STM JOURNALS

Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 1, 2026
DOI (Journal): 10.37591/JoPC

Research JoPC

Characterization of Glass Fiber/Epoxy Laminates Modified with MWCNT–Al_2O_3 Hybrid Nanofillers

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Abstract

Enhancing the performance of fibre-reinforced polymer composites increasingly involves the integration of nanoscale additives that can improve strength, toughness, and overall durability. In the present investigation, woven E-glass/epoxy laminates were modified using a hybrid nanofiller system consisting of multi-walled carbon nanotubes (MWCNTs) and aluminium oxide (Al_2O_3) nanoparticles. The two nanomaterials were combined in a 2:4 proportion and introduced into the epoxy matrix at total loadings of 1%, 3%, and 5% by weight. Laminates were produced in accordance with ASTM D638 and ASTM D256 to ensure consistent tensile and impact characterisation. The mechanical response of the composites showed a progressive improvement with increasing hybrid filler concentration. The formulation containing 5 wt.% hybrid nanofiller displayed the most pronounced enhancement among all tested batches. In particular, the 450 GSM laminate incorporating this filler level demonstrated a 46% rise in tensile strength along with an 84% increase in impact energy when compared to the unmodified E-glass/epoxy reference laminate. Moreover, the 450 GSM specimens consistently outperformed the lower-GSM laminates, indicating that higher fabric areal density, coupled with the synergistic strengthening action of MWCNTs and Al_2O_3 nanoparticles, contributes to more efficient load transfer and crack-resistance mechanisms. These results highlight the potential of hybrid nanofiller reinforcement as a viable route for developing robust, high-performance E-glass/epoxy composites for structural applications.

Keywords: Glass fabric, MWCNTs, Alumina, Nanocomposites, Hybrid fibers

INTRODUCTION

Glass fibre–reinforced laminated composites are extensively employed in structural applications because of their high specific strength and stiffness, enabling substantial weight reduction relative to conventional metallic alloys. Although glass fibres primarily contribute to in-plane load bearing, the out-of-plane response of these laminates is largely controlled by the polymer matrix and the quality of fibre–matrix interfacial adhesion [1-2]. Weak interlaminar performance is typically associated with matrix-dominated cracking at low strain levels and insufficient stress transfer between fibres and the surrounding matrix. Consequently, considerable research has focused on modifying polymer matrices to overcome these limitations and enhance the mechanical behaviour of fibre/polymer composite systems.

Advances in nanotechnology have facilitated the development of next-generation composites with significantly improved performance characteristics. Among various nanoscale reinforcements, carbon nanotubes (CNTs) have

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Received Date: 19 November 2025
Accepted Date: 01 December 2025
Published Date: 19 February 2026

Citation R. Ramkumar, P. Keerthivasan, R. Muthuraja, R. Senthilraja, G. Manickavasaham. Characterization of Glass Fiber/Epoxy Laminates Modified with MWCNT–Al_2O_3 Hybrid Nanofillers. Journal of Polymer & Composites. 2026; 14(Special Issue 1): S350–S368p.

received considerable interest due to their extraordinary strength and stiffness. Incorporating CNTs into fibre-reinforced systems enables the formation of hierarchical composites, where micro-scale fibres and nanoscale reinforcements act synergistically to enhance both in-plane and interlaminar properties. However, integrating CNTs into polymer matrices presents several challenges. Strong van der Waals attractions between nanotubes lead to agglomeration, entanglement, and non-uniform dispersion Furthermore, effective load transfer requires robust CNT–matrix interfacial bonding, while CNT-filled resins often exhibit elevated viscosities that hinder processing [4-7]. Various dispersion and surface-modification strategies—such as ultrasonication, high-shear mixing, and chemical functionalization—have been explored to address these issues. Amino-functionalized CNTs, in particular, have shown improved distribution and stronger interfacial interactions, resulting in measurable enhancements in flexural strength, interlaminar shear strength, and fracture toughness.

Recent work has shifted toward multi-scale hybridization by combining CNTs with ceramic microparticles to design hierarchical architectures with tailored reinforcement effects. Notable examples include CNT–graphene nanoplatelet (GnP) and CNT–silicon carbide (SiC) systems, which have demonstrated promising mechanical performance. Nevertheless, the application of CNT–microparticle hybrids in traditional glass-fibre composites is still limited. Aluminium oxide (Al_2O_3), a ceramic known for its high stiffness and structural stability, has gained attention as a carrier medium for CNTs. CNT–Al_2O_3 hybrids synthesized via chemical vapour deposition (CVD), in which CNTs grow radially on spherical Al_2O_3 particles, assist in dispersing CNTs more uniformly by preventing agglomeration. When incorporated into epoxy matrices, these hybrids promote better filler distribution, and multi-scale glass fabric/epoxy laminates reinforced with CNT–Al_2O_3 structures have shown significant performance potential.

Additional studies further underscore the advantages of hybrid filler systems. K. Devendra *et al*. [2] reported improved hardness in E-glass/epoxy composites with combined Al_2O_3 and MWCNT reinforcement. Similarly, D. Harsha Vardhan *et al*. [2] observed increases in strength, stiffness, and energy absorption in hybrid composites, with carbon-based fillers contributing notably to tensile, impact, and flexural behaviours. Other researchers [3–5] have highlighted the capability of ceramic hybrids to meet demanding mechanical performance criteria, emphasizing CNTs as effective nano-reinforcements in polymer matrices.

Furthermore, investigations [6–20] have shown that incorporating CNTs enhances transverse tensile performance in carbon fibre/epoxy systems. At 1 wt.% MWCNT loading, transverse tensile strength increased by 29.3% at room temperature and by 52.7% at 77 K when compared with neat epoxy. However, raising the CNT content to 3 wt.% resulted in substantial viscosity increases, which induced stress concentrations and ultimately decreased transverse tensile strength. These findings reinforce the need for optimized CNT content and dispersion to achieve maximum reinforcement efficiency.

The study provides a clear justification for incorporating hybrid MWCNT–Al_2O_3 nanofillers into glass fiber/epoxy laminates by addressing both material limitations and the advantages of multi-scale reinforcement. Conventional glass fiber/epoxy systems often suffer from matrix-dominated failures such as poor crack resistance, limited interlaminar strength, and inadequate stress transfer between the fibers and matrix. Although MWCNTs possess exceptional mechanical properties [21-29] capable of improving these shortcomings, their tendency to agglomerate and their impact on resin viscosity restrict their standalone effectiveness. The introduction of nano-Al_2O_3 provides a complementary ceramic phase that not only enhances stiffness and crack resistance but also acts as a dispersive medium that mitigates CNT agglomeration, ensuring better distribution within the epoxy matrix. Previous literature cited in the manuscript supports the synergistic behavior of CNT–ceramic hybrids in improving tensile, flexural, and impact performance. Building on these findings, the present study justifies hybridization as a means to combine the high aspect ratio and crack-bridging ability of MWCNTs with the structural stability and dispersion benefits of Al_2O_3, ultimately enabling more efficient load transfer and

toughening mechanisms in E-glass/epoxy laminates. The below flow chart [Fig.1] represents the flow of experiments.

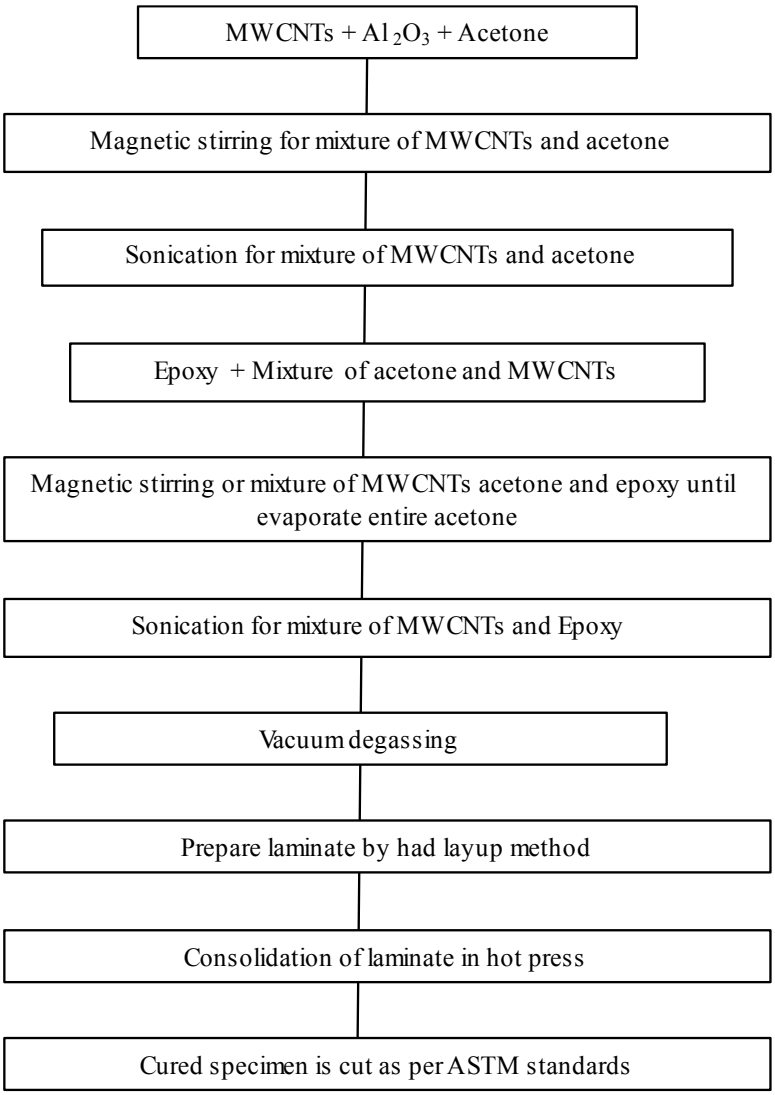

Figure 1. Methodology.

Multi-walled Carbon Nanotubes (MWCNT)

Multi-walled carbon nanotubes (MWCNTs) were produced through a controlled chemical vapour deposition (CVD) technique, a method well known for generating nanotubes with uniform morphology and high structural integrity. Owing to their exceptional mechanical, physical, and surface characteristics [Fig. 2-4], these MWCNTs are extensively used as reinforcement fillers in polymer-based nanocomposites and bio-nanocomposites. The synthesized material appears as a fine black powder, typically confirmed through visual examination. The nanotubes exhibit an average diameter of about 20 nm and lengths ranging from 6 to 9 μm. The purity of the product exceeds 98%, with metallic residues remaining below 3%. In addition, the specific surface area falls within the range of 250–300 m^2/g, and the bulk density is measured between 0.06 and 0.20 g/cm^3 [Table-1].

NANO ALUMINA OXIDE

Nano-sized aluminium oxide (nano-alumina) is extensively used in electronic ceramics, high-strength structural components, and catalyst systems owing to its excellent thermal stability and robust structural properties. It is generally supplied as a fine white powder, easily identifiable through visual inspection.

SEM analysis shows that the particle size typically falls within the 50–200 nm range, while PXRD measurements confirm a crystallite size of approximately 20–30 nm and indicate that the dominant phase is α-alumina The material exhibits high purity (>99%), with metallic contaminants maintained below 2%. Additional physicochemical characteristics include a pH value of around 7.9 and a bulk density between 0.2 and 0.4 g/cm³.

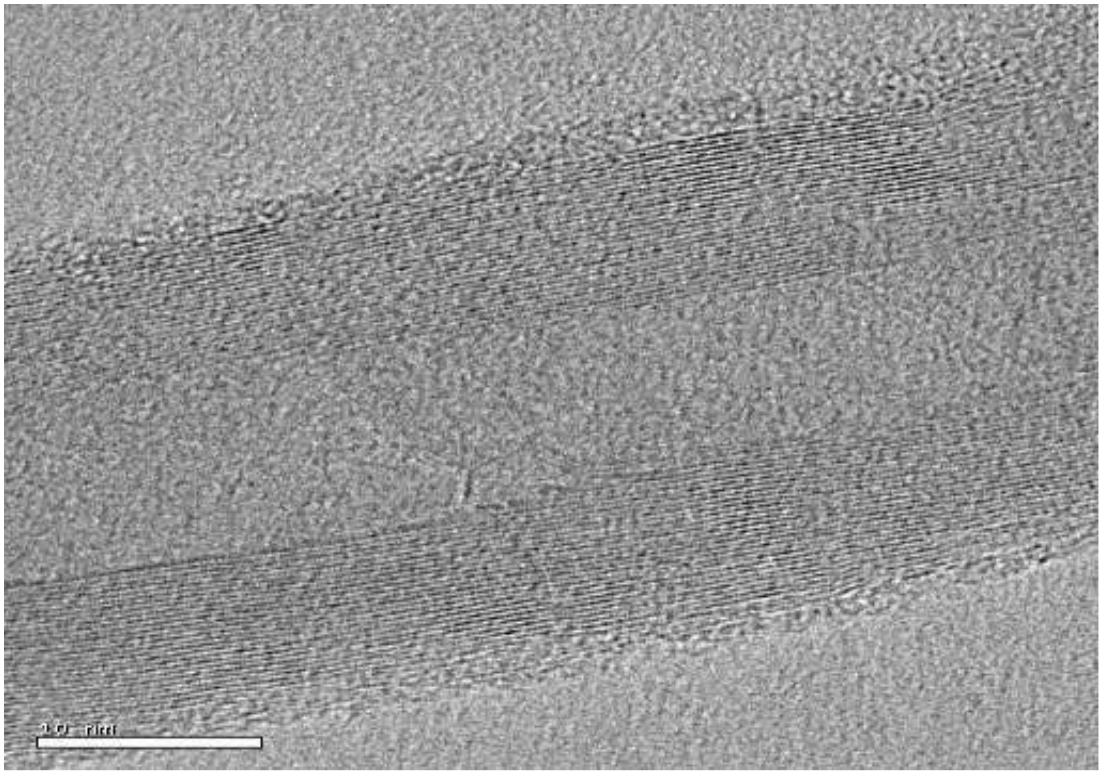

Figure 2. Transmission electron microscopy image of MWCNTs *(TEM)*.

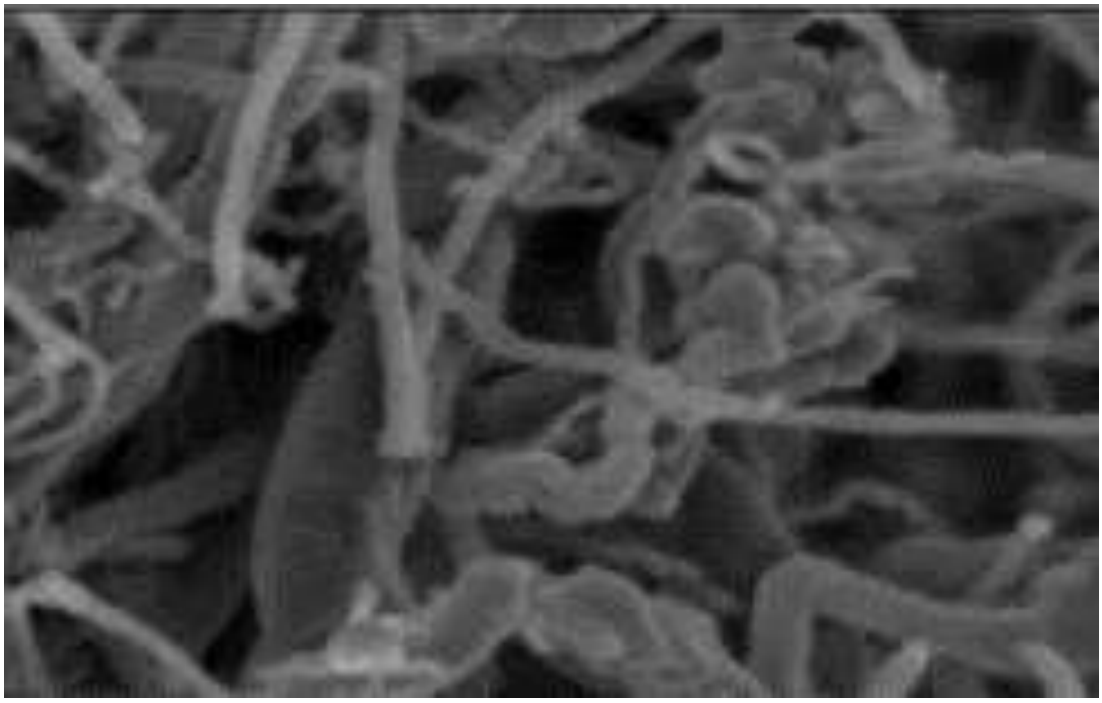

Figure 3. Scanning Electron Microscopy image of MWCNTs (SEM)

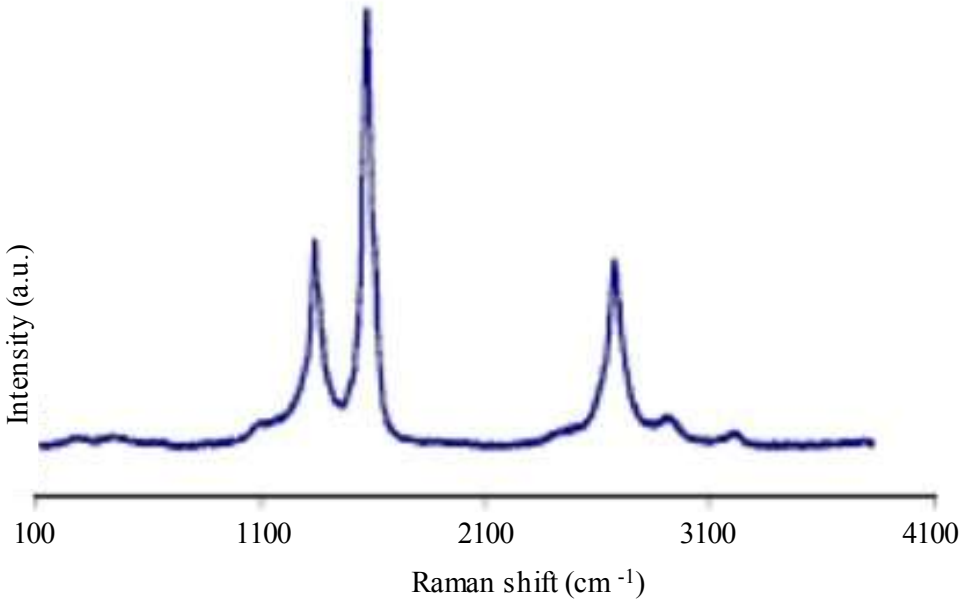

Figure 4. Raman Spectrum Analysis of MWCNTs.

Table 1. Properties of Multi Walled Carbon Nanotubes

S. No.	MWCNT Description	Value / Details	Characterization Method
2	Production method	Chemical Vapor Deposition (CVD)	closed controlled
2	Available form	Black powder	Visual
3	Diameter	~20 nm	SEM, TEM
4	Length	6–9 μm	SEM, TEM
5	Purity	>98%	TGA, Raman spectroscopy
6	Metal particles	<2%	ICP–MS
7	Amorphous carbon	<2%	HRTEM
8	Specific surface area	250–300 m^2/g	BET
9	Bulk density	0.06–0.20 g/cm^3	Pycnometer

The TEM micrograph (Fig.5) shows that the synthesized Nano-alumina possesses a characteristic one-dimensional morphology, with an average crystallite size estimated to be between 10 and 20 nm. Complementary information from the UV spectrum (Fig. 6) indicates the mean aggregate size and provides insight into the aluminium content present within the Nano-alumina powder. Further structural confirmation is obtained from the X-ray diffraction (XRD) pattern (Fig. 7), a widely used non-destructive technique for analyzing crystalline materials. The diffraction peaks correspond to nano-alumina, and the crystallite size calculated from the XRD data is approximately 10–20 nm, which aligns well with the values obtained from TEM observations. Various properties of Aluminum Oxide is represented in the below table [Table 2].

DISPERSION TECHNIQUES FOR MULTI-WALLED CARBON NANOTUBES (MWCNTS) AND ALUMINA

The dispersion of multi-walled carbon nanotubes (MWCNTs) was carried out using an ultrasonic wave mixer without the addition of chemical surfactants. Ultrasonication is particularly effective in overcoming the strong van der Waals interactions responsible for CNT agglomeration, thereby promoting their uniform distribution in aqueous media. During sonication, high-frequency vibrations generate micro- and nano-scale cavitation bubbles within the solution[Fig.9]. The rapid collapse of these bubbles releases localized shock waves and intense shear forces that act on the CNT bundles, supplying sufficient energy to debundle and individualize the nanotubes.

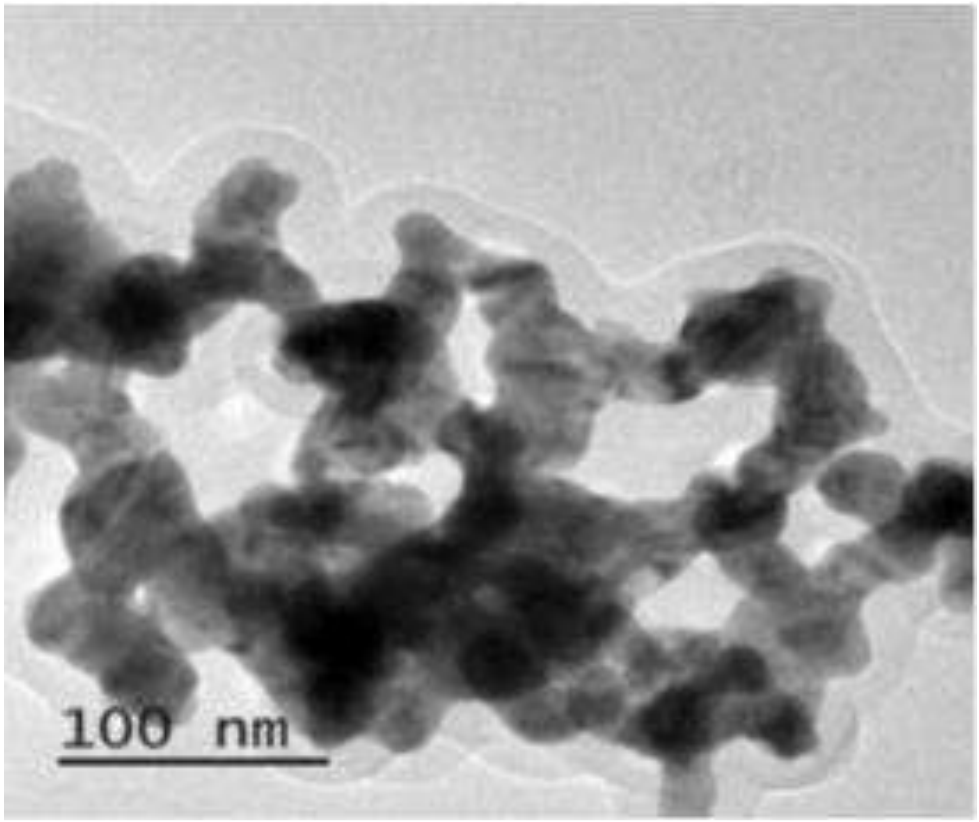

Figure 5. Transmission Electron Microscopy image of Al_2O_3 *(TEM)*

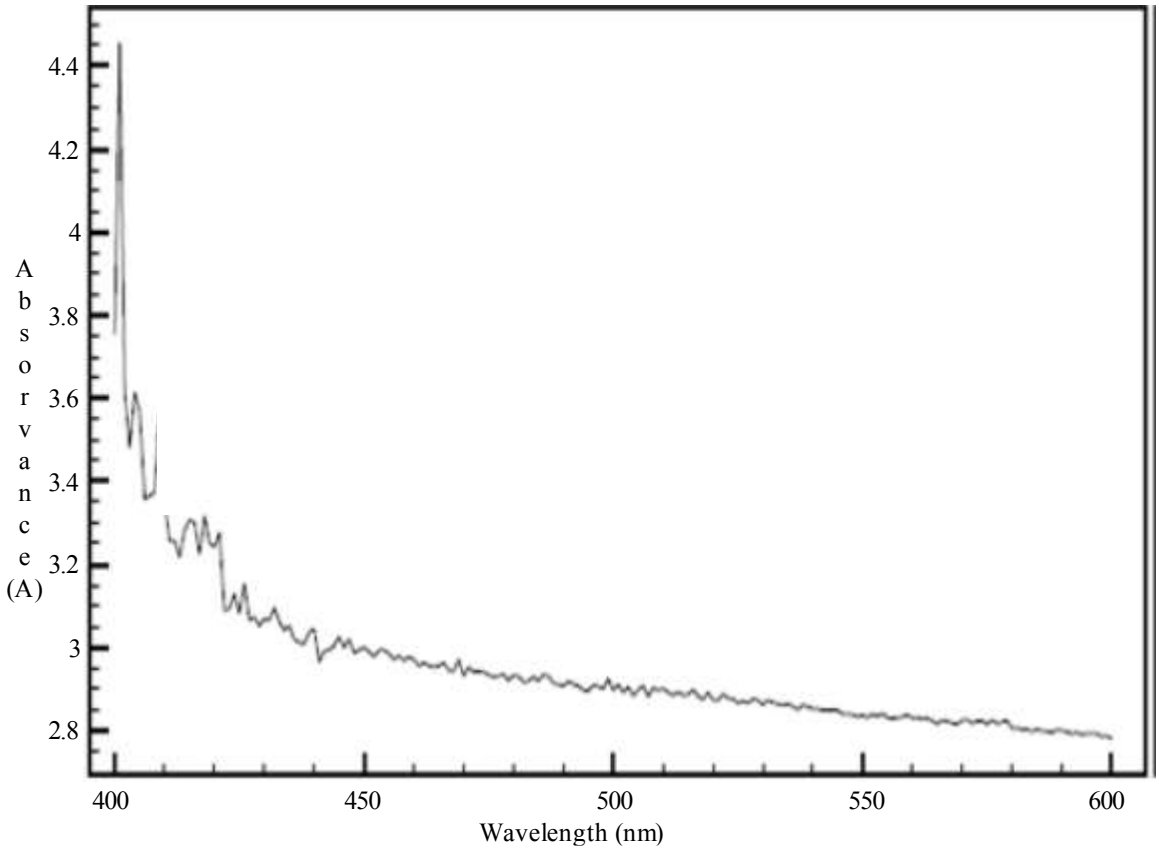

Figure 6. UV Spectrum analysis of Al_2O_3

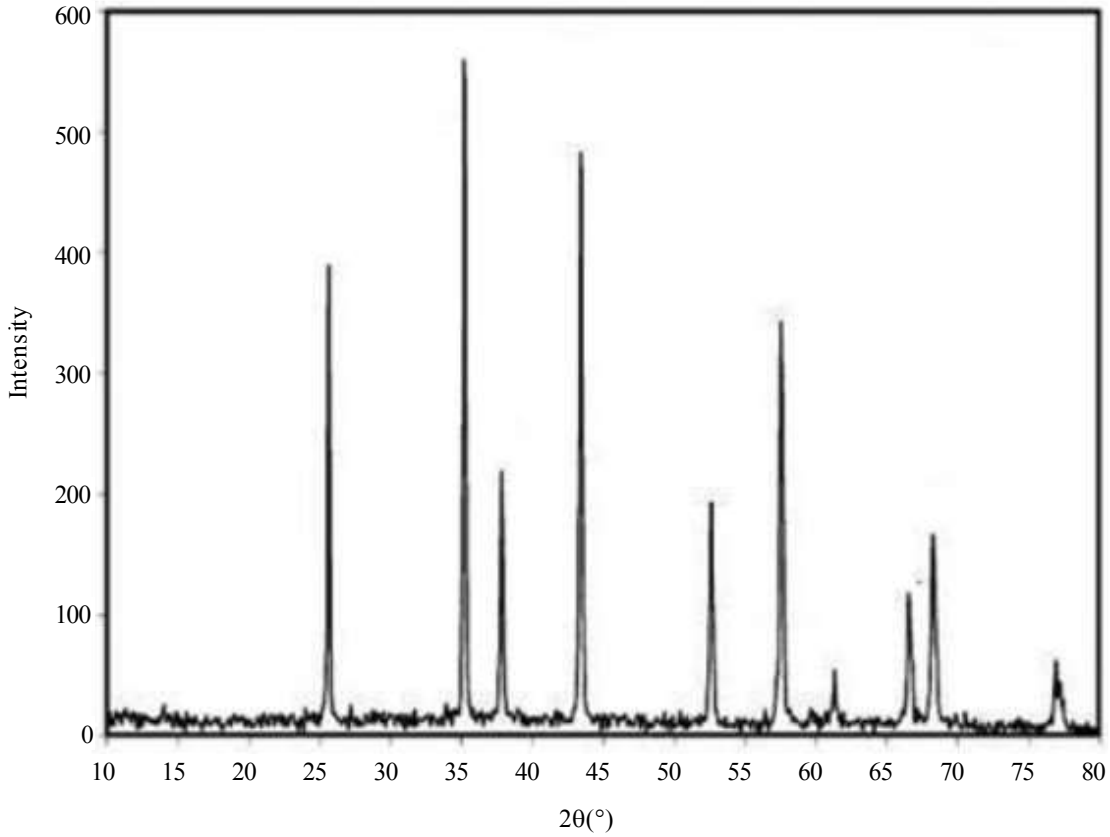

Fig. 7: X-Ray Diffraction (XRD) image of Al2O3

Table 2. Properties of Aluminum Oxide Nano powder

S. No.	Description	Value / Details
2	Product name	Nano Alumina/Aluminium Oxide
2	Molecular weight	202.96
3	Color and form	White powder
4	Specific surface area	≥550 m^2/g
5	True density	2.9 g/cm^3
6	Crystallite size	20–20 nm
7	Mean aggregate size	~5 µm
8	Average pore diameter	220 Å
9	Total pore volume	≥3 cc/g
20	Moisture content	≤22%
22	Bulk density	0.20 g/cm^3
22	Al content (based on metal)	>99.2%

However, once dispersed, CNTs exhibit a natural tendency to re-agglomerate owing to their high surface energy, making precise control of the sonication parameters essential for maintaining suspension stability [15-17]. Key variables—including applied ultrasonic energy, sonication time, nanotube concentration, and solution volume—must be carefully optimized to ensure effective dispersion. Excessive sonication can fracture the nanotubes, reducing their aspect ratio and diminishing their reinforcing efficiency, whereas insufficient sonication results in incomplete debundling [Fig.8]. To enhance long-term stability and minimize re-agglomeration, controlled quantities of anionic, cationic, or non-ionic surfactants may be introduced to act as dispersing agents.

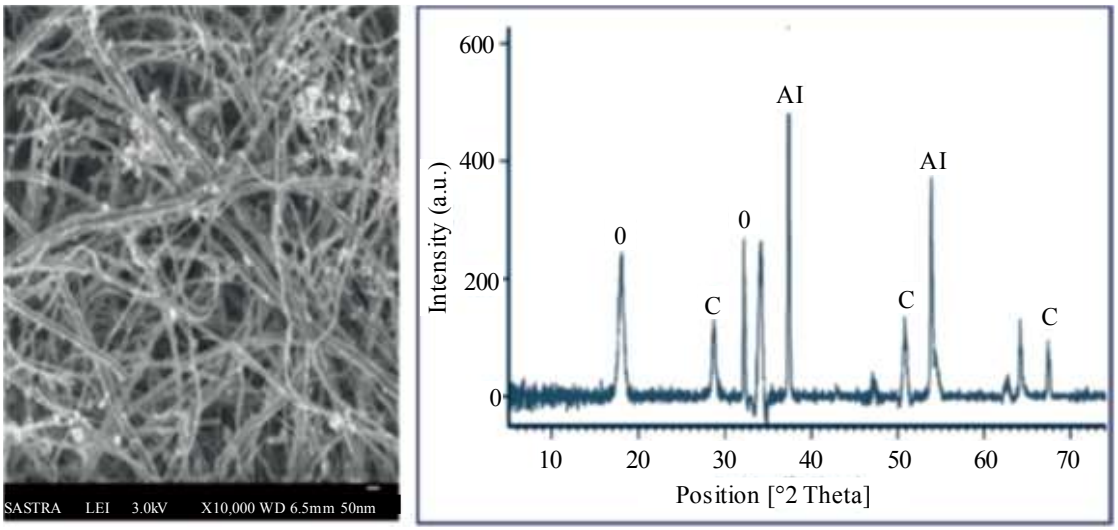

Figure 8. SEM image and XRD pattern of CNT-alumina nanocomposites

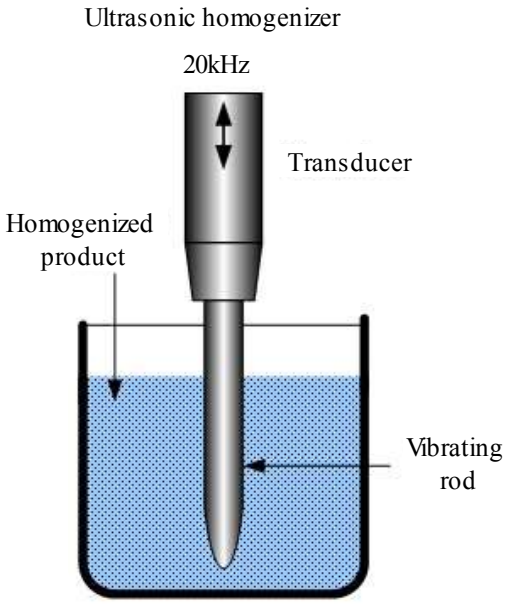

Figure 9. Ultrasonic Homogeniser.

The fabrication of test specimens was carried out using dies prepared in accordance with ASTM standards for tensile and impact testing. Prior to casting, each die was thoroughly cleaned to ensure the removal of contaminants. A mold release agent was applied to facilitate easy removal of the specimens after curing. The die assembly was positioned on a leveled horizontal surface, and grease was applied around the edges to prevent leakage of the reinforced glass fibre/MWCNT–epoxy solution during filling.

While the general specimen preparation steps are described, certain fabrication parameters require clearer documentation to ensure full reproducibility. Details such as the **curing temperature, curing duration, and any post-curing treatment** are not explicitly stated, although these conditions significantly influence the cross-linking behavior and mechanical response of epoxy composites. Similarly, the study does not specify the **fiber lay-up sequence**, number of plies, stacking orientation, or the fiber volume fraction used in the laminates. These parameters are critical because variations in ply arrangement and fiber distribution can lead to substantial differences in tensile and impact performance. Therefore, although the overall fabrication process is outlined, additional information on

curing conditions and lay-up configuration would strengthen procedural clarity and support accurate replication of the experimental work.

SAMPLE PREPARATION

Specimens were fabricated as per the relevant ASTM guidelines[fig.10a,10b,11a,11b], with the number of specimens prepared for each test listed in below table. [**Table 3].**

Table 3. Testing specimens.

S. No.	ASTM Standard	Type of Test	Number of Specimens
1	ASTM D638	Tensile test	22
2	ASTM D256	Impact test	22

ASTM standards offer well-established procedures for assessing the physical, mechanical, and metallographic properties of materials. Key parameters evaluated include elastic modulus, impact strength, ductility, hardness, residual stress, and grain size. These properties can be measured using a variety of techniques, such as scanning electron microscopy (SEM), hole-drilling strain-gage methods, automated image analysis, and X-ray diffraction (XRD)

EXPERIMENTAL STUDY

Tensile Test

Tensile testing was conducted using a Universal Testing Machine (UTM)[Fig.12]. Before testing, the cross-sectional dimensions of each specimen were measured using a caliper to accurately determine the area. The load cell was calibrated and zeroed prior to applying the load to ensure precise measurements. Specimens were mounted in the Instron load frame with a gauge length of 50 mm. The UTM had a maximum load capacity of 600 kN, and the peak load applied to each specimen was approximately 7.50 ± 0.25 kN. Load and displacement data were recorded continuously through the system connected to the UTM until specimen fracture[Table4-7].

Figure 10(a). Tensile Test samples specimens for different weight percentages

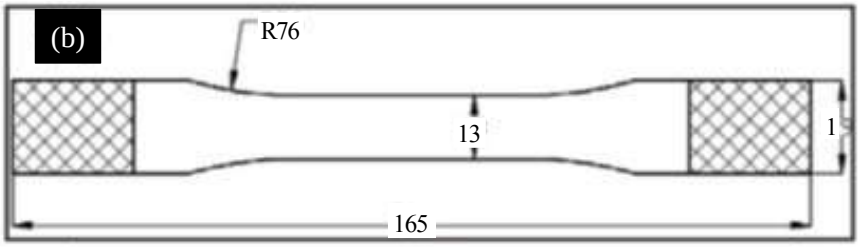

Figure 10(b). Tensile Test samples as per ASTM standard

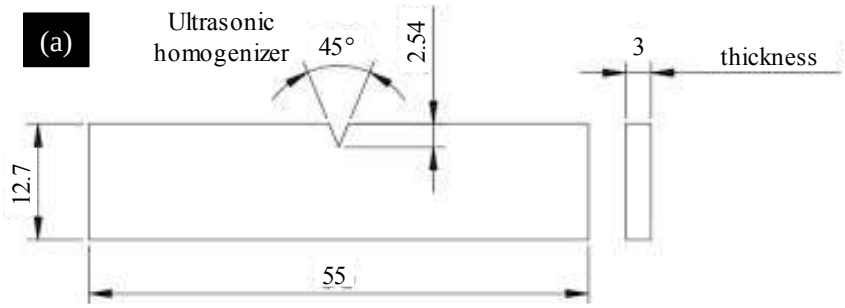

Figure 11(a). Impact Test samples as per ASTM standard

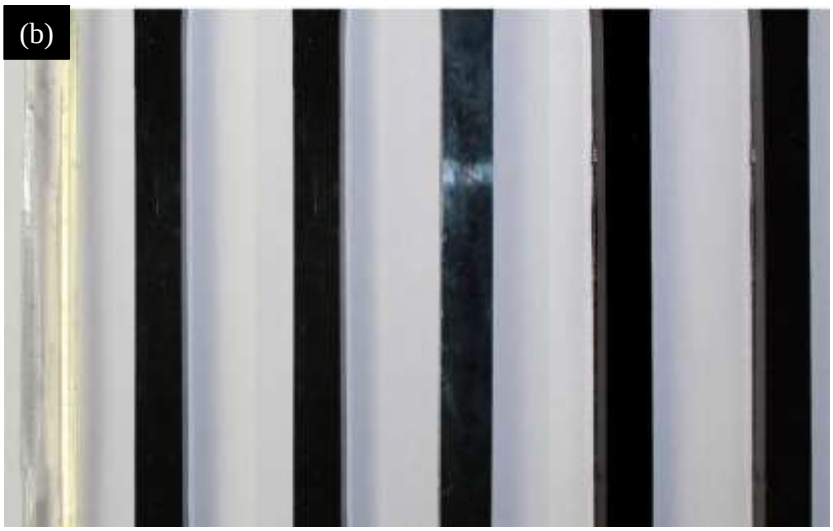

Figure 11(b). Impact Test samples specimens for different weight percentages

Figure 12. Tinius Olsen Tensile Test Apparatus

Table 4. Tensile test results of E-Glass fiber reinforced epoxy.

Specimen Type GSM	Tensile Strength in MPa
225	71.676
300	69.657
450	85.820

Table 5. Tensile test results of 1.0 wt% of MWCNTs, Alumina polymer.

Specimen Type GSM	Tensile Strength in MPa
225	79.380
300	72.878
450	95.235

Table 6. Tensile test results of 3.0wt% of MWCNTs, Alumina polymer

Specimen Type GSM	Tensile Strength in MPa
225	84.027
300	95.121
450	118.269

Table 7. Tensile test results of 5.0wt% of MWCNTs, Alumina polymer.

Specimen Type GSM	Tensile Strength in MPa
225	81.811
300	99.219
450	125.298

The tensile test results revealed that the 450 GSM E-glass/epoxy composite exhibited higher stress and lower strain compared to the 225 GSM and 300 GSM laminates[Fig.13]. The addition of 5 wt.% MWCNTs and Al_2O_3 nanofillers markedly enhanced the tensile performance, with the 450 GSM laminate showing a 46% increase in tensile strength relative to the neat E-glass/epoxy composite[Fig.16].

The neat 450 GSM E-glass/epoxy system already demonstrated superior tensile strength compared to the lower GSM laminates. Incorporation of 1 & 3 wt.% MWCNTs[Fig.14-15], further increased the tensile strength relative to the neat system, while the most significant improvement was observed at 5 wt.% MWCNT loading [Fig.16], delivering the highest overall performance among the tested conditions.

Although the 225 GSM and 300 GSM laminates reinforced with MWCNTs also showed tensile enhancements, the 450 GSM composites consistently outperformed them in both tensile and impact strength. These results confirm that higher GSM fibre reinforcement, combined with an optimized content of MWCNT–Al_2O_3 nanofillers, leads to superior mechanical properties in E-glass/epoxy laminates.

Impact Test

The impact strength of the composites was assessed using a Charpy Impact Testing Machine[Fig.17] equipped with a heavy swing pendulum. The machine has a maximum impact energy capacity of 343.977 J and features a scale ranging from 0 to 264 foot-pounds. During testing, the pendulum's indenter strikes the V-notched specimen after being released from a horizontal static position. Each specimen is supported as a simply supported beam at the base of the machine to ensure consistent impact conditions.

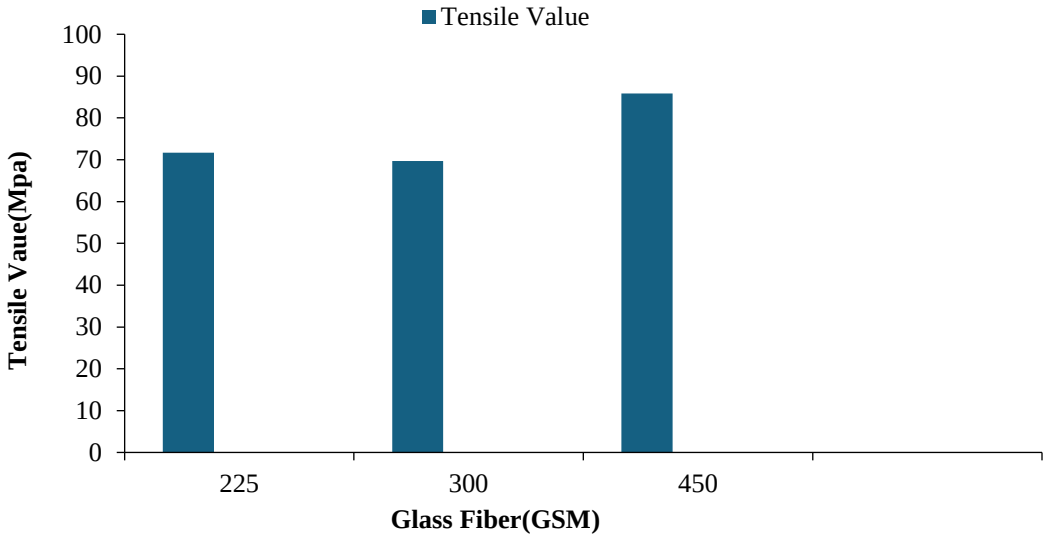

Figure 13. Tensile analysis of E-Glass/Epoxy polymer.

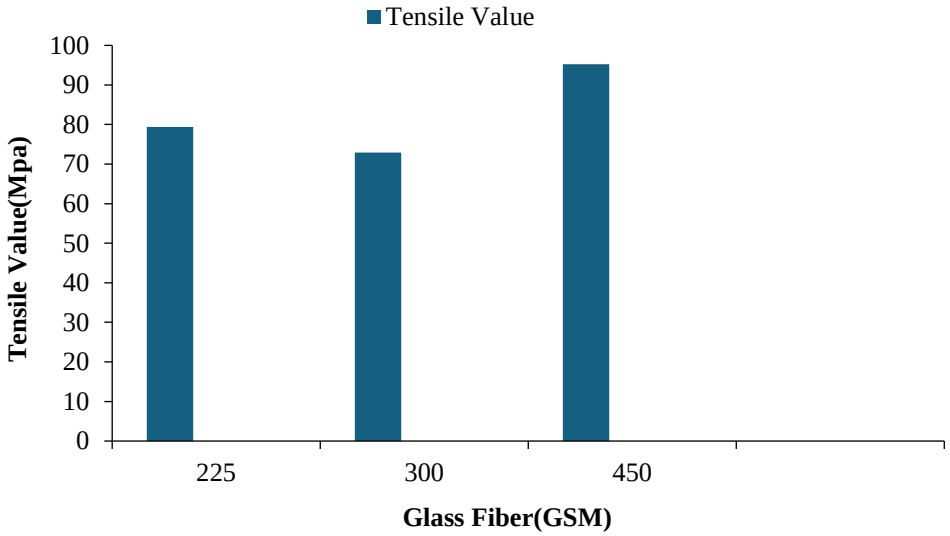

Figure 14. Tensile analysis of 1.0wt% MWCNTs.

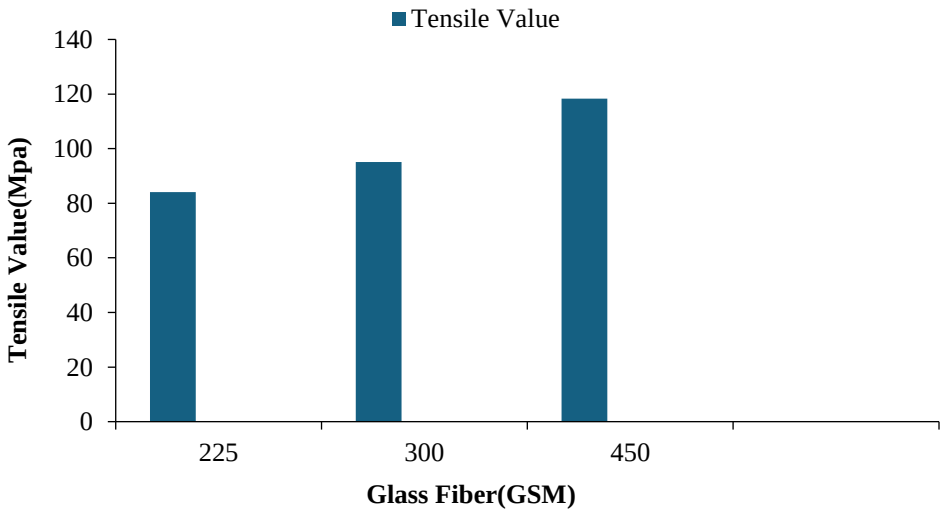

Figure 15. Tensile analysis of 3.0wt% MWCNTs.

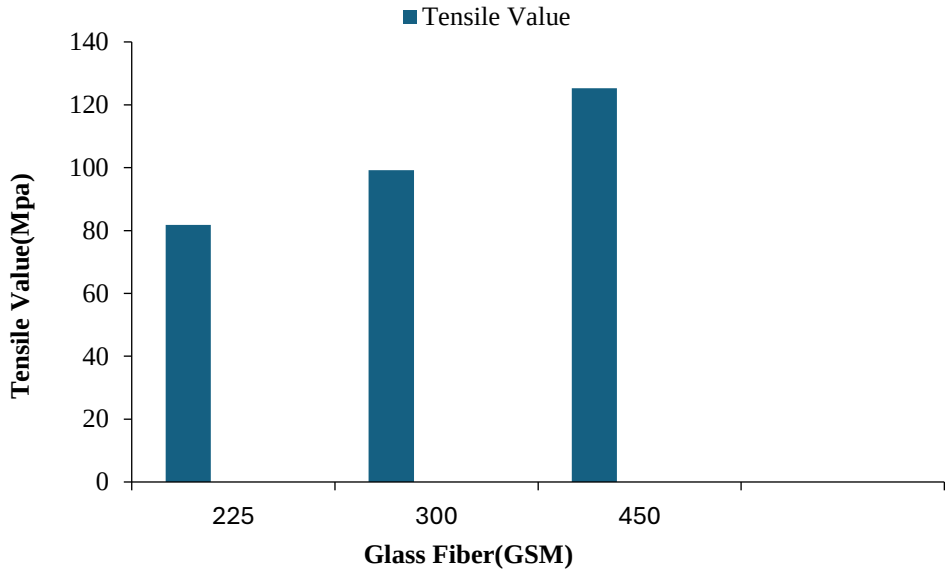

Figure 16. Tensile analysis of 5.0wt% MWCNTs.

Figure 17. Tinius Olsern impact tester

The test specimens had a square cross-section of 20 × 20 mm² and a length of 50 mm. Each specimen featured a V-notch with a depth of 2 mm and a root radius of 0.25 mm. During testing, the pendulum struck the specimen, causing fracture in a single blow. The absorbed impact energy was calculated by measuring the difference between the pendulum's initial height and its rebound height after fracture. This energy difference represents the work dissipated during crack initiation and propagation within the specimen.

Table 8. Impact test results of E-Glass fiber reinforced epoxy.

Specimen Type GSM	Impact value in Joules
225	7
300	9
450	13

The impact test results were compiled and tabulated[Table8-11] for all specimen categories. Analysis indicated that the 450 GSM E-glass/epoxy composite exhibited higher impact strength than the 225 GSM and 300 GSM laminates[Fig.18]. Incorporation of 1&3 wt.% MWCNTs into the 450 GSM system further enhanced the impact performance relative to the neat epoxy[Fig.19-20]. The most pronounced improvement was observed at 5 wt.% MWCNT loading [Fig.21], where the 450 GSM laminate achieved an overall 84% increase in impact strength compared to the neat E-glass/epoxy composite.

These results demonstrate that the addition of MWCNTs, particularly at 5 wt.% in the 450 GSM laminates, significantly enhances impact resistance, highlighting the synergistic effect of high-GSM fibre reinforcement combined with hybrid nanofillers.

Table 9. Impact test results of 1.0 wt. % of MWCNTs, Alumina polymer.

Specimen Type GSM	Impact value in Joules
225	10
300	15
450	19

Table 10. Impact test results of 3.0 wt% of MWCNTs, Alumina polymer.

Specimen Type GSM	Impact value in Joules
225	12
300	18
450	19

Table 11. Impact test results of 5.0 wt. % of MWCNTs, Alumina polymer.

Specimen Type GSM	Impact value in Joules
225	11
300	16
450	24

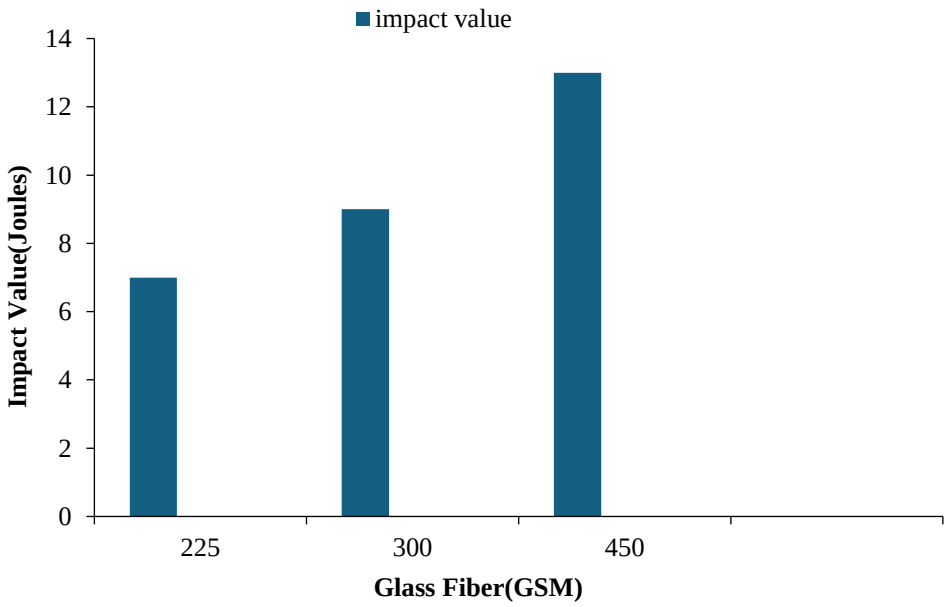

Figure 18. Impact analysis of E-Glass/Epoxy polymer.

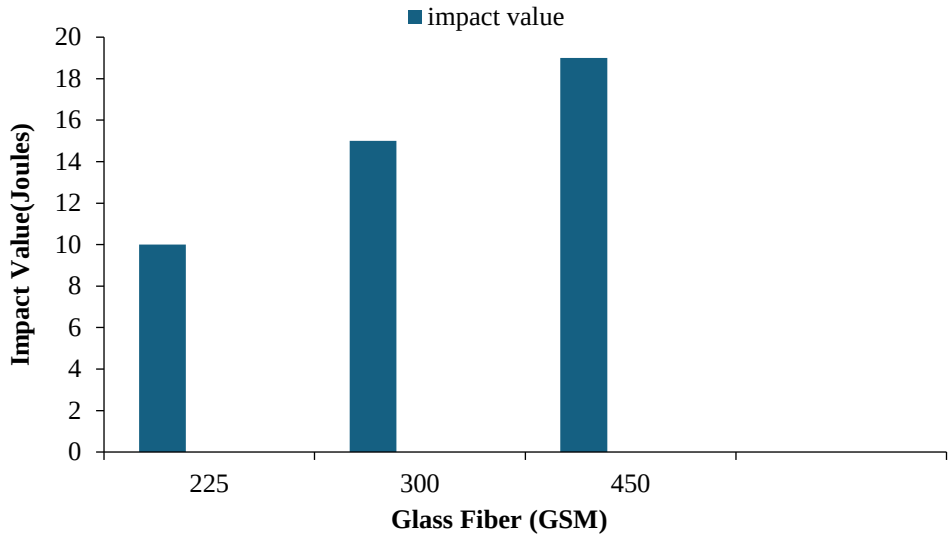

Figure 19. Impact analysis of 1.0wt%.

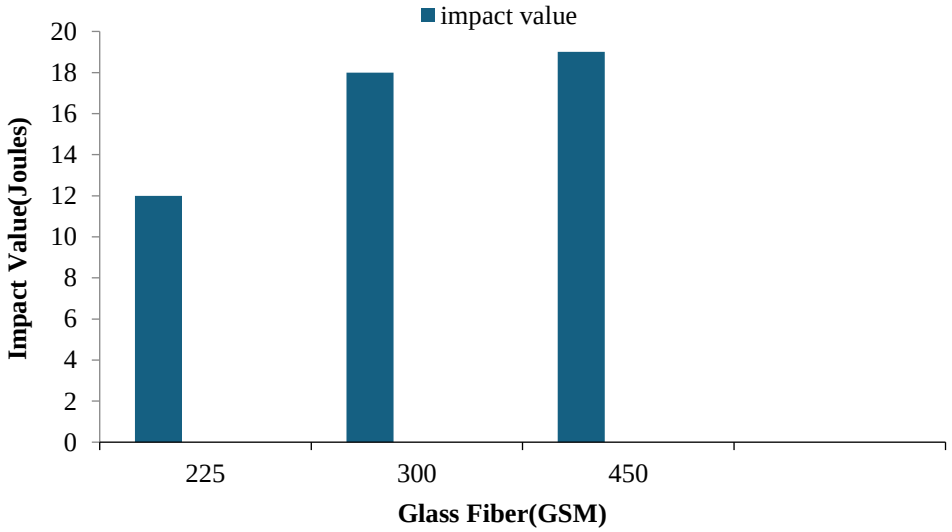

Figure 20. Impact analysis of 3.0wt%.

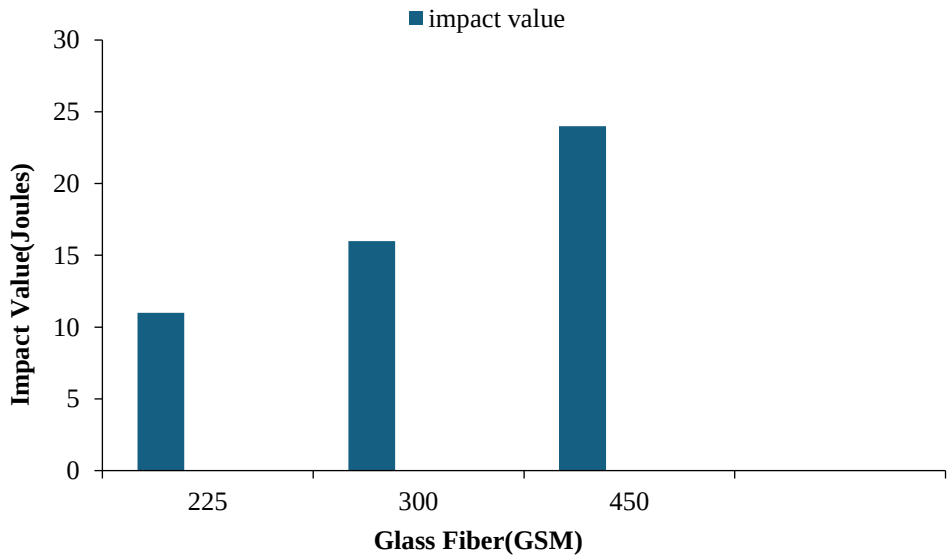

Figure 21. Impact analysis of 5.0wt%.

RESULTS AND DISCUSSION

Tensile Properties

The tensile behavior of the E-glass/epoxy composites reinforced with multi-walled carbon nanotubes (MWCNTs) and aluminium oxide (Al_2O_3) was strongly influenced by both the fabric GSM and the nanofiller content. Among the laminates studied, the 450 GSM composite consistently demonstrated superior performance in terms of ultimate tensile strength and modulus compared to the 225 GSM and 300 GSM laminates. This observation can be attributed to the higher fibre volume fraction in 450 GSM laminates, which enhances load-bearing capability and improves stress transfer between fibres and the polymer matrix.

The incorporation of hybrid MWCNT–Al_2O_3 nanofillers led to a significant increase in tensile strength. At 1 wt.% MWCNT loading, the 450 GSM laminate exhibited a noticeable improvement relative to the neat E-glass/epoxy system, indicating that even a low concentration of hybrid nanofillers can enhance the interfacial bonding between the fibre and matrix. As the MWCNT content increased to 5 wt.%, the tensile strength reached its maximum, with a 46% enhancement over the unreinforced laminate. This enhancement can be explained by several factors:

1. **Load Transfer Efficiency:** MWCNTs act as nanoscale reinforcements, effectively transferring stress from the matrix to the fibres. Their high aspect ratio and strong mechanical properties facilitate load sharing, increasing the overall composite strength.
2. **Crack Bridging and Deflection:** The presence of MWCNTs and Al_2O_3 nanoparticles hinders crack propagation by bridging microcracks and deflecting crack paths, thereby increasing fracture resistance.
3. **Matrix Stiffening:** Hybrid fillers stiffen the epoxy matrix, improving the composite's resistance to deformation and contributing to higher tensile modulus.

Lower GSM laminates (225 and 300 GSM) also benefited from nanofiller incorporation, but their tensile improvements were comparatively lower. This highlights the synergistic effect of combining high fibre volume fraction with optimized nanofiller content for enhanced tensile performance.

Stress–Strain Behavior

The stress–strain curves of the composites reveal that increasing GSM and nanofiller content led to higher tensile stress but slightly reduced elongation at break. This reduction in strain indicates that while the composite becomes stronger, it also becomes stiffer and less ductile. The stiffening effect of MWCNT–Al_2O_3 nanofillers limits polymer chain mobility, resulting in lower strain values. However, the trade-off is acceptable, as the enhanced tensile strength is a critical parameter for structural applications.

Impact Properties

Impact testing further corroborated the reinforcing effect of hybrid nanofillers. The 450 GSM laminates consistently absorbed higher impact energy compared to the 225 GSM and 300 GSM laminates, demonstrating superior resistance to sudden dynamic loading. Addition of 3 wt.% MWCNTs produced noticeable improvements in absorbed energy, while 5 wt.% MWCNTs achieved the maximum enhancement of 84% over the neat 450 GSM E-glass/epoxy system.

The observed increase in impact strength can be attributed to the following mechanisms:

1. **Energy Dissipation through Crack Deflection:** Hybrid nanofillers impede the propagation of microcracks by creating tortuous paths for crack growth, requiring more energy for fracture.
2. **Fibre–Matrix Load Sharing:** The high GSM laminates allow better fibre–matrix interaction, enabling effective load transfer under impact conditions.
3. **Nanofiller Reinforcement:** MWCNTs bridge cracks at the nanoscale, while Al_2O_3 nanoparticles stiffen the matrix and prevent premature failure.

These combined effects indicate a strong synergy between high GSM fibre reinforcement and hybrid nanofillers, leading to enhanced toughness and impact resistance.

Comparative Analysis of Tensile and Impact Performance

A comparative assessment of tensile and impact properties across all laminates shows that 450 GSM composites outperform lower GSM laminates consistently, both in static and dynamic loading conditions. While tensile strength benefits primarily from improved stress transfer and matrix stiffening, impact strength is dominated by crack propagation resistance and energy absorption mechanisms. The results highlight the critical importance of optimizing both fibre volume fraction (GSM) and nanofiller content to maximize composite performance.

Discussion on Filler Content Optimization

The study confirms that 5 wt.% MWCNT–Al_2O_3 is the optimum filler concentration for the 450 GSM system. Lower filler contents (1–3 wt.%) provide incremental improvements, but the highest performance is achieved at 5 wt.% due to better stress transfer, enhanced crack bridging, and uniform distribution of fillers. However, excessive nanofiller loading beyond this threshold could lead to agglomeration, increasing stress concentrations and reducing mechanical efficiency. Therefore, careful control of dispersion and filler content is crucial for achieving the desired mechanical enhancements.

Based on the information provided, the study does **not fully evaluate the interfacial bonding** between the hybrid fillers, matrix, and glass fibers. Although the mechanical test results (tensile and impact) indirectly reflect improvements in stress transfer and crack resistance, the manuscript does not include **direct interfacial characterization techniques** such as SEM fractography, fiber–matrix debonding analysis, pull-out tests, or microscopy of fracture surfaces. These methods are typically required to confirm how effectively the MWCNT–Al_2O_3 hybrid nanofillers interact with the epoxy matrix and whether they enhance adhesion at the fiber–matrix interface. Without such microstructural evidence, the conclusions about interfacial enhancement rely primarily on mechanical performance trends rather than direct observation. Therefore, while the study demonstrates meaningful mechanical improvements, a more comprehensive evaluation of interfacial bonding would require additional microscopic or interfacial tests.

CONCLUSIONS

In this experimental study, the tensile and impact properties of E-glass/epoxy composites reinforced with varying weight fractions of multi-walled carbon nanotubes (MWCNTs) and different GSM grades of glass fibres were systematically evaluated. The key findings are summarized as follows:

1. The incorporation of 5 wt.% MWCNTs led to significant enhancements in mechanical performance, particularly when combined with glass fibre reinforcement.
2. Laminates with 225 GSM and 300 GSM reinforced with MWCNTs exhibited noticeable improvements in both tensile strength and impact resistance compared to neat epoxy composites.
3. The 450 GSM laminates reinforced with 5 wt.% MWCNTs demonstrated the highest overall performance, achieving superior tensile strength, impact resistance, and displacement values relative to lower GSM laminates.
4. Among all tested nanofiller loadings, 5 wt.% MWCNT was identified as the optimum content, outperforming both 1 wt.% and 3 wt.% loadings in terms of mechanical enhancement.
5. Overall, the combination of 450 GSM E-glass fibre reinforcement with 5 wt.% MWCNTs produced the most effective synergistic effect, yielding composites with excellent mechanical properties suitable for high-performance structural applications.

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