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Physical and Mechanical Properties of Epoxy Resin Reinforced PALF-Polyester Fiber, Hybrid Polymer Composites (HPCs)

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Hybrid Polymer Composites, Tensile Strength, Pineapple Leaf Fiber, Polyester, Epoxy Resin

Abstract

Hybrid polymer composites are considered a new generation of advanced materials manufactured from natural and synthetic fibers to improve the physical and mechanical properties. The present paper discusses the properties of tensile strength for HPCs fabricated by laying layers of PALF and polyester mat fiber reinforcement with epoxy resin. The samples were fabricated through the hand lay-up process, while samples of one, two, and three layers of PALF-polyester were analyzed. Results have shown that the three-layer fiber had the best tensile strength and modulus of 22.54 MPa and 431.05 MPa, respectively. Moreover, SEM, XRD, and FTIR studies were done to confirm the structural advantages of hybrid composites. These results tend to indicate a great possibility for HPC in various sustainable applications within the construction sector.

1. Introduction

The growing demand for innovative, lightweight, and eco-friendly materials has driven research into polymer composites [1]. Besides, existing materials often lack the balance of strength, cost-effectiveness, and sustainability. Therefore, there is a need to develop innovative composite materials [2]. HPCs involve two or more reinforcement elements embedded within the polymer matrix and will most likely exhibit an advanced level of properties to result in excellent composites performance that makes it environmental and meeting the goals set forth under Sustainable Development Goals 11 for sustainable cities and communities. The present work focuses on the combination of 50% PALF with 50% polyester in Fiber mat-layer form and epoxy resin as the based polymer composite to develop a sustainable and high-performance material.

These studies focused on the physical properties of the materials involved in HPCs which is epoxy, PALF, and polyester Fiber. It also investigates the mechanical properties of Hybrid Polymer Composites (HPCs) using a thermoset-Epoxy Resin with different number of layers for PALF-Polyester Fiber mat layer which is one layer, two layer and three layers. It aims to determine the optimal layer of PALF and Polyester on Hybrid polymer Composites performance.

2. Methods

This section describes the methodology used in conducting these studies and providing a comprehensive and detailed examination, where the subject of the research is to enhance comprehension of this project. The knowledge gathered is derived from various projects and extensive discoveries related to Hybrid Polymer Composites (HPCs) with three different types of material which is Thermoset (Epoxy), Thermoplastic (Polyester) and Pineapple Leaf Fiber (PALF).

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2.1 Materials

The materials used in this study include Epoxy Resin, Pineapple Leaf Fiber (PALF), and polyester fiber. Figure 1 shows the Epoxy resin, PALF, and Polyester fiber material. Epoxy resin, a thermosetting polymer, served as the polymer matrix due to its excellent mechanical strength and chemical resistance where the ratio of 3:1 with the curing agent transformed the liquid resin mixture into a solid state. PALF, a natural fiber extracted from pineapple leaves, was selected for its high specific stiffness and strength. Polyester fiber was utilized as a synthetic reinforcement to complement PALF and enhance the hybrid composite's structural properties. The PALF and Polyester fiber will be combined in the form of mat fiber with the ration of 50% for PALF and 50% for Polyester. Figure 2 shows the preparation process of PALF-Polyester mat fiber. Table 1 shows the previous studies on conducting composite material

(a) **(b)** **(c)**

Fig. 1: *Materials (a) Epoxy resin; (b) PALF; (c) Polyester*

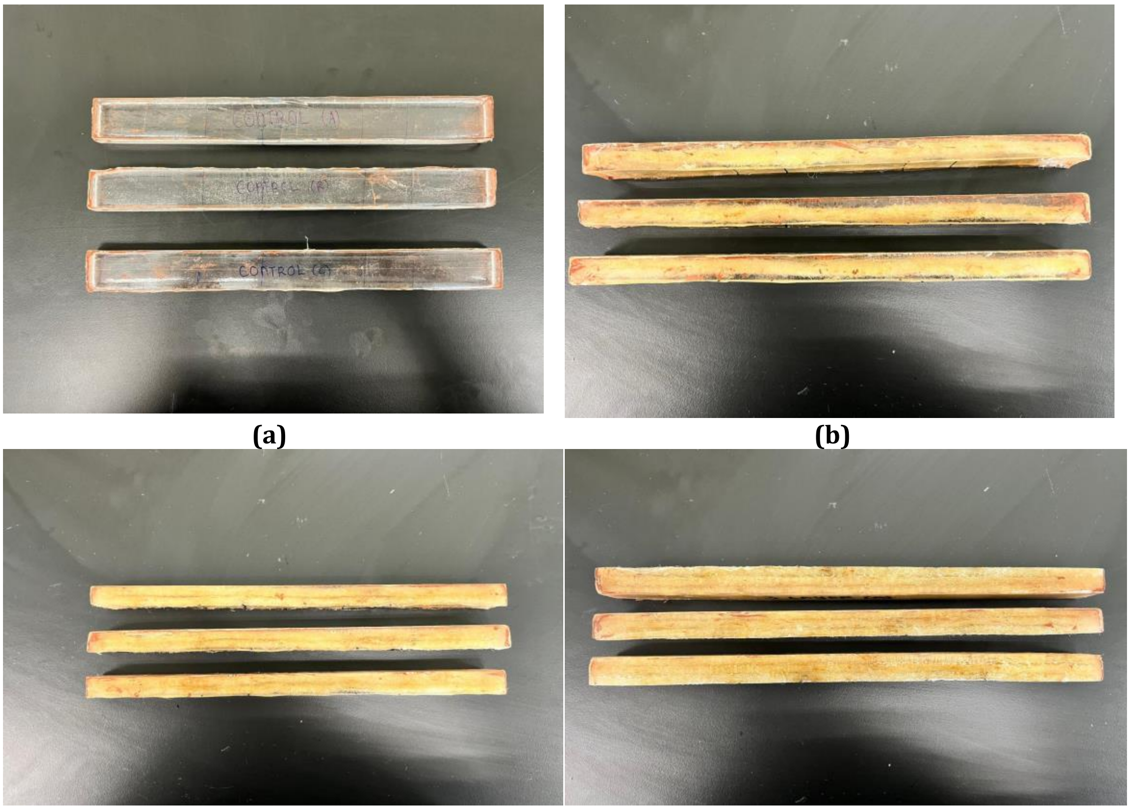
Table 1: *Previous studies on conducting composite material*

Author, Year	Type of Fiber	Type of Resin	Resin and Hardener Ratio	Fabrication Method
[3]	Bamboo	Epoxy	3:1	Vacuum Bagging
[4]	Jute, PALF	Epoxy	5:4	Vacuum Bagging
[5]	Kevlar, Kenaf	Epoxy	10:1	Hand Lay-up
[6]	PALF, Napier, Hemp	Epoxy	3.5:1	Hand Lay-up
[7]	Glass, Kenaf	Epoxy	10:1	Hand Lay-up, Compression Moulding
[8]	Banana	Epoxy	10:1	Hand Lay-up
[9]	Jute, Kenaf, PALF	Polypropylene	-	Heat Press
(Sánchez et al., 2020)	Bamboo	Polyerethane	1:1.5	Compression Moulding

2.2 Specimen Preparation

The Hybrid Polymer Composites (HPCs) were fabricated using the hand lay-up method. 50% of PALF and 50% of polyester fibers were combined into mat fiber layers form as shown in figure 2. These mat layers were reinforced with epoxy resin to form HPCs samples. Three types of HPCs specimen were prepared, which is one, two, and three layers of PALF-polyester mats, respectively. Rectangular molds of dimensions 250 mm × 25 mm × 15 mm were used for specimen fabrication. The curing process was conducted at room temperature for 24 hours to ensure complete polymerization. Figure 3 shows the Control samples, one-layer PALF-Polyester HPCs, two-layer PALF-Polyester HPCs and three-layer PALF-Polyester HPCs samples.

Fig. 2: *Preparation of PALF-Polyester mat fiber*



(a) **(b)**

(c) **(d)**

Fig. 3: *(a)Control samples, (b) 1 layer, (c) 2 layers, (d) 3 layers of Hybrid Polymer Composites (HPCs)*

2.3 Testing and Analysis

Physical properties of HPCs material which is Epoxy, PALF, and Polyester were examined through Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Fourier Transform Infrared (FTIR) Spectroscopy analysis. The SEM analysis was employed to examine the surface morphology and the chemical composition, FTIR analysis was conducted to identify functional groups and chemical interactions and XRD was used to determine the crystallinity of the materials, with diffraction peaks recorded for Epoxy Resin, PALF, and Polyester. Meanwhile, the mechanical properties of HPCs were evaluated through the tensile strength test to determine the tensile strength and tensile modulus of the HPCs specimens. Table 2 and Table 3 show the number of samples being used for the physical and mechanical properties of HPC.

***Table 2**: Number of samples for physical properties*

Testing	Type of Sample	Sample Form	Total
	PALF	Fiber	1
SEM	Polyester	Fiber	1
	Epoxy	Hard Mixture	1
	PALF	Powder	1
XRD	Polyester	Fiber	1
	Epoxy	Hard Mixture	1
	PALF	Powder	1
FTIR	Polyester	Fiber	1
	Epoxy	Hard Mixture	1
		Total Samples	9

***Table 3**: Number of samples for mechanical properties*

Types of Samples	Proportion of Fiber Layer (%)		Ratio for Epoxy and Hardener	No Fiber Layer	Experimental Testing (Sample)
	PALF	Polyester			Tensile Strength
	50	50	3:1	0	1
Control	50	50	3:1	0	1
	50	50	3:1	0	1
	50	50	3:1	1	1
1 Layer	50	50	3:1	1	1
	50	50	3:1	1	1
	50	50	3:1	2	1
2 Layer	50	50	3:1	2	1
	50	50	3:1	2	1
	50	50	3:1	3	1
3 Layer	50	50	3:1	3	1
	50	50	3:1	3	1
				Total Sample	12

2.3.1 SEM

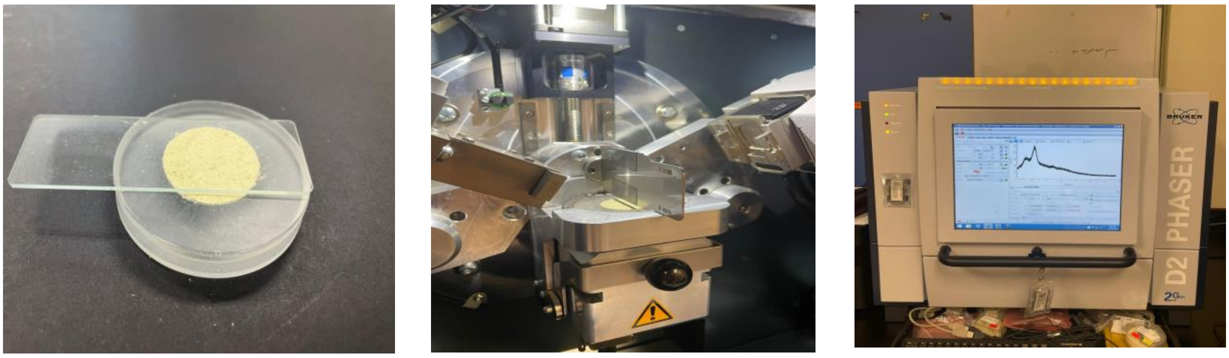
Scanning Electron Microscopic testing shall be conducted in respect of surface fracture studies and composition analysis of Epoxy, PALF, and Polyester. SEM testing can be performed on the COXEM EM-30 AX PLUS SEM machine. A thin layer of gold (Au) was coated on the sample using the Quorum Q150R S machine for 15 minutes to enhance conductivity. The acceleration voltage of the beam was 20 kV, while the procedures for studying surface morphology by means of electron microscopy were outlined by ASTM E2809-22. Images were captured in different magnifications, saved with appropriate labels and scale bars. Using Energy-dispersive X-ray spectroscopy, elements present in the sample could be identified. Figure 4 shows the process of conducting the Scanning Electron Microscopy Analysis of Epoxy, PALF and Polyester

(a) **(b)** **(c)**

***Fig. 4**: The process of SEM analysis; (a) Samples of materials, (b) Coating process of samples with gold (Au), (c) COXEM SEM machine.*

2.3.2 XRD

The XRD test for this research is performed to establish the crystallographic structure and chemical composition of Epoxy, PALF, and Polyester. Testing of XRD can be done by the machine D2 Phaser by using the standard ASTM F3419-22 to outline the step involved in performing the XRD analysis. Scanning parameters were configured, with Cu-Kα selected as the X-ray source. Figure 5 shows the process stages of conducting the X-Ray Diffraction analysis of Epoxy, PALF and Polyester materials.



(a) **(b)** **(c)**

Fig. 5: *The process of SEM analysis; (a) Sample being compacted in base plate, (b) Sample being place in the D2 Phaser XRD machine, (c) D2 Phaser analysing the samples.*

2.3.3 FTIR

FTIR is an analytical technique that will be used in this study to determine the material composition in a molecular level on Epoxy, PALF, and Polyester. Tests on FTIR can be done using a FTIR spectrometer as shown in Figure 6 with respect to ASTM D7653-18. Set up the spectrometer to 4000-400 cm^{-1} wavenumber range at 4 cm^{-1} resolution accordingly. The samples were scanned, and the spectra obtained in absorbance mode were recorded for analysis. Figure 5 shows the process of conducting the FTIR analysis.

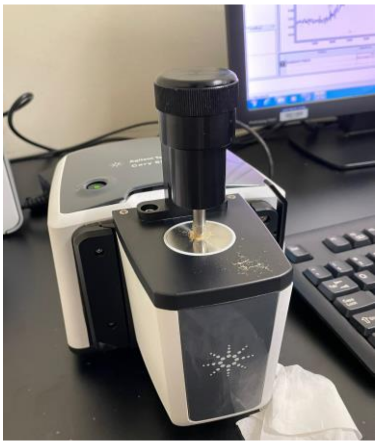


Fig. 6: *The process of analysis FTIR*

2.3.4 Tensile Test

The tensile test is conducted to study the tensile strength and tensile modulus of the HPCs specimen, which is Control sample, single-layer PALF-Polyester, two-layer PALF-Polyester and three-layer PALF-Polyester HPCs. A rectangular shape specimen will be used to conduct the tensile tes as shown in Figure 7, which is 250mm x 25mm x 15mm, aligned with the ASTM D3039. The specimen used in the tensile test is extended along its major longitudinal axis at a constant speed of 10 mm/min until the specimen elongation reaches predetermined value. Based on the recorded data, Tensile strength, modulus, and strain at failure were calculated.

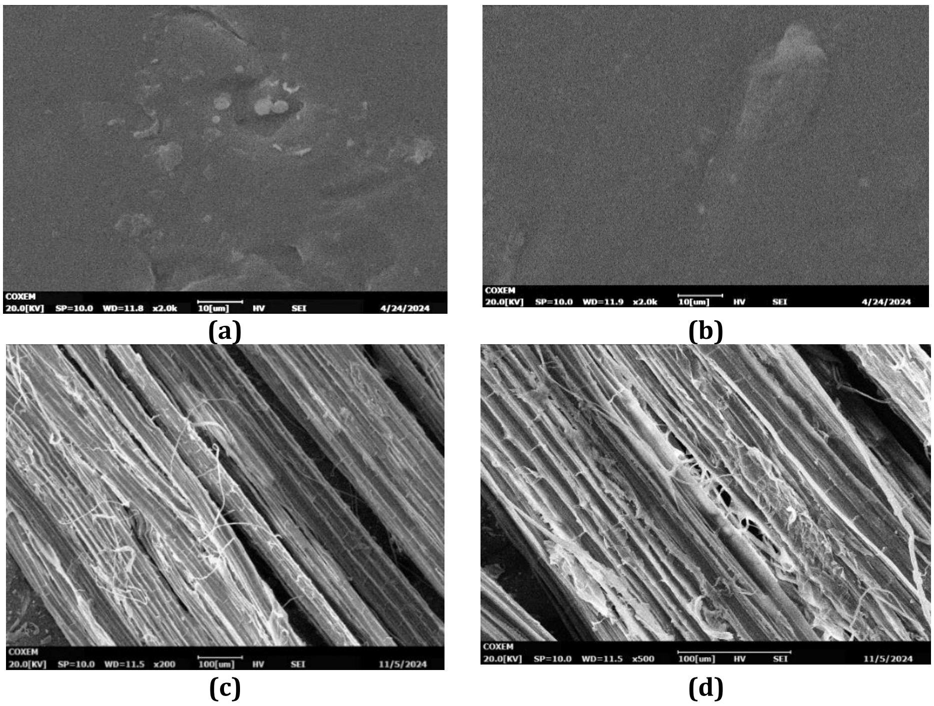
Fig. 7: *The HPCs specimen being placed on the Universal Testing Machine for Tensile Strength Test*

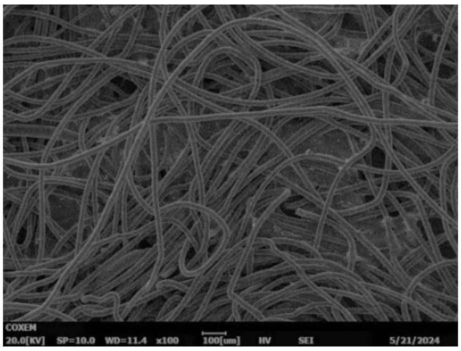
3. Results

A total of four experimental tests were carried out to determine the physical and mechanical properties of the Epoxy resin-based polymer composites reinforced with PALF and Polyester. Experimental tests include SEM, XRD, and FTIR for the physical performance test of the Epoxy, PALF, and Polyester material, while Tensile Strength Test for mechanical performance of the Hybrid Polymer Composites specimens.

3.1 SEM

SEM analysis of the epoxy composites, PALF, and polyester all revealed distinct morphologies again, pointing to the role of the material in these composites. The epoxy composite revealed a smooth, translucent surface with some irregularities as spots, probably due to micro-voids, impurities, or uneven dispersion of fillers during curing, while reflecting a well-dispersed epoxy matrix, which is important for mechanical strength and stress transfer. On the other hand, the PALF showed a rough and irregular surface, typical for natural fibers, and it was attributed to its complex microstructure that enhances bonding with the matrix, hence improving such mechanical properties as tensile strength. In contrast, polyester showed smooth, elongated, and twisted structures, demonstrating high molecular alignment that contributes to tensile strength and flexibility. Roughness in PALF and smoothness in polyester together provide, along with the epoxy matrix, an effective reinforcement system to give an optimum balance of mechanical strength, flexibility, and durability to the composite. Figure 8 represents SEM images of Epoxy, PALF, and Polyester.





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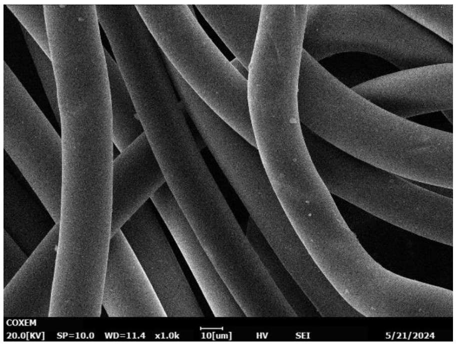
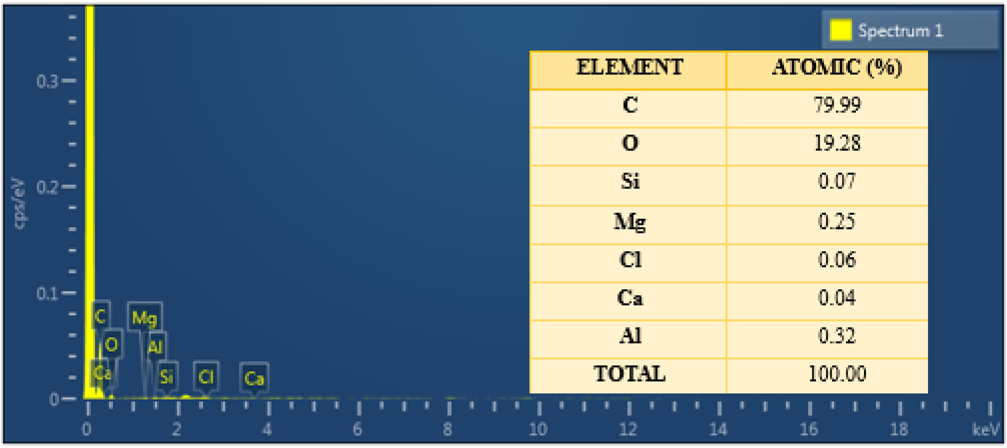


(f)

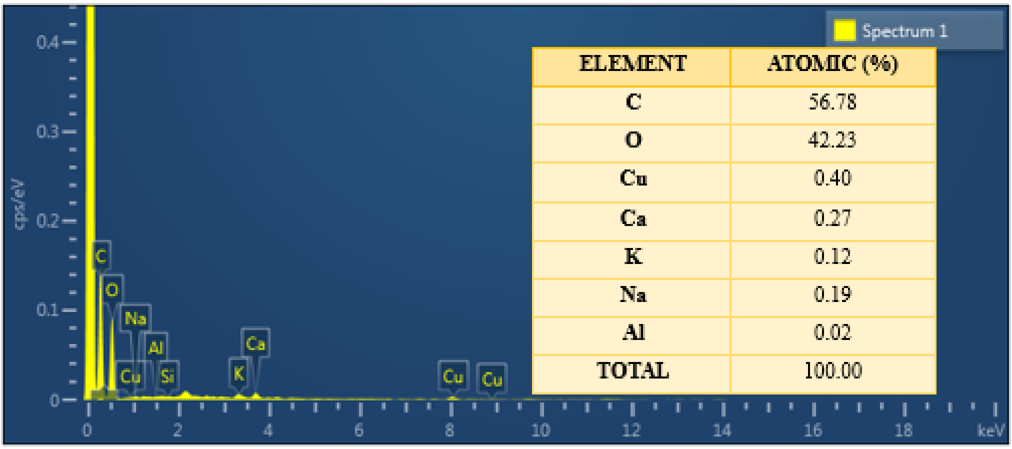
***Fig. 8**: Sem images of (a-b) Epoxy composites at x2000 of magnification; (c-d) Pineapple Leaf Fiber (PALF) at x200 and x500 of magnification; (e-f) Polyester Fiber at x100 and x1000 of magnification.*

The Energy Dispersive Spectroscopy (EDS) analysis revealed distinct elemental compositions of epoxy, Pineapple Leaf Fiber (PALF), and polyester, highlighting their contributions to Hybrid Polymer Composites (HPCs). Epoxy exhibited the highest carbon content (79.99%) and significant oxygen (19.28%), with minor trace elements like magnesium, silicon, and aluminum, indicative of its organic nature and potential additives or contaminants during preparation. PALF showed a carbon content of 56.78% and oxygen at 42.23%, attributed to its natural cellulose, hemicellulose, and lignin composition, alongside trace elements such as copper, calcium, and potassium, likely originating from environmental or processing sources. Polyester consisted of 55.09% carbon, 21.24% oxygen, and 23.67% nitrogen, with the carbon and oxygen reflecting its ester linkage structure, while nitrogen indicated chemical treatments enhancing fiber properties. Figure 9 shows the EDS analysis for Epoxy, PALF and Polyester.



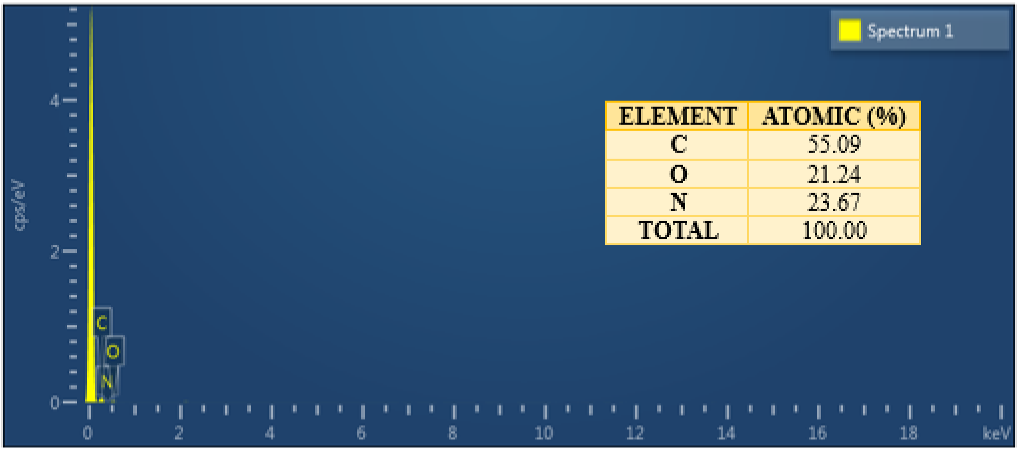
ELEMENT	ATOMIC (%)
C	79.99
O	19.28
Si	0.07
Mg	0.25
Cl	0.06
Ca	0.04
Al	0.32
TOTAL	100.00

(a)



ELEMENT	ATOMIC (%)
C	56.78
O	42.23
Cu	0.40
Ca	0.27
K	0.12
Na	0.19
Al	0.02
TOTAL	100.00

(b)

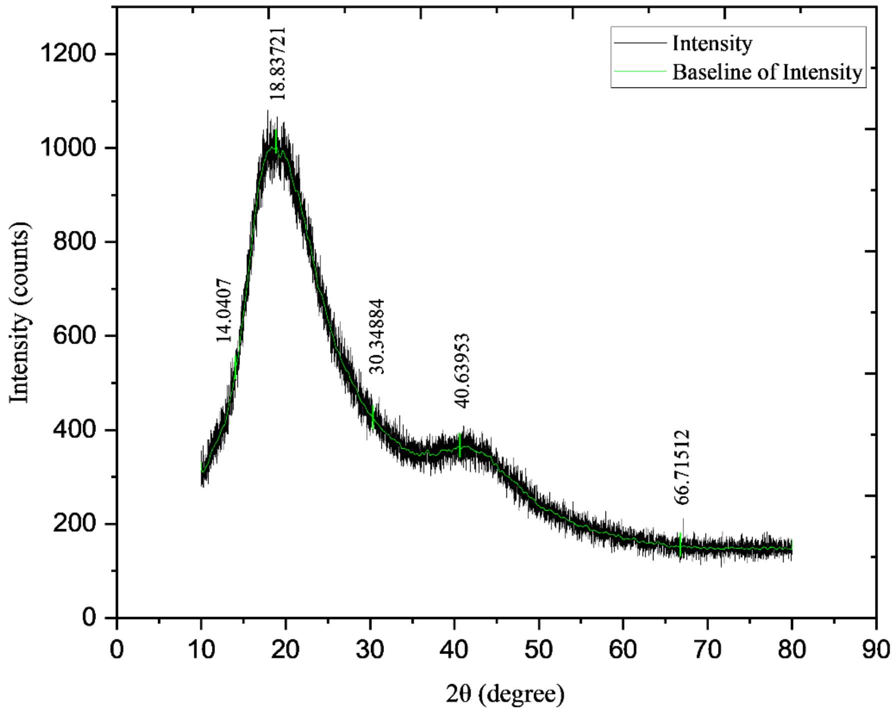


(c)

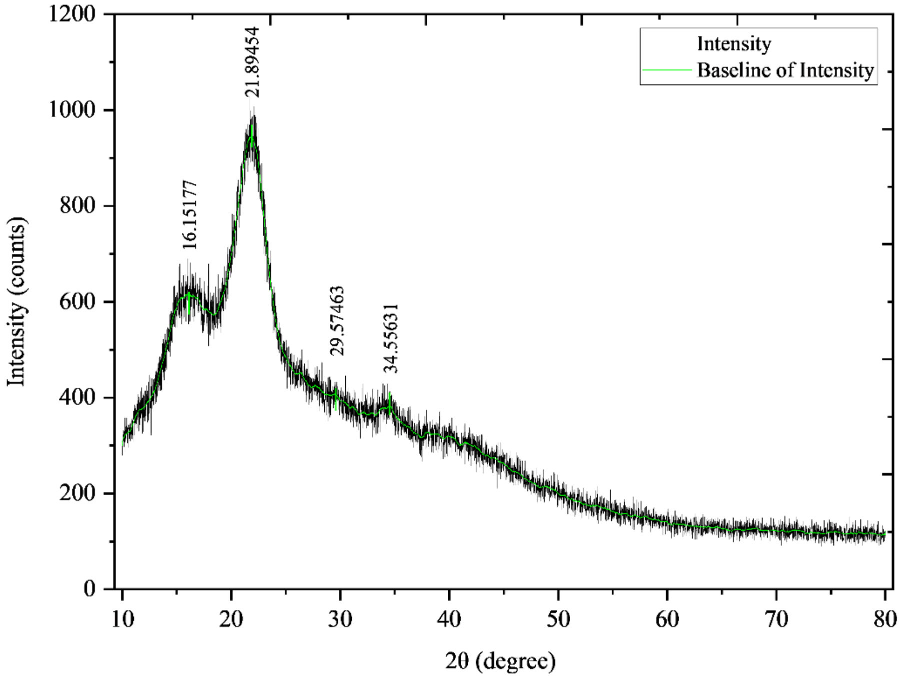
Fig. 9: *Result of EDS-semi quantitative elementary analysis for (a) Epoxy composites, (b) PALF, and (c) Polyester*

3.2 XRD

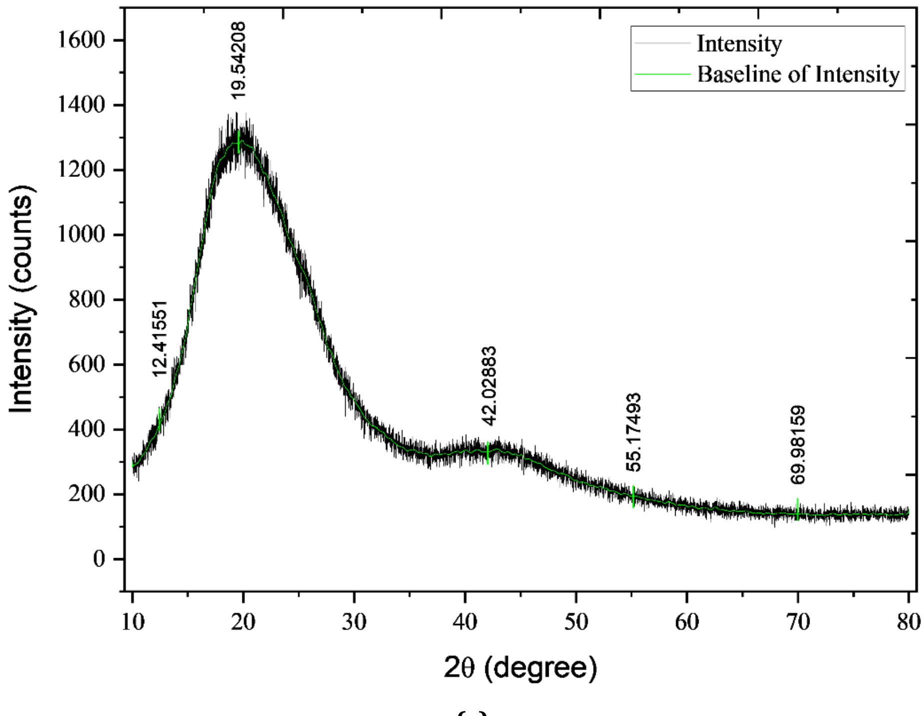
The X-Ray Diffraction (XRD) analysis provided insights into the crystalline structures and Crystallinity Index (CI%) of epoxy, Pineapple Leaf Fiber (PALF), and polyester, emphasizing their synergistic contributions to Hybrid Polymer Composites (HPCs). Epoxy exhibited a CI% of 62.06, with sharp peaks at 2θ values of 18.83° representing its crystalline regions, which enhance mechanical strength, while weaker peaks suggested minor impurities or amorphous domains. PALF displayed a semi-crystalline structure with a CI% of 48.42, marked by a prominent peak at 2θ = 21.89° due to cellulose and additional peaks at 16.15° and 34.55°, which underscore its natural fiber crystallinity and structural reinforcement properties. Polyester, with a CI% of 61.64, showed a sharp peak at 2θ = 19.54°, indicating its high crystalline alignment of polymer chains, contributing to its strength and durability. The integration of these materials which is epoxy for its high crystallinity and mechanical strength, PALF for its moderate crystallinity and lightweight reinforcement, and polyester for its durability and crystalline polymer structure can enhance the HPCs with a balanced strength-to-weight ratio, durability, and high performance, making them ideal for advanced construction applications. Figure 10 shows diffractograms XRD analysis of Epoxy, PALF and Polyester. Table 4, 5 and 6 represent the crystallinity index (%) of Epoxy, PALF and Polyester.



(a)



(b)



(c)

Fig. 10: *Diffractograms XRD analysis of (a) Epoxy, (b) PALF and (c) Polyester*

Table 4: *Crystallinity Index (%) of Epoxy*

Area of Peaks	Total Area of Peaks	Total Area that Consists of Peaks	Crystallinity (%)
1601.048 5917.1285 1817.804 1455.8825 195.4435	10987.3065	17703.723	62.06

Table 5: *Crystallinity Index (%) of PALF*

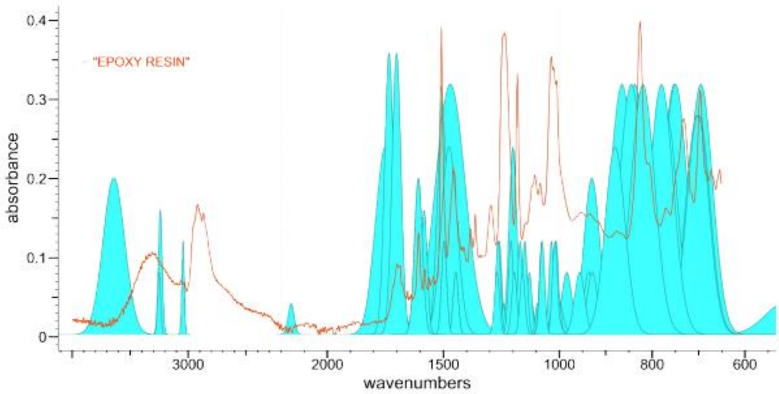
Area of Peaks	Total Area of Peaks	Total Area that Consists of Peaks	Crystallinity (%)
1452.7445 3392.18956 897.50704 1072.47202	6814.91312	14073.92151	48.42

Table 6: *Crystallinity Index (%) of Polyester*

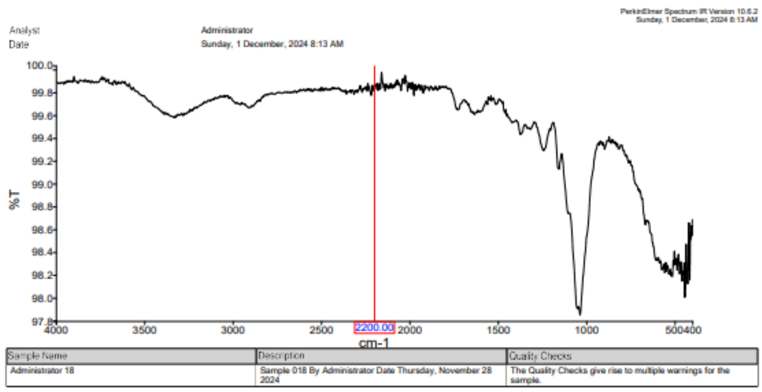
Area of Peaks	Total Area of Peaks	Total Area that Consists of Peaks	Crystallinity (%)
947.496 10358.0085 1421.7315 416.4345 136.3765	13280.047	21543.878	61.64

3.3 FTIR

The Fourier Transform Infrared Spectroscopy (FTIR) analysis identified the molecular compositions and functional groups of epoxy resin, polyester, and Pineapple Leaf Fiber (PALF), emphasizing their roles in Hybrid Polymer Composites (HPCs). The epoxy resin exhibited characteristic peaks for C-H stretching (3000–2800 cm^{-1}), aromatic C=C stretching (1600–1500 cm^{-1}), C-O-C stretching vibrations (1250–1000 cm^{-1}), and epoxide ring deformation (915–830 cm^{-1}), confirming its potential to form strong crosslinked networks. PALF demonstrated peaks for O-H stretching (3400 cm^{-1}), aliphatic C-H stretching (2900 cm^{-1}), C=O stretching from hemicellulose (1720–1740 cm^{-1}), and C-O-C vibrations (1100–1000 cm^{-1}), confirming its natural fiber composition of cellulose, hemicellulose, and lignin. The polyester spectrum revealed ester linkages, with prominent C=O stretching (1710–1720 cm^{-1}), C-O stretching (1250–1000 cm^{-1}), and C-H bending (1500–1400 cm^{-1}), highlighting its durability and compatibility. Figure 11 demonstrates the FTIR spectrum analysis of Epoxy, PALF and Polyester.



(a)



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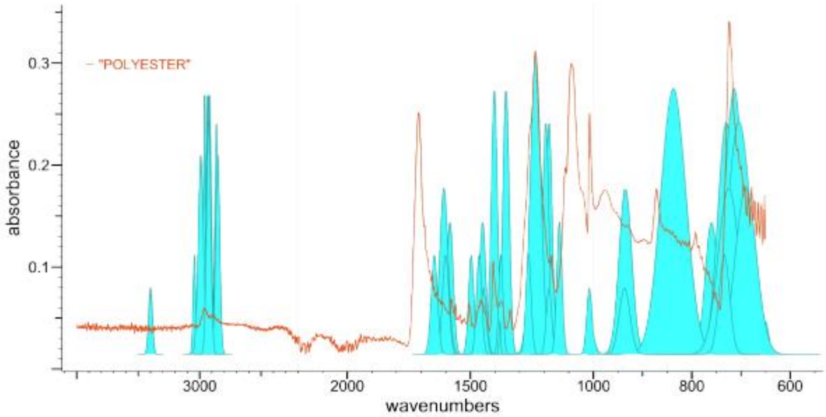

(c)

Fig. 11: *FTIR spectrum analysis of (a) Epoxy; (b) PALF; (c) Polyester*

3.4 Tensile Strength Test

The tensile strength test involved in these studies was conducted on the Hybrid Polymer Composites (HPCs) specimen, which is control sample, one-layer PALF-Polyester, two-layer PALF-Polyester, and three-layer PALF-Polyester HPCs as shown in figure 12. Sample B of three-layer PALF-polyester HPCs had the maximum tensile strength which is 24.82 MPa. Moreover, three-layer PALF-Polyester epoxy composites had the highest average of tensile strength, which is 22.54 MPa, follow by two-layer of PALF-Polyester HPCs with 21.28 MPa, one-layer of PALF-Polyester HPCs with 18.52 MPa and control sample of epoxy composites with 16.38 MPa.

Furthermore, figure 13 shows the relationship between the tensile strength and tensile modulus of HPCs for each type of samples where it results the tensile strength and tensile modulus significantly improves along with the addition number of PALF-polyester mat layers. This is because PALF and Polyester provided an extra reinforcement, which stiffens the composites' structure. Moreover, the higher values of tensile strength of the composites contributes to the ability of the HPCs specimen to withstand a higher load before failure occurs. Tensile strength and tensile modulus have a positive correlation, indicating a relationship between the two characteristics. Higher tensile modulus often contributes to higher tensile strength, as a stiffer material is generally stronger. The three-layer PALF-Polyester HPCs showed the best mechanical performance with the highest tensile strength of 22.54 MPa and the highest tensile modulus of 431.05 MPa. This result shows that adding more layers of PALF and polyester fiber significantly improved the Hybrid Polymer Composites strength and stiffness compared to the other samples.

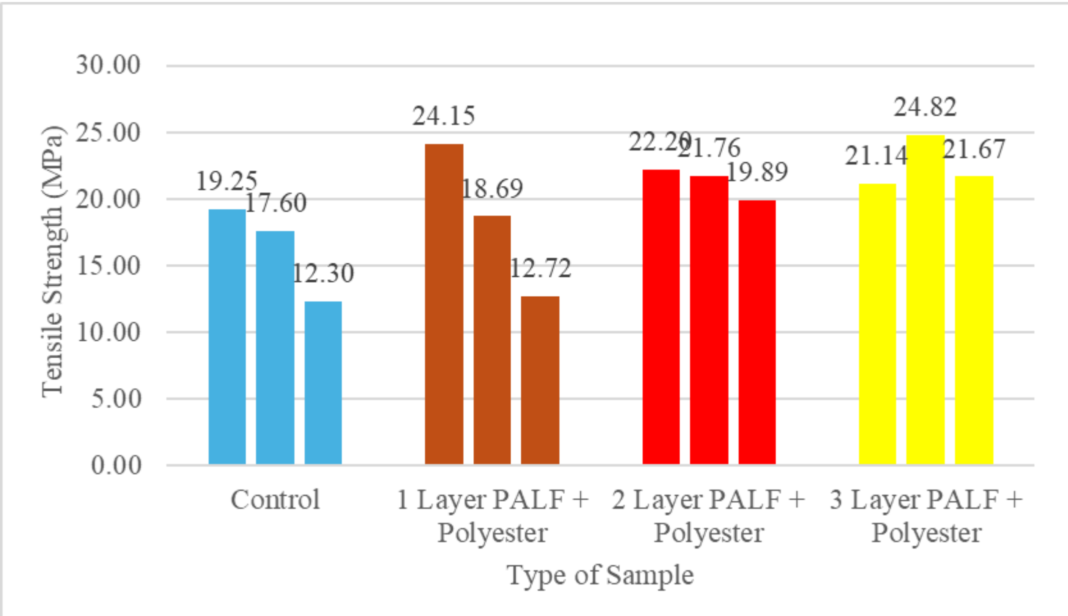

Fig. 12: *Tensile Strength foreach specimen*

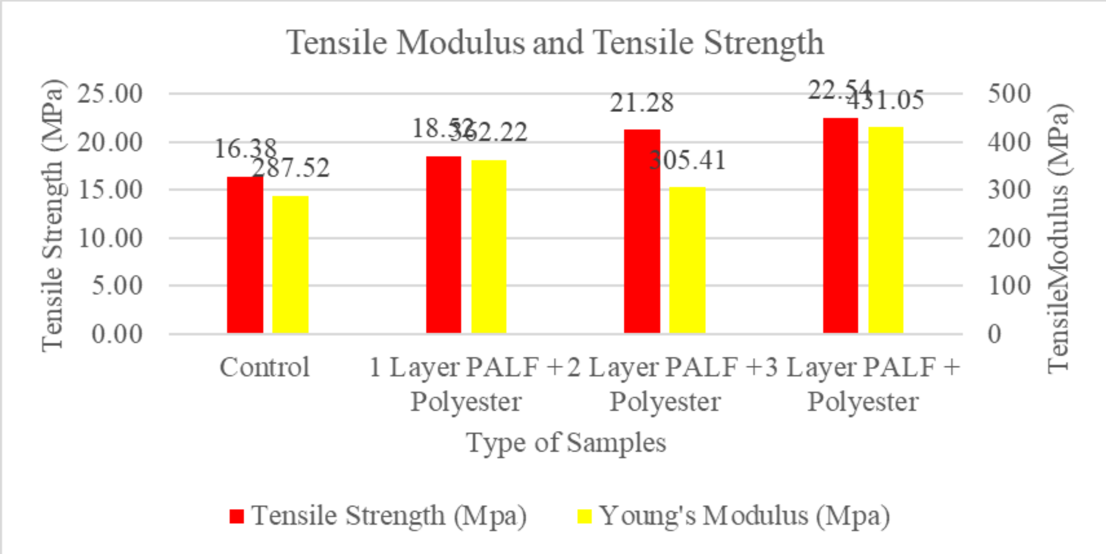

Fig. 13: *Relationship of Tensile Strength and Tensile Modulus of HPCs*

4. Conclusion

This study examines the physical test, which is SEM, XRD, and FTIR analysis to provide a clear understanding towards the physical properties of Epoxy, PALF and Polyester fiber. Moreover, the mechanical test of the Hybrid Polymer Composites (HPCs) specimen with different number of PALF-Polyester fiber layer were analyzed through the tensile strength test. In conclusion, by increasing the number of PALF-Polyester layers can enhance the composites strength and stiffness due to the three-layer PALF-Polyester HPCs recording the highest amount of tensile strength of 22.54 MPa and tensile modulus of 431.05 MPa compared to the control sample and other fewer layered samples.

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