GREEN COMPOSITE BASED ON RECYCLED RUBBER FOR TRACKED DRIVE OF MULTI-PURPOSE AGRICULTURAL ROBOTIC PLATFORM

Olena Nalobina, Mykola Holotiuk, Oleh Bundza, Artem Mykhailov
National University of Water and Environmental Engineering, Ukraine
o.o.nalobina@nuwm.edu.ua

Abstract. Humanity is facing environmental challenges, particularly those associated with air pollution. One of the sources of environmental contamination is worn-out vehicle tires. Uncontrolled stockpiling of end-of-life tires poses a risk of environmental pollution and represents a serious threat to public health. To address this issue, taking into account the global trend toward the use of recycled materials and the development of new products from plant-based resources and polymer waste, a composite material has been developed for manufacturing tracks for an agricultural robotic platform. Reclaimed rubber was used as the composite matrix, while natural technical hemp fibers served as reinforcing elements. Composite samples based on SBR rubber (styrene-butadiene rubber) with varying contents of hemp fibers and reclaimed rubber were produced. Experimental studies were conducted to determine the modulus of elasticity, tensile strength, hardness, and elongation at break. The analysis of the obtained results made it possible to provide recommendations regarding the optimal content of hemp fibers and reclaimed rubber in the green composite formulation. It is recommended to incorporate 10–20 phr (parts per hundred rubber) of hemp fibers and 20–40 phr of reclaimed rubber. The fibers should be pre-treated with a silane coupling agent to enhance interfacial adhesion. The use of treated fibers resulted in an average increase in elongation at break by 14.3%, tensile strength by 9.1%, and hardness by 4.6%. The addition of 20 phr of reclaimed rubber to the composite matrix increases hardness by 2%, while 40 phr increases it by 10.3%. However, tensile strength decreases by 15.2% and 32.7%, respectively. The relative elongation at break also decreases by 6.2% and 18.2%, respectively.

Keywords: fibers, composite, reclaimed rubber, research.

Introduction

The development of the agro-industrial sector within the framework of the modern economic paradigm requires the search for new approaches to increasing growth indicators and production efficiency. One such approach is the implementation of robotics which, according to the world's largest investment bank Goldman Sachs (USA), is capable of increasing agricultural productivity by up to 70% by 2050 [1].

In Ukraine, under conditions of a significant decline in agricultural production due to the loss of a considerable portion of farmland, the active development of small-scale farms, and a substantial labor shortage, the task of developing and implementing domestic agricultural robots is particularly relevant.

Taking into account the urgency of this area, a project is being implemented at the Department of Agroengineering of the National University of Water and Environmental Engineering aimed at the development and testing of multi-purpose robotic platforms for agricultural production. In particular, within the framework of the project, a platform designed for operation on soft and uneven surfaces and equipped with a tracked propulsion system has been developed. The design concept of the robot's propulsion system is based on the synergy of two approaches: engineering-technological and environmental.

The implementation of the first approach is grounded in a comprehensive analysis of existing research [2-5], which has shown that a promising propulsion system is a tracked drive with rubber tracks. To equip the agro-industrial sector, there is a need to develop and manufacture domestic rubber tracks. For agricultural robots, the tracks must have a lightweight design and relatively compact dimensions. Considering the advantages of rubber-reinforced tracks – low noise levels, minimal vibrations, good traction, reduced soil damage, and low ground pressure – the authors selected this type of track model during the research and development of a mobile robotic platform for agricultural applications.

The implementation of the second approach involved taking into account the global trend toward the use of recycled materials and the creation of new products from plant-based resources and polymer waste [6-8]. Environmental problems, particularly those associated with global encourage researchers to work toward replacing traditional materials with materials derived from renewable sources [9-12].

Scientists are increasingly addressing the issue of incorporating natural fibers into composite materials. Natural fibers are used as reinforcing elements. The main objectives pursued in this context

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are: 1) reducing the hazardous environmental impact of synthetic fibers; 2) lowering product cost (since synthetic fibers are relatively expensive) [13].

In [12], the authors investigated the mechanical properties and morphological characteristics of eco-epoxy biocomposites reinforced with hemp, flax, and alkali-treated hemp and flax fibers. Mechanical testing of the manufactured samples included flexural strength, interlaminar shear strength, and water absorption. It was established that such biocomposites can be recommended as reinforcing materials for lightweight biosensor chips and flexible electronics; however, further in-depth studies are required to improve porosity and moisture resistance.

Study [14] focused on EPDM-based composites (high-performance rubber materials based on synthetic elastomers) reinforced with hemp fibers modified with peroxide at elevated temperature. The physical and mechanical properties examined included hardness, elasticity, 100% modulus, tensile strength, and elongation at break. It was found that increasing the hemp fiber content leads to higher hardness and gel fraction. Fiber content also affects water absorption, with the highest water sorption (2.02%) observed in the sample containing 20 phr (parts per hundred rubber) of hemp fibers.

The advantages of natural fiber-reinforced composites were highlighted in [15], including low cost, light weight, high modulus of elasticity, high specific strength, safe manufacturing methods, and wear resistance, in addition to their renewability and biodegradability.

A series of studies [16-18] present results on composites based on natural rubber and EPDM rubber blends reinforced with various amounts of short hemp fibers. To manufacture green composites, the researchers applied an original environmentally friendly crosslinking method using electron beam irradiation. The obtained samples were analyzed to determine physical and mechanical properties and crosslink density. It was established that increasing hemp fiber content in the blends results in higher hardness, tensile strength, and crosslink density, while elongation at break decreases. These results correlate with those reported in [14]. It was also found that electron beam irradiation helps suppress the water absorption effect.

The analysis of literature sources indicates that composites reinforced with natural fibers represent a relevant and actively developing research area within the scientific community. They successfully compete with conventional reinforcing fillers such as silica, calcium carbonate, and carbon black.It was also established that researchers predominantly used natural rubber or EPDM synthetic rubber blends as the composite matrix.Considering the importance of incorporating environmental aspects into the development of new products, the authors decided to use reclaimed rubber as the matrix of the green composite. This decision also takes into account the Tire Industry Project, according to which end-of-life tire material is "an inexpensive but valuable resource for the circular economy that can be utilized in various applications" [19]. Recycling end-of-life tires into green composites contributes to solving environmental degradation problems caused by their improper disposal [20].

The objective of this study is to prepare reclaimed rubber composites reinforced with hemp fibers and to investigate their properties with the aim of further application in the manufacture of tracks for an agricultural robotic platform.

Materials and methods

Fibers

Technical hemp fibers were used for the study (Fig. 1). For the research, we used fiber obtained from hemp of the Liryna variety, which has been included in the State Register of Plant Varieties Suitable for Distribution in Ukraine since 2022.

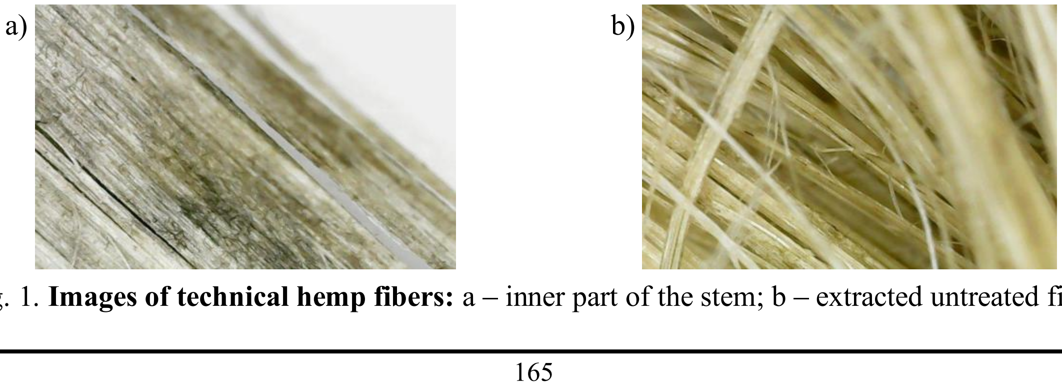

Fig. 1. **Images of technical hemp fibers:** a – inner part of the stem; b – extracted untreated fiber

Industrial hemp is characterized by a high content of long and strong fibers. The chemical composition of the fibers is presented in Table 1 according to [20].

Table 1

Chemical composition and length of hemp fibers

Component/Fiber length	Bast (fibrous part)	Woody core (shiv)
Lignin, %	2.9-4.9	24.8-26.3
Cellulose, %	63.4-76.4	46-52
Hemicellulose, %	8-12	14-16
Fiber length, mm	9-70	1.0

Plant fibers require treatment, particularly moisture removal, to improve compatibility with polymeric materials. To enhance adhesion between the fibers and the polymer matrix of the green composite, and considering studies [12–18, 21], additional fiber treatment was performed according to the procedure described in [21].

The hemp fibers were treated with alkali by immersion in an 8% NaOH solution for 1.5 hours, rinsed with distilled water, and then dried at 60°C in a drying oven (SNOL–58/350) for 12 hours. Subsequently, the fibers were treated in a 3% MPS silane solution and dried for 1.5 hours at 100°C. The fibers were cut to a length of 2.0 cm.

Polymers

SBR (styrene-butadiene rubber), a synthetic elastomer produced from styrene and butadiene, was used as the polymer matrix. It is characterized by high abrasion resistance, resistance to mild chemicals and heat, and lower cost compared to natural rubber. Reclaimed rubber was also used.

Experimental Procedure

The following sample compositions were prepared:

1. SBR – untreated fiber;
2. SBR – treated fiber;
3. SBR – reclaimed rubber – untreated fiber;
4. SBR – reclaimed rubber – treated fiber. The fiber and reclaimed rubber contents (in parts per hundred rubber, phr) are presented below.

Figure 2 shows the sequence of the conducted experiments. The tests were performed according to ISO 37:2017 and ISO 7619-1:2010 standards.

Statistical processing of the experimental data was performed using the application software package “Excel 7.0” (MS Office, USA). The following parameters were determined: the arithmetic mean and the coefficient of variation.

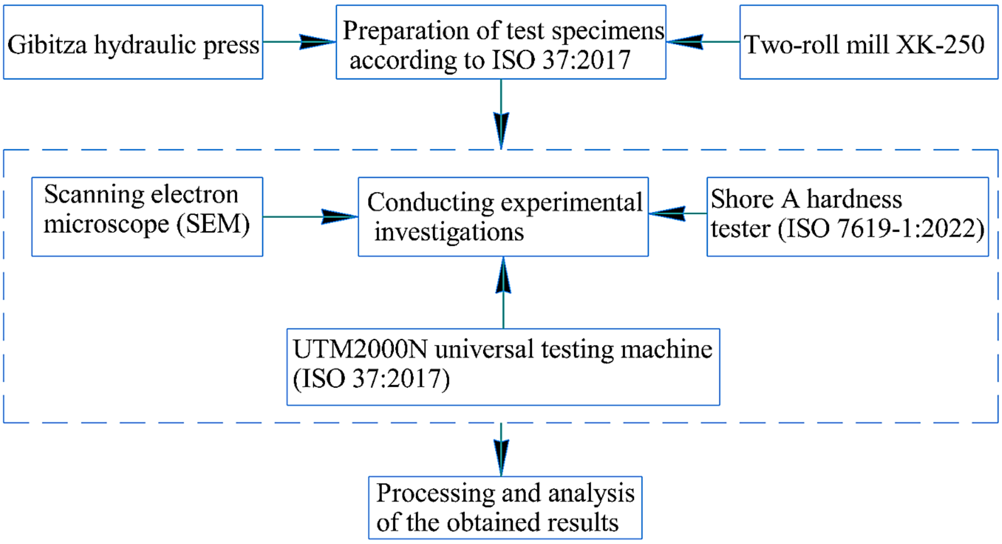

Fig. 2. **Schematic representation of research implementation**

Results and discussion

The control sample was prepared from SBR and hemp fibers. The graphical results for this sample are shown in Fig. 3-6.

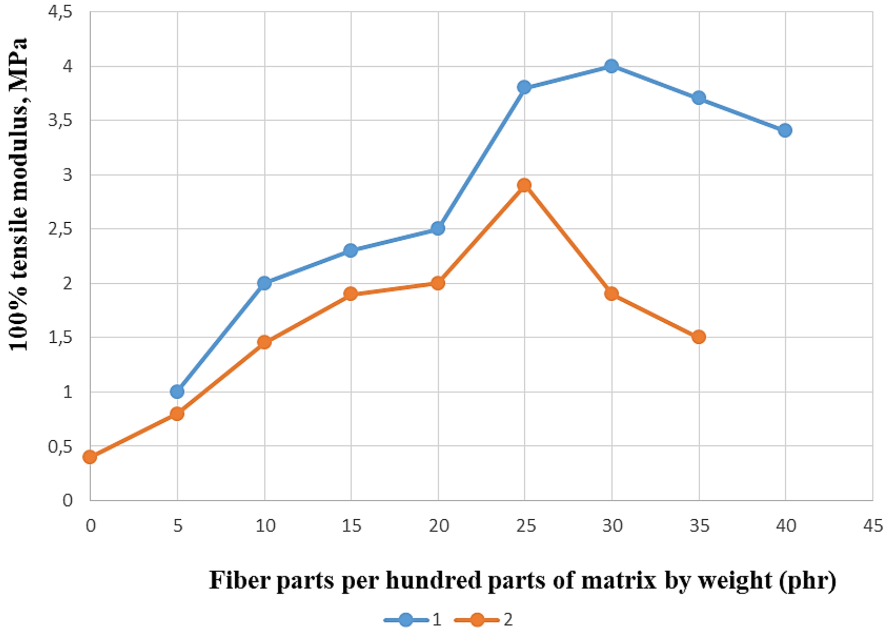

Fig. 3. **Change in 100% modulus of elasticity as a function of fiber content (phr):**
1 – silane-treated fiber; 2 – untreated fiber

The 100% modulus increases with increasing fiber content. A more pronounced increase is observed when the fibers are silane-treated. Peak values are reached at 25 phr for untreated fibers and 30 phr for treated fibers. The increase in modulus for composites with treated fibers is more gradual. The stiffness of the samples increases more significantly for treated fibers due to improved interfacial adhesion with the matrix.

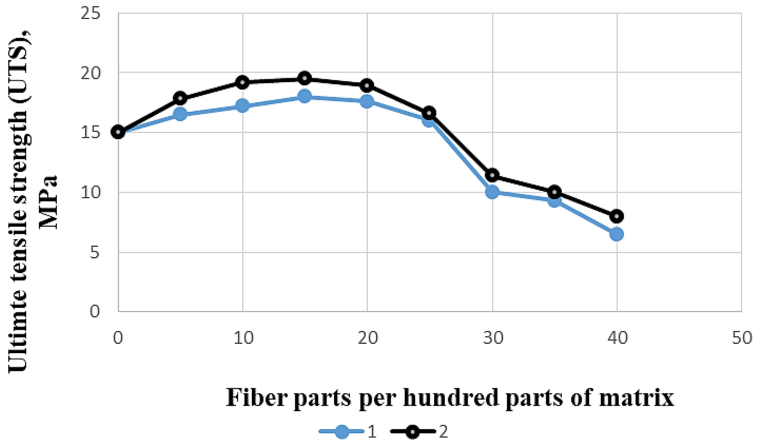

Fig. 4. **Tensile strength as a function of fiber content:**
1 – untreated fiber; 2 – silane-treated fiber

Tensile strength correlates with fiber content. Fiber treatment has a relatively minor effect on strength (maximum difference does not exceed 12.3%).

The highest tensile strength is observed in the range of 10-20 phr, indicating a reinforcement effect. At higher fiber contents, microstructural analysis showed fiber agglomeration and non-uniform distribution, leading to structural defects and reduced strength (Fig. 5).

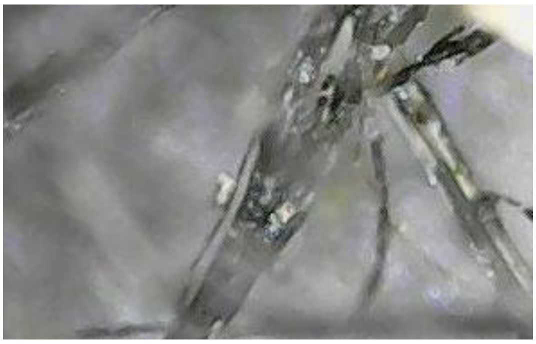

Fig. 5. **Micrograph of a sample with fiber content of 35 phr**

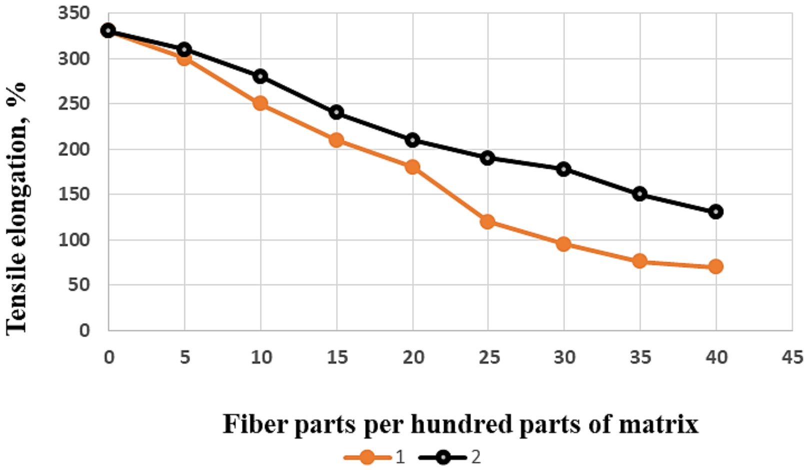

Fig. 6. **Change in elongation of samples depending on fiber content:**
1 – untreated fiber; 2 – silane-treated fiber

As we see in Fig.6, elongation at break decreases as the fiber content increases.

Table 2

Results of measuring hardness of the samples, ShA

Fiber content	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
Hardness (raw fiber)	59	62	63	65	67	68	69	71	73
Hardness (silane treated fiber)	59	62	66	68	70	72	72	74	76

Composite: SBR + Reclaimed Rubber + Fiber. Figure 7 presents a micrograph of a sample containing 25 phr reclaimed rubber without fiber addition. Inclusions (contaminants) originating from recycled tire material were observed.

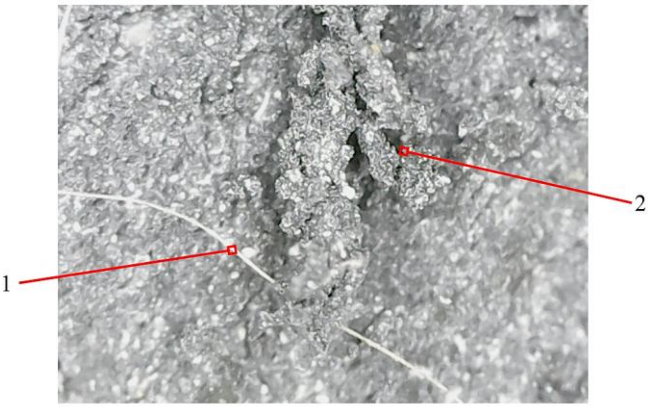

Fig. 7. **Micrograph of a sample (0 phr fibers) of synthetic rubber SBR + reclaimed rubber:**
1, 2 – inclusions (dirt) that got into the mixture from recycled tires

Table 3 summarizes the results for composites containing reclaimed rubber and silane-treated fibers.

Table 3

Results of research on a composite made with addition of reclaimed rubber and silane-treated fiber

Fiber content, (processed), phr	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
20 phr reclaimed rubber									
100% modulus of elasticity	1.5	1.5	2.5	3.0	3.0	4.3	4.8	5.0	5.4
Elongation, %	320	300	280	250	240	190	150	130	110
Tensile strength, MPa	13.6	15.5	17.0	17.0	16.0	14.5	12.0	9.5	7.0
Hardness, ShA	63	65	66	69	73	75	79	81	84
40 phr reclaimed rubber									
100% modulus of elasticity	2.0	2.3	3.5	4.5	4.5	5.7	6.5	7.0	7.5
Elongation, %	280	250	230	200	180	140	110	90	70
Tensile strength, MPa	12.9	13.0	15.0	15.0	13.5	10.6	8.5	7.0	4.5
Hardness, ShA	68	70	72	75	78	80	83	87	90
50 phr reclaimed rubber:									
100% modulus of elasticity	3.5	3.8	4.6	6.8	6.8	7.6	8.3	8.5	8.6
Elongation, %	240	190	180	150	130	100	70	70	50
Tensile strength, MPa	11.5	12.5	13.0	13.0	11.5	9.0	6.5	4.5	3.5
Hardness, ShA	71	73	75	78	80	85	88	90	94

Conclusions

1. The study of a green composite with SBR as the polymer matrix and technical hemp fibers as reinforcing elements showed that the optimal fiber content is 10–20 phr. The fibers should be pre-treated with silane, which increases elongation at break by an average of 14.3%, tensile strength by 9.1%, and hardness by 4.6%.
2. It has been experimentally confirmed that regenerated rubber can be used in the production of green composites, contributing to environmental sustainability. The recommended content of regenerated rubber is 20-40%. Higher content is not recommended due to a significant reduction in tensile strength and elongation. When the regenerated rubber content increases to 50 phr, a decrease in the tensile strength of approximately 25.01% is observed, provided that the fiber content remains within the recommended range (10-20 phr). Regenerated rubber intensifies the strength reduction effect in the composite.
3. Increasing the regenerated rubber content to 50 phr leads to an increase in the coefficient of variation up to 40%, indicating greater structural heterogeneity. This is explained by the occurrence of structural defects due to reduced interfacial adhesion. Attempts to increase the regenerated rubber content beyond 50 phr were unsuccessful due to the manifestation of structural defects in the final product, rendering it unsuitable for further research.
4. Increasing the regenerated rubber content above 40 phr results in an increase in hardness by an average of 12.0%. For the manufacturing of a tracked propulsion system, this is undesirable due to the reduction in the actual contact area with the soil and, consequently, the loss of tractive effort.
5. It was established that increasing the hemp fiber content above 20 phr leads to a decrease in strength and elasticity. The reduction in the tensile strength when increasing the fiber content from 20 phr to 25 phr is 9.4%, while at a fiber content of 40 phr, a decrease of 56.3% is observed (provided that 20 phr of regenerated rubber is incorporated into the composite matrix).

Author contributions

Conceptualization, O.N.; methodology, O.N. and M.H.; software, O.B.; validation, O.N. and O.B; formal analysis, A.M.; investigation, O.N., M.H., O.B. and A.M.; data curation, O.B.; writing – original draft preparation, V.B.; writing – review and editing, A.A. and V.B.; visualization, Y.I., V.N.; project administration, O.N.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

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