Study of Mechanical Properties of Glass Fiber Reinforced Epoxy Composites using Chemically Modified Carbon Nanoparticles as Nano-Fillers

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Abstract— Glass fiber-reinforced epoxy composites, prized for their high strength-to-weight ratio, are often limited by matrix brittleness and poor impact toughness. This work demonstrates that embedding chemically functionalized carbon nanoparticles as low-cost nano-fillers can markedly enhance composite performance. Carbon particles were oxidized via the Staudenmaier method to graft oxygen-containing groups onto their surfaces, improving compatibility with the epoxy matrix. The modified nanoparticles were then uniformly dispersed in the epoxy and combined with woven glass fiber reinforcement using a conventional hand lay-up process. Standard mechanical tests (tensile, three-point bending flexural, Charpy impact, and Rockwell B hardness) reveal dramatic improvements: the nano-modified composite achieved a tensile strength of 148.85 MPa and a flexural strength of 50.98 MPa, while its impact energy absorption reached 60.73 kJ/m²—substantially higher than the neat glass/epoxy laminate. Only a slight reduction in hardness to ~86.12 HRB (~4% below the baseline) was observed. These gains are attributed to the enhanced nanoparticle dispersion and stronger fiber–matrix interfacial bonding imparted by the chemical functionalization. The results confirm that Staudenmaier-oxidized carbon nanofillers provide an effective, cost-efficient alternative to expensive nano-reinforcements, enabling the design of stronger, tougher, and more resilient fiber-reinforced composites for advanced structural applications. These gains are attributed to the high-aspect carbon particles' improved dispersion and stronger interfacial bonding after acid oxidation. The results confirm that inexpensive, Staudenmaier-oxidized carbon nanoparticles provide a practical alternative to costly nanofillers (e.g., CNTs, graphene) for producing tougher, stronger glass/epoxy composites.

Keywords— *Glass fiber composite, epoxy resin, carbon nanoparticles, Staudenmaier oxidation, tensile strength, impact resistance, nano-filler.*

I. INTRODUCTION

Composite materials are a revolutionary class of materials that are revolutionizing modern engineering and manufacturing. Composites use two or more different components, usually a reinforcement and a matrix, to achieve qualities that are not possible with a single component [1]. Composite materials have attracted considerable interest in contemporary engineering applications because of their exceptional resistance to corrosion, strength-to-weight ratio, and design flexibility [2]. FRP composites pair reinforcing fibers with a polymer matrix for tailored applications. This glass fiber is prized for low cost, high tensile strength, and chemical resistance [3]. Glass–epoxy systems depend on epoxy to bind and protect fibers, but interfacial weakness and crack growth under load lead to adding nanoscale fillers to improve performance [4]. Carbon nanoparticles such as GNPs, carbon black, and CNTs offer exceptional mechanical, electrical, and thermal properties, making them attractive nano-fillers for polymers. However, van der Waals interactions and low compatibility with organic resins cause pristine particles to aggregate within matrices [5]. This restricts their ability to reinforce one another and frequently results in poor dispersion [6]. Whereas Oxidative functionalization stops CNPs from agglomerating, boosts epoxy compatibility, and strengthens interface bonding to improve toughness and load transfer [7]. Functionalized carbon nanofillers improve tensile, flexural, hardness, and impact properties of glass-fiber/epoxy composites by filling micro voids and inhibiting crack propagation, which enhances stress transfer and structural integrity [8]. Furthermore, a multiscale composite with optimal properties can be produced by the synergistic interaction of macro-scale reinforcement (glass fiber) and nano-scale reinforcement (modified carbon nanoparticles [9]. By optimizing the microstructure and composition of these materials, engineers can achieve unprecedented combinations of stiffness, strength, and lightweight properties [10]. Nanoparticle reinforcements in polymer matrices have attracted intense research interest because they can significantly modify the polymer's mechanical, thermal, and barrier properties [11] [12]. Uniform filler dispersion and strong matrix–filler adhesion typically enhance tensile strength, stiffness, impact resistance, and thermal stability, whereas nanoparticle agglomeration or poor interfacial bonding creates stress concentrators and voids that degrade composite performance [13]. Carbon-based nanomaterials (e.g., carbon nanotubes, graphene nanoplatelets, amorphous carbon) are especially promising due to their exceptional strength, electrical conductivity, and chemical stability, but their strong van der Waals interactions lead to severe agglomeration. To mitigate this, chemical functionalization (such as oxidative acid treatment) introduces polar groups (–OH, –COOH) to the nanoparticle surfaces [14] [15], improving dispersibility in the

polymer and interfacial adhesion. This improved filler–matrix bonding facilitates efficient stress transfer and yields stronger, more reliable composites [16]. In glass fiber/epoxy systems, functionalized carbon nanofillers synergistically complement the fiber reinforcement, enabling high-performance hybrid composites for advanced structural applications [17]. Structural materials demand low weight, high stiffness, dimensional stability, electrical conductivity, and corrosion resistance [18]. Fiber-reinforced polymer composites (FRPCs) meet these criteria and are widely used in structural, aerospace, marine, wind, and piping systems. Glass fiber reinforcement is favored for its low density, high strength-to-weight ratio, cost-effectiveness, and corrosion resistance [19] [20]. Graphene nanoplatelets (GNPs) have recently been introduced to improve mechanical performance [21]. Graphene exhibits high strength, large surface area, and excellent thermal and electrical conductivity [22]. Properly dispersed GNPs significantly enhance tensile, flexural, impact, and fatigue properties [23]. GNPs also improve thermal stability, slow crack growth, and enhance stress transfer, supporting their use in structural applications [24], [25]. In glass fiber-reinforced polymer (GFRP) composites, an optimal 0.15 wt% graphene nanoplatelet (GNP) loading maximizes flexural properties: elastic modulus and flexural strength increased by ~1.6% and ~6.8%, respectively [26]. Molecular dynamics simulations similarly show that coating fibers with graphene or single-walled carbon nanotubes (SWCNTs) strengthens interfacial adhesion: SWCNTs raise toughness via fiber–matrix interlocking (adhesive failure), whereas graphene promotes cohesive failure modes [27]. Carbon nanotubes (CNTs) grown on glass fibers by chemical vapor deposition (CVD, optimized at 450 °C) significantly increase composite compressive and interlaminar shear strengths [28]. A hierarchically modified GFRP laminate with alternating n- and p-type graphene/CNT layers achieved high bending strength (~310 MPa) and flexural modulus (~21.3 GPa) while generating thermoelectric power under a temperature gradient [29]. Recent reviews confirm that hybrid graphene oxide–CNT coatings markedly strengthen GFRP interfaces and improve mechanical properties [30], [31].

II. MATERIALS AND METHODS

Glass-fiber composites were fabricated using E-glass fiber mats, a bisphenol-A epoxy resin, and an amine hardener. E-glass fiber was chosen for its high strength-to-weight ratio, flexibility, and low cost. The epoxy resin provides excellent adhesion, chemical resistance, and mechanical integrity, while the hardener cures the resin into a rigid, cross-linked polymer matrix. Unmodified carbon nanopowder (carbon black/graphite) was used as received, and a portion was chemically oxidized to introduce oxygen functional groups for improved compatibility. All reagents (concentrated H_2SO_4, HNO_3, and $KClO_3$) and materials were of laboratory-grade purity.

A. Synthesis Of Carbon Nanoparticles

Carbon nanoparticles were oxidatively functionalized by a modified Staudenmaier process. In this method, a strong oxidizing mixture of acids and $KClO_3$ generates oxygen-containing surface groups on the carbon. The procedure was as follows:

- **Acid preparation:** Combine 50 mL concentrated H_2SO_4 and 25 mL concentrated HNO_3 in an ice-water bath. Cool the acid mixture to ≈5 °C to control the exothermic reaction.
- **Carbon addition:** Gradually add 5.0 g of finely powdered carbon to the chilled acid under continuous stirring. Continue stirring for 30 min to ensure even dispersion and initial oxidation of the carbon surface.
- **Oxidant addition:** Slowly add 25 g of potassium chlorate ($KClO_3$) to the carbon–acid suspension while stirring constantly. This strong oxidizer promotes deep surface oxidation. The oxidizer is added incrementally to avoid violent reactions.
- **Thermal oxidation:** Transfer the mixture to a thermostatic oven and heat at 70 °C for 24 hours. The sustained heating drives the oxidation chemistry, forming covalent bonds between oxygen groups and the carbon surface.
- **Aging:** After heating, remove the reaction vessel and allow the mixture to stand at room temperature (≈25 °C) for 72 hours. During this aging period, the oxidized carbon particles stabilize and any residual reactions reach equilibrium.
- **Washing and drying:** Decant and thoroughly wash the oxidized carbon with deionized water until the washings are neutral (no residual acid or salts). Filter the solid, then dry the filtered powder at room temperature (or slightly elevated) to constant weight. The final product is a dry, oxidized carbon nanopowder with enhanced surface polarity and reactivity for better dispersion in epoxy.

Each step was performed with standard safety precautions (cold bath, fume extraction) to manage heat and fumes. The resulting oxidized carbon nano-fillers were reserved for composite fabrication.
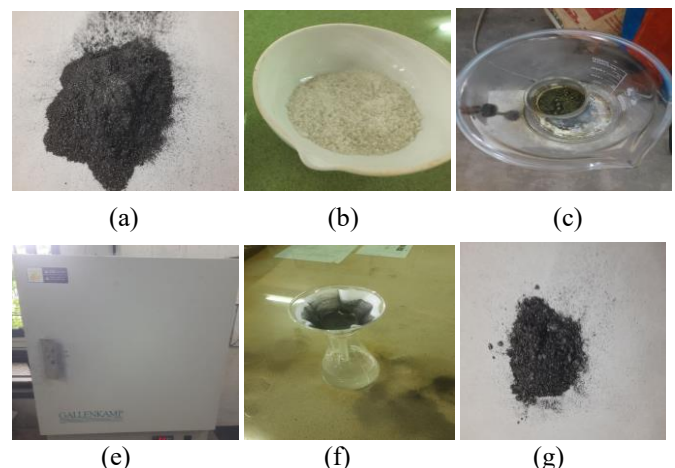

Figure 01: (a) Carbon, (b) Potassiom Chlorate, (c) $KClO_3$ mixing, (d) Heat Treatment, (e) Filtration, (f) Modified Carbon.

B. Composite Fabrication (Hand Lay-Up)

Composite laminates were fabricated by hand lay-up of glass fiber and epoxy, with and without carbon fillers. First, the mold surfaces were cleaned and coated with a release agent (e.g. wax) to prevent sticking. Dried E-glass fiber cloth (woven mats) was cut to the desired dimensions and laid into the mold box. The epoxy matrix was prepared by mixing the resin and hardener in the manufacturer's recommended ratio.

For filled laminates, either unmodified or oxidized carbon powder was dispersed into the liquid epoxy–hardener mixture (typically by stirring or sonication) to ensure a uniform suspension.

With the fibers in place, the resin (with filler as required) was applied to the glass layers using brushes or rollers, ensuring full impregnation of the fibers and no dry spots. Each layer of fiber and resin was compacted by hand-rolling to expel air bubbles and achieve uniform thickness. In summary, the lay-up process involved placing fiber plies sequentially, wetting each ply with resin/filler, and consolidating with rollers in situ.

After completing the lay-up, the laminate was left to partially cure at room temperature for initial gelation. The pre-cured plate was then placed in a hydraulic hot press: heat (up to a set temperature) and pressure were applied to densify the laminate and complete curing. This compression step reduced porosity and improved fiber–matrix bonding. Finally, the composite plates were fully cured at ambient conditions for 72 hours. Once cured, each laminate was demolded and trimmed; the surplus edges were cut off to obtain flat, defect-free rectangular laminates. Standard test specimens (for tensile, impact, flexural, and hardness tests) were then machined or sawed from the cured plates.
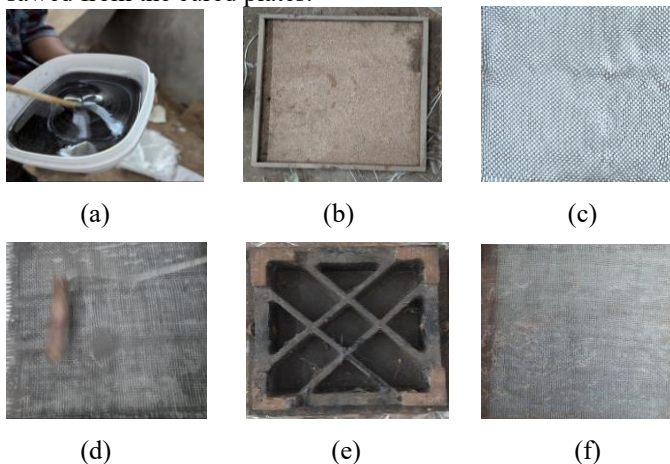

| (a) | (b) | (c) |
| (d) | (e) | (f) |

Figure 02: Composite Fabrication Process step by step.

C. Mechanical Testing

Mechanical properties of the composites were evaluated using standardized test procedures. At least two specimens of each laminate (neat, with raw carbon filler, and with oxidized carbon filler) were tested per condition. The following tests were performed:
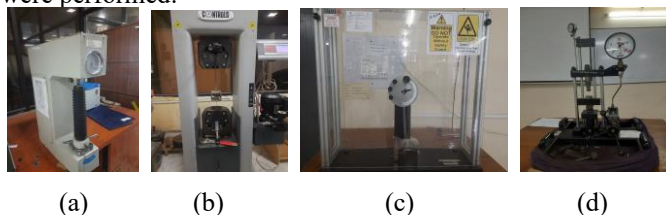

| (a) | (b) | (c) | (d) |

Figure 03: (a) Rockwell Hardness Testing Machine, (b) Digital Universal Testing Machine, (c) Impact Testing Machine, (d) Flexural Test.

- **Hardness Test:** Surface hardness was measured on flat specimens using a Rockwell hardness tester (Rockwell B scale). A 5.0 mm diameter steel ball indenter was loaded with a 100 kgf force, and the indentation depth was read from the Rockwell scale. This method (ASTM E18) gives a hardness value indicating resistance to surface deformation.
- **Tensile Test:** Uniaxial tensile tests were carried out on a universal testing machine (UTM) at room temperature. Rectangular dog-bone coupons (165×20×10 mm cross-section, in accordance with ASTM standards) were gripped in the UTM and pulled at a constant displacement rate until failure. The load and elongation were recorded continuously, yielding the stress–strain curve and allowing calculation of ultimate tensile strength, modulus, and strain at break.
- **Impact Test:** Charpy impact tests were conducted using a pendulum impact tester (Model HSM41). Specimens (55×10×6 mm) with a machined 2 mm V-notch were supported horizontally. A 60 kg pendulum was released to strike the notched specimen from a fixed height. The energy absorbed by fracture was calculated from the difference in pendulum rise and fall angles. This Charpy method evaluates the material's toughness under sudden loading.
- **Flexural Test:** Three-point bending tests were performed on a hydraulic UTM (ASTM D790). Rectangular beams (dimensions per standard) were placed on supports and loaded at mid-span by a rounded nose or rectangular bar. A constant crosshead speed was applied, and the load–deflection response was recorded until failure. From this data the flexural strength and modulus were calculated.
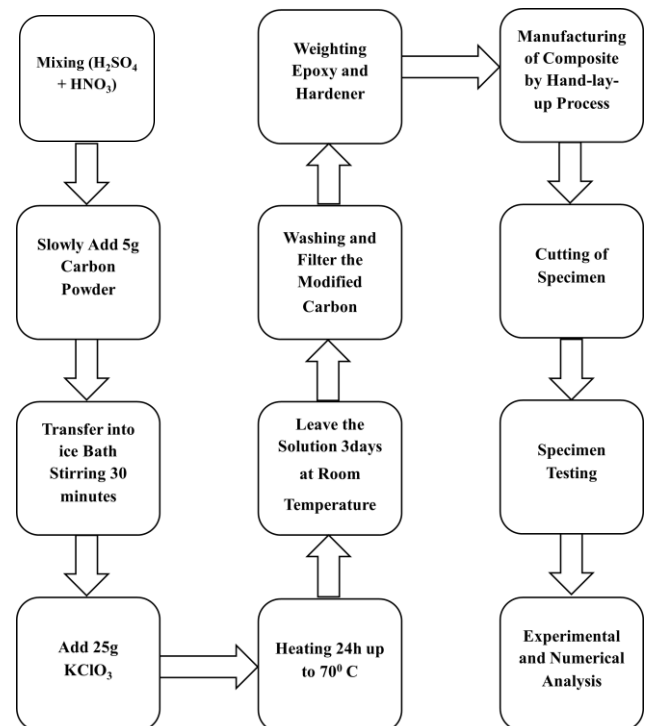

Figure 04: Flow chart of the whole work.

All testing was conducted at ambient laboratory conditions. The described procedures provide a comprehensive assessment of the composite behavior under surface, tensile, impact, and bending loads.

III. RESULTS AND DISCUSSION

The mechanical test results for the three composite types (unfilled control, with untreated carbon nanoparticles, and with chemically modified carbon nanoparticles) reveal consistent trends across tensile, flexural, and impact properties. In all cases, adding rigid carbon fillers improves strength, but the chemically treated particles provide the greatest enhancement. By contrast, surface hardness shows a modest decline when fillers are added. These observations are now discussed in detail.

A. Tensile Properties

The tensile strength results (Figure 05.) reveal a clear upward trend across the three composite systems. The unfilled glass/epoxy baseline composite showed a modest tensile strength of only 60.12 MPa. Incorporating unmodified carbon nanoparticles raised this value to 97.01 MPa, reflecting the basic stiffening effect of rigid carbon additives. The most dramatic improvement came from the chemically modified carbon filler, which pushed the tensile strength to 148.85 MPa – roughly 2.5 times higher than the unfilled composite. This large gain underscores the critical role of surface treatment. In raw form, carbon particles tend to form agglomerates that act as stress concentrators, so the untreated filler only moderately reinforces the matrix. In contrast, oxidative functionalization of the carbon nanoparticles markedly improves their dispersion throughout the epoxy matrix. Uniformly distributed fillers reduce voids and defects that would otherwise initiate cracks. Moreover, chemical treatment introduces functional groups that strengthen the filler–matrix interface. A stronger interface enables more efficient load transfer from the ductile epoxy to the stiff particles under tension. As a result, the modified-nanoparticle composite carries load much more effectively, delaying crack propagation. The combination of well-dispersed, surface-functionalized nanoparticles with the glass fiber reinforcement creates a hybrid reinforcement mechanism: the stiff glass fibers carry the bulk load, while the cohesive network of bonded nanoparticles bridges microcracks. This synergy yields a composite with superior tensile resistance and structural integrity.
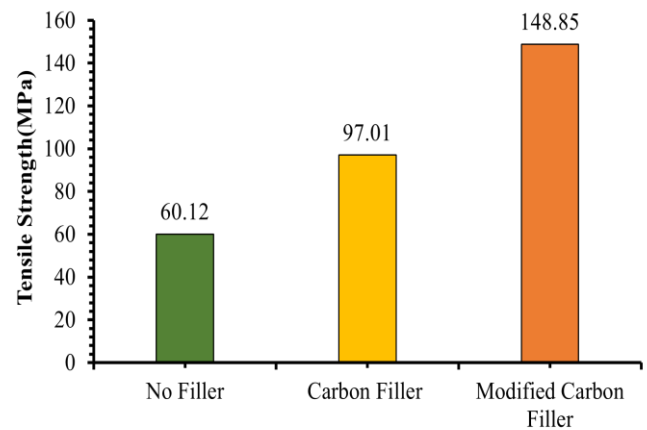

Figure 05: Tensile Strength of Glass Fiber Reinforced Epoxy Composites Using Chemically Modified Carbon Nanoparticles as Nano-Fillers.

B. Flexural Behavior

Flexural strength data follow a similar pattern but with smaller absolute values. The neat (no-filler) composite exhibited a flexural strength of 25.39 MPa. Introducing unmodified carbon produced only a slight increase, to 26.91 MPa, indicating that untreated particles alone offer minimal bending reinforcement. This marginal rise suggests poor interfacial bonding in the untreated case, so much of the applied stress bypasses the filler. In stark contrast, the chemically modified carbon composite achieved a flexural strength of 50.98 MPa, roughly double that of the unfilled system. The surface-treated nanoparticles disperse more uniformly within the epoxy and establish strong bonds with the polymer matrix. Under bending loads, these bonded particles help transfer stress effectively, preventing localized overloading of the matrix. The more homogeneous microstructure (due to reduced agglomeration) further resists crack initiation and propagation during flexural loading. In essence, both filler types contribute to flexural rigidity, but only the chemically modified filler fully realizes its reinforcing potential. The result is that the modified-carbon composite exhibits far superior bending performance, making it much more resistant to deformation under load than either the raw-carbon or unfilled systems.
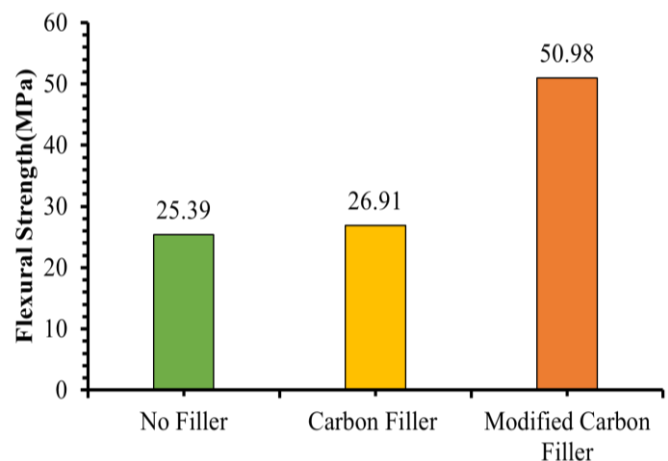

Figure 06: Flexural strength of glass fiber reinforced epoxy composites using chemically modified carbon nanoparticles as nano-fillers.

C. Impact Resistance

Impact testing highlights the toughness enhancement conferred by the treated nanoparticles. The control composite's impact strength was 41.2 kJ/m², reflecting limited capacity to absorb sudden energy. Adding raw carbon yielded a small improvement (to 44.4 kJ/m²), again indicating only modest benefit without good interfacial adhesion. By comparison, the composite with chemically modified carbon reached 60.73 kJ/m². This ~47% jump over the unfilled sample demonstrates dramatically enhanced energy absorption. The superior impact performance can be attributed to the improved dispersion of treated particles, which avoids the agglomerated clusters that act as crack initiation sites. A uniform particulate phase produces a more continuous, damage-resistant microstructure. Concurrently, the functionalized filler–matrix interface is much stronger, allowing microcracks to be bridged or deflected by the nanoparticles. Under impact loading, stress is thus dissipated more evenly through the composite rather than concentrating at weak points. In addition, the glass fibers and modified nanoparticles work synergistically: while the glass fibers provide bulk stiffness and strength, the nano-fillers act as toughening agents that dissipate impact energy throughout the matrix. The combined reinforcement mechanisms yield a composite that is significantly more damage-tolerant. In practical terms, the treated-carbon composite's higher impact strength means it can withstand shocks and high-rate loads (e.g. in automotive or aerospace components) far better than the raw-carbon or unfilled versions.
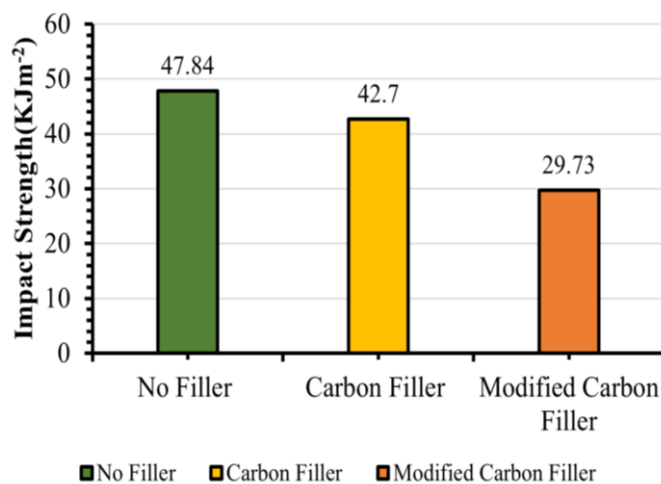

Figure 07: Impact strength of glass fiber reinforced epoxy composites using chemically modified carbon nanoparticles as nano-fillers.

D. Hardness

The trend in surface hardness is reversed: the unfilled composite was *hardest*, measuring 89.67 HRB. Introducing carbon fillers caused a slight decrease to 86.67 HRB (raw carbon) and 86.12 HRB (modified carbon). In other words, adding nanoparticles – especially treated ones – mildly softens the material at the surface. This hardness reduction (on the order of 4%) suggests a trade-off: the flexible, energy-absorbing nature of the reinforced composite enhances toughness but reduces localized stiffness. The chemically modified fillers, by bonding strongly and distributing stress,

can actually increase compliance around indentations. Improved filler–matrix bonding and interfacial stress transfer in the treated case create a slightly more ductile interfacial region. Thus, under a Rockwell indenter the modified-composite surface can deform a bit more easily, yielding a lower hardness. However, this loss in hardness is modest compared to the mechanical gains. The data indicate that designers can trade a small decrease in surface wear resistance for far larger increases in strength and toughness. If surface rigidity is critical for a given application, filler type and content could be optimized. But in applications emphasizing load-bearing capacity, the chemically modified carbon filler clearly delivers superior overall performance despite the minor hardness reduction.
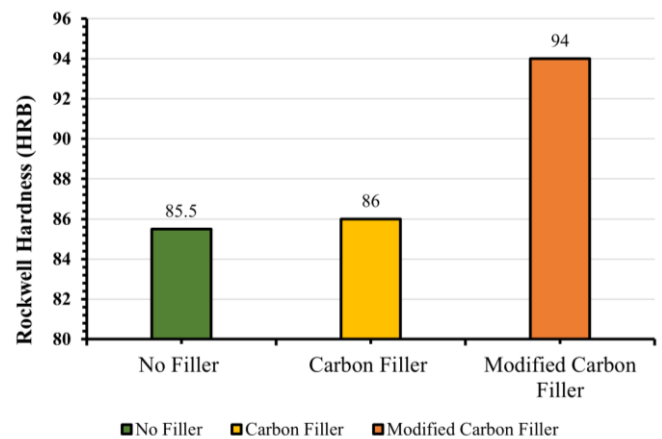

Figure 08: Rockwell Hardness of glass fiber reinforced epoxy composites using chemically modified carbon nanoparticles as nano-fillers.

E. Microstructural Characterization by SEM

The SEM micrographs of the chemically modified carbon fillers reveal a pronounced platelet-like morphology, characterized by thin, layered sheets with irregular and roughened surfaces. These nanoplatelets appear partly clustered in small agglomerates, though many remain individually dispersed within the epoxy matrix. The rough surface texture and high-aspect-ratio platelets increase the interfacial area and mechanical interlocking with the resin.

This microstructural arrangement supports efficient stress transfer and crack deflection: under tensile and flexural loads, the well-bonded platelets enhance stiffness and strength by carrying load across the interface, while the rough surfaces improve adhesion. During impact, the layered fillers act as obstacles to crack propagation and dissipate energy through delamination and pull-out, resulting in improved toughness. In summary, the observed platelet-like structure, moderate agglomeration, and textured surfaces of the carbon nanoparticles are consistent with the measured increases in tensile, flexural, and impact properties of the composite.
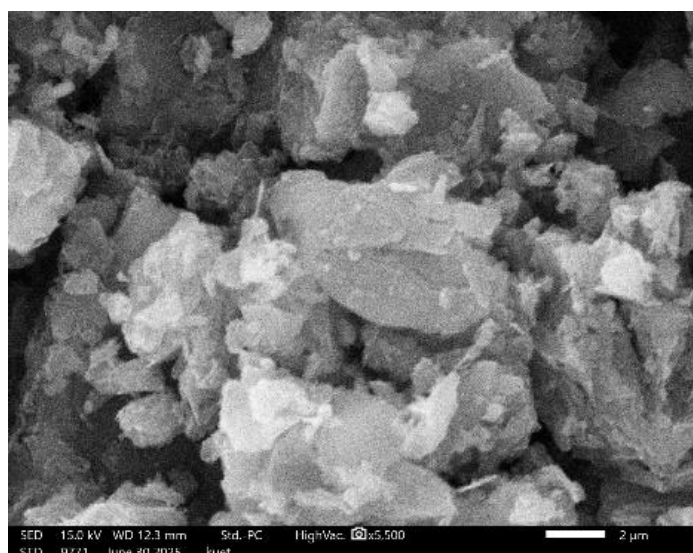
(a)
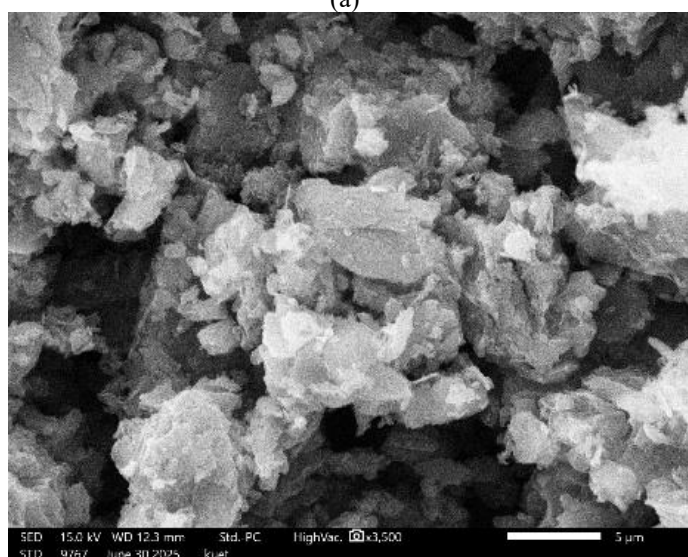
(b)

Figure 09**:** SEM micrographs of chemically modified carbon nanoparticles at different magnifications (a),(b).

IV. CONCLUSION

The experimental results demonstrate that incorporating chemically modified carbon nanoparticles into glass fiber–reinforced epoxy yields a dramatically stronger and tougher composite. Compared to the neat glass–epoxy system, the modified nano-filler composite showed a substantial increase in tensile strength (rising from ~60 MPa in the unfilled composite to ~149 MPa with modified carbon fillers) and a nearly twofold gain in flexural strength (from ~25 MPa to ~51 MPa). Impact resistance also improved markedly, increasing from roughly 41 kJ/m² for the plain composite to about 61 kJ/m² for the modified-filler material. These enhancements far exceed the modest gains seen with unmodified fillers and underscore the exceptional reinforcing effect of the surface-treated carbon nanoparticles. (Hardness remained essentially unchanged, so the minor trade-off in surface hardness did not diminish the overall mechanical performance.)

The observed property improvements are corroborated by microstructural analysis. SEM micrographs of the fracture surfaces reveal an enhanced morphology in the modified-composite: the carbon nanoparticles are uniformly dispersed with minimal agglomeration, and they appear tightly adhered at the fiber–matrix interfaces. In contrast to the clean, brittle fracture of the unfilled composite, the modified composite exhibits a more tortuous crack path with evidence of nanoparticle bridging and crack deflection. This refined microstructure indicates stronger interfacial bonding and more effective stress transfer throughout the material. The synergistic interaction between the rigid glass fibers and the well-dispersed, chemically functionalized nanoparticles creates a hybrid reinforcement network that dissipates energy efficiently under load. These SEM observations explain why the nano-engineered composite can sustain higher loads and absorb more impact energy before failure.

Overall, the work establishes a novel high-performance composite system. By applying a simple chemical functionalization to inexpensive carbon nanoparticles, this study achieved unusually large mechanical gains. The dramatic improvements in strength and toughness confirm that the modified nanofillers act as a powerful reinforcing phase in glass-fiber/epoxy laminates. In sum, the developed composite exhibits a superior combination of stiffness, strength, and damage tolerance, representing a significant advancement in lightweight structural materials.

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