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CHARACTERIZATION OF ABACA-E-GLASS/EPOXY POLYMER COMPOSITES REINFORCED WITH BAMBOO-ACTIVATED CARBON NANOFILLERS

KARAKTERIZACIJA POLIMERNIH KOMPOZITOV NA OSNOVI ABAKE, E-STEKLA, EPOKSIJA IN BAMBUSA Z AKTIVIRANIM OGLJIKOVIM NANOPOLNILOM

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This study aims to investigate the effect of fiber volume fraction and NaOH treatment on the mechanical and physicochemical properties of hybrid abaca–E-glass/epoxy composites reinforced with bamboo-activated carbon nanofiller. Composites were fabricated using hand lay-up and vacuum bagging, with fiber volume fractions (V_f) of (40, 50 and 60) % and fiber orientations of 0° and (0/90)°. Meanwhile, the weight percentage of bamboo-derived activated carbon filler was 2 *w*/%. Tensile tests were conducted according to ASTM D3039, while morphological, elemental, and chemical characterizations were performed using SEM-EDS and FTIR analyses. The results show that the composite with a V_f of 50 % and 0° fiber orientation treated with NaOH exhibited the highest tensile strength of 56.62 MPa, compared to 46.08 MPa for untreated fibers, indicating improved interfacial adhesion due to alkali treatment and hybridization with E-glass fibers. SEM observations revealed relatively uniform nanofiller dispersion and predominant fiber fracture, whereas a higher V_f of 60 % led to void formation and reduced tensile strength. SEM-EDS confirmed dominant carbon content in the nanofiller (90.90 %), while FTIR spectra identified characteristic O–H, C=O, C–O–C, and Si–O–Si groups, demonstrating successful curing and good compatibility among fibers, nanofiller, and epoxy matrix. Overall, the optimized composite at a V_f of 50 % exhibits enhanced mechanical performance and interfacial interaction, highlighting its potential for lightweight structural and radar-absorbing applications.

Keywords: abaca-E-glass, bamboo-derived activated carbon nanofiller, characterization, fiber volume fraction

V članku avtorji opisujejo študijo vpliva volumskega deleža vlaken in obdelave z NaOH na mehanske in fizikalno-kemijske lastnosti polimernih hibridnih kompozitov iz abake (Manilska konoplja), E-stekla (steklena vlakna za elektroniko) in epoksija, ojačanih z nanopolnilom iz bambusa z aktivnim ogljem. Kompozite so avtorji izdelali z ročnim polaganjem in vakuumskim pakiranjem z volumskimi deleži vlaken (V_f) (40, 50 in 60) % ter orientacijami vlaken 0° in (0, 90)°. Medtem ko je bil masni delež polnila iz bambusa z aktivnim ogljem enak 2 *w*/%. Natezne preskuse so izveli v skladu s standardom ASTM D3039. Morfološke, elementarne in kemijske karakterizacije pa so avtorji izvedli s pomočjo vrstičnega elektronskega mikroskopa (SEM), energijske disperzijske spektroskopije (EDS) in Fourierjeve transformacijske infrardeče spektroskopije (FTIR). Rezultati raziskave so pokazali, da je imel kompozit z V_f 50, orientacijo vlaken 0° in obdelan z NaOH najvišjo natezno trdnost 56,62 MPa v primerjavi s trdnostjo kompozita z neobdelanimi vlakni 46,08 MPa. Avtorji poudarjajo, da to kaže na izboljšano medfazno adhezijo zaradi alkalne obdelave in hibridizacije z vlakni iz E-stekla. SEM opazovanja so pokazala relativno enakomerno porazdelitev nanopolnil in prevladujoč lom vlaken, medtem ko je višji V_f 60 povzročil nastanek praznin in nižjo natezno trdnost. SEM-EDS analize so tudi potrdile prevladujočo vsebnost ogljika v nanopolnilu (90,90 %), medtem ko so FTIR spektri identificirali značilne skupine O–H, C=O, C–O–C in Si–O–Si, kar dokazuje uspešno strjevanje in dobro združljivost med vlakni, nanopolnilom in epoksidno matrico. Na splošno je optimiziran kompozit pri Vf 50 pokazal izboljšanje mehanskih lastnosti in interakcijo na površini, kar poudarja njegov potencial za uporabo v lahkih konstrukcijskih materialih in materialih za radarsko absorbcijo.

Ključne besede: abaka-E-steklo, nanopolnilo z aktivnim ogljem iz bambusa, karakterizacija, volumski delež vlaken

1 INTRODUCTION

Composite materials[1] are used in industrial structures to overcome the shortcomings of certain materials. Composites, whose properties are significantly different from those of their constituent materials, have been widely used for advanced applications. Natural fibers[2–5] such as polymer composites have high specific strength, are light, have good mechanical strength, are non-abrasive, environmentally friendly, economical and bio-degradable.

Fibers[6] are divided into three types, namely natural, synthetic, or a mixture of both, and can be defined in a single matrix consisting of two or more fibers. Additional reinforcement[7] of synthetic fibers in natural fiber composites strengthens the mechanical properties of the composite.

Indonesia is a country rich in natural resources, one of which is natural fiber which can be used as a material

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for making composite structures. Abaca,[8] an underutilized part of the banana plant, contains 80 % of cellulose. According to the Central Statistics Agency (BPS), Indonesia produced 9.24 million tons of bananas in 2022, and bamboo[9] contributed 66.92 million stems.

Over the past 10 years,[9] research on polymer nanocomposites has been conducted, focusing on advanced materials used in technological applications, and polymer matrices combined with various fillers in nanometer size. Carbon nanofillers[10] provide improved structural and functional properties due to their high aspect ratio, electrical properties, and mechanical strength. Their better nanofiller dispersion contributes to improved mechanical properties.

Therefore, both types of biomass fiber have the potential to be used as alternative raw materials for strengthening advanced composite materials, optimizing domestic fiber levels and reducing dependence on imported products. An increase in composite properties[10] is caused by an increase in the fiber content in a composite and the decreasing volume fraction of fiber pull-out. Impact test[11] results show that an abaca-E-glass/polyester composite has a higher strength than an abaca/polyester composite.

Composite materials[12] with a V_f (fiber volume fraction) of 40 % perform better in terms of elastic characteristics. The composite made with a fiber volume proportion of 50 % has serves better regarding strength properties. The poor mechanical performance[13] of a natural fiber-reinforced polymer composite is due to various elements, such as fiber length, fiber orientation, fiber volume fraction, and adhesion between the reinforcement and matrix.

A treated composite[14] shows superior results in terms of tensile strength. However, the tensile strength varies with the decrease in the percentage of fiber weight. Maximum tensile strength is achieved at 10 % fiber loading; the NaOH treatment solution effectively reduces the pectin and lignin levels in abaca fiber.

Composites made of thermoset materials[15] may be prone to internal deterioration, including cavities and cracks, which can compromise their longevity. Fillers are one way to solve this issue.

By adding a filler, composites' mechanical, physical, and other qualities can be enhanced.

One of the fillers[16,17] used and investigated by many researchers is activated carbon, which belongs to the class of amorphous carbonaceous materials characterized by large porosity and internal surface area. Moreover, a bamboo-derived activated carbon nanofiller functioning as an absorbent of dirt in the fiber, which is integrated with the epoxy matrix leads to better material characteristics suitable for application in radar-absorber-material (RAM) composites.

2 MATERIALS AND METHODS

The composite was formed using abaca and E-glass fibers as reinforcement in an epoxy matrix, combined with bamboo-derived activated carbon nanofiller. Before specimen manufacturing, the abaca fibers were soaked in 5 % NaOH solution for 2 h. The manufacturing methods used were hand lay-up and vacuum bagging at room temperature of 30°, with curing for 7 h, having fiber orientations of 0° and (0/90)° and V_f values of (40, 50 and 60) %. Composite tensile testing followed ASTM 3039. Scanning electron microscopy was performed to analyze the composite surface, including its microstructure and morphology. The FTIR test on the composite was carried out to identify and characterize the functional groups and chemical bonds present in the composite, determining the composition and structure. **Figure 1** shows the final specimens used for the tensile tests.

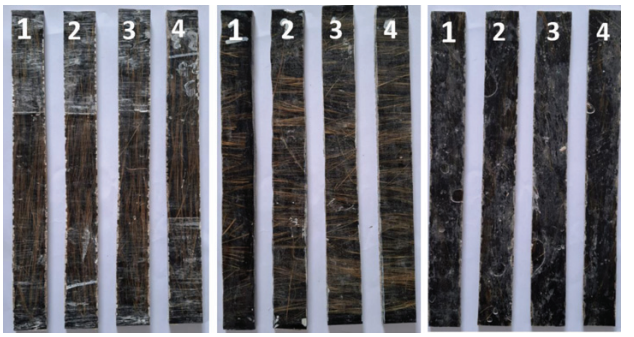

Figure 1: Tests specimens of abaca-E-glass/epoxy composites reinforced with bamboo-derived activated carbon nanofiller: a) V_f of 40 %, b) V_f of 50 % and c) V_f of 60 %

3 RESULTS AND DISCUSSION

3.1 Mechanical characteristics

Tensile tests were done using a universal testing machine Tensilon with a maximum capacity of 10,000 N, according to ASTM D-3039. **Figure 2** shows typical load-displacement curves for hybrid abaca-E-glass/epoxy specimens reinforced with bamboo-derived activated carbon nanofiller with unidirectional (0°) fiber orientation, with a V_f of 50 %, without and with NaOH treat-

Table 1: Results and comparison of the tensile strengths of abaca-E-glass/epoxy composites reinforced with bamboo-derived activated carbon nanofillers, with and without NaOH treatment, and abaca/epoxy composites reinforced with bamboo-derived activated carbon nanofillers with NaOH treatment

Composites	Unidirectional orientation (0°)		
	Strength (MPa)	Strain (%)	Density (g/cm^3)
Abaca-E-glass/epoxy-bamboo activated carbon nanofiller, AEB, NaOH treatment	56.62	1.33	1.50
Abaca-E-glass/epoxy-bamboo activated carbon nanofiller, AEB, without NaOH	46.08	1.09	1.65
Abaca/epoxy-bamboo activated carbon nanofiller, AB, NaOH Treatment[15]	30	2.6	1.1

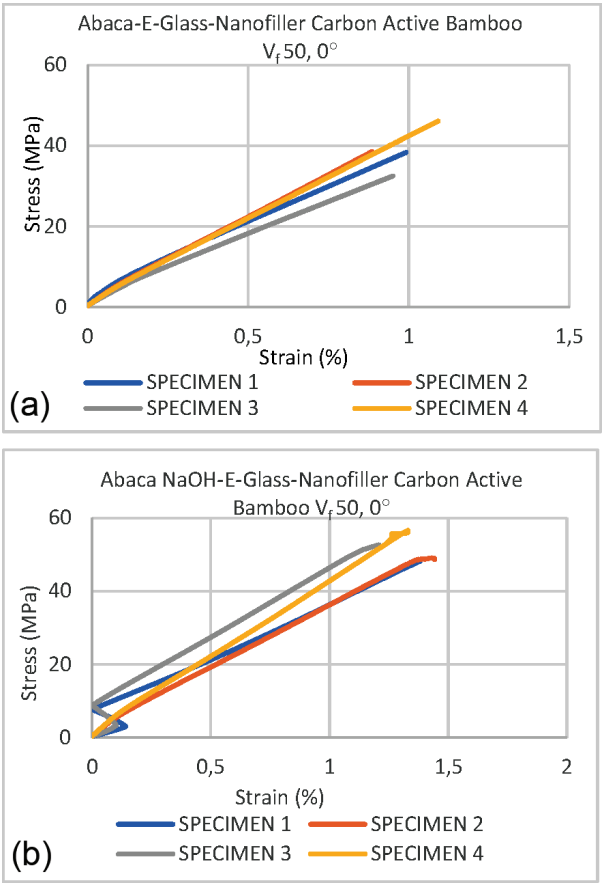

Figure 2: Typical stress-displacement curves for abaca-e-glass/epoxy composites reinforced with bamboo-derived activated carbon nanofiller, with unidirectional (0°) orientation: a) with NaOH tretment; b) without NaOH treatment

ment. The results for abaca-E-glass/epoxy composites reinforced with bamboo-derived activated carbon nanofiller, with the unidirectional (0°) orientation, with and without NaOH treatment are given in **Table 1**.

Figure 3 shows the typical load-displacement curves for the specimens with unidirectional (0/90)° fiber orientation, with V_f values of (40, 50 and 60) %, after the NaOH treatment of the abaca fiber, using a bamboo-derived activated carbon nanofiller content of 2 *w*/% in the resin, according to the previous research by Nawras et al. The tensile modulus[17] decreased when the activated carbon concentration increased by more than 3 *w*/%. The effect of the weight percentage[18] of activated carbon filler of 4 *w*/% leads to an agglomeration filler, which can cause stress concentration and lower the mechanical performance of the composite.

Table 1 shows that the composite of abaca and E-glass fibers, with abaca fiber being treated with NaOH and acting as reinforcement, has a higher strength and lower density. The treatment of the fibers removes some of the pectin and lignin contained in the fibers and makes the fiber surface rough, making it easier for the resin to impregnate the fiber, thus improving the bond between the fibers and the matrix. It is very important to evenly distribute the force and achieve the optimal tensile strength and strain. **Table 2** and **Figure 4** show that the highest strength occurs in the composites with a V_f of 50 compared to a V_f of 40. This shows that increasing the fiber volume fraction increases the strength of the composite. The addition of fiber can increase the elastic modulus (stiffness) of the composite, but the strain value can decrease depending on the type of fiber and matrix. A matrix that is more compliant than the fiber can in-

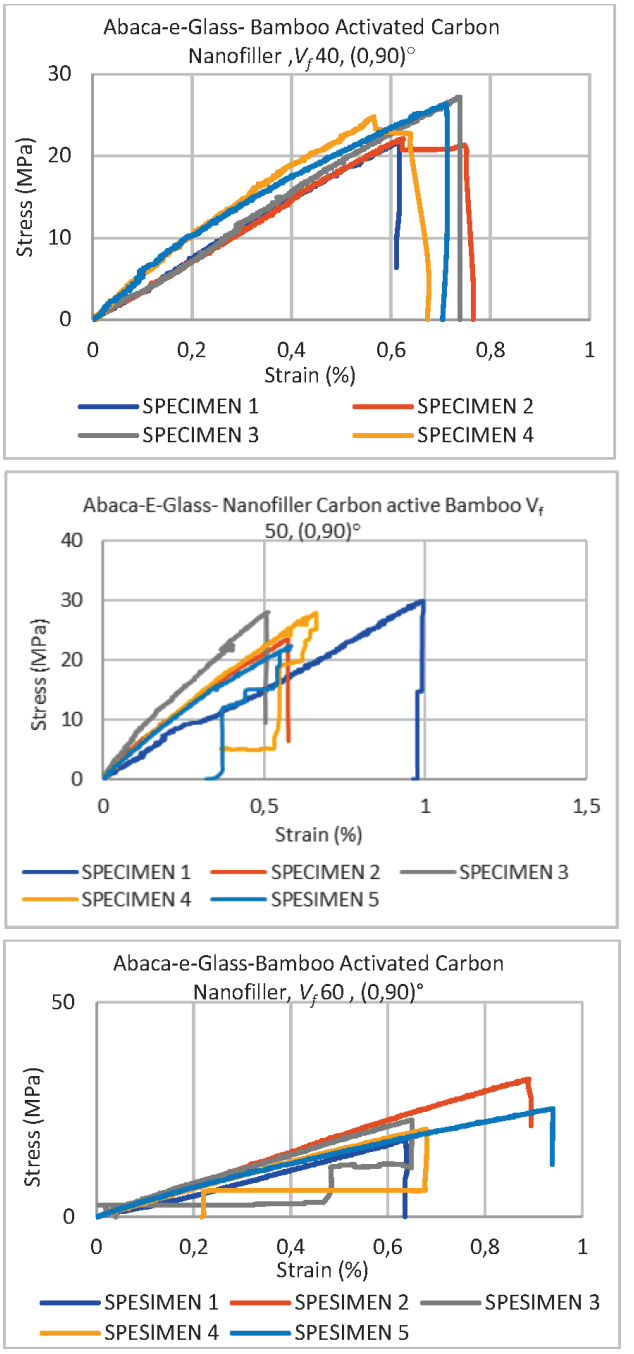

Figure 3: Typical stress-displacement curves for hybrid abaca-E-glass/epoxy composites reinforce with bamboo-derived activated carbon nanofillers, bidirectional orientation (0/90)°: a) V_f of 40, b) V_f of 50, and c) V_f of 60

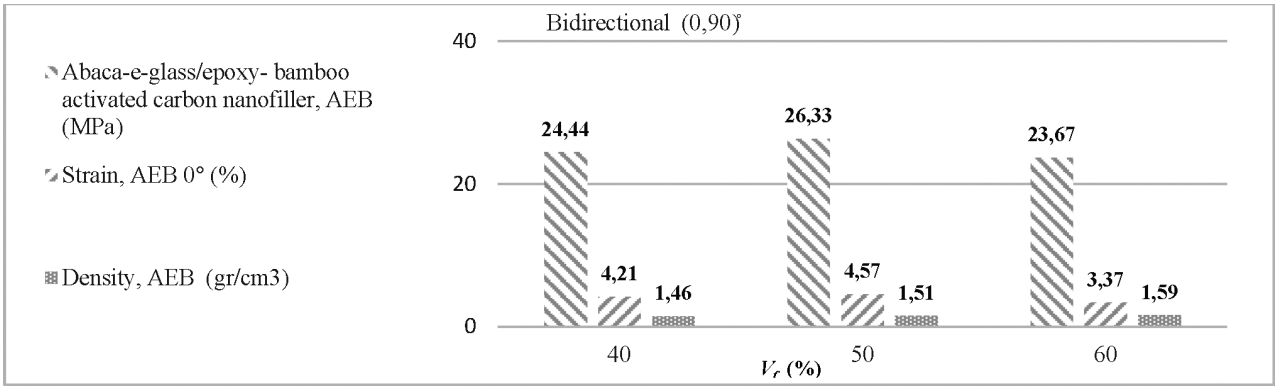

Figure 4: Comparison of histograms for tensile strength, strain and density of abaca-E-glass/epoxy composites with bamboo-derived activated carbon nanofillers with V_f values of 40, 50 and 60 for bidirectional fiber direction (0/90)° with NaOH treatment

crease the strain capacity, particularly when plastic deformation occurs beyond the elastic limit of the matrix.

Table 2: Comparison of tensile strength results for abaca-bamboo-E-glass/epoxy composites reinforced with bamboo-derived activated carbon nanofillers with V_f values of (40, 50 and 60) %, for bidirectional fiber orientation (0/90)° after NaOH treatment

Composites	Bidirectional orientation (0/90)°		
	V_f 40	V_f 50	V_f 60
Abaca-E-glass/epoxy-bamboo activated carbon nanofiller, AEB (MPa)	24.44	26.33	23.67
Strain, AEB (%)	4.21	4.57	3.37
Density, AEB (gr/cm^3)	1.46	1.51	1.59

3.2 SEM Analysis

Figure 5 shows SEM images of the morphological composition of the surface of abaca-E-glass/epoxy bamboo-derived activated carbon nanofiller composite.

Figure 5 shows the morphology of abaca-E-glass/epoxy bamboo-derived activated carbon nanofiller composite in the middle part of the test specimen. It can be seen that the E-glass fibers have a uniform diameter size. **Figure 5a** shows that the black aggregate carbon particles are almost evenly spread throughout the material, showing that the bamboo-derived activated carbon nanofiller has mixed well with the matrix. The bamboo-derived activated carbon nanofiller and matrix receive the tensile test load simultaneously, then distribute the force to the fibers that act as the reinforcement in the composite,

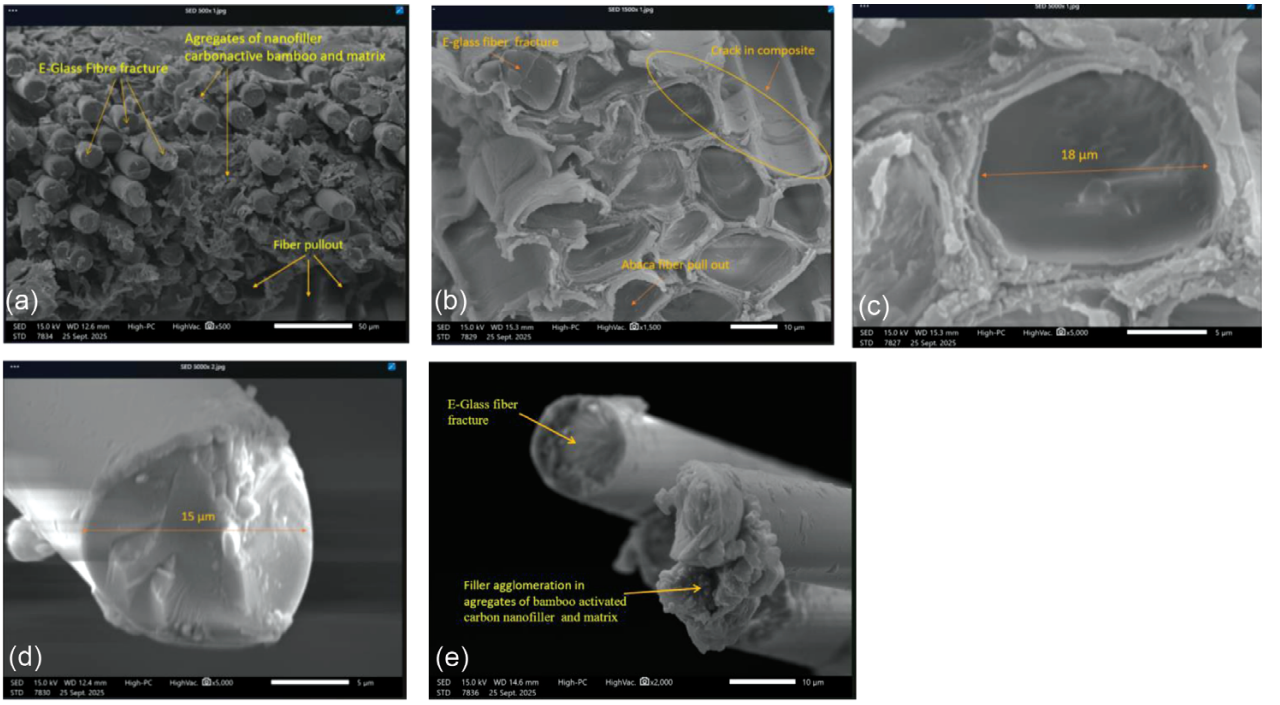

Figure 5: SEM morphology of abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite showing the middle part of the test specimen, at different magnifications: a) ×1500, b) ×2000, c) ×5000, d) E-glass fiber fracture ×5000 and E-glass fiber fracture ×2000

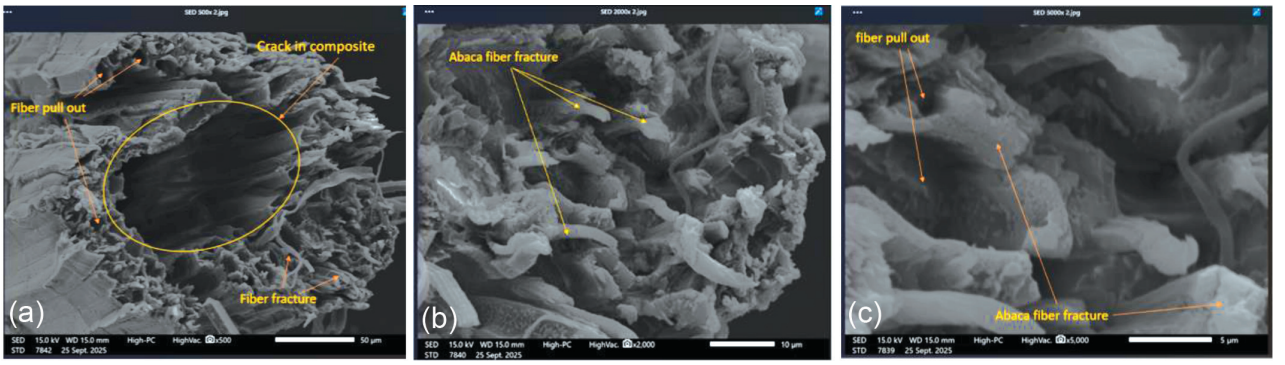

Figure 6: SEM morphology of abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite at the edge of the test specimen, at magnifications: a) ×500, b) ×2000, and c) ×5000

making the composite stronger. A matrix-rich area is found in the composite, also showing voids in several parts. The E-glass fiber fracture shows that the interfacial bond between the fiber and matrix is quite good. However, it can also be seen that there is fiber pull-out, indicating that the bond between the fiber and the matrix is not good enough. **Figure 5b** shows that some cracks extended partially and the fibers are completely pulled out, which is caused by the presence of voids that are large enough to trigger cracks in the composite. These are due to agglomeration and inadequate fiber wetting by the matrix. The amount of filler in the matrix also influences the fiber-wetting process. Debonding and delamination failure indicates weak matrix adhesion to the fiber. Specimen observation showed optimal load transfer capability with a filler content of 2 *w*/%. This is because the matrix, fiber, and filler can withstand the load optimally. However, there are some places where failures occur due to matrix cracks found in the specimen so that the load transfer is not optimal. **Figures 5c** and **5d** show a matrix hole of 18 µm and diameter of the E-glass fiber of 20 µm. **Figure 5e** shows the E-glass fiber fracture, indicating that the bond between the fiber and matrix is good because the fiber is not pulled out of the matrix, while residual aggregates of bamboo-derived activated carbon nanofillers and matrix remain on the fibers. **Figure 6** shows the morphology of the abaca-E-glass/epoxy-bamboo activated carbon nanofiller composites at the edge of the test specimen. There are quite large cracks in the middle and several other parts, triggered by the voids in the composite. **Figures 6a, 6b**, and **6c** show fiber pull-outs and fractures in several parts of the abaca fibers.

3.3 SEM-EDS analysis

The function of SEM-EDS (scanning electron microscopy-energy dispersive X-ray spectroscopy) is to simultaneously provide high-resolution images of a sample's surface and determine its elemental composition. SEM reveals the surface topography and morphology (shape and structure), while EDS analyzes the X-rays emitted by the sample to identify its elements. **Figures 7**, **8**, **9** and **Tables 4**, **5**, **6** show the SEM-EDS analysis of bamboo-derived activated carbon nanofiller and abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite.

Table 4: Elements of bamboo-derived activated carbon nanofiller

Display name	Standard data	Quantification method	Result Type
Spc_001	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	90.90±0.05	93.31±0.05
O	K	8.28±0.05	6.38±0.04
Mg	K	0.08±0.00	0.04±0.00
Al	K	0.06±0.00	0.03±0.00
Si	K	0.23±0.01	0.10±0.00
K	K	0.26±0.01	0.08±0.00
Ca	K	0.20±0.01	0.06±0.00
Total		100.00	100.00
Spc_001			Fitting ratio 0.0147

Table 5: Elements of the upper surface of abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite

Display name	Standard data	Quantification method	Result Type
Spc_001	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	82.94±0.07	86.80±0.08
O	K	16.47±0.10	12.94±0.08
Na	K	0.11±0.01	0.06±0.01
Si	K	0.30±0.01	0.14±0.01
Cl	K	0.18±0.01	0.06±0.00
Total		100.00	100.00
Spc_001			Fitting ratio 0.0185

Table 6: Elements of the fracture surface of abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite

Display name	Standard data	Quantification method	Result Type
Spc_001	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	64.10±0.10	73.42±0.11
O	K	27.83±0.14	23.93±0.12
Na	K	0.85±0.03	0.51±0.02
Si	K	1.75±0.04	0.86±0.02
Cl	K	0.67±0.03	0.26±0.01
K	K	0.54±0.05	0.19±0.02
Ca	K	1.86±0.07	0.64±0.02
Tm	M	2.40±0.12	0.20±0.01
Total		100.00	100.00
Spc_001			Fitting ratio 0.0550

Figure 7a and **Table 4** above show the presence of C, O, Mg, Al, Si, K, and Ca in the particles of the bamboo-derived activated carbon nanofiller. According to the

SEM-EDS analysis, the particle fraction of C has a mass value of 90.90 %. Furthermore, O has a mass value of 8.28 %. **Figure 7b** and **Table 5** show the presence of C, O, Na, Si, and Cl in the upper surface of the abaca-E-glass/epoxy bamboo-derived activated carbon nanofiller composite. According to the SEM-EDS analysis of particle fractions, C has a mass value of 82.94 %, and O has a mass value of 16.47 %. The presence of Na and Cl is due to the activated carbon nanofiller using NaCl. **Figure 7c** and **Table 6** above show the presence of C, O, Na, Si, Cl, K, Ca and Tm in the fracture surface of the abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite. SEM-EDS analysis of the particle fractions shows that C has the largest mass value of 64.10 % and O has a value of 27.83%. This composite has the highest oxygen content, which indicates the presence of voids, causing fractures in the composite.

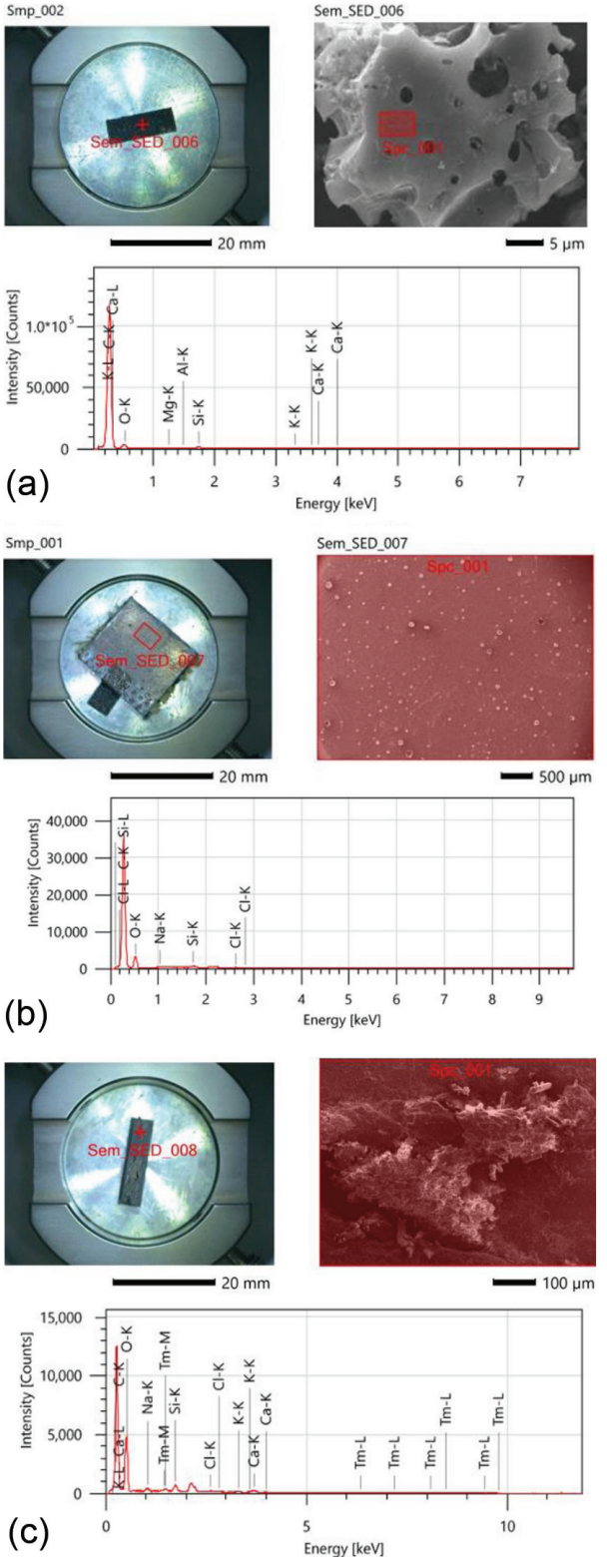

Figure 7: SEM EDS: a) bamboo-derived activated carbon nanofiller; b) upper surface of the abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite; and c) fracture surface of the abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite

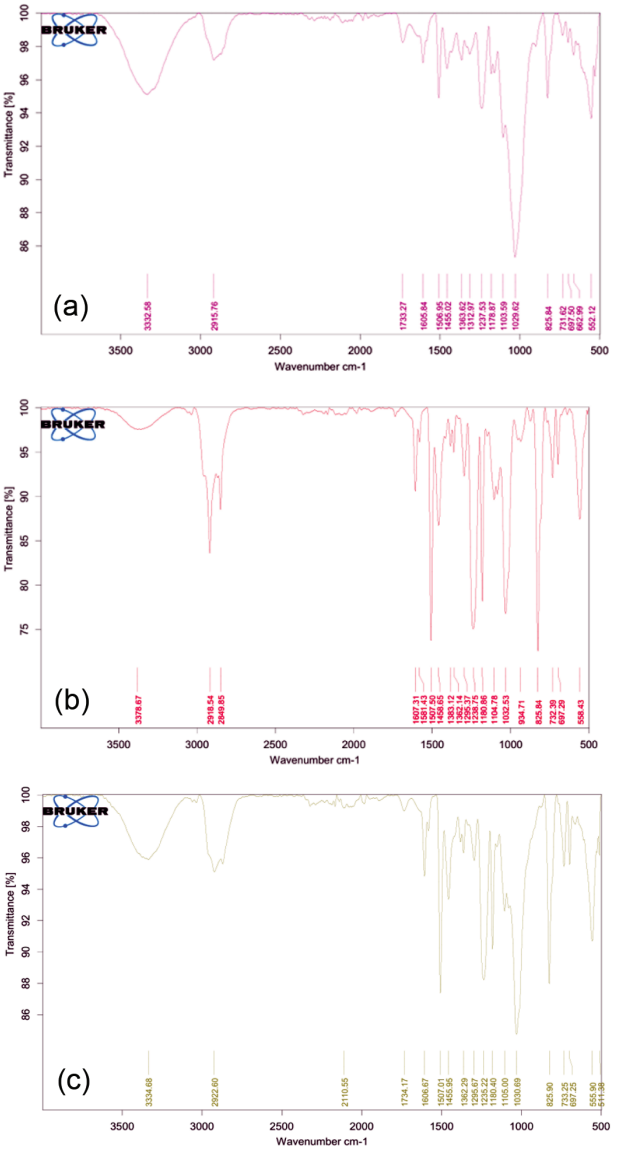

Figure 8: FTIR graphs: a) abaca/epoxy-bamboo activated carbon nanofiller composite; b) abaca-E-glass/epoxy-bamboo activated carbon nanofiller (0°) composite; c) abaca-E-glass/epoxy-bamboo activated carbon nanofiller (0/90)° composite

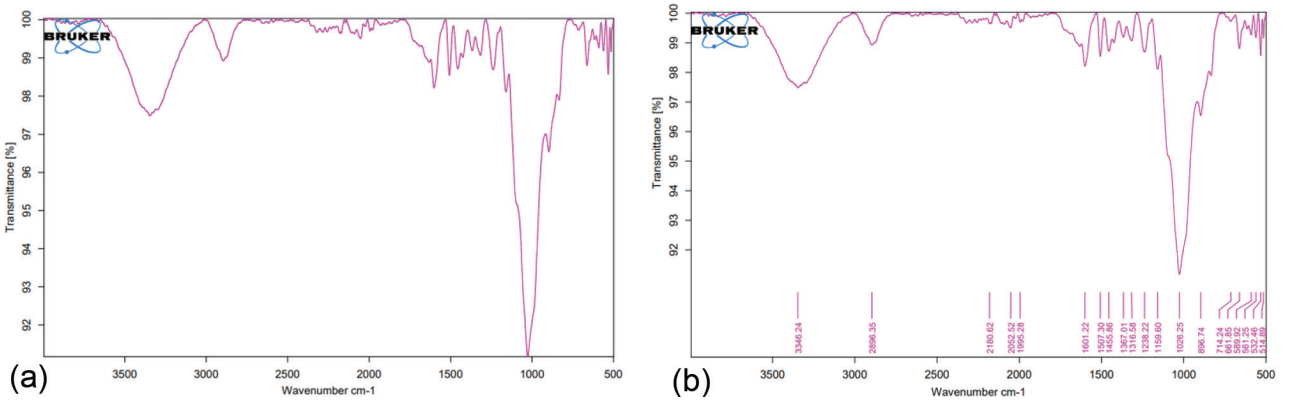

Figure 9: FTIR graphs: a. baseline (0°) abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite; b. (0°) peak-picking specimen of abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite

3.4 FTIR analysis

Fourier transform infrared (FTIR) spectroscopy is a rapid, non-destructive analytical technique used to identify organic and inorganic materials by measuring their absorption of infrared light across a range of wavelengths. It produces a molecular "fingerprint" spectrum, identifying functional groups and chemical elements as shown in **Figures 8** and **9**.

Figure 8a shows the FTIR analysis of the abaca/epoxy composite reinforced with bamboo-derived activated carbon nanofiller, with 0° fiber direction. The band at 3322 cm^{-1} indicates the presence of hydroxyl groups (-OH), which usually originate from moisture or natural polymer materials such as abaca fiber. The band at 2925 cm^{-1} corresponds to the asymmetric C-H vibration of an alkane group. This indicates the presence of hydrocarbon structures in the epoxy matrix or fiber material. The band at around 1723 cm^{-1} indicates the presence of carbonyl groups (C=O), usually derived from the epoxy resin or chemical modification of the material. The bands in the 1500–1600 cm^{-1} region are associated with aromatic C=C stretching or aromatic structures in epoxy materials. The bands at 1025–1150 cm^{-1} probably indicate C-O-C vibrations, which are typical for epoxy and ester structures. The bands below 1000 cm^{-1} are usually associated with Si-O-Si stretching or typical vibrations of inorganic materials in the presence of additives or reinforcements such as nanoparticles.

Figure 8b shows the FTIR analysis of the abaca-E-glass/epoxy bamboo-derived activated carbon nanofiller composite, with 0° fiber direction. The band around 3321 cm^{-1} corresponds to O-H stretching vibration, indicating the presence of hydroxyl groups. They could originate from abaca fibers or residual moisture. The presence of O-H is important for the chemical interactions with the epoxy matrix. The band at 2916 cm^{-1} indicates the C-H stretching vibration of alkane groups. These groups originate from organic components such as abaca fiber or epoxy. The band at 1726 cm^{-1} corresponds to the carbonyl (C=O) stretching vibration, indicating the presence of an epoxy matrix. This band indicates successful curing. The band at 1500–1600 cm^{-1} relates to the aromatic C=C stretching vibration, originating from bamboo-derived activated carbon. This indicates the presence of aromatic structures of activated carbon. The bands at 1020–1250 cm^{-1} relates to C-O-C vibrations, typical of epoxy structures. The intensity of these bands confirms that the epoxy has formed a polymer structure. The bands at around 800–1000 cm^{-1} correspond to Si-O-Si stretching vibrations, typical of e-glass materials. The presence of these bands indicates the contribution of E-glass fibers to the composite. The presence of hydroxyl groups (O-H) in abaca fiber enables the formation of hydrogen bonds with epoxy. The E-glass material provides additional mechanical strength to the composite. The Si-O-Si vibration supports the presence of E-glass. The aromatic structure and active groups (such as hydroxyl) in activated carbon provide mechanical properties and compatibility with epoxy. The carbonyl (C=O) and ether (C-O-C) groups indicate successful curing, creating a solid matrix and compatibility with reinforcing materials.

Figure 8c shows the FTIR analysis of abaca-E-glass/epoxy-bamboo activated carbon nanofiller composite with (0/90)° fiber orientation. A large peak at ≈3500 cm^{-1} indicates the presence of hydroxyl groups (OH), corresponding to natural fibers (abaca) and activated carbon. The peak at ≈1700 cm^{-1} indicates carbonyl groups (C=O), which are often found in lignin structures or activated carbon materials. The peak at around 1000–1200 cm^{-1} corresponds to Si-O-Si groups, indicating the presence of E-glass. The weak peak at around 1400–1600 cm^{-1} may indicate the presence of aromatic structures or activated carbon. This spectrum shows the characteristics of mixed materials including natural fibers (abaca), E-glass fibers, and bamboo-derived activated carbon. The dominance of activated carbon is seen from the intensity of the carbonyl and hydroxyl peaks.

Figure 9a shows FTIR analysis of baseline abaca-E-glass/epoxy composites reinforced with bamboo-de-

rived activated carbon nanofiller at 0° fiber orientation. The absorption band at 3200–3500 cm^{-1} is attributed to hydroxyl groups (O-H). The broad peak detected at ≈3400 cm^{-1} indicates O-H stretching. The band at 2800–3000 cm^{-1} indicates aliphatic C-H groups. The peak at ≈2920 cm^{-1} is related to C-H stretching. These groups may originate from the hydrocarbon structures within the polymer matrix or the lignocellulosic components of abaca. The band at 1700–1750 cm^{-1} corresponds to carbonyl groups (C=O). The peak at ≈1730 cm^{-1} indicates the presence of carbonyl groups. The band at 1400–1600 cm^{-1} relates to aromatic groups or double bonds (C=C). The peak at ≈1500–1600 cm^{-1} indicates C=C vibrations, which may be related to the aromatic structure of the polymer or E-glass. The band at 1000–1200 cm^{-1} relates to siloxane (Si-O-Si) groups. The dominant peak at ≈1100 cm^{-1} is characteristic of the siloxane (Si-O-Si) groups found in E-glass. The region below 900 cm^{-1} corresponds to Si-O vibrations. The sharp peak at ≈800–900 cm^{-1} is related to the vibrations of the silica network in E-glass. Natural fibers exhibit hydroxyl (O-H) and carbonyl (C=O) groups, which originate from cellulose, hemicellulose, and lignin components. Aliphatic C-H groups indicate the presence of a lignocellulosic structure. The peaks at 1000–1200 cm^{-1} and 800–900 cm^{-1} clearly indicate the presence of E-glass, which is dominated by siloxane (Si-O-Si) groups and silica network vibrations. At 0 % activated carbon concentration, there is no strong indication of specific aromatic groups or vibrations characteristic of activated carbon. Therefore, the weak aromatic groups at 1400–1600 cm^{-1} likely originate from resin or other components.

Figure 9b shows FTIR analysis of a peak-picking 0° orientation specimen of abaca-E-glass/epoxy composite reinforced with bamboo-derived activated carbon nanofiller. Region 3200–3500 cm^{-1} corresponds to hydroxyl group (O-H). The broad peak detected at ≈3300 cm^{-1} indicates O-H stretching. Region 2800–3000 cm^{-1} corresponds to aliphatic C-H group. The peak at ≈2800 cm^{-1} is related to C-H stretching. This group may originate from the hydrocarbon structure in the polymer matrix or the lignocellulosic component of abaca. Region 1700–1750 cm^{-1} corresponds to carbonyl group (C=O). The peak at ≈1730 cm^{-1} indicates the presence of carbonyl group. The peak in the ≈1500–1600 cm^{-1} region indicates C=C vibrations, which can be related to the aromatic structure of polymer or E-glass material. Region 1000–1200 cm^{-1} corresponds to siloxane (Si-O-Si) groups. The dominant peak at ≈1100 cm^{-1} is characteristic of the siloxane (Si-O-Si) groups in E-glass. The region below 900 cm^{-1} corresponds to Si-O vibrations. The sharp peak at ≈800–900 cm^{-1} is associated with vibrations of the silica network in E-glass. Sharp peaks typically indicate more defined or rigid vibrations, often associated with isolated functional groups, such as strong bonds or specific functional groups. Sharp peaks can also indicate that the molecule or bond in question experiences little interaction with its environment, or little external perturbation.

Although the current findings demonstrate significant changes in tensile performance with varying fiber volume fraction, fiber orientation, and NaOH treatment, a more in-depth explanation of the underlying mechanisms that govern these influences – such as interfacial bonding, stress transfer efficiency, and microstructural changes – is needed to strengthen the study. Additionally, expanding comparisons with recent relevant literature would better contextualize the results and highlight the novelty and consistency of the findings within the field.

4 CONCLUSION

The abaca-E-glass/epoxy composite reinforced with bamboo-derived activated carbon nanofillers, with 0° fiber direction and NaOH treatment of abaca fiber has a higher tensile strength of 56.62 MPa compared to the composite without NaOH treatment of abaca fiber with a value of 46.08 MPa.

Surface morphology analysis using SEM shows that the failure mode that occurs in the composite is fiber fracture, indicating that the bond between the fiber and matrix is good enough. However, there are also fiber pull-outs in several parts of the composite, which indicate that the bond is not good enough, possibly due to poor resin, so that the matrix has not been evenly distributed over the entire fiber surface. This is shown by the composite with a V_f *of* 60 %, which has a lower tensile strength of 24.44 MPa compared to the composite with a V_f of 50 % with a value of 26.33 MPa. There are also voids in several places, causing cracks in the composite.

SEM-EDS analysis shows that the bamboo-derived activated carbon nanofiller is primarily composed of C and O, with a high C content of 90.90 % and a lower O content of 8.28 %. In the composite, the elemental composition changes to 82.94 % C and 16.47 % O, indicating interaction between the nanofiller and the matrix, which may contribute to reduced void formation. However, in the composite that experienced cracks during the tensile test, the C element content is 64.10 % and the O element is 27.83 %, containing a fairly large O amount in the form of voids that occurred in several parts of the composite. By including E-glass fibers in the composite, the strength of the composite is increased, which is indicated by the presence of bonds between O and Si.

FTIR analysis shows that hydroxyl groups (O-H) in abaca fibers facilitate the formation of hydrogen bonds with epoxy. E-glass fibers provide additional mechanical strength to the composite. Si-O-Si vibrations indicate the presence of E-glass. Bamboo-derived activated carbon nanofillers, with aromatic structures and active groups (such as hydroxyl), enhance mechanical properties and compatibility with epoxy. Carbonyl (C=O) and ether

(C-O-C) groups indicate successful curing, resulting in a solid matrix with good compatibility with the reinforcing materials. Even with simple fabrication methods such as hand lay-up and vacuum bagging, composites with relatively high tensile strength can be produced. Therefore, the abaca-E-glass/epoxy hybrid composite reinforced with bamboo-derived activated carbon nanofillers has good potential to be further developed for wider application in lightweight structural and radar-absorbing materials.

5 REFERENCES

[1] L. A. Carlsson, D. F. Adams, R. B. Pipes, Experimental Characterisation of Advanced Composite Materials, 2014, CRC Press, Boca Raton, FL, USA

[2] M. R. Sanjay, G. R. Arpitha, B. Yogesha, Study on Mechanical Properties of Natural-Glass Fibre Reinforced Polymer Hybrid Composites: A Review, Materials Today, 2 (**2015**) 4–5, doi:10.1016/j.matpr

[3] M. Yaakob, M. Saion, M. Husin, Potency of Natural and Synthetic Composites for Ballistic Resistance: A Review, Appl. Res. Smart Technol., 1 (**2020**) 2, 43–55

[4] K. M. F. Hasan, P. G. Horváth, M. Bak, T. Alpár, A state-of-the-art review on coir fiber reinforced biocomposites, RSC Adv., 11 (**2021**) 18, 10548–71

[5] K. M. F. Hasan, P. G. Horváth, T. Alpár, Potential natural fiber polymeric nanobiocomposites: A review, Polymers (Basel), 12 (**2020**) 5

[6] S. Nunna, P. R. Chandra, S. Shrivastava, A. K. Jalan, A review on mechanical behaviour of natural fibre-based hybrid composites, Journal of Reinforced Plastics and Composites, 31 (**2012**) 11, 759–769

[7] M. R. Sanjay, G. R. Arpitha, B. Yogesha, Study on mechanical properties of natural-glass fibre reinforced polymer hybrid composites: A review, Materials Today: Proceedings, 2 (**2015**) 4–5, 2959–2967

[8] H. Ridwan, Fitri Ariani, Pembuatan Bahan Baku Pulp Dari Pelepah Pisang, Saintis, 3 (**2022**) 2, 28–36

[9] BRIN: Bambu bisa menjadi tanaman alternatif atasi krisis kayu, Antara-Kantor Berita Indonesia, 2023, https://www.antaranews.com/berita/3745872/brin-bambu-bisa-menjadi-tanaman-alternatif-atasi-krisis-kayu

[10] H. Mei, S. Zhang, H. Chen, H. Zhou, X. Zhai, L. Cheng, Interfacial modification and enhancement of toughening mechanisms in epoxy composites with CNTs grafted on carbon fibres, Composites Science and Technology, 134 (**2016**), 89–95

[11] L. Banowati, P. Sari, B. K. Hadi, Comparison analysis of abaca fiber/polyester and abaca-e-glass/polyester hybrid composites to impact strength and its application to ballistic, IOP Conf. Series: Materials Science and Engineering, 1173 (**2021**), doi:10.1088/1757-899X/1173/1/012068

[12] Pulleti Siva Sankar, Shamsher Bahadur Singh, Effect of Fiber Volume Fraction on the Mechanical Properties of NFRP Composites, Advances in Applied Mechanics, (**2024**), 249–254, DOI: 10.1007/978-981-97-0472-9_33

[13] I. Siva, J. T. Jappes, I. Sankar, S. C. Amico, D. Ravindran, Effect of fiber volume fraction on the mechanical properties of coconut sheath/USP composite, J. Manuf. Eng., 8 (**2013**), 60–63

[14] Yadvinder Singha, Jujhar Singha, Shubham Sharmaa, Thanh-Danh Lamb, Duc-Nam Nguyen, Fabrication and characterization of coir/carbon-fiber reinforced epoxy based hybrid composite for helmet shells and sports-good applications: influence of fiber surface modifications on the mechanical, thermal and morphological properties, Journal of Materials Research and Technology, 9 (**2020**) 6, 15593–15603, DOI: 10.1016/j.jmrt.2020.11.023

[15] H. Jiang, C. Li, X. Mao, L. Chen, W. Zhao, X. Si, J. Qi, Z. Dong, J. Cao, Vacuum Brazing of AlON and Ti2AlNb with LiAlSiO4 Enhanced Ag–Cu–Ti Composite Fillers: Microstructure, Mechanical Properties and Measurement of Residual Stress, Mater. Sci. Eng. A., 846 (**2022**), 143277

[16] M. B. Ahmed, M. A. Hasan Johir, J. L. Zhou, H. H. Ngo, L. D. Nghiem, C. Richardson, M. A. Moni, M. R. Bryant, Activated Carbon Preparation from Biomass Feedstock: Clean Production and Carbon Dioxide Adsorption, J. Clean. Prod., 225 (**2019**), 405–413

[17] J. Saleem, U. Bin Shahid, M. Hijab, H. Mackey, G. McKay, Production and Applications of Activated Carbons as Adsorbents from Olive Stones, Biomass Convers. Biorefinery, 9 (**2019**), 775–802

[18] M. I. Nuryanta, L. G. Aryaswara, R. Korsmik, O. K. Korsmik, A. D. Nugraha, S. Darmanto, M. Kusni, M. A. Muflikhun, The Interconnection of Carbon Active Addition on Mechanical Properties of Hybrid Agel/Glass Fiber-Reinforced Green Composite, Polymers, 15 (**2023**), 11, 241, doi:10.3390/polym15112411

[19] L. Banowati, N. Chitraningrum, Hybrid Polymer Composite of Abaca-E-Glass and Epoxy-Bamboo Activated Carbon Nanofiller With Variations in Fiber Orientation, Materials and Technology, 59 (**2025**) 4, DOI: doi:10.17222/mit.2024.1303