Journal of Nano- and Electronic Physics
Vol. **18** No 4, 04002(8pp) (2026)

Журнал нано- та електронної фізики
Том **18** № 4, 04002(8cc) (2026)

OPEN ACCESS

REGULAR ARTICLE

Electrical, Thermal and Mechanical Properties of Epoxy Composites with Carbon Micro- and Nanofillers

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(Received 04 April 2026; revised manuscript received 18 August 2026; published online 21 August 2026)

The electrical, thermal, and mechanical properties of epoxy composites with different types of carbon fillers: colloidal graphite (CGr), carbon black (CB), as well as carbon nanotubes (CNTs) and thermally expanded graphite (TEG) have been investigated. Measurements of surface and volume electrical resistivity of the samples were carried out at room temperature.

It was established that the electrical conductivity of the composites exhibits a percolation behavior and strongly depends on the morphology and concentration of the fillers. It was shown that composites filled with carbon black are characterized by electrical resistivity lower by several orders of magnitude compared to composites with colloidal graphite at the same filler content (10-20 wt. %), which is explained by the formation of a continuous conductive cluster at lower filler concentrations. The addition of 1-2 wt. % of carbon nanotubes or thermally expanded graphite along with CGr or CB particles reduces the electrical resistivity of the composites by 1-2 orders of magnitude due to a synergistic effect between the particles of the basic carbon filler (CGr or CB) and the nanoscale fillers during the formation of a continuous electrically conductive cluster.

The incorporation of 10-20 wt. % of carbon black into the epoxy matrix (also in combination with nanocarbon fillers, CNTs or porous TEG), leads to a significant increase in the electrical conductivity of the composites. It was shown that, unlike electrical conductivity, the thermal conductivity of epoxy composites with carbon fillers, colloidal graphite or carbon black, changes slightly and varies within (0.25-0.55 W/(m·K)) depending on the type and content of the carbon filler.

Load-strain diagrams of carbon-epoxy composite samples under uniaxial compression up to failure were studied. An increase in the effective Young's modulus with increasing content of the basic filler (CGr or CB) and its decrease upon the introduction of nanofillers (CNTs or TEG) were established. The obtained results indicate the potential of the studied materials with thermal insulation properties for use in functional protective systems.

Keywords: Composite material, Carbon black, Colloidal graphite, Electrical resistance, Mechanical properties, Young's modulus

DOI: 10.21272/jnep.18(4).04002 PACS number: 61.48.De

1. INTRODUCTION

The incorporation of carbon components into epoxy resin aims to transform the insulator into a functional material. The key feature is that the mechanisms of charge (electron) and heat (phonon) transport differ significantly, leading to varying efficiencies of the fillers. Electrical conductivity in such composite materials (CMs) is characterized by a percolation threshold-the critical filler concentration at which a continuous conductive network is formed. According to research [1], CMs filled with carbon nanotubes (CNTs) exhibit the lowest percolation threshold due to their extremely high aspect ratio (length to diameter). This allows for the creation of conductive networks at very low concentrations. Works [2, 3] show that carbon black requires higher concentrations to reach the percolation threshold compared to nanotubes, since its particles have a spherical or agglomerated shape with a lower aspect ratio. Authors [4-6] pointed out that the use of reduced graphene oxide or hybrid structures (graphite-graphene) allows for high conductivity while maintaining mechanical integrity. Hybrid fillers often exhibit a synergistic effect, where smaller particles "bridge" the gaps between larger structures [7-11]. Unlike electrical conductivity, where a sudden increase (by several orders of magnitude) is possible, thermal conductivity typically increases gradually. The main obstacle to high thermal conductivity is phonon scattering at the "filler-matrix" interface. Authors of the works [12, 13] Caradonna et al. (2019) emphasize that even at high carbon content, thermal conductivity is limited by the quality of dispersion.

As demonstrated in [14], for CMs with hybrid carbon fillers (graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and carbon black (CB)) in a polypropylene matrix, a pronounced synergistic effect is observed, allowing for targeted control of the fibers'

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Cite this article as: T.A. Len, et al., *J. Nano- Electron. Phys.* 18 No 4, 04002 (2026) https://doi.org/10.21272/jnep.18(4).04002

mechanical and electrical properties. In particular, it has been established that combining fillers of different dimensions (0D/1D/2D) promotes the formation of a multilevel structural network: CNTs act as conductive "bridges," GNPs ensure effective load transfer, and CB fills the microvoids between larger particles. This structure ensures improved dispersion of fillers in the matrix and enhanced interfacial interaction. As a result, the composites demonstrate increased strength and elastic modulus, as well as improved electrical characteristics, including increased charge density and signal stability. This opens up opportunities for the use of such materials in sensor systems and energy harvesting devices. The authors of [15] investigated the influence of modifying agents and hybrid conductive carbon fillers on the properties of butyl rubber composites, specifically their mechanical, thermomechanical, and dynamic characteristics, as well as their ability to undergo re-curing.

The main focus was on the role of interfacial interactions between the matrix and the filler, as well as on the formation of the conductive network in the composite material.

It was shown that the use of modifying agents improves the dispersion of hybrid fillers and enhances adhesion at the matrix-filler interface. As a result, an increase in mechanical strength, elastic modulus, and stability under dynamic loads is observed. Furthermore, the introduction of hybrid conductive fillers ensures the formation of a more efficient percolation structure, which positively affects the electrical conductivity of the composites. It has also been established that such systems exhibit improved thermomechanical properties. This indicates the potential for using hybrid carbon systems in the creation of functional composite materials with tunable properties.

The aim of this work was to determine and conduct a comparative analysis of the effect of the morphology of carbon fillers-colloidal graphite (CG) and carbon black-on the electrical and thermal conductivity as well as the mechanical properties of epoxy composites. Significant attention was also devoted to studying the effect of adding a small amount (1-2 wt. %) of porous thermally expanded graphite (TEG) or carbon nanotubes to the main filler (CG or CB) on the formation of the electrophysical, thermophysical, and mechanical properties of epoxy composites.

2. OBJECTS AND METHODS

To determine the effect of the type of carbon filler in the composite on its electrical properties, measurements of the surface electrical resistance and volume resistivity were conducted on samples of epoxy composites containing colloidal graphite (10-20 wt. %) and technical graphite (carbon black (CB)) (10-20 wt. %) with the addition of carbon nanotubes (CNT) or thermoexfoliated graphite (TEG) (1-2 wt. %).

Electrical resistance measurements of the samples were performed using the Hiresta UX MCP-HT800 (a two-probe sensor for high-resistive samples) and the Loresta GXII MCP-T710 (a four-probe sensor for low-resistive samples).

Epoxy CM samples were prepared as plates with a size of 5.5×5.5 mm^2 and a thickness of 4-4.7 mm to study their mechanical behavior. The deformation-loading curves of the CMs during compression were recorded using an automated system based on serial IMASH-20-78 equipment [16].

3. DISCUSSION

Table 1 presents the measurement parameters for the surface and volume electrical resistivity of the samples, and Fig. 1 shows the bulk electrical resistivity for all samples as a function of the content and type of carbon fillers.

Table 1 – Measurement parameters for the surface and volume electrical resistivity of the samples

Content	h, mm	R, Ohm Hiresta UX	ρ_v, Ohm·sm	ρ_s, Ohm/sm^2
0.25 % TEG-L285	1.42	1.09×10^{14}	2.1×10^{14}	1.1×10^{15}
0.5 % TEG-L285	1.49	2.88×10^{14}	6.54×10^{14}	2.91×10^{15}
1.0 % TEG-L285	1.65	6.87×10^{13}	1.37×10^{14}	6.93×10^{14}
2.0 % TEG-L285	1.59	2.83×10^{11}	$4{,}86 \times 10^{11}$	2.86×10^{12}

As shown in Table 1, the volume electrical resistivity of the CM with 10 wt. % colloidal graphite (CGr) is approximately 9.6×10^{12} Ω·cm, while the surface resistivity is approximately 5.67×10^{12} Ω/cm^2. For CMs with 10 % CGr + 1 % CNT, a slight decrease in both volume and surface resistivity is observed. A more significant decrease in electrical resistance is observed for epoxy CMs with 10 wt. % CGr and 1 wt. % TEG: the surface resistance decreases by two orders of magnitude compared to CMs with 10 wt. % CGr, and the volume electrical resistance decreases by nearly one order of magnitude. Increasing the content of CGr to 20 wt. % results in a reduction in electrical resistance of only a factor of 2 compared to the 10 wt. % Cg-L285 composite, while the surface electrical resistance remains quite high at 9.59×10^{13} Ω/cm^2. Such high surface electrical resistance of samples with colloidal graphite is explained by the formation of an epoxy film on the sample surface during its molding and in the curing process.

Composites filled with CB have an electrical resistivity several orders of magnitude lower than that of composites filled with CGr at the same filler concentrations. For example, the volume electrical resistance of a composite with 10 % CB is 6.07×10^8 Ω·cm, and when 1 wt. % CNT or TEG is added, it decreases by approximately two orders of magnitude.

The lowest volume electrical resistivity was observed for the 20 % CB-L285 sample, $\rho_v = 3.259 \times 10^3$ Ω·cm. This difference in electrical resistance for epoxy composites with CGr and CB fillers is explained by the structural and morphological characteristics of the filler particles, namely the porous structure of spherical CB particles and their low bulk density (0.059 g/cm^3) compared to colloidal graphite particles (0.26 g/cm^3). As a result, the packing parameter for the CB filler is significantly lower than for the CGr filler;

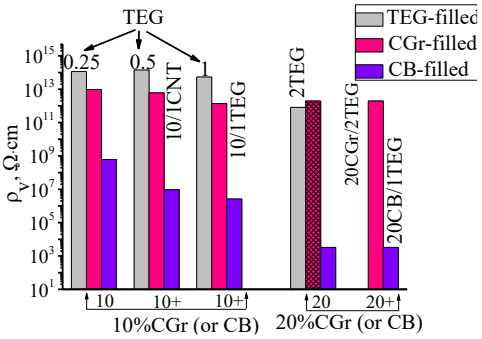


Fig. 1 – Diagrams of volume electrical resistivity for epoxy composite samples with different carbon fillers: a) TEG, b) CGr and CB

that is, the formation of a continuous electrically conductive cluster of nanoparticles occurs at a significantly lower content than when colloidal graphite is used as filler. The addition of a small amount of nanoscale filler (CNT or porous TEG) along with CGr or CB particles improves the electrical properties of composites due to the synergy between the particles of the basic carbon filler (CGr or CB) and the nanoscale fillers during the formation of a continuous electrically conductive cluster and the creation of a large number of connections between the electrically conductive carbon particles.

3.1 Study of the Thermal Conductivity of Epoxy Composites with Carbon Fillers

The use of carbon particles as fillers allows, by varying their type and content in the dielectric polymer matrix, for the controlled achievement of the required electrical properties of the composite to ensure high shielding and absorption properties. Typically, the introduction of carbon fillers will also lead to an increase in the thermal conductivity of the composite compared to the unfilled polymer matrix, since carbon has good thermal properties, which may impair the thermal insulation properties of the composite.

To determine which of the carbon fillers used is best suited for creating composites with thermal insulation properties, studies of the thermal conductivity of the developed composites were conducted. Thermal conductivity measurements were performed in the temperature range of 148-373 K using the method described in [17, 18]. Fig. 2 shows the temperature dependencies for CMs with different types of carbon fillers depending on the filler content and their combination with nanocarbon fillers CNT or TEG at a concentration of 1-2 wt. %.

For epoxy composites containing 10 and 20 wt. % CGr, the thermal conductivity ranges from 0.2 to 0.3 W/(m·K) and gradually increases with heating. Adding 1 wt. % CNT to a system containing 10 wt. % CGr-L285 results in an increase in thermal conductivity to 0.35 W/(m·K) and a decrease in temperature dependence. Adding 1 wt. % TEG to a system containing 10 wt. % CGr-L285 results in a greater increase in thermal conductivity, up to 0.45 W/(m·K), and a non-monotonic temperature dependence. When the colloidal graphite content in the composite is increased to 20 wt. %, the temperature dependence of thermal conductivity takes the form of a smoothly rising curve.

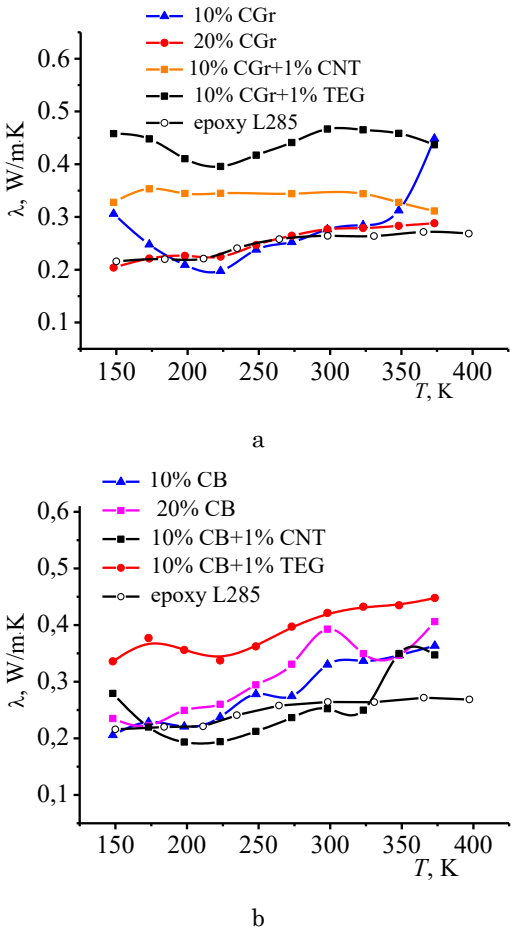


Fig. 2 – Temperature dependence of thermal conductivity for CMs with CGr (a) and CB (b) as basic filler

A slightly different temperature dependence of thermal conductivity is observed for the CM sample containing 10 % CGr and 1 % multi-walled CNTs; the thermal conductivity is described by a smooth curve.

As can be seen from Fig. 2b, the temperature-dependent thermal conductivity curves of the CM with CB for all samples show a gradual increase with rising temperature. The lowest values of λ are observed for the CM 10 % CB + 1 % CNT sample (0.35 W/(m·K) at the maximum temperature, while the highest thermal conductivity values are for CM 10 % CB + 1 % TEG, 0.44 W/(m·K) at a maximum temperature of 373 K.

Fig. 3 shows the comparative diagrams of changes in electrical and thermal conductivity (T = 298 K) for CMs with CB and CGr upon the addition of 1 % CNT and 1 % TEG.

As can be seen from the diagrams, when comparing the CGr-epoxy resin and CB-epoxy CM systems in terms of changes in electrical and thermal conductivity, the following conclusions can be drawn:

1) Incorporating 10-20 wt. % of technical carbon (CB) (in combination with nanocarbon fillers such as TEG or CNT) leads to a significant increase in the electrical conductivity of the composite, which provides good shielding and absorption properties of the composite against microwave radiation; however, the thermal conductivity of these composites remains low;

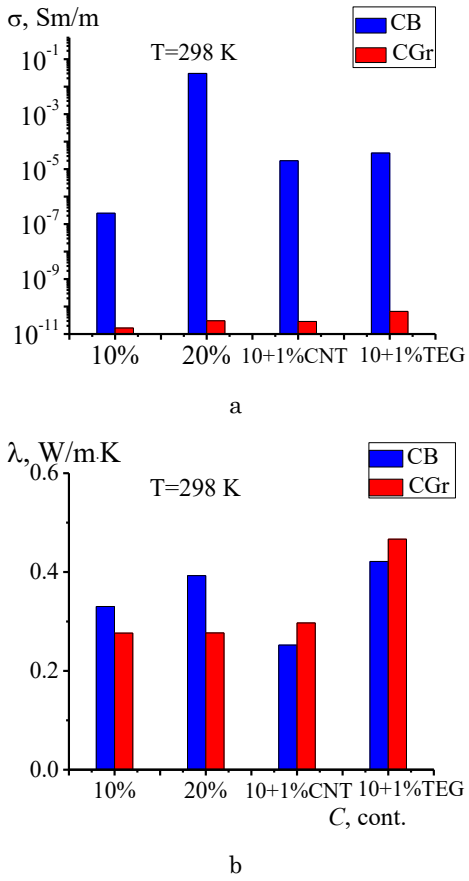


Fig. 3 – Electrical and thermal conductivity diagrams for epoxy composites with CB and CGr (a, b) upon addition of 1 % CNT or 1 % TEG (T = 298 K)

2) In a colloidal graphite-epoxy resin system with a colloidal graphite content of up to 20 wt. %, the electrical conductivity is quite low ($10^{-11} – 10^{-10}$ S/m), while the changes in thermal conductivity are of the same order of magnitude as in the case of carbon-based materials containing CB.

Thus, despite the fact that CM samples made from CGr and CB differ significantly in terms of electrical conductivity, they can be used as components of multifunctional protective materials without compromising their thermal insulation properties.

3.2 Investigation of the Mechanical Properties of Composite Materials Under Cyclic Uniaxial Compression

For the practical application of polymer composites as constituent layers of a multifunctional shielding material (MSM) for protection against microwave radiation, their stability under various external factors-such as fluctuating temperatures and different types of mechanical loads-is of critical importance. For the manufactured carbon-epoxy resin composites, a study was conducted on their mechanical properties (Young's modulus, strength) under cyclic uniaxial compression.

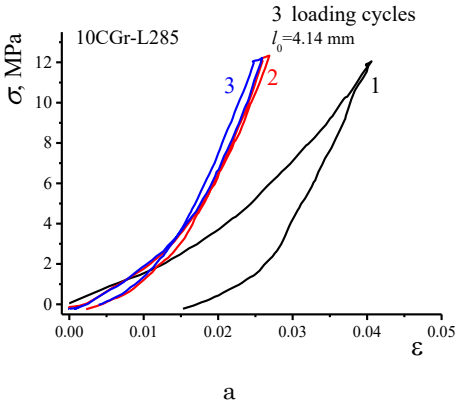
The mechanical properties were tested on plate-shaped specimens with an average size of 5.5 × 5.5 mm and a thickness of 4-4.7 mm. The CM samples were cyclically compressed to loads of σ= 12 MPa (1-3 cycles), then to loads of 25 MPa (1-3 cycles), and during the seventh cycle, the samples were compressed to maximum loads of σ_{max}, at which significant irreversible changes in the sample's shape or sample failure had already occurred. The effective Young's modulus was defined as $E_{ef} = \sigma/\varepsilon_{el}$, where ε_{el} is the elastic strain, which is a component of the total strain of the specimen $\varepsilon_{total} = \varepsilon_{el} + \varepsilon_{pl}$ under a load σ, and ε_{pl} is the irreversible (plastic) strain. To determine the Young's modulus more accurately, data from the diagram for the third loading cycle were used, when the plastic deformation was already minimal, unlike in the first "load-unload" cycle.

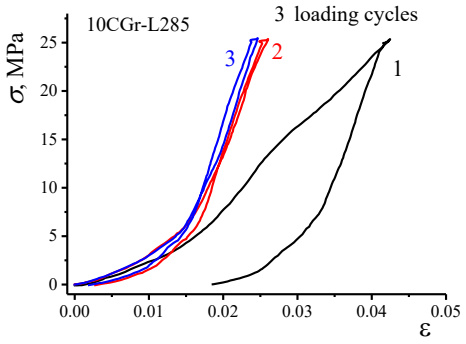
Figs. 4-5 show typical load-strain curves for several specimens of the studied composites containing different types of carbon fillers, while Table 2 shows the values of elastic strain of the specimens and the effective Young's modulus E_{ef}, which were obtained from the experimental load-strain diagrams for all specimens during cyclic compression to loads of 12 MPa and 25 MPa. Fig. 6 presents comparative diagrams for the effective Young's modulus of composites with CGr and CB fillers.

As shown in Table 2, for unfilled epoxy resin, significant irreversible deformations ($\varepsilon_{pl} \approx 0.15$) are observed under compression up to 12 MPa for both the first and second loading cycles, indicating compaction of the specimen, while for the third cycle, the deformation is predominantly elastic (ε_{el}). Increasing the mechanical load to 25 MPa leads to the occurrence, along with elastic deformation, of additional irreversible plastic deformation for the first cycle, the magnitude of which decreases during the second and third loading cycles.

The incorporation of 10 wt.% of CGr (Fig. 4a, b) results in significantly lower values of both total (ε_{total}) and permanent (ε_{pl}) strains under loads of 12 and 25 MPa and an increase in the effective Young's modulus E_{ef} compared to the unfilled epoxy resin.

Increasing the content of CGr in the composite to 20 wt. % (Table 2) results in even smaller deformations of the composite specimens compared to L285 epoxy resin and an even higher Young's modulus. Such changes in deformation values with an increase in the CGr content can be explained by a decrease in the volume of the epoxy matrix, whose contribution is dominant in the total deformation of the samples ε_{total}. The increase in the effective Young's modulus (E_{ef2}) under loads up to 25 MPa, compared to E_{ef1} (under loads up to 12 MPa), indicates further compaction of the specimens as the loading stress σ increases.





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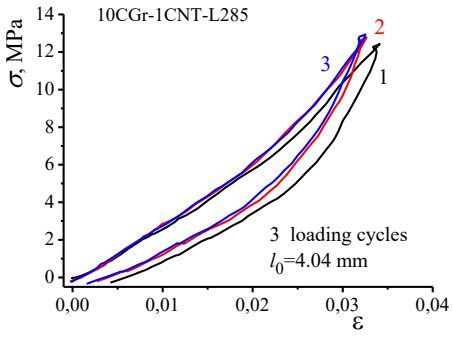
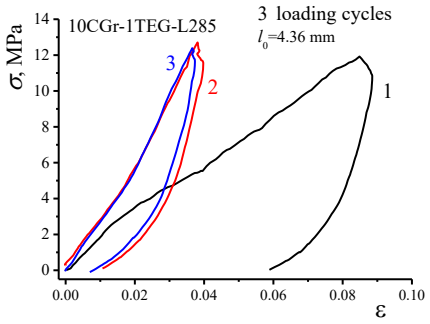
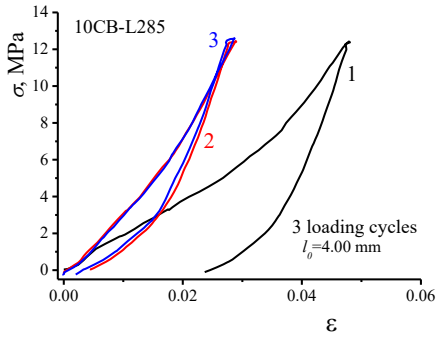


c

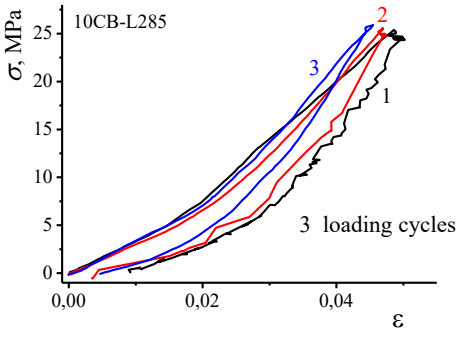


d

Fig. 4 – Load-strain diagrams for uniaxial repeated compression of carbon-epoxy composite specimens: a, b) – 10CGr-L285 at loads of 12 MPa and 25 MPa; (c) – 10CGr-1CNT-L285; (d) – 10CGr-1TEG-L285



a



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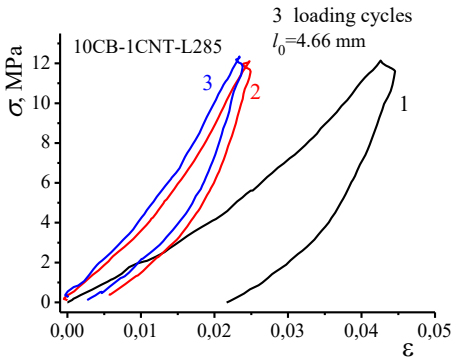

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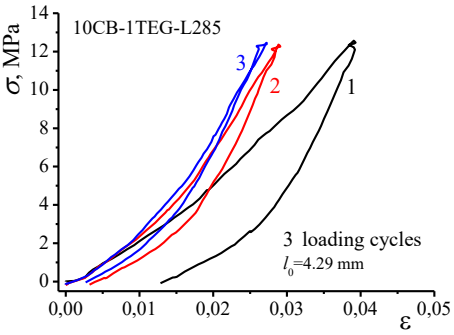

d

Fig. 5 – Load-strain diagrams for uniaxial repeated loading of carbon-epoxy composite specimens: (a, b) – 10CB-L285 at loads of 12 MPa and 25 MPa, respectively; (c) – 10CB-1CNT-L285; (d) – 10CB-1TEG-L285

Table 2 – Values of elastic strain ε_{el} and effective modulus under compressive loads of 12 MPa (σ_1) and 25 MPa (σ_2)

Sample	σ_1, MPa	ε_{el1}	E_{ef1}, MPa	σ_2, MPa	ε_{el2}	E_{ef2}, MPa
Epoxy L285	12,04	0.15* (total) 0.032 (el)	315* 372	25.2	0.031	806.0
10 %CGr-L285	12.22	0.0219	549.1	25.27	0.0240	1052.9
20 % CGr-L285	12.72	0.0136	907.4	25.35	0.0130	1950.0
10 % CGr-1 %BHT-L285	12.93	0.0309	401.3	25.86	0.0313	826.2
10 % CGr-1 %TEG-L285	12.39	0.0297	401.2	25.69	0.0381	674.3

20 % CGr-2 %TEG-L285	12.33	0.0231	534.8	25.26	0.0274	921.9
10 % CB-L285	12.60	0.0268	471.6	25.79	0.0408	632.1
20 % CB-L285	13.20	0.0168	783.2	25.18	0.0168	1498.8
10 % CB-1 %CNT-L285	12.35	0.0201	606.35	25.82	0.0283	912.7
10 % CB-1 %TEG-L285	12.44	0.0245	508.2	25.36	0.0262	967.9

*The total strain $\varepsilon = \varepsilon_{pl} + \varepsilon_{el}$ of unfilled epoxy resin specimens, with a significant contribution from ε_{pl}.

The introduction of 1 wt. % CNT into the epoxy matrix along with 10 wt. % CGr (Fig. 4c) changes the deformation behavior of the CM samples: the total strain (ε_{total}) remains almost unchanged, but at the same time, the permanent deformation ε_{pl} is minimal, i.e., the samples become more elastic, and the effective Young's modulus decreases to 400 MPa (under loads up to 12 MPa).

Unlike the CM 10 % CGr – 1 % CNT-L285 specimens, the addition of 1 wt. % TEG (Fig. 4d) leads to an increase in specimen deformation (ε_{total}) due to an increase in irreversible deformation ε_{pl}, which is associated with the relatively high porosity of the specimens ($P = 0.28$) with the additional porous filler TEG (see Table 1) and, as a result, compaction of the specimens occurs during the first loading cycles up to 12 MPa and up to 25 MPa. In the 20 % CGr - 2 % TEG-L285 composites, the total deformation of the specimens (Table 2) increases compared to the 20 % CGr-L285 control due to the addition of TEG,

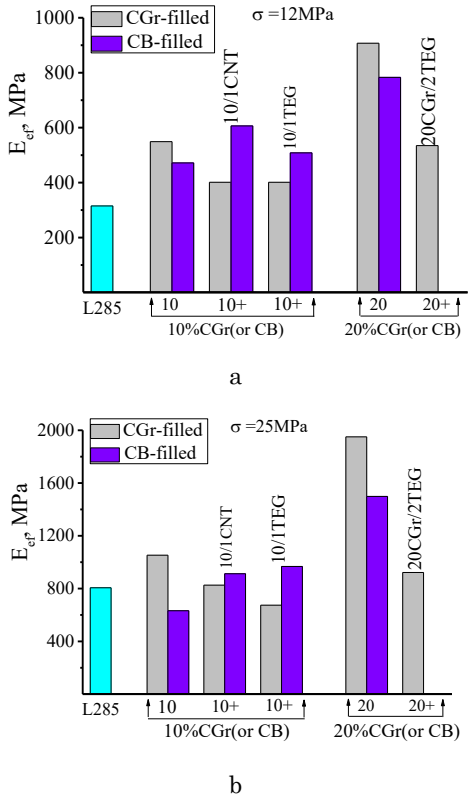

Fig. 6 – Young's modulus of carbon-epoxy composites under uniaxial compression at loads of 12 MPa (a) and 25 MPa (b)

but the effect of TEG on irreversible deformation is smaller compared to the 10 % CGr - 1 % TEG-L285 matrix, since a large volume in the 20 % CGr - 2 % TEG-L285 sample is occupied by CGr particles and the role of the epoxy matrix is reduced. Similarly, the Young's modulus decreases with the adding 2 wt.% TEG, E_{ef} = 534.8 MPa (Fig. 6, Table 2).

Similar changes in deformation values and the relationship between ε_{pl} and ε_{el} were observed for CMs with carbon black as the basic filler, namely a decrease in deformation as the carbon black content increased from 10 to 20 wt. % (due to a decrease in ε_{pl}) and an increase in permanent deformation upon the addition of 1 wt. % CNT or TEG (Fig. 5). In this case, the values of total deformation for samples with carbon black filler are slightly higher compared to CM with CGr as the basic filler. The values of the effective Young's modulus for the samples containing 10 and 20 wt. % CB are lower compared to those for CM with CGr (10, 20 wt. %) (see Table 2), and the addition of 1 wt.% CNT or TEG together with 10 wt. % CB to the epoxy matrix resulted in a slight increase in the E_{ef} value (see Table 2).

Figs. 7-8 show the results of strength tests on CM samples when compressed to the maximum stress values σ_{max}, and Table 3 lists the deformation values at σ_{max}.

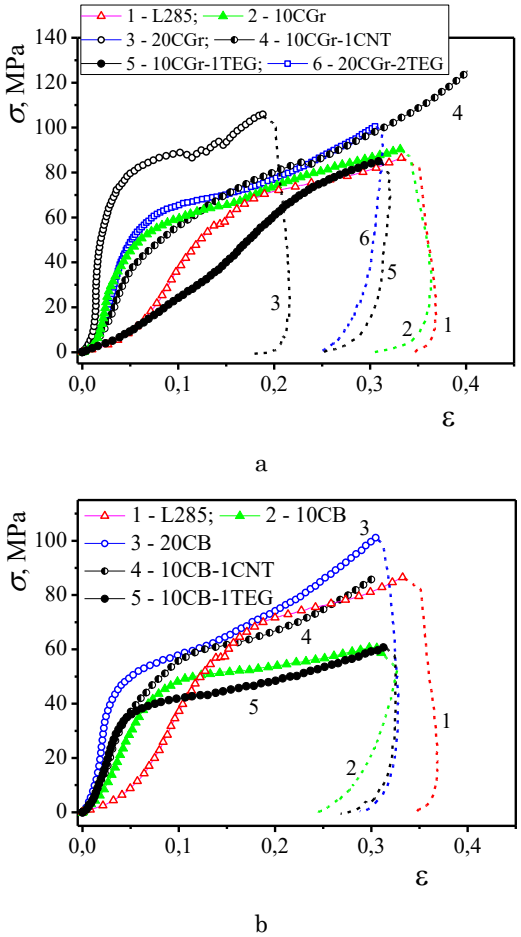

Fig. 7 – Load-strain curves for uniaxial compression of carbon-epoxy composite specimens until failure: a – composites with CGr as the basic filler; b – composites with CB as the basic filler

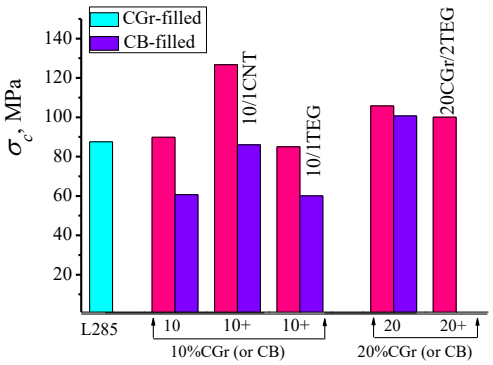

Fig. 8 – Strength of carbon-epoxy composite specimens under uniaxial compression to failure

As can be seen from the data presented, no brittle fracture occurs as such; instead, the specimens simply flatten, their thickness decreases (by 30 %), and the highest compressive strength σ_c (100-126 MPa) was observed for CM specimens containing 20 wt. % CGr or CB and specimens containing 10 wt. % of the basic filler (CGr or CB) + 1 wt. % CNT.

Table 3 – Compressive strength of carbon-L285 specimens and relative deformation of the specimens under maximal load

Composite type	ε_c at σ_c	σ_c, MPa
Epoxy L285	0.345	87.5
10 % CGr-L285	0.338	89.9
20 % CGr-L285	0.201	105.8
10 % CGr-1 % CNT-L285	0.402	126.7
10 % CGr-1 % TEG-L285	0.240	85.0
20 % CGr-2 % TEG-L285	0.313	100.1
10 % CB-L285	0.305	60.7
20 % CB-L285	0.310	100.7
10 % CB-1 % CNT-L285	0.318	86.0
10 % CB-1 % CNT-L285	0.323	60.1

Such an increase in the strength of samples with 20 wt. % KGr or CB, as well as when 1 wt. % of CNTs was added, indicates that the presence of a large amount of these carbon fillers (CGr or CB) and the presence of nanosized CNTs contributes to an increase in the material's ability to resist the applied mechanical load. On the other hand, it is known [19-21] that interfacial adhesion between the components of the composite determines the mechanical load transmitted between them, and such an increase in the compressive strength of the specimens can be explained by the good bonding between the carbon fillers and the epoxy matrix, which results in effective load transfer at the carbon filler-L285 interphase boundaries.

4. CONCLUSION

1. Composites with a CB filler showed significantly higher electrical conductivity compared to CM with a CGr filler due to the low packing parameter, which contributes to the formation of a continuous conductive cluster with a significantly lower CB content. The addition of a small amount of nanosized filler (CNT or porous TEG) improves the electrical properties of the composites due to the synergy between the particles of the basic carbon filler (CGr or CB) and nanosized fillers during the formation of a 3D conductive network and the formation of a large number of connections between conductive carbon particles of different types and morphologies.

2. It has been shown that, unlike electrical conductivity, which increases with the addition of carbon fillers, particularly graphite, there is no significant increase in the thermal conductivity of the composites; its value varies within the range of 0.25-0.55 W/(m·K), which allows these composites to be used as components of multifunctional protective materials without compromising their thermal insulation properties.

3. It was found that the effective Young's modulus E_{ef} for carbon-epoxy resin composites increases compared to the unfilled epoxy resin; for composites with a high filler content (20 wt. % CB or CCr), its value ranges from 780 to 907 MPa, and the addition of 1-2 wt. % of an additional filler, TEG or CNT, leads to a decrease in the E_{ef} value. Compression of the samples to maximum loads (60-125 MPa) showed that no brittle fracture of the samples occurs as such, their thickness decreases (by 30 %), and the highest compressive strength σ_c (100-126 MPa) was exhibited by CM samples containing 20 wt. % CGr or CB and samples with 10 wt. % filler (CGr or CB) + 1 wt. % CNT.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support from the Ministry of Education and Science of Ukraine-Grant no. DZ/161-2025 for scientific and technical work under the state order.

REFERENCES

1. Y.X. Zhou, P.X. Wu, Z-Y. Cheng, J. Ingram, S. Jeelani, *eXPRESS Polym. Lett.* **2** No 1, 40 (2008) https://doi.org/10.3144/expresspolymlett.2008.6.
2. G. Spinelli, R. Guarini, L. Guadagno, L. Vertuccio, V. Romano, *Materials* **17**, 3596 (2024) https://doi.org/10.3390/ma17143596.
3. T. Bera, S.K. Acharya, P. Mishra, *Sci. Technol.* **10** No 4, 12 (2018) https://dx.doi.org/10.4314/ijest.v10i4.2.
4. Li-Xiu Gong, L. Zhao, L.-C. Tang, H.-Y. Liu, Y.-W. Mai, *Compos. Sci. Technol.* **S0266-3538** No 15, 30120 (2015) https://doi.org/10.1016/j.compscitech.2015.10.023.
5. A.P. Malyushevskaya, P.P. Malyushevskii, *Surf. Eng. Appl. Electrochem.* **52** No 3, 263 (2016) https://doi.org/10.3103/S1068375516030091.
6. A.S. Mostovoy, A.V. Yakovlev, *Sci. Rep.* **9**, 16246 (2019) https://doi.org/10.1038/s41598-019-52751-z.
7. X. Luo, G. Yang, D. Schubert, *Adv. Compos. Hybrid. Mater.* **5**, 250 (2022) https://doi.org/10.1007/s42114-021-00332-y.
8. N.I. Kuskova, A.P. Malyushevskaya, S.V. Petrichenko, A.N. Yushchishchina, *Surf. Eng. Appl. Electrochem.* **47** No 5, 446 (2011) https://doi.org/10.3103/S1068375511050140.
9. S. Zhou, A.N. Hrymak, M.R. Kamal, *Nanomaterials* **30** No 8, 779 (2018) https://doi.org/10.3390/nano8100779.
10. Wenwei Wu, Qiuyu Jiang, *Mater. Lett.* **60** No 21-22, 2791

(2006) https://doi.org/10.1016/j.matlet.2006.01.090.
11. E.M. Alosime, A.A. Basfar, *Polymers* **16** No 3, 417 (2024) https://doi.org/10.3390/polym16030417.
12. T. Falat, J. Felba, P. Matkowski, B. Platek, P. Demont, F. Marcq, P. Monfraix, A. Moscicki, K. Poltorak, *11th IEEE International Conference on Nanotechnology*, 97 (Portland Marriott, Portland, Oregon, USA: 2011) https://doi.org/10.1109/NANO.2011.6144654.
13. A. Caradonna, C. Badini, E. Padovano, M. Pietroluongo, *Materials* **12**, 1522 (2019) https://doi.org/10.3390/ma12091522.
14. Y. Cheng, J. Wang, M. Shao, Y. Liang, H. Li, *Adv. Compos. Hybrid Mater.* **8**, 259 (2025) https://doi.org/10.1007/s42114-025-01341-x.
15. P. Luangchuang, T. Sornanankul, Y. Nakaramontri, *Polymers* **15**, 4023 (2023) https://doi.org/10.3390/polym15194023.
16. T.A. Len, L.L. Vovchenko, L.Yu. Matzui, O.V. Turkov, A.V. Zuravkov. *J. Nano- Electron. Phys.* **16** No 1, 01026 (2024) https://doi.org/10.21272/jnep.16(1).01026.
17. L. Vovchenko, T. Len, L. Matzui, O. Turkov, Yu. Perets, *J. Nano- Electron. Phys.* **11** No 3, 03007 (2019) https://doi.org/10.21272/jnep.11(3).03007.
18. T. Len, L. Matzui, I. Ovsiienko, Yu. Prylutskyy, V. Andrievskii, I. Berkutov I.G. Grechnev, Yu. Kolesnichenko, *Fizika Nizkikh Temperatur* **37** No 9-10, 1027 (2011).
19. S. Fu, X. Feng, B. Lauke, Y. Mai. *Compos. B Eng.* **39**, 933 (2008) https://doi.org/10.1016/j.compositesb.2008.01.002.
20. A.P. Malyushevskaya, P.P. Malyushevskii, *Surf. Eng. Appl. Electrochem.* **56**, 400 (2020) https://doi.org/10.3103/S1068375520030114.
21. T. Len, V. Tkachuk, I. Ovsienko, L. Matzui, Y. Prylutskyy, O. Brusylovets, I. Berkutov, I. Mirzoiev, O. Prokopov, *Mol. Cryst. Liq. Cryst.* **639** No 1, 137 (2016) https://doi.org/10.1080/15421406.2016.1255069.

Електричні, теплові та механічні властивості композитних матеріалів з вуглецевими мікро- та нанонаповнювачами

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Досліджено електричні, теплові та механічні властивості епоксидних композитів із різними типами вуглецевих наповнювачів: колоїдний графіт (КГр), технічний вуглець (ТВ), вуглецеві нанотрубки (ВНТ) та терморозширений графіт (ТРГ). Вимірювання поверхневого та об'ємного електроопору зразків проводились при кімнатній температурі.

Встановлено, що електропровідність композитів має перколяційний характер і суттєво залежить від морфології та концентрації наповнювачів. Показано, що композити з технічним вуглецем характеризуються на кілька порядків нижчим питомим електричним опором порівняно з композитами з колоїдним графітом з таким самим вмістом наповнювача (10-20 ваг. %), що пояснюється формуванням безперервного провідного кластера при менших концентраціях наповнювача. Додавання 1-2 ваг. % вуглецевих нанотрубок або терморозширеного графіту знижує електричний опір композитів на 1-2 порядки за рахунок синергетичного ефекту між частинками базового вуглецевого наповнювача (CGr або CB) та нанорозмірними наповнювачами під час формування безперервного електропровідного кластера.

Введення в епоксидну матрицю 10-20 ваг. % технічного вуглецю ТВ (в комбінації також із нановуглецевими наповнювачами ТРГ або ВНТ) призводить до суттєвого зростання електропровідності композитів. Показано, що на відміну від електропровідності, теплопровідність епоксидних композитів із вуглецевими наповнювачами колоїдний графіт та технічний вуглець змінюється незначно і варіюється в межах (0,25–0,55 Вт/(м·К)) залежно від типу і вмісту вуглецевого наповнювача.

Проведені дослідження діаграм навантаження-деформації при одновісному стисненні зразків композитів вуглець-епоксидна смола до руйнування. Встановлено зростання ефективного модуля Юнга при збільшенні вмісту основного наповнювача (КГр або ТВ) та його зменшення при введенні нанонаповнювачів ТРГ або ВНТ. Отримані результати свідчать про перспективність використання досліджених матеріалів з теплоізоляційними характеристиками у функціональних захисних системах.

Ключові слова: Композитні матеріали, Технічний вуглець, Колоїдний графіт, Електричний опір, Модуль Юнга, Механічні властивості.