UDC 678.027.3

S.O. Kopylov, H.M. Cherkashina, I.O. Lavrova, T.T. Chernogor

WOOD-POLYMER COMPOSITE FROM SECONDARY THERMOPLASTICS WITH ENHANCED PROPERTIES

National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine

This article presents the development of novel wood-polymer composites and the investigation of their properties. The study aimed to optimize the composition of wood-polymer composites based on secondary raw materials to achieve improved physical and mechanical characteristics. The effect of modification on the physical and mechanical properties of wood-polymer composites was analyzed in comparison with conventional industrial samples. The dependences of impact strength and static yield strength on the amount of the mixture of petroleum-polymer resin and expanded polystyrene were studied. Additionally, the influence of petroleum-polymer resin content on drying time was evaluated. Key physical and mechanical properties, including impact strength, bending stress, and microhardness, were assessed. The study also explored the climatic effects on wood-polymer composites, particularly the impact of moisture and temperature. Water absorption, wear resistance, and dimensional stability were tested within a temperature range of $+30^0$C to -15^0C. A comparative analysis of the main performance indicators of the proposed composite and existing industrial samples was conducted.

Keywords: composite, wood, secondary raw materials, polyethylene, polypropylene, modification, physical and mechanical properties.

DOI: 10.32434/0321-4095-2025-159-2-4-10

Introduction

Considering the shortage of raw materials and the deterioration of the ecological situation, the utilization of industrial and household waste has become a promising approach. Currently, many enterprises seek to improve technologies and enhance the efficiency of raw material and energy resource consumption. Modern scientific advancements and global experience highlight the widespread application of secondary thermoplastic raw materials [1]. The incorporation of secondary thermoplastics into composite materials not only partially mitigates environmental issues but also proves to be economically viable [2]. These materials comply with sanitary and technical standards in the construction industry and possess a combination of valuable properties, including chemical resistance, heat resistance, frost resistance, mechanical strength, and high dielectric characteristics.

However, the structural peculiarities that determine these properties also complicate the use of this material. The non-polarity of polyolefins, on the one hand, provides them with excellent chemical resistance and dielectric properties, but on the other hand, it limits their adhesion to various fillers. As a result, the obtained composites exhibit low water resistance and mechanical strength [3].

Due to the tightening of environmental regulations, the use of chipboards containing toxic binders is becoming increasingly restricted. This niche is successfully occupied by wood-polymer composites (WPCs), which are characterized by a high filler content and environmental friendliness.

The most promising direction in WPC design is the use of secondary polymer raw materials as both a binder and a filler in the production process. Most polymer waste consists of common polymer materials such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), expanded polystyrene (EPS), and ABS plastic [4–8].

Wood-polymer composites are widely used in construction and architecture, with approximately 70% of global WPC consumption attributed to the construction industry. The composition of these products directly depends on their type and operating conditions and is selected individually in each case. The properties of the resulting composite are determined by the characteristics of the selected polymer, the wood particles, and the nature of the binding interactions between them [9].

This, in turn, influences approaches to optimizing WPC properties, such as selecting a suitable polymer binder to achieve high strength at maximum filler content. The choice of polymer is based on its individual advantages and disadvantages, as well as the properties of the final product.

WPCs based on polypropylene (PP) exhibit high strength, but their brittleness at low temperatures limits their applications. WPCs based on polyethylene (PE) can be used across a wide temperature range but have lower strength. Polyvinyl chloride (PVC)-based WPCs offer the highest stiffness and strength; however, they require the addition of special additives to reduce toxicity. PE and PP are considered more environmentally friendly and safer than PVC. Despite PE's lower mechanical properties compared to PP and PVC, it remains the most commonly used polymer in WPC production.

To control the technological process and properties of WPCs, various additive modifiers are incorporated into their composition, including antioxidants, antimicrobial agents, surface-active binders, impact modifiers, lubricants, thermal stabilizers, pigments, flame retardants, and light stabilizers. To enhance the performance characteristics and production technology of WPCs, new formulations are continuously being developed, and modifications are made to their manufacturing process.

In recent years, polymer materials have posed a serious problem for several reasons. The relatively short life cycle of polymers leads to increased consumption of plastic raw materials and, consequently, a rise in polymer waste volume. At the same time, the depletion of forest resources is a pressing issue of global concern. Wood waste is often either discarded or burned, contributing to soil degradation and air pollution [10]. In developing countries, there is a growing demand for alternative materials produced from waste.

WPC is an almost ideal solution that enables the utilization of waste materials to produce new composites with enhanced properties. Currently, there is growing interest from researchers worldwide in these materials, as they allow for the redirection of unused wood and plastic waste from landfills into building and construction applications. Additionally, products made from WPCs can retain their properties for an extended period without significant degradation.

WPCs offer numerous advantages, including high strength, water resistance, low operating costs, favorable strength-to-weight ratio, stiffness, and resistance to biological degradation. Moreover, as WPCs are made from recycled materials, they provide an additional environmental benefit.

WPCs are primarily used in outdoor applications, where, unlike wood products, they are not significantly affected by light and weather conditions. They are commonly utilized in building structures, including decking, park benches, shingles, fences, landscaping timbers, and window moldings [11]. Additionally, WPCs are suitable for interior applications such as window and door frames, furniture, and flooring [12]. Commercial WPC products are expected to serve as replacements for various materials across different industries, particularly in construction.

The expediency of such an application can be explained not only by the use of modifiers but also by the desire to utilize recycled thermoplastics. However, there are currently very few studies on the use of waste from other industries and recycled wood-polymer composites.

The aim of the research presented in this article is to develop a new wood-polymer composite composition with an enhanced property profile and to create a novel production technology for it.

To achieve the aim of this work, the following objectives were set:

1. To determine the optimal WPC composition with improved physical and mechanical properties.
2. To investigate the effect of modification on the physical and mechanical properties of wood-polymer composites, comparing them with known industrial samples.
3. To study the physical, mechanical, and operational properties of the WPC and compare them with industrial samples.

Experimental

The objects of research were as follows: secondary polyethylene, secondary polypropylene, Styrofoam, petroleum-polymer resin, chipboard waste, microcalcite, and gasoline.

The preparation of wood-polymer composites was carried out according to the following procedure:

1) Gasoline (a solvent) was added to the petroleum-polymer resin and thoroughly mixed to obtain a homogeneous solution (intermediate modifying mixture) for 10–15 minutes.

2) Polystyrene foam waste was added to the intermediate modifying mixture and dissolved by stirring for 10 minutes, resulting in the modifying mixture.

3) Wood filler for impregnation was added to the resulting modifying mixture and mixed for 5–10 minutes until the mixture was completely homogenized.

4) Microcalcite was added to the impregnated, homogenized wood filler and mixed for 5 minutes.

5) The homogenized modifying mixture was dried in a laboratory dryer for 1 hour at 70^{0}C or left for 12 hours at room temperature in the air.

During the wood filler impregnation stage and drying, 12–15% of the excess solvent evaporated. The dried filler was then mixed with secondary polyolefin raw materials (PE and PP), and WPC was produced by the extrusion method using an extruder with a length-to-diameter ratio (L/D) of 40, a screw diameter of 30 mm, a rotation speed of 50 rpm, and a temperature of 190–195^{0}C.

Density determination was carried out in accordance with ASTM D792. Toughness was determined according to ISO 180:2000, maximum bending stress was measured following ISO 178:2010, Brinell hardness was evaluated using ISO 2039-2, and impact strength was assessed in accordance with ISO 6272-1:2002. Water absorption was determined according to ASTM D570[1]. Durability and shrinkage were measured following DIN 53 516, and changes in linear dimensions during heating were determined in accordance with ISO 11501:1995.

Results and discussion

The composition of the developed WPC is presented in Table 1. The WPC physical and mechanical tests results are shown in Table 2.

As the polystyrene waste content in the modified mixture increases, the density of the finished sample also increases (Table 2).

An increase in the petroleum-polymer resin content in the modified mixture enhances the operational characteristics of the samples. A similar effect is achieved by reducing the petroleum-polymer resin content fourfold when polystyrene waste is added to the mixture. It should be noted that the highest physical and mechanical properties are observed in samples where petroleum-polymer resin and polystyrene waste are introduced together into the modified mixture in a 1:2 ratio. The highest toughness for the new WPC is observed in composites No. 5–9 (Fig. 1).

Table 1

Composition of the developed wood-polymer composite

Number of composition	Constituent content								
	secondary PE, %	secondary PP, %	petroleum polymer resin, g	solvent-gasoline Б-70, g	varnish PF-170, g	styrofoam waste, g	furniture production waste, g	wooden waste mixture, g	microcalcite, g
1	25	–	20	25	–	–	30	–	–
2	–	25	20	25	–	–	30	–	–
3	25	–	10	20	–	5	30	–	–
4	–	25	10	20	–	5	30	–	–
5	25	–	10	20	–	10	30	–	–
6	25	–	5	15	–	10	20	–	–
7	25	–	5	15	–	10	20	–	10
8	25	–	5	15	–	10	20	–	20
9	25	–	5	15	–	10	–	35	20
10	25	–	5	15	–	8	–	30	15
11	25	–	5	15	15	–	40	–	–
12	25	–	5	15	15	–	30	–	5
13	25	–	5	15	20	–	35	–	5

[1] ASTM D570-98, Standard Test Method for Water Absorption of Plastics, ASTM Stand., vol. 98, Reapproved 2010, pp. 1- 4, 2010. doi: 10.1520/D0570-98R10E01.2.

Table 2

Physical and mechanical properties of WPCs

Number of composition	Properties				
	P, g/cm^3	A, kJ/cm^2	σ, MPa	$H_{б}$	impact strength
1	1.084	8.70	21.50	38.85	h=40 brittle fracture h=30 dent
2	1.066	6.40	15.50	45.10	h=10 dent h=20 brittle fracture
3	1.067	6.70	16.50	40.50	h=40 crushed h=30 dent
4	1.068	5.70	16.40	49.67	h=10 brittle fracture
5	1.085	9.27	14.38	41.30	h=20 dent h=30 brittle fracture
6	1.125	8.09	14.60	36.40	h=15 dent h=20 brittle fracture
7	1.143	6.98	15.88	34.10	h=15 dent h=20 brittle fracture
8	1.195	9.52	17.23	47.28	h=15 dent h=20 brittle fracture
9	1.191	9.13	15.07	39.95	h=15 dent h=20 brittle fracture
10	1.170	6.02	15.85	29.10	h=10 brittle fracture
11	0.995	6.35	10.90	24.70	h=20 dent h=25 brittle fracture
12	0.996	3.44	10.85	26.00	h=20 dent h=30 brittle fracture
13	0.996	4.96	11.53	28.20	h=15 dent h=20 brittle fracture
WPC commercial sample	1.148	2.74	18.20	48.57	h=10 dent h=15 brittle fracture
OSB sample	0.990	11.03	9.04	30.42	h=10 brittle fracture
Sample chipboard laminated	0.99	11.52	14.7	32.73	h=10 brittle fracture

The highest static bending values for the newly designed WPC are observed in composites No. 5–9 (Fig. 2).

When the wood particle content in WPC increases, toughness decreases and melt fluidity increases [13]. A particularly significant decrease in physical and mechanical properties occurs when the filler particle size is 5 mm or larger, which leads to flow instability, resulting in the melt flow losing integrity [14]. An increase in the petroleum-polymer resin content in the modified mixture affects the drying time of the impregnated wood filler at 70^{0}C in the dryer. The test results are shown in Fig. 3.

The results of the new WPC operational tests are shown in Table 3. As the content of polystyrene foam waste in the modified mixture increases, water absorption decreases (Table 3). The durability result was achieved through the modified mixture, which impregnated the wooden filler in all samples. The best combination of operational characteristics was observed for WPC composites No. 6–9.

A comparative analysis of the physico-mechanical and operational properties of known industrial samples and the newly designed WPC shows that the newly designed WPC is at least on par with industrial samples in most cases and, in some tests, even demonstrates better characteristics (Table 4). It is important to note that the industrial samples are made from primary raw materials, while the proposed composite is made from secondary materials.

Experimental studies showed that the WPCs containing polystyrene foam waste have better physical, mechanical, and operational characteristics. This can be attributed to the impregnation of the wood filler with the modified mixture containing Styrofoam waste, which results in complete filling of the wood's porous structure. The filler particles become compacted and more elastic.

Thus, it was established that the optimal composition for creating an effective wood-polymer composite with enhanced physical, mechanical, and operational characteristics is found in samples

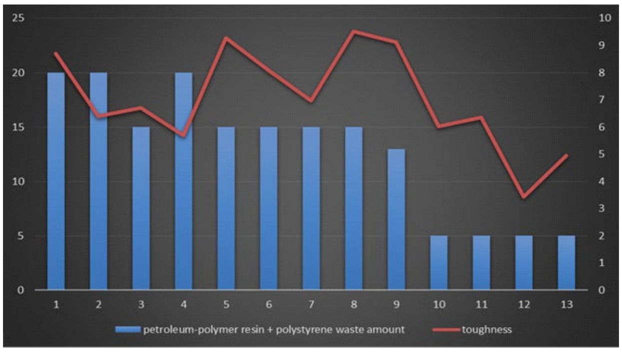

Fig. 1. Dependence of WPC toughness on petroleum-polymer resin and polystyrene waste content

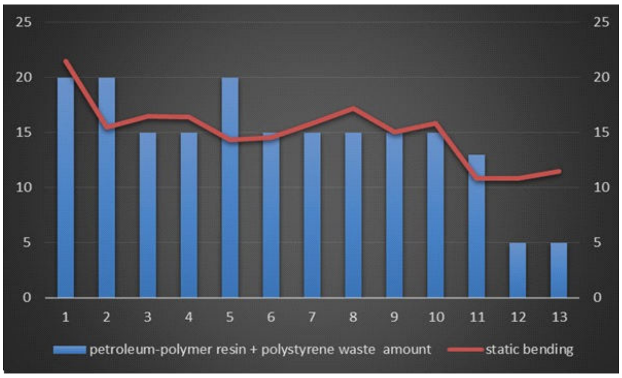

Fig. 2. Dependence of static bending for WPC on petroleum-polymer resin and polystyrene waste content

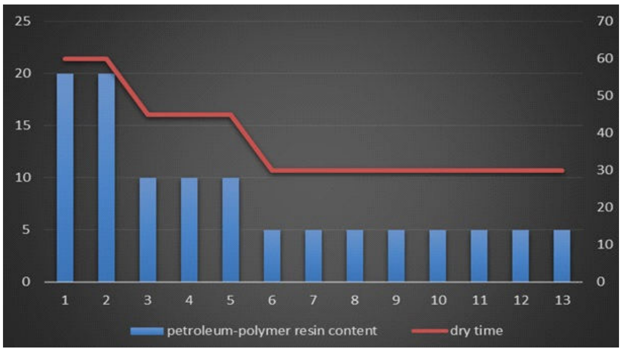

Fig. 3. Dependence of drying time on petroleum-polymer resin content

No. 6–9, which include petroleum-polymer resin, solvent, polystyrene foam waste, microcalcite, and wood filler (wood industry waste).

Conclusions

Based on the research results, it can be concluded that the scientific and production experience accumulated thus far demonstrates the advantages of using the proposed composition with a modified mixture for wood filler impregnation to obtain products with enhanced operational properties.

This article presents studies on the development of processes for producing wood-polymer composites modified with polystyrene foam waste, petroleum-polymer resin, and an inorganic additive.

The impact of petroleum-polymer resin and polystyrene foam waste content on the physical, mechanical, and operational characteristics was studied. The optimal WPC composition with improved physical, mechanical, and operational characteristics was determined. Additionally, the production parameters for the extrusion method were defined.

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Received 24.07.2024

Table 3

Operating characteristics of WPCs

Number of composition		Absorption, W, %	Durability, m	Durability, V	Resize in an range of $+30^0C...+80^0C$	Resize at -15^0C, %
1		+5.7	0.1015	0.2997	not detected	not detected
2		+5.8	0.1336	0.320	not detected	not detected
3		+6.4	0.112	0.304	not detected	not detected
4		+6.6	0.088	0.305	not detected	not detected
5		+6.5	0.108	0.308	not detected	not detected
6		+6.2	0.142	0.288	not detected	not detected
7		+5.4	0.113	0.283	not detected	not detected
8		+5.3	0.101	0.270	not detected	not detected
9		+5.3	0.102	0.325	not detected	not detected
10		+6.3	0.103	0.278	not detected	not detected
11		+6.1	0.052	0.325	not detected	not detected
12		+5.9	0.072	0.327	not detected	not detected
13		+6.2	0.075	0.325	not detected	not detected
Known industrial samples	WPC commercial sample	+10.8	0.309	0.296	length +1.98 thickness +6.78	length –0.97 thickness –2.77 width –1.22
Known industrial samples	OSB sample	+44.18	0.326	0.337	length +3.86 thickness +10.3 width +4.18	length –1.58 thickness –8.62 width –2.94
Known industrial samples	Sample chipboard laminated	+42.15	0.312	0.33	length +2.28 thickness +7.7 width +6.29	length –1.6 thickness –5.13 width –2.37

Table 4

Comparison of key properties and characteristics between the newly designed WPC and industrial samples

Number of composition		Absorption, W, %	Durability, m	A, kJ/cm^2	σ, MPa	Resize in an range of $+30^0C...+80^0C$	Impact strength
6		+6.2	0.142	8.09	14.60	not detected	h=15 dent h=20 brittle fracture
7		+5.4	0.113	6.98	15.88	not detected	h=15 dent h=20 brittle fracture
8		+5.3	0.101	9.52	17.23	not detected	h=15 dent h=20 brittle fracture
9		+5.3	0.102	9.13	15.07	not detected	h=15 dent h=20 brittle fracture
Known industrial samples	WPC commercial sample	+10.8	0.309	2.74	18.2	length +1.98 thickness +6.78	h=10 dent h=15 brittle fracture
Known industrial samples	OSB sample	+44.18	0.326	11.03	9.04	length +3.86 thickness +10.3 width +4.18	h=10 brittle fracture
Known industrial samples	Sample chipboard laminated	+42.15	0.312	11.52	14.7	length +2.28 thickness +7.7 width +6.29	h=10 brittle fracture

ДЕРЕВНО-ПОЛІМЕРНИЙ КОМПОЗИТ З ВТОРИННИХ ТЕРМОПЛАСТІВ З ПІДВИЩЕНИМИ ВЛАСТИВОСТЯМИ

С.О. Копилов, Г.М. Черкашина, І.О. Лаврова, Т.Т. Черногор

У статті описані нові деревно-полімерні композити та охарактеризовані їх властивості. Метою дослідження було створення оптимального складу деревно-полімерних композитів на основі вторинної сировини з кращими фізико-механічними характеристиками. Виявлено вплив модифікації деревно-полімерних композитів на фізико-механічні властивості у порівнянні з відомими промисловими зразками. Встановлено залежність ударної в'язкості та статичного вигину від кількості суміші нафто-полімерної смоли і пінополістиролу, а також залежність часу висушування від вмісту нафто-полімерної смоли. Охарактеризовано фізико-механічні властивості (міцність при ударі, руйнівна напруга при згинанні і мікротвердість). Дано опис кліматичних впливів на деревно-полімерні композити, які включають вплив вологи та температури. Проведено випробування водопоглинання, зносостійкість та зміну розмірів в інтервалі температур від +30⁰C до −15⁰C. Проведено порівняльні характеристики основних показників запропонованого композиту та промислових зразків.

Ключові слова: композит, деревина, вторинна сировина, поліетилен, поліпропілен, модифікація, фізико-механічні властивості.

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S.O. Kopylov, G.M. Cherkashina *, I.O. Lavrova, T.T. Chernogor

National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine

*** e-mail: annikcherkashina@gmail.com**

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