THERMAL, MECHANICAL, AND MICROSTRUCTURE CHARACTERISTICS OF *PAEDERIA FOETIDA* FIBERS/CARBON POWDER HYBRID REINFORCED EPOXY COMPOSITES

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THERMAL, MECHANICAL, AND MICROSTRUCTURE CHARACTERISTICS OF *PAEDERIA FOETIDA* FIBERS/CARBON POWDER HYBRID REINFORCED EPOXY COMPOSITES. Increased environmental and sustainability awareness has fueled efforts to develop bio-based composite materials for a wide range of end-use applications, as well as new alternatives to non-renewable synthetic fibers such as glass and carbon-reinforced composites. Considering development and research, *Paederia foetida* fiber stem (PFs) reinforced composites have recently generated a lot of interest. Hybrids of PFs with carbon powder (CP) have been explored in order to achieve the best properties for composites. This study focused on investigating the microstructural, mechanical, thermal, and density characteristics of hybrid reinforced epoxy composites made of CP/PFs. Several compositions of PFs and CP (30:0, 20:10, 15:15, 10:20, and 0:30 vol.), were prepared to manufacture composite using a hot press method. The effect of the volume fraction of carbon/PFs on the mechanical, thermal, and fracture structure properties of hybrid composites was examined. The findings showed that sample CDS20 which was made up of 20% PFs and 10% CP had the highest tensile strength (42.3 ± 2.7 MPa) and elastic modulus (2310.8 ± 91 MPa). It also had quite high thermal resistance properties with a residual charcoal content of about 23.8%. SEM analysis showed agglomeration of CP and the number of voids decreased as the volume fraction of PFs increased, and the interfaces between CP-PFs-epoxy appeared denser. For infrastructure applications, this composite may serve as an alternative to epoxy composites reinforced with sisal fiber.

Keywords: Composite epoxy, carbon powder, *Paederia foetida* fibers (PFs), tensile properties, thermal properties

KARAKTERISTIK TERMAL, MEKANIK, DAN STRUKTUR MIKRO DARI KOMPOSIT EPOKSI BERPENGUAT HIBRIDA SERAT PAEDERIA FOETIDA/SERBUK KARBON. Meningkatnya kesadaran lingkungan dan keberlanjutan telah memotivasi upaya untuk mencari bahan komposit berbasis bio untuk berbagai aplikasi penggunaan akhir dan sebagai alternatif baru terhadap serat sintetis konvensional yang tidak terbarukan seperti kaca dan komposit yang diperkuat karbon. Dalam hal penelitian dan pengembangan, komposit yang diperkuat batang serat Paederia foetida *(PFs) telah menarik banyak minat. Hibrida PFs dengan bubuk karbon (CP) telah dieksplorasi untuk mencapai sifat komposit terbaik. Tujuan dari penelitian ini adalah untuk menyelidiki sifat termal, densitas, dan struktur mikro epoksi komposit diperkuat hibrida CP/PFs. Rasio PFs dan CP ditemukan masing-masing 30:0, 20:10, 15:15, 10:20, dan 0:30 (% vol), untuk menyiapkan komposit ini menggunakan metode pengepresan panas. Pengaruh fraksi volume karbon/PFs terhadap sifat komposit hibrida diperiksa menggunakan uji mekanik, termal, dan struktur rekahan dengan pemindaian mikroskop elektronik (SEM). Hasilnya menunjukkan bahwa, dibandingkan dengan komposit lainnya, sampel komposit hybrid yang mengandung 20% PFs dan 10% CP (Sampel CDS20) memiliki kekuatan tarik dan modulus tarik tertinggi, masing-masing berukuran 42,3± 2,7 MPa dan 2310.8 ± 91 MPa, dan memiliki sifat tahan panas yang cukup tinggi dengan kandungan sisa arang sekitar 23,8%. Menurut analisis struktur SEM, jumlah rongga tampak berkurang seiring dengan meningkatnya fraksi volume PF, dan antarmuka antara CP-PFs-epoksi tampak lebih padat. Untuk aplikasi yang melibatkan infrastruktur, komposit yang dibuat ini dapat berfungsi sebagai alternatif pengganti komposit epoksi yang diperkuat dengan serat sisal.*

Kata kunci: Komposit epoxy, Serbuk karbon, Serat Paederia foetida *(PFs), Sifat tarik, Sifat termal.*

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I. INTRODUCTION

Due to their many advantages over conventional engineering metals, the use of composite materials has significantly increased. Composites play a significant role in many scientific and engineering fields and have received a great deal of attention in a variety of industries thanks to their unique properties, which include lightweight, specific strength, fracture toughness, corrosion resistance, and wear resistance (Jaswin et al., 2023; Sari et al., 2020; Sari et al., 2021). Due to their high potential for various applications, research on hybrid reinforced composites has recently attracted more attention.

Researchers have extensively studied and reported on composite reinforcement made with natural fibers. Natural fibers are desirable for composite development due to their qualities and potential, which are plentiful, affordable, and safe for human health. One such natural fiber is the Paederia foetida plant (PF) vine, which spreads quickly and develops a canopy, making it a weed in agricultural areas. The plant stem has a diameter of 0.5 cm and can grow up to 10 m in length. This PF plant's stem contains a very sturdy fiber that may one day serve as a significant economic source of cellulose. The fiber from the *Paederia foetida* stem (PFs) is one of the natural fibers with enormous potential for development. Modifying PFs in a solution of 95% ethanol and 25% $NaClO_2$ for 4 hours could potentially increase the cellulose content of fibers by up to 67% (Sari et al., 2023). However, there is still limited information available on the use of PFs in composites. PFs are appealing materials to be developed as a replacement for glass fiber because of their abundance and environmental friendliness. In addition, there has also been no research on PFs-reinforced composites or hybrid PFs-reinforced composites with other types of reinforcing materials. The properties of a number of different natural fiber hybrid reinforced composites have been thoroughly studied. Wang et al. (2023) developed a hybrid composite composed of hemp and carbon fiber. They discovered that adding 26.4% carbon fiber increased the composite's toughness by 32% and strength increased by 129.3% when compared to flax fiber-reinforced polymer. Kudva et al. (2023) investigated the mechanical properties of a hybrid composite reinforced with carbon fiber and bamboo. They stated that this hybrid composite had more tensile strength, flexural strength, and impact strength—74.53%, 41.47%, and 182.24%, respectively—than bamboo fiber-reinforced composites. Furthermore, they mentioned that carbon fiber composites were recognized to have superior tensile and flexural strength qualities than bamboo fiber composites and bamboo/carbon hybrid reinforced composites. According to previous research, more work needs to be done on creating fiber hybrid-reinforced composite materials that meet acceptable standards for mechanical performance. It is important to look into the potential of using cheap PFs as composite reinforcement because they have the best properties.

The mechanical properties of the composites, including their tensile, bending, and thermal strength, have been documented by Cao et al. (2023) as a result of the widespread use of carbon as a filler in polymer composites. The impact of graphene oxide nanoparticles and aluminium powder in carbon fiber epoxy composites has been experimentally studied by Jaswin et al., (2023). According to their findings, the best mechanical and thermal properties were produced by mixing 3 weight percent graphene oxide nanoparticles with 1.5 weight percent aluminium powder. To create carbon-polyvinyl alcohol (PVA) composites, Chaudhuri et al., (2022) used nano-size powdered carbon fiber (CFP). The electrical conductivity, dielectric permittivity, and mechanical properties were found to increase when the CFP content was around 2.36% (volume fraction). In addition, they inferred that very high dielectric permits are found in composites with low dissipation factors (~0.1–0.5).

In order to study the impact of seawater aging on the toughness properties of carbon fiber composites, Mamalis et al. (2021) investigated the mechanical behaviour. A powder epoxy resin (0.3-1%) was manufactured through a hand lay-up. They discovered that seawater had an impact on epoxy plasticization, delamination, and fiber bridges. The aerospace, automotive, and marine industries have all made extensive use of epoxy resins as a matrix in fiber-reinforced composites (Maguire et al., 2018; Mamalis et al., 2021; Robert et al., 2020). According to reports, epoxy has strong mechanical and thermal properties, a high degree of chemical and corrosion resistance, little shrinkage during the curing cycle, excellent electrical insulating properties, etc. (Le Guen-Geffroy et al., 2019; Mamalis et al., 2018). Improvements in the quality and characteristics of composite materials can be made while lowering the overall production cost by taking into account the special properties of epoxy. Researchers and business people are interested in using epoxy for composites with various reinforcement and filler materials due to its superior properties, which can be used for a variety of applications.

The most promising materials for automotive and biomedical applications are carbon and natural fibers because of their high stiffness and specific strength, good dimensional stability, and high damping capacity. These properties have attracted a great deal of research interest. However, carbon powder has advantages like stiffness and lack of flexibility that restrict its use as a high-performance engineering material (Chaudhuri et al., 2022). In contrast, natural fibers are robust and stiff. Increasing the strength of the inclusions in the composite matrix is one way to improve the performance of the composite as a whole. In the past, only one type of reinforcement in polymer composites resulted in a limited improvement in one or two mechanical performance indicators, while other physical properties, such as thermal properties, did not (Li et al., 2020). One of the most promising methods to get a single amplifier's limited intrinsic properties and incorporate the benefits of multiple components is to use a hybrid amplifier (Kikuchi et al., 2017; Li et al., 2017). Numerous studies on hybrid carbon-reinforced composites and other types of reinforcement have been conducted. By using powder metallurgy methods, Li et al. (2020) created a composite made of hybrid carbon nanotube (CNT)-magnesium silicide (Mg_2Si_p) nanoparticles. The yield strength of the Mg matrix composite reinforced with a 0.75 CNTs-0.75Mg_2Si_p hybrid was 180 MPa, which was 143 MPa and 12% (respectively) higher than the yield strengths of the 1.5 CNTs and 1.5 Mg_2Si_p reinforced composites. Ti-7% Cu (vol%) hybrid nanocomposite matrices (TMNCs) reinforced with activated carbon and silica fume were successfully created by Alazwari et al. (2023) at a sintering temperature of 1100°C. According to their findings, Ti interacted with Cu and activated carbon during the milling and sintering processes, resulting in the uniform distribution of hybrid ceramics in the nanocomposite and the in-situ formation of Ti_2Cu and TiC phases. They also stated that the sample had an ultimate strength and longitudinal modulus of 401.20 MPa and 172.40 GPa respectively, without any known reinforcement. These values increased to 591.3 MPa, and 256.24 GPa respectively when 16% carbon (vol.%) was added. At 40 N load, the hybrid reinforcement increased from 0 to 16% vol, while the wear rate dropped from 0.0196 to 0.0089 mg/s. By using colloidal dispersion and suction filtration techniques, Lv et al., (2023) created a hybrid aluminium (Al) matrix composite reinforced with SiC particles and carbon fiber (SiCp-Cfs/Al composite). They discovered that the SiCp-Cfs/Al composite had a tensile strength and modulus of elasticity of 207 MPa and 92 GPa, respectively, when the content of SiCp particles was 5% and carbon fiber was 7%, which values were higher than that of the SiCp/Al composite. The high tensile strength and elastic modulus of SiCp-Cfs/Al composites are brought on by the uniform distribution of carbon fibers and SiC particles in the Al matrix, which acts as co-reinforcement.

The previous research indicates that hybrid boosters with different booster compositions in the composite improve composite properties, particularly the mechanical properties desired for wider applications.

Therefore, the goal of this study is to present a thorough understanding of CP/PFs hybrid reinforced composite epoxy especially on thermal, mechanical, and microstructure properties. In the current paper, we prepared *Paederia foetida* fibers (PFs) and carbon powder (CP). The CP/PFs hybrid reinforced composite epoxy was made using a hot press. The effect of the volume fraction of CP/PFs on the characteristics of hybrid composites was investigated by examining the density, tensile strength, morphology, and thermal properties of the well-characterized composites. The research will help researchers and industrialists develop composite materials with the best properties for infrastructure applications by providing information about *Paederia foetida* fibers/carbon powder hybrid reinforced epoxy composites.

II. MATERIALS AND METHODS

A. Materials

Stems of *Paederia foetida* plants were collected in Pagesangan, Lombok, West Nusa Tenggara, Indonesia (8.5548° South Latitude), where the average monthly rainfall varied from <20 to 200 mm and the air temperature ranged from 21.0°C to 34.0°C (RH= 75 to 95%). In order to keep the uniformity of the rods, plant stems with a diameter range of 11.2 cm were chosen. Approximately 6-7 kilograms of stems were collected from the field.

Epoxy resin and methyl ethyl ketone peroxide (MEXPO), acting as a hardener, formed the matrix. Details are listed in Table 1. The carbon powder used had the following specifications: a particle size (mesh) range of 800 μm, an iron content of 0.02%, a moisture content of ≤10%, and an ash content of ≤ 10%. The 5% solution of sodium hydroxide (NaOH) was procured from PT. Justus Kimia Raya Indonesia.

Table 1. Epoxy resin and hardener specifications

	Epoxy	Hardener
Colour	Clear /Transparent	Yellowish Clear
Viscosity @ 30°C	135 – 140 KU	250 – 350 KU
Density @ 30°C	1.2 – 1.3 kg/liter	0.92 – 0.98 kg/liter

B. Methods

1. Extraction and alkali treatment of fibers

Fresh plant stems were cut to a length of 30 cm (Figure 1a). With the assistance of a plastic comb, the released fibers were separated from the plant's skin and flesh (Figure 1b). After being air dried, the fibers were then submerged in a 5% NaOH solution for two hours at room temperature (Figure 1c). Afterward, the fibers were rinsed with distilled water and further sun-dried (Figure 1d).

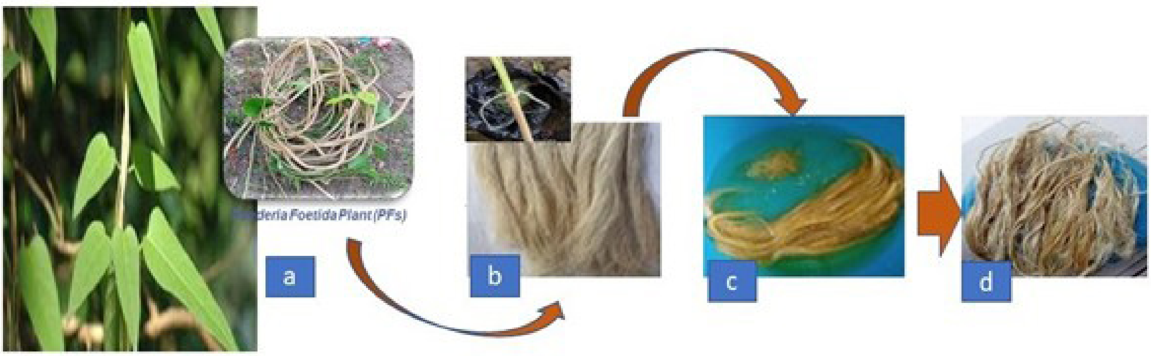

Figure 1. (a) Paederia f. plants, (b) Separation of fibers bundles from the stem (PFs), (cd) NaOH alkaline treatment for 2 h, and (d) Fibers drying

2. Composite Fabrication

First, epoxy resin and carbon powder were combined and stirred for 10 mins. Next, the hardener was added, and the mixture was stirred again for 5 min. The ratio of epoxy resin to hardener was 2:1 vol. The blend was subsequently transferred onto a mold filled with random fibers (4 cm in length). Table 2 displays the composition of materials used. The composite was cooled down until it got hardened. The mold was then closed and pressured to 50 MPa at 110°C. Afterward, the mold was released, and the composite was then heated at 80°C for an hour and then allowed to cool at 24°C before being stored in an airtight plastic box for further testing. Each composition had three replications. Figure 2 depicts the construction of a composite.

2. Experiment procedure

Density test

The specimen dimension for the composite density test was 50 mm x 10 mm x 10 mm, as per ASTMD 792-98. The density of PFs/CP-reinforced epoxy composites was calculated using Archimedes' principle. The volume transferred when the composite sample was submerged in distilled water was used to calculate the composite volume. Previously, analytical balances with an accuracy of 0.0001 g were used to weigh composite samples. To measure the composite density, three composite samples were utilized. Equation 1 can be used to calculate the straightforward relationship between volume change, ΔV ($v1 - vo$, cm^3), mass, m (g), and density, ϱ (g/cm^3) (Sari et al., 2017).

$$\rho = {m(g)}/{v_1 - v_0(cm^3)} \quad \text{.............................(1)}$$

Tensile test

Using a universal testing machine of the RTG-1310 Instron brand, a composite tensile test was performed at a temperature of 25°C. The sample dimensions were 250 mm x 25 mm x 6 mm in accordance with ASTM D3039(2000).

Table 2. Carbon powder, matrix, and fiber composition in the composite

Sample codes	Volume fraction (%)		Epoxy + Hardener (% vol.)
	Carbon powder	fibers	
CDS0	30	0	70
CDS10	20	10	70
CDS15	15	15	70
CDS20	10	20	70
CDS30	0	30	70

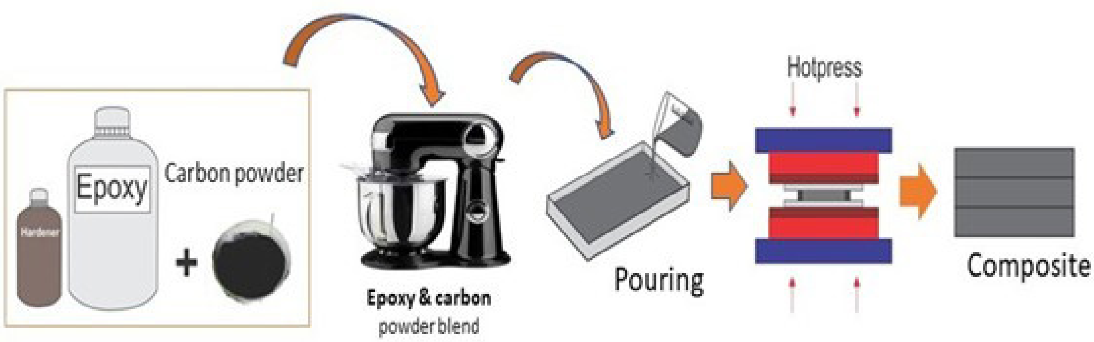

Figure 2. Production of epoxy composites reinforced with carbon powder/*Paederia foetida* fiber.

The tensile test speed used was approximately 1 mm/min, with a 50 kN load cell. For this tensile test, there were a total of 15 samples. In this linear elastic area, stress and strain directly correlate, and the Young's modulus represents the slope of this linear relationship.

Microstructure by SEM

After tensile testing, the composite fracture was used to evaluate the composite morphology. The sample's dimensions were 10 mm x 10 mm (length x breadth). The microstructure/morphology of the composites was examined using scanning electron microscopy (SEM). A Zeiss Evo 40 scanning electron microscope (Oberkochen, Germany) with a 12 kV electron accelerating voltage was used to look at, analyze, and then digitally record the composite's fracture surface structure after the tensile test. For morphological examination, a total of five samples were used, one sample from each composite composition.

Thermogravimetry Analysis (TGA)

Thermogravimetry (TGA) with Mettler Toledo type was used to determine the thermal properties of the CP/PFs composites in a nitrogen atmosphere over a temperature range of 27-900°C and at a heating rate of 10°C/min. In a ceramic vessel, samples with a mass of 10 mg were examined. For thermal testing, a total of five samples were used, one sample for each composition.

III. RESULT AND DISCUSSION

A. Result

Density

The density parameters of hybrid composites are an important factor to consider when evaluating their overall quality. Figure 3 shows the density range of hybrid composites was from 0.87 ± 0.18 g/cm^3 to 1.07 ± 0.18 g/cm^3. Composites reinforced with CP particles or powders (CDS0) had a lower density than composites reinforced with PFs (Sample CDS30). The CDS30 sample has the highest density, while the CDS10 sample has the lowest value, or can be written as CDS0 < CDS10 < CDS30.

Tensile, Elongation and Young's Modulus Analysis

Three different kinds of hybrid composite samples, as well as carbon fiber-reinforced composites and PFs-reinforced composites, were put through tensile tests. The hybrid composites were found to have a tensile strength of up to 98.6%, as shown in Figure 4a. The CP/PFs hybrid composites (CDS10, CDS15,

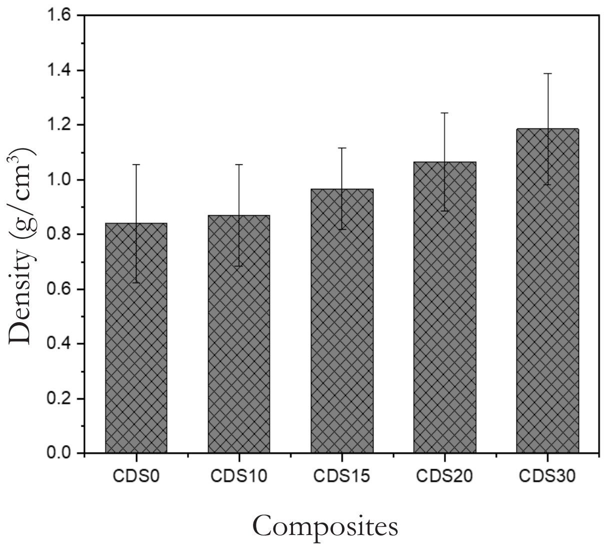

Figure 3. Carbon powder/fibre reinforced epoxy composite density

and CDS20 samples) had higher average tensile strengths and modulus of elasticity than CP composites (sample CDS0) and PF composites (sample CDS30). The highest average tensile strength value was obtained from the sample CDS20 of 42.26 MPa, and the lowest tensile strength was obtained from sample CDS0. In line with this trend, hybrid composites had higher elastic modulus values than the CDS0 and CDS30 samples. These values were between 1249 ± 165 MPa to 2310 ± 91 MPa. The hybrid composite's elongation value ranged from 1.417 ± 0.02 (%) to 1.7278 ± 0.08 (%), which was lower than the CDS30 composite's; but higher than the CDS0 sample (Figure 4b.)

Morphology analysis

Figure 6 displays the fracture morphology of the composites. Figure 5a illustrates the aggregation of carbon powder, which is assumed to be the reason for the composite's poor tensile characteristics. In Figure 5b, there is an agglomeration of carbon powder (20% vol.) in the composite (CDS10). This is likely to create non-uniformity in the distribution of PFs, which will lead to unsatisfactory mechanical strength. A quite similar phenomenon was also observed in samples CDS15 and CDS20 (Figures 5c and 5d), which exhibited less powder agglomeration as a result of a low carbon content. This is believed to be the reason for the composite's increased tensile strength. Further, it is assumed that adding more fiber will greatly boost the composite's mechanical strength. Due to their strong tensile strength and good modulus of elasticity, PFs will significantly increase the composite's tensile strength, and modulus of elasticity (Sari et al., 2023). The fibers' ability to absorb deformation energy was then demonstrated by the presence of broken fibers in the composite fracture, increasing the composite's tensile strength. Moreover, Fig. 5e (sample CDS30) demonstrates how the epoxy matrix's fiber distribution will get denser. By interacting with one another, the fibers create a more cohesive network that can improve load transfer efficiency throughout the composite and support higher levels of tensile strength.

Thermogravimetry Analysis (TGA)

The weight loss process of various composites at various temperatures was observed using TGA. The composite weight loss process, which occurred at temperatures between 30 and 900°C, underwent four stages, as shown in Figure 6.

A. Discussion

The CP/PFs hybrid composite has been reported to yield a higher density of 0.87 ± 0.18 g/cm³ to 1.07 ± 0.18 g/cm³. The hybrid

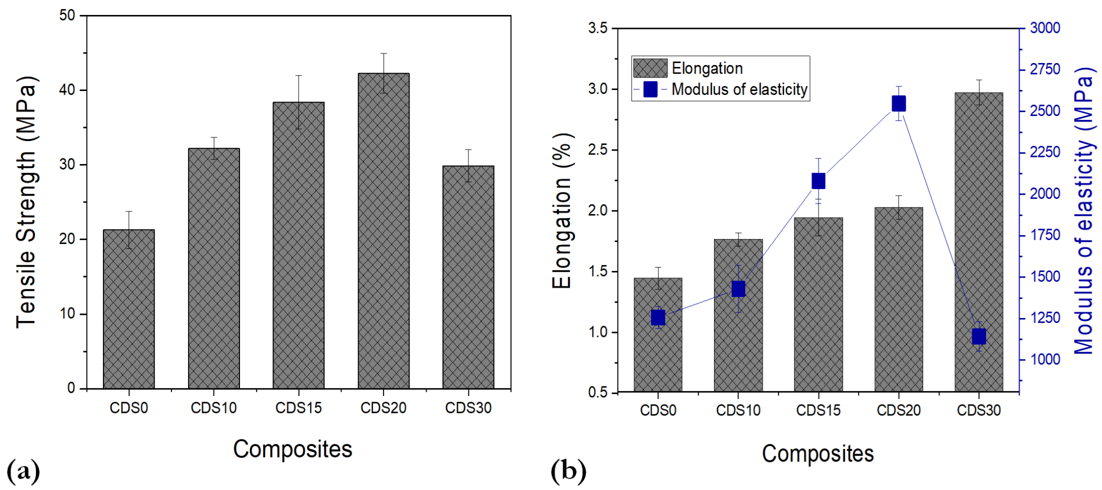

Figure 4. a) Tensile strength, b) Elongation and modulus young of elasticity of the studied epoxy composites

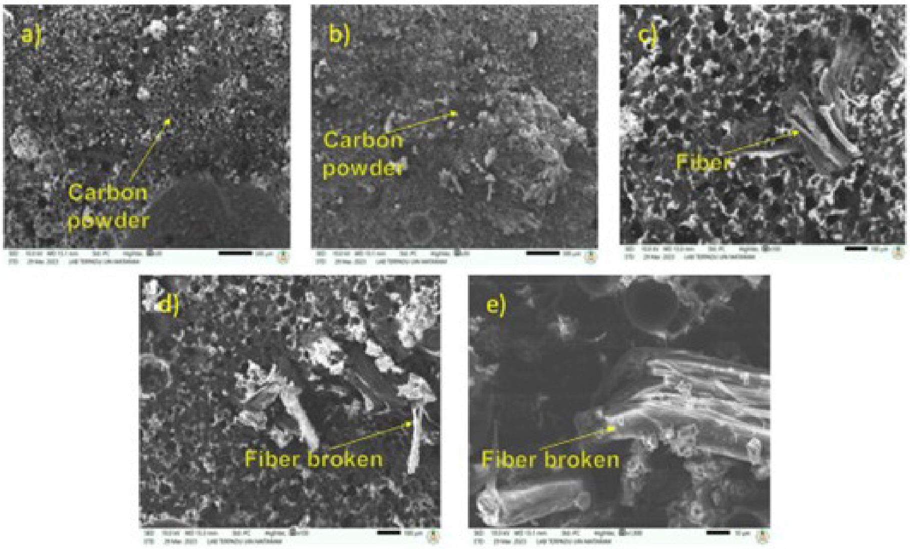

Figure 5. SEM photos of the epoxy composite samples, a) CDS0, b) CDS10, c) CDS15, d) CDS20, and e) CDS30

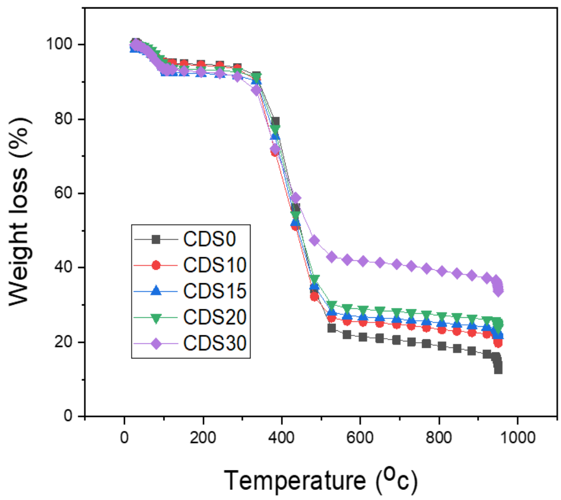

Figure 6. TGA of the studied epoxy composites

composite's maximum density of 1.07 ± 0.18 g/cm^3 was found in sample CDS20. Nevertheless, this hybrid composite's density level was lower compared to that of the PFs composite (refer to sample CDS30) at 1.185 ± 0.203 g/cm^3. Density is a crucial factor that should be considered when developing and manufacturing composites because it can affect the material's efficiency, performance, and manufacturing process. Composite density affects its stiffness and strength, among other qualities. Generally, strength and stiffness can be improved by increasing the composite densities (Mawardi et al., 2022). Nevertheless, this can change based on the types of fiber, the matrix, and the design of the composite used. The density of a composite decreased when the content of CP increased (refer to Figure 3). The resulting composite's many pores and powder agglomeration are assumed to be the causes of this phenomena. Low-density composites are generally lighter than fiberglass composites. Therefore, they can be advantageous in applications like transportation, aerospace, and other lightweight structures where weight is a crucial consideration (Ferrández-García et al., 2017; Mawardi et al., 2022). Comprehensive measurements of further physical characteristics, like color, water content, dimensional stability, shrinkage/swelling, and so forth, are also crucial for assessing how well composites work and are used.

Sample CDS20 yielded the maximum hybrid composite tensile strength of 26,072 ± 2.8695 MPa, whereas sample CDS10 yielded the lowest tensile strength of 19,931 ± 1.6943 MPa. The tensile strength value of sample CDS20 was also greater than those of CP (sample CDS0) and sample CDS30. The increase in tensile strength and elastic modulus of the hybrid composites occurred due to the strong interfacial bonding between CP-PF-epoxy and the stiffness of the material (Figure 3). This can also be explained by the fact that the epoxy resin cannot completely wet CP and PF, resulting in poor tensile strength for the composites. This weak interfacial bonding occurs when there is a lot of CP (as in the CDS0 sample) in the composite. It's also possible that the composite's low fiber count will result in less stress. The carbon powders in the composite, along with the formation of many cavities and agglomeration, are the reasons why the CDS0 sample has poor mechanical properties. The resultant PFs/CP hybrid reinforced composite possesses tensile strength properties that allow it to be substituted for epoxy composite reinforced with sisal fiber, which has a 40.25 MPa tensile strength (Fajrin, 2016). This hybrid composite's tensile strength value is likewise less than that of the Agel/Glass hybrid fiber-reinforced composite (tensile strength = 112.90 MPa, Nuryanta et al., 2023).

SEM images were used to assess the PFs/CP hybrid reinforced composite's morphology. The shape of the composite underwent notable alterations as the quantity of CP or the number of PFs rose. The distribution of PFs, carbon powder, and their interactions within the epoxy matrix could influence the change. The low tensile strength of the composite was found to be caused by the number of voids on the fracture surface of the composite when the carbon powder content was between 10 and 30 percent. Conversely, as the number of fibers rises (as the CP concentration lowers), the aggregation of carbon powder tends to diminish, allowing the fibers to be uniformly dispersed in the epoxy and ultimately producing a high tensile strength. Furthermore, a little quantity of powder may help in the efficient transfer of load along the composite, resulting in a high tensile strength. Furthermore, the discovery of broken fibers on the composite's surface suggests that the tensile load placed on the material was greater than the fiber's tensile strength, which caused the fiber to break.

Four minor stages of decomposition were noticed overall, according to the TGA test results (Figure 6). The first stage was the decrease of each composite sample's weight. This was due to the evaporation of water in the PFs or CP evaporating at a temperature range of 30°C - 110°C. In the second stage, at a temperature range of 150°C-380°C, the three primary constituents of PFs, namely hemicellulose, cellulose, and lignin, broke down. The breakdown of lignin was more difficult than that of cellulose and hemicellulose. The decomposition of lignin was at the third stage. It occurred at 160°C and moved slowly forward. The fourth stage was when there was just charcoal left after the lignin had entirely broken down. The breakdown temperature of lignin can be raised to 900°C. (Norizan et al., 2017; Sahari et al., 2012). Fig. 6 shows that the PF addition to the hybrid composite minimizes the rate of thermal degradation as well as the initial temperature at which the carbon-reinforced composite begins to deteriorate. This is because the PFs have a poorer thermal stability, which lowers the system's total thermal stability. It is clear that the residual content percentage for hybrid composites was higher than that of CPs-reinforced composites and lower than that of PFs-reinforced composites. Table 3 displays the composite's char residue following thermal breakdown.

Table 3. The composite's char residue.

Samples	Char residue (%)
CDS0	12.6
CDS10	19.7
CDS15	21.8
CDS20	23.8
CDS30	33.6

Because of the fiber's stable morphological structure and chemical composition at high temperatures, the CDS30 sample produced the greatest residual charcoal, at 33.6%. Contrary to the volatile CP, the CP-reinforced composite showed the least amount of residual char (12.6%), suggesting that decomposition occurred vastly. The amount of char residue grows as the percentage of PFs increases, forming a thicker layer or barrier between the polymer material and the heat source that further slows or stops the passage of volatile breakdown products out of the composite. Thus, the thermal stability of the likewise composites increases when the quantity of PFs grows and the CP content decreases.

IV. CONCLUSION

The experimental findings show that the density, tensile strength, elastic modulus, elongation, and thermal properties of CP/PFs hybrid composites increased with increasing PFs content, and decreased as the CP content decreased. The sample CDS20 of the other hybrid composites under study had the maximum density, reasonably good thermal characteristics, tensile strength, and elastic modulus for the PFs/CP hybrid composite. Sample CDS20 had tensile strength and modulus of elasticity values of 42.3 ± 2.7 MPa and 2310.8 ± 91 MPa, respectively. SEM images show that voids were the possible causes of the CDS0 sample's lowest elastic modulus, and tensile strength values. The hybrid composite's fracture morphology revealed an increase in fiber fracture and PFs-CP-epoxy interfacial strength. Based on this study's results, hybrid composites made of CP and PFs may substitute sisal fiber-reinforced epoxy composites in infrastructure applications.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Nasmi Herlina Sari: original draft, validation, conceptualization, methodology, supervision. Suteja, Edi Syafri: Investigation, Formal analysis, Data curation, writing – review & editing.

REFERENCES

Alazwari, M. A., Moustafa, E. B., Khoshaim, A. B., & Taha, M. A. (2023). Mechanical and wear evolution of in situ synthesized Ti–Cu alloy matrix hybrid composite reinforced by low-cost activated carbon and silica fume waste ceramic for industrial applications. *Journal of Materials Research and Technology*, *22*, 2284–2296. doi://10.1016/j.jmrt.2022.12.073.

Arockia Jaswin, M., Florence, A., Thirumal Azhagan, M., & Mathialagan, S. (2023). Influence of graphene oxide nano particle and aluminum powder on mechanical and thermal behavior of carbon fiber epoxy composite. Materials Today: *Proceedings*, *72*, 2358–2368. doi://10.1016/j.matpr.2022.09.404.

Cao, L., Chen, B., Wan, J., Shen, J., & Li, J. (2023). Improving carbon nanotube dispersion in aluminum matrix composite powders by a repeating-deformation ball milling process. *Materials Characterization*, *20*1, 112986. doi://10.1016/j.matchar.2023.112986.

Chaudhuri, B., Ghosh, S., Mondal, B., & Bhadra, D. (2022). Preparation and characterization of carbon fibre powder (CFP)-polyvinyl alcohol (PVA) composite films showing percolation threshold behaviour. *Materials Science and Engineering: B*, *275*, 115500. doi://10.1016/j.mseb.2021.115500.

Fajrin, J. (2016). Mechanical Properties of Natural Fiber Composite Made of Indonesian

Grown Sisal. *Info Teknik*, *17*(1), 69–84.

Ferrández-García, C. C., Ferrández-García, C. E., Ferrández-Villena, M., Ferrández-García, M. T., & García-Ortuño, T. (2017). Acoustic and thermal evaluation of palm panels as building material. *BioResources*, *12*(4), 8047–8057. doi://10.15376/biores.12.4.8047-8057.

Kikuchi, K., Yamamoto, K., Nomura, N., & Kawasaki, A. (2017). Synthesis of n-type Mg2Si/CNT Thermoelectric Nanofibers. *Nanoscale Research Letters*, *12*(1), 343. doi://10.1186/s11671-017-2120-y.

Kudva, A., Kotian, A., Mahesha, G. T., & Pai, D. (2023). Experimental investigation of mechanical properties of bamboo/carbon fiber reinforced hybrid polymer matrix composites. *Materials Today: Proceedings*. doi://10.1016/j.matpr.2023.04.398.

Le Guen-Geffroy, A., Le Gac, P.-Y., Habert, B., & Davies, P. (2019). Physical ageing of epoxy in a wet environment: Coupling between plasticization and physical ageing. *Polymer Degradation and Stability*, *168*, 108947. doi://10.1016/j.polymdegradstab.2019.108947.

Li, P., Cao, B., Tan, W., & Gao, M. (2020). Microstructure and synergistic strengthening mechanisms of carbon nanotubes and Mg2Si nanoparticles hybrid reinforced Mg matrix composites prepared by powder thixoforming. *Journal of Alloys and Compounds*, *818*, 152925. doi://10.1016/j.jallcom.2019.152925.

Li, Z., Bi, S., Thompson, B. C., Li, R., & Khor, K. A. (2017). Multifunctional bioceramic-based composites reinforced with silica-coated carbon nanotube core-shell structures. *Ceramics International*, *43*(18), 16084–16093. doi://10.1016/j.ceramint.2017.08.125.

Lv, Z., Sha, J., Lin, G., Wang, J., Guo, Y., & Dong, S. (2023). Mechanical and thermal expansion behavior of hybrid aluminum matrix composites reinforced with SiC particles and short carbon fibers. *Journal of Alloys and Compounds*, *947*, 169550. doi://10.1016/j.jallcom.2023.169550.

Maguire, J. M., Nayak, K., & Ó Brádaigh, C. M. (2018). Characterisation of epoxy powders for processing thick-section composite structures. *Materials & Design*, *139*, 112–121. doi://10.1016/j.matdes.2017.10.068.

Mamalis, D., Flanagan, T., & Ó Brádaigh, C. M. (2018). Effect of fibre straightness and sizing in carbon fibre reinforced powder epoxy composites. *Composites Part A: Applied Science and Manufacturing*, *110*, 93–105. doi://10.1016/j.compositesa.2018.04.013.

Mamalis, D., Floreani, C., & Ó Brádaigh, C. M. (2021). Influence of hygrothermal ageing on the mechanical properties of unidirectional carbon fibre reinforced powder epoxy composites. *Composites Part B: Engineering*, *225*, 109281. doi://10.1016/j.compositesb.2021.109281.

Mamalis, D., Murray, J. J., McClements, J., Tsikritsis, D., Koutsos, V., McCarthy, E. D., & Ó Brádaigh, C. M. (2019). Novel carbon-fibre powder-epoxy composites: Interface phenomena and interlaminar fracture behaviour. *Composites Part B: Engineering*, *174*, 107012. doi://10.1016/j.compositesb.2019.107012.

Mawardi, I., Aprilia, S., Faisal, M., & Rizal, S. (2022). Investigation of thermal conductivity and physical properties of oil palm trunks/ramie fiber reinforced biopolymer hybrid composites as building bio-insulation. *Materials Today: Proceedings*, *60*, 373–377. doi://10.1016/j.matpr.2022.01.249.

Norizan, M. N., Abdan, K., Salit, M. S., & Mohamed, R. (2017). Physical, Mechanical and Thermal Properties of Sugar Palm Yarn Fibre Loading on Reinforced Unsaturated Polyester Composite. *Journal of Physical Science*, *28*(3), 115–136. doi://10.21315/jps2017.28.3.8.

Nuryanta, M. I., Aryaswara, L. G., Korsmik, R., Klimova-Korsmik, O., Nugraha, A. D., Darmanto, S., Kusni, M., & Muflikhun, M. A. (2023). The Interconnection of Carbon Active Addition on Mechanical Properties of Hybrid Agel/Glass Fiber-Reinforced Green Composite. *Polymers*, *15*(11), 2411. doi://10.3390/polym15112411.

Robert, C., Pecur, T., Maguire, J. M., Lafferty, A. D., McCarthy, E. D., & Ó Brádaigh, C. M. (2020). A novel powder-epoxy towpregging line for wind and tidal turbine blades. *Composites Part B: Engineering*, *203*, 108443. doi://10.1016/j.compositesb.2020.108443.

Sahari, J., Sapuan, S. M., Ismarrubie, Z. N., & Rahman, M. Z. A. (2012). Tensile and Impact Properties of Different Morphological Parts of Sugar Palm Fibre-Reinforced Unsaturated Polyester Composites. *Polymers and Polymer Composites*, *20*(9), 861–866. doi://10.1177/096739111202000913.

Sari, N. H., Fajrin, J., Suteja, & Fudholi, A. (2020). Characterisation of swellability and compressive and impact strength properties of corn husk fibre composites. *Composites Communications*, *18*, 49–54. doi://10.1016/j.coco.2020.01.009.

Sari, N. H., Suteja, S., Fudholi, A., Zamzuriadi, A., Sulistyowati, E. D., Pandiatmi, P., Sinarep, S., & Zainuri, A. (2021). Morphology and mechanical properties of coconut shell powder-filled untreated cornhusk fibre-unsaturated polyester composites. *Polymer*, *222*, 123657. doi://10.1016/j.polymer.2021.123657.

Sari, N. H., Syafri, E., Suteja, Fatriasari, W., & Karimah, A. (2023). Comprehensive Characterization of Novel Cellulose Fiber From *Paederia Foetida* and Its Modification For Sustainable Composites Application. *Journal of Applied Science and Engineering (Taiwan)*, *26*(10), 1399–1408. doi://10.6180/jase.202310_26(10).0005.

Wang, A., Liu, X., Yue, Q., & Xian, G. (2023). Tensile properties hybrid effect of unidirectional flax/carbon fiber hybrid reinforced polymer composites. *Journal of Materials Research and Technology*, *24*, 1373–1389. doi://10.1016/j.jmrt.2023.03.078.