Effect of Graphene Nanofillers on the Dynamic Mechanical Properties of Carbon Fiber–Epoxy Composites

V. Nikil Murthy[1], Dr. Ashwin C Gowda[2],

[1]Department of Mechanical Engineering, VTU Regional centre, Muddenahalli, chikballapur, Bangalore, karnataka, India

[2]Department of Mechanical Engineering, VTU Regional centre, Muddenahalli, chikballapur, Bangalore, karnataka, India

Email id: murthy362@gmail.com[1]

Abstract:

The integration of nanomaterials into fiber-reinforced composites has opened new avenues for enhancing their mechanical and functional performance. The work aims to find out the storage modulus, and loss modulus concerning the Time, Frequency, and Temperature and compare the prepared sample values with each other to attain the optimum percentage of the graphene in the composite. The Novelty of the work is to give new ideas on the composite mixtures of epoxy filled with Graphene, carbon fiber-reinforced composite under dynamic loads. The results obtained by the testing of the samples by Dynamic mechanical analysis: Storage modulus and loss modulus. The maximum value of storage modulus of the 2% graphene sample is 15300 Mpa at 10Hz; 240 Celsius; 6 seconds, the loss modulus of the sample is 903 Mpa at 10Hz; 760 Celsius; 10 mins. For 4 % of the graphene sample, the storage modulus maximum value is 11700 Mpa at 10Hz; 260 Celsius; 6 seconds, the loss modulus of the sample is 862 Mpa at 5Hz; 710 Celsius; 8.7min. For a 6% sample, the storage modulus maximum value is at 4790 Mpa at 10Hz; 260 Celsius; 7.3min. The loss modulus of the sample maximum values is 457 Mpa at 0.1 Hz; 740 Celsius; and 9.7min. By comparing the values at different percentages of graphene, it is drawn that on increasing the percentage of the graphene (Nano filler) the value of the tensile, flexural, loss modulus decreases, and on increase in the percentage of the graphene in the composite the storage modulus also decreases for the parameters.

Keywords: Graphene; Storage modulus, loss modulus, Nano fillers, CFRP, Tensile, flexural.

1. INTRODUCTION

This experiment specifically aimed to determine the relationship between the impact of graphene loading at various weight percentages and the ensuing impacts on fracture toughness. several factors, including the aspect ratio of graphene-controlled fracture toughening mechanisms, particle size and shape, orientation, potential synergistic interactions, and enhanced overall toughening of epoxy composites. Among them, homogeneity and homogeneous graphene dispersion in epoxy are unquestionably the most important prerequisites for managing fracture toughness [1]. This study validated the feasibility of modulating elastic-plastic mechanical behavior by applying Nano-sized GnPs and HNT fillers to complicate epoxy resin-based Nanocomposites. Young's modulus of elasticity showed a complex nonlinear pattern as the concentration of GnP filler increased. Concurrently, within the 0–1 concentration range wt% GnP nanofiller concentration, the investigated nanocomposites' ductility increased. [2]. with vacuum bag-only compaction and VBC prepregs, autoclave-quality components can be produced in normal ovens or other non-autoclave setups. Before being completely saturated with surrounding resin during cure, the partially impregnated microstructure of this class of materials encourages gas evacuation and suppresses defect formation during the early phases of processing. The phenomena of linked air evacuation, resin flow, fiber bed compaction, and void formation (or collapse) [3]. Experimental work was done to characterize the static and dynamic mechanical properties of woven fabric plain weave glass/carbon inter-plied hybrid composite laminates. For four-layer composite laminates, the impact of stacking sequence on mechanical properties was examined. Except for impact strength, dedicated carbon laminate has greater mechanical strength than dedicated glass laminate. The H2 hybrid arrangement has a higher flexural strength than the H1 hybrid laminate, and there is very little difference in the tensile and impact strengths of the hybrid laminates. The H2 hybrid laminate has a higher storage modulus, loss modulus, and loss factor in comparison to the H1 hybrid laminate and the dedicated carbon laminate. To enable a greater operating temperature, the glass transition temperature (Tg) of H2 laminate was moved from the dedicated glass laminate by 5 degrees Celsius. [6].

2. MATERIALS AND METHODS

Fiber-reinforced polymer (FRP) composites, particularly those based on carbon fiber and epoxy resin, have garnered significant attention in high-performance structural applications due to their exceptional mechanical strength, stiffness, low weight, and chemical resistance. These composites are widely used in aerospace, automotive, marine, and civil engineering sectors. However, the increasing demand for materials with multifunctional capabilities and enhanced dynamic performance—such as improved damping, thermal stability, and fatigue resistance—has motivated the incorporation of nanomaterials into conventional FRP systems [7]. Dynamic Mechanical Analysis (DMA) is a powerful technique for evaluating the viscoelastic behavior of composites across a temperature range. Parameters such as storage modulus (E′), loss modulus (E″), and damping factor (tan δ) provide valuable insights into the stiffness, energy dissipation, and glass transition phenomena in polymer composites. By analyzing these parameters, the influence of graphene nanofillers on the thermal-mechanical performance of carbon fiber–epoxy laminates can be better understood [8] [9]. This study aims to investigate the effect of graphene nanofiller content on the dynamic mechanical properties of carbon fiber–epoxy composites. Composites with varying graphene concentrations were fabricated, and their viscoelastic response was evaluated using DMA [10]. The findings contribute to the development of high-performance composite systems with tailored dynamic and thermal properties for demanding engineering applications

Plain Carbon fiber: The fiber is utilized for the reinforcement in the polymer composites utilizing carbon fiber of 0.5mm measurement. The carbon fiber is the greatest among the fiber-fortified materials due to its good mechanical and efficient attributes.

2.Epoxy resin (LY-556): Epoxy is used as a lattice in polymer composites. It is obtained from Araldite LY-556 Huntsman, Ciba-Geigy India Ltd association. Epoxies are used by the polymer business in one or two ways. Epoxy in blends with carbon fiber to deliver high-quality composites or strengthened plastics that give enhanced mechanical, and thermal properties.

3.Hardener (HY-951): A hardener is used as a response specialist. It goes probably as an impetus. It is added to the sap at ten to one extent to solidify. In the current work, Aradur HY-951 is used as a binder in the matrix LY - 556. To achieve a higher pot life, the cover lid is to be shut in the wake of utilizing the material.

4.Fabrication of Nanocomposites: The hand rest-up technique is the most un-complex strategy for composite creation

- Fabrication of CFRP Laminates (Hand Lay-up Technique)
- A flat glass mold was cleaned and coated with a releasing agent.
- A layer of plain weave carbon fiber was placed in the mold.
- The prepared epoxy/graphene resin system was uniformly applied over the carbon fiber layer using a brush and roller.
- Additional layers (typically 4–6 plies) were stacked, with resin applied between each layer.
- The entire layup was compacted and covered with a vacuum bag setup (if available) to reduce porosity.
- Curing was performed at room temperature for 24 hours, followed by post-curing at 60°C for 3 hours in an oven to enhance cross-linking.

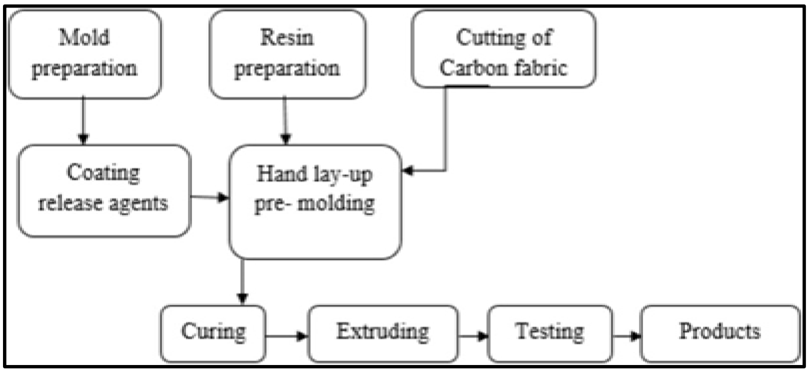

Figure 1: Flowchart of Fabrication

Experimental process:

The samples were prepared by employing the hand layup technique. A mould with dimensions of 300 mm × 300 mm was used for fabrication. The process involved manually layering the reinforcement materials and resin, ensuring proper impregnation and removal of air bubbles before curing

Figure 2: Samples Prepared by Using Hand Layup Process

Hand layup method for CFRP composite: Experimentation is carried out by using the Hand layup method with a mould size of 300 x 300 mm. The mould is prepared using wood planks coated with PVA. CFRP mat at a thickness of 200 gsm is used to fabricate laminate, nanographene filler mixed with epoxy. Ultrasonication is used for uniform distribution of nanofiller, roller impregnation method is adopted to prepare 3 mm laminate from 45°C to 120°C by keeping the closed mould for 24 hours. Graphene filler has been added with different proportions 2%, 4%, and 6%. Post curing temperature adopted between 75°C - 80°C. Extracted laminates from mould as per the ASTM standards. Mechanical and Thermal Properties have been evaluated from the obtained samples to finalize the best proportion of nanographene.

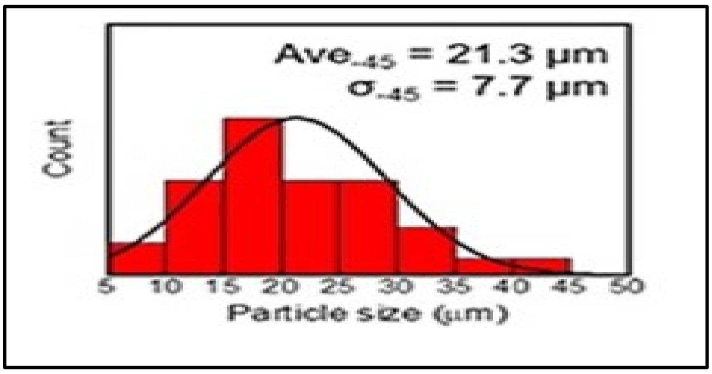

Figure 3: Graphene nano particle size

3. RESULTS AND DISCUSSIONS

The following are the results for the samples prepared with different percentage of graphene added CFRP laminates developed in the hand layup method. The experimental results for the 3 proportionate samples tested for Mechanical properties (Tensile, Compressive and Flexural) to check the strength of the laminate as given in the table

Table 1: Mechanical properties of CFRP with different Graphene proportions

Sample	Tensile strength MPa	Compressive strength MPa	Flexural strength Mpa
2%Nano grephene	220	105	115
4%Nano grephene	205	102	108
6%Nano grephene	201	98.3	103

DMA (Dynamic mechanical analysis) to check the viscoelastic properties of the selected laminates

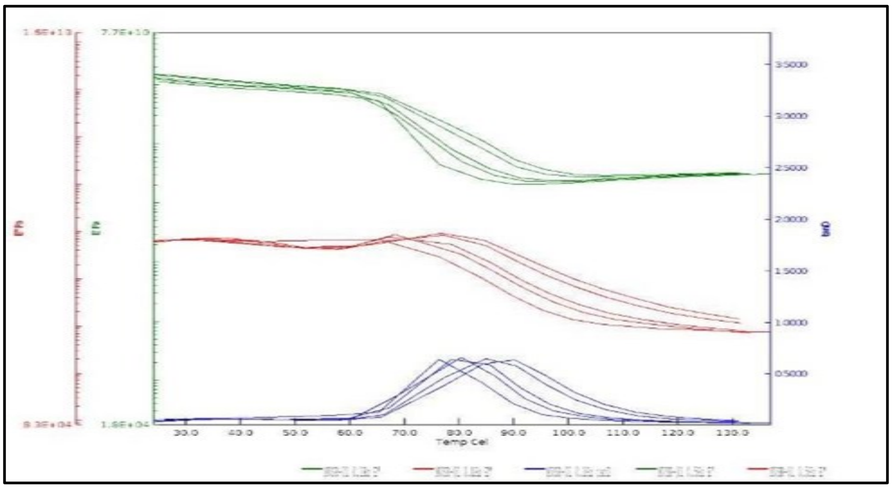

Figure 4: DMA Graph For 2% of the Graphene Sample

Figure 4 shows the Dynamic Mechanical Analysis (DMA) results of a carbon fiber–epoxy composite filled with 2 wt% graphene nanoparticles, plotted over a temperature range (30°C to ~130°C). The three curves represent:

- Green curves (Storage Modulus, E′): Reflects the material's stiffness. It shows a gradual decrease with increasing temperature, with a notable drop around 80–100°C, indicating the glass transition region (Tg).
- Red curves (Loss Modulus, E″): Indicates the energy dissipated as heat. The peak near the Tg region highlights maximum molecular motion and energy dissipation.
- Blue curves (Tan δ): The ratio of loss to storage modulus, representing damping behavior. The tan δ peak gives a precise indication of the glass transition temperature, here occurring around 90–100°C, confirming the improved thermal performance due to graphene addition.

Table 2: Loss Modulus and its Values (Experimental Data, Maximum Values)

Freq. (Hz)	Temp. (°C)	E'(G') (Pa)	E''(G'') (Pa)	dL (um)	tanD	Ft (mN)	Time (min)
0.1	76.30853	4.46E+08	286248003.6	1004.957	0.641468	0	10.38333
10	76.7627	2.43E+09	902595772.4	1006.346	0.370779	0	10.46667
5	77.24136	1.84E+09	841221592.7	1004.957	0.457761	0	10.55
1	78.63354	8.16E+08	523910235.2	1004.957	0.641668	0	10.81667

From above table 2, the Loss modulus (maximum) is 903 Mpa, Frequency 10Hz, Time 10mins, Temperature 760 Celsius.

Table 3: Storage Modulus and Its Values (Experimental Data, Maximum Values)

Freq. (Hz)	Temp. (°C)	E'(G') (Pa)	E''(G'') (Pa)	dL (um)	tanD	Ft (mN)	Time (min)
10	24.0985	15265544374	5.95E+08	985.5128	0.038998	0	0.1
5	24.1007	14780510873	6.00E+08	985.5128	0.040594	0	0.183333

1	24.10007	13401623502	6.28E+08	985.5128	0.04686	0	0.333333
0.5	24.15508	12816618217	6.31E+08	985.5128	0.049259	0	0.516667

From the above Table 3, the Storage modulus (maximum) is 15300 mpa Frequency 10 Hz, Time 6 sec, Temperature 240 Celsius. Values at 700 Celsius Frequency 0.1Hz Temperature 700 Celsius Storage modulus 1380 mpa Loss modulus 618 mpa Time 8.5 minutes. Values at 900 Celsius Frequency 10Hz Temperature 900 Celsius Storage modulus 361 mpa Loss modulus 204 mpa Time 13.16 minutes Loss modulus peak at 740 Celsius Frequency = 0.5 Hz Loss modulus 633mpa Time 9.03 minutes.

Table 4: Storage Modulus and Its Values (Experimental Data, Maximum Values)

Freq. (Hz)	Temp. (°C)	E'(G') (Pa)	E''(G'') (Pa)	dL (um)	tanD	Ft (mN)	Time (min)
10	26.75523	11701028549	244492386.4	-251.979	0.020895	0	0.1
5	26.80772	11493870175	255395694.9	-248.507	0.022222	0	0.183333
1	26.91899	11110947325	248655332.6	-248.507	0.022379	0	0.333333
0.5	27.11451	10955093215	238362108.9	-248.507	0.021758	0	0.516667

From table 4, it shows the Storage modulus (maximum value) is 11700mpa Frequency 10 Hz, Time 6 sec, and Temperature 260 Celsius.

Table 5: Loss Modulus and Its Values (Experimental Data, Maximum Values)

Freq. (Hz)	Temp. (°C)	E'(G') (Pa)	E''(G'') (Pa)	dL (um)	tanD	Ft (mN)	Time (min)
0.100000001	71.15659	1380210284	618150375.4	-254.063	0.447867	0	8.533333
10	71.5469	4007830439	823019514.6	-263.09	0.205353	0	8.616667
5	71.95715	3289286021	861517249.9	-265.174	0.261916	0	8.7
1	72.62331	1821904705	789208877.7	-265.174	0.433178	0	8.85
0.5	73.45917	1156751935	633467302	-264.479	0.547626	0	9.033333
0.100000001	79.25979	252055041.7	130748439.7	-260.313	0.51873	0	10.43333

Loss modulus (maximum) 862mpa, Frequency 05Hz, Time 8.7mins, Temperature 710 Celsius

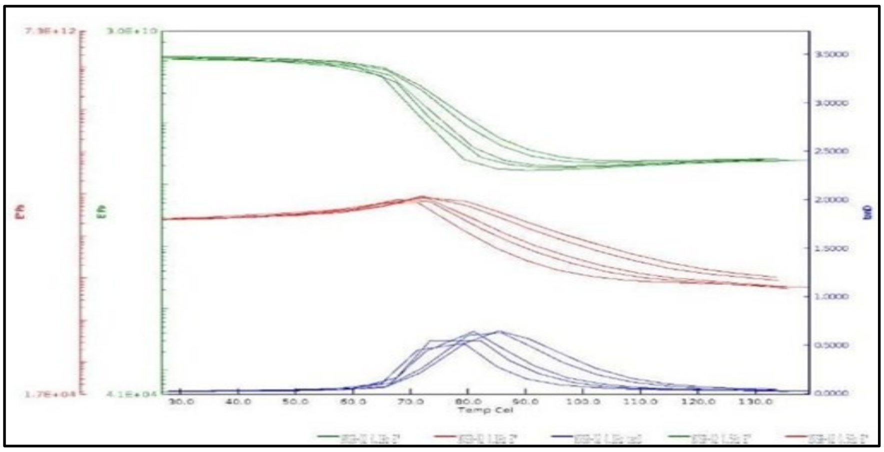

Figure 5: DMA Graph For 4% Of the Graphene Sample

From the figure 5, the red colour curve denotes “loss modulus”. The green color curve denotes “Storage modulus”. The blue colour curve denotes “damping modulus”. Frequency intervals (in Hz) 10, 5, 1, 0.5, 0.1. By comparing the above data figure with the reference figure, we can easily analyze the regions of the curve. The rubber plateau starts at 700 Celsius and ends at 900 Celsius for the storage modulus curve. The peak curve happens at the temperature of 750 Celsius for the loss modulus curve.

Table 6. Storage Modulus Experimental Data (Maximum Values)

Freq. (Hz)	Temp. (°C)	E'(G') (Pa)	E''(G'') (Pa)	dL (um)	tanD	Ft (mN)	Time (min)
0.1	63.0702	3987811783	317042234.2	-398.506	0.079503	0	7.266667
10	63.48942	4791565208	195229897.7	-401.284	0.040744	0	7.35
5	63.93627	4701586990	209045073.3	-401.978	0.044463	0	7.433333
1	64.68787	4406948789	253903483.3	-401.978	0.057614	0	7.583333
0.5	65.64048	4209466274	291762145.5	-402.673	0.069311	0	7.766667

Table 6, shows the Storage modulus and its values Frequency 10Hz, Temperature 630 Celsius Storage modulus 4791 mpa, Time 7.35 minutes

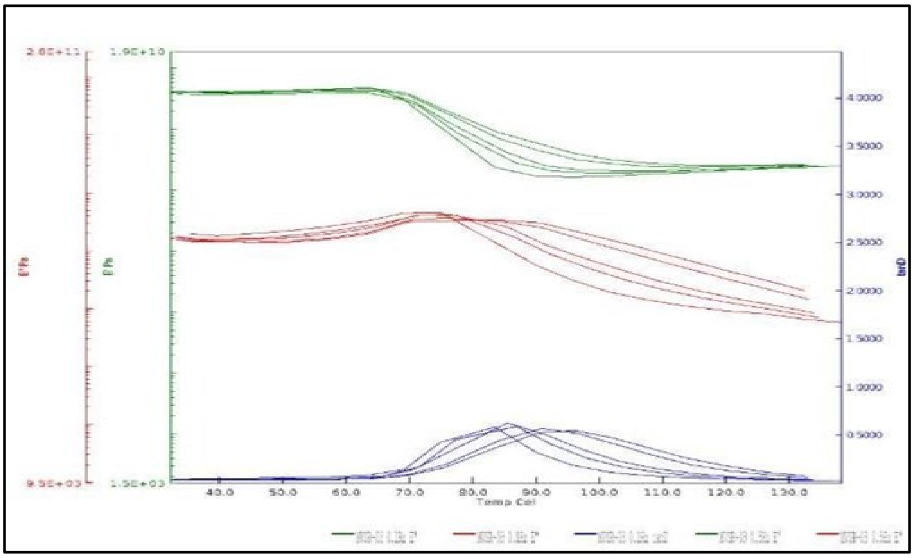

Figure 6: DMA Graph For 6% of the Graphene Sample

Table 7: Loss Modulus Experimental Data (Maximum Values)

Freq. (Hz)	Temp. (°C)	E'(G') (Pa)	E''(G'') (Pa)	dL (um)	tanD	Ft (mN)	Time (min)
0.5	71.57912	2392644099	412188637.7	-429.062	0.172273	0	8.983333
0.1	74.91206	1079474804	456893200.5	-438.089	0.423255	0	9.7
10	75.29181	2143586165	329793314.4	-451.284	0.153826	0	9.783333
5	75.68717	1889154029	364034321.8	-447.117	0.192697	0	9.866667
1	76.3756	1275366111	421930729.4	-440.173	0.330832	0	10.01667

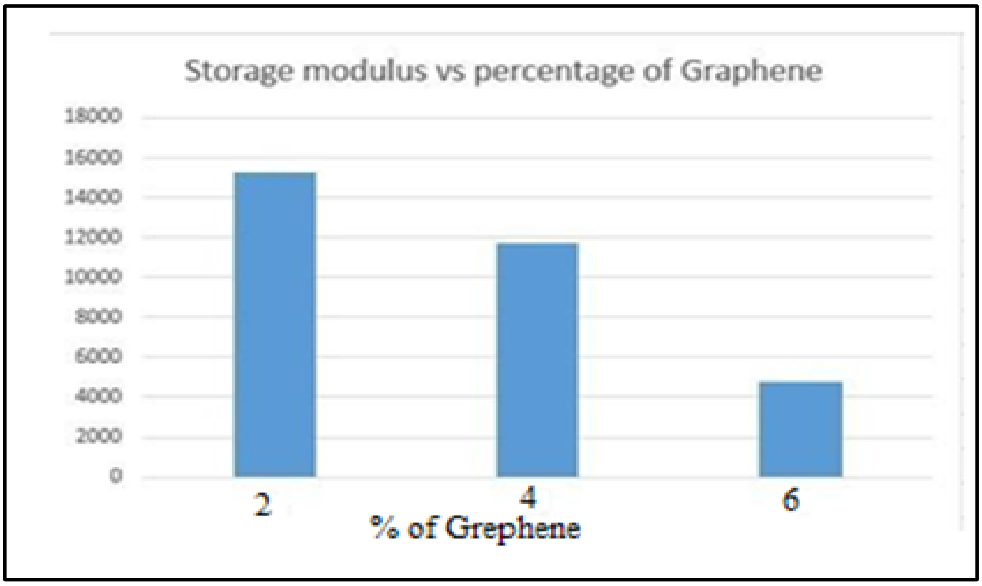

Figure 7: Storage Modulus Vs Percentage of The Graphene

From Table 7, the Loss modulus and its values, the Frequency 0.1 Hz, Temperature 740 Celsius Loss modulus 457mpa, and Time 9.7 minutes. By comparing the Experimental data results provided in the above graphs, a clear analysis of the storage and loss modulus of the carbon fiber graphene Nanocomposite is shown in Table 8.

Table 8. Comparison Table for Percentage of Graphene, Loss Modulus, and Storage Modulus.

S. No.	Sample Nano Grephene (%)	Storage Modulus E'(G')	Loss Modulus (MPa)
1	2%	15300	903
2	4%	11700	862
3	6%	4790	457

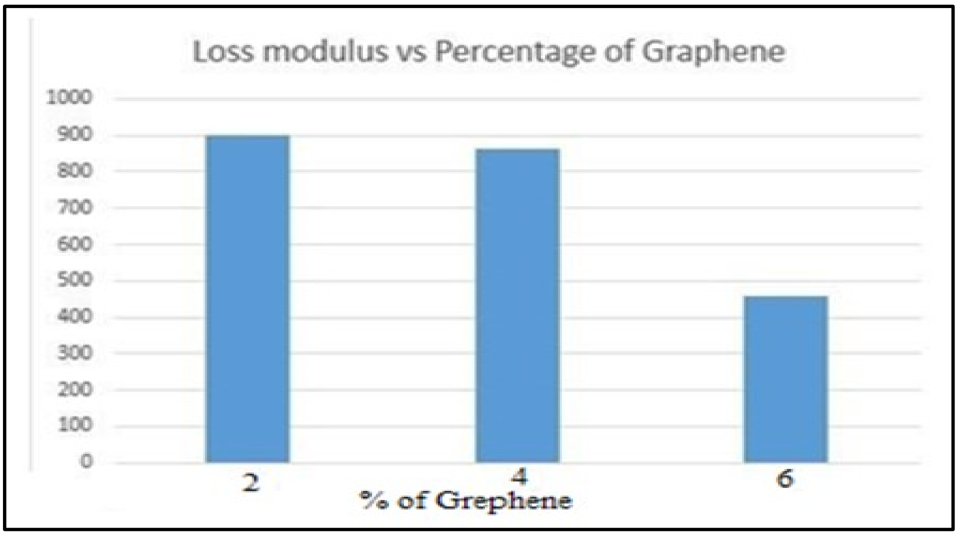

Figure 8: Loss Modulus Vs Percentage of the Graphene

By analyzing the data, we can reason that with an expansion in the graphene rate the capacity and loss modulus diminishes as shown in figures 7 and 8. Loss modulus is reliant upon the temperature since the expansion in temperature the Loss modulus diminishes. Storage modulus is reliant upon the sub-atomic movement of the primary chain of the polymer. During the warming cycle when the intensity goes through the glass progress temperature the most extreme pinnacle will be accomplished in the bend of the Tan (D). At the point when the expansion in the Nano filler content how much free volume diminishes the versatility of particles and builds the contact by an enormous substance in polymers so because of this stockpiling modulus and Tan (D) diminishes.

Conclusion

The incorporation of graphene nanofillers into carbon fiber–reinforced epoxy (CFRP) composites significantly enhance their dynamic mechanical properties. Using plain carbon fiber, LY-556 epoxy resin, and HY-951 hardener, composite laminates were fabricated via the hand lay-up technique with varying graphene nanoparticle loadings (2%, 4%, and 6% by weight). Dynamic Mechanical Analysis (DMA), along with tensile, compression, and flexural strength tests, revealed that the addition of graphene improved the stiffness, damping capacity, and overall mechanical performance of the composites. Notably, the most effective enhancement was observed at lower filler concentrations (2%–4%), where mechanical properties improved by approximately 10–15% compared to the unfilled composite. These improvements are attributed to the high surface area, superior mechanical strength, and excellent interfacial bonding of graphene with the epoxy matrix, resulting in better load transfer and energy dissipation. However, at higher filler content (6%), a slight reduction in performance was noted, likely due to agglomeration of graphene particles, which hinders uniform stress distribution. Thus, an optimal graphene content exists, beyond which the benefits may diminish.

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