RECYCLING OF CONSTRUCTIONAL PLASTICS WITH ADDITIVES OF EXHAUSTED POLYETHYLENE

Kobets A. S.[1], Derkach O. D.[2], Kabat O. S.[2, 3], Kovalenko V. L.[4, 6] and Kotok V. A.[5, 6]
[1]Department of Tractors and Agricultural Machines, Dnipro State Agrarian, and Economic University, Serhiy Yefremov St., Ukraine
[2]Department of Operation of Machine-Tractors Park, Dnipro State Agrarian and Economic University, Serhiy Yefremov St., Ukraine
[3]Department of Mechanical Engineering and Engineering Mechanics, Ukrainian State University of Chemical Technology, Gagarin Ave., Dnipro, Ukraine
[4]Department of Analytical Chemistry and Chemical Technologies of Food Additives and Cosmetics, Ukrainian State University of Chemical Technology, Gagarin Ave., Dnipro, Ukraine
[5]Department of Processes, Apparatus and General Chemical Technology, Ukrainian State University of Chemical Technology, Gagarin Ave., Dnipro, Ukraine
[6]Competence Center "Ecological Technologies and Systems", Vyatka State University, Moskovskaya St., Kirov, Russian Federation
E-Mail: valeriy_e-ch@ukr.net

ABSTRACT

Received polymeric materials with the use of wasted polyethylene of PE-500 and PE-1000 grades can serve, as construction materials at regimes, which correspond to characteristics of new PCM. Presence of carbon fibers in composites such as UPA-6-30+PE-500 (10%) and UPA-6-30+PE-1000 (10%) allows applying details, made of these materials without normative greasings. The use of waste polyethylene of PE mark decreases physicomechanical characteristics in received PCM with the exception of impacting viscosity. It is shown that such an indicator as the stress of the boundary of the volume of compression is high (about 100 MPa), which indicates the possibility of using PCM data, for example, for bearings of parallelogram mechanisms of sewing machines, where the pressure value is within the range of 23 to 30 MPa.

Keywords: recycling, polyethylene, carbon plastic, carbon fibers, exhaust, physicomechanical characteristics.

INTRODUCTION

Polymeric-composite materials (PCM) for the structural approach: carbon plastics, fiberglass, organic plastics, and others take a prominent place in today's' engineering. In particular, construction plastics have been provided the high technological and economic features for modern machines from a wide range of industries: agricultural, chemical, electronic, space, medical, and defense. Meanwhile, they combine properties that are not inherent to structural steels, including non-ferrous metals: low specific weight and high durability, controlled coefficients of friction in the condition of friction without greasing, high wear resistance, programmed (controlled) elastic deformation, etc. It is clear that further progress of technology is impossible without innovative approaches and solutions for these materials.

Characteristics of PCM will increase in performance, and unquestionably, it tends to raise demand for them. For example, there are predictions that the demand for carbon fibers (which is an effective filler of structural plastics) will amount to 117.000 tons by 2022 [1] and will only continue to move forward. Due to the high world demand for PCM, a sharp need to recycle exhausted composites or waste materials from them appears. It is believed that the recycling of carbon fibers, which present in the structure of PCM, is an economically feasible solution [1].

Exhausted polymer materials are an extremely dangerous man-caused impact. In developed countries, new technologies for the sorting, processing, and recycling of plastics are being established and enhanced in emerging countries. Technologies for the processing and recycling of household plastics quite commonly used for - bottles, packaging materials, made of polyethylene terephthalate or polyethylene. The successful business also encourages the world's societies to reduce the use of fossil fuels, which is a raw material for PCM and improve the environmental situation in many parts of the world [2].

The main aim - to estimate an impact on used polyethylene, PE-500, and PE-1000 models, while adding it as a filler, to estimate an impact on physical and mechanical characteristics of structural plastics based on polyamide.

The objects of investigations – are processes of changing properties of polymeric and composite materials with adding used polyethylene.

The subject of investigation. The regularities of the change in the physicomechanical characteristics of the polymer-composite material made with the use of used polyethylene.

Due to reach the goal, in case of adding used polyethylene it is necessary to solve further tasks to estimate characteristics of polymer composite material; 2) to recommend spheres of applications and to make experimental details.

LITERATURE REVIEW

However, today there is still not enough information about recycling or conversion of used construction plastics once again into the construction materials. There are studies that aimed at recycling structural plastics to the spare parts, which can be implemented at lower loads in tribosystems [3]. There are also review articles that do not propose the technology of

ARPN Journal of Engineering and Applied Sciences

recycling waste polyethylene in the design of machines but indicate the relevance of recycling [4].

The number one idea of work is to use household and industrial polyethylene wastes for their use during the recycling process in structural plastics. The technical and economic problems of recycling of polymeric materials are investigated [5]. But this was the case with the incomplete fiber of polymer materials. There are scientific preconditions for conducting such tests [6, 7].

Up to now, various studies have been conducted on the use of PCM in different machines, and sales of large assortment [8 - 10]. Along with them, there are scientifically grounded environmental indexes [11, 12]. Application of carbon fiber reinforced carbon fiber is developing in many scientific fields [13 - 15, 18]. It is proved that carbon-based plastics on the basis of polyethylene have high characteristics [16].

Creation of modification techniques for PCM by polyethylene waste will make it effectively deal with the question of design improvement of construction in machines, will reduce the environmental stress in the regions of technology implementation, will reduce the economic dependence of the manufacturer of machines on external factors, and bring additional topics to the educational process in colleges and universities [17]. Which is why there are all facts to consider the topic of work relevant one.

MATERIALS AND METHODS

Impact toughness

It was set up on pendulum hammer KM-0.4 (Figure-1) by Charpy Impact test according to GOST 4647-80 at temperature 23±2 °C and the average air humidity level was 50 ± 5 %.

The essence of the method was in the test, in which the sample, lying on two supports (the distance between the supports 40 mm), it collapsed when the impact of the pendulum (1), and the line of impact is located halfway between the supports.

Impact toughness of samples estimates by formula, kJ/m^2:

$$a_n = \frac{A_n}{b \cdot s \cdot 1000}$$

where:

A_n - impact energy, spent on destroying the sample, kJ / (kg· sm^2), is fixing on the digital display of the device;
b - width of the sample in its middle, mm;
s - the thickness of the sample in its middle, mm.

The research of strength properties accomplished on test machine_FP-100/1, in accordance with GOST 4651-82. To study the compressive strength, we used samples of diameter 10 and a height of 15 mm applied with the appropriate tool 2. Herewith support surfaces should be parallel in the range of 0.1% in the direction perpendicular to the application of load. The tensile strength was studied with using samples in the form of blades, whose dimensions were 5 × 5 mm in the midway. For this type of research was applied to tool 1. The recorder on a registration form of results 3 carried out registration of the process of destruction of the sample and its extension.

Ultimate tensile strength on compression (σ_p) is calculated by formula:

$$\sigma = P / F,$$

Where

P - stress, MPa;
F - minimum section areas of sample, mm^2;
$F = \pi d^2 / 4;$
d - diameter of sample, mm.

The relevant strain on compression (ε.) is calculated by the formula:

$$\varepsilon = \Delta h_{p.c.} \cdot 100 / h_o$$

where

$\Delta h_{p.c}$ - the value of reduction of sample height at destruction, mm;
h_o - initial height of the sample, mm.

To determine the modulus of elasticity in compression (E) on the pattern determined the value of loads answered to relative stairs of 0.1 and 0.3% (GOST 9550-81). The calculation was performed according to the formula:

$$E = \frac{(F_2 - F_1) h_o}{A_o(\Delta h_2 - \Delta h_1)}$$

where F_1 – the corresponding value of loading to strains 0.1%, H;
F_2 - the corresponding value of loading to strains 0.3%, H;
h_o - the starting height of the sample, mm;
A_o - the cross section area of the sample, mm;
Δh_1 - the corresponding value of changed height to loading F_1;
Δh_2 - the corresponding value of changed height to loading F_2.

In the result of the tests, an average value of all parallel studies was taken.

Determination of density. Research of density of samples conducted by the method of hydrostatic weighing in the aquatic environment according to GOST 15139-69. The sample hung on the arm of the balance of analytical weights, it was successively weighed in the air and in distilled water at a temperature of 20 °C with an accuracy of not less than 0.0001 g. The density was calculated by the ratio of the sample mass in the air to the difference in mass in the air and in the water. An average value of density was obtained as a result of not less than three measurements, they differ no more than 1%, was taken to the final result.

Density is calculated by the formula:

$$\rho_T = \frac{m}{V}$$

where

m - body weight, kg;

V - the volume of the body, m^3.

Body weight is estimated with the aid of a high-accuracy weighing machine. The volume of the body can be determined by measuring its geometric parameters, but for scientific research, this method is out of use, as it results in a significant error of the final result. The hydrostatic weighing method, which is allowed reducing the error, as follows.

The body under investigation is suspended by means of a thin wire or a fishing salmon to the scales and it is weighed. Weighing will give body weight in the air $P_1 = m_1g$. If the neglect of the pushing force acting on the body and on the heavy side by side of the air, then the weight of the heavy loads will be equal to the mass of the body: $m_1 = m$. Then we immerse the body in the distillate-bath of water, the density of which is ρ_0, and again we balance the scales. This weighing will give body weight in water P_2:

$$P_2 = mg - F_A$$

From another side $P_2 = m_2g$,

where m_2 – a mass of plummets at the weighting.

$F_A = \rho_0 Vg$,

where V – the volume of the body.

So, we can equal:

$$m_2 g = m_1 g - \rho_0 V g$$

Whereas: $$V = \frac{m_1}{\rho_T},$$

It can be written as:

$$m_2 g = m_1 g - \rho_0 \frac{m_1}{\rho_T} g$$

After the transformations it send us to final formula, and determine the density of required material:

$$\rho_T = \rho_0 \frac{m_1}{m_1 - m_2}$$

Vicat softening temperature was determined on a device PTB-I-IIG in the aquatic environment in accordance with GOST 15088-83. For tests we were producing samples (cut by hand with the following grinding), with dimensions 4×6×50 mm. The samples had not got imperfections: shells, external damage, and the surfaces of the samples were smooth. The registration of the results was carried out using the potentiometers installed in the control unit 1. Finished samples immersed in silicone oil of the PMFS-4 mark in the test chamber 2 on specially installed supports. In the middle of the sample, a load of 5.025 kg was applied, after which the specimen deflection was fixed by measuring mount 3. The heating of the liquid was carried out at a rate of 120°C/h. During the heating of the liquid, the sample was softened. At the moment of deflection of the sample, equal to 1 mm from the initial state of the study, the temperature of the liquid was stopped and recorded. The temperature is fixed and equal to Vicat softening temperature. The studies conduct for 3 samples at the same time, the results were registered according to 3 independent from each other channels.

Temperature resistance of samples from PCM of UPA-6-30 model, based on appropriate polyethylene and composite are determined by Vicat impact test.

Optical studies. The studies of friction surface and distribution of carbon fibers in the matrix were being compiled on microscope NEOFOT 30 (Figure-1). Moreover, with aid of microscope NEOFOT 30, the pictures of subjects of research were transmitted to large screen 1 for more convenient visual inspection, and they were transmitted on the photographic plate through the screen 2 for taking pictures.

Figure-1. Optical microscope NEOFOT 30.

Test run and experimental details

The samples manufactured of specified carbon fiber on vertical and hydraulic grease gun PL-32 (Figure-2), which implements the necessary technological tools designed for the manufacture of carbon-plastic parts by the specified method. The pressure of the casting was controlled with the help of a pressure gauge 1, that's installed directly in the hydro cylinder 2. The temperature of the carbon fiber melt in the heating chamber 3 was monitored by using a thermocouple whose signals were transmitted to the arrow automatic index 6. The present temperature was maintained by the electric relay in the range of ± 5 °C. The control of the machine was carried out using the control panel 5. The casting of carbon fiber melts into molds was carried out through nozzle - 4, which has a hole, with a diameter of 4 mm.

ARPN Journal of Engineering and Applied Sciences

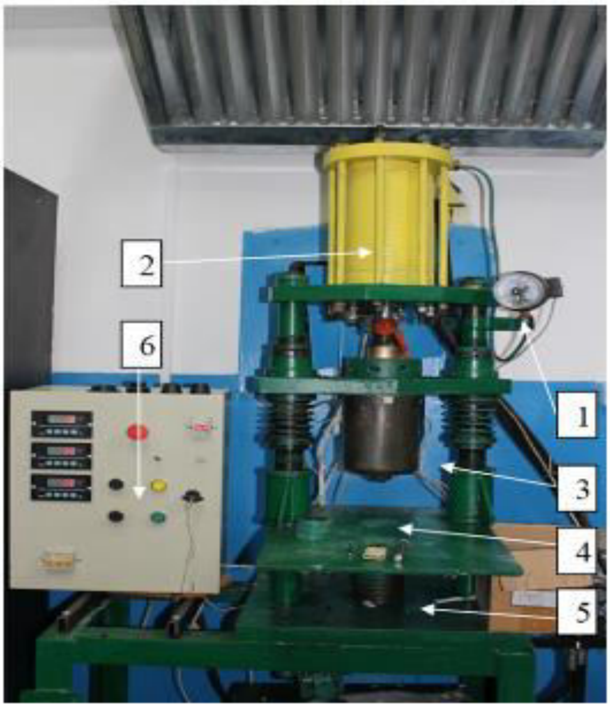


Figure-2. The casting press machine of manual type PL-32: 1- a pressure gauge; 2- hydraulic cylinder; 3- heating chamber; 4 - nozzle; 5 - the platform; 6 - control panel.

The production of samples and batch experimental workpieces carried out manually.

According to protective measures all equipment, which are installed on vibration-damping springs under suction hook complying with the requirements of electrical safety.

The following polymeric materials were subjected to laboratory testing using the above-mentioned procedures:

– UPA-6-30 – as construction material, which consists of polyamide binder, filled with hydrocellulose carbon fiber in amount 30 % of weight;
– Nylon 66 - unfilled polymeric material;
– exhausted polyethylene of PE-500 model;
– exhausted polyethylene of PE-1000 model.

For the production of samples, we brought granules of UPA-6-30 and Nylon 66, manufactured by the industry (Figure-3). The worn out and discarded materials, waste polyethylene PE-500 and PE-1000 were ground to a particle size of 3 ... 5 mm (Figure-4, *b*) and added in the amount of 10 wt. % to UPA-6-30 and Nylon 66.

The raw material was processed into test pieces (Figure-5) on the friction machine in accordance with the regimes provided by the manufacturers and tested by known methods. On Fig. 5, *b* show the test moment of the sample on the strength indicators.

Experimental

The new material composition thus obtained was researched and determined by their physical and mechanical characteristics. To determine the impact of spent polyethylene on new materials, firstly, it was necessary to determine the indices of the raw materials: UPA-6-30 and Nylon 66 and PE (Table-1).

Figure-3. The main view of granules for recycling: Nylon 66 and UPA-6-30.

(a) (b)

Figure-4. The main view of elements of used exhausted polyethylene PE-500 before (a) and after (b) comminuting.

(a) (b) (c)

Figure-5. The main view of samples for physicomechanical tests (a), a moment of the test of strength (b) and the front main view of a sample with recorded parameters (c).

According to the results from the analysis (Table-1), it is shown that used polyethylene kept poor characteristics in comparison with the polyamide group: UPA-6-30 and Nylon 66. In contrast, newly created materials supposed to change their features at the supplementing these materials with polyethylene. For this reason, we assume that used polyethylene added to PCM should be of minute quantity. So, examine it.

Table-1. Physicomechanical and thermos-physical properties of polymers that were investigated.

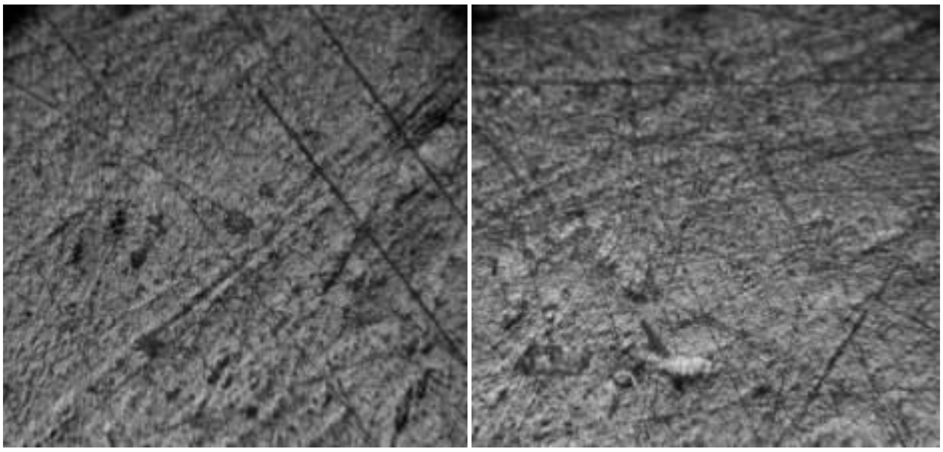
Parameter	A grade of polymeric material			
	PE 500	**PE 1000**	**UPA-6-30**	**Nylon 66**
Density, kg/m^3	960	930	1210	1200
Ultimate tensile strength on compression, MPa	24	19	128	60
Vicat softening point, °C	80	80	224	174
Charpy impact strength, kJ/m^2	50	80	35	44

We added a mass fraction of PE 500 and PE 1000 in the volume of 10 % to UPA-6-30 and Nylon 66. Made samples from new materials by the casting method under pressure were examined on a microscope with regard to the uniform distribution (mixing) of their elements. From Figure-6, a) it can be seen, that for basic substance - UPA-6-30, which contains 30 % of carbon fibers, characterized by the equal distribution of random nature. In compositions *b)* and *c)* uniformity of fibers provided, that denoted on isotropic characteristics of received materials.

(a) (b) (c)

Figure-6. Micrometric measurements of surfaces are shown on shots: a) UPA-6-30; b) UPA-6-30 + exhausted polyethylene PE-500 (10%); c) UPA-6-30 + exhausted polyethylene PE-1000 (10 %) × 300.

We take into consideration, that properties of PE-500 and PE-1000 are close to one another, we added only PE-500 to material Nylon 66. In addition, from the micro photo (Figure-7) we can see that evenness of compounding is satisfactory: there are no locules (cluster, concentration) of filling mass, defects and so on.



(a) (b)

Figure-7. Micrometric measurements of samples' surfaces are shown on shots: a) Nylon 66 and b) Nylon 66+ exhausted polyethylene PE-500 (10%).

Thus, we believed that anisotropic of obtained materials were provided and hereafter samples were put to the following test.

It was estimated, that using used polyethylene, as a filler, applied to Nylon 66 in the amount of 10 % weight lead to declining of ultimate tensile strength on compression to 17 % (from 60 MPa to 49.7 MPa) (Table-2).

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-2. The results of limits of crushing strength (on the example of study Nylon 66+ exhausted polyethylene PE-500).

Deformation (mm of the diagram)	Strain (mm of the diagram)	Relative strain	Deformation stress, MPa	Relative strain, %	Deformation stress is given the scale of the diagram, MPa
0.0	0.0	0.0000	0.0	0.0	0.0
10.0	1.0	0.0143	1.1	1.4	1.2
20.0	4.0	0.0287	4.3	2.9	4.7
30.0	18.0	0.0430	19.5	4.3	21.2
40.0	33.0	0.0573	35.8	5.7	38.8
50.0	41.0	0.0716	44.5	7.2	48.2
60.0	47.0	0.0860	51.0	8.6	55.3
70.0	52.0	0.1003	56.4	10.0	61.2
80.0	56.0	0.1146	60.7	11.5	65.9
90.0	59.0	0.1289	64.0	12.9	69.4
100.0	62.0	0.1433	67.3	14.3	73.0
110.0	64.0	0.1576	69.4	15.8	75.3
120.0	66.0	0.1719	71.6	17.2	77.7
130.0	69.0	0.1862	74.9	18.6	81.2

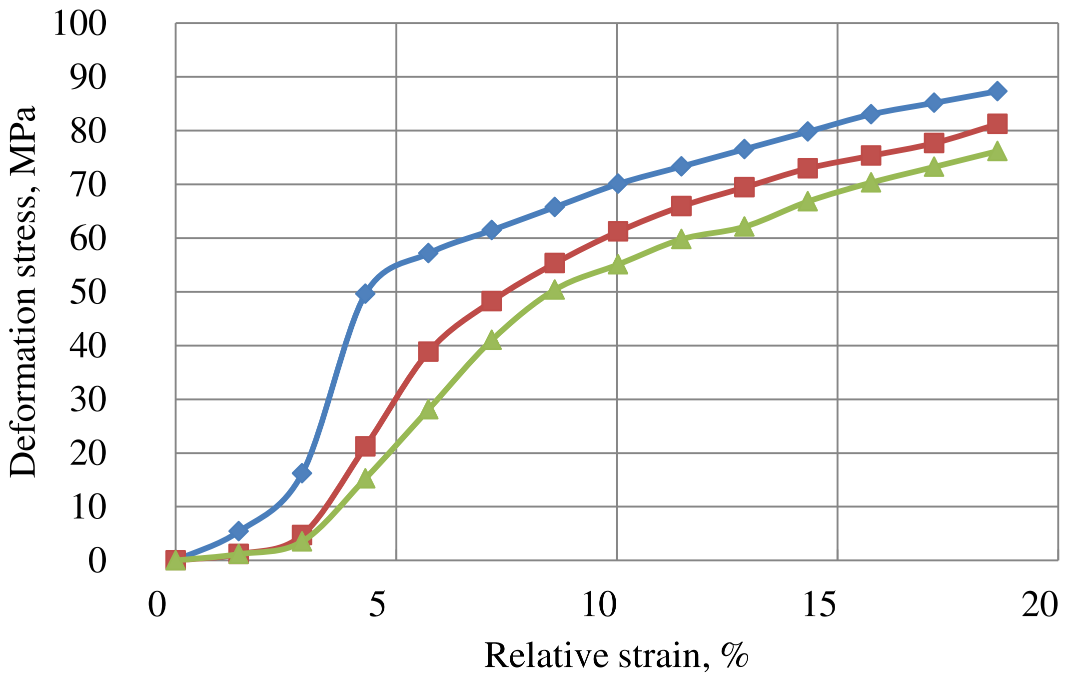


Figure-8. Deformation stress via relative strain at the triple repetition of samples, made from Nylon 66+exhausted polyethylene PE-500 (10 %).

Analysis of curve dynamic on Figure-8 denotes high recoverability of results, which indicates the stability of characteristics in found materials.

The rest results of the test will tabulate in Table-3.

VOL. 14, NO. 13, JULY 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-3. Found physicomechanical and thermophysical properties of polymers, which were tested.

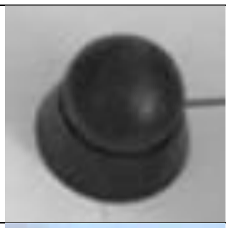
Parameter	**The grade of polymeric material**		
	UPA-6-30 + PE 500 (10%)	**UPA-6-30 + PE 1000 (10%)**	**Nylon 66 + PE 500 (10%)**
Density, kg/m^3	1130	1145	1110
Ultimate tensile strength on compression, MPa	98	101	48
Vicat softening point, ^{o}C	166	168	144
Charpy impact strength, kJ/m^2	38	37	46

RESULTS AND DISCUSSIONS

It can be seen from data analysis, that adding used polyethylene of PE models, in general, decreases physicomechanical properties of received PCM, except for impact toughness. In spite of this, that parameter, as an ultimate tensile strength on compression, remains high level (near to 100 MPa), demonstrated the opportunity of using PCM findings, for example, bearings in parallelogram mechanisms of sewing machines, where the pressure is within range 23…30 MPa [9]. Otherwise, the input of PE will decline water absorption by details, because of polyethylene won't absorb water.

In conclusions, resulting PCM details with use of wasted polyethylene PE-500 and PE-1000 models can serve, as structural materials at the modes, which correspond to characteristics of new PCM. The occurrence of fibrous carbon in composites, such as UPA-6-30+PE-500 (10%) and UPA-6-30+PE-1000 (10%) let us apply the details, made from these materials with no need in greasing. Using received materials we produced a range of commodities, a few of them are listed in the Table-4.

Table-4. Some samples of applications designed PCM in machinery.

Mark of PCM	**The name of the item**	**Front plan view**	**Characteristics**	
			Efforts, that effect on detail, H	
			Required	**Gotten**
UPA-6-30+ exhausted polyethylene PE-1000	Ball of the continuous bearing of turrets' turning mechanisms of mobile combat vehicle		9000	18500
UPA-6-30+ exhausted polyethylene PE-500	Friction bearing of parallelogram mechanism of seeding machines		2300…3000	9800
Nylon 66 + exhausted polyethylene PE 500 (10%)	Details of the moving joints of the grain combine		45	479

Designed materials can be used and applied in a large number of moving joints, even in the conditions of limited greasing, no presence of moisture, no abrasives and considerable efforts. Received materials can be used for producing, for instance, movable frames of solar batteries.

CONCLUSIONS

a) It is determined, that on a modern level of engineering, it is impossible producing machines and mechanisms without using polymer composite materials for structural applications.

b) It is shown, that waste polymer materials, thus, exhausted polyethylene is the largest ecological treat and it is common in all regions of the world.

c) It's developed new polymeric-composite materials with the use of wasted exhausted polyethylene PE-500 and PE-1000 models adding to polymer composites UPA-6-30 and Nylon 66, in which equally distributed the elements, that provides anisotropic properties and high strength properties – close to 100 MPa.

d) Adding of used exhausted polyethylene to before mentioned materials allows significantly decline impact of environmental stress.

REFERENCE

[1] Plastics Today / [Electronic source]. Access mode: https://www.plasticstoday.com/recycling/recycled-carbon-fiber-key-mass-market-applications/7344798259925. The date of the last review: 02/17/2019.

[2] Vance A., Mask Elon. 2015. Tesla, Space X, and the Quest for a Fantastic Future. NY: Harper Collins, 402.

[3] Burya A. I., Derkach A. D., Sviridenyuk A. I. 2000. Vliyaniye vtorichnoy pererabotki na udarnuyu vyazkost' ugleplasticovna osnovie posiamida-6. Resursozberegaucsie technologii: vozobnovleniye I economia energii, syria I materialov: abstracts of the fourth international scientific and technical conference. Grodno: Grodnietskoye otdelenie belorusskoy ingenerno-technicheskoy akademii, 42-43.

[4] Thomas G. P. Recycling of High-Density Polyethylene (HDPE or PEHD). Saved from URL: https://www.azocleantech.com/article.aspx?ArticleID=255

[5] Starke L., Braginsky, V. 1987. Ispolzovanie promyshlennyh I bytovyh othodov plasmas. Leningrad: Khimiya. 176.

[6] Bortnikov V. G. 1993. Osnovy technologii I pererabotki plasticheskich. Uchebnoye posobiye dlia vuzov. Himia, Donetsk. p. 304.

[7] Burya A. I., Chigvintseva O. P., Burmisrt M. V. 2000. Pererabotka, svoystva I primeneniye kompositnych materialov na osnove poliamidov. Voprosy himii i himicheskoy technologii. 3: 36-41.

[8] Scaled Composites. [Electronic source]. Access mode: www.scaled.com. The date of last review: 02/20/2019.

[9] CHP «Ava Plast». [Electronic source]. Access mode: https://avaplast.com.ua/p541125251-polietilen-500-list.html. The date of last converting: 02/20/2019.

[10] Makarenko D. O. 2018. Pidvyschenia dovgovichnosti paralelogramnogo mechnizmu posivnych komplexiv zminou konstrukcii ruchomych zjednan'. Athors' abstract, candidate of tech. science: 05.05.11 / Makarenko Dmytro Oleksandrovych; Centralnoukr. nac. tech. un-t. - Kropyvnytski, 20.

[11] Sytar V. I., Burmistr M. V., Kabat O. S. 2011. Promyslova ecologia pry vyrobnytstvi ta pererobci polimernych materialiv. Dnipropetrovsk: DVNZ UDHTU. 117.

[12] Francesco La Mantia. 2006. Handbook of plastic recycling. Parpa Technology Limited, Shawbury, Shewsbury, Shropshire, SY4 4NR, United Kingdom. 421.

[13] Kabat O., Sytar, V., Sukhyy K. 2018. Antifrictional polymer composites based on aromatic polyamide and carbon black. Chemistry & Chemical Technology. 12(3): 326-330.

[14] Kabat O. S., Kobelchuk Y. M., Chervakov D. O., Chervakov O. V. 2018. Polymer composite materials with a high level of thermal stability based on phenolic resins and disperse silica fillers. Science, Technologies, Innovations. 2(6): 48-53.

[15] Burya A. I., Kuznetsova O. Yu., Derkach A. D., Sergiyenko V. P., Bukharov S. N. 2013. Investigation of fullerene C 60 influence on tribotechnical and dynamical mechanical properties of composite materials based on phenilon. 5th World Tribology Congress, WTC 2013. P. 1070-1073 / 2013 | conference-paper/ EID 2-s2.0-84919696818.

[16] Burya A. I., Kozlov H. V. 2007. Mechanisms of yield of carbon-reinforced plastics based on high-density polyethylene. Materials Science.

[17] Kulgeiko M. P., Tsarenko I. V. 2018. Polimernye kompozitsionnye materialy v obrazovatel'noy programme podgo-tovki inzhenera-mashinostroitelya [The polymer composite materials in study program for machine-building engineer]. Polimernye materialy

i tekhnologii [Polymer Materials and Technologies]. 4(2): 70-76.

[18] Burmistr M. V., Boiko V. S., Lipko O. O., Gerasimenko K. O., Gomza Yu. P., Vesnin R. L., Chernyayev A. V., Ananchenko B. A., Kovalenko V.L. 2017. Antifriction and construction materials based on modified phenol-formaldehyde resins reinforced with mineral and synthetic fibrous fillers. Mechanics of Composite Materials. 50(2): 213-222.