

Application of Polysulfone Cardo Copolymer in Epoxy Resin Binders for the Production of Carbon Fiber Reinforced Plastics

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Abstract Carbon-fiber-reinforced plastics (CFRP) with improved mechanical properties based on modified epoxy binders were investigated in this study. By adding 15 parts by weight (p.b.w.) of copolymer of polysulfone with cardo phthalide group (PSFP-70C) to the epoxyanhydride binder, the flexural strength of the epoxy polymer was increased by 60%, the CFRP based on it by 57%, the flexural modulus of the epoxy polymer was increased by 83%, and the composite by 96%. The adhesion strength of the binder to carbon fiber reached a high level at 10 p.b.w. of thermoplastic modifier and increased by 65% compared to the unmodified binder. Scanning electron microscopy (SEM) was used to determine that in epoxyanhydride systems with a polysulfone content of 5–15 p.b.w., the structure belongs to the "matrix dispersion" type and with a content of 20 p.b.w. to the "interpenetrating phase" type. A heterogeneous structure was also observed using dynamic mechanical analysis.

Keywords Adhesion strength; Carbon-fiber-reinforced plastics; Epoxy resin; Polysulfone; Cardo polymers; Vacuum-assisted resin transfer molding

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INTRODUCTION

Epoxy resins are widely used as matrix materials in the manufacture of polymer composites. The utilization of polymer composites has applications in myriad industries, including the automotive, aerospace, and shipbuilding industries. In such fields, the significance of composite materials lies in their capacity to exhibit low density, enhanced corrosion resistance, and resistance to crack propagation, which are of paramount importance in the development of products for these industries. To improve the mechanical properties of the end products, the most appropriate way to modify epoxy resins is to introduce heat-resistant thermoplastics into the matrix.^[1–3] Because the phase structure has a significant influence on the mechanical properties of the materials, the question of phase equilibrium and interdiffusion of the components is important when modifying epoxy resins with thermoplastics, which is the subject of researches.^[4–7]

Epoxy resin was cured with methyltetrahydrophthalic anhydride, and polyetheretherketone was added as a modifier up to 7% by weight in a study.^[8] An increase of 33% in tensile strength, 36% in three point bending, and some increase in compressive strength was observed. Simultaneously, the corresponding elastic modulus was improved. The increase in the mechanical characteristics can be explained by the formation of a new heterogeneous structure of the "matrix-dispersion" type, where the dispersed phase is enriched with a ther-

moplastic modifier.

The introduction of 15.36 wt% polyphenylene oxide resulted in an improvement in tensile and flexural strength, which may be due to the heterogeneous matrix-dispersion type structure in the epoxy polymer as determined by scanning electron microscopy.^[9] The dispersed particles in this system are enriched with polyphenylene oxide. However, when the same amount of polysulfone was introduced, an "inverted matrix dispersion" was obtained, where the quasi-spherical particles were already enriched with cured epoxy. It should be noted that in this case, the mechanical properties were inferior to those of the neat epoxy polymer. The "interpenetrating phase" type structure was obtained in Ref. [10] when the polysulfone content in the epoxy polymer was 13 wt% and in Ref. [11] when the polyethersulfone content in the epoxy polymer was 15 and 20 parts by weight (p.b.w.) per 100 p.b.w. of epoxy resin. The crack resistance of the epoxy polymer increased steadily with increasing thermoplastic content, but the impact strength and tensile strength reached a maximum at a polyethersulfone content of 10 p.b.w. and at the achievement of the "matrix dispersion" type structure present in this material.

In Ref. [12], the authors found that the addition of polysulfone reduced the degree of conversion of epoxy binders because the glass transition temperature of the material decreased. However, owing to its phase structure, the modified epoxy polymer exhibited improved flexural properties, stress intensity factor, and impact strength. Structural changes in materials based on epoxy binders, when modified with thermoplastics, have also been observed in reinforced plastics. For example, dispersed inclusions were observed in scanning

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electron microscopy (SEM) images of fracture surfaces of carbon fiber reinforced plastic samples.^[13] Here, the interlayer reinforcement of carbon fiber-based polymer composites with polyphenylenesulfide increased the crack initiation and propagation energies by 134% and 345%, respectively.

In Ref. [14], when epoxy oligomer was modified with polyetherimide, a significant increase in the crack resistance of the matrix and the carbon fiber reinforced plastic (CFRP) based on it was observed by 360% and 80%, respectively, at a thermoplastic content of 25 wt%. This is due to the formation of "interpenetrating phases" in this sample. The addition of polyetherimide also resulted in a 70% increase in impact toughness, which is explained by the high impact toughness of the thermoplastic itself. Polyetherimide was also added to epoxy binders in Ref. [15], resulting in an increase in flexural strength and modulus of elasticity of 20% and 17%, respectively, at a thermoplastic content of 2 wt% and a two-fold increase in stress intensity factor at the same modifier content. The infrared (IR) spectra of the modified polymer revealed a shift towards lower wavenumbers of the peak characteristic of the hydroxyl group, which the authors attributed to the formation of hydrogen bonds between the imide groups of the polyetherimide and the hydroxyl groups of the epoxy resin.

The use of polyethersulfone with cardo groups in Ref. [16] allowed the glass transition temperature (T_g) of the epoxy polymer to increase by 19 °C, which the authors attributed to the possibility of the cardo groups being involved in the curing process. This assumption was supported by the homogeneous structure observed in the electron micrographs. The most widely used method for determining the adhesive strength of composites is "pull-out." In Ref. [17], unmodified epoxyanhydride binders with an average adhesion strength of 30 MPa were studied using this method. With the addition of thermoplastics to the matrix, a decrease in this parameter can be observed; as for example in Ref. [18]. When epoxy oligomer was modified with polysulfone, the adhesion strength decreased by 18 MPa at a modifier content of 10% by mass. This may be because of the low adhesion of the thermoplastic to the filler.

There appears to be a paucity of research data available in the extant literature on the effect of cardo polysulfones used as modifiers on the properties of both epoxy polymers and reinforced plastics based on epoxy resins. The aim of this work is to develop a thermoplastic-modified epoxy binder with improved mechanical properties and a carbon fiber-reinforced plastic that can be used in the aircraft industry.

MATERIALS AND METHODS

Materials

In this work, binders based on epoxy oligomer Diglycidyl Ether

of Bisphenol A (DGEBA) grade ED-20 (GOST 10587-84, FSUE "Ya.M. The Sverdlov Plant", Dzerzhinsk, Russian Federation). The binder hardeners used were isomethyltetrahydrophthalic anhydride (iso-MTHPA, produced by Shanghai Institute of Chemical Industry Testing Co., LTD (Shanghai, China)) and 2-methylimidazole (Acros Organics Bvba, Geel, Belgium) as a curing accelerator. The epoxy binders were modified with a thermoplastic copolymer of polysulfone with cardo phthalide group grade PSFP-70C (JSC "G.S. Petrov Institute of Plastics", Moscow, Russian Federation), T_g of 236 °C, viscosity number of 40.6 mL/g, the chemical formula of which is shown in Fig. 1. Carbon laminates were produced from UMT 40-3K-EP (UMATEX JSC, Moscow, Russian Federation) equal-strength carbon fabric, 2 × 2 twill weave, with an epoxy-compatible coating on the fiber surface.

Preparation of Epoxy Polymers

The epoxy resin was mixed with 5, 10, 15, and 20 parts by weight (p.b.w.) of PSFP-70C per 100 p.b.w. of DGEBA. The mixture was stirred with an axial turbine type stirrer until the thermoplastic was completely dissolved at 110 °C with temperature ramp 10 °C/min for 2 h to 3 h. The stirring speed was 150 r/min. The binders were then cooled to 60 °C and iso-MTHPA was added at 80 p.b.w. per 100 p.b.w. of DGEBA and 2-methylimidazole in an amount of 0.2 p.b.w. per 100 p.b.w. of DGEBA was added and stirred until homogeneous mixtures were obtained. The binders were then degassed in a thermovacuum oven at 60 °C temperature and a 0.08 MPa vacuum for 30–40 min to remove air bubbles. The binders were then poured into fluoroplastic molds and cured in an oven under a step-by-step regime of 90 °C for 3 h and 120 °C for 12 h.

Preparation of CFRP

Vacuum-assisted resin transfer molding (VARTM)^[19] was used to produce the reinforced plastics. A schematic of the VARTM system is shown in Fig. 2. This method is based on the pressure difference between the vacuum pressure and environmental pressure, which causes the resin to be injected. The cleaned steel mold was lubricated with a mold release agent to facilitate the removal of CFRP after curing. The precut dry-fabric reinforcement was layered. A layer of peel ply was placed on top to separate the CFRP from the vacuum bag. This was followed by a flow medium to allow air to escape and distribute the binder evenly over the fabric reinforcement area. A spiral tube attached to the vacuum outlet was used as the resin distribution channel within the vacuum bag, which was connected to a resin inlet on one side of the bag (to supply binder) and to a vacuum pump on the other side of the bag (to vent and remove excess binder). The assembled package was sealed with a vacuum film, which was attached to the mold around the perimeter using sealant tape. Prior to composite manufacturing, the mold was tested for leak tightness by creating a vacuum inside the mold for 24 h. Then, after checking that the mold was hermetic, vacuum infusion was performed, and the binder was preheated to 60 °C with a

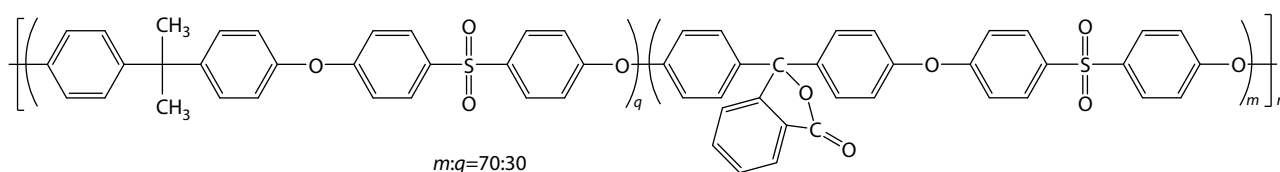


Fig. 1 The chemical formula of copolymer of polysulfone with cardo phthalide group PSFP-70C.

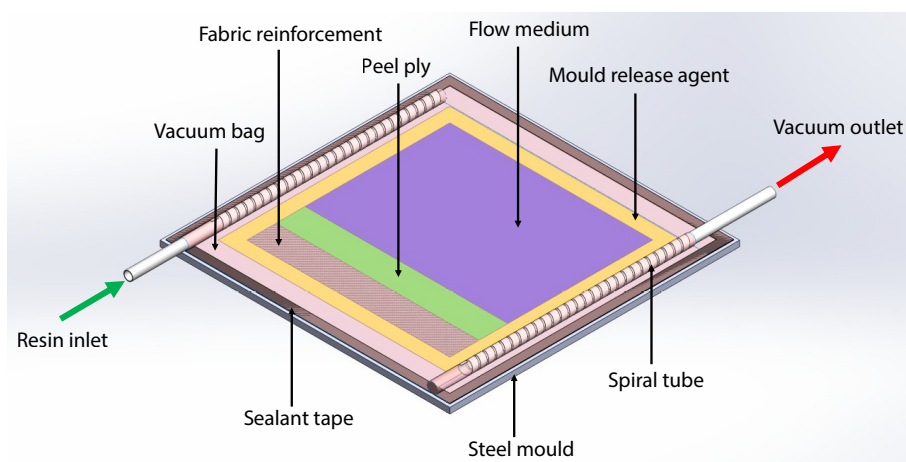


Fig. 2 Scheme of VARTM.

temperature ramp of 10 °C /min to decrease its viscosity and facilitate the impregnation of the carbon fiber. The pressure during infusion was 0.09 MPa vacuum. The binder temperature was maintained at 55 °C during impregnation. When the injection was complete, the vacuum line was shut off, and the mold was placed in an oven to cure according to the step-by-step regime: 90 °C for 3 h and 120 °C for 12 h.

Methods

The flexural strength and modulus were determined using a three-point scheme on a Tinius Olsen 50 ST testing machine (Tinius Olsen Testing Machine Company, Horsham, Pennsylvania, United States). For the epoxy polymers, tests were performed according to ISO 178:2010 with the following specimen dimensions: length of 80 mm, width of 10 mm, and thickness of 4 mm. The CFRP tests were performed according to ASTM D790-10 with the following specimen dimensions: length of 45 mm, width of 12.7 mm, and thickness of 2 mm. The speed of the moving crosshead in the testing machine was 5 mm/min. The morphology and structure of the epoxy polymers were studied by scanning electron microscopy (SEM) on a Thermo Scientific Quattro C (Thermo Fisher Scientific Inc., Waltham, Massachusetts, United States of America) on specimens pre-sprayed with activated carbon to provide an electrically conductive surface. Dynamic mechanical analysis (DMA) was performed on a Gabo Eplexor DMA instrument (NETZSCH, Selb, Germany) according to ISO 6721-11:2012. Optical microscopy was used to determine the effective fiber lengths required to calculate the adhesion strength values of the CFRP specimens fractured after flexural testing. Optical microscopy was performed using an OLYMPUS DSX 1000 metallographic microscope (Olympus Corporation, Tokyo, Japan).

RESULTS AND DISCUSSION

Flexural Properties of Epoxy Polymers

In the first part of the work, the effect of the thermoplastic modifier PSFP-70C on the flexural strength of epoxy anhydride polymers was studied (Fig. 3). The dependence of the flexural force on the displacement indicates the brittle nature of the epoxy polymer fracture, which is the same for all thermoplastic contents. The highest flexural strength (83 MPa) was observed for

the system with 15 p.b.w. PSFP-70C (Fig. 4), which surpassed the performance of the cured epoxy resin by 60%. With 20 p.b.w. thermoplastic, a slight decrease (about 8 MPa) in flexural strength was noted, probably because of a decrease in the degree of conversion due to the increased viscosity of the binder

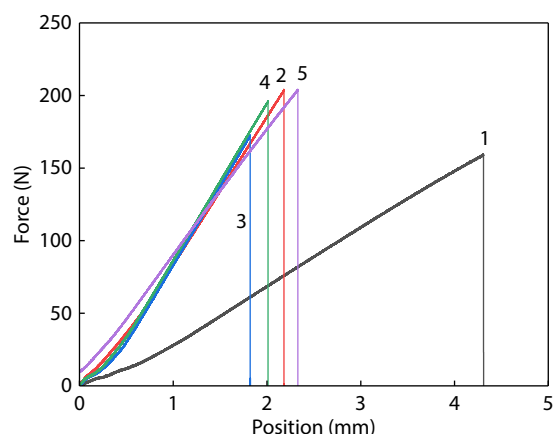


Fig. 3 Force-position diagram of epoxyanhydride polymers containing PSFP-70C: 1, 0 p.b.w.; 2, 5 p.b.w.; 3, 10 p.b.w.; 4, 15 p.b.w.; 5, 20 p.b.w.

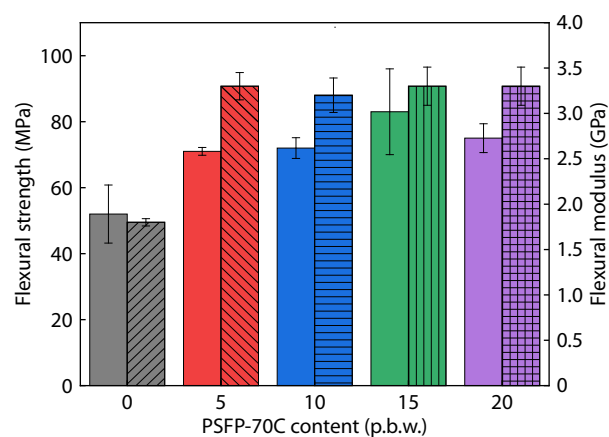


Fig. 4 Flexural strength (solid fill) and flexural modulus (patterned fill) of elasticity of epoxyanhydride polymers containing PSFP-70C.

containing 20 p.b.w. thermoplastic.

The flexural modulus of epoxyanhydride polymers was significantly changed by the modification of polysulfone copolymers with cardo copolymers. The introduction of even 5 p.b.w. PSFP-70C led to an increase in modulus by 83% compared to the unmodified polymer. Further increases in the thermoplastic content (10–20 p.b.w.) had almost no effect on the flexural modulus. The increase in modulus is probably due to the high modulus of PSFP-70C compared to that of the neat epoxyanhydride polymer.

Increasing the flexural modulus increased the stiffness, which was also reflected in the decreasing relative strain during bending (Fig. 5).

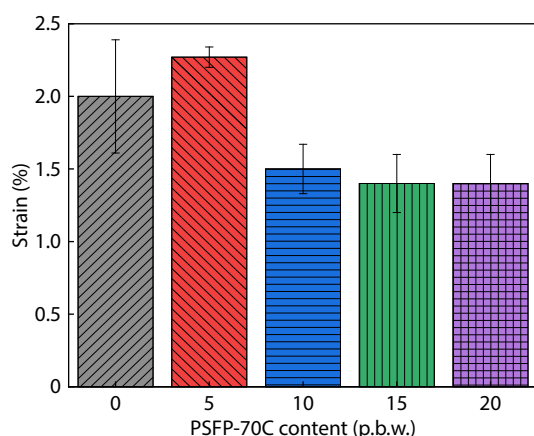


Fig. 5 Flexural strain of epoxyanhydride polymers containing PSFP-70C.

A binder containing of 5 p.b.w. PSFP-70C to 20 p.b.w. PSFP-70C shows a strain decrease of 0.4% to 0.6% compared to the unmodified epoxyanhydride polymer, which correlates with the increased stiffness of the system.

SEM-images of Epoxy Polymers

To understand the reasons for the improved mechanical properties of the modified systems, we studied their structure and morphology using scanning electron microscopy. Micrographs are shown in Fig. 6.

The unmodified epoxyanhydride polymer is characterized by a mirror-smooth surface, indicating a brittle fracture pattern (Fig. 6a) as well as epoxy polymers with 5 p.b.w. PSFP-70C (Fig. 6b). When modified with 10–15 p.b.w. PSFP-70C, the samples were characterized by a developed morphology where branched cracks were present, indicating a less brittle fracture type (Figs. 6c and 6d). This explains the improved strengths of the composites.

The neat epoxy polymer has a homogeneous structure (Fig. 7a). In Fig. 7, the structure of the epoxies shows that as the PSFP-70C content increased from 5 p.b.w. (Fig. 7b) to 10 p.b.w. (Fig. 7c), there was an increase in the size and number of dispersed particles enriched with thermoplastic. Furthermore, in the epoxy polymer containing 15 p.b.w. PSFP-70C (Fig. 7d), there is a tendency for the continuous phase enriched with thermoplastic to form as the quasi-spherical particles become closer together. Thus, epoxy polymers containing 5–15 p.b.w. polysulfone were characterized by the "ma-

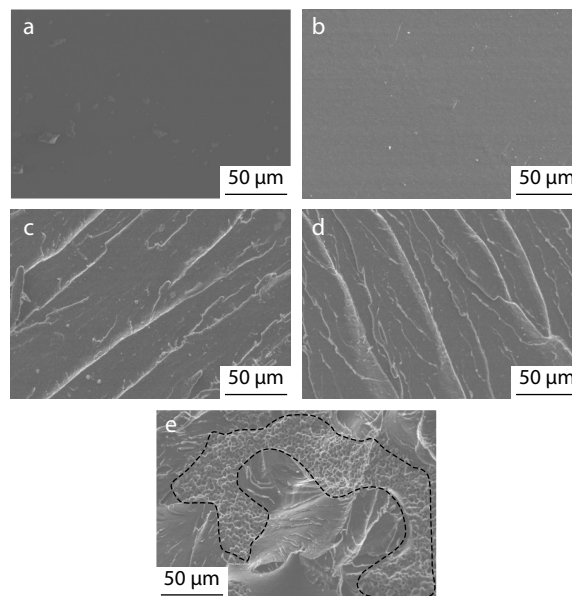


Fig. 6 Morphology of epoxyanhydride polymers containing PSFP-70C: (a) 0 p.b.w.; (b) 5 p.b.w.; (c) 10 p.b.w.; (d) 15 p.b.w.; (e) 20 p.b.w.

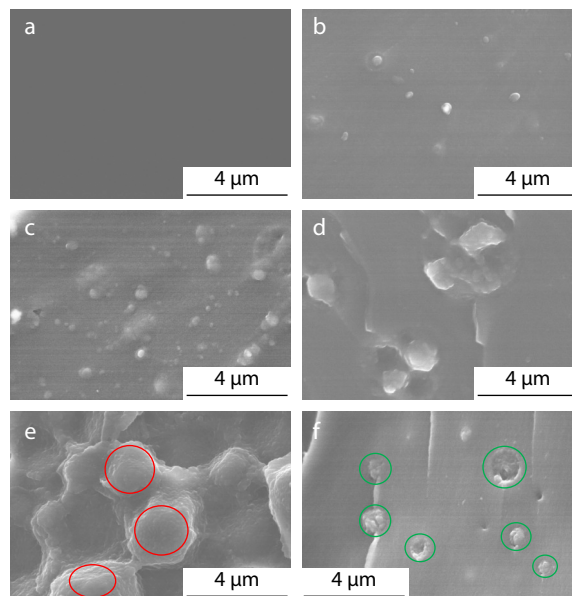


Fig. 7 Structure of epoxyanhydride polymers containing PSFP-70C: (a) 0 p.b.w.; (b) 5 p.b.w.; (c) 10 p.b.w.; (d) 15 p.b.w.; (e) 20 p.b.w., polysulfone riched area; (f) 20 p.b.w., epoxyanhydride riched area.

trix dispersion" type of structure.

With the addition of 20 p.b.w. of polysulfone cardo copolymer, a more complex structure was formed (Figs. 7e, 7f), in which two continuous phases, one enriched with a thermoset – dashed area and the other area enriched with thermoplastic (Fig. 6e). At the same time, the first continuous phase also contains dispersed particles enriched in thermoplastic (Fig. 7f, green circles), whereas in the second, these particles are enriched in thermoset (Fig. 7e, red circles), which allows us to describe the last one as an "inverted matrix dispersion".

Dispersed particles enriched with thermoplastics are

known to strengthen epoxy polymers. In heterogeneous structures, a crack encountering a thermoplastic-enriched particle may bypass it (increasing the crack path and hence the fracture energy), tear it away from the matrix (requiring additional energy to overcome the adhesive interaction), partially destroy it (again increasing the fracture energy), or a combination of the above mechanisms may occur at fracture.

In Fig. 7, the crack propagation paths through the thermoplastic modifier-enriched particles are clearly visible, and a combined failure mechanism under mechanical loading is observed. It is likely that when 15 p.b.w. PSFP-70C was modified, the heterogeneous material structure was the major contributor to the strengthening of the epoxyanhydride polymer. The sample containing 20 p.b.w. PSFP-70C, despite having a more advanced type of structure, exhibited a slightly reduced flexural strength compared to the polymer containing 15 p.b.w. modifier, probably because of the lower degree of conversion.

It was found that the introduction of PSFP-70C at a content of 5–20 p.b.w. leads to an increase of 37%–60% in flexural strength and 78%–83% in flexural modulus of epoxyanhydride polymers, owing to the formation of new heterogeneous structures.

Viscoelastic Properties of Epoxy Polymers

The heterogeneous nature of the obtained epoxy polymers

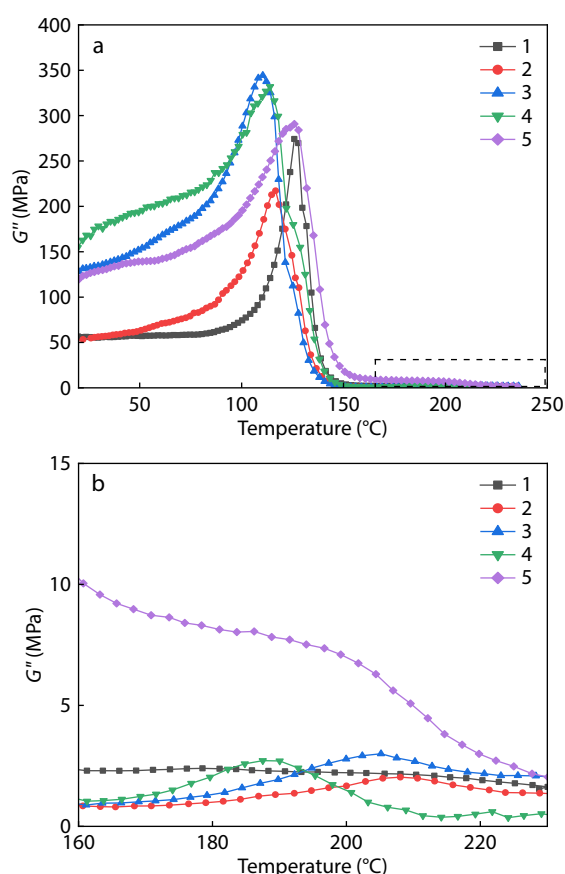


Fig. 8 Loss modulus versus temperature (a) and its enlarged dashed area (b) of epoxyanhydride polymers containing PSFP-70C. 1: 0 p.b.w.; 2: 5 p.b.w.; 3: 10 p.b.w.; 4: 15 p.b.w.; 5: 20 p.b.w.

modified with PSFP-70C was also confirmed by dynamic mechanical analysis (DMA), in which the loss modulus (G'') was plotted as a function of temperature (Fig. 8). The peaks in Fig. 8(a) correspond to the glass transition temperature of the epoxy-enriched phase (T_{g1}). In the higher temperature range (>170 °C), epoxy polymers modified with 5–15 p.b.w. polysulfone showed a second glass transition peak (T_{g2}) corresponding to the thermoplastic-enriched phase (Fig. 8b). In particular, T_{g2} was -31 °C to 46 °C lower than that of neat PSFP-70C (236 °C) (Table 1). This is because the epoxy oligomer had a plasticizing effect on the polysulfone-enriched phase. The higher the thermoplastic content, the greater the effect until the second glass transition peak is combined with the first, as in the case of 20 p.b.w. As the amount of epoxy oligomer increases in the modified epoxy polymers, it can be assumed that they are characterized by a reduced extent of conversion compared to neat epoxy polymers. This explains the 9 – 16 °C decrease in T_{g1} in the polysulfone-modified polymers compared to the unmodified epoxy polymer (Table 1). The introduction of polysulfone limits the interaction of the epoxy resin with the curing agent molecules, which is the reason for the decrease in the extent of conversion.^[12]

Mechanical Properties of CFRP

The effect of thermoplastic modifiers on the properties of CFRP was investigated in the second stage of this study. Fig. 9 shows the loading diagram for the CFRP. It can be seen that the fracture character is also brittle. The highest flexural strength index (1090 MPa) was observed for CFRP with 15 p.b.w. PSFP-70C (Fig. 10), which exceeded the values of unmodified composite material by 57%.

The composite with 20 p.b.w. thermoplastic showed a slight decrease in flexural strength (937 MPa) compared to

Table 1 DMA data of epoxyanhydride polymers.		
Polysulfone content (p.b.w.)	T_{g1} (°C)	T_{g2} (°C)
0	126	–
5	117	208
10	110	205
15	114	190
20	126	–

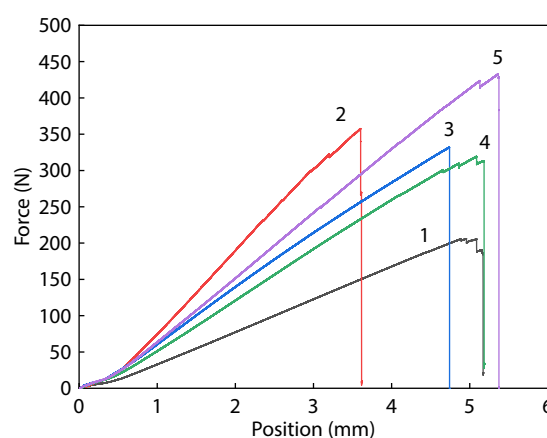


Fig. 9 Force-position diagram of CFRP containing PSFP-70C: 1, 0 p.b.w.; 2, 5 p.b.w.; 3, 10 p.b.w.; 4, 15 p.b.w.; 5, 20 p.b.w.

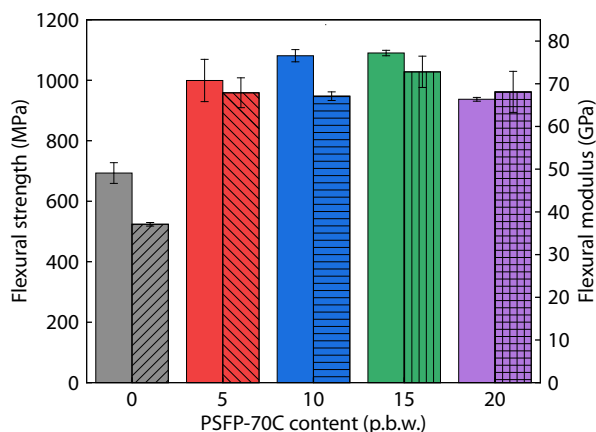


Fig. 10 Flexural strength (solid fill) and flexural modulus (patterned fill) of elasticity of CFRP containing PSFP-70C.

the 15 p.b.w. sample. The properties of carbon plastics correlate well with those of epoxy polymers. In particular, as shown above, the high modulus values of the matrices themselves are responsible for the increased strength of reinforced plastics based on modified binders.

The values of the flexural modulus of elasticity sharply increased with the addition of thermoplastic, which surpassed the values for the unmodified system by 96% at the PSFP-70C content in the matrix in the amount of 15 p.b.w. It can be seen that the introduction of different amounts of thermoplastic (from 5 p.b.w. to 20 p.b.w.) does not significantly affect the flexural modulus of the composite material, but the CFRP based on all modified matrices are significantly stiffer than the composite material based on the unmodified matrix. The effect of polysulfone on the flexural strain of the CFRP was also investigated (Fig. 11). It can be seen, the introduction of PSFP-70C has no significant effect on the flexural strain value of the reinforced plastics.

The fracture surfaces of the CFRP specimens were examined after the flexural tests. In this work, crack propagation in CFRP was investigated by optical microscopy, and the effective length of the carbon fiber at the fracture point of epoxy oligomer-based composite specimens was determined. From the optical micrographs taken using panorama imaging, it can be seen that the CFRP with the unmodified matrix (Fig.

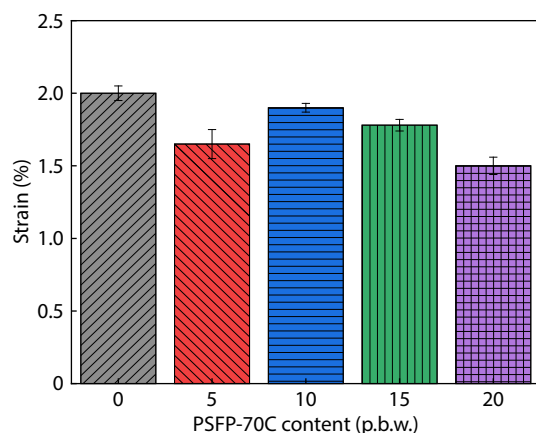


Fig. 11 Flexural strain of CFRP containing PSFP-70C.

12a) is characterized by the presence of a long main crack, which is 1.5 times longer compared of the modified specimen. This long crack suggests that these samples have reduced crack resistance, which is likely to be reflected in the physical and mechanical properties of the material. It can also be observed that the unmodified system shows delamination from the top of the sample, whereas the PSFP-70C modified system (Figs. 12b–12e) shows a deeper fracture with delamination of several filler layers, which may indicate a better adhesion strength in this system compared to the unmodified system. The micrographs also show the presence of fiber microbending, which is more significant in the modified system than in the unmodified system. In Fig. 12(b), the [1] refers to the left crack length and [2] refers to the right crack length.

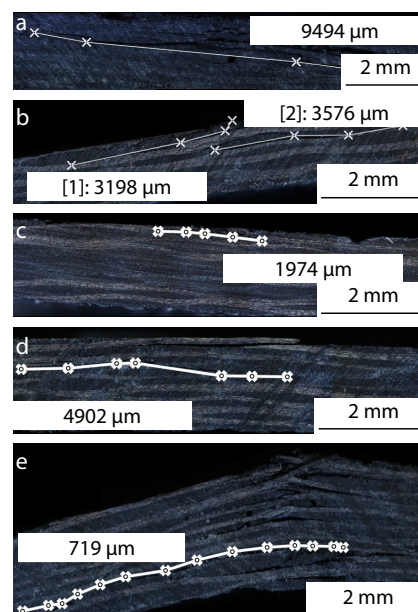


Fig. 12 Micrographs of the fracture surface after the flexural test of CFRP: (a) unmodified matrix; (b) matrix modified with 5 p.b.w. PSFP-70C, (c) matrix modified with 10 p.b.w. PSFP-70C, (d) matrix modified with 15 p.b.w. PSFP-70C, (e) matrix modified with 20 p.b.w. PSFP-70C obtained by panorama imaging.

There is no "kink-band" in the CFRP based on neat epoxy resin (Fig. 13a). Figs. 13(b)–13(e) show the formation of "kink-band" in the delamination region, probably due to high tangential stresses causing the fiber to be partially pulled out of the matrix. This could be due to the compressive forces between the fiber and matrix.

Adhesion of Polymer Matrixes to Carbon Fiber

In addition to the matrix stiffness, the interfacial adhesion at the fiber-binder interface determines the mechanical properties of reinforced plastics. The adhesion between the fiber and polymer matrix affects the strength properties of the composite, as it determines the effective redistribution of stresses in the material. The values of adhesion strength in CFRP based on the epoxyanhydride matrix modified with different contents of PSFP-70C were calculated using Eq. (1):

$$\sigma_A = \frac{E_d \epsilon}{4h} \quad (1)$$

where σ_A is the adhesive strength (MPa), E is Young's modulus of the fiber (MPa), d is the fiber diameter (μm), ϵ is the strain at break (%), and h is the critical length of the fiber (μm).^[20]

The values of Young's modulus, strain at break, and fiber diameter were taken from the TDS of the fiber from which the fabric used in this work was woven ($E=2.6\times10^5$ MPa, $\epsilon=1.5\%$,

$d=10\ \mu\text{m}$), and the effective fiber length was determined from optical micrographs of the samples after breakage at fiber pull-out regions (Fig. 14, red ellipses).

The values of the adhesion strength at the matrix-fiber interface from the PSFP-70C content in the binder are shown in Fig. 15 and are in agreement with the literature.^[21]

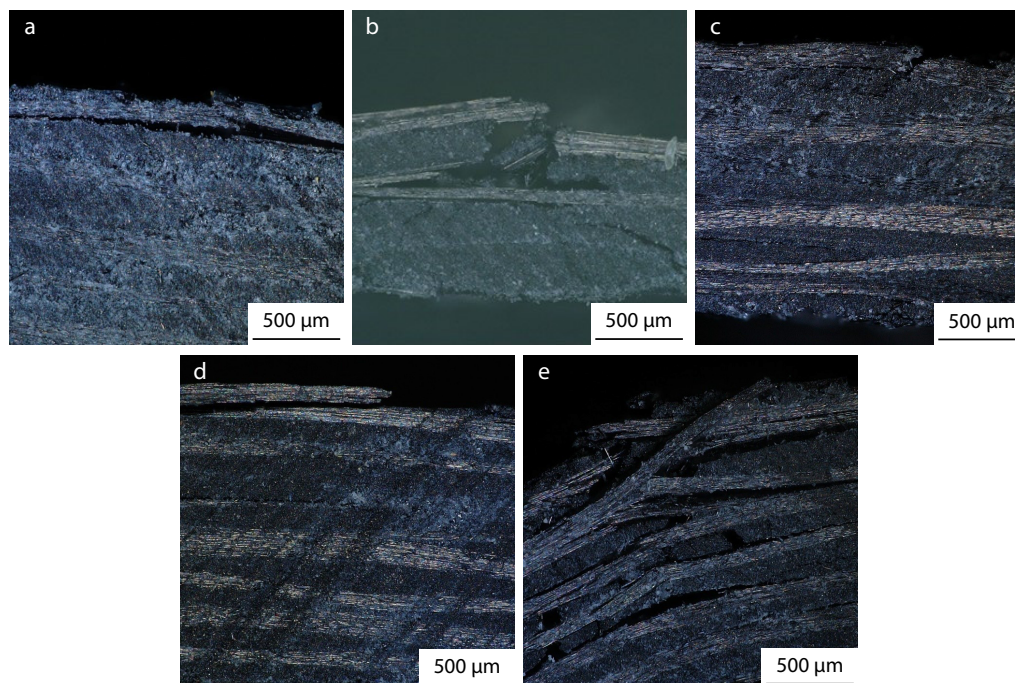


Fig. 13 Micrographs of the fracture surface after the flexural test of CFRP: (a) unmodified matrix, (b) matrix modified with 5 p.b.w. PSFP-70C, (c) matrix modified with 10 p.b.w. PSFP-70C, (d) matrix modified with 15 p.b.w. PSFP-70C, (e) matrix modified with 20 p.b.w. PSFP-70C.

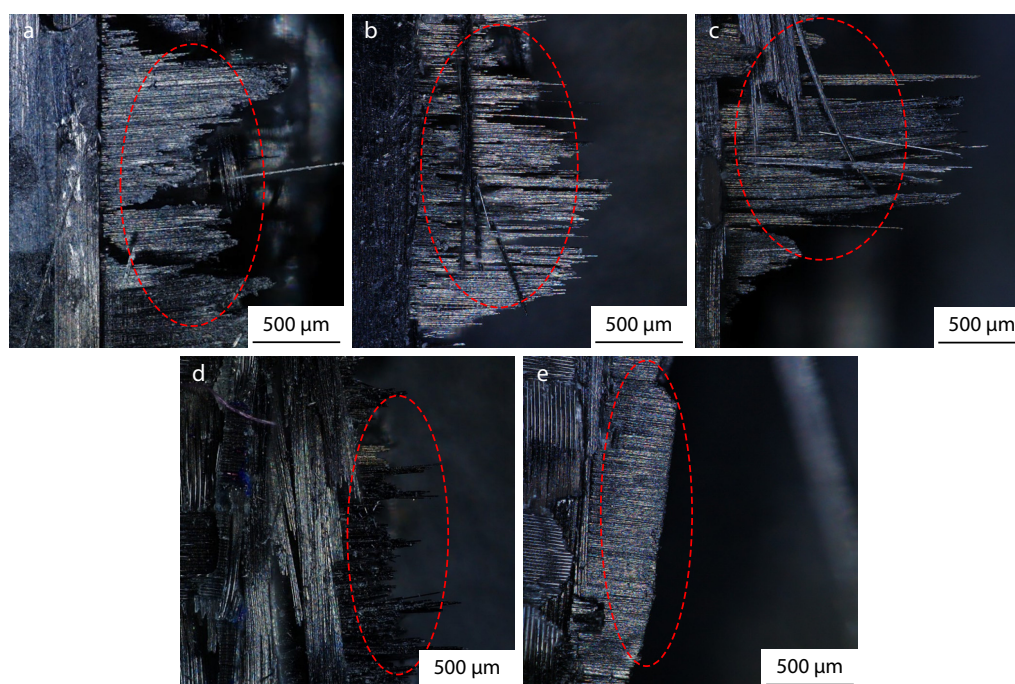


Fig. 14 Micrographs of the fracture surface after breakage of CFRP containing PSFP-70C: (a) 0 p.b.w.; (b) 5 p.b.w.; (c) 10 p.b.w.; (d) 15 p.b.w.; (e) 20 p.b.w.

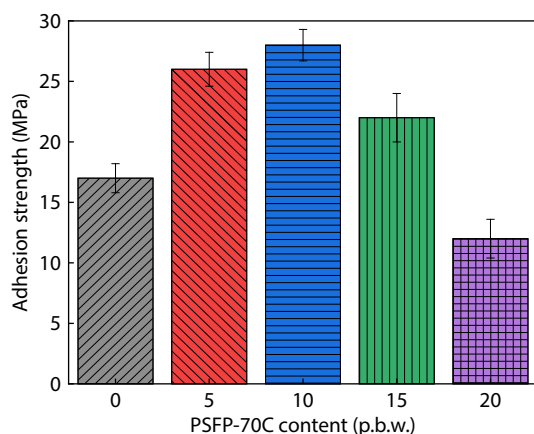


Fig. 15 Adhesion strength at the matrix-fiber interface of CFRP containing PSFP-70C.

The highest value was found in the system with 10 p.b.w. thermoplastic (28 MPa), which was 65% higher than the adhesion strength of CFRP based on unmodified matrix. This means that both the increased stiffness of the matrix itself and the improved adhesion strength are responsible for the strengthening of carbon plastics based on epoxy binders with 5–20 p.b.w. of thermoplastic.

CONCLUSIONS

Carbon plastics with improved mechanical properties have also been developed. The CFRP showed the most significant increase in flexural strength values with the addition of 5–15 p.b.w. thermoplastic, which surpasses the values of unmodified samples by 44%–57%. Modification of PSFP-70C by 5–20 p.b.w. also resulted in an increase in the stiffness of both the matrices themselves (78%–83%) and the composites (81%–96%). The adhesion strength at the fiber-matrix interface was also calculated for these systems. The highest value was found in the 10 p.b.w. PSFP-70C system, 65% higher than that of CFRP based on unmodified binder. The fracture surfaces of epoxyanhydride polymers containing PSFP-70C were analyzed by scanning electron microscopy, and heterogeneous structures of "matrix dispersion" and "interpenetrating phases were detected in the modified samples. A heterogeneous structure was also found by the DMA method, and it was shown that the introduction of polysulfone leads to a decrease in the glass transition temperature by 9–16 °C.

Conflict of Interests

The authors declare no interest conflict.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon request.

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REFERENCES

- Deng, H. Y.; Yuan, L.; Gu, A. J.; Liang, G. Z. Facile strategy and mechanism of greatly toughening epoxy resin using polyethersulfone through controlling phase separation with microwave-assisted thermal curing technique. *J. Appl. Polym. Sci.* **2020**, *137*, 48394.
- Chen, Z. G.; Luo, J.; Huang, Z.; Cai, C. Q.; Tusiime, R.; Li, Z. Y.; Wang, H. X.; Cheng, C.; Liu, Y.; Sun, Z. Y.; Zhang, H.; Yu, J. Y. Synergistic toughen epoxy resin by incorporation of polyetherimide and amino groups grafted MWCNTs. *Compos. Commun.* **2020**, *21*, 100377.
- Zhou, J. L.; Zhu, S.; Jia, W. P.; Cheng, C.; Hassan, E. A. M.; Yu, M. H. Curing process and heat-resistance of polyethersulfone toughened epoxy resins. *MSF* **2017**, *898*, 2302–2308.
- Ponomarenko, A. D.; Nikulova, U. V.; Shapagin, A. V. Phase equilibria and interdiffusion in the ternary system epoxy oligomer-polysulfone-alkyl glycidyl ether. *Polymers* **2024**, *16*, 130.
- Petrova, T. V.; Tretyakov, I. V.; Kireynov, A. V.; Shapagin, A. V.; Budylin, N. Y.; Alexeeva, O. V.; Beshtoev, B. Z.; Solodilov, V. I.; Yurkov, G. Y.; Berlin, A. A. Structure and properties of epoxy polysulfone systems modified with an active diluent. *Polymers* **2022**, *14*, 5320.
- Plyusnina, I. O.; Budylin, N. Y.; Shapagin, A. V. Phase equilibria, diffusion and structure in the epoxypolycaprolactone system. *Polymers* **2023**, *15*, 117.
- Shapagin, A. V.; Budylin, N. Y.; Chalykh, A. E.; Solodilov, V. I.; Korokhin, R. A.; Poteryaev, A. A. Phase equilibrium, morphology, and physico-mechanics in epoxy-thermoplastic mixtures with upper and lower critical solution temperatures. *Polymers* **2021**, *13*, 35.
- Zheng, T.; Xi, H.; Wang, Z. X.; Zhang, X. H.; Wang, Y.; Qiao, Y. J.; Wang, P.; Li, Q. W.; Li, Z. N.; Ji, C.; Wang, X. D. The curing kinetics and mechanical properties of epoxy resin composites reinforced by PEEK microparticles. *Polym. Test.* **2020**, *91*, 106781.
- Li, H. F.; Zhao, L. W.; Su, K.; Feng, H.; Wang, D. Z.; Qu, C. Y. A comparative study on the rheological, thermal, and mechanical performance of epoxy resin modified with thermoplastics. *J. Adhes. Sci. Technol.* **2021**, *35*, 1393–1403.
- Ling, Q. H.; Wang, D. Y.; Zhang, Y.; Lu, X. T.; Zhao, S. M.; Sun, F. L. Morphology, thermal and mechanical performance of epoxy/polysulfone composites improved by curing with two different aromatic diamines. *J. Appl. Polym. Sci.* **2020**, *137*, 49265.
- Jung, H. S.; Park, Y.; Nah, C. W.; Lee, J. C.; Kim, K. Y.; Lee, C. S. Evaluation of the mechanical properties of polyether sulfone-toughened epoxy resin for carbon fiber composites. *Fibres. Polym.* **2021**, *22*, 184–195.
- Sun, Z.; Xu, L.; Chen, Z.; Wang, Y.; Tusiime, R.; Cheng, C.; Zhou, S.; Liu, Y.; Yu, M.; Zhang, H. Enhancing the Mechanical and Thermal Properties of Epoxy Resin via Blending with Thermoplastic Polysulfone. *Polymers* **2019**, *11*, 461.
- Quan, D.; Yue, D. S.; Ma, Y. N.; Zhao, G. Q.; Alderliesten, R. On the mix-mode fracture of carbon fibre/epoxy composites interleaved with various thermoplastic veils. *Compos. Commun.* **2022**, *33*, 101230.
- Korokhin, R. A.; Solodilov, V. I.; Zvereva, U. G.; Solomatina, D. V.; Gorbakina, Y. A.; Shapagin, A. V.; Lebedeva, O. V.; Bamborin, M. Y. Epoxy polymers modified with polyetherimide. part II: Physicomechanical properties of modified epoxy oligomers and

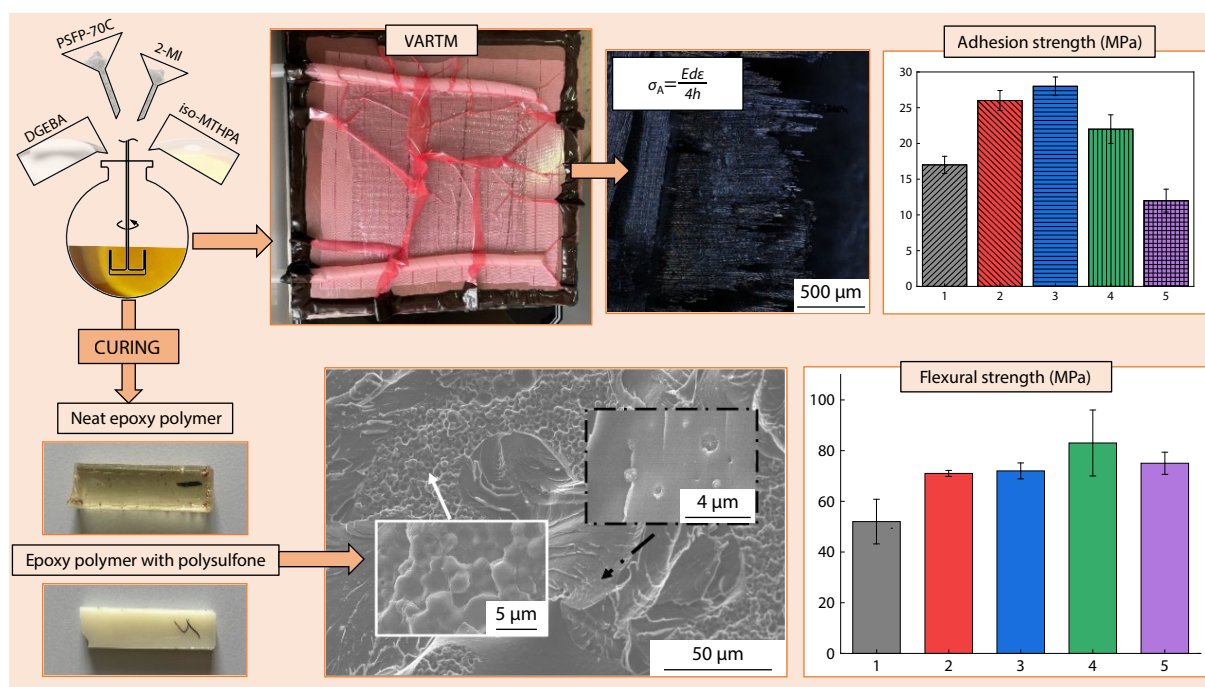
Graphical Abstract

Application of Polysulfone Cardo Copolymer in Epoxy Resin Binders for the Production of Carbon Fiber Reinforced Plastics

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The structure-properties relationship of epoxy polymers modified with polysulfone copolymer was determined. Carbon fiber-reinforced plastics containing cardo polysulfone as a modifier are characterized by increased crack resistance and adhesion strength.



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carbonfiberreinforced plastics based on them. *Polym. Bull.* **2020**, 77, 2039–2057.

- 15 Lee, S. Y.; Kang, M. J.; Kim, S. H.; Rhee, K. Y.; Lee, J. H.; Park, S. J. Roles of Small Polyetherimide Moieties on Thermal Stability and Fracture Toughness of Epoxy Blends. *Polymers* **2021**, 13, 3310.
- 16 Yan, C.; Wang, H. H.; Song, L. X.; Zhou, G. Y. Preparation, characterization, and performance of reactive phenolphthalein poly(aryl ether sulfone) tougheners highly compatible with epoxy resin. *J. Appl. Polym. Sci.* **2024**, 141, e55480.
- 17 Vyatkina, M. A.; Gorbatkina, Y. A.; Petrova, T. V.; Solodilov, V. I. Adhesive strength formation of the epoxy-anhydride matrix–fiber systems. *Russ. J. Phys. Chem. B* **2023**, 17, 1323–1329.
- 18 Tretyakov, I. V.; Petrova, T. V.; Kireynov, A. V.; Korokhin, R. A.; Platonova, E. O.; Alexeeva, O. V.; Gorbatkina, Y. A.; Solodilov, V. I.; Yurkov, G. Y.; Al Berlin, A. Fracture of epoxy matrixes modified

with thermo-plastic polymers and winding glass fibers reinforced plastics on their base under low-velocity impact condition. *Polymers* **2023**, 15, 2958.

- 19 Prabhakar, M. N.; Cabo, M. C.; Yu, R. W.; Gebrekstos Weldemhret, T.; Woo, L. D.; Jung-il, S. Surface flame retardancy of clay mineral powder infused onto the top of the layer of vinyl ester/bamboo composites through a modified VARTM process. *Polym. Test.* **2024**, 132, 108367.
- 20 Ilyin, S. O.; Kotomin, S. V. Effect of nanoparticles and their anisometry on adhesion and strength in hybrid carbon-fiber-reinforced epoxy nanocomposites. *J. Compos. Sci.* **2023**, 7, 147.
- 21 Zhu, T. Y.; Lu, C. X.; Lu, X. X.; Zhi, J. Y.; Song, Y. J. Interfacial and tensile properties improvement of composites using a modified matrix with epoxy-terminated hyperbranched polyether sulfone. *J. Appl. Polym. Sci.* **2022**, 139, e53169.

<https://doi.org/10.1007/s10118-025-3498-0>