation block gravel filters.

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