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# Analysis of Strength Parameters of Polymer–Glass Composites Modified with Rubber Recyclate Through Bending Tests

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## Abstract

The study aims to analyze the strength properties obtained from three-point bending tests of epoxy-glass composite samples modified by adding rubber recyclate. A pure epoxy-glass composite is used as a comparative variant. The tested materials, which varies in the percentage of rubber recyclate and distribution, are cut through waterjet cutting to minimize the influence of temperature. The results undergo statistical analysis, and the microstructures are examined using scanning electron microscopy. The decreasing bending strength of the composites is observed, as the content of rubber recyclate in the material increased. However, adding rubber recyclate directly into the resin subtly decreases in bending strength compared to adding in the layers between the glass mat layers. Composites with rubber recyclate exhibits lower deflection under load compared to pure composites. The most favorable bending test parameters are obtained for the material containing 5% rubber recyclate distributed in three layers.

**Keywords:** epoxy–glass composites, rubber recyclate, statistical analysis, bending test

## 1. Introduction

Performing bending tests on composite materials is essential for assessing their strength and mechanical properties, especially for application in fields such as aviation, automotive, construction, and biomedicine [1-2]. Bending tests can evaluate the strength of composite materials, i.e., their ability to transfer bending loads, thereby ensuring the safety and reliability of structures composed using particular materials. The results of bending tests can help determine the limits of flexural strength and deflection along with fracture toughness [3]. Numerous studies have conducted bending tests as a crucial method to examine the strength of materials, especially new composite materials. Such tests are necessary for determining the strength characteristics of both existing materials in the industry and newly developed variants [4]. Conducting bending tests on materials produced using new technologies or compositions helps identify weak points, facilitating necessary modifications in the design or manufacturing process to improve the performance and durability of materials.

Epoxy matrix composites exhibit favorable strength and physicomechanical properties, along with low weight, and can be manufactured using simple techniques [5-6]. The desirable properties of composites and the potential for modification through the use of various additives render these materials applicable in diverse industries. Organic and inorganic additives can be used to produce various composites, with the applicability depending on the corresponding properties.

Natural additives can be used in the production or modification of environmentally friendly composites. For instance, plant fibers (e.g., coconut fibers, flax, and hemp) or fillers (e.g., coconut shell powder), can be added to epoxy–glass composites to improve the mechanical strength, stiffness, and fracture toughness [7-9]. Natural fillers, such as silica and mica, can be used to improve the thermal properties (e.g., thermal resistance) of epoxy–glass composites [10]. The natural additives including

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plant fibers and fillers are often less expensive than synthetic alternatives, enhancing the cost-effectiveness of epoxy–glass composites [11-12]. In addition, the use of natural additives can improve sustainability, particularly by reducing the use of petrochemical raw materials, thereby mitigating the environmental impact [13].

Additives can also enhance the strength parameters of composite materials. Glass, carbon, or aramid fibers, are frequently introduced to improve the tensile, bending, and impact strength of composites [14-15]. The aforementioned fibers act as mechanical enhancers, increasing the stiffness and strength of the composites. Fillers, such as silica, alumina, or titanium oxide, can be added to composites to improve overall compressive strength, hardness, and wear resistance [16]. Antioxidant additives, such as corrosion inhibitors, can protect composites from degradation caused by weathering, i.e., exposure to UV radiation, moisture, or aggressive chemicals [17]. Additives can also increase adhesion between different layers of the composite material to improve the structural integrity and strength [18].

In composite production, additives, which are derived from harmful and non-degradable waste, can also be employed [19-20], contributing to a reduction in the amount of waste sent to landfills and promoting sustainable recycling practices [21-22]. Concerning the costs, the components investigated herein are often less expensive than traditional composite constituents, reducing production costs. Moreover, the introduction of waste fibers, such as glass fibers, can improve the strength of composites [23-24]. Some additives derived from recycled waste can also enhance the aesthetic qualities of composites, such as color, texture, or surface pattern.

Numerous researchers have explored the influence of adding rubber products to epoxy–glass composites and highlighted the potential of modifiers such as devulcanized rubber or reactive liquid rubber [25-26]. Given the elasticity par excellence, recycled rubber products can consequently enhance the elasticity of composites. Modifying the composition of composites with rubber products can improve the ability of the material to absorb energy during bending, thereby enhancing the fracture toughness of composites [27].

However, the overall effect of the addition of rubber recyclate on the flexural resistance of epoxy-resin-based composites depends on the type and content of recyclate, mixing and curing methods, and specific application requirements. Therefore, extensive studies and tests are required to clarify the influence of the recyclate on the composite.

Many studies have demonstrated that composites containing recycled rubber may be suitable for applications requiring high resistance to impact loads. However, the research on epoxy–glass composites incorporating rubber recyclate derived from car tires, the influence on the strength parameters, and resistance of materials to bending loads, are scarcely investigated. Therefore, in this study, the results of flexural strength tests of composite materials based on glass mats and epoxy resin were examined.

Notably, this research builds on previously conducted strength tests of composites modified with the addition of rubber recyclate from industrial recycling of car tires [28-29]. The results of experimental studies were subjected to statistical analyses to determine whether the observed differences were statistically significant or attributable to random fluctuations. Moreover, microstructural observations of the cross-sections of the samples were used to examine the adhesion between composite components.

Overall, this study aims at examining the effects of strength properties in bending tests concerning addition and distribution of rubber recyclate within the composite structure. Such analyses are crucial to clarify the effect of the addition of rubber recyclate on the elastic properties of materials, which influence the resistance of the composite to bending and bending force transfer. The objective was to identify composites with the most favorable flexural strength parameters from seven material variants, with a pure epoxy–glass composite obtained using the same method serving as the control.

## 2. Research Materials

Fig. 1 Constituents of the tested composite materials

The tested materials were made of the following components (Fig. 1):

(1) Reinforcement: E-type glass mat (Table 1) with randomly oriented fibers, weighing 350 $g/m^2$. The low linear density fibers in this type of mat help minimize texture and entrapment of air bubbles on the surface.

Table 1 Characteristics of E-type glass fiber

| Parameter | Unit | Value |
|---|---|---|
| Density | $g/cm^3$ | 2.6 |
| Tensile strength | MPa | 3.400 |
| Elongation | % | 3.5 |
| Maximum operating temperature | °C | 550 |
| Peak temperature | °C | 700 |

(2) Matrix: Epidian®6 epoxy resin (Table 2) with Z-1 (aliphatic amine) hardener (13 g of hardener per 100 g of resin).

Table 2 Characteristics of Epidian®6 epoxy resin

| Parameter | Unit | Value |
|---|---|---|
| Epoxy number | mol/100 g | 0.510-0.540 |
| Density at 25 °C | $g/cm^3$ | 1.17 |
| Viscosity at 25 °C | mPa·s | 1000-1500 |
| Gel time 100 g at 20 °C | min | 20 |
| Curing time in 20 °C | days | 7 |

Epidian®6 is a multifunctional epoxy resin, habitually used in the production of linings of chemically resistant tanks, solvent-free coatings, floor masses and primers, fiber-reinforced pipes, tanks, adhesive composites, laminate silicates, potting compounds used in electrical engineering, electronics, and compositions containing organic or inorganic fillers. These compositions, as listed above, are cured at room temperature with polyamides, polyamides, cycloaliphatic amines, or their adducts. Epidian®6 is also used for manufacturing compositions cured at higher temperatures with hardeners, for applications requiring high thermal, chemical, and dielectric resistance.

(3) Modifier: Rubber recyclate (Table 3) with a grain size of 0.5 mm to 1.5 mm, derived from the recycling process of car tires. Recyclate fractions were obtained by sieving recall from an industrial source with granulation of 0.5 to 3 mm using a laboratory sieve shaker. Depending on the material variant, 3%, 5%, and 7% of rubber recyclate was added based on the total weight of the composite.

Table 3 Composition of the rubber recyclate used

| Ingredient | Content |
|---|---|
| Natural rubber | 15% |
| Styrene-butadiene rubber (SBR) | 20% |
| Butadiene rubber (BR) | 10% |
| Butadiene rubber br applications (IIR/XIIR) | 5% |

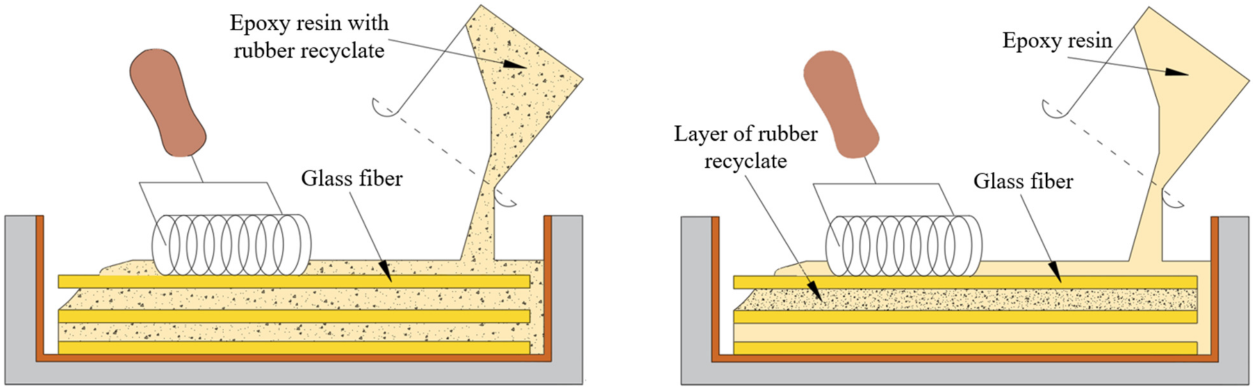
Table 3 Composition of the rubber recyclate used (continued)

| | |
|---|---|
| Silica | 15% |
| Soot | 15% |
| Sulphur | 2% |
| Resin | 2% |
| Mineral and vegetable oils | 10% |
| Other (zinc oxide, stearic acid) | 6% |

To produce the research materials, manual lamination technology was adopted using stainless-steel molds measuring 0.9 × 0.3 m, brushes, rollers, and synthetic wax. Seven variants of composite materials in the form of plates were produced for the study. After lamination, each composite in the mold was pressed vertically with a stainless-steel sheet (0.89 m × 0.29 m × 0.06 m) and eight weights with a total weight of 60 kg. The weights were symmetrically distributed over the surface of the composite pressure plate. The total pressure applied by the sheet metal and weights on each composite material in the mold was experimentally determined, preventing excessive filtration of the composite and leakage of the matrix from the mold. For each material modified with rubber recyclate, the same values of resin, reinforcement, pressure, curing time (7 d), and curing temperature (22 °C) were used.

Table 4 Content and proportions of produced composites

| Material | Method of adding recyclate rubber to composite | Number of reinforcement layers | Resin content (%) | Rubber recyclate content (%) |
|---|---|---|---|---|
| K0 | No add-on | 12 | 60% | 0% |
| K1 | Rubber recyclate added to the composite as one sandwich layer: between the 6th and 7th reinforcement layers | 12 | 60% | 5% |
| K2 | Rubber recyclate added to the composite as two sandwich layers: between the 4th and 5th and between the 8th and 9th reinforcement layers | 12 | 60% | 5% |
| K3 | Rubber recyclate is added to the composite as three sandwich layers: between the 3rd and 4th, between the 6th and 7th, and between the 9th and 10th reinforcement layers | 12 | 60% | 5% |
| L3 | Random in warp | 12 | 60% | 3% |
| L5 | Random in warp | 12 | 60% | 5% |
| L7 | Random in warp | 12 | 60% | 7% |

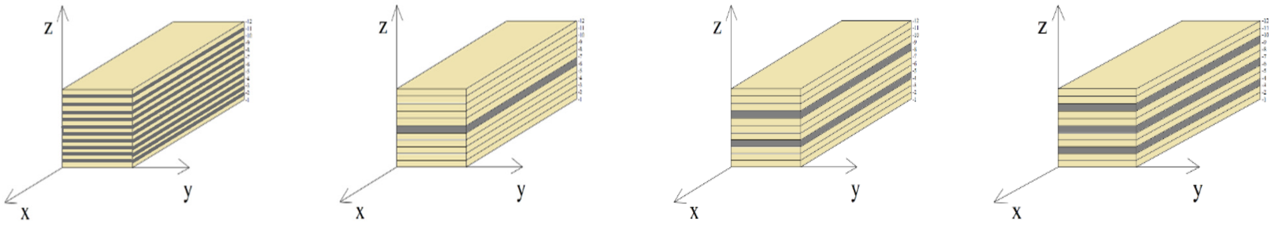


(a) Schematic of the process of manufacturing the *L3*, *L5*, and *L7* variants: random addition of rubber recyclate to the epoxy matrix

(b) Schematic of the process of manufacturing the *K1*, *K2*, and *K3* variants: addition of rubber recyclate in the form of a sandwich layer

Fig. 2 Methods for producing research materials

The test materials included a fixed number of layers of glass mat, layers of rubber recyclate derived from shredded car tires, and epoxy resin Epidian®6. The comparative material was the *K0* variant, an epoxy–glass composite without rubber recyclate. The main difference in the composite production method pertained to the percentage of rubber recyclate added and its distribution within the composite structure. In variants *K1*, *K2*, and *K3,* 5% of rubber recyclate was added, albeit with different distributions in the layers. Specifically, the rubber material was appropriately separated and distributed symmetrically in layers (*K1*: 5% in one layer, *K2*: 2.5% in one layer, *K3*: 1.67% in one layer) between the glass mat layers. Table 4 and Figs. 2, 3, and 4 show the manufacturing technology and structure of the produced composites.



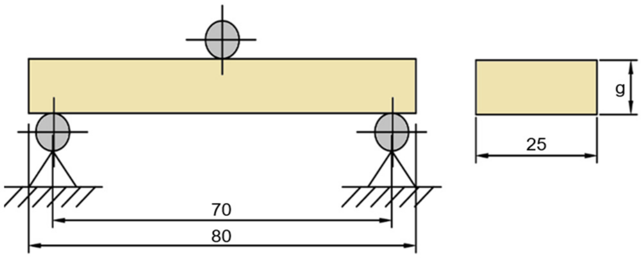
Composites *L3, L5,* and *L7* Composite *K1* Composite *K2* Composite *K3*

▭ glass fiber; ■ rubber recyclate

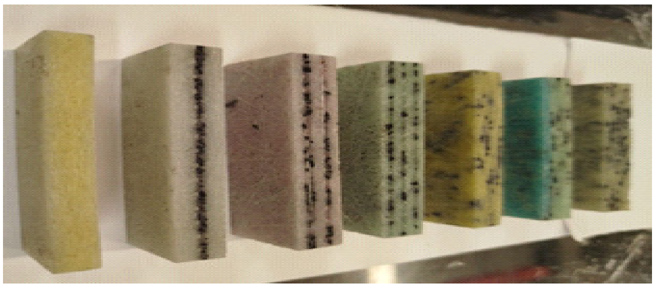
Fig. 3 Arrangement of rubber recyclate layers in *L3, L5, L7, K1, K2*, and *K3* composites

Fig. 4 Mold used during composite production

## 3. Methodology



(a) Sample dimensions and load diagram



(b) Examples of specimens prepared for testing (c) Zwick Roell MPMD P10B testing machine

Fig. 5 Dimensions of samples and setup of the testing machine

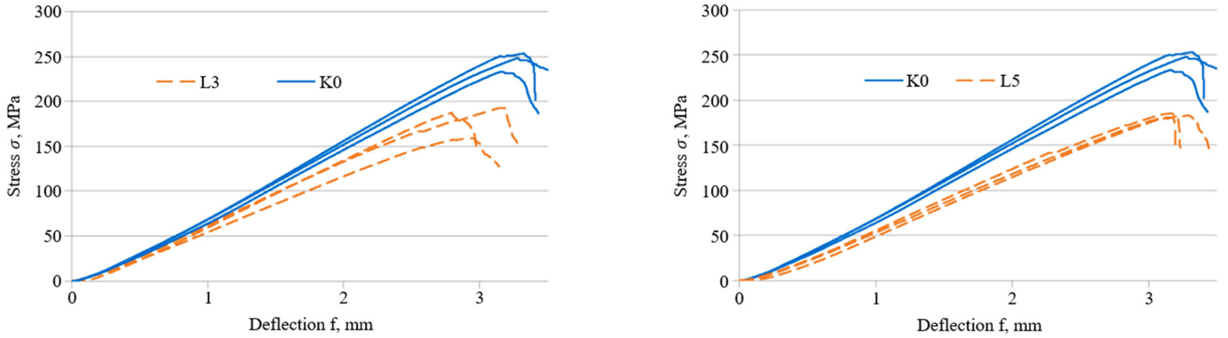
Samples of the tested composite materials, prepared according to the PN-EN ISO 14125:2001 standard, were cut from the produced boards through waterjet cutting (Figs. 5(a) and 5(b)). The cutting technology was chosen to minimize the influence of temperature on the structure of the obtained samples. The prepared samples were subjected to three-point bending tests on a station coupled with a Zwick Roell MPMD P10B testing machine with a hydraulic drive and TestXpert II 3.6.1 software (Fig. 5(c)). Bending tests were conducted on five samples of each material variant produced. Fig. 6 shows samples of *L3* and *K1* materials during the bending test.

(a) Sample of material *L3* during the bending test (b) Sample of material *K1* during the bending test

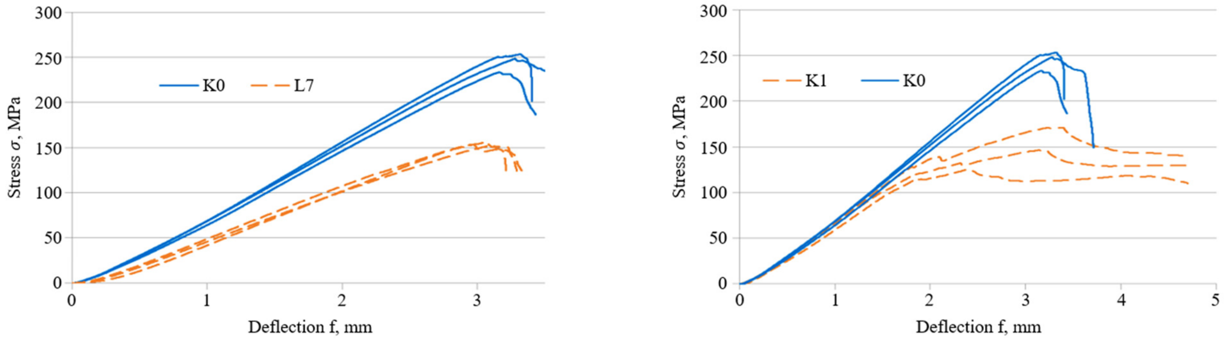
Fig. 6 Samples of composite materials during the bending test

## 4. Research Results and Their Analysis

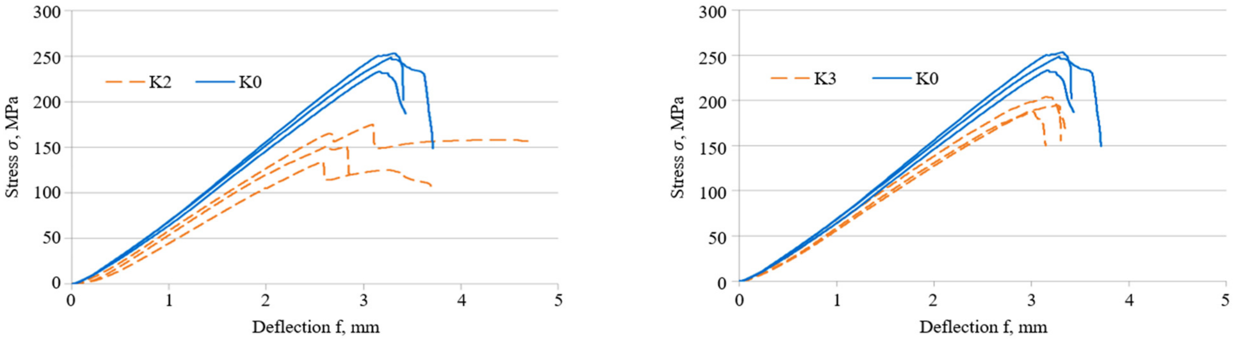
Fig. 7 shows stress–deflection diagrams obtained from the testing machine software during the three-point bending tests. Three sample bending curves were selected for each tested material variant. Table 5 presents the average values of the strength parameters of the material variants, obtained during the bending test. The results presented in Fig. 6 and parameter values in Table 5 confirmed previously reported results regarding the influence of the content and distribution of the recyclate on the mechanical properties of the material.



(a) Comparison of bending curves of *K0* and *L3* (b) Comparison of bending curves of *K0* and *L5*



(c) Comparison of bending curves of *K0* and *L7* (d) Comparison of bending curves of *K0* and *K1*



(e) Comparison of bending curves of *K0* and *K2* (f) Comparison of bending curves of *K0* and *K3*

Fig. 7 Three representative bending curves for each tested material variant, compared with the bending curves of *K0* composite (without rubber recyclate)

Table 5 Mean values of parameters obtained from the bending test of tested composite materials

| Material | Flexural strength Rmg, MPa | Deflection f, mm | Flexural modulus in bending Ef, MPa |
|---|---|---|---|
| K0 | 234.77 | 3.29 | 5430 |
| L3 | 183.58 | 2.92 | 6816 |
| L5 | 181.07 | 3.07 | 2980 |
| L7 | 154.13 | 3.16 | 4282 |
| K1 | 168.56 | 2.86 | 4232 |
| K2 | 159.31 | 2.83 | 3843 |
| K3 | 190.72 | 3.16 | 2817 |

Analyzing the flexural strength results, the following conclusions were derived: With the increase in the content of rubber recyclate in the composite, the strength properties deteriorated, and the elastic properties of the materials were enhanced. For a 7% rubber recyclate content in the composite matrix, a decrease of approximately 36% in *ΔRmg* was recorded, while for contents of 3% and 5%, the decrease in *ΔRmg* was approximately 23%. Notably, the arrangement of the rubber recyclate in the structure influenced the flexural strength values of composites with 5% additive: When the recyclate was distributed in one sandwich layer (*K1*), the flexural strength significantly reduced by approximately 33% in *ΔRmg*. In contrast, when the rubber recyclate was distributed in three sandwich layers (*K3*), *ΔRmg* decreased by only 11%.

According to the analysis of the bending curves, the addition of rubber recyclate changed the characteristics and crack patterns of the composite during bending tests. The elasticity of rubber influenced the type of cracks, leading to different failure mechanisms. The differences were especially evident in bending curves for composites with recyclate layers (*K1*, *K2*, and *K3*). The structure with recyclate layers influenced the fracture dynamics during bending, resulting in irregular curves. The most symmetrical distribution of the recyclate layers in the *K3* composite helped unify the irregularities in the bending curve.

According to the deflection results (*f*), as the amount of recyclate increased, the material deformation reduced. For a material with a 3% recyclate content, *f* decreased by 8%, while for a 7% addition, *f* was approximately 3% smaller than that of the pure *K0* composite. For materials in which recyclate was added as sandwich layers, the deflection *f* decreased by 4% compared with that of the pure composite. *K1* performed the most favorably, with a 17% decrease in deflection, compared with that of the *K0* base material. The results indicated that the addition of recyclate tended to reduce the flexural strength of the material.

The analysis of the parameters highlighted that the addition of rubber recyclate could reduce both the flexural strength and elastic modulus of composites. Rubber typically has a lower tensile strength than epoxy resin and fiberglass. Therefore, the use of its derivative in a composite structure could weaken composites. However, the addition of rubber recyclate increased the energy required to fracture the composite during bending tests. Recyclate grains, with excellent elastic properties, could absorb more energy during deformation, resulting in higher energy-to-fracture strength, as evidenced by the lower deflection values of recyclate-modified composites compared with those of base composites. The bending test results demonstrated that the *K3* material yielded the most favorable parameters concerning flexural strength. A statistical analysis of the impact measurements confirmed the results obtained during the experiments. Overall, the obtained results and elastic properties of the rubber recyclate used as a modifier indicated that the addition of recyclate in selected distribution and percentages could reduce the sample deflection, with the greatest reduction observed for the *K1* variant (with one layer of recyclate).

### *4.1. Statistical analysis of test results*

To investigate the effect of adding rubber recyclate on the composite properties, five tests ($n = 5$) were performed for each material. *K0* material served as the comparative variant. Selected empirical distribution measures for the seven samples are presented from Tables 6-7 and Figs. 8-9, specifically.

Table 6 Selected measures of the empirical distribution of flexural strength of the tested materials

| Material/ Parameter | Flexural strength *Rmg*, MPa | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | Lower quartile | Upper quartile | Standard deviation | Coefficient of variation | Kurtosis |
| K0 | 234.77 | 232.97 | 219.54 | 253.23 | 223.39 | 248.42 | 13.38 | 5.69 | -1.50 |
| L3 | 183.58 | 182.34 | 169.34 | 202.81 | 174.20 | 192.57 | 12.59 | 6.84 | -0.99 |
| L5 | 181.07 | 182.13 | 167.26 | 194.74 | 176.09 | 185.26 | 9.22 | 5.09 | 0.77 |
| L7 | 154.13 | 156.19 | 142.06 | 159.06 | 153.36 | 158.58 | 6.31 | 4.09 | 3.88 |
| K1 | 168.56 | 162.81 | 145.08 | 237.89 | 146.49 | 171.13 | 34.30 | 20.05 | 4.27 |
| K2 | 159.31 | 164.67 | 134.18 | 175.04 | 151.40 | 169.57 | 14.90 | 9.32 | 0.96 |
| K3 | 190.72 | 190.84 | 182.01 | 204.14 | 182.80 | 194.63 | 8.43 | 4.42 | -0.46 |

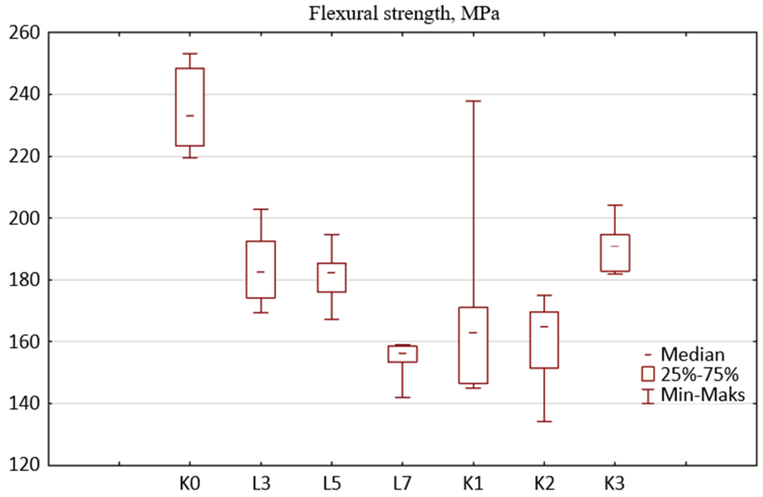


Fig. 8 Distribution of flexural strength measurements for individual samples

Table 7 Selected measures of the empirical distribution of deflection values in the bending test of materials

| Material/ Parameter | Deflection *f*, mm | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | Lower quartile | Upper quartile | Standard deviation | Coefficient of variation | Kurtosis |
| K0 | 3.29 | 3.28 | 3.16 | 3.43 | 3.26 | 3.32 | 0.10 | 3.02 | 1.24 |
| L3 | 2.92 | 2.93 | 2.79 | 3.08 | 2.86 | 2.93 | 0.11 | 3.64 | 0.93 |
| L5 | 3.07 | 3.06 | 2.91 | 3.19 | 3.06 | 3.16 | 0.11 | 3.57 | 0.30 |
| L7 | 3.16 | 3.16 | 2.96 | 3.34 | 3.06 | 3.26 | 0.15 | 4.82 | -1.47 |
| K1 | 2.86 | 2.90 | 2.42 | 3.28 | 2.49 | 3.19 | 0.40 | 13.84 | -2.83 |
| K2 | 2.83 | 2.83 | 2.58 | 3.10 | 2.77 | 2.87 | 0.19 | 6.55 | 1.29 |
| K3 | 3.16 | 3.15 | 3.02 | 3.28 | 3.08 | 3.26 | 0.11 | 3.59 | -2.28 |

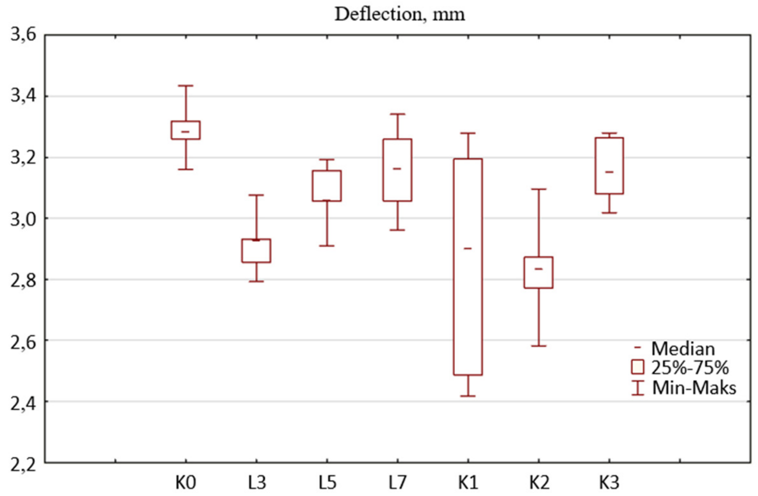
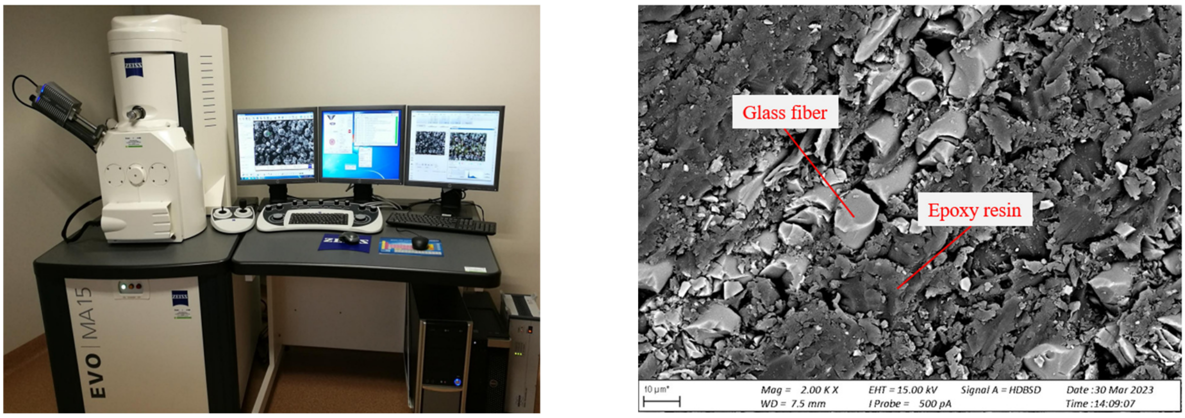


Fig. 9 Distribution of deflection measurements for individual samples

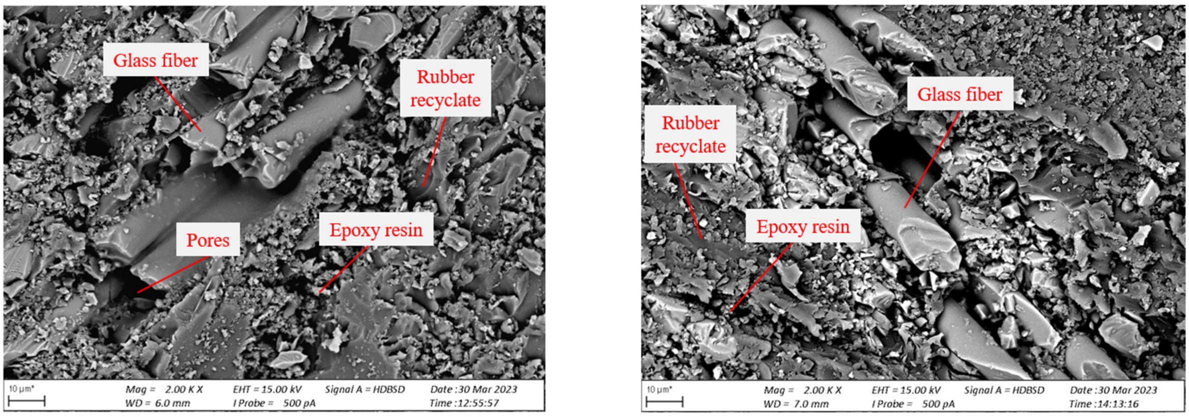
The analysis of the measurement distributions revealed asymmetry in the empirical distributions of the studied features. Significant differences were observed in the distribution of the strength parameters for the composites modified with rubber recyclate. The dissimilitude was evident from the different lengths of the whiskers and asymmetrical positioning of the median and box in the frame–whisker diagrams for the material variants with rubber recyclate. Furthermore, the bending strength *Rmg* values exhibited significant variations. The largest dispersion of results corresponded to the *K1* material, as indicated by uneven whiskers on the box plot and high standard deviation values for both *Rmg* and *f* parameters. Conversely, the most favorable parameters were obtained for *K3*, where the distributions of strength values *Rmg* and deflection *f* were more symmetrical than those of the other rubber composite variants. Samples with a random distribution of recyclate grains directly added to the resin matrix corresponded to lower strength parameters. However, the samples (especially *L3* and *L5*) exhibited more symmetrical *Rmg* distributions than the samples including *K1*, *K2*, and *K3*.

The addition of 7% of the recyclate in *L7* negatively affected the strength parameters, resulting in the lowest *Rmg* value and high asymmetry in the *Rmg* and *f* value distributions. The *K3* material showed greater reproducibility in deflection values *f*, while the *K2* material exhibited repeatability in tensile strength *Rmg* results. Materials with randomly added recyclate to the matrix (*L3*, *L5*, and *L7*) showed a high dispersion of results, indicating the mechanical properties per se were characterized by high variability and low reproducibility owing to the heterogenous internal structure of these materials.

### 4.2. Evaluation of microscopic structures



(a) Setup for observation of SEM structures (b) Cross-sectional structure of *K0*



(c) Cross-sectional structure of *L3* (d) Cross-sectional structure of *K1*

Fig. 10 Scanning electron microscope Zeiss EVO MA 15 and SEM cross-sectional structures (magnification: 2000×)

A scanning electron microscope (SEM, Zeiss EVO MA 15) was used to analyze the structures of the materials (Fig. 10(a)). The SEM observations aimed to assess the influence of the rubber modifier on the internal structure, i.e., the distribution and adhesion of the components of the produced material variants. The samples for observation were produced from fragments of the plates from which the bending test samples were cut. In preparing the cross-sections, sandpapers were used (320, 800, and

1200 grit), and the surfaces of the cross-sections were polished using a polishing slurry with a grain size of 3 μm. Figs. 10(b)-(d) shows images of the microstructures of cross-sectional sections of samples of composite materials *K0*, *L5*, and *K1*, obtained at 2000× magnification.

The SEM analysis of the composite structures helped clarify the effect of the addition of recyclate on the structures of all the tested materials relative to *K0*. Observations of cross-sections demonstrated that composites with rubber recyclate added to the matrix (*L3*, *L5*, and *L7*) exhibited more heterogenous structures, compared with the composites including the recyclate in sandwich layers. Images of the *L3* material structure reveal the presence of numerous voids and air pores, which weaken the bonds between the composite components, resulting in higher measured deflections for these variants compared with the *K1* and *K2* composites.

Microscopic observations indicate that the addition of rubber recyclate adversely affects the adhesion between the glass fiber and epoxy resin, especially in the *L3*, *L5*, and *L7* variants. The internal balance of the composite is disrupted by the irregular grains of recyclate scattered in the epoxy resin, increasing the heterogeneity in the internal structure of the composites. The random distribution of glass fibers in the reinforcement, combined with the random distribution of rubber recyclate in the resin in the *L3*, *L5*, and *L7* composites, results in a high anisotropy of the structure and corresponding reduction in strength parameters.

The cross-sectional structures of *K1*, *K2*, and *K3* appeared more compact than those of other variants. The reinforcement layers on both sides of the rubber recyclate layers likely slightly altered the stiffness of the cross-sections. The symmetrical arrangement of the reinforcement layers and rubber recyclate layers in the *K1*, *K2*, and *K3* composites influenced the microstructure, contributing to lower deflection values than those of *K0*. Microscopic observations suggested that improving the adhesion of rubber recyclate grains to the material components (by modifying the surface of rubber recyclate grains through mechanical or chemical methods) may result in better mechanical properties of composites modified with rubber recyclate.

## 5. Discussion

In interpreting the test results, it is essential to consider previous analyses (static tensile tests and impact tests) of the manufactured composites. Static tensile tests by Żuk et al. [30] show that the addition of rubber recyclate reduces the strength properties of the composite. Conversely, the impact test results by Abramczyk et al. [29] indicate that the modification of composites with the addition of rubber recyclate increases the impact value compared with that of the base material *K0*. The strength parameters obtained in these tests are presented in Tables 8 and 9.

Table 8 Average values of strength parameters obtained in the static tensile test of materials [30]

| Material | Tensile strength $\sigma_m$ [MPa] | Strain in tensile test $\varepsilon$ [%] | Young modulus $E$ [MPa] |
|---|---|---|---|
| K0 | 127.37 | 1.86 | 8446 |
| K1 | 108.42 | 1.82 | 7946 |
| K2 | 103.71 | 2.15 | 6418 |
| K3 | 100.63 | 2.13 | 6255 |
| L3 | 98.25 | 2.02 | 6198 |
| L5 | 97.74 | 2.06 | 6066 |
| L7 | 93.16 | 2.11 | 5829 |

Table 9 Medium impact strengths of the composite materials [29]

| Composite/ Parameter | Maximum force $F_{MAX}$ [N] | Deflection $f$ [mm] | Work $W$ [J] | Impact strength $U$ [kJ/m$^2$] |
|---|---|---|---|---|
| K0 | 2983 | 1.52 | 5.06 | 74 |
| K1 | 2774 | 1.85 | 4.82 | 67 |
| K2 | 3240 | 1.81 | 4.88 | 82 |
| K3 | 2889 | 1.67 | 5.56 | 64 |

Table 9 Medium impact strengths of the composite materials [29] (continued)

| Composite/ Parameter | Maximum force $F_{MAX}$ [N] | Deflection $f$ [mm] | Work $W$ [J] | Impact strength $U$ [kJ/m$^2$] |
|---|---|---|---|---|
| L3 | 2651 | 1.44 | 5.59 | 60 |
| L5 | 2542 | 1.46 | 5.31 | 63 |
| L7 | 3105 | 1.27 | 5.81 | 66 |

The effect of adding rubber recyclate on the internal structure of glass mat and epoxy-resin-based composites depends on various factors, such as the content, size, and morphology of the rubber recyclate, as well as the mixing, forming, and curing processes of the composite. Therefore, to fully understand the effect of the addition of rubber recyclate on the internal structure of the composite, detailed laboratory tests and analyses must be performed. The analysis of strength tests presented in the study indicated that the addition of rubber recyclate significantly affects the mechanical properties of the produced composites. The results showed that distributing rubber recyclate in the composite as one, two, or three sandwich layers (i.e., *K1*, *K2*, and *K3*) yields comparable or more favorable properties compared with the pure epoxy–glass composite *K0*. Statistical analysis of the results of the bending test confirmed the conclusions.

Notably, the effect of rubber recyclate on mechanical properties depends on its quantity and distribution within the composite. Excessive additives can significantly reduce the mechanical strength, while the addition of rubber recyclate can negatively affect the flexural strength, especially if not properly dispersed in the epoxy matrix. The heterogeneous distribution of the additive can lead to local weaknesses and decreased strength. In the bending tests of the *L3*, *L5*, and *L7* variants, the deflection $f$ values were higher than those obtained for the *K1* and *K2* composites. In contrast, the use of recyclate in *K1*, *K2*, and *K3* materials can help absorb energy during bending, potentially increasing flexural strength by dissipating load energy. Cracks occurring in composites during bending tests can result from a combination of interface failure, matrix cracking, fiber cracking, deformation, or damage to the recyclate grains, depending on the composite structure and loading scenario. Understanding fracture mechanisms is crucial in designing and constructing composite materials with increased durability.

## 6. Conclusions

Rubber recyclate, obtained from recycling used car tires, is a valuable secondary raw material for producing new multilayer composites. The addition of rubber recyclate as a modifier enables the creation of new value-added materials while contributing to environmental protection. The possibilities of using *K1*, *K2*, and *K3* composites depend on the type of loads encountered by certain materials. Notably, the basic strength parameters obtained for these composites, such as tensile strength $\sigma_m$, Young’s modulus $E$, and flexural strength $Rmg$, were comparable to materials used in the yacht industry for constructing yacht cabin elements (furniture and walls). Considering the beneficial effects of rubber recyclate on sound-insulating properties, it is feasible to use the tested materials *K1*, *K2*, and *K3* to prepare low-load elements in the interior structure of vessels. These materials introduced in this study are expected to have functional qualities, resistance to water and chemical agents, and applicability to soundproof rooms, enhancing the comfort of use.

In summary, materials can be designed to satisfy specific applications and manufacturer requirements. The conducted research demonstrates that waste materials can be used to create new materials with functional and environmental benefits. The newly designed materials can help manage waste effectively while further leveraging the advantages (i.e., favorable sound insulation properties, increased impact strength, and low cost) for specific applications where high strength parameters are not critical. Future research will include an analysis of the influence of temperature on the structure of composites. Additional analyses can be focused on the absorbability of composites, thermal conductivity, porosity, and electrical conductivity.

## Conflicts of Interest

The authors declare no conflict of interest.

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