The Use of Products of Microwave Aminolytic Destruction of Polyethylene Terephthalate in Vibration-absorbing Polymer Composite Materials

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Abstract: The aim of this work is to study the possibility of using the products of aminolytic destruction of polyethylene terephthalate (PET) and their derivatives in polymer composite materials with vibration-absorbing properties, which provide effective damping of vibrations of technogenic and natural origin in a wide temperature and frequency range. The paper considers a modern method of recycling PET waste with a mixture of amino alcohols - monoethanolamine and triethanolamine, taken in two different ratios. As a result of the destruction reaction, terephthalic acid diamide (N, N'-bis (2-hydroxyethyl) terephthalamide) is formed. To accelerate the destruction process, microwave radiation of various powers of 200, 540 and 700 watts was used. The optimal conditions for aminolytic decomposition of PET were determined: the time and power of microwave radiation with PET conversion up to 95% and the yield of the target product (terephthalic acid diamide) 80-85%. The destruction process was carried out according to a closed cycle of using reagents, without the use of catalysts and at atmospheric pressure, which to a certain extent reduces the energy consumption and increases the environmental friendliness of this method of PET decomposition. The aminolytic degradation product of PET (terephthalic acid diamide) was used as a monomer in the polycondensation reaction to obtain a new oligomer (terephthalic acid oligoesteramide). The degree of polymerisation (n) is in this case 7 to 11 (number of chain links). The obtained oligomer and the PET degradation product were investigated as new components in elastomeric compositions based on chloroprene rubber and in compositions based on thermoplastic elastomers. It has been demonstrated that the introduction of an oligomer based on a PET degradation product reduces the viscosity of elastomeric compositions by 25-35%. The study was supported by a grant from the Russian Science Foundation No. 21-79-00301, https://rscf.ru/project/21-79-00301/.

Keywords: aminolysis, PET, microwave radiation, chloroprene rubber, vibration absorption

1. Introduction

The processing of household or industrial solid waste of polyethylene terephthalate (PET) attracts more and more attention every year. This is due not only to the desire to reduce the environmental load on the environment, but also to the fact that PET processing products can be used in various industries [1], including as fillers or additives to vibration-absorbing materials operating in a wide temperature range.

Currently, there are several main methods for recycling PET waste: landfill, mechanical recycling (shredding and reuse), chemical recycling and incineration [2-5].

Chemical processing is one of the processing methods by chemical modification or deconstruction of polymer macromolecules. There are several solvolytic methods that are effective for PET deconstruction. These methods are: alcoholysis (reaction with alcohol) [6-11]; aminolysis (reaction with amines) [12-15]; ammonolysis (reaction with ammonia) and hydrolysis (reaction with water) [16-19].

The obtained compounds can be used as additives in asphalts and bitumen [20 - 22]; as a modifying or

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Mater. Plast., 59 (1), 2022, 8-17 8 https://doi.org/10.37358/MP.22.1.5555
crosslinking additive in epoxy resins [23-25], to obtain protective coatings [26-28]; as one of the components of polyurethanes [29-32] and so on.

Solvolitic methods of PET destruction can proceed under various conditions, with and without catalysts [33-37]. Destruction methods using microwave radiation instead of convective heating are of particular interest. Microwave radiation allows destruction processes to be carried out several times faster than with convective heating. This is primarily due to the fact that all reacting components in PET degradation reactions are polar compounds [38-42].

The obtained materials can be used as fillers for vibration-absorbing materials operating in a wide temperature range and used in transport [43-45] and in construction [46-48].

The aim of this work is to study the process of aminolytic destruction of PET waste under microwave radiation of various power. The effect of aminolytic degradation products of PET and their derivatives on sulfur vulcanization and elastic-strength properties of vibration-absorbing composite materials based on chloroprene rubber has been studied.

2. Materials and methods

For PET destruction, a mixture of amino alcohols was used - monoethanolamine (MEA) technical (TU 2423-159-00203335-2004) and triethanolamine (TEA) (TU 2423-168-00203335-2007) produced by Kazanorgsintez PJSC. PET waste is shredded plastic bottles without labels, with a particle size of 5x5 mm.

Study of the effect of the degradation product of PET and its derivatives of wires in formulations based on chloroprene rubber of three types of crystallization (controlled by mercaptans) CR121, CR232 and CR244, made in China, Shanxi Synthetic Rubber Group Co. Ltd. The formulations of model rubber compounds are presented in Table 1.

| Ingredients                        | Mass parts per 100 mass parts of rubber, mass.p. |
|------------------------------------|-----------------------------------------------|
|                                    | 1 (CR232) | 2 (CR244) | 3 (CR121) |
| Rubber                             | 100       | 100       | 100       |
| Magnesium oxide                    | 4         | 4         | 4         |
| Zinc oxide                         | 5         | 5         | 5         |
| Sulfur                             | 1         | 1         | 1         |
| Tetrathiomethylthiuram disulfide   | 1         | 1         | 1         |
| Diphenylguanidine                  | 1         | 1         | 1         |
| Carbon black (P 803)               | 40        | 40        | 40        |
| Total                              | 160       | 160       | 160       |

Three mixtures with different brands of rubbers differing in the rate of crystallization were taken as basic.

Rubber mixtures were made on a laboratory micro-mixer with a loading chamber volume of 0.1 l (manufactured by Polimermash Group LLC).

The vulcanization characteristics were measured using the Moving Die Rheometer equipment manufactured by Prescott Instruments Ltd. Mooney viscosity was determined on a Mooneyline MV Variable Speed rotational viscometer, Prescott Instruments Ltd. The determination of the elastic-strength properties was carried out on an AG-X 5 kN tensile testing machine, manufactured by Shimadzu.

The studies of the manufactured rubbers were carried out according to standard methods in accordance with GOST: removal of the vulcanization characteristics of rubber compounds (GOST 12535-84), determination of the viscosity of the crude rubber mixture according to Mooney on a rotary viscometer (GOST 10722-76), elastic-strength properties (GOST 270-75), rubber hardness according to Shore A (GOST 263-75), tests for accelerated aging and heat resistance (GOST ISO 188-2013).
3. Results and discussions

3.1. Kinetics of aminolytic destruction of polyethylene terephthalate by microwave radiation

The laboratory setup for the aminolytic destruction of PET was based on a household microwave oven with the ability to control the microwave radiation power (Figure 1). The main major design change is the ability to connect a reflux condenser to a reaction flask inside the microwave.

Aminolytic destruction of PET particles (particle size 5x5 millimeters) was carried out in a mixture of amino alcohols in a ratio of 1: 4: 5 and 1: 3: 4, respectively, for PET: MEA: TEA. The choice of these ratios of amino alcohols is due to the need for a sufficient amount of amino alcohols to degrade PET particles. PET weight in these cases is 10 g. The kinetics of PET destruction at different microwave power (220, 540 and 700 watts) and two component ratios are shown in Figures 2 and 3.

The yield of BHETA was calculated using (1):

\[
\text{Yield}_{\text{BHETA}}(\%) = \frac{M_{\text{BHETA}}}{M_{\text{BHETA}_0}},
\]  

where \(M_{\text{BHETA}}\) and \(M_{\text{BHETA}_0}\) are the experimental weight of BHETA and the theoretical weight of BHETA that would be produced upon complete decomposition of PET, respectively.
From the data presented in Figure 2, it can be seen that the maximum product yield, 85%, is achieved with a reaction time of 6 min and a microwave power of 540 W. With a longer time of exposure to microwave radiation under these conditions, the product yield decreases due to significant evaporation of the reaction mass (a mixture of amino alcohols) and its presence at the junction of the reflux condenser and the reaction flask in the form of vapors.

When using a power of 220 W, the highest product yield (84%-86%) is achieved at 8 min of reaction, which is associated with a slow heating of the reaction mixture and a decrease in the rate of evaporation of the mixture of amino alcohols.

The use of a radiation power of 700 W is impractical due to too rapid heating, boiling and evaporation of the reaction mass. The contact time of the mixture of amino alcohols with PET particles is short, which leads to a lower product yield (up to 74%).

When the ratio of the components is 1:3:4, there is a general decrease in the yield of the target product at all utilized capacities (Figure 3). In this case, the maximum product yield reaches only 74%. The decrease in the product yield is due to the absence of MEA in the mixture of amino alcohols, which, under the action of microwave radiation, especially at a power of 700 W, evaporates very quickly and does not have time to completely condense when it enters the reverse condenser. As a consequence of this, the concentration of MEA in the reaction mass decreases very quickly.

After the destruction process, the resulting product was purified by double recrystallization from hot water. The products obtained were identified by NMR analysis (\(^1\)H and \(^{13}\)C), gas chromatography-mass spectrometry (at a temperature of 500°C) and FT-IR spectroscopy.

![Figure 3. Kinetics of PET destruction at a component ratio of 1:3:4 (PET:MEA:TEA)](image)

3.2. Obtaining an oligomer based on a PET degradation product

The PET degradation product (terephthalic acid diamide) was used as a monomer in the polycondensation reaction to obtain an oligomer. The reaction was carried out in the temperature range from 200 to 215°C, with evacuation to remove reaction by-products (ethanolamine). Phosphoric acid was used as a catalyst.

As a result of the reaction, a light yellow resinous substance was obtained, which crystallizes upon cooling, with a slight odor of amino alcohols. The color and odor of the resulting product is due to incomplete removal of polycondensation by-products of terephthalic acid diamide, namely mono-ethanolamine.

The resulting oligomer is soluble in highly polar solvents - dimethyl sulfoxide and dimethylformamide; has a good ability to stretch into fibers (up to several meters) in a warm and hot state. The
melting point of the resulting product is in the range from 75 to 80°C.

3.3. Chloroprene rubber compounds
Rubber compounds based on three types of chloroprene rubbers with different crystallization rates were made in accordance with the formulations shown in Table 2.

| Table 2. Chloroprene rubber based rubber formulations |
|------------------------------------------------------|
| Ingredients                                           | The rubber compound of the masses, part |
|                                                      | 4 | 5 | 6 | 7 | 8 | 9 |
| Rubber                                                | 100 |
| Magnesium oxide                                       | 4 |
| Zinc oxide                                            | 5 |
| Sulfur                                                | 1 |
| Tetramethyli thiuram disulfide                        | 1 |
| Diphenylguanidine                                     | 1 |
| Carbon black (P 803)                                  | 39 |
| BHETA                                                 | 1 |
| oATPA                                                 | - |
| Total                                                 | 152 |

Note:
*BHETA is a product of aminolytic degradation of PET
** oATPA - oligomer based on PET degradation product

Rubber compounds 4 and 7 are made on the basis of CR232 rubber; mixtures 5 and 8 - CR244; mixtures 6 and 9 - CR121.

3.4. Kinetics of vulcanization of rubber compounds
First of all, the influence of terephthalic acid diamide and an oligomer based on it on the kinetics of sulfur vulcanization of rubber compounds was considered. Table 3 presents data on the key vulcanization characteristics of sulfur vulcanization of the investigated rubbers T₁₀, T₅₀ and T₉₀.

| Table 3. The duration of the periods of vulcanization of rubber compounds |
|------------------------------------------------------------------------|
| Parameter | Modeling | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| T₁₀, s     |          | 87 | 75 | 74 | 91 | 60 | 84 | 93 | 84 | 69 |
| T₅₀, s     |          | 220 | 226 | 148 | 265 | 229 | 149 | 278 | 242 | 158 |
| T₉₀, s     |          | 1107 | 967 | 833 | 1082 | 953 | 797 | 1094 | 961 | 723 |

According to the data in Table 3, it can be seen that the accelerating effect on the sulfur vulcanization process was observed in almost all cases with the addition of terephthalic acid diamide and an oligomer based on it, which is especially clearly seen in the T₉₀ parameter. In mixtures with the addition of the PET degradation product, T₉₀ decreased by 1.5-4%, and in mixtures with the addition of an oligomer based on terephthalic acid diamide, T₉₀ decreased by 0.5-13%. The strongest reduction in T₉₀ was observed in mixture 9 - by 13.2% (reduction in vulcanization time by 2 min).

Such an accelerating effect on the sulfur vulcanization process may be due to the fact that the added ingredients (terephthalic acid diamide and oligomer based on it) are alkaline in nature. In the case of parameters T₁₀ and T₅₀, a slight (within 5%) slowdown of the process was observed, which leads to an increase in the induction period of vulcanization.

3.5. Elastic-strength properties of the obtained rubbers
Subsequently, the viscosity of raw rubber mixtures, as well as the elastic-strength characteristics of vulcanizates, were investigated. The vulcanization of rubbers took place at the optimum vulcanization at a temperature of 160°C for 15-17 min.
In addition, in addition to the main elastic-strength properties of rubbers, the influence of terephthalic acid diamide and an oligomer based on it on the aging process of rubbers was evaluated. Table 4 shows data on the viscosity of raw rubber compounds, as well as some indicators of elastic-strength properties of rubbers before and after thermal aging for 24 h.

**Table 4. Elastic-strength characteristics of vulcanizates before and after thermal aging**

| Indicator / rubber compound | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|---------------------------|----|----|----|----|----|----|----|----|----|
| Viscosity, Mooney units   | 69 | 90 | 79 | 70 | 83 | 75 | 70 | 79 | 72 |
| Hardness, Shore A         | 89 | -  | 51 | 102| -  | 32 | 77 | -  | 39 |
| fp, MPa                   | 20.1| 24.7| 18.8| 20.6| 23.5| 18.1| 21.7| 25.9| 18.9|
| εp, %                     | 330| 210| 240| 310| 240| 290| 350| 280| 310|
| Stress at 100%, MPa       | 4.3| 12.8| 7.2| 5.2| 10.7| 5.6| 4.5| 9.8| 5.13|
| Stress at 200%, MPa       | 10.7| 22.3| 16.3| 12.9| 21.5| 12.5| 11.2| 21.0| 11.7|
| After aging (24 h at 100°C) | | | | | | | | |
| fp, MPa                   | 19.1| 21.7| 16.6| 20.2| 24.0| 17.7| 20.1| 21.5| 17.9|
| εp, %                     | 290| 220| 260| 360| 300| 260| 310| 270| 270|

From the data in Table 4 (study of elastic-strength properties) it can be seen that with the addition of terephthalic acid diamide, no significant changes in the relative strength at break were observed, this indicator remained at the level of the base mixtures of comparison. However, the addition of this component had an effect on the elongation at break: an increase in this indicator was observed for mixtures 5 and 6, especially in the case of the latter mixture, the increase was more than 50%.

In the case of using an oligomer based on terephthalic acid diamide, the relative strength of mixtures based on chloroprene rubbers CR232 and CR244 increased, and in the case of CR121 rubber it remained comparable to the base mixture. The relative elongation at break of the studied mixtures in all three cases increased by 20 to 70%, which indicates the plasticizing effect of the obtained oligomer.

In addition, the plasticizing effect of the obtained oligomer is confirmed by the data on the viscosity of rubber compounds. The viscosity of crude rubber compounds 7 and 9 is reduced by 13 and 24%, respectively.

Comparing the elastic-strength parameters of the obtained vulcanizates before and after aging, we can say that in some cases (mixtures of 4 and 5 with the addition of terephthalic acid diamide), an increase in the elongation at rupture of vulcanizates after aging was observed by 49 and 65%, respectively.

The conditional tensile strength after aging in vulcanizates with the addition of terephthalic acid diamide decreased to a lesser extent in comparison with the model mixtures: the decrease in the conventional strength at break in model mixtures is about 13%, in mixtures with the addition of terephthalic acid diamide 2%. This may be due to the fact that terephthalic acid diamide acts as an inhibitor of the thermooxidative process of chloroprene rubber due to the presence of an amide group.

### 4. Conclusions

The process of aminolytic destruction of polyethylene terephthalate waste was studied under microwave radiation of different power and with different use of components. The most optimal conditions for PET destruction under microwave radiation with a product yield of 82-85% and a destruction time of 4-6 min have been revealed.

The possibility of using the product of aminolytic destruction of PET and its oligomer in new ingredients as vibration-absorbing composite materials based on chloroprene rubber is considered. Some elastic-strength characteristics and the nature of their change with the addition of new ingredients. It was revealed that the new ingredients slightly accelerate the process of sulfur vulcanization of rubbers based on chloroprene rubbers; have a plasticizing effect on the studied vulcanizates, and can also act as inhibitors of thermo-oxidative processes.
A more detailed consideration of the influence of the new results obtained on the basis of polar rubbers and thermoplastics on the physicochemical and physicomechanical parameters is proposed.

Acknowledgments: The study was supported by a grant from the Russian Science Foundation No. 21-79-00301. https://rscf.ru/project/21-79-00301

References
Please completely adapt your references as the following formats:
1. YUN, X., XIN-YI, Y., DUN-HONG, G., YONG-BO, D., LIANG, S., Preparation and characterization of waterborne alkyd-amino baking coatings based on waste polyethylene terephthalate. Royal Society open sci., 7(1), 2020, 191447. DOI: 10.1098/rsos.202375
2. VESNIN, R.L., ALALYKIN, A.A., VOKHMYANIN, M.A., Technology of recycling polyethylene terephthalate waste to obtain terephthalic acid amide. Proceedings of higher educational institutions. Chemistry and Chemical Technology, 63 (2), 2020. DOI: 10.6060/ivkt.2020602.6055
3. AL-SABAGH, A. M., YEHIA, F. Z., ESHAQ, G., RABIE, A. M., ELMETWALLY, A. E., Greener routes for recycling of polyethylene terephthalate. Egyptian Journal of Petroleum, 25(1), 2016, 53-64. https://doi.org/10.1016/j.ejpe.2015.03.001
4. JAMDAR, V., KATHALEWAR, M., SABBONIS, A., Depolymerization study of PET waste using aminoethylethanolamine and recycled product application as polyesteramide synthesis. Journal of Polymers and the Environment, 26(6), 2018, 2601-2618. https://doi.org/10.1007/s10924-017-1149-4
5. LOGINOVA, A., TISHIN, D., KASIANOVA, O., Modern methods of recycling polyethylene terephthalate and the field of application of the materials obtained. In Globalization of Environmental Issues: Past, Present and Future, 2017, (pp. 221-221).
6. SPASOJEVIĆ, P. M., PANIĆ, V. V., DŽUNUZOVIĆ, J. V., MARINKOVIĆ, A. D., WOORTMAN, A. J. J., LOOS, K., POPOVIĆ, I. G., High performance alkyd resins synthesized from postconsumer PET bottles. RSC Advances, 5(76), 2015, 62273-62283. DOI: 10.1039/C5RA11777A
7. SCREMIN, D. M., MIYAZAKI, D. Y., LUNELLI, C. E., SILVA, S. A., ZAWADZKI, S. F., PET recycling by alcoholysis using a new heterogeneous catalyst: study and its use in polyurethane adhesives preparation. In Macromolecular Symposia, 2019, Vol. 383, No. 1, p. 1800027. https://doi.org/10.1002/masy.201800027
8. ZHOU, L., LU, X., JU, Z., LIU, B., YAO, H., XU, J., ZHANG, S., Alcoholysis of polyethylene terephthalate to produce diocyl terephthalate using choline chloride-based deep eutectic solvents as efficient catalysts. Green Chemistry, 21(4), 2019, 897-906. https://doi.org/10.1039/C8GC03791D
9. ZHOU, X., WANG, C., FANG, C., YU, R., LI, Y., LEI, W., Structure and thermal properties of various alcoholysis products from waste poly (ethylene terephthalate). Waste management, 85, 2019, 164-174. https://doi.org/10.1016/j.wasman.2018.12.032
10. LI, Y., LI, M., LU, J., LI, X., GE, M., Decoloration of waste PET alcoholysis liquid by an electrochemical method. Water Science and Technology, 77(10), 2018, 2463-2473. https://doi.org/10.2166/wst.2018.191
11. LINLIN, D. Y. M. Y. Z., Study on the chemical recycling technologies on hydrolysis and alcoholysis of PET waste [J]. Plastics Manufacture, 7, 2011.
12. TEO TIA, M., TARANNUM, N., SONI, R. K., Depolymerization of PET waste to potentially applicable aromatic amides: Their characterization and DFT study. Journal of Applied Polymer Science, 134(31), 2017, 45153. https://doi.org/10.1002/app.45153
13. PANFILOV, D.A., DVORKO, I.M., Chemical destruction of secondary polyethylene terephthalate as a method for producing polymer modifier resins. Scientific almanac, (3-2), 2018, 183-186.
14. TAWFIK, M. E., ESKANDER, S. B. Chemical recycling of poly (ethylene terephthalate) waste using ethanolamine. Sorting of the end products. Polymer Degradation and Stability, 95(2), 2010, 187-194. https://doi.org/10.1016/j.polymdegradstab.2009.11.026
15. PARAB, Y. S., SHUKLA, S. R., Novel synthesis, characterization of N1, N1, N4, N4-tetraakis (2-hydroxyethyl) terephthalamide (THETA) and terephthalic Acid (TPA) by depolymerization of PET bottle waste using diethanolamine. *Journal of Macromolecular Science, Part A*, 50(11), 2013, 1149-1156. https://doi.org/10.1080/10601325.2013.830044

16. AGUADO, A., MARTINEZ, L., BECERRA, L., ARIETA-ARAUNABEÑA, M., ARNAIZ, S., ASUETA, A., ROBERTSON, I., Chemical depolymerisation of PET complex waste: hydrolysis vs. glycolysis. *Journal of Material Cycles and Waste Management*, 16(2), 2014, 201-210. DOI 10.1007/s10163-013-0177-y

17. MALIK, N., KUMAR, P., SHRIVASTAVA, S., GHOSH, S. B., An overview on PET waste recycling for application in packaging. *International Journal of Plastics Technology*, 21(1), 2017, 1-24.

18. SINGH, V., PATEL, M. R., PATEL, J. V. PET waste management by chemical recycling: a review. *Journal of Polymers and the Environment*, 18(1), 2010, 8-25. https://doi.org/10.1007/s10924-016-9164-1

19. SINGH, S., SHARMA, S., UMAR, A., MEHTA, S. K., BHATTI, M. S., KANSAL, S. K., Recycling of waste poly (ethylene terephthalate) bottles by alkaline hydrolysis and recovery of pure nanospindle-shaped terephthalic acid. *Journal of nanoscience and nanotechnology*, 18(8), 2018, 5804-5809. https://doi.org/10.1166/jnns.2018.15363

20. SREERAM, A., LENG, Z., PADHAN, R. K., QU, X., Eco-friendly paving materials using waste PET and reclaimed asphalt pavement. *HKIE Transactions*, 25(4), 2018, 237-247. https://doi.org/10.1080/1023697X.2018.1534617

21. PADHAN, R. K., MOHANTA, C., SREERAM, A., GUPTA, A., Rheological evaluation of bitumen modified using antistripping additives synthesised from waste polyethylene terephthalate (PET). *International Journal of Pavement Engineering*, 21(9), 2020, 1083-1091. https://doi.org/10.1080/10298436.2018.1519192

22. MERKEL, D. R., KUANG, W., MALHOTRA, D., PETROSSIAN, G., ZHONG, L., SIMMONS, K. L., COSIMBESCU, L., Waste PET chemical processing to terephthalic amides and their effect on asphalt performance. *ACS Sustainable Chemistry & Engineering*, 8(14), 2020, 5615-5625. https://doi.org/10.1021/acssuschemeng.0c00036

23. DĘBSKA, B., LICHOŁAI, L., The effect of the type of curing agent on selected properties of epoxy mortar modified with PET glycolisate. *Construction and Building Materials*, 124, 2016, 11-19.

24. DĘBSKA, B., LICHOŁAI, L. The selected mechanical properties of epoxy mortar containing PET waste. *Construction and Building materials*, 94, 2015, 579-588. https://doi.org/10.1016/j.conbuildmat.2016.07.085

25. DĘBSKA, B., LICHOŁAI, L., SZYSZKA, J., Innovative composite on the basis of an aerogel mat with an epoxy resin modified with PET waste and PCM. *In E3S Web of Conferences*, Vol. 44, p. 00031, 2018. EDP Sciences. https://doi.org/10.1051/e3sconf/20184400031

26. MORE, A., MHASKE, S., Epoxy-based anticorrosive coating developed with modified poly (o-anisidine) and depolymerized product of PET waste. *Iranian Polymer Journal*, 27(6), 2018, 359-370. https://doi.org/10.1007/s13726-017-0589-y

27. SAIDI, N. M., SHAFAMRI, A. S., MA, I. A. W., KASI, R., BALAKRISHNAN, V., SUBRAMANIAM, R., Development of anti-corrosion coatings using the disposable waste material. *Pigment & Resin Technology*, 2018. https://doi.org/10.1108/PRT-03-2018-0030

28. YUN, X., XIN-YI, Y., DUN-HONG, G., YONG-BO, D., LIANG, S., Preparation and characterization of waterborne alkyd-amino baking coatings based on waste polyethylene terephthalate. *Royal Society open science*, 7(1), 2020, 191447. https://doi.org/10.1098/rsos.191447

29. SADEGHI, G. M., SHAMSII, R., SAYAF, M., From aminolysis product of PET waste to novel biodegradable polyurethanes. *Journal of Polymers and the Environment*, 19(2), 2011, 522-534. https://doi.org/10.1007/s10924-011-0283-7

30. SADEGHI, G. M., SAYAF, M., From PET waste to novel polyurethanes. *Material Recycling–Trends and Perspectives*, 2012, 357-390.
31. STOJILJKOVIC, D. T., B-SIMENDIC, J. K., Glycolized products from PET waste and their application in synthesis of polyurethane dispersions. Progress in organic coatings, 74, 2012, 115-124. https://doi.org/10.1016/j.porgcoat.2011.11.024
32. LUO, X., LI, Y., Synthesis and characterization of polyols and polyurethane foams from PET waste and crude glycerol. Journal of Polymers and the Environment, 22(3), 2014, 318-328. DOI 10.1007/s10924-014-0649-8
33. PALEKAR, V. S., SHAH, R. V., SHUKLA, S. R., Ionic liquid-catalyzed aminolysis of poly (ethylene terephthalate) waste. Journal of applied polymer science, 126(3), 2012, 1174-1181. https://doi.org/10.1002/app.36878
34. SHOJAEI, B., ABTAHI, M., NAJAFI, M., Chemical recycling of PET: A stepping-stone toward sustainability. Polymers for Advanced Technologies, 31(12), 2020, 2912-2938. https://doi.org/10.1002/pat.5023
35. FUKUSHIMA, K., LECUYER, J. M., WEI, D. S., HORN, H. W., JONES, G. O., AL-MEGREN, H. A., HEDRICK, J. L., Advanced chemical recycling of poly (ethylene terephthalate) through organocatalytic aminolysis. Polymer Chemistry, 4(5), 2013, 1610-1616. https://doi.org/10.1039/C2PY20793A
36. WANG, Y., ZHANG, Y., SONG, H., WANG, Y., DENG, T., HOU, X., Zinc-catalyzed ester bond cleavage: Chemical degradation of polyethylene terephthalate. Journal of Cleaner Production, 208, 2019, 1469-1475. https://doi.org/10.1016/j.jclepro.2018.10.117
37. DELLE CHIAIE, K. R., MCMAHON, F. R., WILLIAMS, E. J., PRICE, M. J., DOVE, A. P., Dual-catalytic depolymerization of polyethylene terephthalate (PET). Polymer Chemistry, 11(8), 2020, 1450-1453. DOI: 10.1039/C9PY01920K
38. BÅCKSTRÖM, E., ODELIS, K., HAKKARAINEN, M., Ultrafast microwave assisted recycling of PET to a family of functional precursors and materials. European Polymer Journal, 151, 2021, 110441. https://doi.org/10.1016/j.europoly.2021.110441
39. ACHILIAS, D. S., TSINTZOU, G. P., NIKOLAIDIS, A. K., BIKIARIS, D. N., KARAYANNIDIS, G. P., Aminolytic depolymerization of poly (ethylene terephthalate) waste in a microwave reactor. Polymer International, 60(3), 2011, 500-506. https://doi.org/10.1002/pi.2976
40. PARAB, Y. S., PINGALE, N. D., SHUKLA, S. R., Aminolytic depolymerization of poly (ethylene terephthalate) bottle waste by conventional and microwave irradiation heating. Journal of applied polymer science, 125(2), 2012, 1103-1107. https://doi.org/10.1002/app.34855
41. SHAH, R. V., BORUDE, V. S., SHUKLA, S. R., Recycling of PET waste using 3-amino-1-propanol by conventional or microwave irradiation and synthesis of bis-oxazin there from. Journal of Applied Polymer Science, 127(1), 2013, 323-328. https://doi.org/10.1002/app.37900
42. PARK, R., SRIDHAR, V., PARK, H., Taguchi method for optimization of reaction conditions in microwave glycolysis of waste PET. Journal of Material Cycles and Waste Management, 22(3), 2020, 664-672. https://doi.org/10.1007/s10163-019-00958-7
43. KURZINA, E. G., KOLMAKOV, A. G., AKSENOV, YU. N., KURZINA, A. M., BOGACHEV, A. YU., SEMAK, A. V., Investigation of elastic-hysteresis properties of damping composite materials for railway transport at low temperatures under static and dynamic loading. Deformation and Fracture of Materials, 3(3), 2019, 43-48. DOI: 10.31044/1814-4632-2019-3-43-48
44. KURZINA, E. G., KOLMAKOV, A. G., AKSENOV, YU. N., KURZINA, A. M., BOGACHEV, A., YU., SEMAK, A. V. Comparative evaluation of composite materials for shock-absorbing elements of railway transport and rolling stock infrastructure. Deformation and fracture of materials, (12), 2018, 39-44. DOI: 10.31044/1814-4632-2018-12-39-44
45. KURZINA, E.G., KOLMAKOV, A.G., FILIPPOV, V.N., SEMAK, A.V., KURZINA, A.M., Damping composites made of materials with different elastic-hysteresis properties for railway sandwich shock absorbers. Materials Science, (1), 2020, 25-32. DOI: 10.31044/1684-579X-2020-0-1-25-32
46. ZHANG, J., YAO, D., SHEN, M., WANG, R., LI, J., & GUO, S., (2021). Effect of multi-layered IIR/EP on noise reduction of aluminium extrusions for high-speed trains. *Composite Structures*, 262, 2021, 113638. https://doi.org/10.1016/j.compstruct.2021.113638
47. LISANEVICH, M. S., GALIMZYANOVA, R. YU., KHAKIMULLIN, YU. N., Influence of petroleum resins and asphaltene-resinous substances on the properties of sealants based on butyl rubber. *Adhesives. Sealants. Technology*, (1), 2020, 14-17.
48. LISANEVICH, M. S., GALIMZYANOVA, R. Y., KHAKIMULLIN, Y. N., The Effect of Petroleum Resins and Asphaltene-Resin Substances on the Properties of Butyl Rubber Sealants. *Polymer Science, Series D*, 13(3), 2020, 270-273. https://doi.org/10.1134/S1995421220030120

Manuscript received: 3.11.2021