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Development and Characterization of Carbon Fiber Kenaf and Flax Fiber-Reinforced Epoxy Composite for Aerospace Application

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ABSTRACT

This study focuses on the development and characterization of epoxy-based composites reinforced with three distinct types of fibers: carbon, kenaf, and flax. The materials was fabricated using hand lay-up technique, which involves the application of reinforced fibers layer by layer onto a mold until the desired thickness is attained. The reinforcement used in this project was epoxy resin. A fixed load was applied to the top of the laminates and left to cure for 24 hours at room temperature. Mechanical testing including tensile, flexural and impact tests was carried out to evaluate the performance of these composites. Water absorption test was carried out to gain insights into their moisture resistance properties. The results reveal that the carbon fiber reinforced epoxy composite stands out as the optimal choice for aerospace application. The composite displayed excellent mechanical properties, which include high strength (27.702 N/mm^2) and high stiffness (2179.889 N/mm^2). In addition, exceptional water resistance property was observed.

1. INTRODUCTION

The strength of natural fibers and that of conventional reinforcing fibers, such glass fibers, still differ significantly at this time. One of the key reasons why natural fibers cannot completely replace glass fibers is the difference in strength (Hamidon et al., 2019). As a result, there is a need for investigation into the hybridization of composites, which is the process of fusing two or more types of fibers to create a new material with enhanced properties over the original components.

Composite materials are created by combining two or more materials that are very different from one another in terms of their physical and chemical composition. The distinctive features are due to the interaction between the constituents (Ngo, 2020).Also, metal matrix composites, consists of a metal that is mixed with another phase. This is frequently nonmetallic to obtain materials with appealing technical properties (Mortensen & Llorca, 2010). It is also important to note that ceramic matrix composites have ionic bonds and at times covalent bonds (Dhiman & Sharma, 2021). Ceramics can be mixed with fibers to produce materials known as fibrous composites. They are lightweight and embedded in a matrix (Herakovich, 2017).

A crucial component of composites is resin. Unsaturated polyesters, epoxies, and vinyl esters are the most often used resins in composites; polyurethanes and phenolics are the least frequently utilized (Staab, 2015). Epoxy is a type of thermosetting resin or matrix material that contains one or more epoxide groups. When hardeners are used with epoxy, the epoxy resin cures and transforms into a thermosetting polymer (Saba et al., 2015). They can also be mixed with carbon fiber. The carbon fiber is a material substance made of incredibly thin carbon atom filaments. Applications requiring significant criteria for high strength and stiffness, lighter weight, and exceptional fatigue properties are best suited for carbon fibers (Zhang et al., 2023).

One of the natural (plant) fibres utilized in Polymer Matrix Composites (PMCs) as reinforcement is kenaf. Kenaf is well known as a cellulosic source with benefits to both the economy and the environment. It can grow in a variety of climatic conditions (Akil et al., 2011). The leaves and tender branches can be used for animal feed or forage, while its woody core can be utilized for structural purposes. Its fibres can be obtained from stems either at its core or stem bark. Its seed contains a protein and oil composition similar to cotton seed (Ramesh, 2016)

Advanced hybrid composites are observed to be a better candidate material than single fiber-reinforced polymer composites in the manufacture of automotive parts. It is, acknowledged that hybrid composites obtained by combining natural and synthetic fibers are economical, cost-effective, and have mechanical qualities just like a glass fiber-reinforced with virgin composites from polymers (Ojetoye et al., 2023). Bustillos et al. (2018) investigated the mechanical characteristics of five distinct natural fibers reinforced with hybrid composites by 3D printing. The following conclusions were reported as; (i). Comparing the flax/kenaf/epoxy (FKE) hybrid composite to pineapple/sisal/epoxy, kenaf/sisal/epoxy, pineapple/kenaf/epoxy, and flax/pineapple/epoxy hybrid composites, the tensile strength of the FKE hybrid composite increased by 50.53%, 37.40%, 45.21%, and 14.26%, respectively. (ii). Comparing the FKE hybrid composite to pineapple/sisal/epoxy, kenaf/sisal/epoxy, pineapple/kenaf/epoxy, and flax/pineapple/epoxy hybrid composites, the impact strength of the FKE hybrid composite is enhanced by 70.27%, 65.78%, 46.51%, and 14.54%, respectively. (iii). Comparing the flax/kenaf/epoxy hybrid composite to pineapple/sisal/epoxy, kenaf/sisal/epoxy, pineapple/kenaf/epoxy, and flax/pineapple/epoxy hybrid composites, the flexural strength of the flax/kenaf/epoxy hybrid composite is enhanced by 58.42%, 4.80%, 7.23%, and 156.7%, respectively and (iv). Compared to other hybrid composites, the FKE hybrid composite exhibits superior adhesion to epoxy resin in the SEM micrograph of flexural fracture surface samples.

Therefore, the aim of this study is the development and characterization of carbon fiber kenaf (CFK) and flax fiber reinforced epoxy composite for aerospace applications. This will involve a development of the composites using carbon fiber, kenaf fiber and flax fiber reinforcements in an epoxy matrix, characterize the physical and mechanical properties of the composites and an examination of the microstructure of the composite materials using scanning electron microscope (SEM).

2. MATERIALS AND METHODS

2.1. Materials

In this study, Epoxy resin (LY556)(Karthik et al., 2022) served as the matrix material, while the reinforcements included Carbon fibre, kenaf, and flax fibre mat. The hardener (HY 951) (Dhiman & Sharma, 2021)was used as a curing agent, and both epoxy resin and hardener were sourced from a local supplier in Lagos. A succinct representation of the equipment used for this study is shown in Table 1 and in Figure 1.

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Table 1: Equipment and location

S/N	Equipment	Locations
1	Brush, gloves, mixing cup, hand roller, electronic weighing balance	Materials and Metallurgical Engineering Department, University of Ilorin.
2	Universal testing machine and Impact testing machine	Engineering Central Workshop, University of Ilorin.

Figure 1: A picture showing the equipment used for composite development

Carbon fibres, consisting of carbon atoms arranged in a crystal-like structure, are a high-strength, lightweight material that presents as long, thin, and flexible filaments. They exhibit good thermal and electrical conductivity, low density, high thermal and chemical stability, and impressive resistance to creep. Carbon fibres find applications in various industries, including military, aerospace, and construction. For this work, bidirectional woven carbon fiber mats were utilized.

Kenaf fibre, derived from the *Hibiscus cannabimus* L plant, is gaining popularity as a natural fibre reinforcement in polymer matrix composites due to its rapid growth, affordability, and favourable mechanical properties. It was sourced from a local market in Ilorin, Kwara State, and its chemical composition includes cellulose, hemicellulose, and lignin. This is shown in Figure 2. The chemical composition of the fibre is shown in Table 2.

Figure 2: Kenaf fibre mat

Table 2: Chemical composition of kenaf fiber

Cellulose content (%)	Hemicellulose (%)	Lignin (%)
66.47	75.43	2.39

Flax fibre, a bast fibre obtained from the linseed/flax plant, is known for its long fibres and use in textile production. It was, acquired from a local market in Ilorin, Kwara State, and its chemical composition includes cellulose, hemicellulose, lignin, pectin, and ash. This is shown in Figure 3. Represented in Table 3 is the chemical properties of the flax fibre.

Figure 3. Flax fibre mat

Table 3: Chemical properties of flax fiber (Sampaio et al., 2005)

Cellulose	Hemicellulose	Lignin	Pectin	Ash
71-78%	18.6-20.6%	2.3-3%	2.3-2.5%	1.5%

2.2. Preparation of Composite

The hand lay-up method, an established technique, was used for composite fabrication. This manual process involved the meticulous layering of plies to achieve the desired thickness. Epoxy resin and hardener were mixed at a 2:1 ratio, and aluminium foil was applied to the mould with a layer of coconut oil to prevent resin sticking. Carbon fibre mats were, added layer by layer, with resin mixture applied using a brush and roller to eliminate air bubbles. The laminate was then subjected to a fixed load, covered, and left to cure at room temperature for 48 hours. This form of the mould and the final laminate is shown in Figure 4. Figure 5 shows the templates used to cut the samples according to ASTM standard. The produced laminate is shown in Figure 6. The composition of the samples is shown in Table 4.

Figure 4: Mould and the final laminate

Figure 5: Mechanical samples before and after being cut according to ASTM

Figure 6: 5 mm thickness of one of the laminates produced

Table 4: Composite sample and their compositions

Composite name	Composite type	Layer 1	Layer 2	Layer 3
C1	Carbon fiber reinforced epoxy	Carbon fiber	Carbon fiber	Carbon fiber
C2	Flax Kenaf and Carbon fiber reinforced epoxy (Hybrid)	Flax fiber	Kenaf fiber	Carbon fiber
C3	Flax Carbon and Kenaf fiber reinforced epoxy (Hybrid)	Flax fiber	Carbon fiber	Kenaf fiber

2.3. Mechanical Tests

2.3.1. Tensile test

An actual test used to determine a material's mechanical characteristics is the tensile test. In order to determine the modulus, ultimate tensile strength, and elongation break of the samples, the final composite was, put through a tension test. Stress, strain, and elastic modulus are three crucial tensile qualities (Meenakshi & Krishnamoorthy, 2018)

2.3.2. Flexural test

The flexural test was carried out in a UTM. The purpose of this test is to find out the ability of the material to resist deformation under loading.

2.3.3. Impact test

Izod impact testing is an ASTM standard procedure for evaluating a material's impact resistance. A pendulum was, released from a specific height. This then strikes the specimen, and, breaking it. The specimen's energy absorption was, used to calculate the impact energy.

2.4. Physical Tests

2.4.1. Water absorption test

One of the crucial tests for natural fibre reinforced composites is the water absorption test since natural fibre has a tendency to detect moisture, which must be carefully considered when using it in structures that will be exposed to moisture. Water absorption is determined by soaking the sample in water and measuring the weight periodically. The experiment would be carried out for 24 hours. A rectangular piece (65mmx40mmx5mm) is immersed in beaker of 500ml water for 24 hours. The weighing balance is used for measuring the weight. The weight of the sample before and after immersion would be measured. The water absorption percentage was calculated using Equation 1.

$$W.A.\ (\%) = \frac{w_2 - w_1}{w_1} \times 100 \qquad (1)$$

where W_2 is the weight of the sample after it was taken out of distilled water (g) . W_1 is the initial weight of the sample (g).

2.5. Morphological Test

Given that interfacial bonding is a crucial factor that determines the mechanical strength of the composite material, a scanning electron microscope and a transmission electron microscope will be used to analyse the interaction between the fibers and the matrix (Prasad, 2019). The Appearance of a typical SEM equipment is shown in Figure 7.

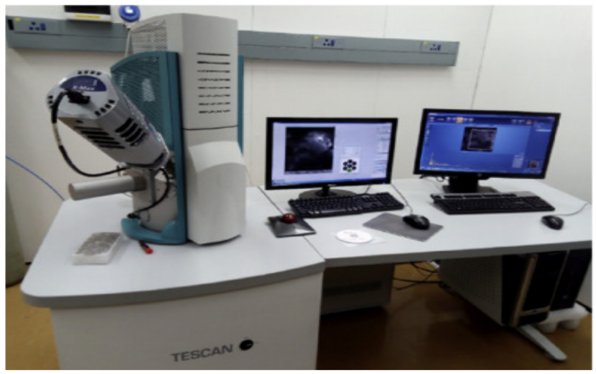

Figure 7: SEM machine (Simeon Ogbonna et al., 2019)

3. RESULTS AND DISCUSSION

3.1. Tensile Test

The tensile test, conducted following ASTM D-638 standards, was carried out using a universal testing machine (UTM) at the University of Ilorin's Faculty of Engineering and Technology. This test provided insights into parameters such as ultimate tensile strength, strain, and Young's modulus. From the results, it is evident that the position of carbon fiber significantly impacts the maximum stress of the composites. Based on the average stress values presented in Table 5, carbon fiber-reinforced epoxy composite exhibited the highest tensile strength at 27.702 N/mm^2. It was followed by the flax carbon and kenaf-reinforced epoxy composite with a tensile strength of 18.039 N/mm^{2}as shown in Table 6. In contrast, from Table 7, the flax kenaf and carbon fiber-reinforced epoxy composite displayed the lowest tensile strength at 14.063 N/mm^2. An average tensile value of the composites is presented in Table 8. It represents the fact that carbon fiber-reinforced epoxy ,CE has the highest stress at peak value followed by Flax + Carbon + Kenaf (FCK) and Flax + Kenaf + Carbon (FKC) having the least value. The strain at the peak represents the maximum deformation the material can undergo before failing. The average strain results indicated that the flax kenaf and carbon fiber-reinforced epoxy composite is more brittle, with a strain of 2.317%. In contrast, the carbon fiber-reinforced epoxy composite displayed higher ductility with a strain at the peak of 8.01%. it is important to note that the order in addition of the materials affects the physical properties of the composite. The Young's Modulus, which reflects the material's stiffness for the samples, was highest for the carbon fiber-reinforced epoxy composite at 2179.889 N/mm^2. This suggests that it is the stiffest among the three composites.

Table 5: Tensile strength values of different laminates (*Composite name*: Carbon + Epoxy)

Specimen	Stress at peak (N/mm^2)	Strain at peak (%)	Young's modulus (N/mm^2)
S1	26.460	3.123	2159.889
S2	20.346	2.416	1936.200
S3	36.301	18.491	2443.578

Table 6: Tensile strength values of different laminates (*Composite name*: Flax + Kenaf + Carbon)

Specimen	Stress at peak (N/mm^2)	Strain at peak (%)	Young's modulus (N/mm^2)
S1	12.631	2.140	1026.934
S2	13.093	1.922	951.901
S3	17.550	2.890	1097.890

Table 7: Tensile strength values of different laminates (*Composite name*: Flax + Carbon + Kenaf)

Specimen	Stress at peak (N/mm^2)	Strain at peak (%)	Young's modulus (N/mm^2)
S1	22.532	4.565	952.717
S2	14.063	2.744	783.041
S3	18.039	3.698	863.087

Table 8: Average tensile values of the composites

Compositions	Stress at peak (N/mm^2)	Strain at peak (%)	Young's modulus (N/mm^2)
Carbon + Epoxy	27.702	8.01	2179.889
Flax + Kenaf + Carbon	14.425	2.317	1025.575
Flax + Carbon + Kenaf	18.211	3.669	866.282

3.2. Flexural Test

In compliance with ASTM D-790 standards, the flexural test was conducted using a Universal Testing Machine at the University of Ilorin. The three-point bending test was performed to assess flexural strength and bending modulus. Results indicated that carbon fiber-reinforced epoxy composite displayed the highest flexural strength at 40.318 N/mm^{2}as shown in Table 9, followed by the flax kenaf and carbon-reinforced epoxy composite at 32.770 N/mm^2 as shown in Table 10. The flax carbon and kenaf-reinforced epoxy composite exhibited the lowest flexural strength at 30.177 N/mm^2 as shown in Table 11. It is also important to note that CE has the highest average stress at break followed by FKC and FCK having the least average stress at break. This trend is also observed for the average bending modulus of CE, FKC and FCK. Bending modulus, which measures stiffness during flexural loading, was highest for the carbon fiber-reinforced epoxy composite, reaching 3402.763 N/mm^2, signifying its superior stiffness among the three composites, this is shown in Table 12.

Table 9: Flexural strength values of different laminates (Composite name: Carbon + Epoxy)

Specimen	Stress at peak (N/mm^2)	Bending modulus (N/mm^2)
S1	36.265	2706.630
S2	28.397	2525.407
S3	56.291	4976.253

Table 10: Flexural strength values of different laminates (Composite name: Flax + Kenaf + Carbon)

Specimen	Stress at peak (N/mm2)	Bending modulus (N/mm^2)
S1	45.547	2807.783
S2	27.804	2176.606
S3	24.960	1858.763

Table 11: Flexural strength values of different laminates (Composite name: Flax + Carbon + Kenaf)

Specimen	Stress at peak (N/mm2)	Bending Modulus (N/mm2)
S1	24.538	1083.377
S2	34.107	1703.846
S3	31.885	1777.923

Table 12: Average flexural values of the composites

Composition	Stress at peak (N/mm^2)	Bending modulus (N/mm^2)
Carbon + Epoxy	40.318	3402.763
Flax + Kenaf + Carbon	32.770	2281.051
Flax + Carbon + Kenaf	30.177	1521.715

3.3. Impact Test

An impact test was carried out using an Izod and Charpy impact tester with a notch cutter machine, complying with ASTM D256 standards. The tests were, conducted at the University of Ilorin. Shown in Figure 8 is the, equipment used for the impact testing. The specimen used are, shown in Figure 9. Results from the testing as presented in Table 13 showed that the flax kenaf and carbon fiber composite exhibited the highest energy absorption at 80 J/m, indicating its superior ability to absorb energy during impacts. From Figure 9b, the Carbon fiber-reinforced epoxy composite displayed less effectiveness in absorbing energy during impacts. The flax carbon and kenaf fiber-reinforced epoxy composite (FCK) absorbed a moderate amount of energy at 74 J/m while the FKC has the highest energy absorption for about 80 J/m. this is due to the fact that the outermost part of the fiber contains carbon which makes it absorb more energy. Impact tests are crucial in aerospace applications where materials must withstand various impacts.

Figure 8: izod and Charpy impact tester with a notch cutter machine

(a) (b)

Figure 9: Impact test specimen before testing (a) and after testing (b)

Table 13: Impact test value

Composition	Energy absorbed (J/m)
Carbon + Epoxy	71
Flax + Kenaf + Carbon	80
Flax + Carbon + Kenaf	74

3.4. Physical Tests

3.4.1. Water absorption test

Water absorption tests were, conducted over a period of 4 days, with samples submerged in 500 ml of water. The results revealed that all three samples exhibited minimal to no water absorption over the 4-day immersion period, indicating a high level of water resistance. This property is crucial for aerospace applications, as materials with low water absorption are less prone to structural degradation and dimensional changes when exposed to moisture. The consistent weight of the samples over the test period signifies that the materials are water-resistant, making them suitable for aerospace components requiring long-term durability in various environmental conditions.

3.5. Microstructural Analysis

Microstructural examination was conducted on the carbon fiber-reinforced epoxy composite, along with an EDX measurement. The EDX analysis shown in Figure 10 revealed the elemental composition of the composite, with silicon, oxygen, calcium, carbon, iron, magnesium, aluminum, sodium, and potassium detected. Silicon had the highest composition at 40.5%, followed by oxygen at 20.6%, and sodium had the least composition at 0.9%.

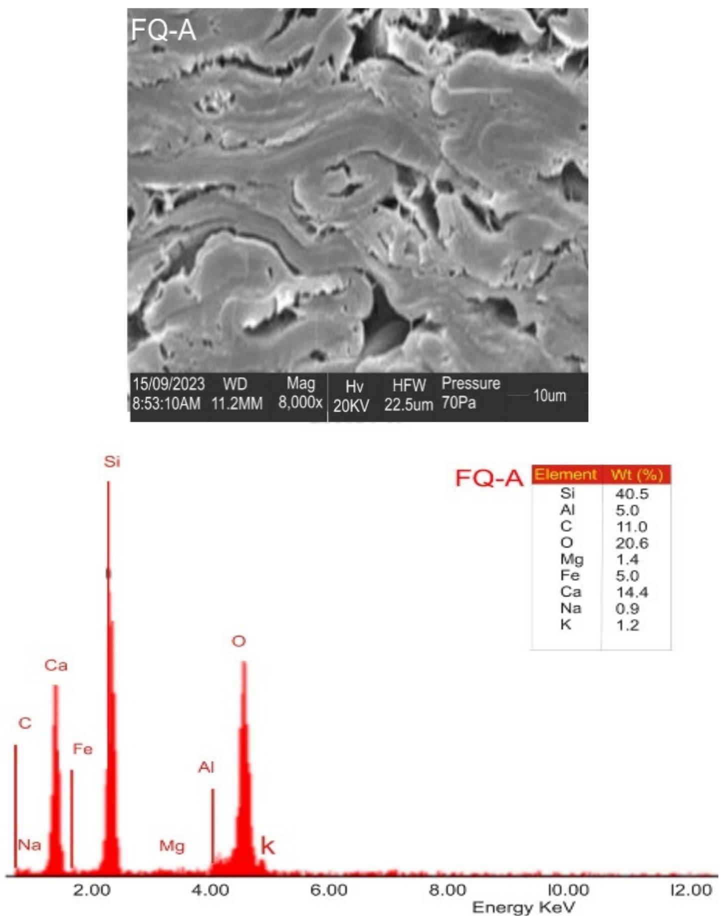

Figure 10: EDX measurement of carbon fiber reinforced epoxy composite

4. CONCLUSION

The results of this work have revealed that in the process of determining the mechanical strength of the composites, the physical properties of the composites, and to determine the composite which is more suitable for aerospace application. The following outcomes holds:

1. A hand layup technique can be used to successfully produce the composites.
2. Carbon fibre reinforced epoxy exhibited the highest tensile strength and stiffness of 27.702 N/mm^2 and 2179.889 N/mm^2 respectively. Flax kenaf and carbon fibre reinforced epoxy composite had the lowest strength of 14.425 N/mm^2 but had a higher stiffness of 1025.575 N/mm^2 compared to flax carbon and kenaf fibre reinforced epoxy composite.
3. The composites exhibited no water absorption over the 4 days immersion period, hence, they are impervious.

Therefore, for applications such as aircraft frames requiring high stiffness and strength, carbon fibre reinforced epoxy composite, because of its well-rounded properties, makes it a suitable material for such application.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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