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Mechanical characterization of composites containing carbonized furniture waste in static tensile testing

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ABSTRACT

The purpose of this study was to investigate the strength properties of a new composite material produced by hand lamination. There is a clear gap in the literature regarding the use of MDF-derived pyrolysis carbonizate as a functional component in composite materials. This study addresses that gap by proposing a novel composite in which the carbonizate acts as a filler. The tested composite consisted of carbonizate obtained through the pyrolysis of furniture waste, particularly MDF boards, along with glass mats containing fibers of different orientations and epoxy resin. The resulting carbonizate was crushed and separated by particle size using a sieving method. Composites with carbonizate contents of 5%, 7.5%, and 10% were produced, varying in terms of additive fraction size. Based on the current standard PN-EN ISO 527-4: 2023 28, samples were prepared for static tensile testing. SEM (scanning electron microscope) analysis of cross-sections of fractured composite samples was conducted, and the test results were evaluated in detail. The findings indicate that the addition of carbonizate weakens the mechanical strength of the composite by disrupting fiber–matrix adhesion and introducing structural defects. The material with a 10% carbonizate fraction of 1.5 mm exhibited a very high elastic modulus (E_t = 8708.78 MPa) and the lowest strain (ε = 0.82%) among the tested materials. Meanwhile, the composite with a 7.5% carbonizate content and a 0.5 mm fraction achieved the highest tensile strength (σ_m = 72.29 MPa). Microscopic analysis of the fracture surfaces revealed numerous pores, delamination, and cracks. This study pioneers the use of MDF-derived carbonizate as a filler in epoxy composites, analyzing particle size (0.5–1.5 mm) and loading content (5–10%). The optimal formulation (7.5%, 0.5 mm) enhanced mechanical strength, offering a sustainable solution for furniture waste valorization.

Keywords: carbonized composites, pyrolysis, strength properties, static tensile test, glass fibers.

INTRODUCTION

With the rapid development of the economy, rising consumption levels, and changing consumer preferences, the way furniture is used has undergone a significant transformation. The increasing frequency of furniture replacement and the accelerated pace of modernization contribute to the generation of large amounts of waste, both from discarded furniture and from the manufacturing process [1].

Furniture production generates significant amounts of wood waste, including wood scraps, wood dust, and residues from particleboard and MDF. These materials are often difficult to reuse due to the presence of adhesives, varnishes, and other chemical coatings. Most of the collected waste from medium-density fiberboard (MDF) is either burned or landfilled. A method for recycling it that is both economically viable and environmentally safe has not yet been developed [2]. During processing operations (cutting, milling, sanding), waste generation rates range from 10–30 kg/m^3 of processed material, increasing significantly during final furniture production stages. Furthermore, approximately 5–15% of finished product mass enters the waste stream after end-of-life, primarily through furniture dismantling [3] Studies show that boards produced entirely from particles obtained from the second grinding of particleboards using the mechanical recycling method exhibit a significant reduction in mechanical properties. [4]. Additionally, disposing of or recycling furniture materials is challenging because of the plastics, laminates, and foams used in their production, which can take decades to decompose in the environment.

The furniture manufacturing process also involves the use of chemicals, such as adhesives and varnishes, which can be toxic and complicate waste processing [5]. If not properly treated or disposed of, furniture waste (WFB) can release harmful substances, such as formaldehyde and volatile organic compounds, posing environmental hazards when dumped in landfills or burned under uncontrolled conditions.

Through pyrolysis, furniture board waste can be converted into fuels with a higher calorific value, reducing emissions of pollutants such as carbon oxides and fine dust. This process also enables the recovery of valuable chemical compounds, such as phenols, which can be used in industry as additives for fuels, dyes, or pharmaceuticals [6-8]. Pyrolysis is a thermochemical process that breaks down long-chain polymer molecules into smaller fragments under high temperatures and anaerobic conditions. It is highly reliable and flexible, as its parameters can be precisely controlled to achieve optimal product properties. Unlike direct combustion, which generates harmful emissions such as formaldehyde and volatile organic compounds, pyrolysis offers a more environmentally friendly alternative, allowing materials to degrade safely under controlled conditions.

Pyrolysis experiments were conducted in a laboratory solid bed reactor at different reaction temperatures of 350, 400, 450, 500 and 550 °C and a heating rate of 20 °C/min. The study observed that the pyrolysis temperature had a significant effect on product yields. The highest bio-oil yield, reaching 41.9% by weight, was recorded at 450 °C. Gas chromatography (GC) was used to analyze the chemical composition of the liquid oil product. The results confirm that pyrolysis of MDF can provide a source of renewable fuels while helping to reduce environmental problems related to waste [9].

To solve the problems associated with landfilling and incineration of MDF waste, an effective method of managing this waste has been developed, allowing it to be converted into lower quality fuel. In this study, MDF waste was used as a feedstock for pyrolysis biofuel production due to its high organic material content [1]. Pyrolysis products, such as carbonizate and bio-oil, have market value and can find applications in both the energy sector and the chemical industry. Such an approach not only valorizes waste material but also supports the principles of circular economy and sustainable materials development. Furthermore, the utilization of MDF waste aligns with the objectives of a circular economy, offering an environmentally responsible alternative to conventional fillers. The carbonizate derived from the pyrolysis of MDF furniture boards represents a currently underutilized by-product, which-given its carbon-rich composition-should be effectively integrated into material applications to minimize environmental impact.

Waste is increasingly being used to create new materials [4]. One example is the use of fly ash as an additive in concrete. Fly ash can serve as a substitute for cement, reducing cement consumption and providing both environmental and economic benefits [4, 10, 11].

The significant reserves of oil shale indicate its continued use as an energy source in the cement industry. However, the large amounts of oil shale ash (OSA) generated in this process can have negative environmental impacts. For this reason, researchers are exploring alternative methods to recycle and repurpose OSA in various applications [12].

Composites are increasingly being used in areas such as construction, infrastructure, energy and automotive industries due to their outstanding mechanical properties and durability. In recent years, there has been a noticeable increase in research interest in lightweight composite materials [13]. Mainly glass fibers (GFs) and carbon fibers (CFs) have been widely used in the production of advanced polymer composites. Due to their customized properties and unique characteristics, such as high strength, flexibility and stiffness. Glass fiber reinforced composites (GFRPs) and carbon fiber reinforced composites (CFRPs) are produced using various technologies and have found wide application in various engineering fields [14, 15]. Combinations of carbon and glass fiber composites, manufactured using the hand lay-up method, were studied. The research allowed for the evaluation of composites in terms of mechanical properties in tensile and flexural tests. Composites consisting solely of carbon fibers exhibited the highest mechanical strength and stiffness, both in flexural tests (380 MPa, 40 GPa) and tensile tests (504 MPa, 5.36 GPa). The addition of glass fiber provided an optimal balance between mechanical strength, material availability, and cost-effectiveness. However, the inclusion of basalt and its combination with glass fiber resulted in reduced strength and stiffness. Glass fibers are reinforcing materials [14] and glass fibers have high tensile and compressive strengths, which makes composites based on them highly resistant to loading [16]. They are flexible, allowing composites to be formed into a variety of shapes, depending on design needs. Fiberglass is valued for its unique properties, such as low weight, high tensile strength, corrosion resistance, excellent strength-to-weight ratio, high stiffness and low thermal expansion [17].

Based on the research conducted so far, it is possible to determine the desired properties of the composite material – a carbon-epoxy composite (laminate). Some studies have made it possible to present an approximate research methodology, allowing the determination of approximate values of the composite material (mean values with standard deviation), for mechanical (elastic), as well as strength properties. Based on the conducted tests and referring to the average values, Young's modulus was estimated depending on the direction of fiber arrangement. Composite materials are a special group of materials with significant differences in stiffness and strength depending on the direction of loading. Key principles and characteristics of the microcellular foaming process (MCP) were studied to reduce warping in glass-fiber-reinforced polymer (GFRP), which tends to be more severe than in solid polymer. The effect of glass fiber content (GFC) on warpage was analyzed, taking into account two key factors: reduction of shrinkage difference and directionless fiber orientation. Shrinkage was measured both in the flow direction and in the transverse direction, confirming that the shrinkage difference between these directions is the main cause of warping of GFRP samples [18].

Carbon fibre and graphite have a very large role in the production of composites. They are attractive due to their low coefficient of thermal expansion, thermal stability and chemical resistance The mechanical properties of the fibres must be obtained by measuring the corresponding properties of the composites [19, 20]. In the work of Wieczorska et al. composite materials were made by hand lamination with 10% polyester-glass recyclate and also nano-added graphite [21]. In this study, it was shown that the addition of 5% graphite powder to a matrix with 10% recycled polyester-glass resulted in a slight deterioration of mechanical properties compared to materials without graphite powder. Thus, graphite powder does not increase the mechanical properties of composites with recycled polyester-glass, but may have a positive effect on other properties.

Experimental tests were carried out: static tension, shear and compression on carbon-epoxy composite, in order to determine material properties for thin-walled composite structures – made of carbon-epoxy composite. Tests were conducted on 5 different types of specimens. The tests were carried out using a Zwick Z100 universal testing machine (UTM), under room temperature conditions, using two types of test heads that allow static experimental tests. The tests proved that composite materials are a special group of materials with significant differences in stiffness and strength depending on the direction of loading [22].

Carbon fiber composites, which have been used to date, take advantage of their ability to store and release large amounts of thermal energy during phase transitions, making them suitable for renewable energy systems and their various applications. Carbon fibers are characterized by light weight, high tensile modulus, high thermal conductivity and dimensional stability [23, 24]. Many works have discussed the effects of carbon fiber reinforcement on the mechanical, tribological and morphological properties of various metal matrix materials. Various processing techniques of carbon fiber reinforced composite material are used to develop processing in closed-loop composites [25].

The carbonizate obtained from the waste pyrolysis process, which is a material with a high carbon content, has interesting properties that can significantly affect the structure and characteristics of epoxy composites. The pyrolysis process, which involves the thermal decomposition of materials under anaerobic conditions, makes it possible to obtain carbon-rich products that can act as an effective reinforcement in polymer matrices. Adding carbonizate to epoxy composites can result in improved mechanical and thermal performance, as well as increased resistance to external agents [26]. In addition, the pyrolysis process of MDF enables efficient waste conversion, which supports the idea of circular economy, which is crucial for sustainable construction. Studies have shown the significant potential of carbonizate from carpentry waste as an additive to improve the hardness of epoxy composites, especially in terms of using industrial waste in recycling processes [8]. According to research by Wieczorska et al., the presence of carbonizate significantly increased the hardness of the composites. The analysis focused on composite samples consisting of glass fiber, carbonizate – a product of the pyrolysis of woodworking waste-and epoxy resin. Each sample containing 5% and 7.5% carbonizate exhibited higher hardness compared to the sample composed solely of glass fiber and resin. The greatest increase in hardness was observed in the sample containing 7.5% carbonizate and 32.5% glass fiber, which reached carbonizate, which-given a value of 33.6 HBa. To assess the quality of the samples, the Kruskal-Wallis test was applied, enabling the comparison of ranges and deviations and identifying this sample as the most homogeneous in terms of hardness [27]. There is a clear gap in the literature regarding the use of MDF-derived pyrolysis carbonizate as a functional component in composite materials. This study addresses that gap by proposing a novel composite in which the carbonizate acts as a filler. Such an approach not only valorizes waste material but also supports the principles of circular economy and sustainable materials development.

The literature increasingly examines the use of alternative reinforcing materials in composites, driven by both environmental and economic considerations. In their study, Herath et al. (2020) demonstrated that fly ash addition to concrete can enhance its compressive strength while reducing cement consumption, thereby providing environmental benefits [10]. In our case, the MDF waste-derived carbonizate, while similarly serving as a filler, showed less favorable effects on tensile strength. This difference may originate from distinct particle morphology and interfacial interactions with the matrix. For instance, Scheibe et al. (2023) demonstrated that hemp fiber-reinforced composites, while exhibiting lower mechanical strength than glass fiber composites, are attractive due to their low carbon footprint [16]. Similarly, the addition of graphite powder (5%) to polyester-glass composites, as reported by Wieczorska et al. (2022), leads to a slight deterioration in mechanical properties, suggesting that even minor compositional modifications can significantly influence material behavior [21].

In the case of MDF waste-derived carbonizate, despite its recycling potential, there is a lack of systematic studies on its optimal content and particle morphology in an epoxy matrix. Rajak et al. (2021) emphasize that the key to composite performance lies not only in selecting the right filler but also in precise control of its parameters (e.g., particle distribution) [14]. This study addresses that gap by investigating the influence of carbonizate with varying particle sizes (0.5–1.5 mm) and contents (5–10%) on the mechanical properties of composites.

The aim of this study was to analyse the effect of carbonizate from MDF pyrolysis on the mechanical properties of a new epoxy resin-based composite material. As this is a new material, it was necessary to test it from different angles, taking into account both the carbonizate content (5%, 7.5% and 10%) and the size of its fraction (0.5 mm, 1.0 mm and 1.5 mm). The tests were aimed at determining the optimum additive parameters in terms of tensile strength, Young's modulus and nominal elongation. In this context, a static tensile test was carried out to better understand the influence of these factors on the properties of the composite [27].

The use of carbonizate in construction materials can improve their strength, structural stability and optimize energy efficiency. It has been shown that carbonizate can be an example of an innovative material that supports overcoming barriers to implementing sustainable solutions in the construction sector, offering an alternative to traditional materials based on non-renewable raw materials.

Although previous studies have explored the use of wood waste in composites, none have systematically investigated the combined effects of MDF-derived carbonizate particle size (0.5–1.5 mm) and loading content (5–10%) on the mechanical properties of epoxy composites. This gap is critical, as optimizing these parameters could enable the valorization of MDF waste while balancing material performance. Our study fills this gap by providing a comprehensive analysis of how carbonizate morphology and concentration influence tensile strength, Young's modulus, and failure mechanisms, offering a foundation for sustainable composite design.

MATERIALS AND METHODS

The research focused on a new composite material with the addition of carbonizate formed as a product of furniture waste pyrolysis, glass mat and epoxy resin used for the matrix.

EM 1002 emulsion glass mat with a surface weight, 450, g/m^2, was used to make the composite. It is manufactured from cut strands of E-type glass fiber, with nominal diameters of 12 μm distributed in different directions, bonded together with an emulsion binder. It is a soft, well-moldable mat that saturates in unsaturated polyester resins. The product has satisfactory air removal capability during the lamination process. The chemical composition of the mat is given in Table 1.

For the second component of the composite, carbonizate obtained from the recycling of MDF-type furniture waste (Figure 1) was used, with the chemical composition given in Table 2. The chemical composition of the carbonizate was determined in an accredited laboratory following the standards in force, allowing a reliable characterization of the material used in the study.

Carbonizate obtained by pyrolysis of furniture waste, such as MDF boards, is characterized by irregular form and high porosity. To prevent the deterioration of the composite's mechanical properties, it is necessary to obtain the right shape and optimal particle size of the additive. To accomplish this, the carbonizate was groundusing a laboratory rotary mill from Brabender (Germany). In the next stage, screening was applied using a sieve shaker from Irwin (USA), which made it possible to select particles with the required size parameters. As a result, the following carbonizate fractions were separated: 0.5 mm, 1.0 mm, and 1.5 mm. The obtained fractions of carbonizate are shown in Figure 2.

To obtain information about the shape of the particles, the carbonizate was examined with a Zeiss EVO MA 15 electron microscope from Germany (Figure 3).

An SEM image of the carbonizate was taken immediately after the pyrolysis process (Figure 4). Microscopic evaluation of grain shape was determined after the screening process for the 0.5 mm fraction (Figure 5), with a 1.0 mm fraction (Figure 6) and a 1.5 mm fraction (Figure 7).

Analysis of the obtained SEM images showed that the carbonizate is characterized by high porosity, irregular particle shape and the presence of inclusions such as ash and residues of other components contained in the carbonizate.

Epoxy- Epidian 6 resin was used as the matrix of the composite, along with Z-1 hardener, manufacturer: Sarzyna Chemical. Composites with different proportions of glass mat and carbonizate were formed from the given components using the manual lamination method. This is a method based on manual placement of reinforcement from emulsion glass mat soaked in resin. For the production of the composite with carbonizate, molds with a wax distributor were used. The proportion of the various components of the composite was determined. The next step was to mix the appropriate amount and particle size of carbonizate with epoxy resin. Once these components were evenly combined, the hardener was added. This mixture was percolated and a glass mat was placed in the mold (Figure 8). Table 3 summarises the properties of the epoxy resin Epidian 6.

In order to determine comparative parameters, a composite without carbonizate consisting only of resin and glass mat was also made. The materials were labeled according to the scheme recorded in Table 3 according to the different carbonizate content. Each of the A-C materials was made with carbonizate with grain sizes of 0.5, 1 and 1.5 mm. The method of marking the samples is shown in Table 4.

After the material had cured, static tensile test specimens were prepared in accordance with the

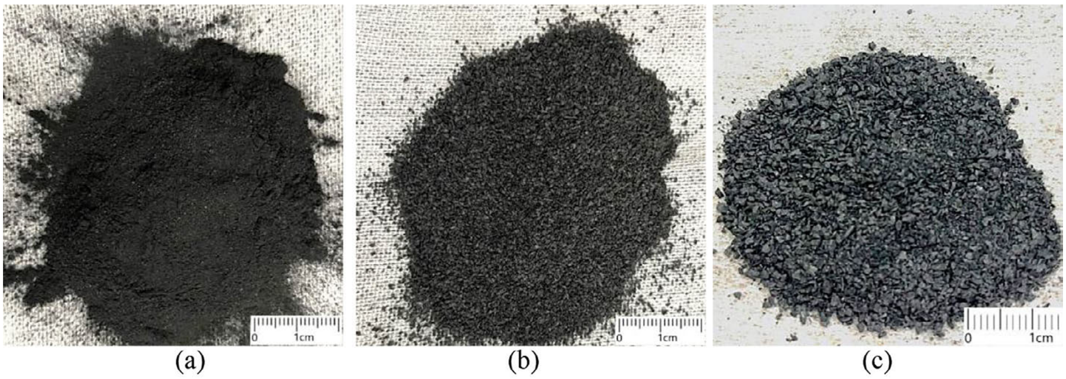
Table 1. Chemical composition of glass mat EM 1002/450/125

Ingredient (Oxide)	Silica (SiO_2)	Aluminum oxide (Al_2O_3)	Calcium oxide (CaO)	Boron oxide (B_2O_3)	Magnesium oxide (MgO)
Content [%]	Approx. 52–56	Approx. 12–16	Approx. 16–25	Approx. 5–10	< 5

Table 2. Chemical composition of the carbonizate obtained by pyrolysis of MDF boards

Ingredient	C	N	H	Cl	Si	Ash	Other
Content [%]	79.19	4.43	2.99	0.08	0.07	6.95	6.29

Figure 1. Carbonizate after the pyrolysis process



(a) (b) (c)

Figure 2. Carbonized grains obtained by sieve screening. Fraction: (a) 0.5 mm, (b) 1 mm, (c) 1.5 mm

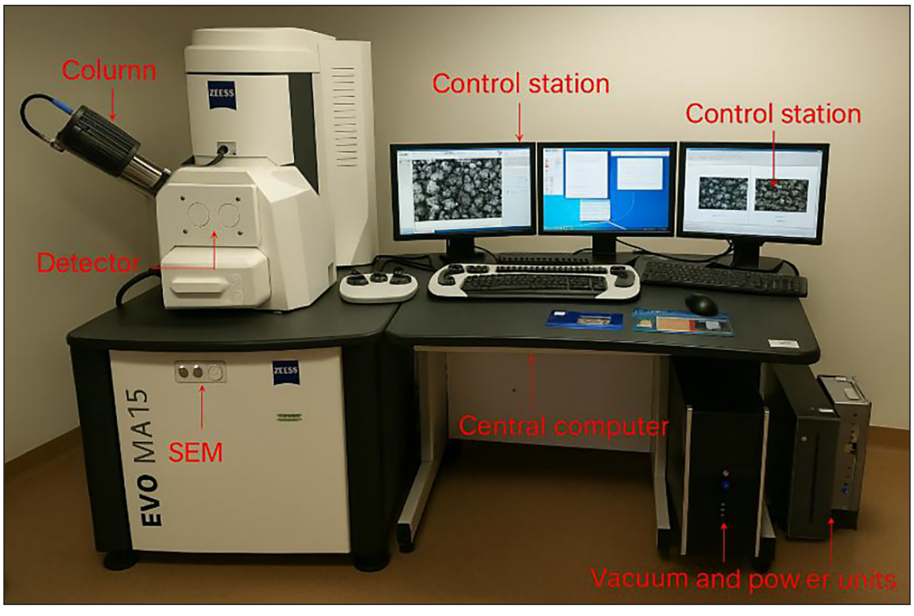


Figure 3. Zeiss EVO MA 15 scanning electron microscope

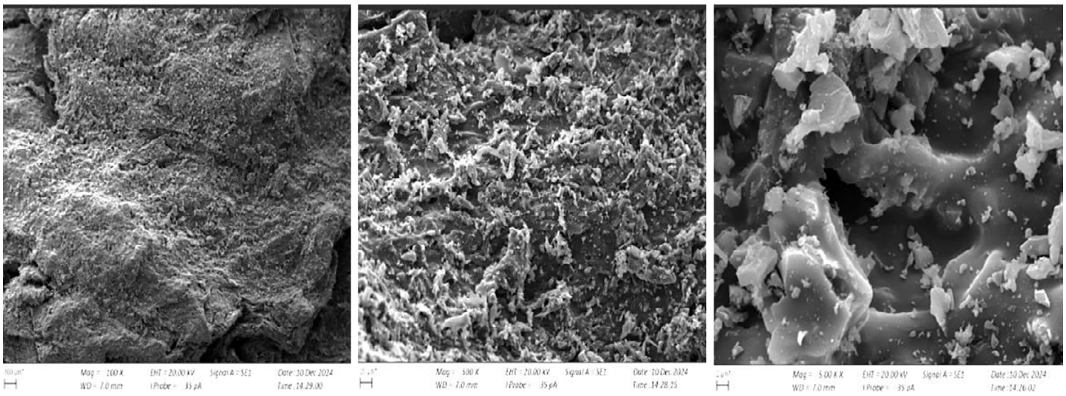

(a) (b) (c)

Figure 4. Structure of carbonizate immediately after pyrolysis (a) magnification 100x; (b) post-magnification 500x; (c) magnification 5000x

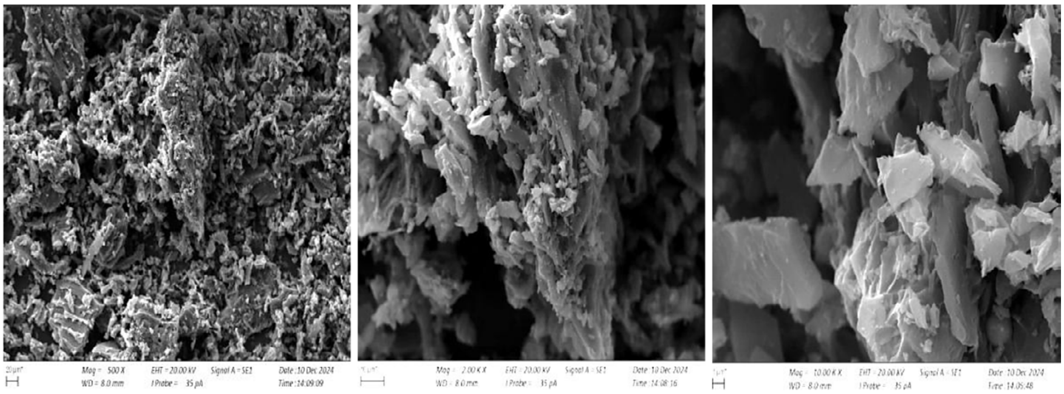

(a) (b) (c)

Figure 5. Structure of carbonizate of 0.5 mm fraction (a) magnification 500x; (b) magnification 2000x; (c) magnification 10000x

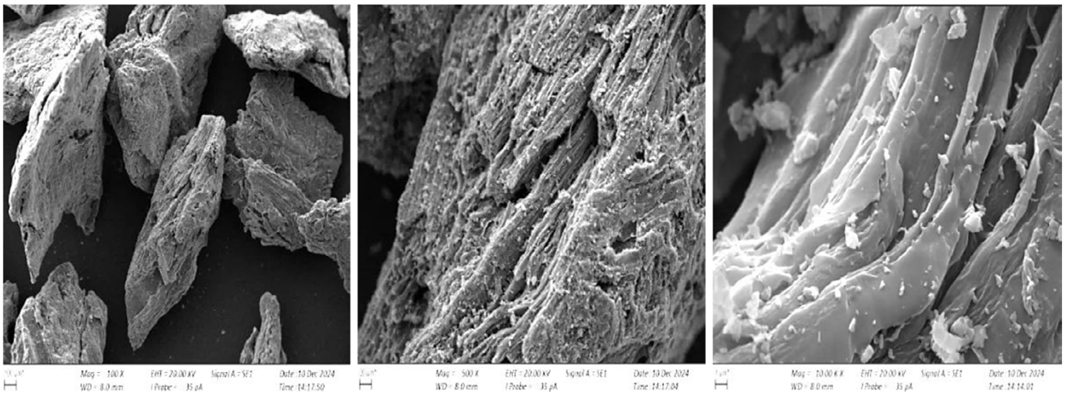
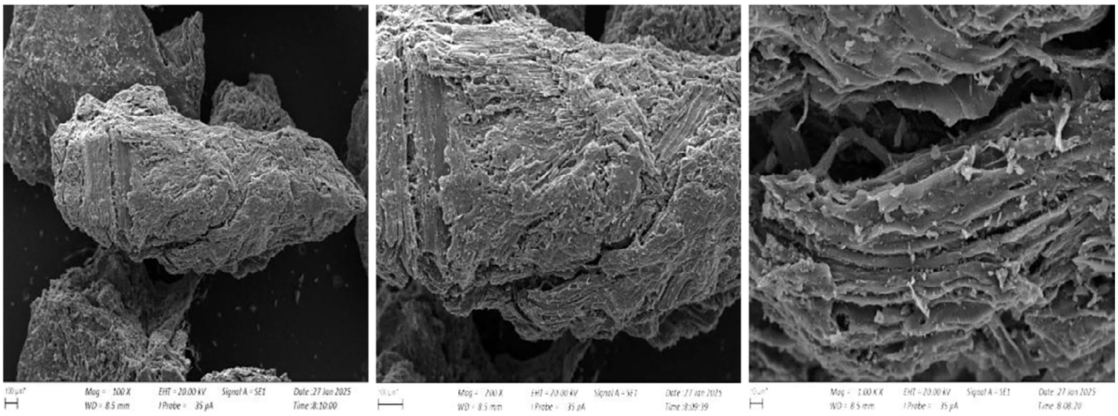

(a) (b) (c)

Figure 6. Structure of carbonizate of 1.0 mm fraction (a) magnification 100x; (b) magnification 500x; (c) magnification 10000x

requirements of the current standard PN-EN ISO 527-4: 2023 28 [28]. The shape and dimensions of the specimens are shown in Figure 9 and Table 5. To prevent edge damage and temperature effects, a water jet cutting method was used to cut the specimens from the composite.

The samples were cut from larger composite plates using a high-precision waterjet cutting



(a) (b) (c)

Figure 7. Structure of carbonizate of 1.5 mm fraction (a) 100x magnification; (b) 200x magnification; (c) 1000x magnification

Table 3. Epoxy resin characteristics Epidian 6

Parameter	Unit	Value
Viscosity at 25 °C	MPa·s	10000–15000
Density at 20 °C	g/cm^3	1.17
Gelation time, at 25 °C	min	33
Flash point	°C	> 200
Epoxy number	mol/100g	0.510–0.540

service provided by an external company, in order to ensure dimensional accuracy and avoid thermal or mechanical damage.

Figure 10 shows static tensile test specimens made from a composite without carbonizate. Figure (a) and from a composite containing 10% carbonizate (material C) with fractions Figure (b) 0.5 mm. Figure (c) 1mm and Figure (d) 1.5 mm.

For static tensile testing, a hydraulic-powered testing machine type MPMD P10B with TestXpert II software version 3.61. from Zwick&Roell from Germany was used. The elongation of the material during the tensile test was measured with an Epsilon strain gauge type 3542 with an initial measuring length L_0 of 50 mm (Epsilon Technology Corp., Jackson, WY, USA). The tests were carried out on tests at ambient temperature (22 °C) at the strain rate equal to 2×10^{-5} s^{-1}. (Figure 11).

RESULTS

As a result of tests conducted under static loading conditions, the mechanical properties of composites with carbonizate were determined: tensile strength σ_m, Young's modulus E_t, strain ε and nominal elongation A. Five samples of each material type were prepared for testing to determine the values of the examined mechanical properties. Arithmetic averages were calculated as representative data of a given material.

Tensile strength test

In order to accurately assess the mechanical properties of the new composite, the waveforms

Figure 8. Method of hand lamination of the composite to be tested

Table 4. Determination of samples according to the proportion of composite components

Designation	Content epoxy resin	Content glass mat	Content carbonizate
	% (by Mass)		
0	60	40	0
A	60	35	5
B	60	32.5	7.5
C	60	30	10

of the curves obtained during the static tensile test were analyzed. Figures 12–14 shows example plots of strain ε and tensile stresses for materials with carbonizate and specimens made only of glass mat and epoxy resin. Data from tests on individual specimens were used to visualize the results.

In the example graphs, it can be seen that the highest stresses and the largest strains are achieved by the sample without the carbonizate. When carbonizate with a particle size of 0.5 mm is added to the composite, the highest tensile deformation is achieved by material B, that is, with 7.5% of this additive. This material appears to be the most ductile among the tested materials enriched with carbonizate. Adding a 1 mm fraction of carbonizate to the composite, it can be seen that material B has the highest strain and tensile stress results than the other materials. The composite with the addition of a 1.5 mm fraction of carbonizate has a decrease in strain values. The material becomes more brittle. The best deformation results are achieved for material A, that is, with the addition of 5% carbonizate.

Table 5. Dimensions of the static tensile test specimen according to ISO 527-4:2023

Symbol	Dimensions [mm]
L_3	≥50
L_1	60±0.6
r	≥60
b_2	20±0.2
b_1	10±0.2
h	2 to 10
L_0	50±0.5
L	115±1

Material with the same proportion of individual composite components but with different particle sizes of carbonizate was compared with each other to analyze the effect of particle size on its mechanical properties (Figures 15–17). Composite A, that is, with 5% carbonizate (Figures 15) in its composition, shows the highest plastic deformation of about 1.5% with a grain size of 1.5 mm. The highest tensile stresses can be obtained for the 0.5 mm fraction (about 60 MPa).

Among the tested specimens with a 7.5% carbonizate content (Figure 16), the composite with a carbonizate grain thickness of 0.5 mm has the highest strain factor, reaching values of about 1.5% tensile stress of 75 MPa. The coarser the grain, the worse the mechanical coefficients results for the static tensile test.

Adding 10% carbonizate (material C) to the composite lowers the strain and stress ratios. The best result is achieved by a sample with carbonizate of 0.5 mm fraction, with stresses around 62 MPa. (Figure 17).

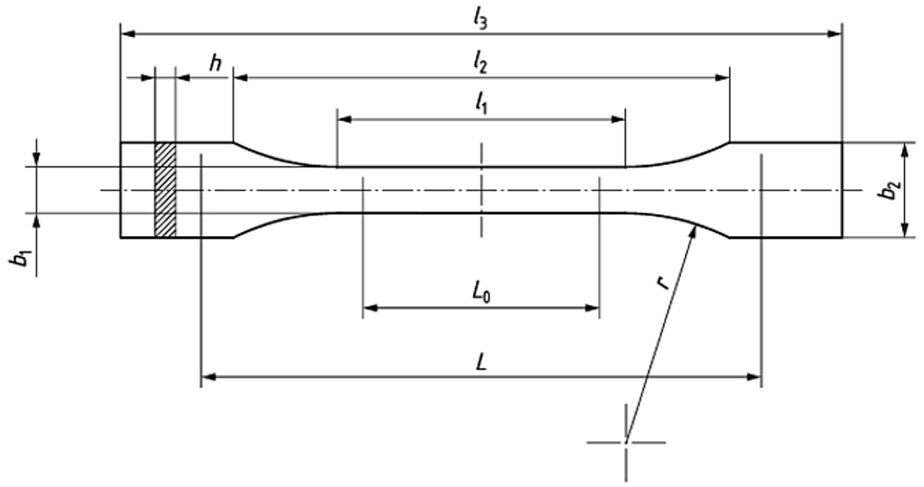


Figure 9. Technical drawing of a static tensile test specimen in accordance with ISO 527-4:2023

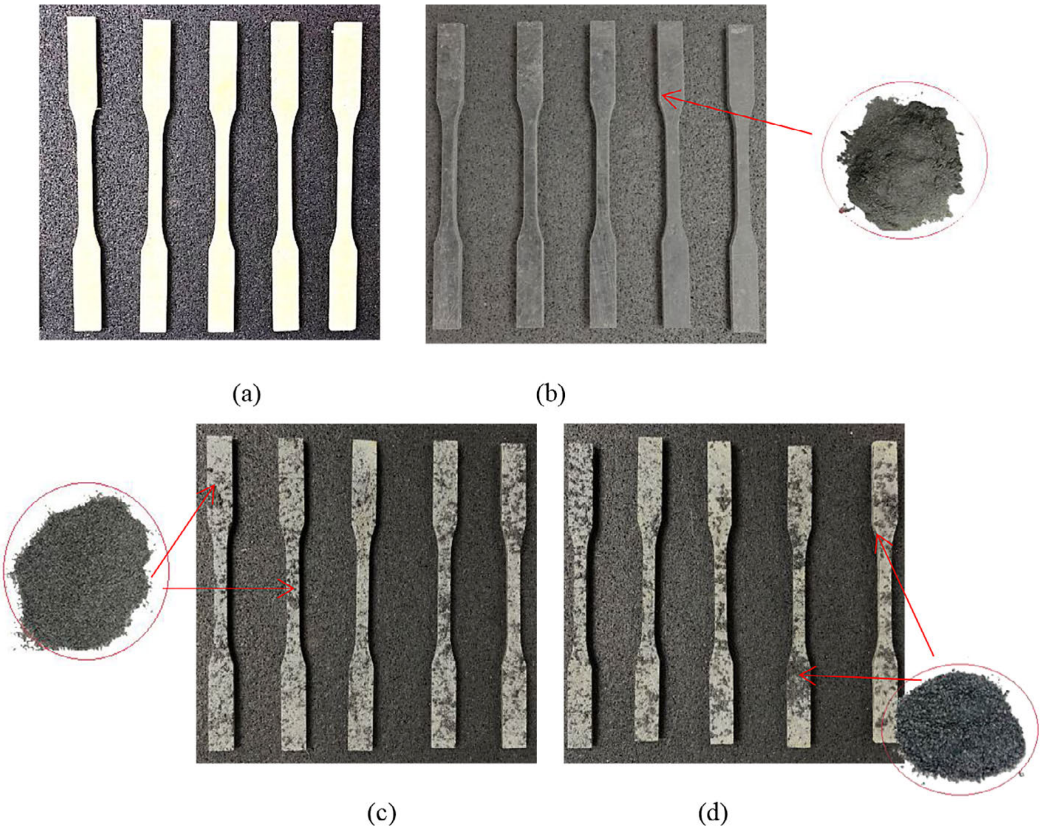


Figure 10. Composite specimens for static tensile test. (a) no carbonizate, (b) carbonizate 0.5 mm fraction, (c) carbonizate 1.0 mm fraction, (d) carbonizate 1.5 mm fraction

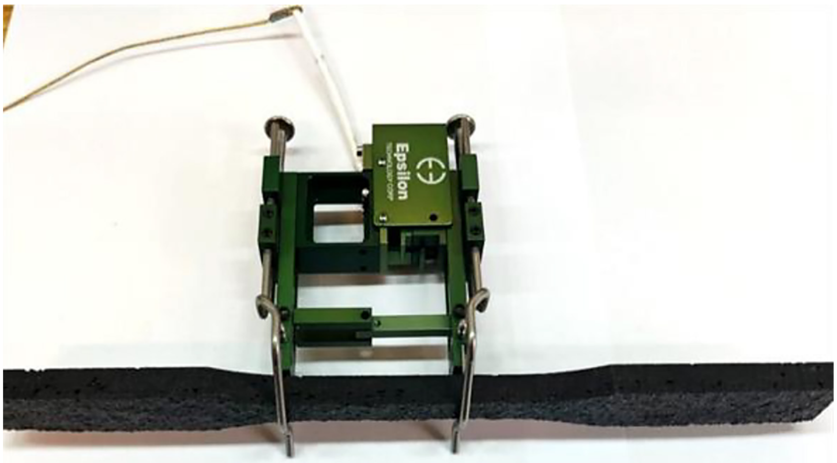


Figure 11. Epsilon 3542 strain gauge installed on a specimen prepared for a static tensile test

Mechanical properties – statistical analysis

For mechanical testing, the standard specifies a minimum number of specimens. For fiber-reinforced composites: at least 5 specimens for each test direction [29]. According to the standard, 5 specimens from each composite variant were prepared for static tensile testing. After testing, parameters such as tensile strength σ_m, Young's modulus E_t, strain ε and nominal elongation A were determined for each prepared specimen. To estimate the magnitude of the coefficients for the composite, the arithmetic mean (1) was determined for each type of test material, where x - the result of the measurement, n - the number of measurements.

$$\bar{x} = \frac{\sum x}{n} \tag{1}$$

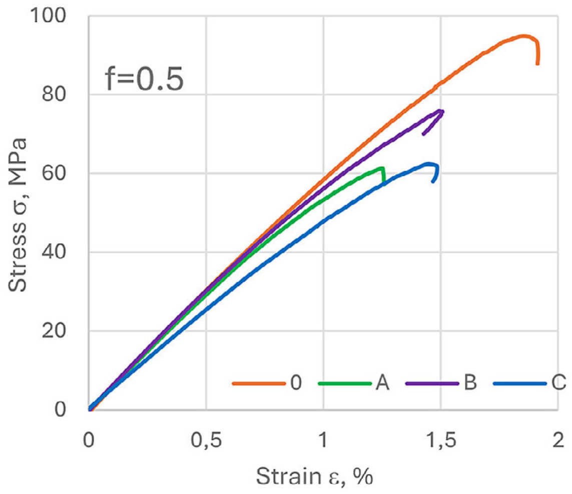


Figure 12. Comparison of tensile curves of composite materials with the addition of carbonizate with particle size f = 0.5 mm with the material without carbonizate

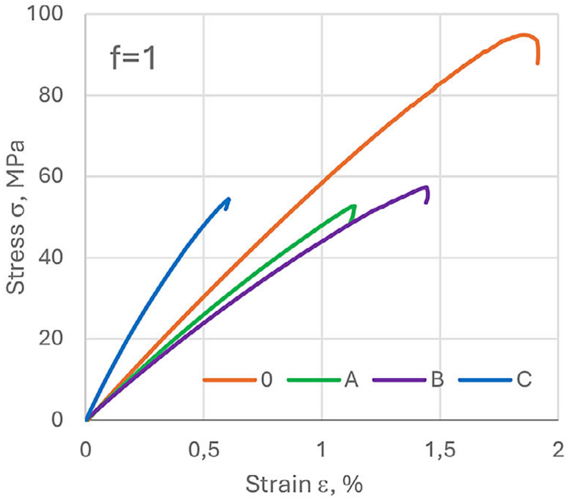


Figure 13. Comparison of tensile curves of composite materials with the addition of carbonizate with particle size f = 1 mm with the material without carbonizate

Calculations of variance, standard deviation, dispersion and CV coefficient of variation were performed to show the difference in test results for each material and their averages.

The variance tells how widely the data are dispersed around the mean (2). Small values of variance mean that the data are close to the mean, while large values indicate large differences between the data and the mean.

$$S_x^2 = \frac{\sum(x-\bar{x})^2}{n-1} \tag{2}$$

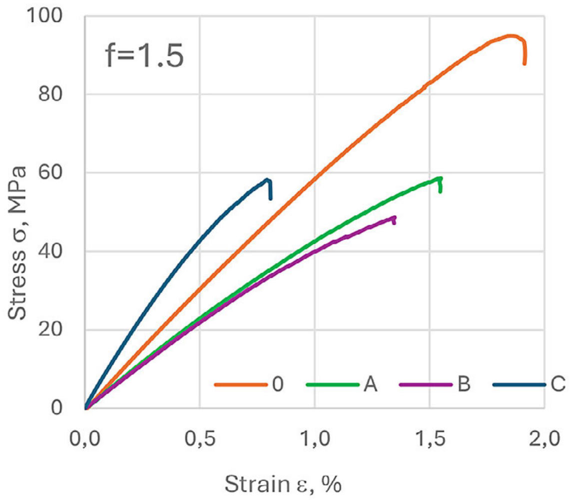


Figure 14. Comparison of tensile curves of composite materials with the addition of carbonizate with particle size f = 1.5 mm with the material without carbonizate

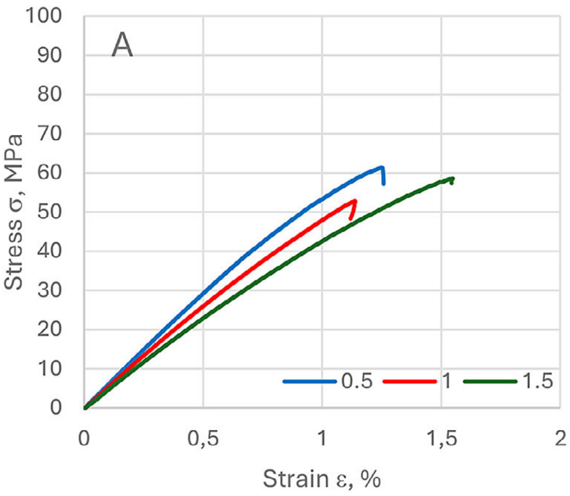


Figure 15. Tensile curves of composite materials with the addition of 5% carbonizate

The calculation of the standard deviation (3) aims to determine how much the data in the set differs from the mean value.

$$S_x = \sqrt{S_x^2} \tag{3}$$

The coefficient of variation CV (4) allows comparison of variability between different data sets, allows comparison of data with different averages.

$$CV = \frac{S_x}{\bar{x}} \times 100\% \tag{4}$$

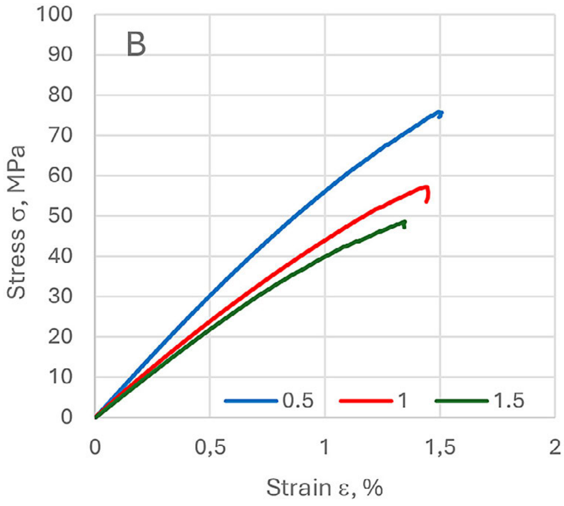


Figure 16. Tensile curves of composite materials with the addition of 7.5% carbonizate

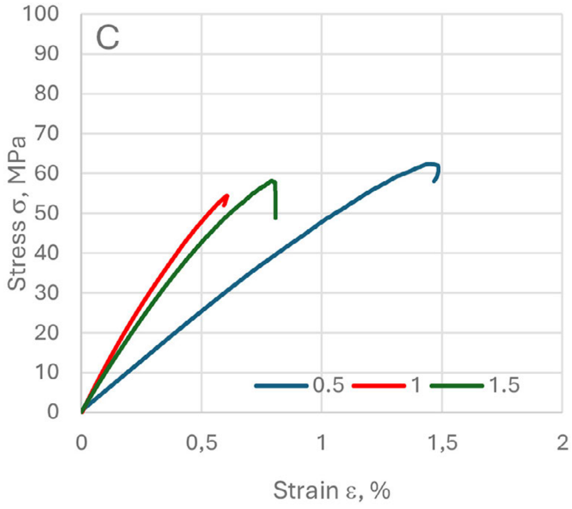


Figure 17. Tensile curves of composite materials with the addition of 10% carbonizate

The spread (5) indicates how scattered the data is. It is a simple measure of the range of values in a data set. The spread allows you to quickly compare the spread of data in different sets.

$$R = x_{max} - x_{min} \tag{5}$$

The highest tensile strength σ_m is achieved by the material without the addition of carbonizate, averaging about 89.65 MPa. Analyzing the average values for materials with carbonizate addition, a decrease in this parameter is observed as the proportion of carbonizate increases. Nevertheless, for a composite containing 7.5% carbonizate with a grain size of 0.5 mm, the tensile strength is only 19% lower than that of the material without the additive, and amounts to 72.29 MPa (Figure 18). The results of the measurements show dispersion (Table 6). Material A with carbonizate of 1 mm fraction has the smallest differences between the measurement results, amounting to 4.87 MPa, while for material B with the addition of carbonizate of 0.5 mm grain size, the differences are 25.05 MPa.

The composite without the addition of carbonizate has the highest plastic deformation ε of 1.64% as shown in Figure 19 and Table 7. The addition of carbonizate reduces the plastic deformation capacity of the material. The best result is achieved by the composite with 7.5% carbonizate with a fraction of 0.5 mm, showing a deformation of 1.56%. The material with the least plastic deformation is a composite containing 10% carbonizate with a grain size of 1.5 mm, with a result of 0.82%. The highest scatter of results (44%) was recorded for composite B samples with a grain size of 1.5 mm, indicating a large scatter of test results.

The highest elasticity is exhibited by the composite with the addition of 0.5% carbonizate with a grain size of 1.5 mm, for which the Young's modulus E_t is 4020.18 MPa (Figure 20). In contrast, the highest value of Young's modulus is achieved by the composite with the addition of 10% carbonizate with a grain size of 1.5 mm, amounting to 8708.78 MPa. The larger grain size of the additive leads to an increase in the stiffness of the material and, at the same time, a decrease in its elastic deformation capacity. The largest variation in test results was observed for composite A with a 1.5 mm fraction, where the coefficient of variation (CV) was 25,119% (Table 8).

The highest nominal elongation A_n was observed for samples containing 10% carbonizate with a particle size of 1.5 mm (Table 9 and, Figure 21). The average value of nominal elongation for this composite was 1.89 mm, which is higher compared to the composite without carbonizate. The lowest average elongation was recorded in the composite samples with 5% carbonizate of 0.5 mm fraction, which reached 1.44 mm.

Composite density

The density of the produced composite was calculated based on volume and mass measurements of the samples. The density values are presented in Table 10. The obtained results indicate that the carbonizate particle size (0.5 mm, 1 mm, 1.5 mm) has

Table 6. Tensile strengths σ_m of composites depending on the content of carbonizate additive - statistical analysis

Material/ fraction	$\bar{x}$	S_x^2	S_x	R	CV
	MPa	MPa^2	MPa	MPa	%
A/0.5	64.35	23.09	4.81	12.44	7.47
B/0.5	72.29	81.23	9.01	25.05	12.47
C/0.5	63.89	13.89	3.73	9.45	5.83
A/1	53.70	2.65	1.63	4.87	3.03
B/1	52.74	8.24	2.87	8.62	5.44
C/1	48.37	17.91	4.23	13.02	8.75
A/1.5	48.24	61.98	7.87	19.69	16.32
B/1.5	43.22	15.95	3.99	6.29	9.24
C/1.5	56.93	54.03	7.35	20.74	12.91
0	89.65	53.23	7.30	19.12	8.14

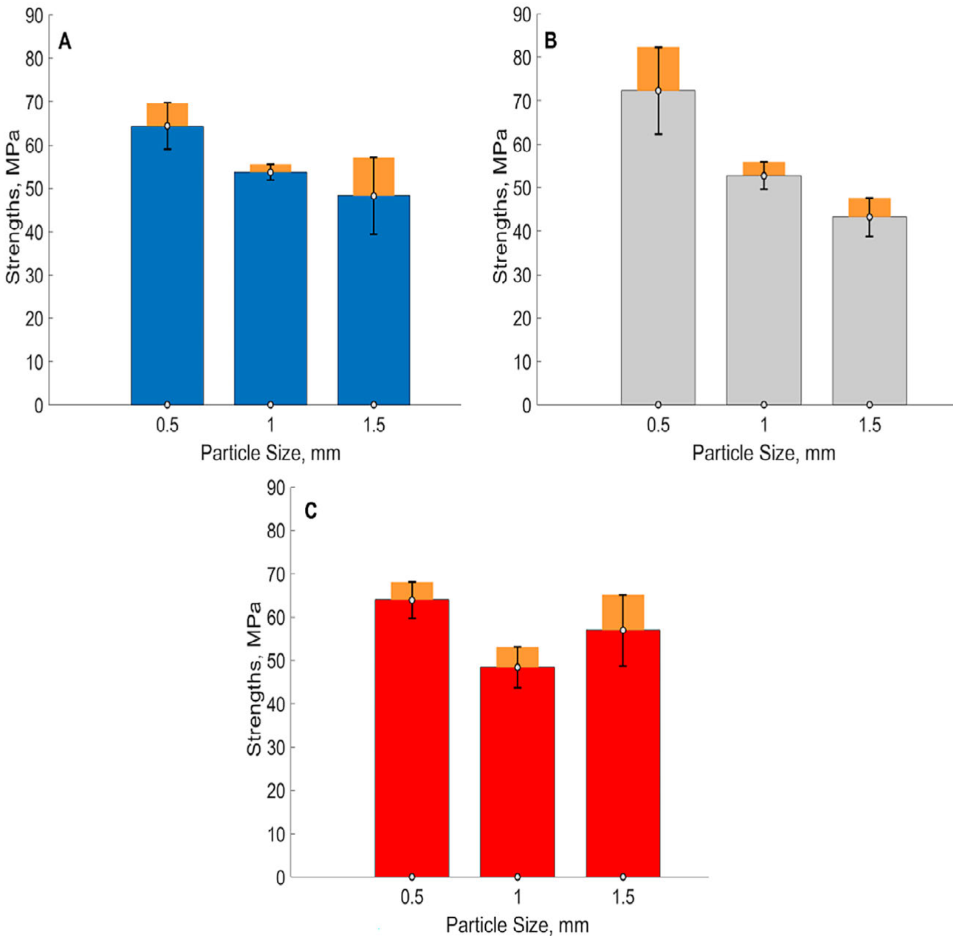


Figure 18. Graph of average tensile strength values σ_m of composites depending on the content of carbonizate additive

no significant effect on the composite density. At a constant filler mass content (5%, 7.5%, 10%), the total filler volume remains practically unchanged. The observed variations in sample density primarily result from the amount of carbonizate used rather than its particle size distribution.

Microscopic analysis

SEM studies of cross sections of composite specimens after fracture were performed to analyze the damage mechanism and evaluate the material structure after loading. Representative

Table. 7. Plastic strain rate ε of composites depending on the content of carbonizate additive – statistical analysis

Material/ fraction	$\bar{x}$	S_x^2	S_x	R	CV
	%	$\%^2$	%	%	%
A/0.5	1.26	0.046	0.03	0.07	2.13
B/0.5	1.56	0.001	0.15	0.38	9.53
C/0.5	1.39	0.022	0.05	0.13	3.52
A/1	1.21	0.002	0.08	0.19	6.85
B/1	1.24	0.007	0.12	0.30	9.57
C/1	1.29	0.014	0.14	0.33	10.98
A/1.5	1.41	0.020	0.23	0.55	16.39
B/1.5	1.28	0.053	0.56	1.51	44.00
C/1.5	0.82	0.316	0.13	0.34	16.41
0	1.64	0.046	0.21	0.33	13.03

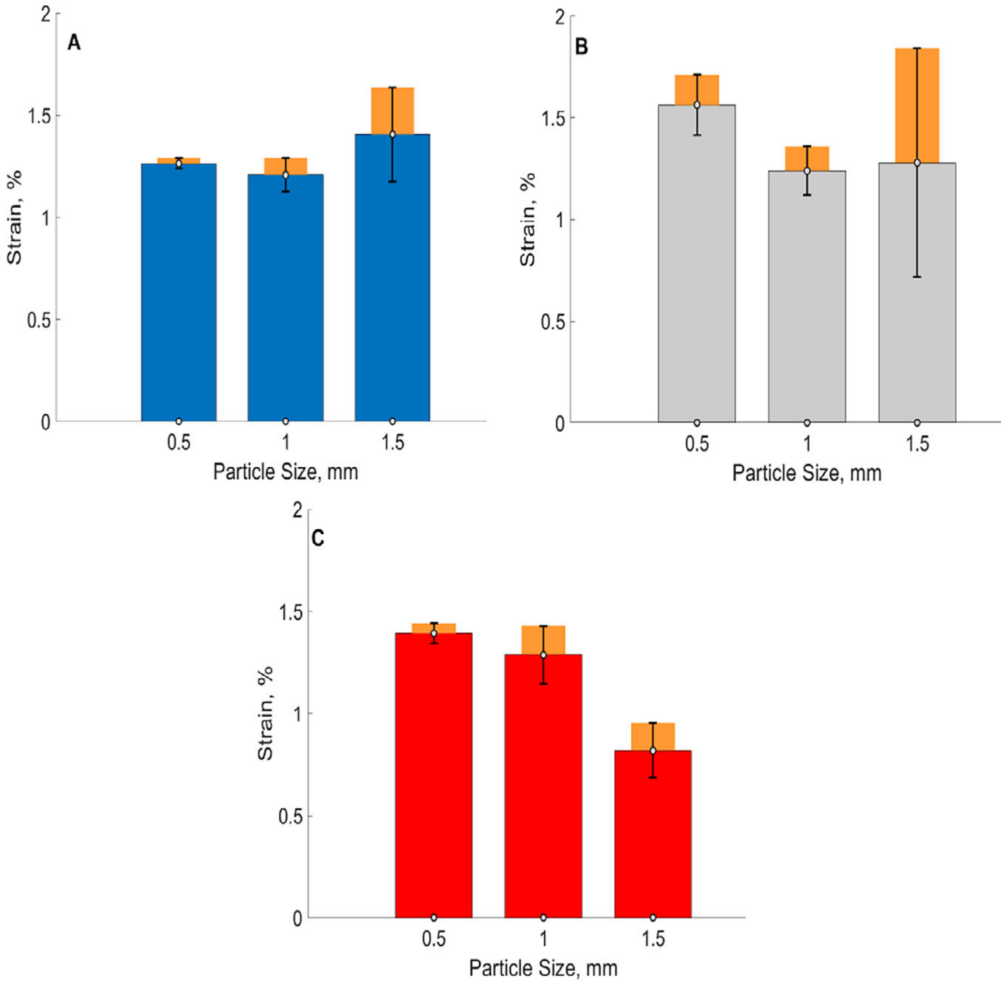


Figure 19. Graph of average plastic strain values ε of composites depending on the content of carbonizate additive

specimens for each variant were selected to present the results. Figure 22 shows the structure of the composite without carbonization (variant 0), Figure 23 illustrates the composite with the addition of carbonization for variant A where the fraction f = 0.5 mm. Figure 24 shows the structure of variant B for f = 1 mm. The structure of variant C with a carbonizate particle size of f = 1.5 mm is in Figure 25.

Table 8. Young's modulus E_t of composites depending on the content of carbonizate additive - statistical analysis

Material/fraction	$\overline{x}$	S_x^2	S_x	R	CV
	MPa	MPa	MPa^2	MPa	%
A/0.5	6235.53	261442.82	511.31	1334.49	8.200
B/0.5	5866.89	463025.21	680.46	1779.09	11.598
C/0.5	5164.52	64703.32	254.37	529.00	4.925
A/1	5243.60	60699.26	246.37	548.21	4.699
B/1	5105.97	160386.73	400.48	1003.72	7.843
C/1	4854.35	552385.48	743.23	1642.62	15.311
A/1.5	4020.18	1019733.80	1009.82	2503.43	25.119
B/1.5	4480.76	76328.21	276.28	380.31	6.166
C/1.5	8708.78	761002.20	872.35	1929.61	10.017
0	6666.22	168656.25	410.68	905.66	6.161

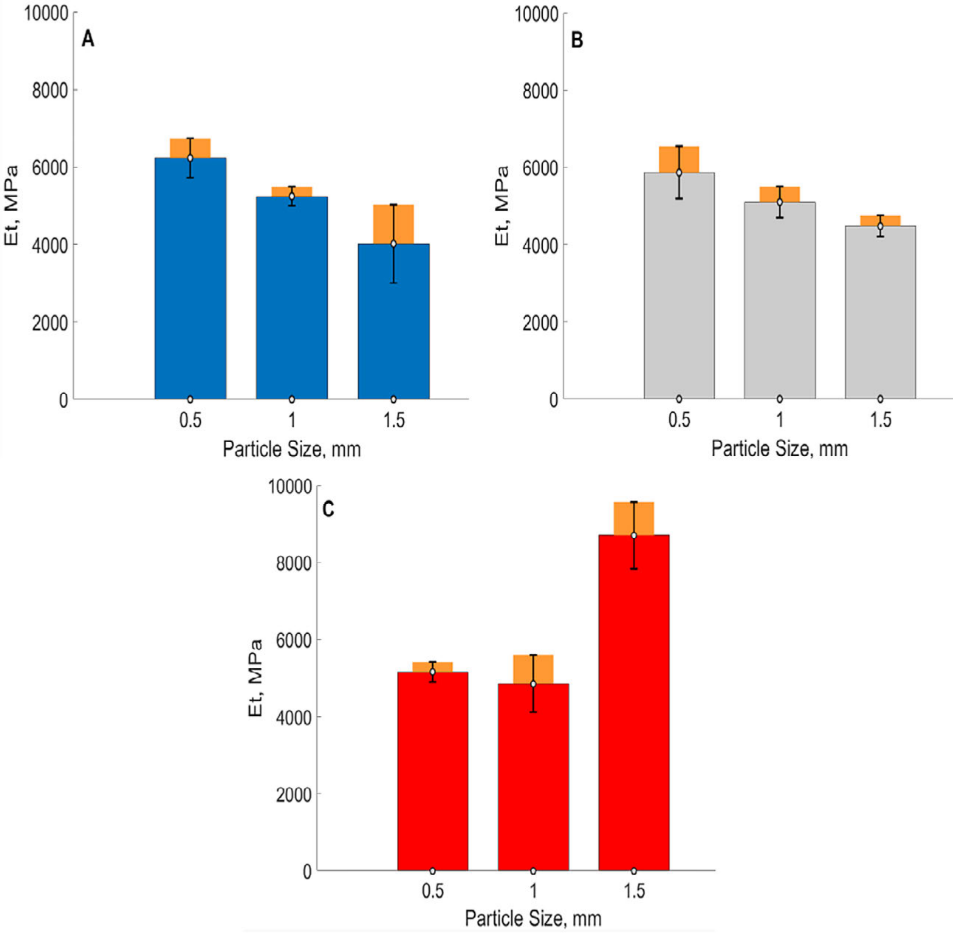


Figure 20. Mean values of Young's modulus E_t of composites depending on the content of carbonizate additive

DISCUSSION

The study analyzed the effect of carbonizate on the mechanical properties of epoxy composites. It was observed that this additive significantly influences the tensile strength and elongation of the material. The results indicate the need to find a compromise between the benefits of carbonizate and its potential impact on the mechanical integrity of the composite. The values of standard deviation and coefficient of variation for some samples indicate high variability. This dispersion and lack of repeatability in measurement results may stem from the composite

Table 9. Relative elongation of A_n composites depending on the content of carbonizate additive – statistical analysis

Material/ fraction	$\bar{x}$	S_x^2	S_x	R	CV
	mm	mm^2	mm	mm	%
A/0.5	1.44	0.017	0.130	0.353	8.980
B/0.5	1.77	0.007	0.085	0.205	4.825
C/0.5	1.53	0.007	0.084	0.222	5.468
A/1	1.54	0.017	0.130	0.306	8.489
B/1	1.47	0.036	0.190	0.466	12.934
C/1	1.56	0.012	0.109	0.271	6.974
A/1.5	1.71	0.024	0.155	0.335	9.058
B/1.5	1.58	0.056	0.237	0.598	14.979
C/1.5	1.89	0.062	0.249	0.617	13.200
0	1.86	0.036	0.189	0.403	10.122

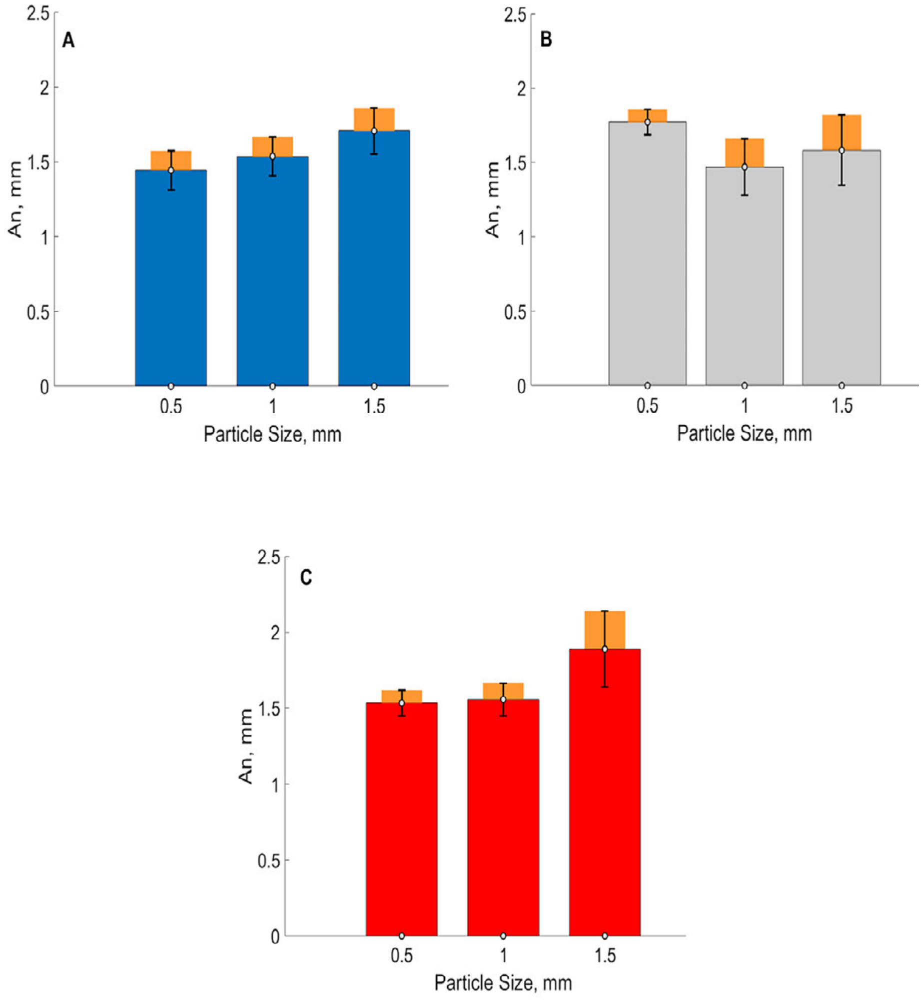


Figure 21. Graph of average nominal elongation values of A_n composites depending on the content of carbonizate additive

manufacturing process. In the hand lay-up method, ensuring a perfectly even distribution of the glass mat and carbonizate within the epoxy resin is challenging. This can lead to localized areas with varying fiber content, affecting mechanical strength. Uneven fiber distribution (both glass and carbonizate) may create weak points in the composite structure.

Table 10. Composite density as a function of carbonizate content and particle size

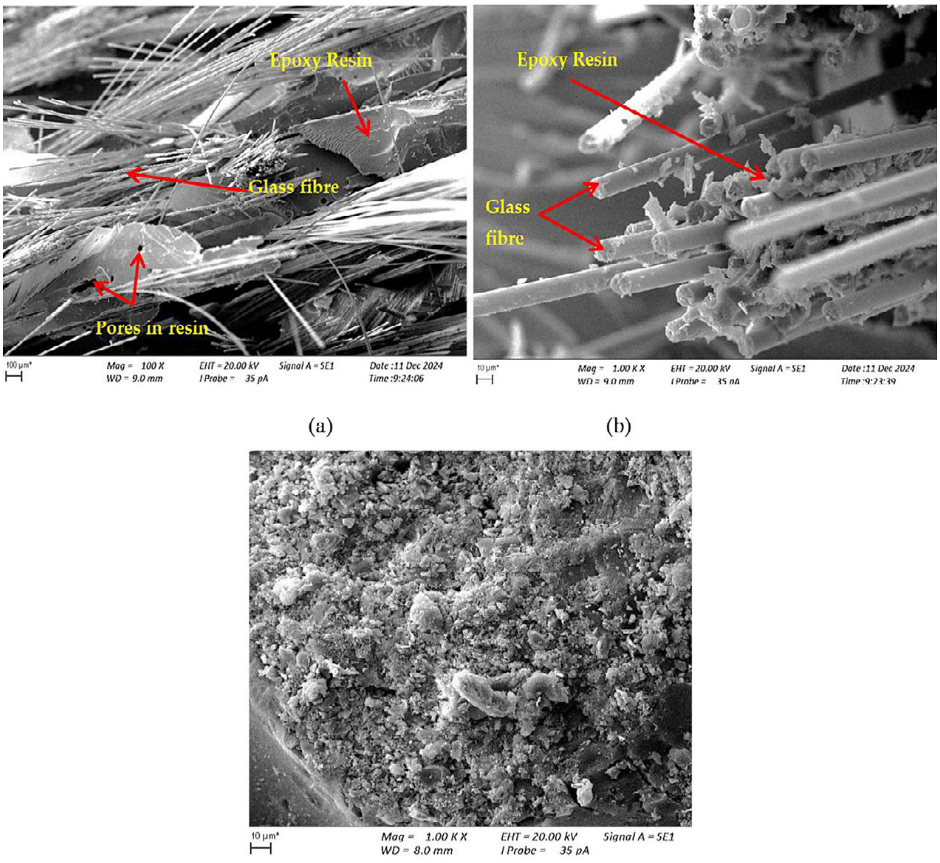
Material/ fraction	Density ρ
	kg/m^3
A/0.5	1509
B/0.5	1527
C/0.5	1545
A/1	1509
B/1	1527
C/1	1545
A/1.5	1509
B/1.5	1527
C/1.5	1545
0	1474

During hand lay-up, air bubbles frequently form and become trapped within the material. These defects can significantly reduce mechanical strength and contribute to high variability in results. Air bubbles act as crack initiation sites, leading to premature sample failure. Additionally, if the epoxy resin is not evenly distributed and the glass mat is insufficiently impregnated, weak interfacial adhesion areas may develop.

Hand lay-up is a process highly dependent on the operator's skill. Variations in resin application, pressure, or curing time can lead to significant differences in the final composite's quality. All these manufacturing imperfections may contribute to reduced composite strength and increased scatter in test results.

For the composite with 5% carbonizate, the highest tensile strength σ_m = 64.35 MPa was achieved for the fraction f = 0.5 mm, which had an average elongation ε = 1.26% and Young's modulus E_t = 6235.35 MPa. The lowest tensile strength of this material was achieved for fraction f =1.5 mm, where σ_m = 48.24 MPa, ε = 1.41%, and E_t = 4020.18 MPa.

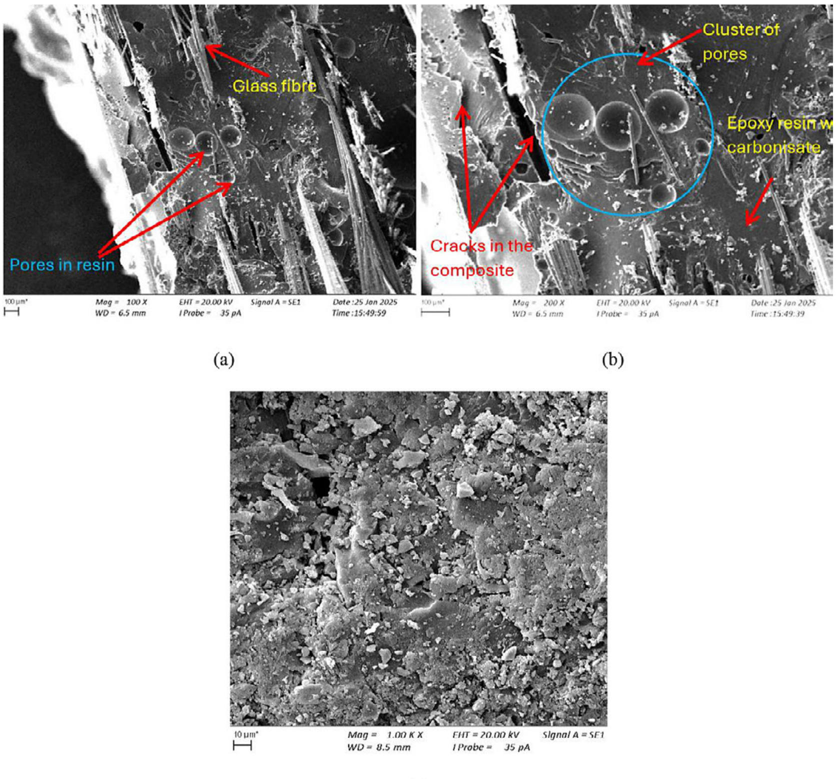
The composite with a 7.5% share of carbonizate with an f = 0.5 fraction has a tensile strength of σ_m = 72.29 MPa. The decrease in strength observed with larger particle sizes (1.5 mm) likely stems from stress concentration



(a) (b)

(c)

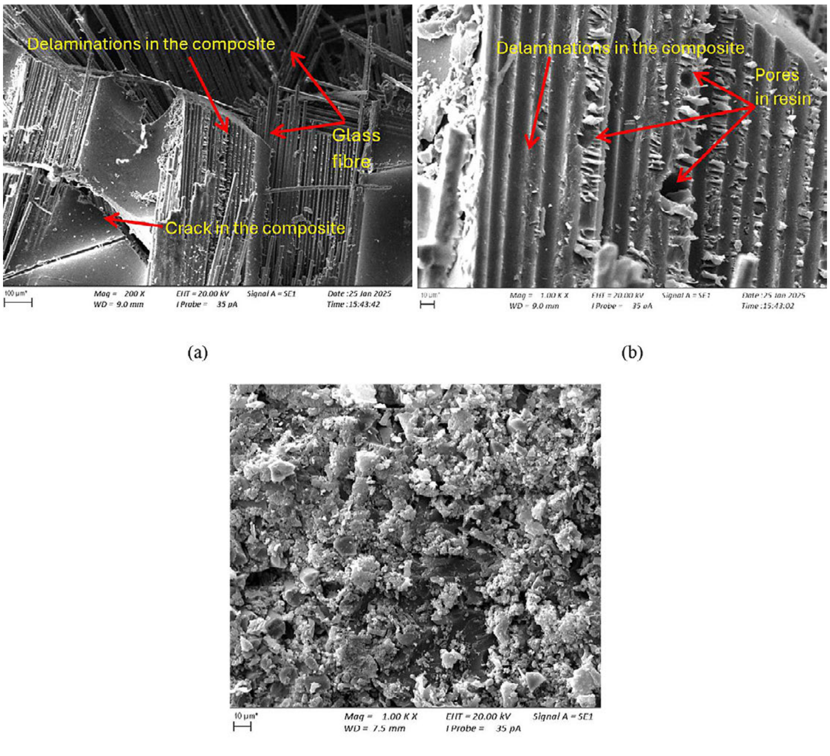
Figure 22. Structure of the composite (variant 0) after static tensile test, cross sections after fracture (a) magnification 100x; (b) magnification 1000x; (c) before static tensile test magnification 1000x



(a) (b)

(c)

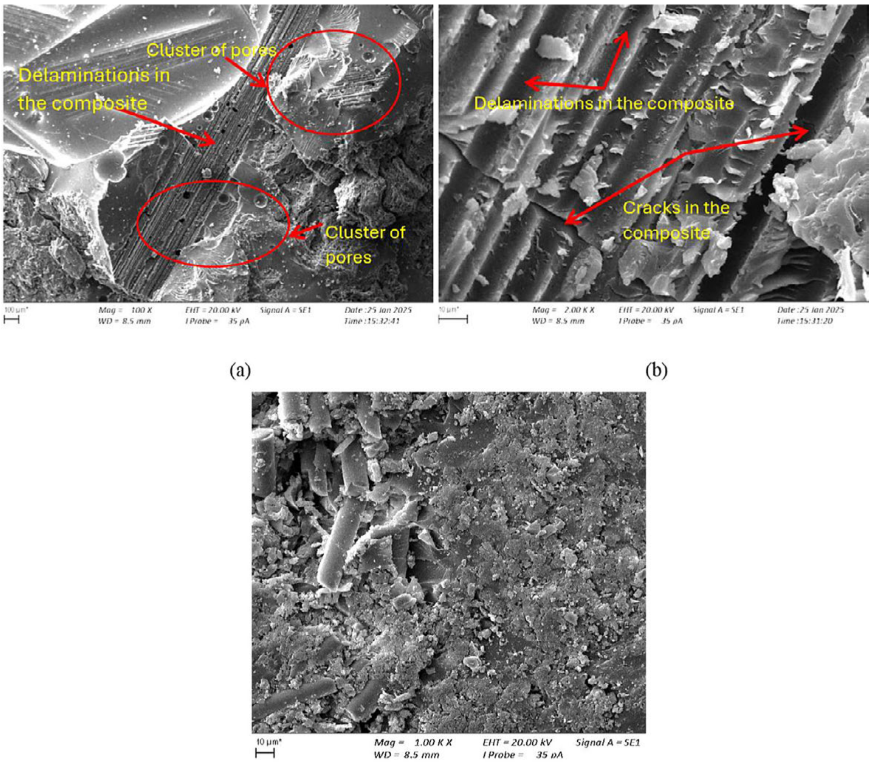
Figure 23. Structure of the composite (variant A) with the addition of carbonizate with a particle size of f = 0.5 mm after static tensile testing, cross-sectional areas after fracture (a) magnification 100x; (b) magnification 200x; (c) before static tensile test magnification 1000x



(a) (b)

(c)

Figure 24. Structure of the composite (variant B) with the addition of carbonizate with a particle size of f = 1 mm after static tensile testing, cross-sectional areas after fracture (a) magnification 100x; (b) magnification 200x; (c) before static tensile test magnification 1000x



(a) (b)

(c)

Figure 25. Structure of the composite (variant C) with the addition of carbonizate with a particle size of f = 1.5 mm after static tensile testing, cross-sectional areas after fracture (a) magnification 100x; (b) magnification 200x; (c) before static tensile test magnification 1000x

around larger particles, which accelerates crack initiation. The stress-strain curves presented in Figures 15–17 suggest strain localization and nonlinear damage mechanisms that are not evident in averaged values.

Figures 15–17 demonstrate that samples containing 1.5 mm particles exhibit: steeper σ-ε curves (rapid stress increase at low strain), indicating brittle fracture behavior and lower failure strain values (0.82% for composite C with 1.5 mm fraction vs. 1.56% for composite B with 0.5 mm fraction), confirming localized damage

SEM analysis (Figure 25) reveals cracks propagating from large carbonizate particles, validating the stress concentration hypothesis.

The high nominal elongation (A_n) observed for composite C with a 1.5 mm fraction, despite a low strain value (ε = 0.82%), may result from non-uniform deformation of the specimens (e.g., local cracking before uniform strain is achieved) or measurement errors (such as sensor slippage). Another possible cause is the anisotropy of the composite. The use of manual lay-up in the manufacturing process may have led to an uneven distribution of glass fibers and carbonizate, causing certain areas of the sample to elongate more before final failure.

The high Young's modulus (E_t = 8708.78 MPa) indicates the stiffness of the material, while the low ε = 0.82% suggests that failure occurs within the elastic phase. However, An measures the total elongation up to the point of rupture, which can be greater due to micro-displacements between composite layers (delaminations) and partial plasticization in areas where the matrix-fiber adhesion is stronger.

SEM analysis revealed numerous pores and cracks, which may have acted as damage initiation sites but did not necessarily lead to immediate sample failure. Slow crack propagation along weak carbonizate–matrix interfaces can result in an apparently higher An value, even though the actual material strain (ε) remains low. Large carbonizate particles (1.5 mm) may create localized thermal or mechanical bridges that carry the load but do not deform uniformly. As a result, the material may appear more ductile at the macro scale, even though it is microscopically brittle [30].

Increasing the size of the fraction causes a decrease in tensile strength. The material shows a strain of ε = 1.56%, with the larger fraction leading to an increase in the strain rate. Young's modulus decreases with increasing grain size of the carbonaceous material. For a material with a B/0.5 fraction, it is E_t = 5866.89 MPa, while for B/1.5 it decreases to E_t = 4480.76 MPa. The addition of 7.5% carbonizate with a grain size of 0.5 mm improves the tensile strength of the composite to 72.29 MPa, which is only 19% lower compared to the composite without carbonizate (89.65 MPa). This is the best result among the tested configurations. However, the results show a large range (R = 25.05 MPa) and a high coefficient of variation (CV = 12.47%), indicating significant property heterogeneity between samples, likely due to manual lamination. The high result variability (e.g., CV = 44% for fraction of 1.5) compromises property predictability, which poses risks in critical applications (e.g., construction or automotive industries). Quality control improvements are essential, including composition homogenization and production automation.

The composite material with 10% carbonizate shows the lowest tensile strength coefficients among the tested materials. The highest tensile strength of σ_m = 63.89 MPa is achieved by the fraction with f = 0.5, were ε = 1.39%, and E_t = 5164.52 MPa. The composite with a fraction of 1.5 mm has the highest elastic modulus E_t = 8708.78 MPa among the composites tested, and the lowest strain ε = 0.82% where σ_m = 56.93MPa. The high stiffness (E_t = 8708.78 MPa) of the composite with 10% carbonizate (1.5 mm) is associated with significant brittleness (ε = 0.82%), which limits its use in structures requiring impact resistance or flexibility. This material may be useful where stiffness is a priority (e.g., low-deformation load-bearing elements) but is unsuitable for dynamic or variable-load applications.

In the structural images of the analyzed composites, numerous pores, delaminations, and cracks were observed. This may indicate potential problems with both the material's structure and the manufacturing process. SEM analysis reveals numerous pores, delaminations, and cracks, primarily resulting from uneven carbonizate distribution and poor adhesion to the epoxy matrix. Other factors such as grain morphology (irregular shapes, porosity) or contaminants (ash) may also contribute to defects, but the key issue appears to be the lack of optimal interfacial bonding. These findings underscore the need for improved homogenization techniques or surface modification of the carbonizate to enhance compatibility with the resin. Manual lamination could be the cause of this phenomenon. The lack of repeatability and the potential for introducing air bubbles during this manufacturing method significantly affect the mechanical properties of composites containing carbonizate. Excessive porosity can lead to mechanical weakening of the material and a reduction in its resistance to cracking. The observed delamination and cracking suggest problems with the adhesion of the resin to the carbonizate, which may be due to improper selection of component proportions, insufficient chemical interaction between them, or inhomogeneous distribution of the carbonizate particles. Additionally, the quality of the carbonizate itself, especially if derived from waste, can significantly impact its effectiveness in the composite. The presence of impurities, such as ash or residues from other substances, can negatively affect the material's structure, leading to its weakening.

Filler in the form of carbonizate can act as a brittleness-reducing element in the composite, increasing its ability to deform before failure. Too little carbonizate would not have this effect, while too much could lead to greater stiffness and earlier cracking. Filler in the right amount can reduce the number of micropores and irregularities in the composite structure, which reduces stress concentration phenomena and delays crack initiation. In the case of our research, such an optimum value of carbonate addition is 7.5%.

In the context of potential composite applications, analysis of carbonizate addition effects revealed that filler particle size significantly influences material density. Gravimetric analysis confirmed that partial resin replacement with carbonizate increases composite density - for the 1.5 mm fraction, density rose from approximately 1474 to 1545 kg/m³, representing a > 5% increase. This property may limit material use in weight-sensitive applications such as load-bearing structures or components in aerospace, automotive, and transportation industries. Conversely, the enhanced density could prove advantageous in applications where mass is non-critical, including vibration-damping elements, technical fillers, casings, or insulation materials

CONCLUSIONS

1. Effect of carbonizate on the mechanical properties of composites: The study demonstrated that the addition of carbonizate significantly influences the mechanical properties of glass fiber-reinforced composites. The incorporation of carbonizate resulted in a decrease in mechanical strength compared to the epoxy resin composite reinforced with glass fibers.
2. Mechanism of composite structure weakening: The presence of carbonizate may disrupt adhesion bonds between the fibers and the composite matrix, leading to the formation of structural defects at the interface. The high scatter of results (44%) in static tensile tests indicates challenges associated with the hand lay-up process, which hinders the uniform distribution of the filler and reinforcing fibers.
3. Optimal carbonizate content and particle size: The highest tensile strength and greatest deformation capability were achieved for the composite containing 7.5% carbonizate with a particle size of 0.5 mm. The highest Young's modulus was observed for the composite with 10% carbonizate content and a 1.5 mm fraction, indicating high stiffness and resistance to elastic deformation, but also suggesting potential brittleness.
4. Technological limitations and their impact on mechanical properties: The hand lay-up process promotes the formation of air bubbles within the composite structure, which weakens mechanical strength and contributes to structural defects. Uneven distribution of resin and reinforcing materials results in thickness variations within the composite, further affecting its mechanical performance.
5. Technological limitations and recommendations: The variability in mechanical properties is substantial. For instance, in the B/1.5 samples, the coefficient of variation (CV) for strain reaches as high as 44%. This limits process repeatability and scalability, indicating the need for manufacturing process optimization (e.g., switching to vacuum bag lamination) to reduce structural defects. Process optimization should incorporate: vacuum-assisted lamination (to minimize porosity), surface modification of carbonizate (through chemical treatment to enhance interfacial adhesion), strict control of composition ratios and filler dispersion.
6. Environmental trade-offs and future directions: Although the addition of carbonizate reduces mechanical strength, its use is justified by environmental benefits, such as MDF waste valorization, and potential improvements in other properties (e.g., hardness). For high-performance applications, further material optimization (e.g., surface modification of carbonizate) or alternative manufacturing methods (e.g., vacuum-assisted lamination) are recommended to mitigate strength losses.
7. Potential and limitations of carbonizate applications: Although carbonizate offers benefits such as reduced material density and the utilization of MDF waste, it weakens the bond between the reinforcement and the composite matrix, which must be considered in material design.

This study provides valuable insights into the mechanical properties and microstructural characterization of the composites, but several limitations should be acknowledged. Firstly, the manual laminating process used in the preparation of the composites may have led to uneven resin impregnation, which could affect the consistency of the composite properties. To address this limitation, future studies should focus on employing more controlled lamination techniques, such as the use of compression plates or vacuum bagging, which would ensure more uniform resin distribution and improve the overall quality of the composites.

While the current research lays the groundwork for future developments, further investigations into the long-term durability and performance of the composites, including fatigue testing and environmental degradation studies, are necessary to fully evaluate their suitability for practical applications.

The next step in evaluating the mechanical properties of the new carbonized composite will involve tribological tests, the coefficient of thermal expansion, and the effect of temperature on the material's behavior.

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