

Sustainable Transport Reliability: Exploring the Creep of Eco-Friendly Polymer Nanocomposites

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The paper presents research results on the creep of polymer composites containing organic tissues. It discusses the technology of forming functional polymer composites and protective coatings based on them, which exhibit enhanced operational characteristics for protecting means of transport. To create polymer materials, epoxy resin ED-20 was polymerized with the polyethylene polyamine (PEPA) hardener in the following ratio: ED-20 epoxy oligomer – 100 % and PEPA hardener – 10 %. In addition, to enhance the properties of epoxy composites and protective coatings, a nanofiller in the form of diaminoazobenzene carboxylic acid was incorporated into the binder. Micro-disperse fillers and organic tissues were also introduced. A synthesized powder titanium-aluminum charge was utilized as a microdispersion filler for experimental studies. The formation of the filler was achieved through high-voltage electric discharge synthesis, resulting in the production of high-modulus compounds such as Ti, Al₃Ti, and Ti₃AlC₂. Fabrics based on organic fibers were additionally used as fillers. Cotton fabrics with a thickness of $h = 1.5...2.0$ mm and linen fabrics with a thickness of $h = 1.5...1.7$ mm were employed in this study.

Keywords: Epoxy resin, Hardener, Nanopowder, Filler, Creep, Fabrics, Eco-Friendly composite, Sustainable transport.

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1. INTRODUCTION

An important characteristic of epoxy composite materials (CM) is their creep under the influence of static loads during vehicle operation. It should be noted that creep, which occurs during the operation of materials, leads to the deterioration of fundamental physical and mechanical properties of CM, such as the modulus of elasticity and destructive stresses in tension, compression, bending, torsion, impact toughness, cyclic and cohesive strength [1-8]. The creep of materials is significantly intensified when operating under the influence of aggressive environments with various physical properties. Additionally, it is worth noting that creep plays a pivotal role in assessing the impact of hydroabrasion on equipment durability and inter-repair service life.

It has been established [9] that the properties of the materials mentioned above can be improved, resulting in a reduction of creep under the influence of hydroabrasives, static loads, and temperature gradients. This improvement can be achieved by using epoxy composite 'hybrid' materials that incorporate continuous fibers of different physical natures and fabrics based on them. When forming composites with enhanced physical and mechanical properties, 'hybrid' CMs are commonly employed. In these composites, fibers are arranged in a regular alternation within a single material layer, or different types of fabrics are used for each composite layer. Glass, basalt, carbon, boron, and metal fibers or fabrics are often utilized for creating composites and protective coatings based on them. Additionally, it is interesting to analyze the

behavior of materials formed using an epoxy binder and organic fabrics, specifically linen and cotton, under critical operating conditions. With a developed raw material base, these materials are ecologically friendly and economically advantageous. Therefore, the formation of 'hybrid' CMs incorporating these fabrics and studying their properties, particularly in relation to creep, is of scientific and practical interest.

The authors [10-15] have demonstrated that using polymer CMs substantially enhances the physical and mechanical properties and the wear resistance of transportation components exposed to aggressive environments. Consequently, this significantly extends the service life of mechanisms and machines, contributing to their reliability [16-20]. Based on these findings, it can be affirmed that the investigation of the effects of static loads on the alteration of the physical and mechanical properties of materials during operation, while considering environmental safety concerns, stands as a critical objective in contemporary polymer materials science.

The purpose of this study is to investigate the creep characteristics of epoxy nanocomposites that incorporate environmentally safe fabrics of organic origin.

2. MATERIALS AND METHODS

2.1 Research Materials

The epoxy dian oligomer brand ED-20 (ISO 18280:2010) was selected as the primary

component for forming the binder. Figure 1 illustrates the structural formula of the ED-20 epoxy dian oligomer fragment [9]. As a nanofiller, 2,4-diaminoazobenzene-4'-carboxylic acid was employed. The molecular formula of the nanofiller is $C_{13}H_{12}N_4O_2$, and its structural formula is depicted in Fig. 2.

The epoxy compositions were polymerized using the polyethylene polyamine (PEPA) hardener, which enables curing at room temperatures. The molecular formula of the hardener is $[-CH_2-CH_2-NH-]_n$. Fig. 3 illustrates the structural formula of the PEPA hardener fragment [9, 15, 16].

To determine the optimal ratio of components for desired characteristics, different cross-linking stages were modeled and investigated by introducing the hardener into the composition at a content of 10 wt.% (based on 100 parts by weight of the epoxy oligomer ED-20).

The characteristics of the epoxy dian oligomer, nanofiller, and hardener are presented in Table 1.

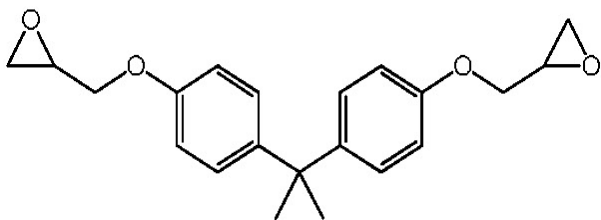


Fig. 1 – Structural formula of the ED-20 epoxy dian oligomer fragment

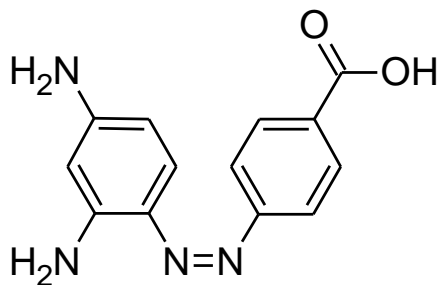


Fig. 2 – General view of the chemical bonds of the nanofiller 2,4-diaminoazobenzene-4'-carboxylic acid (DAABCA)

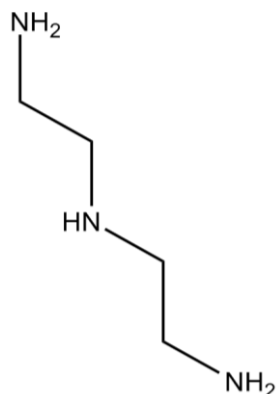


Fig. 3 – Structural formula of the PEPA hardener fragment

Additionally, in order to enhance the properties of epoxy composites and protective coatings, a micro-disperse filler and organic fabrics were incorporated into the binder. For experimental investigations, a synthesized titanium-aluminum powder charge was

used as the micro-disperse filler. The formation of the filler involved high-voltage electric discharge (HVED) synthesis, using a testing bench described in [16].

Table 1 – Characteristics of epoxy binder components

Characteristics	Epoxy oligomer ED-20	Nanofiller	PEPA hardener
Molecular weight	390...430	256	230...250
Epoxy group content, %	20.0...22.5	–	–
Hydroxyl group content, %	1.25	–	–
Average functionality by epoxy groups, f_n	2.0	–	–
Nitrogen content, %	–	21.86	19.5...22.0
Carbon content, %	–	60.93	–
Oxygen content, %	–	12.49	–
Hydrogen content, %	–	4.72	–
Viscosity, η , Pa s	13...20	–	0.9
Density, ρ , g/sm ³	1.16	–	1.05

The starting material for the HVED synthesis consisted of a powder mixture with the following initial composition: 15 % Al + 85 % Ti. The HVED synthesis process involved varying the distribution of the electric field and plasma formations within the discharge chamber [16]. During the study, a single discharge accumulated an energy of 1 kJ (W1), and the integral specific processing energy (ISPE) was 25 MJ/kg.

The research results demonstrated that as a result of the VER treatment, all treated particles underwent crushing, and their phase composition underwent changes, leading to the creation of high-modulus compounds such as Ti, Al_3Ti , and Ti_3AlC_2 (Table 2).

Table 2 – Results of HVED-synthesis of the filler

Initial composition n	Composition after processing	Electrode system m	Diameter after processing, d , μm		
			d_{min}	d_{max}	d_{mid}
Al (15 %) + Ti (85 %)	Ti (75 %) + Al_3Ti (15 %) + Ti_3AlC_2 (10 %)	3	~1	122	9,5

Fabrics based on organic fibers were used as fillers. Plant fibers primarily consist of cellulose. Cotton fibers contain 97.0 to 98.5 % cellulose. The length of cotton fiber ranges from 18 to 50 mm, and the diameter is $d = 15...25 \mu m$. Increasing the fiber length and reducing its thickness enhance its technological and operational

properties.

Flax fiber mainly comprises cellulose (77 to 80 %) and also contains higher amounts of pectin substances, lignin, and nitrogenous compounds compared to cotton. The maximum length of individual flax fibers is $l = 130...135$ mm, with an average size of $l = 17...20$ mm and a diameter ranging $d = 12...17$ μm .

It is worth noting that cotton quality depends on the length of the fibers obtained from seed cotton. Cotton is a relatively strong fabric, resistant to tearing and high temperatures. One of the distinctive characteristics of cotton is its high hygroscopicity, as it can absorb up to 20 % of moisture. Cotton enhances its tear resistance through mercerization and nearly eliminates its tendency to shrink.

Due to the natural origin of the raw materials, there is no doubt about the environmental friendliness of the moisture used. Additionally, flax fibers possess high thermal conductivity and air permeability. Linen fabrics are characterized by enhanced wear resistance and antistatic properties. It is also well-known that flax has antiseptic properties.

It should be noted that cleaned cotton and linen fibers have hygroscopic properties. They effectively absorb moisture from the air, and under normal atmospheric conditions (temperature: 20 °C, relative humidity: 65 %), cotton fibers contain 6 to 8 % moisture, while linen can contain up to 12%. Therefore, prior to using the fabric, it is necessary to subject it to heat treatment following the temperature-time parameters: heating for a duration of $\tau = 120$ to 140 minutes at temperatures of $T = 70$ to 80 °C.

Cotton and linen fibers are virtually impermeable to dyes in a dry state. However, they swell in liquid media, and the pore diameter can reach $d = 3$ to 7 nm. This facilitates the diffusion of dyes into the fiber volume and their interaction with active centers on the solid phase's surface.

In this work, cotton fabrics with a thickness of $h = 1.5$ to 2.0 mm and linen fabrics with $h = 1.5$ to 1.7 mm were used.

Epoxy composites were fabricated using the following process [9]:

- the resin was heated to a temperature of $T = 353 \pm 2$ K and maintained at this temperature for a duration of $\tau = 20 \pm 0.1$ min;
- a hydrodynamic combination of oligomer and modifier was performed for a duration of $\tau = 1 \pm 0.1$ min;
- ultrasonic treatment (USO) was conducted for a duration of $\tau = 1.5 \pm 0.1$ min;
- the mixture was cooled to room temperature over a period of $\tau = 60 \pm 5$ min;
- a hydrodynamic combination of binder and filler particles was carried out for a duration of $\tau = 10 \pm 0.1$ min;
- ultrasonic treatment (USO) was performed again for a duration of $\tau = 1.5 \pm 0.1$ min;
- the mixture was cooled to room temperature over a period of $\tau = 60 \pm 5$ min.
- hardener was introduced and mixed for a duration of $\tau = 5 \pm 0.1$ min.

The cured material (CM) underwent the following process:

- sample formation and maintenance for a duration

of $\tau = 12.0 \pm 0.1$ hours at a temperature of $T = 293 \pm 2$ K;

- heating at a rate of $v = 3$ K/min to a temperature of $T = 393 \pm 2$ K and maintaining that temperature for a duration of $\tau = 2.0 \pm 0.05$ hours;

- slow cooling to a temperature of $T = 293 \pm 2$ K.

To stabilize the structural processes in the matrix, the samples were kept in ambient air for a duration of $\tau = 24$ hours at a temperature of $T = 293 \pm 2$ K followed by experimental tests.

2.2 Research Methodology

The research focused on investigating the creep behavior of epoxy composites under load in atmospheric conditions, considering the operational requirements of technological equipment with protective coatings. The samples under study consisted of two layers of carefully chosen fabrics, with a modified epoxy composition containing a dispersed filler inserted between them. These samples were formed using a press, applying a load force of $F = 60$ H for a duration of $\tau = 72$ hours at a temperature of $T = 293 \pm 2$ K. This process resulted in the impregnation of the fabrics throughout their entire thickness. The samples had the following parameters: length $L = 120$ mm, width $b = 15$ mm, and height $h = 0.1$ to 0.2 mm. The formation scheme of the samples for investigating the creep of materials is illustrated in Fig. 4.

The creep of the cured material (CM) was investigated using the standard method outlined in ISO 899-2:2003. The study involved subjecting the CM to a static load of $F = 2$ H, as determined experimentally. The device used to examine the material creep is illustrated in Fig. 5. Throughout the investigation, the materials were observed over a period of $\tau = 72$ hours, during which the absolute deflection of the sample under load was measured at specific time intervals.

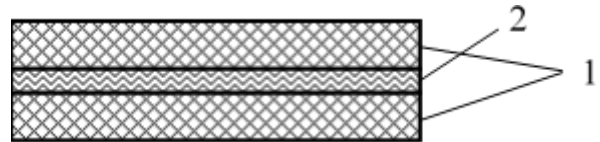


Fig. 4 – The scheme of forming samples for researching the creep of materials: 1 – cotton or linen fabric; 2 – modified epoxy composition with dispersed filler

The relative deformation of the samples was determined based on the values of the initial and final (or intermediate) value of the deflection of the sample (at the beginning and at the end of the study), according to the formula:

$$\varepsilon = \frac{l_k - l_n}{l_n} \cdot 100\%, \quad (2.1)$$

where: l_n is the absolute value of the deflection of the sample after loading at the beginning of the research; l_k is the absolute value of the deflection of the sample after loading at the end (or at an intermediate stage) of the studies.

The creep rate was determined by the formula:

$$V_n = \frac{\varepsilon(t_2) - \varepsilon(t_1)}{t_2 - t_1}, \quad (2.2)$$

where: $\varepsilon(t_2)$, $\varepsilon(t_1)$ are the value of the relative deformation of materials at time points t_1 and t_2 respectively.

The rate of recovery after creep was determined by the formula:

$$R = \frac{l_k - l(t)}{l_k - l_n} \cdot 100\%, \quad (2.3)$$

where: $l(t)$ is the absolute value of the deflection of the sample at the time point t .

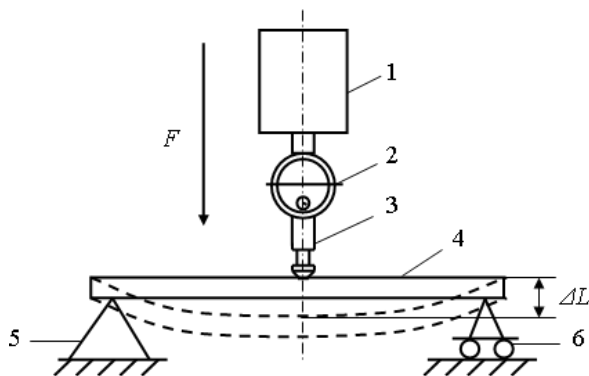


Fig. 5 – Scheme of the device for studying the creep of materials: 1 – carrying load; 2 – indicator; 3 – indenter; 4 – sample; 5 – fixed support; 6 – movable support

3. DISCUSSION OF RESEARCH RESULTS

It is well-established [9, 19, 20] that the physico-mechanical properties of CM, including creep and relaxation characteristics, are significantly influenced by the intermolecular interaction at the interface between the binder and filler phases during composite formation. The structural processes involved in composite formation are governed by the surface activity, chemical structure, and physical properties of the ingredients incorporated into the CM. Therefore, the application of "hybrid" composites exhibits great promise.

Hybrid composites offer a synergistic effect in enhancing material properties by combining dispersed and fibrous fillers. This approach ensures isotropic properties of the composites at the micro-level through the use of dispersed and active particles for interfacial interaction. Simultaneously, the inclusion of reinforcing additives in the form of fabrics introduces anisotropy to the materials at the macro level. This anisotropy increases creep indicators and destructive stresses during the bending and twisting of CM and, consequently, enhances their wear resistance.

Taking into account the information provided, as well as the results of previous tests, the creep characteristics of the following epoxy composites were investigated in this study:

– CM 1: This composite consists of an unmodified epoxy matrix based on dian resin ED-20 (100%) and a polyethylene polyamine hardener (10%);

– CM 2: This composite was formed with the following component ratio: epoxy binder: nanofiller (2,4-diaminoazobenzene-4'-carboxylic acid): microdisperse filler (synthesized titanium-aluminum charge: Ti (75 %) + Al_3Ti (15 %) + Ti_3AlC_2 (10 %) (diameter $d = 10...12 \mu\text{m}$) in a ratio of 100:1.0:0.5;

– CM 3: This composite was created by stacking two cotton fabrics (with a thickness of $h = 1.5...2.0 \text{ mm}$) impregnated with a composition described in CM 2;

– CM 4: This composite was formed by stacking two linen fabrics (with a thickness of $h = 1.5...1.7 \text{ mm}$) impregnated with the same composition described in CM 2.

Based on experimental findings (Fig. 6, Table 3), it was determined that the unmodified epoxy matrix (CM 1) exhibited a maximum deflection of $\Delta l = 0.6 \times 10^{-3} \text{ m}$ and a relative deformation of $\varepsilon = 45.9 \%$ during the initial stages of the study. However, the use of the CM 2 composite, which incorporates a modifier and a dispersed filler at an optimal content, resulted in a significant reduction in the maximum deflection relative to the epoxy matrix. The maximum deflection decreased by half, from $\Delta l = 0.6 \times 10^{-3} \text{ m}$ to $\Delta l = 0.27 \times 10^{-3} \text{ m}$. Additionally, the relative deformation during the study, under the selected temperature-time parameters, decreased by 1.4 times, from $\varepsilon = 45.9 \%$ to $\varepsilon = 33.3 \%$ (as shown in Table 3). These results indicate improved cohesive properties of the CM 2 composite compared to the original matrix, as observed during the initial stages of the creep study. Previous research [9, 15] has established that the incorporation of ingredients such as nanofillers or dispersed particles enhances the structure formation processes in composites. This enhancement is attributed to the presence of active centers, such as Al_3Ti and Ti_3AlC_2 , on the surface of the dispersed phase, as well as chemical groups including carbonyl C=O, carboxyl COOH-, hydroxyl -OH-, and side groups of primary amines - NNH_2 within the modifier's chemical structure. The interaction between these active centers/groups and the segments/side groups of the epoxy oligomer leads to improved cohesive strength in epoxy composites. Consequently, this contributes to the reduction of creep indicators, even during the initial stages of applying static loads.

In addition, it should be noted that the use of "hybrid" composites (CM 3, CM 4), which incorporate dispersed particles and fabrics in a combined manner, results in a significant decrease in the maximum deflection of the samples compared to the epoxy matrix by 3.3...6.6 times (from $\Delta l = 0.6 \times 10^{-3} \text{ m}$ to $\Delta l = (0.09...0.18) \times 10^{-3} \text{ m}$). Furthermore, the relative deformation during the study, under the selected temperature-time parameters, decreases by 1.7...1.9 times (from $\varepsilon = 45.9 \%$ to $\varepsilon = 24.3...26.2\%$) (Fig. 6, Table 3).

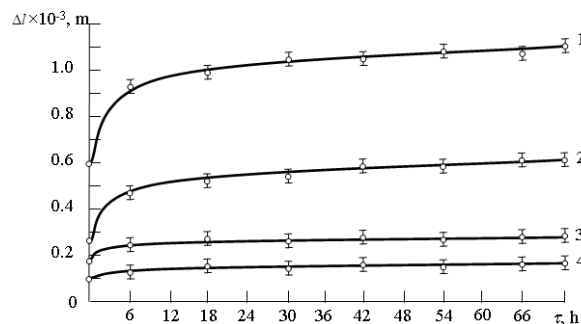


Fig. 6 – Dependence of the absolute deformation of the CM on the duration of exposure to a static load ($F = 2 \text{ H}$): 1 – CM 1; 2 – CM 2; 3 – CM 3; 4 – CM 4

It is worth noting that this improvement is attributed to the enhanced interphase interaction during the formation of the composite, facilitated by the presence of the modifier and dispersed particles on one hand, and the active centers on the surface of the fibers on the other hand. The latter also interacts with the macromolecules of the epoxy oligomer, contributing to additional crosslinking of the polymer binder. This increase in the gel fraction within the heterogeneous systems improves their cohesive properties and, consequently, enhances the creep resistance of the investigated epoxy "hybrid" composites.

Table 3 – Characteristics of CM creep

Sample No	The absolute value of the sample deflection after the initial load, $\Delta l \times 10^{-3}$, m	Relative deformation, ε , %	Creep speed, $V_n \times 10^{-4}$, %/h ($\tau = 30$ h)	Recovery index after creep, R , % ($\tau = 60$ min)
CM 1	0.60	45.9	3.9	20
CM 2	0.27	33.3	3.0	48
CM 3	0.18	26.2	2.4	62
CM 4	0.09	24.3	2.0	69

Later, during the analysis of the creep rate of the samples, it was found that the composites exhibited deformation throughout the entire duration of the study (Fig. 7). The high rate of creep indicates significant damage to the effective bonds within the structural network of the matrix. The maximum creep rate was observed at the time $\tau = 30$ h for all developed materials. Subsequently, the creep rate of the samples gradually decreased, indicating the establishment of an equilibrium state in the systems. This suggests that while there is partial bond destruction at the micro level, relaxation processes are simultaneously intensified at the macro level. These relaxation processes hinder the transition from elastic to plastic deformations, thereby enhancing the durability of the materials.

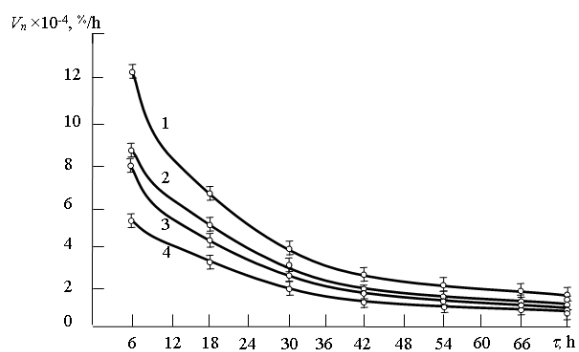


Fig. 7 – Dependence of the creep rate of CM on the duration of exposure to static load ($F = 2$ H): 1 – CM 1; 2 – CM 2; 3 – CM 3; 4 – CM 4

Additionally, it should be noted that within the selected research time parameters ($\tau = 30$ h), the sample based on the original epoxy matrix CM 1 exhibited the highest creep rate, with a value of $V_n = 3.9 \times 10^{-4}$ %/h. The formation of a composite using a modified epoxy resin and dispersed filler particles (CM 2) resulted in a

1.3-fold decrease in the matrix creep rate during the specified research time (from $V_n = 3.9 \times 10^{-4}$ %/h to $V_n = 3.0 \times 10^{-4}$ %/h). The incorporation of cotton fibers in the material significantly decelerated the creep of heterogeneous systems. It has been demonstrated (Fig. 7, Table 3) that for CM 3, within the selected research range, the creep rate decreased by 1.6 times compared to the matrix (from $V_n = 3.9 \times 10^{-4}$ %/h to $V_n = 2.4 \times 10^{-4}$ %/h). The composite containing dispersed particles and linen fabrics exhibited the minimum creep rate. Using such material reduced the creep rate by nearly 2.0 times compared to the epoxy matrix (from $V_n = 3.9 \times 10^{-4}$ %/h to $V_n = 2.0 \times 10^{-4}$ %/h).

As mentioned earlier, the addition of a fibrous filler enhances the cohesive properties of composites by altering the molecular mobility in the adsorption layer surrounding the fibers during the initial stages of composite formation. Simultaneously, the incorporation of a dispersed additive facilitates both chemical and physical interactions at the phase separation boundary, owing to the presence of active centers on the surface of particles, which leads to changes in the conformational arrangement of macromolecules in the matrix's surface layers surrounding the filler [17, 18]. This interaction is significantly enhanced through the pre-drying of fabrics according to predetermined temperature and time conditions, resulting in a subsequent reduction in the creep rate of the studied materials.

In order to confirm the above-mentioned results, the recovery index after creep of the developed composites was investigated in the study (Table 3, Fig. 8). After removing the load, the ability of the composites to restore their properties was determined. A low recovery value indicates a significant percentage of broken bonds in the network formed by the binder macromolecules. This results in significant plastic deformation of the samples. Therefore, it can be stated that the cohesive strength of systems made from such composites is low. On the other hand, restoring the initial shape of the samples after load removal indicates significant elastic properties, allowing us to assert their high cohesive characteristics. In this case, the composites are formed in which, under the influence of the applied load, they deform only in the elastic region (with minor plastic deformation) and are further characterized by high operational performance.

It was established (Table 3) that the minimum value of the recovery index after creep ($R = 20$ %) was observed for the epoxy matrix (CM 1). In our opinion, this is caused by a small percentage of the gel fraction in such materials. Using a modifier and a dispersed filler during the formation of CM helps to increase the recovery rate after the creep of epoxy composites by 2.4 times (from $R = 20$ % to $R = 48$ %).

It is demonstrated (Table 3) that the highest recovery characteristics (R) after load removal are exhibited by composites containing cotton and linen fabrics with a dispersed filler. The use of such materials results in a significant increase in this indicator compared to the unmodified matrix by 3.1...3.5 times (from $R = 20$ % to $R = 62$ to 69 %). This confirms the earlier assumption regarding the enhanced cohesive strength of these "hybrid" materials due to the combined

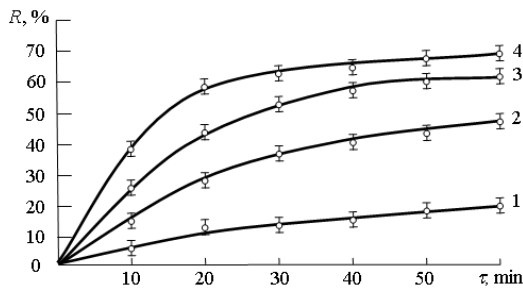


Fig. 8 – Dependence of the recovery index on the duration of exposure to a static load ($F = 2$ H): 1 – CM 1; 2 – CM 2; 3 – CM 3; 4 – CM 4

use of dispersed and fibrous fillers. It is worth noting that these findings are consistent with the results obtained from the analysis of the advanced composites' relative deformation and creep rate. Additionally, it can be concluded that after being subjected to a load for the entire study duration ($\tau = 72$ h), the presence of broken bonds at the phase separation boundary and within the volume of the composites is insignificant.

4. CONCLUSIONS

The development of modified "hybrid" materials incorporating both dispersed fillers and cotton or linen fabric leads to a significant reduction in the creep of epoxy plastics under static load conditions. It has been observed that the use of such composites, with a specific ratio of components including epoxy binder, nanofiller

(2,4-diaminoazobenzene-4'-carboxylic acid), and micro-disperse filler (synthesized titanium-aluminum charge: Ti (75 %) + Al_3Ti (15 %) + Ti_3AlC_2 (10 %), with the particle size of 10-12 μm) in a ratio of 100:1.0:0.5, along with the addition of two layers of cotton or linen fabric, improves the following creep indicators compared to the epoxy matrix under ambient air conditions:

- the maximum deflection of the composites is reduced by 3.3 to 6.6 times, ranging from $\Delta l = 0.6 \times 10^{-3}$ m to $\Delta l = 0.09$ to 0.18×10^{-3} m. Furthermore, the relative deformation during the research process, under the selected temperature-time parameters, decreases by 1.7 to 1.9 times, ranging from $\varepsilon = 45.9$ % to $\varepsilon = 24.3$ to 26.2 %;

- the creep rate of epoxy plastics is decreased by 1.6 to 2.0 times, ranging from $V_n = 3.9 \times 10^{-4}$ %/h to $V_n = 2.0$ to 2.4×10^{-4} %/h;

- the rate of recovery after creep is increased by 3.1 to 3.5 times, ranging from $R = 20$ % to $R = 62$ to 69 %.

The study demonstrated that incorporating dispersed fillers and fibrous fabrics in the polymer matrix resulted in notable improvements in various creep indicators. These included a significant reduction in maximum deflection, a decrease in creep rate, and an increase in recovery after creep. These findings suggest that these modified materials have the potential to enhance the durability and performance of eco-friendly composites, making them suitable for sustainable transportation applications. The study contributes to developing innovative materials that can contribute to more reliable and sustainable transport systems.

REFERENCES

1. M. Iurzenko, Y. Mamunya, G. Seytre, G. Boiteux, E. Lebedev, *e-Polymers* **11**, 25 (2011).
2. K.O. Dyadyura, L.F. Sukhodub, *Proceedings of the 2017 IEEE 7th International Conference on Nanomaterials: Applications and Properties, NAP 2017*, 04NB14 (2017).
3. V. Zaloga, K. Dyadyura, I. Rybalka, I. Pandova, T. Zabrowski, *MSPE* **4**, 28 (2020).
4. V. Zaloga, K. Dyadyura, I. Rybalka, I. Pandova, *MSPE* **4** (2019).
5. G. Hongbo, G. Jiang, H. Qingliang, T. Sruthi, Y. Xingru, H. Yudong, A.C. Henry, W. Suying, G. Zhanhu, *Indu. Eng. Chem. Res.* **52** (2013).
6. R.D. Brooker, A.J. Kinloch, A.C. Taylor, *J. Adhes.* **86**, 726 (2010).
7. L. Bilogurova, *Mat.-wiss. u. Werkstofftech* **40** No 4, 331 (2009).
8. M.R. Ayatollahi, E. Alishahi, R.S. Doagou, S. Shadlou, *Compos. Part B: Eng.* **43**, 3425 (2012).
9. O.O. Saponov, A.V. Buketov, P.O. Maruschak, S.V. Panin, M.V. Brailo, S.V. Yakushchenko, A.V. Saponova, O.V. Leshchenko, A. Menou, *Functional Materials* **1**, 26 (2019).
10. P. Valášek, R. D'Amato, M. Müller, A. Ruggiero, *Compos. Part B: Eng.* **146**, 88 (2018).
11. M. Milosevic, D. Dzunic, P. Valasek, S. Mitrovic, A. Ruggiero, *J. Compos. Sci.* **7** No 6, 204 (2022).
12. R.A. Kurien, D.P. Selvaraj, M. Sekar, R. Rajasekar, C.P. Koshy, *Mater. Sci. Forum* **1019**, 25 (2021).
13. F.Z. Alshammari, K.H. Saleh, B.F. Yousif, A. Alajmi, A. Shalwan, J.G. Alotaibi, *Tribology in Industry* **40** No 3, 335 (2018).
14. N. Barhoumi, A. Ghanem, M. Koudhai, K. Khelifi, Ali Terras Mohamed, *Exp. Polym. Lett.* **16** No 5, 476 (2022).
15. A. Buketov, M. Brailo, S. Yakushchenko, O. Saponov, V. Vynar, O. Bezbakh, R. Negrutza, *PPME* **63** No 3 171 (2019).
16. A.V. Buketov, O.M. Sizonenko, D.G. Kruglyj, T.V. Cherniavska, E.S. Appazov, K.M. Klevtsov, Ye.V. Lypian, *J. Eng. Appl. Sci.* **67**, No 7 (2020).
17. A.V. Buketov, P.D. Stukhlyak, I.G. Dobrotvor, N.M. Mytnyk, N.A. Dolgov, *Strength of Materials* **41** No 4, 431 (2009).
18. I.H. Dobrotvor, P.D. Stukhlyak, A.V. Buketov, *Mater. Sci.* **45** No 6, 582 (2009).
19. C. Cerbu, *Procedia Technol.* **19**, 268 (2015).
20. V. Demchenko, S. Riabov, V. Shtompel', *Nanoscale Res. Lett.* **12**, 235 (2017).

Стала надійність транспортування: вивчення повзучості екологічно чистих полімерних нанокompозитів

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У роботі наведено результати дослідження повзучості полімерних композитів, що містять органічні тканини. Наведено технологію формування функціональних полімерних композитів і захисних покриттів на їх основі з підвищеними експлуатаційними характеристиками для захисту засобів транспорту. Для формування полімерних матеріалів використовували епоксидну смолу ЕД-20, яку полімеризували твердником поліетиленполіаміном РЕРА у співвідношенні: епоксидний олігомер ЕД-20 – 100 %, твердник РЕРА – 10 %. Додатково для поліпшення властивостей епоксидних композитів і захисних покриттів у зв'язувач вводили нанонаповнювач у вигляді діаміноазобензол карбонової кислоти. Також вводили мікродисперсний наповнювач та органічні тканини. Як мікродисперсний наповнювач для експериментальних досліджень використано синтезовану порошкову титано-алюмінієву шихту. Формування наповнювача проводили високовольтним електророзрядним синтезом. У результаті такої обробки отримали високомодульні сполуки Ti , Al_3Ti і Ti_3AlC_2 . У вигляді наповнювача додатково використано тканини на основі волокон органічного походження. У роботі використано бавовняні тканини товщиною $h = 1.5...2.0$ мм, а лляні тканини товщиною $h = 1.5...1.7$ мм. Доведено, що формування модифікованих «гібридних» матеріалів, які містять у комплексі дисперсний наповнювач і бавовняну чи лляну тканини забезпечує суттєве зменшення повзучості матеріалів в умовах статичного навантаження. Встановлено, що використання таких композитів (за наступного співвідношення компонентів – епоксидний зв'язувач : нанонаповнювач : мікродисперсний наповнювач і бавовняна чи лляна тканини (два шари) забезпечує покращення порівняно з епоксидною матрицею наступних показників повзучості матеріалів: зменшення максимального прогину композитів у 3.3...6.6 разів, зменшення швидкості повзучості у 1.6...2.0 разів, підвищення показника відновлення після повзучості у 3.1...3.5 разів.

Ключові слова: Епоксидна смола, Твердник, Нанопорошок, Наповнювач, Повзучість, Тканини, Нанокompозит.