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Development and Characterisation of Continuous Carbon Fiber Reinforced Epoxy Composites

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Abstract Epoxy composites, in their pure form, generally lack strength, but this limitation can be overcome by integrating carbon fibre, a resource often discarded after fruit harvesting. The addition of carbon fibre, a sustainable and eco-friendly material, offers considerable potential to enhance the strength and resilience of the resulting composite. This study investigated the potential of reinforcing epoxy with carbon fibre to create high-strength composites. Carbon fibre, a sustainable and eco-friendly material, was added to epoxy in varying volume percentages (0-20%) using a hand lay-up method. The results showed that the epoxy composite reinforced with 20 vol.% carbon fibre exhibited superior mechanical properties, including increased hardness (55 BHN), impact strength (5.1 J), and thermal stability (15.0% mass residue). The composite also displayed a well-distributed fibre arrangement with minimal agglomeration and voids. These findings demonstrate that reinforcing epoxy with 20 vol.% carbon fibre can significantly enhance its properties, making it suitable for high-strength applications. The use of carbon fibre, a renewable alternative to fossil fuel-based products, offers environmental benefits and a sustainable solution for composite materials.

Keywords: polymer composites, Carbon fibre, mechanical properties, Thermal properties, microstructural characteristics.

I. Introduction

The quest for innovative materials is driven by the need for enhanced mechanical properties to address the escalating demands of modern technologies and increasingly complex environments. In this context, composite materials have experienced significant advancements over the past few decades, owing to their numerous benefits and potential [1]. These materials are engineered by combining two or more distinct components to achieve enhanced properties, as noted by Azhagiri, et al. [2]. Typically, the reinforcing components enhance stiffness and strength, while the matrix components provide flexibility and protection, as observed by Bachchan, et al. [3]. Consequently, composite material designs are tailored to meet specific application requirements, such as high strength, thermal resistance, and customized physical characteristics, as highlighted by Oyewo [4]. Furthermore, advancements in fabrication techniques have expanded the application scope of composite materials, offering improved stability and cost-effectiveness, as noted by Ezeamaku, et al. [5], thereby driving their adoption across various industries. Composite materials are typically categorized based on their matrix material, comprising Polymer Matrix Composites, Ceramic Matrix Composites, and Metal Matrix Composites, each offering distinct advantages for specific industries [6]. Metallic materials inherently possess a unique combination of ductility, toughness, and strength, along with high electrical and thermal conductivity, making them versatile engineering

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materials for various applications. The incorporation of strengthening phases and reinforcements further expands the range of achievable structures, properties, and performance in metal-based composites. For instance, MMCs have been effectively utilized in the automotive and transportation sectors due to their exceptional strength-to-weight ratios [7].

Additionally, MMCs exhibit superior elastic modulus and creep resistance, making them highly competitive in the aerospace industry. The properties of metal-based composites, such as wear resistance, electrical resistance, thermal conductivity, and corrosion resistance, can be optimized through various combinations of constituents [8]. Carbon fiber stands out as a prime reinforcement material for next-generation composites, owing to its exceptional elastic modulus, and is playing a crucial role in the composite industry. Notably, continuous fiber-reinforced Metal Matrix Composites (MMCs) have been successfully employed in the Hubble space telescope's waveguide booms, leveraging their lightweight and superior electrical conductivity [9]. Furthermore, carbon fiber-reinforced metal matrix composites have been utilized as blade sleeves in military aircraft due to their high Young's modulus and fatigue resistance. Aluminum alloys, in particular, are gaining traction in engineering structures due to their wide range of outstanding properties, including excellent economic efficiency and workability, driving the adoption of carbon fiber-reinforced aluminum matrix composites across various industries. This study aims to investigate the potential of carbon fiber in developing epoxy matrix composites for engineering applications [9-11].

The growing need for enhanced vehicle body strength, rigidity, and weight reduction to improve safety, handling, and fuel efficiency has driven the increased adoption of lightweight materials with high specific modulus in the automotive industry. The escalating demand for high fuel efficiency and reduced fuel consumption has become a primary driver for the development and characterization of novel engineering materials. As a result, traditional metallic materials are being gradually replaced by innovative, lighter, and stronger composite materials [12]. Additionally, polymer-based composites offer versatility in design, property optimization, and microstructural modification. Although polymer-based composites have a long history of application in automotive and aerospace components, their use has been limited to small-volume, specialized parts due to high costs. The utilization of continuous carbon fiber reinforced composite offers a valuable opportunity to convert waste into wealth, thereby enhancing the livelihoods of a segment of the population. Processing carbon fiber composite will yield lightweight materials, boost efficiency in automotive applications, and provide a novel solution for addressing inadequate waste management, ultimately leading to wealth creation. The integration of carbon into epoxy not only strengthens and thermally stabilizes the epoxy-carbon fiber composite but also enhances its fracture toughness. Thus, this study aims to investigate the mechanical, thermal and microstructural properties of composites prepared from reinforcement of varying continuous carbon fibre content via lamentation method for automobile application. This research will contribute to job creation through the development of nanocomposites for structural applications and advance knowledge in recycling and waste utilization, supporting sustainable practices.

II. Materials and Methods

A. Materials

In the experiment, a composition of epoxy and hardener was prepared in a 2:1 ratio to fulfil the roles of resin and binder, respectively. 3 rolls of plain carbon fibers of density 128 g will be supplied by a chemical store in Lagos. **Error! Reference source not found.** presents the carbon fibre for reinforcement in the composites. The glass composite mould, mould releasing agent, stirrer, roller, disposable cup, veneer caliper, weighing balance and other materials was obtained within from the same supplier.

Figure 1: Carbon Fibre

B. Preparation of composites

Table 1 presents various mixing ratios of carbon fiber composites prepared using the hand lay-up method. The thickness of the carbon fiber was measured using a vernier caliper. A glass mold with dimensions of 150 x 150 x 3 mm was polished with a mold-releasing agent prior to preparation to facilitate easy removal of the composite from the mold. Initially, the mold was prepared with 0 wt.% carbon fiber and 100% epoxy resin. Subsequently, the mold was prepared with 5 wt.% carbon fiber and 90% epoxy resin, which was prepared by mixing epoxy resin with hardener in a ratio of 2:1.

Designation	Epoxy Resin (ER) wt. %	Carbon Fiber (wt.%)
1	100	---
2	95	5
3	90	10
4	85	15
5	80	20

The epoxy resin mixture was poured into the prepared mold and allowed to set for 24 hours. To eliminate voids and trapped air, a load of 20 kg was exerted on the mold, pressed at room temperature, and excess resin was allowed to flow out as flash. The pressure was held constant during the curing process. After curing, the pure epoxy composite served as a control sample for the fiber-reinforced epoxy composites. Additionally, calculated amounts of carbon fibers (10-20 wt.%) were mixed with 90-80 vol.% of epoxy resin and poured into the mold to form a thin layer. A stack of carbon fibers was carefully arranged in a unidirectional manner, and then more epoxy matrix was poured into the mold. A brush and roller were used to impregnate the fibers. To ensure

accuracy, three samples were prepared for each fiber ratio, and their standard deviation was calculated using Equation (1).

$$\sigma = \sqrt{[\frac{1}{N}\sum_{n=1}^{N}(x_i + \mu)^2]} \quad (1)$$

C. Mechanical properties

i. Tensile strength

In accordance with ASTM (D3039-76), a dumbbell-shaped specimen was adopted for testing the reinforced composite. The tensile test specimen dimensions were 150 mm x 20 mm x 3 mm (length x width x thickness), as depicted in **Error! Reference source not found.**. The tensile test samples were conducted in a standard laboratory atmosphere of 23°C ± 2°C and 50 ± 5% relative humidity. A Universal Testing Machine (Instron 5567) was utilized at a cross-head speed of 5 mm/min. The details and dimensions of the dumbbell-shaped specimen, conforming to ASTM (D3039-76).

ii. Impact strength

The area under the stress-strain curve was found to be proportional to the toughness of a material. However, impact strength was determined to be a measure of toughness. The Pendulum Impact Test, specifically the Notched Izod Impact Test, was utilized for the test. Test method A (Izod type) according to ASTM D256 was employed for testing. The stress concentration area that promoted a brittle failure rather than a ductile one was determined. Moreover, notching significantly reduced the energy loss due to plastic deformation. The impact strength was calculated using Equation (2).

$$Impact\ Stenght = \frac{Energy\ of\ fracture\ (Joule)}{cross\ sectional\ \ Area\ (m^2)} \quad (2)$$

iii. Hardness test

The specimen's hardness was assessed using a Brinell hardness tester, following the ASTM E10 standard for specimen preparation. A 100 kg load was applied for 30 seconds using a 1.6 mm ball indenter, and the indentation diameter was measured. Three measurements were taken at different locations, and the average hardness value was calculated. The hardness was determined by measuring the indentation diameter and applying Equation (3).

$$BHN = \frac{2p}{\pi D[D - \sqrt{D^2 d^2})]} \quad (3)$$

The equation parameters are defined as follows: P represents the applied load on the test specimen, A denotes the surface area of the indentation mark, D signifies the diameter of the spherical indenter, and d corresponds to the diameter of the resulting indentation.

D. Scanning Electron Microscopy

The insulating samples were carefully positioned and grounded with carbon, resulting in visually identical samples with engraved markings. Following this, the samples were dried in the oven at a precise temperature of 60 °C and stored in the dry box overnight to ensure optimal conditions. The vent button, conveniently located on the microscope stage's display panel, was activated, allowing a brief interval of approximately 1 minute for the chamber to fill with nitrogen gas. Subsequently, the taller sample hole was precisely placed, ensuring a secure and stable position for the sample holder. After a thorough observation period of approximately 2 minutes, the green light on the display panel illuminated, indicating the completion of the process. The SEM was then meticulously shut down by reducing the magnification to 10X, increasing the spot size,

adjusting the accelerating voltage to 15 KV, and switching the key to the VAC position. Finally, a sufficient amount of nitrogen gas was released, and the sample was carefully removed from the chamber.

III. Results and Discussion

A. Tensile Strength

Figure 1 (a) demonstrate a substantial improvement in the Ultimate Tensile Strength (UTS) on composite material. The addition of carbon fibers yields a remarkable enhancement in the tensile properties of the aluminum alloy matrix, surpassing the performance of the unreinforced matrix across all carbon fiber loadings. The yield and tensile strength values exhibit a consistent and predictable increase, mirroring the trends reported by Vimalanathan et al. (2021), who observed a steady rise in strength with increasing carbon fiber content. The optimal tensile strength is achieved at a carbon fiber loading of 20 wt%, representing a significant improvement. This substantial enhancement in due to synergistic interplay of several key processes, such as good bonding, lower diameter of the reinforcement, good compatibility and the effective reinforcement provided by the carbon fibers in epoxy resin, as demonstrated by Huda and Widiastuti [13]. The findings suggest that the incorporation of carbon fiber particles significantly enhances the mechanical properties of the composites, leading to improved performance and potential applications in various fields.

The incorporation of carbon fibers played a pivotal role in enhancing the mechanical properties of the composite, with the crystalline fibrils of the fibers shouldering the majority of the load and inducing a synchronized extension of the helically wound fibrils and the matrix. While a proportional increase in tensile properties was observed with rising carbon fiber content, a notable exception occurred at a fiber loading of 10 wt%, where an unexpected value reduction. Such unusual behaviour May be ascribed to imperfection during the manufacturing process, due to human error, stress concentrations, and crazing, altering the quality of the samples [14]. Furthermore, the excessive incorporation of carbon fibers, beyond 20 wt%, resulted in a composite with poor quality, characterized by non-uniformity, hardness, and brittleness. This deterioration in properties can be ascribed to the surpassing of the practical reinforcement limit, where the high fiber volume fraction renders the matrix material insufficient to provide effective support to the fibers, thereby undermining the composite's structural integrity, as supported by the findings of Bachchan, et al. [3], Shahar, et al. [15]. The excessive fiber loading led to a breakdown in the composite's microstructure, resulting in reduced mechanical properties and highlighting the importance of optimal fiber loading for achieving enhanced performance.

A progressive enhancement in the tensile properties of the composites was observed with increasing carbon fiber content, although a slight yet notable diminution in properties occurred at a loading of 20 wt.%. This anomaly suggests that the composite became excessively brittle, losing its capacity to absorb additional stress. The carbon fibers served as a highly effective reinforcement, absorbing the primary load through their crystalline fibrils, which induced a synchronized extension of the helically wound fibrils and the matrix, thereby significantly augmenting the composite's tensile properties, as corroborated by the research of Bachchan, et al. [3], Gaddam, et al. [16], Gupta and Tiwari [17].

B. Impact Strength

Figure 1 (b) illustrates the impact of carbon fiber addition on the impact strength of a composite material, which measures its energy absorption capacity before failure. The capacity of a material to resist cracking or disintegration under sudden, high-energy impacts is a vital safety consideration, and this is precisely what impact strength measures [18]. In essence, a material's impact strength directly affects its ability to absorb impact energy without failing, making it a vital property for materials exposed to high-energy impacts.

The addition of carbon fiber reinforcement to aluminum composites typically yields enhanced ductility and elongation, as previously reported by Alabi, et al. [18]. Similarly, incorporating carbon fibers into the epoxy matrix resulted in a significant improvement in impact strength, with values increasing progressively from 0 (unreinforced control) to 10 wt.% carbon fiber, followed by a moderate increase up to 15 wt.%, and culminating in a substantial enhancement at 20 wt.% carbon fiber reinforcement. The homogeneous dispersion of carbon fibers within the epoxy matrix likely played a crucial role in establishing a robust interfacial bond, which in turn contributed to the enhanced mechanical properties of the composite. In a contrasting study, Oyewo, et al. [8] observed increase in strength to the improvement fibre-matrix composition, especially with the short fibres of pineapple, leading to stress accumulation and inducement of cracks as a result of lower energy imputation. According to Gideon and Atalie [19], describes the energy absorption principle, which entails releasing energy to break the strong bond affinity of the fibre from the matrix, thus puking the apart as a result of a comparatively feeble fiber-matrix structure. Notably, a large of energy that are being absorbed via impact loading cas be ascribed to the fiber pull-out mechanism, underscoring the significance of interfacial properties in determining the performance of composite materials.

As previously documented by to Gideon and Atalie [19], the integration of carbon fiber reinforcement into aluminum composites typically yields a significant enhancement in their ductile behavior, manifesting as increased elongation and improved ductility. Also, the strength of the epoxy matrix increased due to carbon fiber inclusion, from control to 10 wt.% carbon fiber composites, with a slight increase until 15 wt.% and a significant boost at 20 wt.% carbon fiber reinforcement composites. The homogeneous distribution of carbon fibers throughout the epoxy matrix likely facilitated the formation of a robust interfacial bond, thereby contributing to the enhanced mechanical properties of the composite. In contrast, research conducted by Badyankal, et al. [20] highlighted this as a result of the increase in strength to the improved enhancement in pineapple reinforcement and the resin structure, formulating local stress accumulation that induced crackling with lower energy requirement.. Furthermore, Asim, et al. [21] provided insight into the energy absorption mechanisms in composites, highlighting the role of fiber debonding and pull-out, which is facilitated by a relatively weak fiber-matrix interface. Importantly, the fiber pull-out mechanism is a significant contributor to energy absorption during impact loading, emphasizing the critical importance of interfacial properties in

determining the performance of composite materials

C. Hardness

The results of the Brinell Hardness Test, shown in Figure 1 (c), reveal the impact of carbon fiber reinforcement on the hardness of composites. The base polymer, without carbon fiber, had a hardness of 34 BHN, the lowest value recorded. Adding 5 wt% carbon fiber led to a notable increase in hardness to 46 BHN, setting the baseline for the reinforced composites. As the carbon fiber content rose incrementally, hardness values consistently increased, reaching a maximum of 59 BHN at 20 wt% carbon fiber, with moderate hardness of 56 and 57 BHN at 10 and 15 wt% carbon fiber, respectively.

The synergistic combination of epoxy resin and 20 wt% carbon fiber yielded the highest hardness value, demonstrating a direct relationship between carbon fiber content and hardness, with incremental increases observed up to 20 wt% carbon fiber. This finding aligns with the optimal stoichiometric ratio reported in the work of Chhetri and Bougherara [22]. The marked improvement in hardness, from 34 BHN to 59 BHN, resulting from the addition of 20 wt% carbon fiber, can be attributed to the enhanced presence of hard carbon fibers within the aluminum matrix, which is a consequence of the intrinsic hardness of carbon fibers stemming from their chemical composition and structural properties. Additionally, the integration of carbon fiber into epoxy generates increased dislocation density at the interface between particles and matrix, primarily due to thermal expansion coefficient mismatches, which induces incompatibilities in its deformation behaviour [23]. Proportional increase in hardness with reinforcement addition has been reported by Chandradass, et al. [24]. The hardness improvement is attributed to synergistic factors, including improved interfacial bonds, well dispersed reinforcement in the matrix, thereby establishing a strong correlation between the hardness and reinforcement addition, as earlier substantiated by Chandradass, et al. [24].

D. Thermogravimetric Analysis

The Thermo-Gravimetric Analysis (TGA) results for composite samples with varying carbon fiber percentages (0%, 5%, 10%, 15%, and 20%) are presented in Figure 2 (a). This analysis is crucial for assessing the thermal stability of these composites. The TGA curves exhibit a consistent three-stage decomposition pattern across all samples, spanning temperatures from 283°C to 600°C. A detailed examination of the TGA plots reveals information on the initial, intermediate, and final degradation stages, as well as the temperatures at which fiber residues remain. The thermal decomposition of composite samples with varying carbon fiber content was investigated, revealing a three-stage process. Initially, between 30°C and 90°C, all samples experienced moisture loss, resulting in a 5-10% weight reduction. Further heating led to decomposition between 225°C and 239°C, with the 0% sample exhibiting a decomposition temperature of 216°C, while the 9% and 15% samples reached 220°C, and the 12% sample had the highest initial decomposition temperature (IDT) at 222°C. The second stage, spanning 311°C to 322°C, involved a significant weight loss (approximately half of the sample) due to cellulosic breakage. The final stage, occurring between 353°C and 387°C, involved the

decomposition of lignin, a challenging constituent to decompose. The final temperature. Furthermore, the increased fiber loading in the 20% sample mitigates alkali-

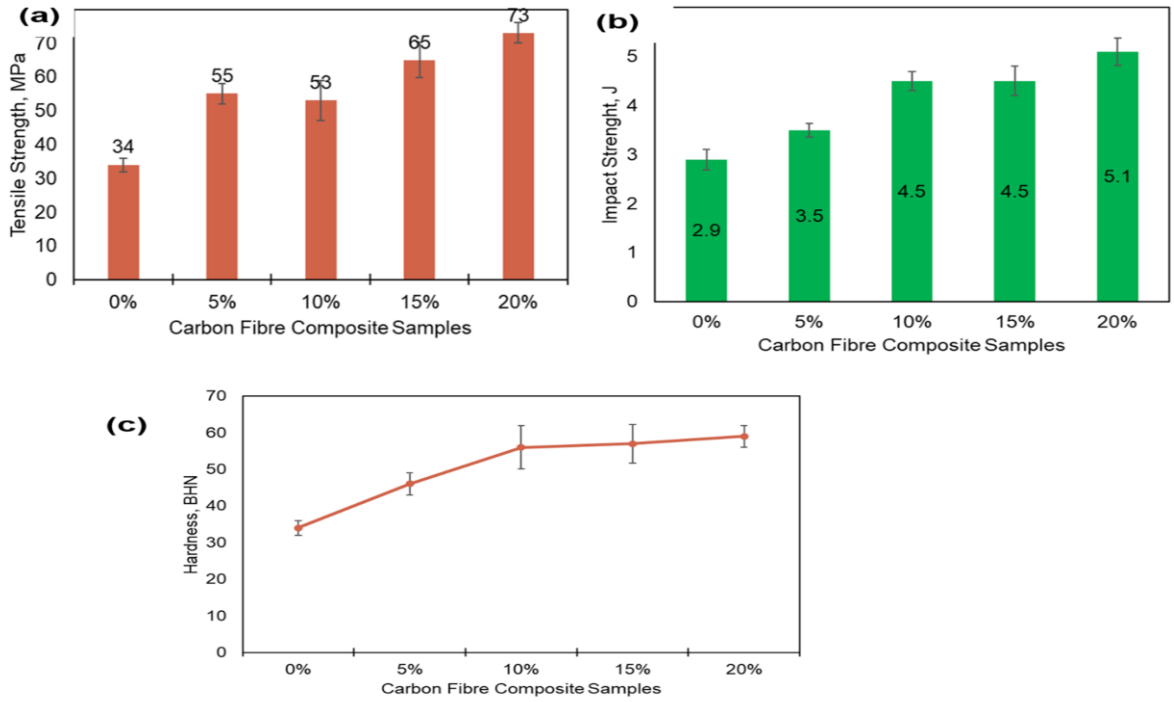

Figure 1: (a) Tensile Strength (b) Impact Strength (c) Hardness of 0, 5, 10, 15 and 20 % Carbon Fibre Composites

with 20%, 15%, 10%, and 5% carbon fiber content were 391°C, 379°C, 369°C, and 380°C, respectively. Complete lignin decomposition occurred at temperatures up to 550°C.

The residual mass of the composite samples, as shown in Figure 2 (b), exhibits a consistent correlation between increased residue percentage and enhanced crystallinity levels, aligning with previous findings [12]. The elevated residue value of the composite samples indicates a significant increase in crystallinity, specifically 16%, compared to other samples. This phenomenon can be attributed to the structure's capacity to retain moisture firmly, resulting in the release of absorbed moisture with reduced force when heated, a behavior prominently observed sample with an elevated finishing absorption, leading to enhanced lignin and hemicelluloses, which consequently minimizes water absorption [25]. Moreover, the TGA curve presented in Figure 2 illustrates the thermal decomposition behavior of composite samples with varying carbon fiber content (0, 5, 10, 15, and 20%), providing valuable insights into their thermal stability.

The sample with a 20% concentration demonstrates enhanced thermal stability, primarily due to its higher value. This enhancement can be attributed to the more structured and tightly packed arrangement of cellulose molecules, leading to improved thermal stability. As noted by Adeniyi, et al. [25], the organized region in natural particulates contributes to thermal stability by immobilizing

cellulose through strain and reducing the presence of existing hydrogen bonds, thereby reinforcing the material's thermal resistance

proceeding section. Also, the composites reinforced with 15 and 20 wt% carbon fiber display a remarkably uniform microstructure

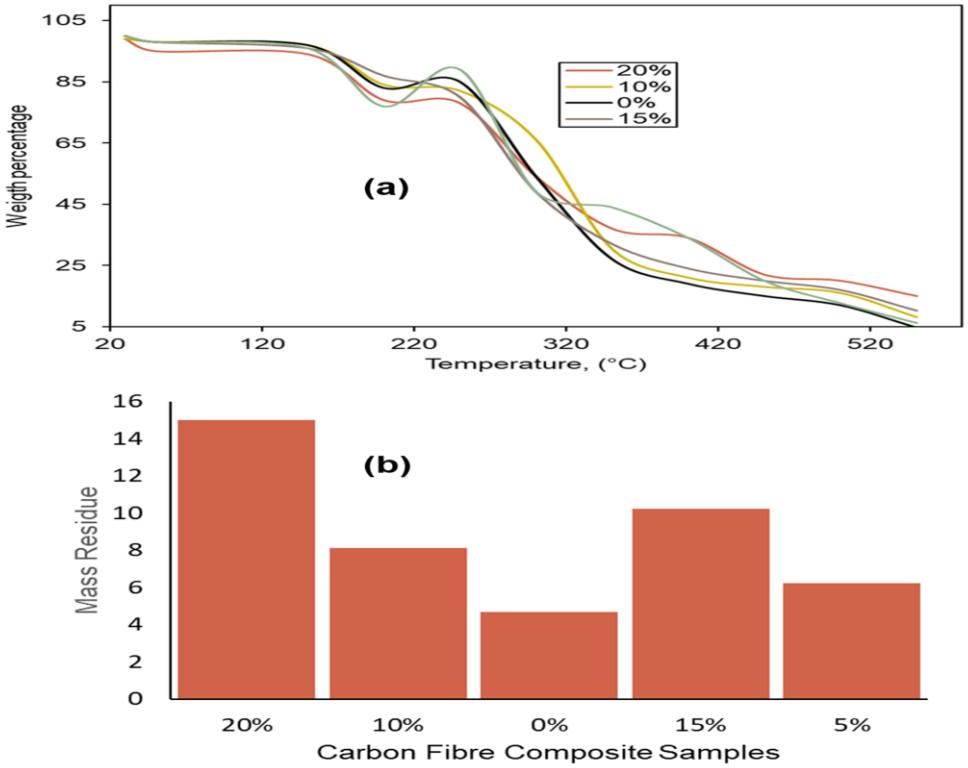

Figure 2: (a) Thermogravimetric Analysis (b) Percentage Left Over of Mass Residue for 0, 5, 10, 15 and 20 % Carbon Fibre Composites

A. Scanning Electron Microscopy

SEM analysis was conducted on carbon fiber-reinforced epoxy specimens with varying carbon fiber loadings (0, 5, 10, 15, and 20 wt%), with the results discussed in Figure 4 (a-e). The SEM micrographs show various morphologies, illustrating the impact of incorporation of carbon fiber into the epoxy matrix up to 10 wt%. However, the micrographs corresponding to the 15 and 20 wt% carbon fiber composites exhibit a distinctly uniform distribution of reinforcement throughout the epoxy composite, indicating improvement in strength and corroborating the superior mechanical behaviour as highlighted in the results discussed in proceeding section. Also, the composites reinforced with 15 and 20 wt% carbon fiber display a remarkably uniform microstructure characterized by the absence of pores, agglomerates, as well as fiber pulling out of fibres, indicating a strong compatibility that exist in interface between the composite structure. On the other hand, the microstructure of the 10 wt% carbon fiber reinforced sample exhibits a non-uniform distribution, likely resulting from inadequate reinforcement loading within the matrix. This observation aligns with the findings of earlier work of Ganesan, et al. [26], Hanan, et al. [27] revealing an optimal reinforcement dispersion within the matrix is achieved when the reinforcing materials is not beyond the maxim capacity of the matrix, as typified by the 20 wt% carbon fiber reinforced composite.

strength of 5.1 J. With a mass residue of 15%, 20 wt.% composite was stable at elevated temperature. Scanning electron microscopy

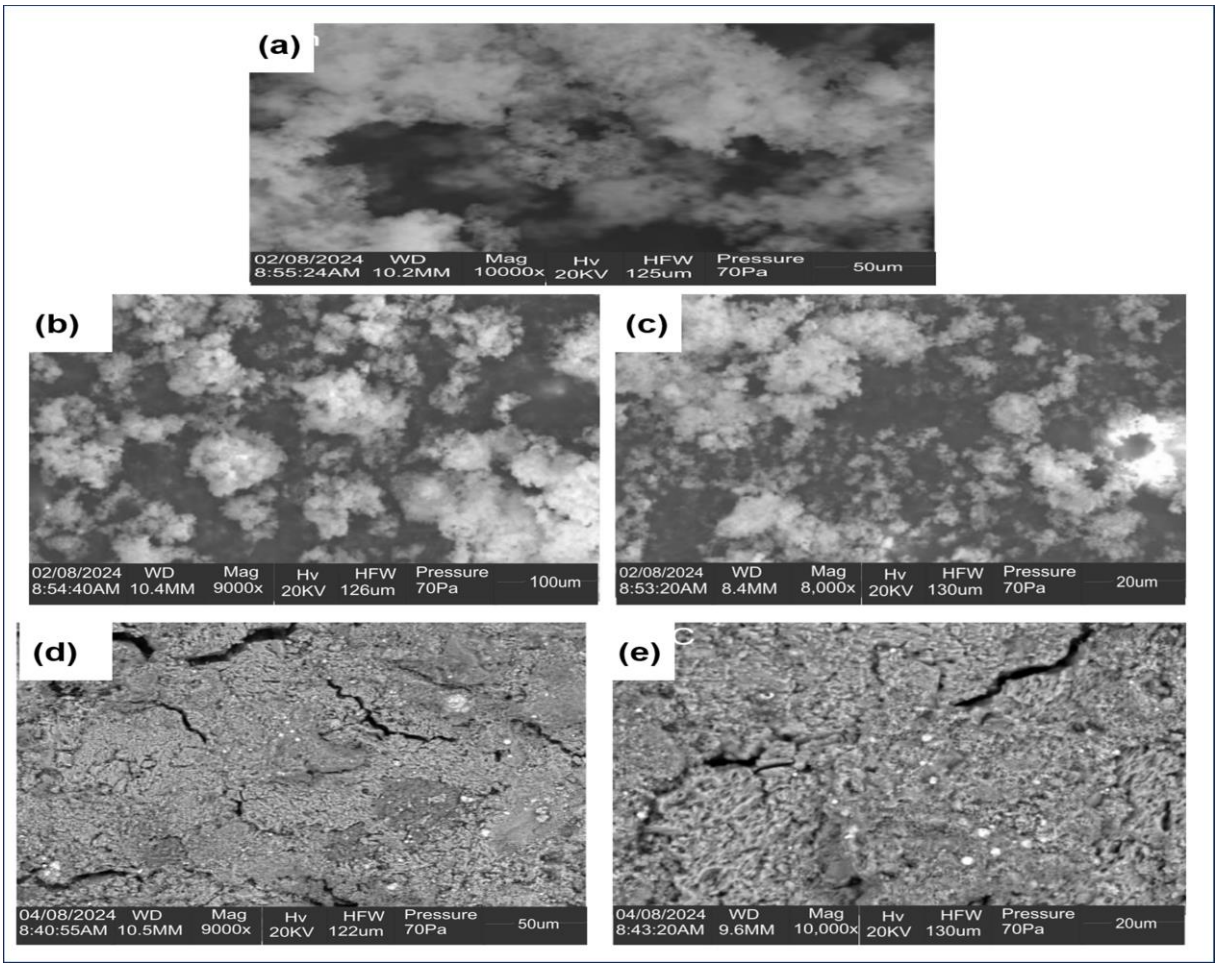

Figure 3: SEM Micrograph of carbon fibre composites for (a) 0 % (b) 5 % (c) 10 % (d) 15 % (e) 20 % reinforcement

IV. Conclusion

This research explored the effects of carbon fiber incorporation on sustainable epoxy matrix composites, utilizing a lamination technique with varying carbon fiber loadings (0, 5, 10, 15, and 20 wt%). The study revealed significant improvements in mechanical properties, including a progressive increase in hardness from 34 BHN to 59 BHN with the addition of 20 wt% carbon fibers, exceptional tensile strength of 73 MPa, and enhanced impact (SEM) analysis showed a homogeneous distribution of carbon fibers within the matrix, with minimal voids and agglomeration, indicating effective reinforcement and optimal interfacial bonding. These findings demonstrate the potential of carbon fiber-reinforced epoxy composites for various applications, offering improved mechanical properties and sustainability.

To further advance the development of these sustainable composites, optimizing the synthesis process to achieve uniform nanoparticle sizes is recommended. Exploring alternative biodegradable reinforcement materials, such as natural materials, and investigating the influence of various techniques on the composite's properties could also provide valuable insights. Furthermore, in-depth studies on interfacial reactions, hybrid reinforcement systems, and corrosion behavior are necessary to enhance the overall performance of these composites. Upscaling and conducting comprehensive mechanical methods under various conditions will enable a thorough evaluation of their industrial applicability. Moreover, investigating the potential applications of these sustainable composites in the aviation and energy industries can uncover new opportunities for their utilization, ultimately contributing to a more environmentally friendly and sustainable materials landscape.

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