Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume II, 73-77

Invesigation the Influence of Multi-Walled Carbon Nanotubes and Amorphous Carbon on the Mechanical Properties of Thermosetting Polymers

Boyan Dochev
Faculty of Mechanical Engineering
Technical University of Sofia, Branch Plovdiv
Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies"
Plovdiv, Bulgaria
dochev@tu-plovdiv.bg

Desislava Dimova
Faculty of Mechanical Engineering
Technical University of Sofia, Branch Plovdiv
Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies"
Plovdiv, Bulgaria
d.dimova@tu-plovdiv.bg

Filip Ublekov
Institute of Polymers
Bulgarian Academy of Sciences
Sofia, Bulgaria
fublekov@polymer.bas.bg

Hristo Penchev
Institute of Polymers
Bulgarian Academy of Sciences
Sofia, Bulgaria
h-penchev@polymer.bas.bg

Nikola Tomanov
Faculty of Mechanical Engineering
Technical University of Sofia, Branch Plovdiv
Plovdiv, Bulgaria
nikotomanov75@gmail.com

Yavor Boychev
Institute of Metal Science, Equipment and Technology with Hydroaerodynamic Center
Bulgarian Academy of Sciences
Sofia, Bulgaria
boichev.yavor@gmail.com

***Abstract*—Composites based on thermosetting polymers (epoxy, polyester and vinylester resins) with integrated carbon particles have been developed. MWNTs and amorphous carbon, a waste product from the production of “green” hydrogen, have been used. The influence of different concentrations (0.02 wt %, 0.06 wt % and 0.1 wt %) of the two types of particles used on the mechanical properties of the developed composites has been studied, a comparative analysis has been conducted. The results of the studies show that the two types of carbon particles used reduce the tensile strength, but increase the hardness and impact toughness of the resulting composite compared to pure epoxy resin. The composite based on polyester resin with integrated MWNTs has reduced impact toughness, but with significantly higher hardness values compared to the resin used. A relative elongation of the newly obtained material was also registered, and at a concentration of 0.02 wt% MWNTs an increase in tensile strength was registered. The addition of amorphous carbon to the polyester resin has a positive effect on the mechanical properties of the resulting composite. Relative elongation, increased hardness, impact toughness, and higher values of tensile strength were registered. The amorphous carbon and MWNTs used are the basis for obtaining a composite with a vinyl ester resin matrix with improved mechanical properties. The different concentrations of the two types of carbon particles contribute to obtaining composites with improved mechanical properties compared to pure resin. In this case, multi-walled carbon nanotubes have a greater influence on the studied characteristics compared to amorphous carbon.**

Keywords— amorphous carbon, composites, mechanical properties, MWNTs, thermosetting polymers

I. INTRODUCTION

The development of modern nanocomposites is closely related to the optimization of polymer matrices by incorporating carbon nanomaterials. Epoxy, polyester and vinylester resins occupy a central place in the industry due to their excellent technological properties, but their high brittleness and low electrical conductivity often limit their application in critical structures.

Carbon nanotubes (CNTs) are an allotropic form of carbon with a one-dimensional (1D) structure. Depending on the number of concentric graphene layers they are made of, they are classified as single-walled (SWCNTs) and

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol2.110

multi-walled (MWCNTs). Despite their enormous potential, the integration of CNTs in industrial applications is associated with various challenges related to purity control, dispersion in different matrices and precise surface functionalization.

Amorphous carbon (a-C) is an allotropic form of carbon characterized by the lack of long-range order in its atomic structure. In contrast to the well-defined crystal lattices of diamond (sp^3 hybridization) and graphite (sp^2 hybridization), amorphous carbon is a metastable phase consisting of a mixture of these two states. In recent years, interest in amorphous carbon materials has grown significantly due to their exceptional adaptability. The integration of carbon nanotubes (CNTs) and amorphous carbon as stand-alone modifiers offers radically different approaches to overcome these shortcomings.

While multi-walled carbon nanotubes (MWCNTs) are considered as highly effective structural reinforcing agents capable of significantly improving mechanical strength and elastic modulus at minimal concentrations, amorphous carbon remains the preferred choice for modifying the physicochemical and protective properties of polymers. The effectiveness of these fillers depends not only on their morphology but also on the specific interactions with the thermosetting matrix—from high adhesion in epoxy systems to shrinkage and thermal stability in vinylester and polyester resins.

This paper investigates and compares the individual effects of MWCNTs and amorphous carbon on the mechanical properties of epoxy, polyester, and vinylester resins.

II. Materials and methods

In this study, composites based on a polymer matrix and with carbon particles integrated into them were developed. The following thermosetting polymers were used as matrices of the composites: epoxy resin - "LETOXIT" PR 227, polyester resin - "DISTITRON" 429 BSX25Q and vinyl ester resin - "DISTITRON" VE 100). For the polymerization of the indicated polymers, the following hardeners were used - "LETOXIT" EM 315 for the epoxy resin, "MEKR 50" for the polyester resin, "MEKR 50" and accelerator "MEKR" for the vinyl ester resin, and for the preparation of the resin systems, the ratios prescribed by the manufacturer were observed [1].

In recent years, a number of researchers have integrated carbon nanotubes (CNTs) into polymer matrix composites due to their good mechanical, electrical and thermal properties [2]-[17]. Amorphous carbon is a waste product in the production of pure hydrogen using catalytic methane decomposition, and due to its exceptional adaptability, there is considerable interest in it [18]-[30]. Two types of carbon particles were used for the studies. One is multi-walled carbon nanotubes (MWCNTs) with a length ≥ 2 µm, a diameter of 10 - 40 nm, a number of walls of 10 - 20 and a specific surface area of 55 m²/g. The second type of carbon particles is amorphous carbon with a composition: carbon (C) content of 99.1 at % and oxygen (O_2) content of 0.9 at %. The two types of carbon particles were used in three concentrations: 0.02 wt %, 0.06 wt % and 0.1 wt %.

The developed composites were obtained by mechanical dispersion of the used carbon particles in the liquid resin systems. In order to ensure maximum breaking of the larger agglomerates, intensive mechanical stirring was carried out. The preparation, casting and curing of the composites was at room temperature (25⁰ C according to the manufacturers' prescription), with the epoxy resin-based test bodies undergoing secondary polymerization at the manufacturer's prescribed temperature (55⁰ C) and process duration (12 h) [1].

The uniaxial tensile test was conducted using a Zwick Roell Z050 testing machine, the hardness of the developed composites was measured using the Shore method (D - HSD scale) using an EQUOTIP hardness tester, and impact toughness was examined using the Izod Impact Test.

III. Results and discussion

The results of the mechanical tests conducted on the developed composites with epoxy resin matrix "LETOXIT" PR 227 and both types of carbon particles used are presented in Table 1 and Table 2.

Table 1 Results of mechanical tests of epoxy resin and MWCNTs composite

MWNTs [wt. %]	**σ_m[MPa]**	**ε [%]**	**HSD**	**$KCV_{1/10,2}$ [J/cm²]**
0 wt. %	49	0.8	76.7	0.180
0.02 wt. %	31.5	0.3	83.2	0.250
0.06 wt. %	26.9	0.7	84.5	0.729
0.1 wt. %	19.8	0.5	84.1	0.313

Table 2 Results of mechanical tests of epoxy resin and a-Carbon composite

a-Carbon [wt. %]	**σ_m[MPa]**	**ε [%]**	**HSD**	**$KCV_{1/10,2}$ [J/cm²]**
0 wt. %	49	0.8	76.7	0.180
0.02 wt. %	45	1.2	82.2	0.225
0.06 wt. %	36.9	0.7	83.4	0.604
0.1 wt. %	23.5	0.2	80.8	0.238

The integration of multi-walled carbon nanotubes into the epoxy matrix has a positive effect only on the hardness and impact toughness of the resulting composites. A significant decrease in the tensile strength and a slight decrease in the relative elongation of the newly obtained materials were recorded. When using other carbon particles (a-Carbon), the results are similar. It is noteworthy that when using a concentration of 0.06 wt % of the carbon materials used, the developed composites have the highest values of impact toughness and hardness. The results obtained when using the lowest concentration (0.02 wt %) of amorphous carbon are of interest. At this concentration of carbon particles, a slight decrease in the tensile strength of the composite was recorded, but an increase in hardness, impact toughness and the highest value of relative elongation were measured. The composite prepared in this way based on an epoxy matrix has an optimal set of mechanical properties. Based on the results obtained, we can say that when developing a composite with an epoxy resin as the base, the use of amorphous carbon is preferred over MWCNTs.

Table 3 and Table 4 show the results of the tests conducted on composites based on polyester resin "DISTITRON" 429 BSX25Q and the two types of carbon particles used.

TABLE 3 RESULTS OF MECHANICAL TESTS OF POLYESTER RESIN AND MWCNTS COMPOSITE

MWNTs [wt. %]	σ_m[MPa]	ε [%]	HSD	$KCV_{1/10,2}$ [J/cm^2]
0 wt. %	34.8	0	79.8	0.03
0.02 wt. %	37.3	1.1	88.7	0
0.06 wt. %	31.6	0.9	91.4	0
0.1 wt. %	31.6	0.6	90.4	0.0625

TABLE 4 RESULTS OF MECHANICAL TESTS OF POLYESTER RESIN AND A-CARBON COMPOSITE

a-Carbon [wt. %]	σ_m[MPa]	ε [%]	HSD	$KCV_{1/10,2}$ [J/cm^2]
0 wt. %	34.8	0	79.8	0.03
0.02 wt. %	37.7	0.5	91.0	0
0.06 wt. %	38.7	0.3	91.8	0.125
0.1 wt. %	34.9	0.4	89.4	0.0875

The MWNTs used in the developed composites based on polyester resin “DISTITRON” 429 BSX25Q have a positive effect on their mechanical properties. At a concentration of 0.02 wt. %, an increase in the tensile strength, relative elongation and hardness of the newly obtained material compared to the base polymer was recorded, but the impact toughness was reduced. The tendency to increase the hardness and relative elongation is also preserved when using 0.06 wt. % MWNTs, but a slight decrease in the strength of the composite compared to the polyester resin was recorded. Increasing the amount of these carbon particles to 0.1 wt. % is the basis for obtaining a composite with the best balance of mechanical properties. After integrating amorphous carbon particles into the polyester matrix, composites with increased properties were obtained. Only at a concentration of 0.02 wt. % was no positive effect on the impact toughness of the composite compared to the starting resin. The highest mechanical properties are possessed by the composite with 0.06 wt. % amorphous carbon integrated into it. As with epoxy and polyester resins, waste amorphous carbon has a better effect on the mechanical properties of the developed composites.

Unlike the cases considered so far, in which amorphous carbon had a more favorable effect on the mechanical properties of composites based on epoxy and polyester resin, in the case of the vinylester resin “DISTITRON” VE 100, the MWCNTs used had a more favorable effect. It was found that at all three concentrations of carbon nanotubes used, the mechanical properties of the composites are higher than the initial values of the base polymer, with the exception of the impact toughness of the composite with 0.02 wt. % MWCNTs (Table 5). The obtained values for the tensile strength are also higher than the values of the same indicator of the composites in the composition of which the same amounts of amorphous carbon are integrated, and the values of the other studied characteristics are comparable (Table 6).

TABLE 5 RESULTS OF MECHANICAL TESTS OF VINYLESTER RESIN AND MWCNTS COMPOSITE

MWNTs [wt. %]	σ_m[MPa]	ε [%]	HSD	$KCV_{1/10,2}$ [J/cm^2]
0 wt. %	20.5	0	75.7	0.039
0.02 wt. %	45.2	0.8	86.3	0
0.06 wt. %	38.3	1.1	85.6	0.475
0.1 wt. %	31.5	0.7	84.9	0.588

TABLE 6 RESULTS OF MECHANICAL TESTS OF VINYLESTER RESIN AND A-CARBON COMPOSITE

a-Carbon [wt. %]	σ_m[MPa]	ε [%]	HSD	$KCV_{1/10,2}$ [J/cm^2]
0 wt. %	20.5	0	75.7	0.039
0.02 wt. %	18.5	0.7	85.8	0.375
0.06 wt. %	26.9	0.9	84.2	0.350
0.1 wt. %	26.7	0.5	85.7	0.475

Table 6 presents the results of mechanical tests of composites made of vinylester resin “DISTITRON” VE 100 with amorphous carbon particles integrated into it. The minimum amount used of 0.02 wt. % leads to an increase in hardness, impact toughness and relative elongation at a comparable value of the tensile strength of the composite with that of the base resin. With increasing concentrations of the particles used, no significant changes are observed in the hardness of the composites, but the tensile strength increases. The highest value of relative elongation is registered at a quantity of 0.06 wt. % a-Carbon, and the highest value of impact toughness at 0.1 wt. % a-Carbon.

The development of innovative composite materials with a polymer matrix and carbon particles embedded in it, which should have increased mechanical and operational characteristics, including those intended for the construction of systems and devices for detecting and countering low-flying unmanned aerial vehicles, is a current engineering topic. This study examines the possibility of expanding the spectrum of composite materials with a polymer matrix by using thermosetting polymers and carbon particles. At present, waste amorphous carbon has found application mainly in the processing and vulcanization of rubber mixtures, due to its morphology and the average diameter of its particles. The results of the mechanical tests conducted show that in certain cases, composites with reinforcing waste amorphous carbon particles have properties competing with composites with MWCNTs integrated into them. Obtaining a machine-building material using a waste product, in addition to engineering, has an ecological and economic aspect. By implementing the waste obtained from an innovative technology for producing green hydrogen into a construction material, this technology becomes completely waste-free, i.e. it does not have a negative impact on the environment.

IV. Conclusions

The integration of 0.02 wt % amorphous carbon in an epoxy matrix leads to the production of a composite with an optimal set of mechanical properties.

The use of MWNTs in an amount of 0.1 wt. % is the reason for the production of a composite based on a polyester resin with the best balance of mechanical properties.

It has been established that waste amorphous carbon has a better effect on the mechanical properties of the developed composites with epoxy and polyester resin bases.

The used MWCNTs have a more favorable effect on the mechanical properties of the vinylester resin compared to amorphous carbon. It has been established that at all three used concentrations of carbon nanotubes, composites with increased mechanical properties were obtained.

Acknowledgments: The authors would like to thank the European Regional Development Fund within the OP "Research, Innovation and Digitalization Programme for Intelligent Transformation 2021-2027", Project № BG16RFPR002-1.014-0005 Center of competence "Smart Mechatronics, Eco- and Energy Saving Systems and Technologies"

REFERENCES

[1] B. Dochev; D. Dimova; M. Zagorski; F. Ublekov; N. Tomanov; D. Valeva, „Investigation of the Mechanical Properties of Thermosetting Polymers Reinforced with Carbon Particles". Eng. Proc. 2025, 100, 21. https://doi.org/10.3390/engproc2025100021

[2] A. Abd El-Moez Mohamed, M. Mohamed, „2-Carbon nanotubes: Synthesis, characterization, and applications". Carbon Nanomaterials for Agri-Food and Environmental Applications, 2020, pp. 21-32 https://doi.org/10.1016/B978-0-12-819786-8.00002-5

[3] N. Gupta, S.M. Gupta, S.K. Sharma, „Carbon nanotubes: synthesis, properties and engineering applications". Carbon Letters Volume 29, 2019, pp. 419-447 https://doi.org/10.1007/s42823-019-00068-2

[4] A. Kausar, I. Rafique, B. Muhammad, „Review of Applications of Polymer/Carbon Nanotubes and Epoxy/CNT Composites". Polymer-Plastics Technology and Engineering 2016, Volume 55, pp.1167–1191 https://doi.org/10.1080/03602559.2016.1163588

[5] A. Iqbal, A. Saeed, A. Ul-Hamid, „A review featuring the fundamentals and advancements of polymer/CNT nanocomposite application in aerospace industry". Polymer Bulletin 2021, Volume 78, pp. 539–557 https://doi.org/10.1007/s00289-019-03096-0

[6] S. Hema, C.U. Greeshma, S. Malavika, K. R. Sulthan, S. Sambhudevan, „8 - Polymer blend nanocomposites with CNTs for energy storage applications". Polymer Blend Nanocomposites for Energy Storage Applications 2023, pp. 241-270 https://doi.org/10.1016/B978-0-323-99549-8.00020-0

[7] N. M. Nurazzi, M.R.M. Asyraf, A. Khalina, N. Abdullah, F.A. Sabaruddin, S.H. Kamarudin, S. Ahmad, A.M. Mahat, C.L. Lee, H.A. Aisyah et al., „Fabrication, Functionalization, and Application of Carbon Nanotube-Reinforced Polymer Composite: An Overview". Polymers 2021, Volume 13, 1047 https://doi.org/10.3390/polym13071047

[8] R. K. Prusty, D. K. Rathore, B. C. Ray, „CNT/polymer interface in polymeric composites and its sensitivity study at different environments". Advances in Colloid and Interface Science 2017, Volume 240, pp. 77-106 https://doi.org/10.1016/j.cis.2016.12.008

[9] M.T. Byrne, Y. K. Gun'ko, „Recent Advances in Research on Carbon Nanotube–Polymer Composites". Advanced Materials 2010, Volume22, Issue15, pp. 1672-1688. https://doi.org/10.1002/adma.200901545

[10] M. Tarfaoui, K. Lafdi, A. El Moumen, „Mechanical properties of carbon nanotubes based polymer composites". Composites Part B: Engineering 2016, Volume 103, pp. 113-121. https://doi.org/10.1016/j.compositesb.2016.08.016

[11] M. R. Zakaria, H. Md Akil, M. H. Abdul Kudus, F. Ullah, F. Javed, N. Nosbi, „Hybrid carbon fiber-carbon nanotubes reinforced polymer composites: A review". Composites Part B: Engineering 2019 Volume 176, 107313. https://doi.org/10.1016/j.compositesb.2019.107313

[12] A.V. Desai, M.A. Haque, „Mechanics of the interface for carbon nanotube–polymer composites". Thin-Walled Structures 2005, Volume 43, Issue 11, pp. 1787-1803. https://doi.org/10.1016/j.tws.2005.07.003

[13] B. Arash, Q. Wang, V. Varadan, „Mechanical properties of carbon nanotube/polymer composites". Sci Rep 4, 6479 (2014). https://doi.org/10.1038/srep06479

[14] T. Takeda, Y. Shindo, Y. Kuronuma, F. Narita, „Modeling and characterization of the electrical conductivity of carbon nanotube-based polymer composites". Polymer 2011, Volume 52, Issue 17, pp. 3852-3856. https://doi.org/10.1016/j.polymer.2011.06.046

[15] X. Sun, H. Sun, H. Li, H. Peng, „Developing Polymer Composite Materials: Carbon Nanotubes or Graphene?". Advanced Materials 2013, Volume25, Issue37, pp. 5153-5176. https://doi.org/10.1002/adma.201301926

[16] M. Tarfaoui, A. El Moumen, K. Lafdi, „Progressive damage modeling in carbon fibers/carbon nanotubes reinforced polymer composites". Composites Part B: Engineering 2017, Volume 112, pp. 185-195. https://doi.org/10.1016/j.compositesb.2016.12.056

[17] B. Dassan, G. Emayaruba, A. Ab Rahman, A. Abidin, M. S. Zainol, A. Hazizan Md, „Carbon nanotube–reinforced polymer composite for electromagnetic interference application: A review". Nanotechnology Reviews 2020, Volume 9, pp. 768-788. https://doi.org/10.1515/ntrev-2020-0064

[18] G. Franchi, M. Capocelli, M. De Falco, V. Piemonte, D. Barba, „Hydrogen Production via Steam Reforming: A Critical Analysis of MR and RMM Technologies". Membranes 2020, Volume 10. https://doi.org/10.3390/membranes10010010

[19] N. A. K. Aramouni, J. G. Touma, B. A. Tarboush, J. Zeaiter, M. N. Ahmad, „Catalyst design for dry reforming of methane: Analysis review". Renewable and Sustainable Energy Reviews 2018, Volume 82, Part 3, pp. 2570-2585 https://doi.org/10.1016/j.rser.2017.09.076

[20] G. Voitic, V. Hacker, „Recent advancements in chemical looping water splitting for the production of hydrogen". RSC Advances 2016, Issue 100, https://doi.org/10.1039/C6RA21180A

[21] L. Alves, V. Pereira, T. Lagarteira, A. Mendes, „Catalytic methane decomposition to boost the energy transition: Scientific and technological advancements". Renewable and Sustainable Energy Reviews 2021, Volume 137, 110465 https://doi.org/10.1016/j.rser.2020.110465

[22] P. Arku, B. Regmi, A. Dutta, „A review of catalytic partial oxidation of fossil fuels and biofuels: Recent advances in catalyst development and kinetic modelling“. Chemical Engineering Research and Design 2018, Volume 136, pp. 385-402 https://doi.org/10.1016/j.cherd.2018.05.044

[23] F.M.Alptekin, M.S. Celiktas, „Review on catalytic biomass gasification for hydrogen production as a sustainable energy form and social, technological, economic, environmental, and political analysis of catalysts“. ACS Omega 2022, Volume 7, https://doi.org/10.1021/acsomega.2c01538

[24] M. Cadek; J. N. Coleman; V. Barron; K. Hedicke; W. J. Blau, „Morphological and mechanical properties of carbon-nanotube-reinforced semicrystalline and amorphous polymer composites“. Appl. Phys. Lett. 81, 5123–5125 (2002), https://doi.org/10.1063/1.1533118

[25] S. Shekhar, V. Prasad, S.V. Subramanyam, „Transport properties of conducting amorphous carbon–poly(vinyl chloride) composite“. Carbon 2006, Volume 44, Issue 2, pp. 334-340. https://doi.org/10.1016/j.carbon.2005.07.018

[26] X. M. Dong, R. W. Fu, M. Q. Zhang, B. Zhang, M. Z. Rong, „Electrical resistance response of carbon black filled amorphous polymer composite sensors to organic vapors at low vapor concentrations“. Carbon 2004, Volume 42, Issues 12–13, pp. 2551-2559. https://doi.org/10.1016/j.carbon.2004.05.034

[27] J. Kalfus, J. Jancar, „Reinforcing mechanisms in amorphous polymer nano-composites“. Composites Science and Technology 2008, Volume 68, Issues 15–16, pp. 3444-3447. https://doi.org/10.1016/j.compscitech.2008.06.004

[28] M.P. Ho, A.K.-T. Lau, „12 - Amorphous carbon nanocomposites“. Fillers and Reinforcements for Advanced Nanocomposites 2015, Woodhead Publishing Series in Composites Science and Engineering, pp. 309-328. https://doi.org/10.1016/B978-0-08-100079-3.00012-0

[29] S. Gupta, C. Chang, C.-H. Lai, N.-H. Tai, „Hybrid composite mats composed of amorphous carbon, zinc oxide nanorods and nickel zinc ferrite for tunable electromagnetic interference shielding“. Composites Part B: Engineering 2019, Volume 164, pp. 447-457. https://doi.org/10.1016/j.compositesb.2019.01.060

[30] Q. Xue, Q. Guo, B. Tao, Z. Han, J. Zhang, X. Pan, „Ultrahigh permittivity of polymer nanocomposites based on surface-modified amorphous carbon/MWCNTs shell/core structured nanohybrids“. Composites Part A: Applied Science and Manufacturing 2017, Volume 100, pp. 324-332. https://doi.org/10.1016/j.compositesa.2017.05.027