

Research Paper

Comparative Mechanical and Thermal Properties of Epoxy Matrix Composite Reinforced with Coco Peat and Coconut Shell Charcoal Fillers for Automotive Brake Friction Applications

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Abstract

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Developing epoxy-based composites reinforced with natural materials has become a significant concern in supporting friction materials and sustainable automotive industries. Coco peat and coco shell charcoal are coconut wastes that have the potential as natural fillers to support the mechanical properties of friction material composites while supporting the reduction of biomass waste. This study aims to evaluate the effect of weight fraction variation of coco peat and coco shell charcoal on composite mechanical and thermal properties. Specimens were prepared using the hand lay-up method with 5 wt.%, 10 wt.%, and 15 wt.% filler weight fractions. Mechanical tests were conducted, including tensile test, bending test, Rockwell hardness, and Charpy impact. Results show that the addition of 5 wt.% coco peat increased the tensile strength to 28.36 MPa and impact strength to 123.33 J/m², while coco shell charcoal at 10% recorded the highest flexural strength of 36.10 MPa and hardness of 93.66 HRB. However, increasing the filler concentration caused a decrease in tensile and impact strength due to the formation of voids, agglomeration, and micro-cracks. These findings confirm that coco peat is effective for tensile and impact strengthening at low fractions. In contrast, coco shell charcoal improves flexural strength and produces higher hardness values than the commercial brake pad product (59.59-66.90 HRB). Furthermore, the composite with 5 wt.% coco shell charcoal showed good thermal stability with a final residue value of 3.83%. Further studies can focus on surface modification of fillers, hybrid composites, and evaluation of tribological properties and the environment to promote applications in the automotive industry sector.

Keywords: Friction material composite; Natural filler; Coco peat; Coco shell charcoal; Mechanical properties; Thermal properties

1. Introduction

Polymer matrix composites have been widely used in various engineering and industrial fields, including building materials, thermal insulation,

food packaging, automotive, sports equipment, telecommunications equipment, medical equipment, ships, and aerospace industries, because they have good mechanical properties, create light products, good corrosion resistant,



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easy to mold, and can be combined with various types of fillers [1]. Fillers are crucial in polymer matrix composites as reinforcement, filling the space between the matrix and fiber, maintaining dimensional stability, supporting the composite structure, and significantly reducing production costs. These advantages make polymer matrix composite a strategic choice in the development of modern functional materials [2], [3], [4].

Using natural fillers such as fiber, shell, biochar, starch, and ceramic in polymer matrix composites can create a sustainable industry, green products, support economic growth, and control environmental change [5], [6]. The selection of filler types and characteristics in the friction material composite is influenced by several important aspects, including compatibility with the matrix, filler ratio, particle size, and distribution [7]. These factors contribute to composite performance, including flexural strength, hardness, impact strength, tensile strength, and flame resistance [8], [9]. This indicates that optimizing the role of natural fillers is related to achieving mechanical strength, controlling micro defects, and improving the matrix's dispersion effectiveness.

Coconut is one source of natural filler categorized in the form of coir, coco peat, and coco shell [10], [11], [12]. Variation in coir particle size affects the polyester matrix composite. Large particle sizes contribute to an increase in compressive strength due to the ability of large particles to reduce stress concentrations. In contrast, composites with smaller particles tend to experience inter-particle compaction and detachment, which can lead to cracks and structural failure quickly [13]. Studies show that adding 5 wt.% coco peat particles to epoxy can support hybrid composites' tensile and bending strength [14]. In 2021, Pai *et al.* evaluated the contribution of 3 wt.% coco peat particles into 37% epoxy resin and 60% natural filler types of jute and silk, where the results of the Izot impact test showed the highest absorbed energy achieved was 0.702 J, the highest bending strength was 69.1 MPa, and the highest flexural modulus was 3630 MPa [15]. These findings emphasize the importance of low-weight fractions in maintaining homogeneous dispersion and effective reinforcement of coco peat.

On the other hand, the evaluation of coco peat charcoal continues to be explored due to its hard,

stiff, and activated carbon nature. This will provide different interaction behavior with the matrix during the fabrication process into composites, thus affecting the composites' hardness, wear resistance, and thermal stability [16], [17]. Previous studies reported that coco shell charcoal in polymer matrix composite can increase hardness and thermal stability, but tends to sacrifice tensile strength due to weak interlocking of filler with matrix [18]. In addition, the formation of agglomeration creates stress concentrations that accelerate composite failure [19]. Moreover, ineffective composition can disrupt the interfacial adhesion between the filler and matrix, thus affecting the performance of the composite [19].

Natural fillers with different characteristics and structures presented by coco peat and coco shell charcoal create different interactions with the polymer matrix during fabrication. In addition, the weight fraction variation contributes to the composites' mechanical performance and thermal properties. However, the comparative study of coco peat and coco shell charcoal has not previously been evaluated as a natural filler candidate in a brake pad composite. Therefore, this study compares the mechanical and thermal properties of epoxy matrix composite reinforced with coco peat and coco shell charcoal for automotive brake friction applications.

2. Methods

2.1. Material

The natural filler used in this study is coconut fruit waste of coco peat and coco shell charcoal from local plants in Indonesia. Coco peat is part of the outer skin fused with fibers, while coco shell charcoal is obtained from burning coco shells in a furnace at a temperature of 500-800 °C for 60 minutes [20]. The polymer matrix used was epoxy (EPIKOTE 828), with a density of 1.2 g/cm³, in a 3 : 1 ratio and epoxy hardener (651) product from Hexion, USA, which was purchased from the IZE solution company in Kuala Lumpur, Malaysia.

2.2. Fabrication of Specimen

Coco peat and coco shell charcoal were made into particles using a crusher machine type Retsch ZM 200 (Haan, Germany) and sieved to obtain a size of 100 mesh. The natural filler was dried in a vacuum oven at 105°C for 24 hours to remove its

water content [21], [22] and stored in a sealed plastic box to avoid direct contact with a humid environment. Epoxy resin and filler were poured into a plastic container with the composition that can be seen in Table 1 and stirred using a wooden stick until the filler was well distributed. Then, the mixture was poured into a plastic mold measuring 30 x 30 x 0.3 cm, and hardened at room temperature for 24 hours. The composite was cut using a cutting tool to obtain five specimens for each composition and stored in a closed plastic box.

2.3. Mechanical Testing of Specimen

Epoxy matrix composite reinforced with coco peat and coco shell charcoal was prepared, 5 test specimens for each composition. All specimens were subjected to mechanical testing to obtain tensile strength, bending strength, impact strength, and hardness. Tensile and bending tests were conducted using a Universal Testing Machine (INSTRON 3367, USA) with a capacity of 30 kN and a crosshead speed of 2 mm/min. These tests aimed to obtain tensile strength, modulus strength, flexural strength, and flexural modulus based on ASTM D638 [23] and ASTM D790. In addition, the specimens were tested for hardness using a ZwickRoell Rockwell Hardness tester (Germany). The impact test was conducted based on ASTM D6110 standard [24] using a Go Tech Charpy impact tester GT-7045-MD machine, with an impact energy applied to the specimen of 25 joules and a pendulum speed of 3.46 m/s. The tensile test specimens were prepared for fracture surface analysis using a microscope.

2.4. Thermal Characterization

Epoxy, coconut peat, coconut shell charcoal, CP5, and CS5 were tested for thermal behavior using a thermogravimetric analysis (TGA). TGA was performed to calculate mass changes in the raw material and composite. TGA was conducted

using a STA7200RV thermal analyzer (Hitachi High-Tec Science Corporation, Japan) at temperatures ranging from 30 to 700 °C, with a heating rate of 10 °C/min in a nitrogen atmosphere and a specimen weight of 19 mg.

3. Results and Discussion

3.1. Mechanical Properties

Table 2 shows the results of mechanical testing of epoxy matrix composite reinforced with coco peat and coco shell charcoal at variations of weight fraction of 5 wt.%, 10 wt.%, and 15 wt.%. The results showed that adding 5 wt.% CP contributed the highest increase in tensile strength of 28.36 MPa, compared to pure epoxy (E100), which only reached 19.85 MPa. However, increasing the weight fraction of CP to 10 wt.% and 15 wt.% decreased the tensile strength, tensile modulus, flexural strength, modulus flexural, and hardness. In contrast, the addition of CS showed a decrease in tensile strength of 15.43 MPa (5 wt.%), dropping dramatically to 8.25 MPa (15 wt.%). Meanwhile, in terms of flexural strength, the 5 wt.% CS concentration showed the highest value of 36.10 MPa, which is higher than pure epoxy (33.74 MPa) and all variations of CP weight fraction, where the addition of CP in the epoxy matrix composite only reached a maximum bending strength of 17.06 MPa (CP5). On the other hand, the presence of CP and CS (5–15 wt.%) resulted in a decrease in flexural modulus from 2,318.13 MPa (E100) to the lowest values of 569.32 MPa (CP15) and 572.94 MPa (CS15), indicating a degradation in the material's ability to withstand elastic strain. This phenomenon can be caused by the distribution of filler in the matrix, agglomeration and voids formed, as presented by the results of the microscope analysis in Figure 3.

This study's findings indicate that composites' mechanical properties are strongly influenced by the structure of the constituent materials, material interactions during the fabrication process, and

Table 1. Composition epoxy matrix composite reinforced with coco peat and coco shell charcoal

Specimen Code	Epoxy (wt.%)	Coco Peat (wt.%)	Coco Shell Charcoal (wt.%)
E100	100	0	0
CP 5	95	5	0
CP 10	90	10	0
CP 15	85	15	0
CS 5	95	0	5
CS 10	92	0	10
CS 15	90	0	15

Table 2. Mechanical properties of epoxy matrix composite reinforced with coco peat and coco shell charcoal

Sample	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (MPa)	Modulus Flexural (MPa)	Hardness Rockwell B (HRB)
E100	19.85	1,409.42	33.74	2,318.13	42.18
CP 5	28.36	1,565.04	17.06	949.36	38.46
CP 10	23.73	1,474.73	15.78	876.86	34.2
CP 15	22.69	1,296.58	13.27	569.32	33.84
CS 5	15.43	1,315.80	36.10	2,020.32	93.66
CS 10	11.21	1,036.08	19.87	1,483.61	88.32
CS 15	8.25	666.81	16.70	572.94	86.16

stress distribution from the matrix to the filler. At 5 wt.% CP, the presence of coco peat with fine fibers is crucial as micro-reinforcements that help resist elastic deformation and strengthen the internal network of the epoxy matrix. These fibers also form a bridging effect that dampens crack propagation [25]. The interfacial bond between the CP filler and epoxy remains relatively stable at low concentrations, thus supporting uniform stress distribution. This phenomenon evidences the high tensile strength and tensile modulus values of 28.36 MPa and 1,565.04 MPa at 5 wt.% CP. However, particle distribution might become inhomogeneous in the presence of increasing CP concentration, forming agglomeration-type defects that weaken the composite structure. This condition causes a decrease in the ability of the composite to withstand tensile loads, including modulus and flexural strength [26].

In contrast, coco shell charcoal particles, which have a complex structure, tend to increase stiffness and resist deformation but are ineffective in evenly distributing stress. Its brittle and rigid nature causes the interlocking between the filler and matrix to debond when receiving tensile loads [27]. This can be seen by the high bending strength, modulus, and hardness achieved by CS compared to CP, where 5 wt.% CS produced the highest values at 36.10 MPa, 2,020.32 MPa, and 93.66 HRB. On the other hand, the tensile strength was noticeably lower and continued to decrease after adding 10 wt.% and 15 wt.% CS. Moreover, increasing the CS concentration in epoxy matrix composite contributes to the deterioration of internal structure due to the formation of voids and agglomeration, where internal defects act as stress concentration points that accelerate crack initiation and mechanical failure [18]. Therefore, selecting the type and amount of filler is closely related to understanding the deformation

mechanism, stress transfer, and defects formed during the fabrication process.

The hardness of the composite affects the friction properties, wear, and performance of brake materials in automotive applications. Kamar and Ghosh reported hardness values in commercial brake pad products ranging from 59.59-66.90 HRB [28]. This indicates that the hardness values of composites CP (33.84-38.46 HRB) are still below those of commercial products, while composites CS produce higher hardness values of 86.16-93.66 HRB. The other studies also demonstrated the potential of other natural materials as friction material composites, where leucas aspera fiber produces a hardness of 87-93 HRB and and cyperus pangorei fiber produces a hardness of 82.88-89.3 HRB [29], [30].

Impact strength is essential in evaluating composites' toughness in resisting shock loads. In this study, epoxy matrix composites reinforced with natural fillers such as coco peat and coco shell charcoal showed diverse impact strength and absorbed energy as filler loading increased by 5 wt.%, 10 wt.%, and 15 wt.%, as shown in Figure 1. The results showed that 15 wt.% CP achieved the highest impact strength and absorbed energy values at 123.33 J/m² and 0.00555 J, a drastic increase compared to pure epoxy of 38.7 J/m² and 0.00174 J. This indicates that adding coco peat in high concentrations contributes significantly to improving the ability of the composite to absorb impact energy. However, coco shell charcoal also shows an increase of 71.11 J/m² compared to pure epoxy [31]. The energy absorbed by the composite reflects the ability of the internal structure to absorb sudden shock forces. The greater the absorbed energy, the better the material's ability to withstand the crack propagation rate, sudden deformation, and structural failure caused by the impact [32], [33].

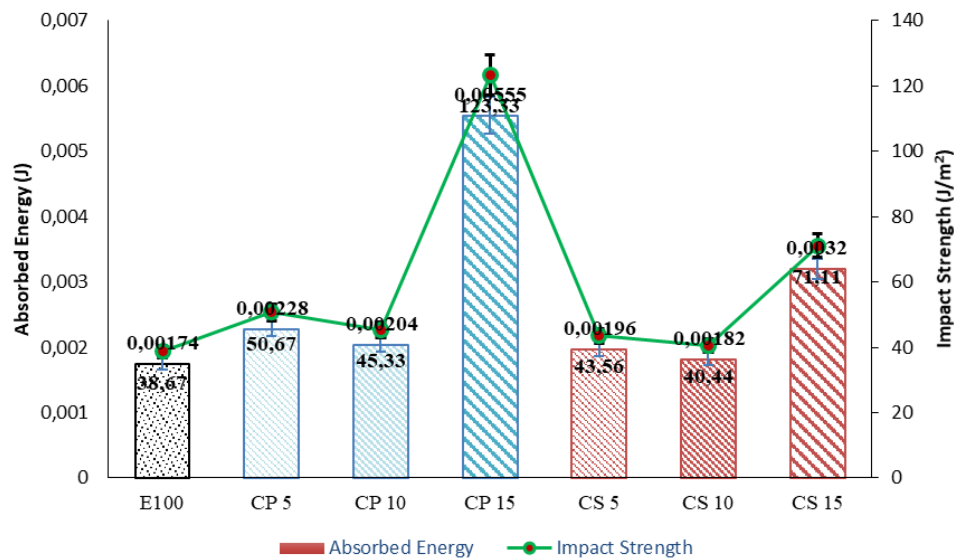


Figure 1. Impact strength of epoxy matrix composite reinforced with coco peat and coco shell charcoal

As a lignocellulose fiber-based filler, Coco peat can resist micro deformation and create relatively good interlocking with the matrix, especially at higher concentrations. However, increasing the CP concentration generally causes a decrease in tensile and flexural strength due to agglomeration that disrupts the continuity of the matrix. The findings of this study indicate that the structures formed can act as energy absorbers when the composites are subjected to impact loads. Cracks formed due to impact can be inhibited from spreading by the presence of fibers. This creates a deflection path and increases energy dissipation [15]. On the other hand, composites reinforced with coco shell charcoal showed a trend of lower impact strength than coco peat. Composites with 5% CS produced an impact strength of 43.56 J/m², slightly above pure epoxy, but the value decreased at a weight fraction of 10 wt.% (40.44 J/m²) and experienced a slight increase at 15 wt.% CS of 71.11 J/m². This phenomenon proves the role of CS structure, which is hard but brittle and does not have good micro-deformation flexibility like

CP. In addition, the relatively poor adhesive properties between CS and epoxy can cause debonding during impact, where particles are easily detached from the matrix and increase the crack propagation rate [34].

3.2. Thermal Properties

Thermogravimetric analysis (TG) and derivative thermogravimetry (DTG) were performed to evaluate the thermal stability of pure epoxy matrix (E100) [35], natural fillers of coco peat (CP) and coco shell charcoal (CS), as well as composites reinforced with 5 wt.% of each filler (CP5 and CS5), as shown in Table 3 and Figure 2. The TG results indicate that the E100, CP5, and CS5 samples undergo the most significant mass loss in the 400–600 °C temperature range, at 53.35%, 58.50%, and 48.00%, respectively. This phenomenon indicates that the primary decomposition stage occurs due to damage to the epoxy polymer structure [36]. On the other hand, CP experienced the most significant mass loss in the low temperature range of 50–200 °C,

Table 3. Thermogravimetric analysis data for epoxy matrix composite reinforced with coco peat and coco shell charcoal

Sample	Mass Loss (%)			Total Mass Loss (%)	Degradation Temperature Peak (°C)	Residual Mass at 700 °C (%)
	50-200 °C	200-400 °C	400-600 °C			
E100	2.07	35.78	53.35	91.12	428.90	0.57
CP	45.81	37.31	16.39	99.51	90.55	0.40
CS	12.76	3.00	23.83	39.59	85.85	49.80
CP5	3.57	27.41	58.50	89.48	430.93	0.78
CS5	4.87	34.82	48.00	87.69	423.56	3.83

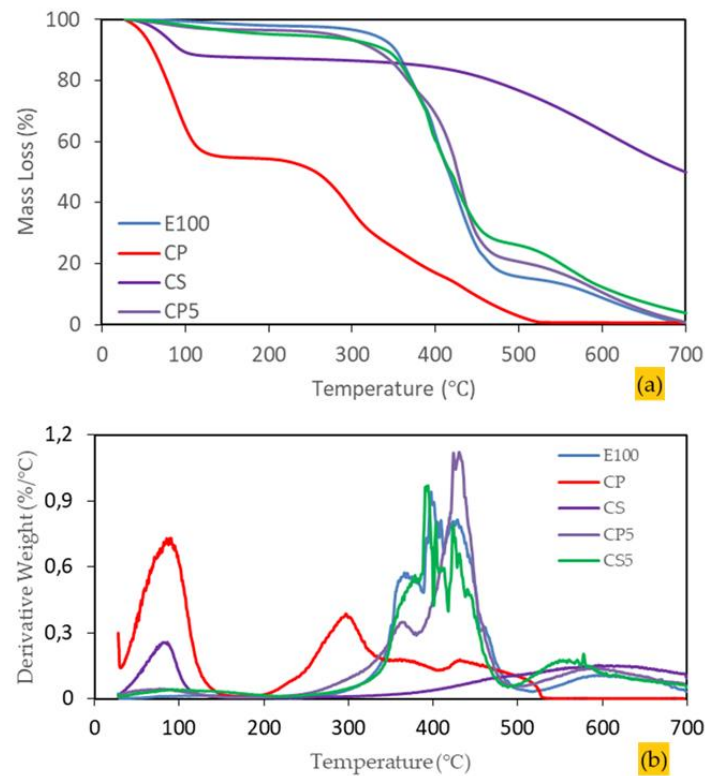


Figure 2. Thermal decomposition of epoxy matrix composite reinforced with coco peat and coco shell charcoal: (a) thermogravimetric; (b) derivative thermogravimetry

amounting to 45.81%, which is closely related to the volatility of hemicellulose, binding water, and other organic compounds in the fibers [34]. Meanwhile, CS exhibits a more gradual and stable degradation pattern, with a total mass loss of only 39.59% and a final residue of 49.80% at 700°C. This clearly reflects residual carbon's high content and thermal deformation resistance [17].

DTG data supports the TG results by providing information on the peak decomposition temperature at very low temperatures, 90.55 °C and 85.85 °C, respectively, indicating that these natural fibers contain volatile compounds [37]. In contrast, E100 exhibits peak decomposition at 428.90 °C, reflecting the thermal characteristics of a more stable polymer network. Additionally, the CP5 and CS5 composites exhibit decomposition peaks at 430.93 °C and 423.56 °C, respectively, indicating that adding 5% natural filler can enhance the thermal stability of the epoxy matrix. Furthermore, CP5 showed the highest maximum decomposition rate of 1.12%, indicating increased interlocking between the filler and matrix during chain scission [38].

3.3. Morphology of Fracture Surface

Figure 3 shows the fracture surface morphology of the tensile test samples for coco peat (a-c) and coco shell charcoal (d-f), adding 5 wt.%, 10 wt.%, and 15 wt.% in epoxy matrix composite. The microstructure observations showed that increasing the CP and CS concentrations caused significant agglomeration and void formation. At 5 wt.% CP, the particles were relatively evenly dispersed and showed good bonding with the matrix, where the fracture surface showed a diffuse crack pattern and firmly embedded fibers. This indicates that the adhesion force between the filler and the matrix can withstand the tensile load. However, at weight fractions of 10 wt.% and 15 wt.%, the cohesion force between CP particles is more dominant than the adhesion force with the matrix [18]. This phenomenon causes the particles to cluster and create weak zones that trigger early cracking, debonding, and faster structural failure. Similar is the case with CS, where an increase in weight fraction causes the fracture surface to be dominated by sharp cracks and particle detachment due to weak bonding between

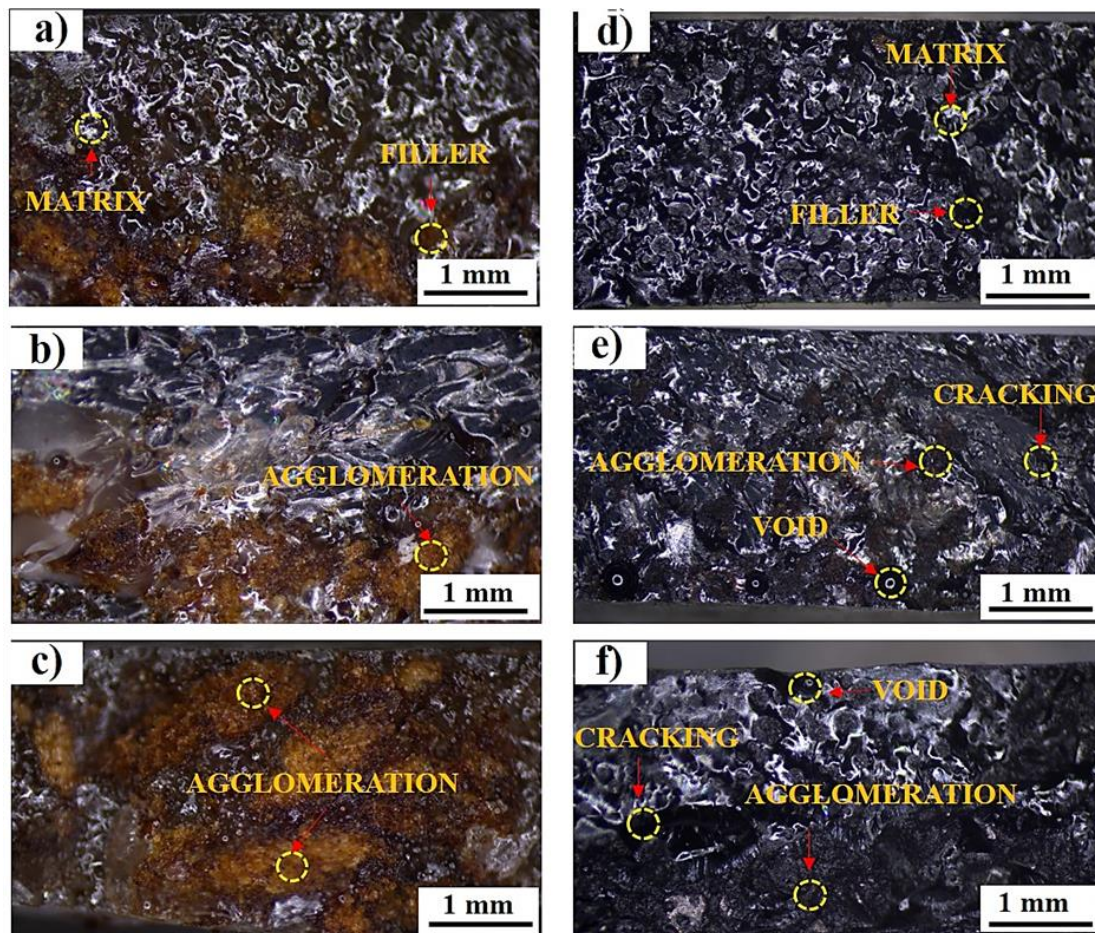


Figure 3. Tensile surface fractured of epoxy matrix composite reinforced with CP 5 wt.% (a), 10 wt.% (b), 15 wt.% (c), and CS 5 wt.% (d), 10 wt.% (e), 15 wt.% (f)

phases. The hard and sharp CS particles cannot blend mechanically well into the epoxy matrix, so high concentrations facilitate the formation of interfacial cracks, resulting in a drastic decrease in tensile strength [32], [39].

4. Conclusion

This study examined the effect of the addition of natural filler types of coco peat (CP) and coco shell charcoal (CS) by 5 wt.%, 10 wt.%, and 15 wt.% on the mechanical properties of epoxy matrix composite as friction material, including tensile strength, flexural strength, hardness, and impact strength. The results showed that CP contributed the highest values of tensile strength, tensile modulus, and impact strength of 28.36 MPa (5 wt.%), 1,565.04 MPa (5 wt.%), and 123.33 J/m² (15 wt.%). In contrast, CS contributed the highest values of bending strength, flexural modulus, and hardness of 36.10 MPa (5 wt.%), 2,020.32 MPa (5 wt.%), and 93.66 HRB (5 wt.%). The finding of this study is that CP creates a strong

interlocking with epoxy so that the matrix can distribute stress well to the filler and form a structure capable of absorbing impact energy. In contrast, CS has a complex structure resulting in a stiff composite that can resist deformation but is brittle, prone to void formation, and has weak adhesion bonds with the matrix, resulting in low tensile and impact strength. Moreover, morphological analysis of the fracture surface proved the presence of agglomeration and cracks in CS with high filler concentration. This research contributes to utilizing coconut waste as a sustainable filler alternative and supports the development of environmentally friendly composite materials. Furthermore, the composite with 5 wt.% coco shell charcoal showed good thermal stability with a final residue value of 3.83%. The evidence from this study suggests that coco shell charcoal 5 wt.% as natural filler in brake pad composite. Further studies can evaluate tribological behavior under actual braking conditions.

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Author's Declaration

Authors' contributions and responsibilities

A.I Imran (Writing-original draft; Methodology; Formal analysis); N. Endriatno (Conceptualisation; Methodology); J.P. Siregar (Supervision; Writing-review & editing); M.Z.M. Rejab (Supervision; Project administration); S.A. Wibowo (Methodology; Formal analysis); T. Cionita (Writing-review & editing; Data Curation); D.F. Fitriyana (Data Curation; Validation).

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Competing interests

The authors declare no competing interest.

Additional information

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