

Experimental Analysis of Mechanical Properties of Carbon Fiber Composite with Nanoparticle Integration

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ABSTRACT

This thesis investigates the mechanical properties of composite materials with varying fiber orientations and nanoparticle compositions. Tensile tests reveal distinct mechanical properties: the unidirectional (0-degree) composite demonstrates the highest strength (657.41 MPa), stiffness (32.39 GPa), and ductility (5.437% strain), while the 90-degree composite exhibits lower strength (437.95 MPa) and stiffness (19.25 GPa) but higher ductility (4.847% strain). The 45-degree composite falls between the other two in terms of mechanical properties. Three-point flexural tests show similar trends, with the unidirectional (0-degree) composite displaying the highest strength (589.09 MPa) and stiffness. Charpy impact tests confirm the superior impact strength of the 0-degree composite, with an average impact strength of 13.51 J/cm² and a maximum of 14.1287 J/cm² for the 0-degree-1 sample, while the 90-degree composite exhibits the lowest average impact strength of 7.27 J/cm². Overall, this study provides valuable insights into composite material properties for specific applications.

Keywords: Carbon Fiber, Unidirectional, Nanoparticle, Orientation, Composite



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1. Introduction

1.1. General Introduction

A composite material is a substance created by combining two or more distinct materials, each possessing its own unique properties, to produce a new material with characteristics different from those of its individual components. The primary objective of composite materials is to harness the strengths of each constituent material while reducing their individual weaknesses, thereby achieving superior overall performance [1].

Various types of composites exist, each categorized based on the type of matrix and reinforcement materials employed. According to matrix: Polymer Matrix Composites (PMCs) represent one of the most common types of composites. These materials comprise a polymer matrix reinforced with fibers or particulate fillers. Metal Matrix Composites (MMCs) feature a metal matrix reinforced with ceramic, metal, or carbon fibers. The metal matrix is composed of aluminum, magnesium, or titanium, provides the base material in which the reinforcement fibers are distributed. Ceramic Matrix Composites (CMCs) consist of a ceramic matrix reinforced with ceramic fibers or whiskers. Natural Fiber Composites utilize renewable and biodegradable fibers such as bamboo, hemp, or flax embedded in a polymer matrix. [1]

According to types of reinforcement: Fiber-Reinforced Composites consist of fibers embedded in a matrix material, typically a polymer, metal, or ceramic. Particle-Reinforced Composites incorporate particles, often of a different material than the matrix, dispersed throughout the matrix material. Whisker-Reinforced Composites are single-crystal fibers typically used as reinforcement in composites to improve strength and stiffness. Layered or Laminate Composites consist of multiple layers of different materials

stacked together. Hybrid Composites combine two or more types of reinforcements within the same matrix material. Hybrid composites can offer synergistic effects, combining the advantages of each reinforcement type to achieve superior properties [2].

1.2. Carbon Fiber Composite

Renowned for their exceptional strength-to-weight ratio and adaptability across industries, carbon fiber composites have revolutionized the way people design and manufacture various structural components. Carbon fiber composites owe their remarkable properties to the unique structure of carbon fibers, which are typically derived from precursor materials such as polyacrylonitrile (PAN), pitch, or rayon through processes like carbonization and graphitization [3]. Carbon fibers can be categorized based on their orientation within composite materials.

a. Unidirectional carbon fibers are aligned in a single direction, providing exceptional tensile strength and stiffness along the fiber axis. This orientation is advantageous in applications where directional strength is crucial, such as aerospace components and sporting goods.

b. Woven carbon fibers feature interlaced bundles arranged in patterns like plain weave or twill weave, offering improved mechanical properties in multiple directions. Woven fibers are commonly utilized in automotive and marine industries for components requiring isotropic properties, including body panels and boat hulls.

c. Chopped carbon fibers are randomly dispersed within the matrix material which provide isotropic mechanical properties suitable for various applications such as fillers in automotive body panels and construction materials [3].

1.3. Nanoparticle

Titanium dioxide nanoparticles act as effective reinforcements within materials matrices due to their high aspect ratio, large surface area, and strong interfacial interactions with the host material. These nanoparticles can distribute loads more efficiently and impede the propagation of cracks, leading to enhanced mechanical performance. Incorporating TiO₂ nanoparticles into polymers, metals, or ceramics can significantly increase their tensile strength, modulus of elasticity, and hardness.

This study is focused on the analysis of the mechanical properties of carbon fiber composites embed by titanium dioxide nanoparticles. The mechanical properties will be examined with different orientation of the carbon fiber composite layer, keeping the percentage of the nanoparticle constant.

2. Literature Review

The application of carbon fibers (CFs) composites has continuously risen during the last decade, especially in car and aerospace industry, due to the improvement in the electrical conductivity and mechanical stiffness. CFs possess exceptional specific strength and stiffness, and hence they find important applications in structural composites. The performance of such composites depends on the properties of the fibers due to the manufacturing process and the surrounding matrix and also on the interface between them [5][6]. Li Zhenhua examined the effect of titanium dioxide (TiO₂) dispersion on the tribological properties of carbon fiber reinforced-polyimide matrix composites. The incorporation of TiO₂ leads to a significant improvement in friction and wear properties of the CF/PI composite [7]. Chang Hyo Kim et al. investigated the photocatalytic degradation ability of Graphene/Carbon Composite Nanofibers (CCNFs) with attached TiO₂ nanoparticles (TiO₂-CCNF) under visible light irradiation. Results indicated that the presence of graphene in the composite fibers prevented TiO₂ particle agglomeration and facilitated uniform dispersion of TiO₂ on the fibers [8]. Mr. Shiva Chandan Reddy Modugu et al. compare the properties of CFRPs with varying concentrations of nanomaterials, specifically 0%, 0.5%, 1%, and 2% by weight. Results revealed a notable increase in properties with the incorporation of nanomaterials, particularly at the 2% weight concentration [9]. Basim A Abass et al. investigated the development of a hybrid epoxy composite reinforced with unidirectional carbon, glass fibers, and nano-TiO₂ powder to assess its mechanical properties. Tensile strengths of the composites increased with fiber content and TiO₂ nanoparticles up to 3 wt%, with a subsequent decrease observed beyond this threshold. Modulus of elasticity, tension resistance, and hardness exhibited an upward trend with increasing fiber loading [10]. B.R. Lokesh Yadhav et al. investigated the use of titanium dioxide (TiO₂) nanoparticles as nanofillers to enhance the properties of plain weave bidirectional carbon fabric reinforced epoxy (CE) composites. Test specimens were prepared using a hand lay-up stacking method followed by hot pressing according to ASTM standards. Mechanical properties, including flexural strength, modulus, and impact energy absorption, were evaluated through three-point bend and Izod impact tests. Results showed a significant 35% improvement in impact energy of the epoxy material when combined with carbon fabric and nano-TiO₂. Flexural strength increased with nano-TiO₂ addition, even at low loading levels (up to 1 wt%)

[11]. Kui Mao et al. synthesized Chitin-modified TiO₂ on carbon fibers via a hydrothermal method to enhance the catalyst properties of TiO₂ under visible light irradiation. Results showed that the synergetic effect of TiO₂ crystal phase, carbon fiber, and chitin improved the photocatalytic activity. The sample with 0.6 wt% chitin exhibited the highest activity, degrading RhB under visible light about 2.25 times faster than pure TiO₂/carbon fiber [12]. Leonardo Yuan et al. presented a method for preparing titanium dioxide particle-coated carbon fibers via reaction spinning. This resulted in the formation of a titanium hydroxide layer on the PAN fiber surface, which decomposed during heat treatment to yield titanium dioxide nanoparticles [13]. Hao Cheng et al. synthesized TiO₂ powder and carbon fiber separately, then combined to form TiO₂/carbon fiber composites. The composite with a TiO₂ to carbon fiber ratio of 2:1 exhibited the highest degradation rate of 97.7% in 120 minutes. Even after 5 uses, the composite maintained high activity [14].

3. Materials and Methodology

3.1. Description of Materials

In this experiment analysis, unidirectional carbon fiber, titanium dioxide nanoparticles, epoxy resin and hardener were used to prepare the samples. Hand lay-up method was used to produce the samples. Unidirectional carbon fiber refers to a type of carbon fiber where the individual carbon filaments are predominantly aligned along a single direction within the composite structure. Titanium dioxide is a molecule comprising one titanium atom and two oxygen atoms. It is famous for ultrafine titanium dioxide (TiO₂) particles, nano-crystalline titanium dioxide, or microcrystalline titanium dioxide. Epoxy resin plays a crucial role in composite materials, where it acts as the matrix that holds together the reinforcing fibers. Paraffin wax is commonly used as a releasing agent due to its low cost, ease of application, and effectiveness in preventing adhesion between the composite material and the mold surface.

3.2 Fabrication Process

The whole fabrication process can be divided into sub-groups as mold preparation, fiber mat sizing, sonication of measured epoxy and nanoparticle mixture, hand lay-up technique.

Mold Preparation:

Typically, a glass frame is utilized during the lay-up process to create composite materials. However, it has some drawbacks, such as the need for supplementary load systems, multiform load distribution and restricted load bearing capacity. Therefore, I made the decision to employ a 20 kg of bricks over a flat rectangle of glass as the basis and a similarly weighted flat structure to press the fiber uniformly in order to prevent the usage of additional load systems. The mixture of fibers and epoxy resin between two unyielding stones functioned like a sandwich.



Figure 1: Mold

Fiber Mat Sizing:

Determining the dimensions of the composite before the lay-up process is indeed crucial for ensuring that the final product meets the required specifications. Here's a breakdown of the steps that have been followed:

1. **Plate Size Determination:** The dimensions of the composite plate are decided based on the requirements. In this case, a 26 cm by 26 cm plate size is chosen for mechanical property testing and 100 cm diameter plate size is chosen for thermal conductivity testing.

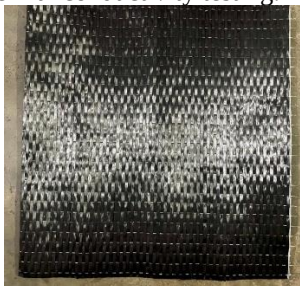


Figure 2: Carbon fiber mat cut into required size

2. **Cutting Fibers:** Unidirectional carbon fiber is cut into the same shape to match the plate size having 0-degree, 45-degree and 90-degree orientation. This ensures uniformity in the composite material.

3. **Preventing Edge Damage:** To prevent damage to the edges of the fibers during cutting, masking tape and a permanent marker are used. Masking tape can be applied along the edges of the fiber mat to provide stability and prevent fraying. The permanent marker is used to mark the cutting lines accurately.

4. **Precision Cutting:** Using the marked lines as a guide, the fibers are carefully cut to the desired size using appropriate cutting tools such as scissors. It's important to ensure precision during this step to maintain consistency in the dimensions of the fibers.

5. **Lay-up Process:** Once all the fibers are cut to size, they are arranged in layers according to the desired fiber orientation and material combination. This lay-up process is critical for determining the final properties and performance of the composite plate.

Sonication of epoxy resin and titanium dioxide nanoparticles:

1. **Preparation of Epoxy Resin and Titanium Dioxide Nanoparticles:** It was ensured that the resin is free from any contaminants before adding the nanoparticles. Depending on the 6 layers of the carbon fiber and 1% titanium dioxide nanoparticles, 180 gm epoxy resin was measured. For thermal conductivity, epoxy resin was measured 90 gm individually for 1%, 2% and 3% titanium dioxide nanoparticles with 8 layers of carbon fiber.

2. **Sonication:** Sonication involves the use of high-frequency sound waves to agitate the mixture, breaking apart any clusters of nanoparticles and dispersing them uniformly throughout the resin. The epoxy resin and titanium dioxide nanoparticles were combined in a suitable container.

4. **Sonication Setup:** The probe sonicator is placed in the container containing the resin and nanoparticles. The sonicator emits ultrasonic waves into the mixture, creating cavitation bubbles that implode, generating intense localized agitation.

5. **Duration and Intensity:** The duration and intensity of sonication depend on various factors such as the volume of the mixture, the concentration of nanoparticles and the desired level of dispersion. For all the samples, sonication was carried out for 5 minutes.

6. **Monitoring:** Throughout the sonication process, the dispersion of nanoparticles within the resin was monitored visually. The mixture appeared uniform with no visible sedimentation.

7. **Hardener mixing:** After sonication, the containers were placed at room temperature for proper cooling. Hardener was measured individually of 60 gm for 25 cm by 25 cm samples and 30 gm for 100 cm diameter thermal conductivity testing samples. Then those were added to the epoxy resin and titanium dioxide nanoparticles mixture beforehand lay-up.



Figure 3: Sonication Process

Hand Lay-up Technique:

In order to prevent any movement, transparent polythene was first placed on the glass mold. It was secured to the block with masking tape. Then a hand roller was used to evenly disperse the resin-hardener mixture that had been placed onto the polythene. Making ensuring that all of the fibers were saturated with resin and that there were no dry spots was of utmost importance. The entire composite was covered in polythene to prevent air from passing through once all layers had been saturated with resin. Thus, the possibility of void fraction was eliminated [15].

3.3. Specimen Variation

Specimen variation in composites refers to the inherent differences observed among individual samples or specimens made from composite materials.

Table 1 Specimen Variation of Unidirectional Carbon Fiber

Sample	Fiber Orientation
0-degree-1%-TiO ₂	First Layer - 0°
	Second Layer - 0°
	Third Layer - 0°
	Fourth Layer - 0°
	Fifth Layer - 0°
	Sixth Layer - 0°
45-degree-1%-TiO ₂	First Layer - 0°
	Second Layer - 90°
	Third Layer - 45°
	Fourth Layer - 45°
	Fifth Layer - 90°
	Sixth Layer - 0°
90-degree-1%-TiO ₂	First Layer - 0°
	Second Layer - 90°
	Third Layer - 0°
	Fourth Layer - 90°
	Fifth Layer - 0°
	Sixth Layer - 90°

3.4. Volume Fraction Calculation

In this work, the volume fraction is calculated using a theoretical approach of density method.

The carbon fiber mat was 26cm×26cm

Area, $A = 26 \times 26 \times 10^{-4} = 0.0676 \text{ m}^2$

$m = 29.2032 \text{ gm}$

Carbon fiber density, $\rho = 1800 \text{K kg/m}^3$

Epoxy density, $\rho = 1100 \text{K kg/m}^3$

So, weight of the single fiber = $29.2032 \times 10^{-3} \times 9.81 = 0.285 \text{ N}$

Weight of the total fiber (6 layers) = $0.285 \times 6 = 1.71 \text{ N}$

Plate weight of the composite = $462.28 \text{ gm} \times 10^{-3} \times 9.81 = 4.535 \text{ N}$

Weight of the resin = Plate weight of the composite - Weight of the total fiber = $4.535 \text{ N} - 1.71 \text{ N} = 2.825 \text{ N}$

Now, for carbon fiber to resin volume,

$$\frac{V_{\text{carbon_fiber}}}{V_{\text{resin}}} = \frac{W_{\text{carbon_fiber}}}{W_{\text{resin}}} \times \frac{\rho_{\text{resin}}}{\rho_{\text{carbon_fiber}}}$$

$$= \frac{1.71}{2.825} \times \frac{1100}{1800}$$

$$= 0.3699$$

$V_{\text{carbon_fiber}} = 0.3699 \times V_{\text{resin}}$

$V_{\text{carbon_fiber}} + V_{\text{resin}} = 0.3699 \times V_{\text{resin}} + V_{\text{resin}} [V_{\text{carbon_fiber}} + V_{\text{resin}} = 1]$

$$V_{\text{resin}} = \frac{1}{1 + 0.3699}$$

$$= 0.7299 = 73\%$$

So, volume fraction of carbon fiber is = $(100 - 73) = 27\%$

This is applicable to all the prepared samples.

4. Experimental Procedure

4.1.1. Tensile Test

According to standard for composite material tensile test ASTM D3039 [16] was followed and test with 4 specimens for each sample. The test was done in an Advanced Universal Testing Machine (UTM) in Department of Mechanical Engineering, KUET. According to ASTM D3039, tensile test specimen of size 200mm×13mm was prepared.

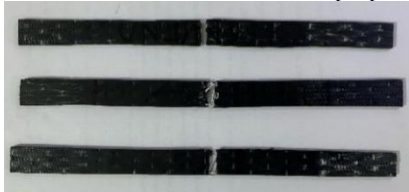


Figure 4: Tensile specimen after test

4.1.2. Flexural Strength Test

For the flexural test specimen were set up according to the ASTM D790 [17] standards. Each specimen was 54 mm by 13 mm. The test was carried out in the UTM in mechanics lab, Department of Mechanical Engineering, KUET. The test was completed by three-point bending method.

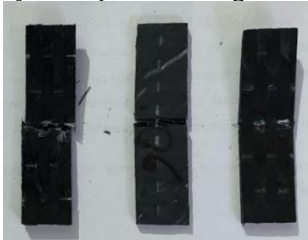


Figure 5: Schematic size flexural specimen after test

4.1.3. Impact Strength Test

For, impact test ASTM A370 was followed. To evaluate the impact strength 2 specimen of per sample was tested and then average the value to get appropriate impact strength. The pendulum weight of Charpy impact tester was 20 kg. The

specimen size is 123 mm by 14 mm with 45-degree notch having 2 mm depth.



Figure 6: Schematic size Impact specimen after test

5. Results and Discussions

5.1. Tensile test

The tensile test is performed over three sample of each composite. A cross head speed of 5mm/ min of stroke was used to test the whole specimen while testing on UTM. Thus, the Load vs Displacement in figure and Stress vs Strain curve in figure 7 is plotted below from obtained testing data.

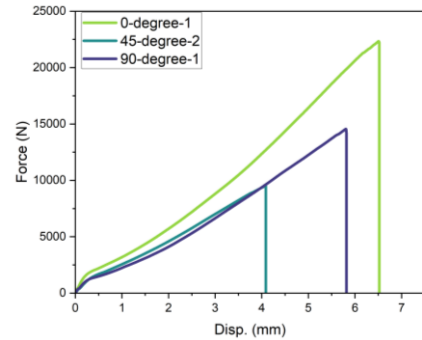


Figure 7: Tensile test Force vs Displacement curve
With a maximum load of 22331.71 N, the unidirectional(0-degree-1) composite sample easily outperforms the other two samples (the 90-degree-1 composite sample has a maximum load of 14554.21 N and the 45-degree-2 sample reaches its limit at a lower value of 9617.15 N). This data shows that the unidirectional(0-degree-1) composite outperforms the other two samples in terms of strength. Finally, unidirectional(0-degree-1) composite sample has displacement of 6.524mm. As a result, it can be concluded that the 45-degree-2 sample composite is the stiffest of the three.

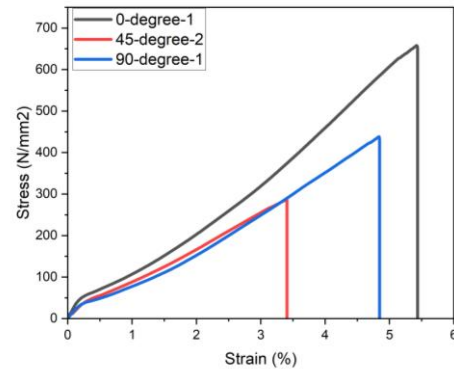


Figure 8: Tensile test Stress vs Strain curve
According to the stress vs strain curve it is cleared that the maximum stress value for the unidirectional(0-degree-1) composite sample (657.41 MPa) is the highest among the three samples. The strain value for the unidirectional(0-degree-1) composite sample (5.437%) is the highest among the three samples, followed by the 90-degree-1 composite sample (4.847%) and then the 45-degree-2 sample (3.408%). This indicates that the unidirectional(0-degree-1) composite is the most ductile among the three samples.

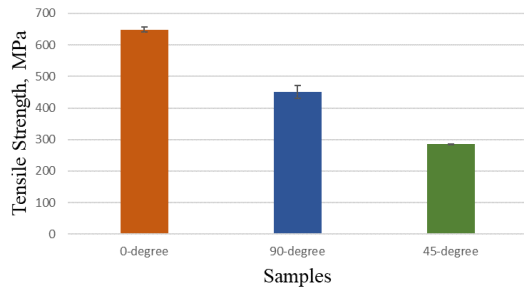


Figure 9: Tensile strength value comparisons of specimens. Based on the bar chart data, it is clear that the three different orientated composite (0-degree, 45-degree and 90-degree) have significantly different mechanical properties. In terms of strength, the unidirectional(0-degree) composite has the highest strength of 648.34 MPa, followed by the 90-degree composite at 450.75 MPa and then the 45-degree composite at 285.5 MPa. This indicates that the unidirectional(0-degree) composite shows the strongest material properties of the three while the 45-degree composite is the weakest.

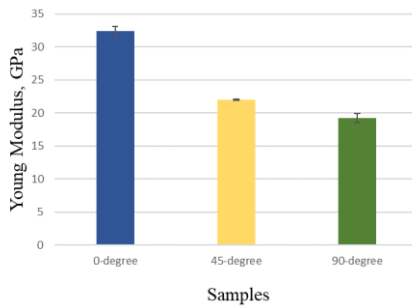


Figure 10: Young modulus value comparisons of tensile test specimens

In terms of stiffness, the unidirectional(0-degree) composite also has the highest tensile Young's modulus of 32.39GPa, followed by the 45-degree at 22.02GPa and then the 90-degree composite at 19.25GPa. This indicates that the unidirectional(0-degree) is the stiffest of the three while the 90-degree composite is the most flexible.

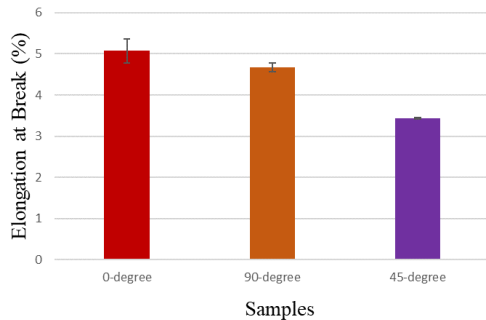


Figure 11: Elongation break value comparisons of tensile test specimens

In terms of elongation, the unidirectional(0-degree) composite has the high strain of 5.07 followed by the 90-degree composite's strain 4.67 and then 45-degree composite strain is 3.43. In the case of a carbon fiber composite, the material properties can be influenced by orientation which includes the strain at break. When fibers are oriented at 90 degrees to the direction of loading, they are effectively resisting the applied load in that direction. This orientation maximizes the stiffness and strength of the composite in that particular direction. On the other hand, fibers oriented at 45 degrees to the loading direction provide some resistance to the applied load but not as much as fibers oriented at 90 degrees. So, 90-degree oriented fibers are stiffer and more

brittle than 45-degree oriented fibers, which means they are more prone to fracture under tensile loading.

5.2. Bending Test

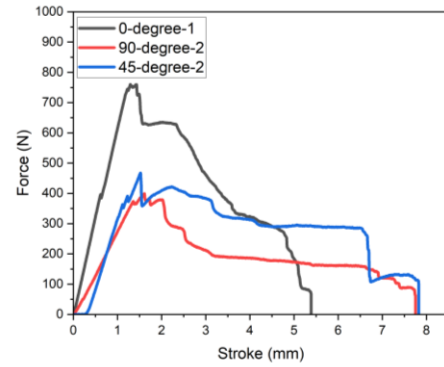


Figure 12: Bending test Force vs Stroke curve. With a maximum force of 758.23 N, the unidirectional(0-degree-1) composite sample easily outperforms the other two samples (the 90-degree-2 composite sample has a maximum force of 398.88 N and the 45-degree-2 sample reaches its limit at a lower value of 467.33 N). This data shows that the unidirectional(0-degree-1) composite outperforms the other two samples in terms of strength. Stroke values for the three samples don't trend in the same direction as the maximum load values.

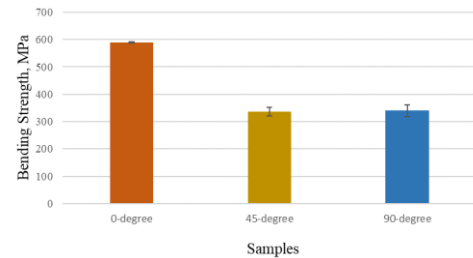


Figure 13: Bending strength value comparisons of test specimens

Based on the bar chart data, it is clear that the three different orientated composite (0-degree, 45-degree and 90-degree) have significantly different mechanical properties. In terms of bending strength, the unidirectional(0-degree) composite has the highest strength of 589.09 MPa, followed by the 90-degree composite at 340.29 MPa and then the 45-degree composite at 335.73 MPa. This indicates that the unidirectional(0-degree) composite shows the strongest material properties of the three while the 45-degree composite is the weakest.

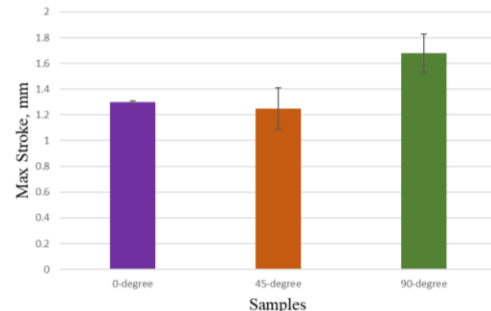


Figure 14: Max stroke value comparisons of test specimens. It is evident from the bar chart data that the mechanical properties of the three different orientated composites 0, 45, and 90 degrees differ greatly from one another. In terms of max stroke, the 90-degree composite has the maximum stroke 1.68mm, followed by the 0-degree composite at 1.3 mm and then the 45-degree composite at 1.25mm.

5.3. Comparison of Impact Strength of Composite

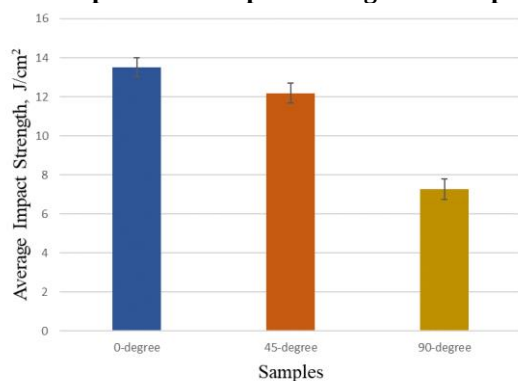


Figure 15: Average impact strength value comparisons of test specimens

It has been seen that the values of average impact strength from the experimental investigation are 13.51 J/cm², 12.19 J/cm² and 7.27 J/cm² for 0-degree, 45-degree and 90-degree composite respectively. The 0-degree composite exhibits high impact strength due to its high resistance to stress propagation. The maximum impact strength (14.1287 J/cm²) obtained for 0-degree composite of sample 1. On the other hand, 90-degree oriented composite has the lowest average impact strength (7.27 J/cm²).

6. Conclusion

This research work aims at evaluating the mechanical characteristics of carbon composites when incorporating different fiber orientations. From the tensile tests, it was found that unidirectional (0 degrees) composites had the highest statistically significant strength where it attained 657.41 MPa, stiffness of about 32.39GPa and ductility of 5.437%, therefore, making it mostly useful for structural purposes while, the 90 degrees composite experienced reduced strength of 437.95MPa and stiffness of 19.25GPa but better flexibility as measured by about 4.847 % strain. From the three-point flexural test, high strength of composite material was recorded at 0 degrees as denoted by 589.09MPa. Composites at 45 degrees yielded intermediate values. Both Charpy impact tests and three-point bending determined the strain energy for 0-degree composites attains the highest value at 13.51 J/cm² whilst the 90 degrees composites had the lowest value of 7.27 J/cm². These findings highlight the influence of fiber orientation and nanoparticle composition on the mechanical performance of composites, guiding material selection for specific applications.

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