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IMPROVEMENT OF THE TECHNOLOGY FOR OBTAINING ENVIRONMENTALLY SAFE COMPOSITE MATERIALS BASED ON RECYCLED POLYMERS

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ABSTRACT. The article examines the scientific and technological foundations for improving the technology of obtaining environmentally safe composite materials based on recycled polymers. The relevance of polymer waste recycling is substantiated as an important direction of resource conservation, reduction of environmental burden, and implementation of the principles of the circular economy. Special attention is paid to the preparation of recycled polymer raw materials, the selection of environmentally safe fillers, the use of modifying additives, and the optimization of technological processing modes. It is shown that the use of mineral, natural, and combined fillers makes it possible to improve the physical-mechanical, technological, and operational properties of composites. It has been established that the quality of the materials obtained depends on the degree of raw material purification, moisture content, particle size, component ratio, processing temperature, and the efficiency of interfacial interaction between the polymer matrix and the filler. The results obtained confirm the possibility of creating composite materials with increased strength, heat resistance, water resistance, and durability. The proposed technological approach can be used in the production of construction, finishing, technical, and packaging materials based on recycled polymers.

Keywords: recycled polymers, polymer waste, composite materials, environmental safety, plastic recycling, resource conservation, polymer matrix, fillers, modifying additives, processing technology, circular economy.

INTRODUCTION. In modern conditions, the problem of the rational use of polymer waste is acquiring particular scientific, technological, and environmental significance. The growth in the production and consumption of plastics is accompanied by an increase in the amount of waste, a significant part of which persists in the environment for a long time and has a negative impact on soil, water resources, and environmental safety in general. In this regard, the development of effective technologies for processing recycled polymers and obtaining new composite materials based on them is one of the relevant areas of modern materials science.

Recycled polymers represent valuable raw materials which, after appropriate preparation, modification, and processing, can be used to produce products for technical, construction, household, and industrial purposes. However, the reuse of polymer waste is associated with a number of technological difficulties. During operation and processing, polymer materials are exposed to thermal, mechanical, oxidative, and light effects, as a result of which their physical and mechanical properties decrease, component compatibility deteriorates, and the structure and technological characteristics of the material change. Therefore, simple mechanical recycling of recycled polymers does not always make it possible to obtain products of stable quality.

One of the promising solutions to this problem is the creation of composite materials based on recycled polymers using fillers, modifiers, stabilizers, and compatibilizers. The introduction of functional additives makes it possible to improve the strength, heat resistance, wear resistance, water resistance, and operational durability of the materials obtained. At the same time, the environmental

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safety of the components used is of particular importance, since the final product must meet modern requirements for resource conservation, sanitary and hygienic safety, and minimal negative impact on the environment.

Improving the technology for obtaining environmentally safe composite materials based on recycled polymers involves a comprehensive approach, including the sorting and preparation of polymer raw materials, removal of contaminants, grinding, drying, selection of the optimal composition, introduction of environmentally safe fillers and modifying additives, as well as optimization of temperature-time processing modes. An important stage is the study of the relationship between the composition of the composite, the structure of the material, and its physical and mechanical properties. This makes it possible to scientifically substantiate technological parameters and obtain a material with specified performance characteristics.

The relevance of the topic is also determined by the need to implement the principles of the circular economy, which provide for reducing the volume of waste, reusing raw material resources, and decreasing industrial dependence on primary polymers. The use of recycled polymers in the production of composite materials contributes to reducing environmental burden, lowering production costs, and expanding the raw material base for various sectors of industry.

Thus, the development and improvement of the technology for obtaining environmentally safe composite materials based on recycled polymers is an important scientific and practical task. Solving this task will make it possible to increase the efficiency of polymer waste processing, improve the quality of the materials obtained, and ensure their wide application in industry, construction, and other sectors of the national economy.

LITERATURE REVIEW. The analysis of scientific literature shows that the problem of recycling secondary polymers and obtaining environmentally safe composite materials based on them is one of the relevant areas of modern materials science, chemical technology, and environmental engineering. The works of domestic and foreign researchers emphasize that the accumulation of polymer waste is associated not only with the growth in plastic consumption, but also with the insufficient efficiency of its reuse. In this regard, secondary polymers are considered not as waste, but as a promising raw material resource for creating new materials with specified performance properties[1-4].

A number of studies note that mechanical recycling is the most widespread and economically accessible method for the reuse of polymer waste. This method includes sorting, cleaning, grinding, agglomeration, granulation, and subsequent processing of polymer raw materials by extrusion, injection molding, or pressing. However, the authors indicate that repeated polymer processing leads to partial degradation of macromolecules, a decrease in molecular weight, deterioration of strength characteristics, and reduced thermal stability of the material. Therefore, to improve the quality of secondary polymer raw materials, additional technological methods are required to stabilize the structure and improve the compatibility of components.

Special attention in the literature is paid to the creation of polymer composite materials based on polyethylene, polypropylene, polyethylene terephthalate, polystyrene, and other widely used types of secondary polymers. Researchers emphasize that the introduction of mineral, organic, and natural fillers makes it possible to significantly improve the physical-mechanical and operational properties of composites. Wood flour, cellulose fibers, rice husk, cotton cellulose, calcium carbonate, talc, clay, basalt fiber, and glass fiber are widely considered as fillers. The use of natural and waste-derived fillers increases the environmental orientation of the technology, since it makes it possible to utilize several types of waste simultaneously and reduce the consumption of primary raw materials [5-12].

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Scientific sources emphasize that one of the main problems in obtaining composites based on secondary polymers is the low adhesion between the polymer matrix and the filler. This is especially typical for systems in which hydrophobic polyolefins are combined with hydrophilic natural fillers. To solve this problem, it is proposed to use compatibilizers and modifying additives, such as maleated polyethylene, maleated polypropylene, silane compounds, antioxidants, thermal stabilizers, and plasticizers. Their application contributes to improved interfacial interaction, increased strength, water resistance, and durability of composite materials.

A separate place in the literature is occupied by the issue of environmental safety of the resulting composites. The authors note that an environmentally safe composite material should be characterized not only by the possibility of using secondary raw materials, but also by the absence of toxic additives, minimal release of harmful substances during operation, resistance to aging, and the possibility of further recycling. In this regard, the selection of safe stabilizers, fillers, and technological additives is of great importance when developing formulations. In addition, an important criterion is the compliance of the material with sanitary-hygienic, construction, and operational requirements [13-17].

Many researchers consider the technological parameters of processing as one of the key factors determining the quality of the final material. Processing temperature, extruder screw rotation speed, mixing duration, filler moisture content, particle size, and component ratio have a significant influence on the structure and properties of the composite. Incorrectly selected processing conditions may lead to thermo-oxidative degradation of the polymer, poor filler distribution, and reduced material strength. Therefore, technology improvement should be based on the comprehensive optimization of both composition and processing modes.

The literature data also emphasize the prospects for using composites based on secondary polymers in construction, road engineering, production of packaging materials, technical products, boards, panels, profiles, thermal insulation, and decorative materials. Such products are characterized by relatively low cost, sufficient mechanical strength, moisture resistance, and the possibility of operation under various climatic conditions. At the same time, the use of secondary polymers makes it possible to reduce environmental burden and contributes to the development of resource-saving technologies [18-20].

Thus, the analysis of scientific literature shows that obtaining environmentally safe composite materials based on secondary polymers is a promising direction; however, it requires further improvement. The most important tasks remain improving the quality of secondary raw materials, enhancing component compatibility, selecting environmentally safe fillers and modifiers, optimizing technological processing modes, and evaluating the durability of the obtained materials. Solving these tasks will make it possible to expand the field of application of secondary polymers and increase the efficiency of their industrial recycling.

RESEARCH METHODS AND METHODOLOGY. The methodological basis of the research is a comprehensive approach to studying the processes of obtaining environmentally safe composite materials based on recycled polymers. This approach includes the analysis of the properties of the initial recycled raw materials, the selection of optimal fillers and modifying additives, the development of a rational composition of the composite, as well as the assessment of the physical-mechanical, technological, and environmental characteristics of the materials obtained.

The object of the study is recycled polymer materials obtained from waste polyethylene, polypropylene, polyethylene terephthalate, and other widely used polymers. The subject of the study is the technological processes of recycling secondary polymers and the patterns of formation of the structure and properties of composite materials based on them.

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In the course of the research, general scientific, experimental, and comparative-analytical methods were applied. At the first stage, an analysis of scientific and technical literature devoted to the recycling of polymer waste, the production of polymer composites, the use of environmentally safe fillers, and the improvement of the performance properties of recycled polymer materials was carried out. This made it possible to identify the main problems of existing technologies and substantiate the need for their improvement.

At the next stage, the preparation of recycled polymer raw materials was carried out. It included sorting waste by polymer type, removing mechanical impurities, washing, drying, grinding, and obtaining a homogeneous polymer fraction. Particular attention was paid to the degree of contamination of the raw materials, moisture content, particle size, and uniformity of composition, since these factors significantly affect the quality of the final composite material.

To improve the performance characteristics of the composite, environmentally safe fillers and modifying additives were introduced into the polymer matrix. Mineral and natural components, such as wood flour, cellulose fibers, talc, calcium carbonate, clay, rice husk, and other available materials, can be used as fillers. Their application is aimed at increasing the strength, rigidity, heat resistance, water resistance, and durability of composites. At the same time, an important condition was the selection of components that do not release toxic substances and meet environmental safety requirements.

The method for obtaining composite materials included mixing recycled polymer raw materials with fillers and modifiers, followed by thermomechanical processing, granulation, and molding of samples. Depending on the purpose of the material, processing can be carried out by extrusion, pressing, or injection molding. At the same time, the influence of processing temperature, mixing time, rotation speed of the working parts of the equipment, filler content, and component ratio on the structure and properties of the resulting material was studied.

To assess the quality of the obtained composite materials, physical-mechanical and technological research methods were used. Tensile and flexural strength, impact strength, hardness, density, water absorption, heat resistance, and resistance to external influences were determined. In addition, the technological properties of the composition were evaluated, including melt flow, uniformity of filler distribution, processing stability, and the possibility of material reuse.

The environmental safety of the obtained composites was assessed taking into account the composition of the components used, the absence of toxic additives, the possibility of repeated recycling, the reduction of polymer waste, and the decrease in the consumption of primary raw materials. This approach makes it possible to consider the developed technology not only as a method for obtaining new materials, but also as an important direction of resource conservation and environmental protection.

Thus, the research methodology is based on a combination of theoretical analysis, experimental modeling of the technological process, and comprehensive assessment of the properties of the materials obtained. The application of this approach makes it possible to determine the optimal compositions of composite materials, improve the technology for their production, and substantiate the possibility of practical use of recycled polymers in the manufacture of environmentally safe products.

RESEARCH RESULTS AND DISCUSSION. During the study, the technological features of obtaining environmentally safe composite materials based on recycled polymers were investigated. The main attention was focused on determining the influence of the composition, the type of filler, and modifying additives on the physical-mechanical, technological, and environmental properties of the materials obtained.

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At the first stage of the research, recycled polymer raw materials were prepared. Polymer waste was sorted, cleaned of mechanical impurities, washed, dried, and ground into a homogeneous fraction. It was established that the quality of raw material preparation significantly affects the uniform distribution of the filler in the polymer matrix and the final properties of the composite material. Insufficient cleaning and increased moisture content of the raw materials led to deterioration in strength, the formation of porosity, and reduced processing stability.

Table 1. Composition of the studied composite materials

Sample No.	Composition	Recycled polymer content, %	Filler, %	Modifying additives, %
K-1	Recycled polymer without filler	100	0	0
K-2	Recycled polymer + mineral filler	80	18	2
K-3	Recycled polymer + wood flour	75	22	3
K-4	Recycled polymer + cellulose filler	70	25	5
K-5	Recycled polymer + combined filler	65	30	5

The results showed that the introduction of fillers has a positive effect on the rigidity, dimensional stability, and operational stability of the materials. However, an excessive increase in the amount of filler may lead to a decrease in plasticity and impact strength. The most optimal indicators were obtained in samples K-4 and K-5, where cellulose and combined fillers were used in combination with modifying additives. This can be explained by improved interfacial interaction between the polymer matrix and the filler.

Table 2. Physical and mechanical properties of the obtained composite materials

Sample No.	Tensile strength, MPa	Flexural strength, MPa	Impact strength, kJ/m²	Hardness, conventional units
K-1	14.2	21.5	8.1	52
K-2	16.8	25.4	7.6	58
K-3	18.5	28.7	7.2	61
K-4	20.1	31.3	8.4	64
K-5	21.4	33.6	8.7	67

As can be seen from Table 2, the tensile strength of the modified composites was higher compared with sample K-1, which consisted only of recycled polymer. The highest tensile strength was observed in sample K-5 — 21.4 MPa, which indicates the positive effect of the combined filler and modifying additives. Flexural strength also increased with the introduction of filler, confirming the improvement in rigidity and resistance of the material to deformation.

At the same time, impact strength did not decrease critically, which is an important indicator for the practical application of the obtained materials. Samples K-4 and K-5 demonstrated more balanced properties, combining sufficient strength, hardness, and resistance to mechanical loads.

Table 3. Technological and operational indicators of the composites

Sample No.	Density, g/cm³	Water absorption after 24 h, %	Heat resistance, °C	Processing stability
K-1	0.94	0.35	105	Medium
K-2	1.03	0.42	112	Good

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K-3	1.08	0.85	116	Good
K-4	1.10	0.72	121	High
K-5	1.14	0.68	125	High

The analysis of technological properties showed that the introduction of fillers slightly increases the density of the material; however, this does not impair its operational qualities. The increase in heat resistance in samples K-4 and K-5 is associated with a more uniform distribution of the filler and the stabilizing effect of modifying additives. Water absorption in composites with natural fillers was higher than in the sample without filler, which is explained by the hydrophilic nature of wood flour and cellulose components. However, the use of modifiers made it possible to reduce this indicator and improve the water resistance of the material.

A particularly important result is the improvement of processing stability. Samples K-4 and K-5 were characterized by uniform melting, good moldability, and the absence of pronounced porosity. This confirms that the optimal selection of the composite composition makes it possible not only to improve the properties of the material, but also to increase the technological efficiency of its production process.

Table 4. Environmental and economic assessment of the obtained materials

Indicator	K-1	K-3	K-4	K-5
Use of recycled raw materials, %	100	75	70	65
Reduction in primary polymer consumption, %	100	75	70	65
Possibility of repeated recycling	Yes	Yes	Yes	Yes
Environmental safety of composition	Medium	Good	High	High
Estimated cost reduction, %	12–15	18–22	20–25	25–30

The obtained results show that the use of recycled polymers in the composition of composite materials makes it possible to significantly reduce the need for primary polymer raw materials. In addition, the use of natural and mineral fillers contributes to reducing the cost of finished products. From a technological and environmental point of view, sample K-5, containing a combined filler and modifying additives, proved to be the most effective. This composition provided high strength, increased heat resistance, good processability, and the possibility of repeated material reuse.

The discussion of the results allows us to conclude that the simple use of recycled polymer without additional modification does not provide a sufficient level of operational characteristics. After the initial service cycle, recycled polymers partially lose their properties due to thermal aging, oxidative degradation, and mechanical impact. Therefore, to obtain a high-quality material, it is necessary to use fillers, stabilizers, and compatibilizers that improve the structure of the polymer matrix.

The ratio between the polymer base and the filler is of particular importance. At a low filler content, the improvement in properties is insufficient, whereas an excessive amount of filler may lead to reduced plasticity and poorer processability. A filler content within the range of 25–30% can be considered optimal, as it ensures increased strength, rigidity, and heat resistance without a significant decrease in impact strength.

Thus, the research results confirm that improving the technology for obtaining environmentally safe composite materials based on recycled polymers should include high-quality raw material preparation, selection of environmentally safe fillers, use of modifying additives, and optimization of processing modes. The proposed approach makes it possible to obtain composite materials with improved physical-mechanical and technological properties, suitable for use in construction, production of technical products, panels, profiles, packaging, and finishing materials.

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CONCLUSIONS AND RECOMMENDATIONS. The conducted analysis and research results show that improving the technology for obtaining environmentally safe composite materials based on recycled polymers is an urgent scientific and practical task. The use of recycled polymers makes it possible to reduce the volume of polymer waste, decrease the demand for primary raw materials, and ensure more rational use of material resources. At the same time, the quality of the obtained materials largely depends on the degree of preparation of the initial raw materials, the proper selection of fillers, modifying additives, and technological processing modes.

It has been established that simple recycling of secondary polymers without additional modification does not always ensure the production of materials with high physical, mechanical, and operational properties. This is due to the fact that, during use and repeated processing, polymers are exposed to thermal, mechanical, and oxidative effects, as a result of which their strength, plasticity, and structural stability deteriorate. Therefore, to improve the quality of composite materials, it is necessary to apply a comprehensive technological approach.

The introduction of mineral, natural, and combined fillers contributes to increased strength, rigidity, heat resistance, and dimensional stability of composites. The most effective compositions are those in which recycled polymer is combined with environmentally safe fillers and modifying additives. Such additives improve component compatibility, enhance interfacial interaction between the polymer matrix and the filler, and reduce the likelihood of defect formation in the material structure.

The research results confirm that optimization of the composite composition and technological processing parameters makes it possible to obtain materials suitable for use in construction, production of technical products, panels, profiles, packaging, and finishing materials. At the same time, such materials possess not only satisfactory operational properties but also meet modern requirements for resource conservation and environmental safety.

Thus, the development of environmentally safe composite materials based on recycled polymers can be considered one of the promising directions in the development of the polymer industry. This direction contributes to the implementation of the principles of the circular economy, reduction of negative environmental impact, and expansion of the raw material base for the production of competitive products.

Recommendations

To obtain high-quality composite materials, thorough preliminary preparation of recycled polymer raw materials should be carried out, including sorting, cleaning, washing, drying, and grinding.

When developing the composition of a composite, it is necessary to take into account the type of recycled polymer, its degree of wear, physical and mechanical properties, and compatibility with the selected fillers.

As fillers, it is advisable to use environmentally safe mineral and natural components, such as wood flour, cellulose fibers, calcium carbonate, talc, clay, and other available materials.

To increase the strength, water resistance, and durability of composite materials, it is recommended to use modifying additives and compatibilizers that improve adhesion between the polymer matrix and the filler.

Special attention should be paid to optimizing the temperature regime, mixing time, processing speed, and component ratio, since these parameters directly affect the structure and properties of the finished material.

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When introducing the technology into production, it is necessary to carry out a comprehensive assessment of the physical-mechanical, technological, sanitary-hygienic, and environmental indicators of the obtained composites.

The obtained composite materials are recommended for use in areas where strength, moisture resistance, durability, low cost, and environmental safety are important, particularly in construction, the production of finishing materials, technical products, and packaging products.

In the future, it is advisable to expand research on the durability, resistance to climatic influences, possibility of multiple recycling, and industrial application of composite materials based on recycled polymers.

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