

# Experimental Evaluation of Carbon Fiber Reinforced Epoxy Composites for Structural Applications

Praveena B.A.<sup>1,\*</sup>, Shivaji Lamani<sup>2</sup>, Venugopal M.M.<sup>3</sup>, Srikanth H.V.<sup>4</sup>, Santhosh N.<sup>5</sup>

## Abstract

Composites made of carbon fibre reinforced polymer (CFRP) are currently one of the most widely used material classes in advanced engineering applications because of their remarkable environmental resistance, dimensional stability, and strength-to-weight ratio. The vacuum bag moulding method was used in this study to create CFRP laminates with different fiber-to-resin weight ratios: 50:50, 55:45, 60:40, 65:35, and 70:30. The reinforcement phase was made of unidirectional carbon fibre fabric and the matrix was made of epoxy resin based on bisphenol-A and amine hardener. In compliance with ASTM guidelines, the laminates underwent tensile, flexural, Shore D hardness, impact, and wear tests to assess the impact of fibre loading. According to the findings, the fiber-to-resin ratio of 60:40 performed best in every test. The maximum tensile strength (432 MPa), flexural strength (580 MPa), tensile modulus (39.2 GPa) and flexural modulus (42.0 GPa) were all attained. Superior surface integrity was indicated by a peak Shore D hardness of 85. Confirming its exceptional toughness and durability, the same composition also demonstrated the lowest wear rate ( $1.48 \times 10^{-5} \text{ mm}^3/\text{N}\cdot\text{m}$ ) and maximum impact resistance (58 kJ/m<sup>2</sup>). Because of insufficient resin infiltration and decreased interfacial bonding, laminates with fibre contents higher than 60% performed worse. These results highlight how important the fiber-to-resin ratio is for maximising the mechanical and tribological properties of composites or applications where weight reduction and mechanical efficiency are crucial, such as in the wind energy, automotive, marine, and sports industries, the optimised 60:40 configuration is ideal.

**Keywords:** Carbon fiber reinforced polymer, epoxy composites, vacuum bag molding, mechanical properties, structural applications

### \*Author for Correspondence

Praveena B.A.

<sup>1</sup>Associate Professor, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Nitte (Deemed to be University), Yelahanka, Bangalore, Karnataka, India.

<sup>2</sup>Assistant Professor, Department of Aerospace Engineering, School of Mechanical Engineering, REVA University, Yelahanka, Bangalore, Karnataka, India

<sup>3</sup>Assistant Professor, Department of Aeronautical Engineering, Nitte Meenakshi Institute of Technology, Nitte (Deemed to be University), Yelahanka, Bangalore, Karnataka, India

<sup>4</sup>Professor, Department of Aeronautical Engineering, Nitte Meenakshi Institute of Technology, Nitte (Deemed to be University), Yelahanka, Bangalore, Karnataka, India

<sup>5</sup>Professor, Department of Mechanical Engineering, Dayananda Sagar Academy of Technology and Management, Bangalore, Karnataka, India

Received Date: August 19, 2025

Accepted Date: October 27, 2025

Published Date: February 16, 2026

**Citation:** Praveena B.A., Shivaji Lamani, Venugopal M.M., Srikanth H.V., Santhosh N. Experimental Evaluation of Carbon Fiber Reinforced Epoxy Composites for Structural Applications. Journal of Polymer & Composites. 2026; 14(Special Issue 1): S401–S415p.

## INTRODUCTION

Composite materials are increasingly being regarded as the backbone of modern engineering because of their ability to offer a unique combination of high performance, low weight, and tailored properties. Unlike traditional monolithic metals or alloys, composites allow engineers to design structures with specific mechanical, thermal, and tribological properties suited for demanding applications. Among the wide range of composite classes, carbon fibre reinforced polymers (CFRPs) have emerged as one of the most important due to their extraordinary strength-to-weight ratio, high stiffness, resistance to corrosion, and long-term dimensional stability [1–3]. These advantages have placed CFRPs at the forefront of industries where efficiency, safety, and lightweight performance are critical, such as aerospace, defense, marine, sports equipment, and the rapidly growing renewable energy sector [4–6]. The mechanical behaviour of

CFRP laminates is strongly influenced by the synergistic interaction between two key phases: the carbon fibre reinforcement and the polymer matrix. Carbon fibres are characterised by their high tensile strength, modulus, and fatigue resistance, making them the principal load-bearing component of the composite [7]. On the other hand, the polymer resin phase, typically an epoxy system, ensures load transfer between fibres, provides toughness, and enhances resistance to environmental degradation [8,9]. In this context, epoxy resins based on bisphenol-A combined with amine curing agents are widely preferred due to their superior adhesion, excellent chemical resistance, low shrinkage during curing, and ability to withstand harsh operating environments [10].

Despite these inherent advantages, the final performance of CFRP composites depends heavily on the processing technique and the fibre-to-resin ratio used during fabrication. A common issue faced in CFRP manufacturing is achieving the right balance between fibre loading and resin infiltration. If the fibre fraction is too low, the material may not fully exploit the strength potential of carbon fibres, leading to reduced stiffness and mechanical efficiency. Conversely, when the fibre fraction is too high, incomplete wetting and weak interfacial bonding can occur, resulting in void formation and premature failure under loading conditions [11–13].

Therefore, identifying the optimal fibre-to-resin weight ratio is essential to achieve high mechanical strength, durability, and wear resistance. Among the several processing methods available for fabricating CFRP laminates, vacuum bag moulding has gained considerable recognition for producing high-quality composites. This method is relatively simple, cost-effective, and capable of generating laminates with reduced void content and improved surface finish compared to conventional hand lay-up techniques [14]. The application of vacuum pressure ensures better fibre wetting and resin infiltration, while also minimising entrapped air. Consequently, laminates manufactured through vacuum bag moulding typically display enhanced tensile, flexural, and tribological behaviour, making this process particularly suitable for experimental investigations into fibre loading effects [15].

Another important consideration is the testing and evaluation of CFRP composites. To ensure reliability and reproducibility, most mechanical and tribological assessments are conducted according to international standards such as ASTM. Tests commonly include tensile and flexural behaviour to evaluate strength and stiffness, hardness measurements to gauge surface integrity, impact tests to assess energy absorption capacity, and wear tests to understand tribological performance under sliding conditions. Together, these properties provide a comprehensive understanding of how fibre content influences the structural and functional performance of CFRPs [12]. Recent investigations have highlighted that a moderate fibre-to-resin ratio often provides the most balanced performance. At intermediate fibre contents, the composite typically shows optimum strength, toughness, and wear resistance, as the resin can fully infiltrate the fibre network while maintaining strong interfacial bonding [13]. In contrast, excessively high fibre content may lead to resin starvation and weak bonding, while too much resin can reduce the load-bearing capability of the composite. This balance becomes particularly important for real-world applications such as wind turbine blades, automotive body panels, aircraft fuselage components, and marine structures, where a combination of lightweight design and mechanical robustness is required [14, 15].

In the present study, CFRP laminates were fabricated using vacuum bag moulding with varying fibre-to-resin ratios (50:50, 55:45, 60:40, 65:35, and 70:30). The mechanical and tribological properties of these laminates were systematically evaluated using tensile, flexural, hardness, impact, and wear tests in accordance with ASTM standards. The results revealed that the 60:40 fibre-to-resin configuration exhibited superior tensile and flexural strength, modulus, hardness, impact energy absorption, and wear resistance compared to other ratios. The findings emphasise that optimisation of fibre loading plays a decisive role in enhancing CFRP performance and in developing materials that are suitable for demanding engineering applications. These insights not only expand the understanding of CFRP behaviour but also provide valuable guidance for industries seeking to design lightweight yet durable structures that meet the evolving challenges of advanced engineering.

### **Importance of Mechanical and Wear Testing**

Estimating CFRP composites mechanical and tribological characteristics under varied loading scenarios is essential to determining their suitability for demanding structural roles. Mechanical characteristics that explain a materials resistance to different stress regimes include flexural strength, tensile strength, surface hardness and impact resistance. Flexural testing assesses performance under bending forces, whereas tensile testing determines behaviour under uniaxial loading. Impact testing quantifies energy absorption under dynamic conditions, while hardness testing shows the surface integrity and resistance to localised deformation. In addition to these, wear testing techniques like the pin-on-disc test aid in measuring surface durability and material loss during frictional contact. When multi-axial loading and abrasion occur simultaneously. CFRP composites can be deployed safely and effectively thanks to this thorough characterisation [16].

### **Vacuum Bag Moulding with Epoxy Resin**

The final properties of the material are defined in large part by the manufacturing process used for composite fabrication. The ability to create superior laminates with less void content, even fibre distribution and enhanced mechanical integrity makes vacuum bag moulding stand out among the many other techniques. By using vacuum pressure on a sealed composite layup method helps to eliminate air and extra resin enhancing fibre wet-out and interfacial bonding. Because of its exceptional adhesion, thermal stability chemical resistance and epoxy resin is frequently utilised in this procedure. Vacuum bag moulding is a preferred technique in both research and medium-scale industrial applications because of the improved dimensional accuracy and structural reliability of the CFRP laminates that are produced [17–18]. CFRP composites have been the subject of substantial research but most of these studies have only examined mechanical or tribological aspects separately. Furthermore, there are not many consistent experimental investigations that assess the mechanical and wear properties of CFRP laminates made of epoxy vacuum bag moulding. By examining the tensile, flexural, hardness, impact and wear performance of CFRP composites produced using this method. This study fills this research gap. The findings should provide a comprehensive understanding of these materials structural properties, allowing for their optimal application in practical settings like high-performance mechanical parts such as automobile body panels and aircraft panels.

### **Vacuum Bag Moulding Machine**

A vacuum bag molding machine is a device used in composite manufacturing to shape and cure materials under vacuum pressure. It works by sealing composite layers within a flexible bag then removing air to compact the materials evenly. This process enhances the strength and quality of the final product. It's commonly used in aerospace, marine, and automotive industries for fabricating lightweight durable parts. The vacuum ensures uniform resin distribution and minimizes air bubbles. Machines can be manual or automated, depending on production scale. They support various resins and fiber types. Vacuum bag molding boosts precision, efficiency and structural integrity in composite fabrication. Figure 1 shows Vacuum Bag Moulding machine.



**Figure 1.** Vacuum bag moulding machine.

## MATERIALS AND METHODS

### Materials

The materials used in this study were carefully chosen to give the CFRP composites the best mechanical performance possible. The primary reinforcement was made of unidirectionally woven carbon fibre fabric, which offers directional stiffness and high tensile strength. For structural applications requiring a high load-bearing capacity this material is suitable. To start the cross-linking process during curing, an amine-based hardener was mixed with an epoxy resin system based on bisphenol-A as the matrix material. Epoxy resin was selected because of its superior mechanical qualities after curing, good thermal stability and outstanding fibre adherence. The composite lay-up and moulding process also involved the use of a flexible vacuum bagging film, peel ply, breather cloth and a chemical release agent. During the vacuum bag moulding process, these consumables are necessary to guarantee adequate resin flow gas evacuation and surface finish [5]. Figure 2 shows the carbon fibre.

Carbon fiber is a lightweight, high-strength material made from tightly bonded carbon atoms arranged in a crystalline structure. It exhibits exceptional mechanical properties, including high tensile strength, stiffness, fatigue resistance, while maintaining a low density. These characteristics make carbon fiber highly suitable for aerospace applications. In aircraft structures it is extensively used in fuselage sections, wings, tail assemblies and interior components to reduce overall weight, improve fuel efficiency and enhance performance. Its resistance to corrosion and thermal stability further contributes to increased durability and reduced maintenance requirements in aviation systems.

### Fabrication Process

The vacuum bag moulding technique, which is popular in the automotive and aerospace industries because it can create high-quality, void-free laminates without the need for an autoclave. Initially, the carbon fiber fabric was cut according to the desired lay-up dimensions and manually impregnated with the epoxy resin. Care was taken during this wet lay-up to guarantee even resin distribution and get rid of any dry areas. The assembly was put on a flat mould surface that had been treated with a chemical release agent before the necessary number of layers had been stacked. To guarantee a clean surface finish after curing a peel ply was applied over the laminate [19–21]. The entire lay-up was then sealed with a vacuum bagging film after a breather layer was added to let air and volatile compounds escape. To guarantee total vacuum integrity tacky tape was used to firmly seal the edges. A vacuum pump was then used to apply a vacuum pressure of roughly -0.8 bar to the system [22]. This vacuum allowed the laminate to cure for 24 hours at room temperature, which helped to remove air and consolidate the resin. To improve the epoxy's cross-linking and thermal characteristics a post-curing step was carried out in a controlled oven environment for two hours at 80 degrees. The laminate's resistance to thermal degradation, dimensional accuracy and mechanical stability were all enhanced by this two-step curing cycle [23–24].



**Figure 2.** Carbon fiber

### **Mechanical Testing**

The CFRP laminates were mechanically characterised in accordance with ASTM standards to guarantee reproducibility and relevance to industrial applications. To lessen experimental variability, five specimens underwent the corresponding tests, and the average value was reported. Tensile testing was carried out in compliance with ASTM D3039 using a Universal Testing Machine (UTM) equipped with a 50 kN load cell. The specimens were rectangular and had standard dimensions (250 mm × 25 mm × thickness) and hydraulic wedges were used to prevent slippage. A constant crosshead speed of 2 mm/min was maintained while strain gauges were fastened at the gauge length for accurate strain measurements. Based on the test results tensile strength, elasticity modulus and elongation at break were computed. According to ASTM D790, flexural testing was conducted using the three-point bending method. A span-to-depth ratio of 16:1 was used to test specimens with dimensions of 127 mm × 12.7 mm × thickness. A crosshead speed of 1.5 mm/min was used for the test. The maximum load and deflection information gleaned from the load-deflection curve were used to estimate the resulting flexural strength and flexural modulus.

A Shore D durometer was used to measure hardness in accordance with ASTM D2240. The average hardness of each specimen was determined after testing it five times. The surface quality and resistance to localised deformation were revealed by this test. Impact testing was conducted using the Charpy impact method according to ASTM D256. Notched specimens with standard dimensions were prepared to evaluate the impact energy absorption of the laminate. The test was conducted using a pendulum impact tester and the absorbed energy was recorded in kJ/m<sup>2</sup>, reflecting the toughness of the composite under sudden loading conditions. Wear testing was performed in as per ASTM G99 using a pin-on-disc apparatus. Cylindrical pins (Ø10 mm) were machined from the laminates and tested against hardened steel discs under dry sliding conditions.

The total sliding distance was 1000 m, the applied normal load was 20 N, the sliding speed was 1 m/s. The coefficient of friction (COF) was continuously recorded throughout the test and wear loss was computed by measuring the volume loss and calculating the specific wear rate. The suitability of the composite for tribological applications involving sliding contact and abrasive conditions was assessed with the aid of this analysis [7]. The results are applicable to structural and functional applications where high performance under combined stresses is crucial because the combination of these tests offers a thorough understanding of the composite's mechanical behaviour and durability

### **Universal Testing Machine**

A Universal Testing Machine (UTM) with a 25 kN capacity is a versatile mechanical testing device widely used in research to evaluate the mechanical behavior of materials under various loading conditions. It can perform tensile, compressive and flexural tests with high accuracy. The 25 kN load range makes it ideal for testing polymers, composites, metals and other engineering materials. The machine typically includes a load frame, grips, extensometer and digital control system for precise data acquisition. In research applications, it helps determine properties such as ultimate strength, yield strength, modulus of elasticity and elongation, which are essential for material development and validation. Figure 3: shows the Universal Testing Machine.

### **Hardness test Machine**

A hardness testing machine is an essential instrument used to measure a material's resistance to localized plastic deformation, typically through indentation. It operates by pressing a specific indenter, such as a steel ball, diamond cone, or carbide tip, into the surface of the specimen under a controlled load. Common methods include Brinell, Rockwell, and Vickers hardness tests, each suited for different materials and applications. Figure 4: Hardness test machine equipment, the machine provides precise hardness values, which are critical for evaluating material strength, wear resistance and suitability for engineering applications. It is widely used in quality control, material selection and research analysis.



**Figure 4.** Hardness test machine

## RESULTS AND DISCUSSION

### Tensile Test

The uniaxial load-carrying capacity and failure characteristics of CFRP laminates made with different fiber-to-resin ratios were examined through tensile testing. When assessing CFRP composites' suitability for structural applications like load-bearing components, automotive panels, and aerospace skins, the mechanical response under tensile loading is a crucial factor. ASTM D3039, a standard test method for determining the tensile properties of polymer matrix composites was followed in the experimental work. Bisphenol-A-based epoxy resin with an amine hardener as the matrix and unidirectional carbon fibre fabric as reinforcement were used to create five distinct sets of specimens. Five groups (50:50, 55:45, 60:40, 65:35, and 70:30) had their fiber-to-resin weight ratios systematically changed to evaluate the impact of matrix content on tensile performance. Vacuum bag moulding, a low-pressure composite processing technique that reduces voids and enhances the quality of the fiber-matrix interface, was used to fabricate all laminates. The curing cycle consisted of a 24-hour room-temperature cure under continuous vacuum pressure (0.8 bar), followed by post-curing at 80 degree for 2 hours to improve cross-linking in the epoxy system.

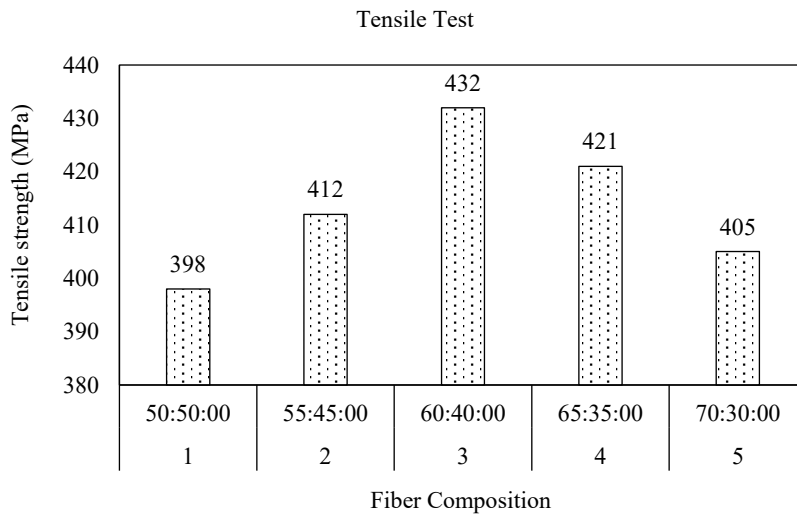
The cured laminates were cut into tensile specimens of dimensions 250 mm × 25 mm × 3 mm with a gauge length of 150 mm. The tests were executed using a UTM fitted with a 50 kN load cell and strain was measured using high-accuracy resistive strain gauges placed at the midsection of the gauge length to capture elongation with precision. The stress-strain behaviour for all five specimens displayed linear elasticity up to failure, consistent with the brittle nature of carbon fibers and stiff epoxy matrices. No yielding or plastic deformation was observed in any of the samples. The failure was typically sudden and occurred near the gauge centre, primarily through matrix cracking followed by fiber rupture. Table 1.

As shown in Table 1, the maximum tensile strength was recorded at the 60:40 fiber-resin ratio, with a value of 432 MPa. The corresponding tensile modulus was also highest at this composition measured at 39.2 GPa. This improvement is attributed to the optimal fiber alignment and the sufficient matrix phase to ensure good interfacial adhesion and load transfer. The increased stiffness and strength are due to the dominant role of the carbon fibers at this ratio, which effectively resisted deformation under axial loading. Interestingly as the fiber content increased beyond 60% (i.e., 65:35 and 70:30) a marginal decrease in tensile strength and modulus was observed. This can be attributed to insufficient resin to adequately impregnate and bind the densely packed fiber tows. As a result, interfacial bonding weakens, increasing the likelihood of micro-voids, dry spots and fiber pull-out during testing. These imperfections reduce the efficiency of load transfer between fiber and matrix, causing a drop in

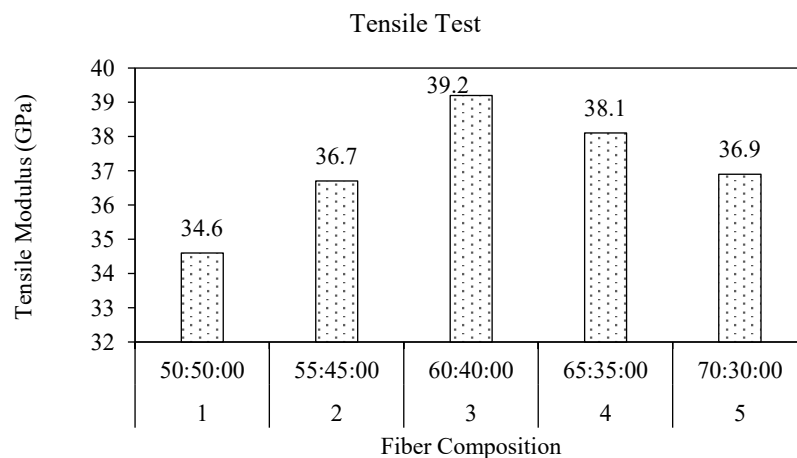
performance. Additionally, elongation at break showed a declining trend with increasing fiber content, from 1.4% in the 50:50 composition to 1.0% in the 70:30 composition. This reflects the typical stiff-but-brittle behavior of carbon-rich laminates. High resin content allows for more deformation before failure but compromises overall strength, while fiber-rich systems fail at smaller strains due to limited ductility. Figure 5 tensile strength for carbon fiber reinforced polymer composition for different fiber to epoxy ratios. Figure 6 tensile modulus for different fiber epoxy ratio and Figure 7 shows percentage of elongation for different fibre epoxy ratio.

**Table 1.** Tensile Properties of CFRP Laminates with Varying Fiber-Resin Ratios

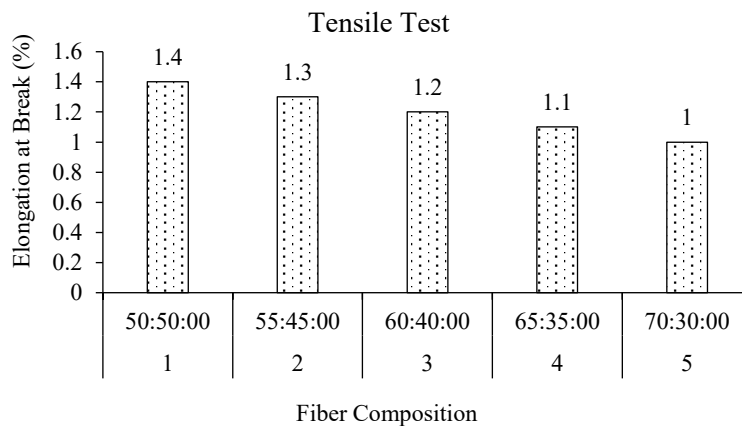
	Fiber-Resin Ratio (Percentage of weight)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)
1	50:50	398	34.6	1.4
2	55:45	412	36.7	1.3
3	60:40	432	39.2	1.2
4	65:35	421	38.1	1.1
5	70:30	405	36.9	1.0



**Figure 5.** Tensile strength for carbon fiber reinforced polymer composition.



**Figure 6.** Tensile modulus for different carbon fiber reinforced polymer composition.



**Figure 7.** Percentage of elongation for different carbon fiber reinforced polymer composition.

**Table 2.** CFRP Laminates' Flexural Characteristics with Different Fiber-Resin Ratios

Specimen No.	Fiber-Resin Ratio (wt%)	Flexural Strength (MPa)	Flexural Modulus (GPa)
1	50:50	540	38.2
2	55:45	556	39.6
3	60:40	580	42.0
4	65:35	565	40.8
5	70:30	548	39.1

### Flexural Test Result

The bending behaviour of CFRP laminates under transverse loading was assessed using flexural testing. For structural applications where components like panels, beams, and ribs are exposed to bending stresses, this test is especially pertinent. A laminate's stiffness, load-bearing capacity and interlaminar bonding quality are all indicated by its ability to withstand bending without failing.

To ensure valid bending behaviour the test specimens were cut from the same laminates used in tensile testing. They had dimensions of 127 mm × 12.7 mm × 3 mm and a span length of 64 mm. To ensure this the span-to-depth ratio was kept at 20:1.

The load was applied using a UTM at a constant crosshead speed of 1.5 mm/min and the ASTM standard equations were used to compute the flexural strength and modulus from the load-deflection data. Each group of specimens was fabricated using different fiber-to-resin weight ratios (50:50, 55:45, 60:40, 65:35, and 70:30) to investigate how variations in composite composition influence flexural response. The results demonstrated a strong dependence of bending strength and stiffness on the fiber content. As shown in Table 2, the flexural strength and modulus increased with fiber content up to a 60:40 ratio, which yielded the highest values: 580 MPa for flexural strength and 42.0 GPa flexural modulus.

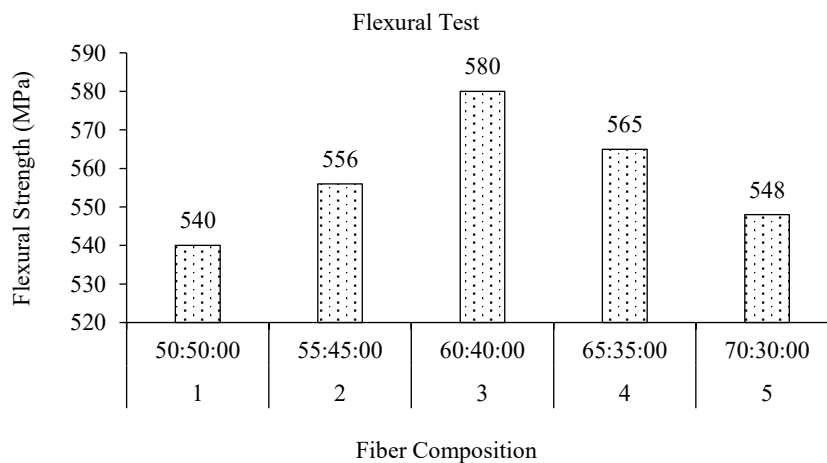
This enhancement due to the high-modulus carbon fibers, which dominate the tensile face during bending and significantly enhance the material's resistance to deformation. Additionally, the resin at this ratio provides adequate wetting and bonding maintaining a robust interfacial adhesion between fibres and matrix. The result is a laminate that efficiently distributes stress across the thickness and delays the onset of failure. However, beyond the 60:40 composition a decline in flexural performance was observed. Reduced resin content may have resulted in incomplete fibre impregnation, poor interlaminar bonding and a higher void content in the 65:35 and 70:30 specimens, which also showed lower strength and stiffness.

These flaws cause failure at lower loads by acting as stress concentrators. The composite becomes more brittle under bending due to the decrease in resin volume, which also impacts crack arresting ability. Figure 8 Flexural strength for different composition and Figure 9 Indicates the Flexural modulus for different fibre resign ratio.

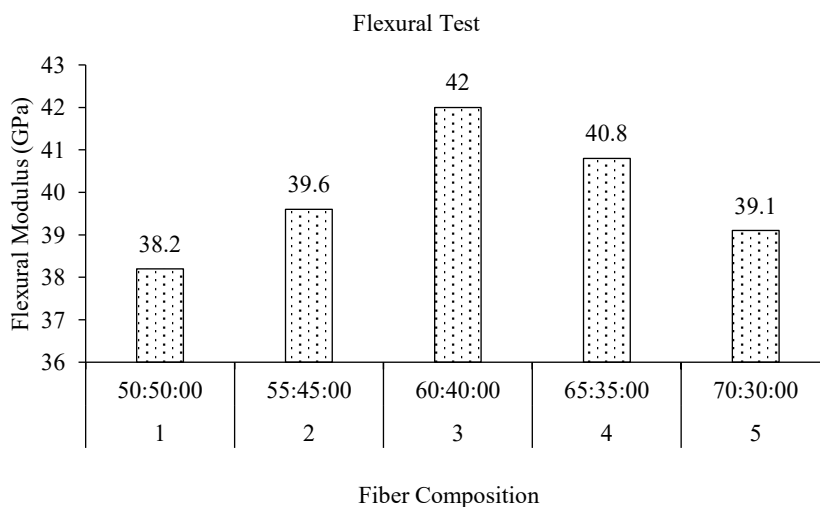
### Hardness Test Result

The Shore D hardness test, which is frequently used to gauge the hardness of hard plastics and composite materials was used to assess the surface hardness of CFRP laminates. The test gives information about how resistant the laminate is to abrasion, surface indentation and wear over time. Additionally, it serves as an indirect indicator of matrix continuity, fibre dispersion and surface integrity. The standard procedure for determining the hardness of polymer materials using durometer instruments, ASTM D2240 was followed during testing.

Five sample sets—50:50, 55:45, 60:40, 65:35 and 70:30 each representing a distinct fiber-to-resin weight ratio were analysed. To guarantee consistent readings the specimens were cut to 100 mm × 20 mm × 3 mm dimensions and all surfaces were finished flat and defect-free. Table 3 Shore D Hardness of CRPF Laminates with varying fiber-resign ratios.



**Figure 8.** Flexural strength for different carbon fiber reinforced polymer composition.



**Figure 9.** Flexural modulus for different carbon fiber reinforced polymer composition.

A calibrated Shore D durometer was used and for each specimen, three measurements were taken at separate positions on the surface. The mean value of these readings was reported for each sample. The results summarized in Table 3, showed a clear trend of increasing Shore D hardness with rising fiber content, up to a fiber-to-resin ratio of 60:40, which recorded the highest average hardness of 85 Shore D. This increase can be attributed to the inherently maximum hardness and modulus of the carbon fibers, which dominate the composite's surface at optimal reinforcement levels. Additionally, the matrix at this ratio effectively binds the fibers resulting in a compact and well-bonded structure that resists indentation. However, for the 65:35 and 70:30 compositions, a slight decrease in hardness was observed. This reduction is likely due to resin deficiency which leads to incomplete fiber impregnation, increased surface porosity and potential micro-voids. Such defects create softer regions on the surface, reducing overall hardness. These findings suggest that beyond a certain fiber loading, the matrix becomes insufficient to provide proper fiber wetting and consolidation, adversely affecting surface quality. Figure 10 Graph shows Shore D Hardness for different carbon fiber reinforced polymer composites.

### Impact Test Result

The impact strength of CFRP laminates is an essential property in structural applications, particularly where components are exposed to sudden loads, accidental strikes or dynamic environments. Unlike tensile and flexural tests, which evaluate gradual loading conditions, impact testing reveals the material's toughness and energy absorption capacity under high strain rates. The Izod impact test, as per ASTM D256 was selected to measure the notched impact resistance of the fabricated composite laminates. All specimens were prepared using the same fiber-to-resin weight ratios as in previous tests (50:50, 55:45, 60:40, 65:35, and 70:30), dimensions of 65 mm × 12.7 mm × 3 mm and single edge notch of 2.5 mm depth to ensure consistent crack initiation. Testing was carried out using an instrumented pendulum impact tester with a 5J hammer and each result was calculated in terms of absorbed energy per unit thickness (kJ/m<sup>2</sup>).

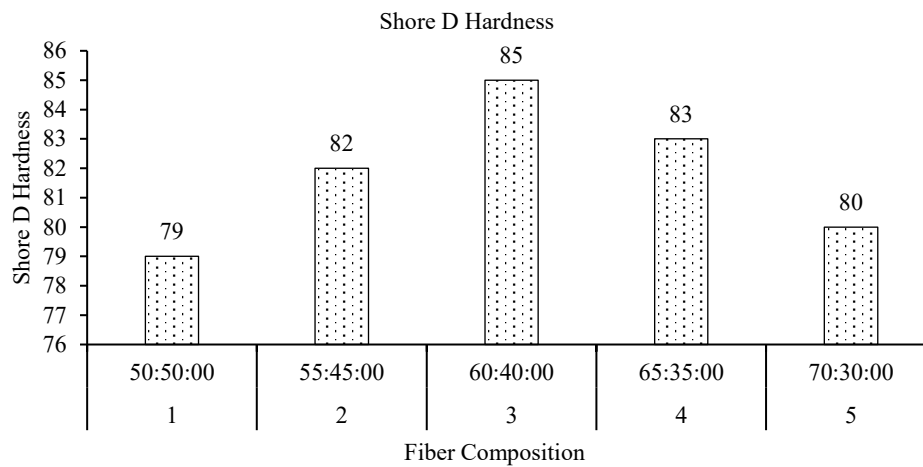
As shown in Table 4: impact energy absorption value for different fiber resin ratio values for impact energy, increased with fiber content up to a 60:40 ratio, reaching a maximum of 58 kJ/m<sup>2</sup>. This can be characterized to the efficient energy transfer and crack arresting mechanisms provided by the carbon fibers embedded in a well-bonded epoxy matrix. At this ratio, the matrix adequately wets the fiber surfaces, providing a strong interfacial bond that helps in delaying crack propagation. Beyond the 60:40 ratio, however, the impact resistance began to decline. The 65:35 and 70:30 specimens exhibited lower impact strength, likely due to incomplete resin infiltration, which can introduce voids, dry spots, and interfacial defects.

**Table 3.** Shore D hardness of CFRP Laminates with varying fiber-resin ratios.

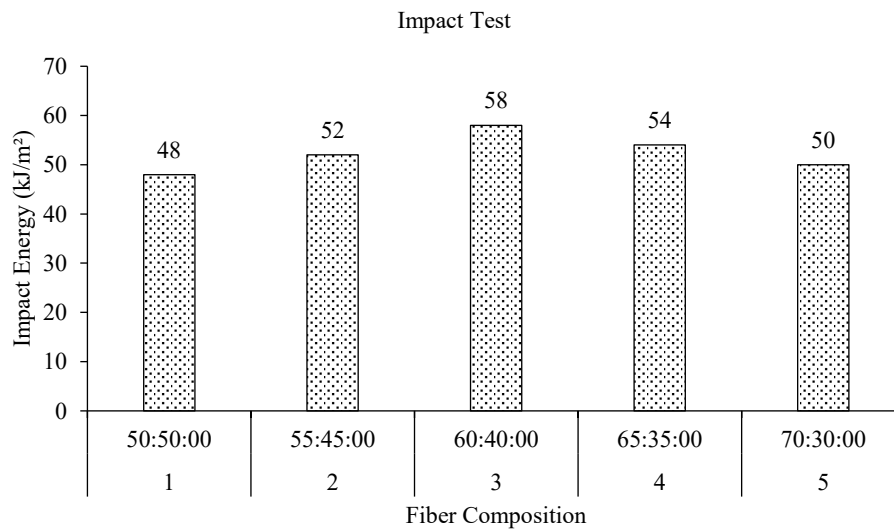
Specimen No.	Fiber-Resin Ratio (wt%)	Shore D Hardness
1	50:50	79
2	55:45	82
3	60:40	85
4	65:35	83
5	70:30	80

**Table 4.** Impact energy absorption of CFRP laminates with varying fiber:resin ratios

Specimen No.	Fiber-Resin Ratio (wt%)	Impact Energy (kJ/m <sup>2</sup> )
1	50:50	48
2	55:45	52
3	60:40	58
4	65:35	54
5	70:30	50



**Figure 10.** Shore D hardness for different carbon fiber reinforced polymer composition.



**Figure 11.** Impact energy for different carbon fiber reinforced polymer composition.

These microstructural imperfections act as initiation sites for brittle fracture under dynamic loading, reducing the material's ability to dissipate energy effectively. The decline also reflects the brittle nature of high-fiber-content composites when the matrix phase is insufficient to bridge cracks or deform plastically.

The data indicates that fiber volume fraction plays a crucial role in dynamic toughness, as it affects crack propagation, delamination resistance, and fiber pull-out mechanisms. The 60:40 composition again demonstrates the best overall mechanical synergy, where the reinforcing effect of carbon fibers is fully supported by adequate resin bonding. Impact performance is not merely a function of fiber stiffness or strength, but also of the material's ability to resist fracture initiation and absorb energy through microstructural interactions. At higher fibre loadings, insufficient resin compromises these mechanisms, leading to embrittlement shown in Figure 11.

### Wear Test Result

Wear resistance is a key factor in figuring out the durability over time and tribological performance of CFRP composites, particularly in applications involving mechanical contact, sliding motion or

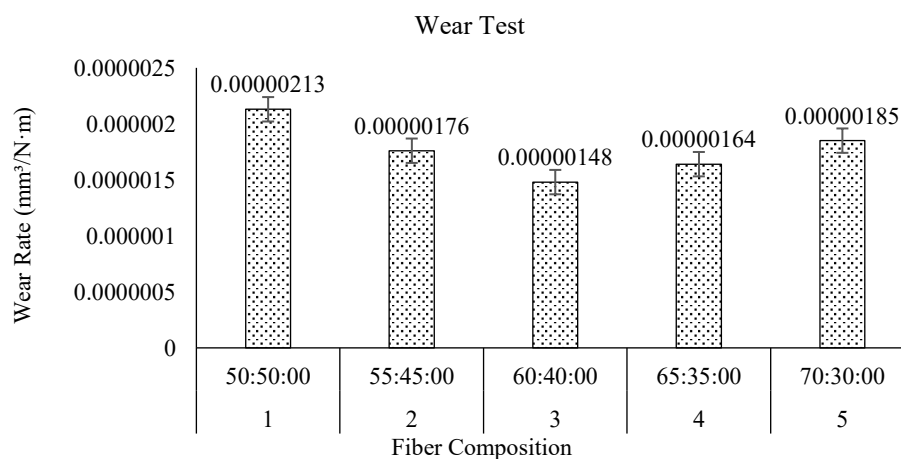
abrasive environments. To evaluate the wear characteristics of the fabricated laminates, A test for dry sliding wear was conducted using a pin-on-disc tribometer, conforming to the procedures outlined in ASTM G99. Test specimens with dimensions of 10 mm × 10 mm × 3 mm, were prepared from laminates with varying fiber-to-resin weight ratios: 50:50, 55:45, 60:40, 65:35 and 70:30. A hardened EN31 steel disc (HRC 60) was used as the counter face. Every test was carried out at room temperature with a normal load of 20 N and a sliding speed of 1.5 m/s across 1000 m.

The wear rate was calculated by measuring the volume loss (mm<sup>3</sup>) and normalized to the applied load and sliding distance, expressed in mm<sup>3</sup>/N·m. The test results (Table 5) revealed that wear resistance improved as the fiber content increased up to 60:40, where the lowermost wear rate of  $1.48 \times 10^{-5}$  mm<sup>3</sup>/N·m was recorded. This is attributed to the high hardness and strength of carbon fibers, which dominate the contact surface and limit material removal. The matrix phase at this composition effectively binds the fibers, forming a tough and compact surface layer that resists abrasion and micro-fracture during sliding. Table 5: Wear rate of CFRP Laminates with varying fiber resin ratio However, with further increase in fiber content (65:35 and 70:30), the wear rate increased. This reversal is primarily due to insufficient resin, which leads to exposed or weakly bonded fibers, higher surface roughness, and interfacial voids that act as initiation points for micro-cracking and fiber pull-out. These mechanisms accelerate material loss during sliding, reducing wear resistance. Thus, beyond 60% fiber content the structural compactness and cohesive strength of the laminate are compromised.

The results confirm that the 60:40 fiber-to-resin ratio is optimal for minimizing wear in carbon/epoxy composites under dry sliding conditions. At this composition, the material offers a well-bonded microstructure with minimal voids, enabling superior surface protection against friction-induced damage. The increased wear rate at higher fiber contents reflects the limitations of excessive reinforcement without adequate matrix coverage. Poor resin saturation can result in fiber fracture, detachment, and increased debris formation factors that collectively accelerate wear. Figure 12: Shows graph for wear rate for different fibre -resin composition.

**Table 5.** Wear Rate of CFRP Laminates with Varying Fiber: Resin Ratios

Specimen No.	Fiber-Resin Ratio (wt%)	Wear Rate (mm <sup>3</sup> /N·m)
1	50:50	$2.13 \times 10^{-5}$
2	55:45	$1.76 \times 10^{-5}$
3	60:40	$1.48 \times 10^{-5}$
4	65:35	$1.64 \times 10^{-5}$
5	70:30	$1.85 \times 10^{-5}$



**Figure 12.** Wear rate for different carbon fiber reinforced polymer composition.

## CONCLUSION

The mechanical and surface characterisation of carbon fibre reinforced polymer (CFRP) laminates made with vacuum bag moulding and varied fiber-to-resin weight ratios were the main objectives of this experimental study. The study systematically evaluated tensile, flexural, hardness, impact, and wear properties to determine the optimal fiber loading for enhanced performance. Based on the results obtained through standardized testing procedures. The 60:40 fiber-to-resin ratio delivered the highest tensile strength (432 MPa) and tensile modulus (39.2 GPa), reflecting efficient load transfer and strong fiber-matrix interaction. Maximum flexural strength (580 MPa) and modulus (42.0 GPa) were observed at the same 60:40 composition, indicating superior resistance to bending and rigidity. Shore D hardness peaked at 85 units for the 60:40 laminate, signifying a well-compacted surface with high resistance to indentation and surface degradation. The Izod impact strength reached a maximum of 58 kJ/m<sup>2</sup> at the 60:40 ratio, suggesting optimal energy absorption under dynamic loading. Minimum wear rate of  $1.48 \times 10^{-5}$  mm<sup>3</sup>/N·m was recorded for the 60:40 laminate, confirming enhanced abrasion resistance due to compact structure and strong bonding. Specimens with fiber content above 60% showed a decline in all tested properties, attributed to resin starvation, dry zones, and poor fiber wetting. Overall, the 60:40 composition was found to provide the best balance of mechanical strength, surface hardness, impact toughness, and wear durability, making it the most suitable ratio for structural applications involving carbon/epoxy composites.

## REFERENCES

1. Mao L, Jiao Y, Geng H, Tang Y. Understanding friction and wear properties of carbon fiber/epoxy stitched composites. *Compos Part A Appl Sci Manuf.* 2023;169:107501. doi:10.1016/j.compositesa.2023.107501
2. B A Praveena, Balachandra P Shetty, A S Akshay, B Kalyan (2020). Experimental study on mechanical properties of pineapple and banana leaf fiber reinforced hybrid composites. *AIP conference proceedings*, Vol. 2274, Issue. 1, pp. 1–8. DOI: doi.org/10.1063/5.0022381
3. Grisin B, Carosella S, Middendorf P. Vacuum Chamber Infusion for fiber-reinforced composites. *Polymers (Basel).* 2024;16(19):2763. doi:10.3390/polym16192763
4. Praveena B A, Balachandra P Shetty, Shiv Pratap Singh Yadav (2020). Physical and mechanical properties, morphological behaviour of pineapple leaf fibre reinforced polyester resin composites. *Advances in Materials and Processing Technologies*, Vol. 8, Issue. 1, pp. 1147–1159. DOI: doi.org/10.1080/2374068X.2020.1853498
5. Boursier Niuitta C, Ciardiello R, Tridello A, Paolino DS. Epoxy and bio-based epoxy carbon fiber twill composites: comparison of the quasi-static properties. *Materials (Basel).* 2023;16(4):1601. doi:10.3390/ma16041601
6. Praveena B A, Balachandra P Shetty, Vinayaka N, Srikanth H V, Shiv Pratap Singh yadav, Avinash L (2020). Mechanical properties and water absorption behaviour of pineapple leaf fibre reinforced polymer composites. *Advances in Materials and Processing Technologies*, Vol. 8, Issue. 2, pp. 1336–1351. DOI: doi.org/10.1080/2374068X.2020.1860354
7. Sun Z, Li X, Zhang X, Wang J, Xu H, Guo J, et al. Tribological properties of carbon fiber/epoxy composites filled with functionalized graphit, *Polymers (Basel).* 2022;14(18):3716. doi:10.3390/polym14183716
8. Praveena B A, Vijay Kumar S, Manjunath H N, Sachin B, Shiv Pratap Singh yadav, B Rakshith lochan, Arun Kumar G L, Sudheer Reddy J (2021). Investigation of Moisture Absorption and Mechanical Properties of Natural Fibre Reinforced Polymer Hybrid Composite. *Materials Today: Proceedings*, Vol. 45, Issue. 9, pp. 8219-8223. DOI: doi.org/10.1016/j.matpr.2021.04.254
9. Li S, Wang K, Zhang Q, Chen H, Liu J. Effect of vacuum-assisted resin infusion parameters on voids and mechanical properties of CFRP laminates. *Compos Struct.* 2022;289:115476. doi:10.1016/j.compstruct.2022.115476
10. B A Praveena, Abdulrajak Buradi, N Santhosh, Vikram Kedambadi Vasu, Jaibheem Hatgundi, D Huliya (2021). Study on characterization of mechanical, thermal properties, machinability and biodegradability of natural fiber reinforced polymer composites and its Applications, recent

- developments and future potentials: A comprehensive review. *Materials Today: Proceedings*, Vol. 52, Issue. 3, pp. 1255-1259. DOI: doi.org/10.1016/j.matpr.2021.11.049
11. Rans C, de Rooij MB, Schipper DJ. Wear mechanisms in carbon/epoxy composites under dry sliding. *Wear*. 2021;477–478:203894. doi:10.1016/j.wear.2021.203894
  12. N Santhosh, BA Praveena, HV Srikanth, Santosh Angadi, 1st Amaresh Gunge, M Rudra Naik, G Shankar, K Ramesha, G Ravichandran (2022). Experimental Investigations on Static, Dynamic, and Morphological Characteristics of Bamboo Fiber-Reinforced Polyester Composites. *International Journal of Polymer Science*, Vol. 2022, Issue. 1, pp. 1916-1922. DOI: doi.org/10.1155/2022/1916877
  13. Zhao Y, Xu L, Liu C, He X, Wang S. Influence of consolidation pressure in out-of-autoclave vacuum bagged CFRP laminates on porosity and mechanical properties. *Mater Des*. 2020;193:108791. doi:10.1016/j.matdes.2020.108791
  14. BA Praveena, N Santhosh, DP Archana, Abdulrajak Buradi, E Fantin Irudaya Raj, C Chanakyan, Ashraf Elfasakhany, Dadapeer Basheer (2022). Influence of Nanoclay Filler Material on the Tensile, Flexural, Impact, and Morphological Characteristics of Jute/E-Glass Fiber-Reinforced Polyester-Based Hybrid Composites: Experimental, Modeling, and Optimization Study. *Journal of Nanomaterials*, Vol. 2022, Issue. 1, pp. 1–17. DOI: doi.org/10.1155/2022/1653449
  15. Wang H, Zhou Y, Li J, Chen X, Xu P. Double-vacuum-bag processing of carbon fiber/epoxy laminates: parameter optimization and void reduction. *Adv Eng Mater*. 2025;27(6):e2202136. doi:10.1002/adem.202402136
  16. B A Praveena, N Santhosh, Abdulrajak Buradi, HV Srikanth, G Shankar, K Ramesha, N Manjunath, SN Karthik, M Rudra Naik, S Praveen Kumar (2022). Experimental Investigation on Density and Volume Fraction of Void, and Mechanical Characteristics of Areca Nut Leaf Sheath Fiber-Reinforced Polymer Composites. *International Journal of Polymer Science*, Vol. 2022, Issue. 1, pp. 1-23. DOI: doi.org/10.1155/2022/6445022
  17. M. Sussmann, M. Amirhosravi, M. Pishvar, and M. C. Altan, “Fabrication of high quality, large wet lay-up/vacuum bag laminates by sliding a magnetic tool,” *Polymers* 10( 9), 992 (2018). <https://doi.org/10.3390/polym10090992> MDPI
  18. Praveen Bindiganavile Anand, Avinash Lakshmikanthan, Manjunath Patel Gowdru Chandrashekarappa, Chithirai Pon Selvan, Danil Yurievich Pimenov, Khaled Giasin (2022). Experimental Investigation of Effect of Fiber Length on Mechanical, Wear and Morphological Behavior of Silane Treated Pineapple Leaf Fiber Reinforced Polymer Composites. *Fibers*, Vol. 10, Issue. 7, DOI: doi.org/10.3390/fib10070056
  19. K. Abdurrohman et al., “A comparison of vacuum infusion, vacuum bagging, and hand lay-up for composite manufacturing,” *Indonesian Journal of Aerospace* 21, 25–38 (2023). (DOI not available; cite based on journal conventions) Ejournal Portal
  20. Santhosh N, Praveena Bindiganavile Anand, Rudra Naik Mahadeva Naik, Shankar Gunashekarana (2022). Effect of Aging on the Biopolymer Composites: Mechanisms, Modes and Characterization. *Polymer Composites*, Vol. 43, Issue. 7, DOI: doi.org/10.1002/pc.26708
  21. BA Praveena, N Santhosh, DP Archana, Abdulrajak Buradi, E Fantin Irudaya Raj, C Chanakyan, Ashraf Elfasakhany, Dadapeer Basheer (2022). Influence of nanoclay filler material on the tensile, flexural, impact, and morphological characteristics of jute/E-glass fiber-reinforced polyester-based hybrid composites: experimental, modeling, and optimization study. *Journal of Nanomaterials*, Vol. 2022, Issue. 1, DOI: doi.org/10.1155/2022/1653449
  22. J Nagendra, MK Srinath, G Shaikshavali, C Labesh Kumar, Din Bandhu, Praveena Bindiganavile Anand, Santhosh Nagaraja, Ashish Saxena (2023). Evaluation of surface roughness of novel Al-based MMCs using Box-Cox transformation. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, Vol. 18, Issue. 2, pp. 3369–3382. DOI: doi.org/10.1007/s12008-023-01561-9
  23. Muhammad Imam Ammarullah Praveena Bindiganavile Anand, Santhosh Nagaraja, Nagendra Jayaram, Shashank Paidi Sreenivasa, Naif Almakayeel, T. M. Yunus Khan, Raman Kumar, Raman Kumar (2023). Kenaf Fiber and Hemp Fiber Multi-Walled Carbon Nanotube Filler-Reinforced

- Epoxy-Based Hybrid Composites for Biomedical Applications: Morphological and Mechanical Characterization. *Journal of Composites Science*, Vol. 7, Issue. 8, pp. 1–12. DOI: [doi.org/10.3390/jcs7080324](https://doi.org/10.3390/jcs7080324)
24. Muhammad Imam Ammarullah Santosh nagaraja, Praveena Bindiganavile Anand, Mohan Kumar K (2024). Synergistic advances in natural fibre composites: a comprehensive review of the eco-friendly bio composite development, its characterization and diverse applications. *RAC Advances*, Vol. 17594, Issue. 14, pp. 17594-17611. DOI: [10.1039/D4RA00149D](https://doi.org/10.1039/D4RA00149D)