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Enhancing the physical and mechanical properties of materials used for metal-polymer systems in structures operating under dry friction conditions through double reinforcement

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Abstract: In this article, double-reinforced heterocomposite polymer materials based on ED-20 epoxy resin were developed, and their mechanical properties and performance under dry friction conditions were investigated. The study utilized silk and basalt fibers, as well as kaolin as a dispersed filler, to evaluate the composite materials' properties such as tensile strength, bending resistance, hardness, and impact resistance. Results indicated that composites containing 25 wt.% silk and 5 wt.% basalt fiber exhibited optimal mechanical properties and significantly enhanced impact resistance. These findings enable more efficient operation of machine parts subjected to dry friction conditions, particularly the blades of pneumatic transport fans.

Keywords: Heterocomposite, polymeric material, epoxy ED-20, silk fiber, basalt fiber, kaolin, mechanical properties, dry friction, pneumatic transport fan

1. Introduction

Today, the development of the modern machine-building industry necessitates the creation of competitive and import-substituting technologies, machines, and mechanisms that meet global requirements. In this process, conducting in-depth fundamental research, developing new functional materials, and effectively solving existing scientific and technical problems are of paramount importance. In particular, one of the pressing scientific and technical challenges is the use of highly effective polymer composite materials to ensure the operational reliability of cotton processing machines and to reduce the negative impact of abrasive particles and dry friction on the working surfaces of technological equipment. Concurrently, the potential for polymers and composite materials based on them to exhibit new operational properties depending on their composition, structural characteristics, and production technology necessitates comprehensive research in this field.

This research was conducted in close alignment with the priority objectives outlined in regulatory and legal documents aimed at developing the mechanical engineering and materials science sectors in the Republic of Uzbekistan, as well as expanding the production of import-substituting and competitive products [1-5].

In the development of the modern machine-building industry, it is crucial to create competitive, import-substituting, and highly efficient technologies, machines, and devices, as well as to conduct fundamental research. Scientists worldwide and in Uzbekistan are carrying out scientific studies on composite polymer materials and proposing innovative solutions for their structure, properties, and production [6-16]. Concurrently, reducing the negative impact on the working surfaces of cotton processing machines and developing heterocomposite materials resistant to abrasive wear and dry friction for the working components of pneumatic transport systems remains a pressing scientific and technical challenge.

Fiber-reinforced polymer composites are widely used in engineering and are distinguished by their high strength-to-weight ratio, corrosion resistance, and long service life. Glass, carbon, aramid, and basalt fibers create materials capable of withstanding high loads and absorbing energy. Simultaneously, there is a growing demand for environmentally friendly natural fibers, particularly hemp, bamboo, flax, and silk. Silk fibers are lightweight, cost-effective, and possess sufficient mechanical properties, finding applications in automotive, aerospace, and other industries. Heterogeneous composites created by combining natural silk fibers and synthetic basalt fibers, which unite high strength, abrasive wear resistance, and environmental safety, can serve as a promising material for the working components of pneumatic transport systems.

Blades of pneumatic transport fans operating under dry friction conditions were selected as the object of research. Observations have shown that their working surfaces wear out rapidly due to abrasive effects and mechanical loads, resulting in decreased operational reliability. To address this issue, it is necessary to utilize metal-polymer double-reinforced composite materials that possess high mechanical strength, hardness, and resistance to dry friction. The aim of this study is to determine the optimal composition of double-reinforced heterocomposite polymer materials based on a metal-polymer system for pneumatic transport fan blades operating under dry friction conditions, to systematically investigate their physical and mechanical properties, and to

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scientifically substantiate the technology for manufacturing these new materials.

This work is expected to serve in implementing new technologies used in the field of modern mechanical engineering and materials science, as well as significantly increasing the operational lifespan of technological equipment.

2. Research methodology

Table 1

Composition of the prepared samples

№	Epoxy resin	Silk fiber	Basalt fiber	Kaolin	DBF	PEPA
	Massa qism					
1	100	-	-	-	12	12
2	100	50	-	-	11	12
3	100	25	5	-	10	13
4	100	30	4	-	12	13
5	100	25	5	30	10	12

In the process of preparing composite samples for each composition, epoxy resin ED-20 was initially heated to 60°C to reduce its viscosity and ensure better mixing of components. Subsequently, dibutyl phthalate (DBP) was added as a plasticizer in a specified mass fraction, and the mixture was stirred using a mechanical stirrer until a homogeneous state was achieved.

In the next stage, basalt fiber and finely dispersed kaolin powder were gradually introduced into the mixture as reinforcing components. To ensure uniform distribution of fillers throughout the epoxy matrix, the mixing process was continued for a certain period. As a result, a visually homogeneous composite mass without aggregation was obtained.

After achieving a homogeneous structure of the mixture, polyethylenpolyamine (PEPA) was added as a hardener and carefully mixed. The composite mass was poured into molds with pre-placed silk mesh, providing double reinforcement. Curing was carried out in two stages: initially at 20°C for 24 hours, followed by thermal treatment at 80°C for 2 hours. The prepared samples were then readied for testing.

3. Results and discussion

The results of the conducted experimental tests demonstrated that the physical and mechanical properties of heterocomposite polymer materials doubly reinforced with silk, basalt fibers, and kaolin based on the ED-20 binder are directly dependent on their composition and structural characteristics. During the research process, the density of the composites, void fraction, surface hardness, and resistance to interlayer shear were determined, and their interrelationships were analyzed.

The surface hardness of doubly reinforced heterocomposites exhibited higher values compared to pure epoxy material. The combined use of basalt and silk fibers increased the load-bearing capacity of the composite and improved its resistance to mechanical stresses. The results of interlayer shear strength indicated that a sufficiently effective interfacial bond had formed between the reinforcing components and the epoxy matrix.

The mechanical properties under tensile stress of double-reinforced heterocomposite polymer materials based on epoxy and ED-20 binder are presented in Table 2. During the research process, the total amount of reinforcing fiber was maintained at a constant level of 50 percent by weight, and the effect of basalt fibers on the tensile properties of silk/epoxy composites was determined.

Table 2

Mechanical properties of doubly reinforced heterocomposite polymer materials based on ED-20 binder

Designation	1	2	3	4	5
Tensile strength (MPa)	38,1	38,12	145,6	119,4	151,2
Tensile modulus (GPa)	1,21	1,21	3,36	2,18	3,92
Flexural strength (MPa)	64,3	64,35	188,9	150,9	202,3
Flexural modulus (GPa)	3,39	10,72	11,29	6,24	13,6
Impact resistance (J/m)	7,49	168,1	443,8	416,9	458,8

SEM images of the fractured surfaces of pure epoxy and samples 2 and 3 are shown in Figure 3.3. In the pure epoxy sample, smooth and sharp fracture lines characteristic of brittle failure were observed. In composites reinforced with silk fiber, fiber breakage and pull-out from the matrix were identified, indicating the presence of effective interfacial bonding between the fiber and matrix.

In hybrid composites, the breakage of basalt fibers and the penetration of silk fibers into interlaminar zones confirm the effective distribution of load. However, increasing the amount of silk fiber to 30 mass % led to a decrease in tensile properties due to a reduction in the proportion of the epoxy matrix. Thus, the failure mechanism is determined by the degree of adhesive bonding at the basalt-matrix and silk-matrix interfaces.

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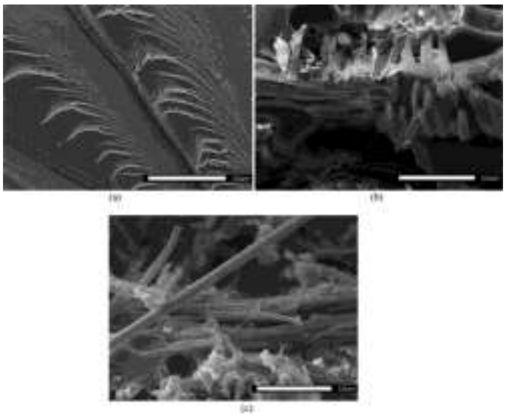

Fig. 1. SEM images of samples fractured after stretching: a - sample 1, b - sample 2, c - sample 3

The results of the impact test are presented in Table 2. The incorporation of silk fiber significantly increased the impact resistance of the composites, reaching a maximum value of 167.4 J/m. The presence of basalt fiber in the hybrid composition further enhanced the ability to absorb impact energy. However, with an increase in the amount of silk fiber, a decrease in impact resistance was observed in some compositions, indicating the presence of changes in the material structure related to technological factors (Figure 5).

Fig. 2. Impact strength of doubly-reinforced heterocomposite polymer materials based on the ED-20 binder

As a result of the conducted experiments, the main physical and mechanical properties of double-reinforced heterocomposite polymer materials based on silk, basalt fibers, and kaolin were determined, including density, hardness, tensile strength, interlaminar shear, and impact resistance. The results demonstrated a significant influence of the composite composition and the ratio of reinforcing components on the material's structure. SEM analyses revealed the failure mechanisms and the state of interfacial bonding. These experimental data are discussed in the following section with scientific explanations and causal relationships.

The results of experimental studies demonstrated that the mechanical properties of heterocomposite polymer materials doubly reinforced with silk, basalt fibers, and kaolin based on the ED-20 binder depend on the ratio of the constituent components. While pure epoxy (sample 1) had a tensile strength of 38.12 MPa, tensile modulus of 1.21 GPa, and impact strength of 7.49 J/m, sample 2 with 25% silk fiber addition showed an increase in tensile strength to 137.98 MPa (3.6-fold increase), tensile modulus to 3.13 GPa, and impact strength to 168.01 J/m. This result indicates a significant improvement in mechanical properties due to effective interfacial bonding between silk fibers and the epoxy matrix.

In sample 3, which included basalt fibers, the tensile strength reached 145.63 MPa, the tensile modulus 3.36 GPa, and the impact strength 443.80 J/m. The results show that basalt fibers, due to their high elastic modulus (85-93 GPa) and tensile strength (2800-4800 MPa), act as a load-bearing framework and enable effective absorption of impact energy as a result of hybrid reinforcement. Meanwhile, sample 4 (30% silk, 4% basalt) exhibited a tensile strength of 119.42 MPa and impact strength of 416.95 J/m, which is attributed to a decrease in matrix proportion and insufficient wetting of the fibers due to the high silk content.

The bending properties also increased significantly: pure epoxy measured 64.35 MPa, while hybrid composites yielded results in the range of 150-200 MPa, indicating a strong interface between the fibers and the matrix and effective transfer of interlayer loads. In SEM images, silk fibers bind layers, and the holes formed by fiber breakage and pullout from the matrix increase mechanical strength. With the addition of 30% silk fiber, the elongation slightly decreased, which is attributed to a reduction in the epoxy fraction and insufficient wetting of the fibers.

Sample 5 demonstrated the highest impact resistance at 458.8 J/m, which is 61 times higher than Sample 1. This is explained by the synergistic effect of silk and basalt fibers: silk absorbed energy through deformation, while basalt slowed crack propagation. In some compositions, improper fiber distribution or excess silk led to a slight decrease in impact properties.

Overall, hybrid composites showed significant improvements in tensile strength (38.12 → 151.2 MPa) and impact resistance (7.49 → 458.8 J/m) compared to Sample 1, demonstrating their effectiveness for structures operating under dry friction conditions, such as pneumatic transport fans.

4. Conclusion

In this study, heterocomposite polymer materials with dual reinforcement of silk and basalt fibers based on the ED-20 binder were developed, and their mechanical properties and impact resistance were evaluated. The research results showed that the combination of two types of fibers enhances the positive properties of the base composite materials, mitigates their negative aspects, and balances the mechanical properties. The addition of 5 wt.% basalt fiber to silk-epoxy composites resulted in a significant increase in the strength and hardness of the hybrid composites. Concurrently, silk fiber effectively transferred interlayer stresses and played a crucial role in improving Barkol hardness and tensile properties.

In tests, the 5th sample demonstrated 166% higher impact resistance compared to the 2nd sample, confirming the synergistic effect of hybrid reinforcement. Based on the obtained results, it was determined that the optimal combination for enhancing mechanical properties is the inclusion of 25 wt.% silk fiber and 5 wt.% basalt fiber in the composite composition. Consequently, the dual-reinforced heterocomposite polymer materials based on the ED-20 binder demonstrated the potential for effective use in pneumatic transport fans and other machine parts operating under dry friction conditions.

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