Experimental investigation on mechanical and wear properties of GNP/Carbon fiber/epoxy hybrid composites

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Abstract

In this research, carbon fiber and Graphene nanoplatelets (GNP) of different weight percentages of GNP (0, 0.1, 0.3, and 0.5 wt%) reinforced hybrid composites were fabricated via hand layup technique followed by compression molding. For wear analysis to understand the correlation between control parameters (wt% of filler, normal load, velocity, and sliding distance) and response measurements (weight loss), the design of experiments and analysis of variance (ANOVA) is used. The control variables such as normal loads (5, 10, 15, and 20 N), velocity (1, 2, 3 and 4 m s\(^{-1}\)), and sliding distance (200, 300, 400, and 500 m) are selected for the research. It was observed that 0.5 wt% GNP-filled carbon fiber/epoxy composite shows higher tensile and flexural strength than another composite. It has been discovered that adding GNP reduces the wear in terms of weight loss. Scanning electron microscopy (SEM) was used to examine composites’ worn surfaces. The analysis concluded that experimental results are closer to optimum results.

1. Introduction

Polymer matrix composites (PMC) have been more popular than metal matrix composites due to their lightweight, low cost, and easy processibility. Thermoset and thermoplastic are the two types of matrix material used in PMC. Thermoset polymer composites have better mechanical properties as compared to thermoplastic composites. So, thermoset polymer composites are applied mainly in automotive, structural components, aerospace, sport, and chemical industries [1–3]. The epoxy resin used as a matrix material in polymer composites has several advantages. It is highly recommended for many structural, automotive, and other applications due to its high-temperature resistance, high stiffness, and better corrosion resistance. Inherent brittleness and low toughness sometimes are the main disadvantage of epoxy used as a matrix in the composites [4–6]. Automobile components and industrial equipment are increasingly made of hybrid fiber-reinforced polymer composites. These are widely utilized in applications that require abrasion resistance [7, 8]. As matrices, various polymers are being used, with epoxy, the most commonly used thermostetting polymer due to its high mechanical characteristics, moisture, and corrosion resistance. The fiber reinforcement improves the load-bearing capability in the polymer matrix [9–11]. In addition, polymer composites reinforced with woven fiber have better wear properties [12]. Due to their greater physical and mechanical qualities, mainly carbon-based filler and fiber-based composites, are being investigated as prospective predicted materials for diverse tribological usage [13, 14]. All mechanical properties were maximum at 0.5 wt% combination of GNP/NCA in environmental aging conditions [15]. Different wt% of GNP (0.1, 0.2, 0.3) were used to make CFRP, glass fiber reinforced (GFRP) and aramid fiber reinforced polymer (AFRP) composites. Results show that maximum tensile strength was achieved at 0.2 wt% GNP for CFRP and GFRP composites. For AFRP it does not give any effect. Kevlar and flex fiber used with different layer combination to make epoxy hybrid composites [16]. Mechanical properties were studied with different combination and configurations of layers. Thermal conductivity, thermal stability, storage modulus, damping ratio are improved by using CNT and GNP nanofiller [17]. Boron nitride (BN) or GNP is used for making epoxy composites at different wt% (1, 2, 3 and 4). GNP-filled epoxy composites show excellent mechanical characteristics and thermal conductivity as compared...
BN-filled composites. At 4% of GNP, thermal conductivity is the maximum of epoxy composite [18]. The addition of GNP lowered the wear volume loss in the GFRP composites from a tribological viewpoint. Furthermore, a considerable amount (1 wt%) of GNP improved the composite materials’ tribo-mechanical performance significantly. However, the tensile strength increased slightly when one wt% of GNP was used instead of 0.5 wt% of GNP [19]. To investigate the advancement of the tensile and tribological performance of epoxy composites containing MWCNT and nano-silica [20]. Ultrahigh molecular weight polyethylene and MoS2 fillers improve load-bearing applications’ mechanical and tribological properties [21]. The influence of multi-wall carbon nanotubes and graphene oxide nanosheets on the tribological characteristics of epoxy composites is investigated [22]. The results show that adding CLP (citrus limetta peel) fillers to the epoxy matrix.

![Figure 1. (a) FESEM image of GNP (b) EDS spectrum area & (c) EDS map for element distribution for GNP.](image)

| Table 1. Properties of woven Carbon fiber and GNP (supplier data). |
|-------------------|------------------|---------------------|
| Materials         | Specifications   | Units               |
| Carbon fiber      | Density          | 1.8 g cm$^{-3}$     |
|                   | Filament diameter| 7 um                |
|                   | Tensile strength | 3450 MPa            |
|                   | Tensile modulus  | 230 GPa             |
|                   | Melting point    | 3652 °C–3697 °C     |
| GNP               | Thickness        | 2–10 nm             |
|                   | Appearance       | Black grey powder   |
|                   | Carbon content   | 99.5%               |
|                   | Bulk density     | 0.10 g ml$^{-1}$    |
|                   | Surface area     | 20–40 m$^2$ g$^{-1}$|
|                   | Melting point range | 3650 °C–3700 °C    |
enhances the wear resistance of the composites significantly [23]. Carbon–epoxy and glass–epoxy composites’ abrasive wear behavior have been examined [24]. These studies revealed that functional fillers such as carbon nanofiller and inorganic nanofilms significantly impact wear characteristics. Many different model of wear calculated wear rate as a function of weight percent of filler, mechanical qualities, normal load, etc [25–27]. The previous wear models and experimental investigations have one major flaw: they do not account for the impact of specific parameters on composite abrasive wear. The traditional and Taguchi methods can investigate the effect of particular elements on single response situation optimization [28–30]. However, in tribological situations, multiple response optimization is required. Each response’s optimization is calculated separately to use the technique mentioned above to tackle optimization problems with numerous replies. Then the total optimization is determined by engineering expertise [31, 32].

The current study is unique because it intends to analyze the mechanical and abrasive wear performance of GNP/Carbon fiber reinforced epoxy composites. The novelty of this work is to investigate and compare the effect of adding GNP to the CFRP composites on its mechanical and abrasive wear properties. Hybrid laminates with different weight percentages (0, 0.1, 0.3, and 0.5) of GNP with eight bidirectional carbon woven fibers followed by stacking sequence [0/−45°/+45°/90°] were prepared. This combination and stacking sequence of fiber orientation have never been used before for comparing mechanical and wear characteristics. Currently, there is limited work on the phenomena of abrasive wear in multi-pass settings [19, 33–36]. The present findings could lead to a rise in the use of GNP/Carbon fiber reinforced epoxy composites. ANOVA and Taguchi’s method is implemented to determine the best parameters for wear in terms of weight loss (M) and then compare with optimum experimental results.

2. Experimentation

2.1. Materials
Thermosetting epoxy (LY-556) and hardener (HY-951) were bought from Go Green Pvt. Ltd, India. Bidirectional carbon woven fabric of 200 GSM (grams per square meter) and fibers of about 6–8 μm diameter were obtained from Go Green Pvt. Ltd, India. Graphene nanoplatelets (GNP) were used as a secondary reinforcement obtained from Sisco Research Laboratories Pvt. Ltd, India. Table 1 shows the properties of reinforcing materials. Figure 1 shows the FESEM image, EDS spectrum, and elements present in GNP.
2.2. Fabrication method
First of all, epoxy was taken in a beaker as per requirement and preheated in a muffle furnace between 75 °C–85 °C for at least half an hour to increase the viscosity of epoxy. The different weight percentages of GNP (0, 0.1, 0.3, and 0.5%) were taken and preheated in a furnace for 2 h. Preheating of GNP is required for removing the moisture content in GNP powder. Then GNP powder was mixed with acetone, and a probe ultrasonicator was used for proper dispersion of GNP powder for half an hour. Then epoxy is mixed with GNP/acetone solution, and this solution was put on the magnetic stirrer at 300 rpm for 20 min. Then speed was increased to 600 rpm for another 10 min to get a homogeneous mixture of GNP and epoxy. The temperature of the magnetic stirrer was maintained at 75 °C for complete removal of acetone. After this ultrasonicator was used in ice-cooled water for mixing and proper dispersion of nanoparticles in epoxy for one hour. Then epoxy is mixed with GNP/acetone solution, and this solution was put on the magnetic stirrer at 300 rpm for 20 min. Then speed was increased to 600 rpm for another 10 min to get a homogeneous mixture of GNP and epoxy. The temperature of the magnetic stirrer was maintained at 75 °C for complete removal of acetone. After this ultrasonicator was used in ice-cooled water for mixing and proper dispersion of nanoparticles in epoxy for one hour. Then furnace was used at 60 °C for 10 min for removal of the remaining acetone in the mixture. A curing hardener was added to the mixture at room temperature in a ratio of 10:1. After cooling at room temperature, the hand layup technique was used for making laminated composites of eight layers of carbon fabric. After proper mixing, it was poured into the die, and carbon fibers were piled up one above the other with epoxy/GNP solution. Then the die was placed in the compression molding machine under the 25KN load for 24 h. A flat steel roller was used to maintain the uniform thickness of the laminate composites. At the top and bottom of the die, wax was used to remove composite sheets easily. After curing, the sheet (150 mm × 150 mm × 4 mm) was removed and cut the samples from the prepared sheet. Figure 2 shows the equipment used for the fabrication process.

Table 2. Composites designation and physical properties.

| Materials (Designation) | Density | Shore-D hardness |
|-------------------------|---------|-----------------|
| Neat carbon fiber/Epoxy  | 1.415   | 81              |
| Epoxy/Carbon fiber/0.1% GNP (GFE-1) | 1.386 | 84              |
| Epoxy/Carbon fiber/0.3% GNP (GFE-3) | 1.357 | 86              |
| Epoxy/Carbon fiber/0.5% GNP (GFE-5) | 1.326 | 87              |

Figure 3. (a) Tensile specimen and testing machine (b) Flexural specimen and testing machine.
2.3. Sample preparation and testing
Table 2 shows the designation of all the samples and shore hardness of composites. For finding mechanical properties, tensile and flexural tests were performed. Tensile and flexural tests of laminated composites were performed on UTM (universal testing machine) INSTRON 3382/50 K. According to ASTM D638- TYPE IV, specimens were prepared for the tensile test. The test was done with a cross-head rate of 1 mm min$^{-1}$, conducted at room temperature. Composite specimens were constructed according to ASTM D790 for the flexural test. Figure 3 shows the specimen and testing machine for tensile and flexural tests.

2.4. Abrasive wear test
The abrasive wear performance [19, 26] of different composites was investigated using a pin-on-disc machine using waterproof SiC (400 grits size) paper from DUCOM, Bangalore, India. A diamond cutter was utilized to cut 10 mm $\times$ 10 mm square specimens from composite laminates for wear testing according to the ASTM G99 standard. These composite specimens were attached to a 30 mm long steel pin with a diameter of 10 mm. After that, the specimen and pin assembly were attached and abraded using SiC paper (1200 grit) to achieve homogeneous surface contact. The experiment was revised three times, and the average value was taken to calculate the wear loss. The following operating parameters were used to explore the effect of abrading distance: variable load: 5, 10, 15, and 20 N, the sliding velocity of 1, 2, 3, and 4 m s$^{-1}$, and abrading distances of 200, 300, 400, and 500 m were used. Electronic balance was used to determine the specimen’s weight loss. Figure 4 shows the wear test specimen and pin on the disc machine for test.

2.5. Design of experiments: Taguchi method
Table 3 shows the operating range of input parameters and the levels used. This method employs two essential tools: (i) the S/N ratio to assess the quality and (ii) orthogonal arrays to adopt several elements impacting wear simultaneously. From table 4, an L16 orthogonal array was adopted according to the Taguchi design principle [25, 28–32, 37]. Minitab statistical software was used to create all of the designs, graphs, and analyses in this study. Depending on the sort of characteristics, different S/N ratios are available. ‘Smaller is better’ refers to a property where a lower value indicates more outstanding performance [31].

![Figure 4. (a) Wear specimen (b) Pin on disc machine.](image)

| Parameters          | Units | Level 1 | Level 2 | Level 3 | Level 4 |
|---------------------|-------|---------|---------|---------|---------|
| Percentage of filler (P) | %     | 0       | 0.1     | 0.3     | 0.5     |
| Normal load (Q)     | N     | 5       | 10      | 15      | 20      |
| Velocity (R)        | m s$^{-1}$ | 1       | 2       | 3       | 4       |
| Sliding distance (S) | m     | 200     | 300     | 400     | 500     |

Table 3. Levels of input parameters.
2.6. SEM analysis

The morphology of worn surfaces of composites was analyzed by scanning electron microscopy using the ‘EV018, ZEISS’ setup. Gold coating using a sputter coater (model: JEOL JFC 1600, USA) was done on the top surface of the sample before imaging.

3. Results and discussion

3.1. Microstructural analysis

Figures 5(a) and (b) show SEM images of pure epoxy and epoxy/GNP composite. Image 5(b) clearly shows the uniform dispersion of GNP in the epoxy matrix. Fiber orientation and volume fraction of fiber have an important impression on the mechanical properties of hybrid epoxy composites. FESEM images characterized the morphology study of GNP-filled carbon/epoxy composites. In figures 6(a)–(d) are the FESEM images of 0%, 0.1%, 0.3% and 0.5% GNP filled epoxy hybrid composites respectively. The images clearly show the bonding between the carbon fiber, GNP filler, and epoxy. It was discovered that adding GNP to the carbon fibers and epoxy enhances their adhesiveness. This adhesive nature increases the bonding strength between fiber and resin. The addition of GNP can suppress the crack formation and expansion and improve epoxy composites’ mechanical and other properties.

For analyzing the mechanical properties, it was observed that the best dispersion of GNP is achieved in 0.5% GNP-filled composites. The maximum tensile and flexural properties are found in 0.5% GNP-filled composites.

| Exp.no. | Percentage of filler (P) in (%) | Normal load (Q) in N | Velocity (R) in m s⁻¹ | Sliding distance (S) in m | Weight loss (M) in mg | SNRA1 |
|---------|--------------------------------|---------------------|-----------------------|-------------------------|----------------------|-------|
| 1       | 0                              | 5                   | 1                     | 200                     | 44                   | −32.869 |
| 2       | 0                              | 10                  | 2                     | 300                     | 58                   | −35.2686 |
| 3       | 0                              | 15                  | 3                     | 400                     | 69                   | −36.7770 |
| 4       | 0                              | 20                  | 4                     | 500                     | 80                   | −38.0618 |
| 5       | 0.1                            | 5                   | 2                     | 400                     | 45                   | −33.0643 |
| 6       | 0.1                            | 10                  | 1                     | 500                     | 53                   | −34.4855 |
| 7       | 0.1                            | 15                  | 4                     | 200                     | 59                   | −35.4170 |
| 8       | 0.1                            | 20                  | 3                     | 300                     | 63                   | −35.9868 |
| 9       | 0.3                            | 5                   | 3                     | 500                     | 46                   | −33.2352 |
| 10      | 0.3                            | 10                  | 4                     | 400                     | 51                   | −34.1514 |
| 11      | 0.3                            | 15                  | 1                     | 300                     | 50                   | −33.9794 |
| 12      | 0.3                            | 20                  | 2                     | 200                     | 49                   | −33.8039 |
| 13      | 0.5                            | 5                   | 4                     | 300                     | 35                   | −30.8814 |
| 14      | 0.5                            | 10                  | 3                     | 200                     | 32                   | −30.1030 |
| 15      | 0.5                            | 15                  | 2                     | 500                     | 37                   | −31.3640 |
| 16      | 0.5                            | 20                  | 1                     | 400                     | 38                   | −31.5957 |

Figure 5. SEM of (a) Pure epoxy and (b) Epoxy and GNP composite.
In images 6 (a), non-uniform dispersion, higher void content, and filler aggregation are observed. Due to this, tensile and flexural properties are less for GFE-0 than other composites. From FESEM images, it is monitored that good dispersion and bonding of GNP nanofiller in carbon fiber, and epoxy matrix in the case of GFE-3 and GFE-5 samples enhance the mechanical strength of these hybrid nanocomposites [16]. Figure 7 shows the EDS mapping of all the composites. EDS images show the element distribution present in composites. EDS image show as GNP percent increases, the weight percent of C is increased.
Figure 8. Tensile properties of composites.

Figure 9. Tensile stress versus strain graph of different composites.

Figure 10. Flexural properties of composites.
3.2. Mechanical properties

3.2.1. Tensile strength

The tensile behavior of the neat and GNP-filled carbon fiber/epoxy composites is shown in figure 8. The stress versus strain graph shows the tensile behavior of all the composites, shown in figure 9. It is seen that tensile strength and Young’s modulus increase with an increase in wt% of GNP. It was observed that at 0.1%, 0.3% and 0.5% of GNP, tensile strength is increased by about 3.2%, 7.3, and 11.4% compared to GFE-0. The value of Young’s modulus is higher in all GNP-reinforced composites than in GFE-0. The addition of GNP reduces the mobility of the epoxy-fiber interface, resulting in a stiffer structure. Even though nanofillers have many areas to scatter at low weight percent, they can form strong contacts with the matrix, which improves stress transmission to the matrix. The fillers become swarming and aggregating at high percentages, increasing the chances of clustering. Because these aggregates produce stress concentration zones, cracks can quickly form [18].

More elevated nanofiller up to a certain level involved in composites leads to non-uniform dispersion of nanoparticles in composites and agglomeration of filler [16]. These are the two leading causes of stress concentration in hybrid polymer composites. Sometimes, the bonding among matrix, fiber, and nanoparticles becomes poor due to difficulty wetting carbon fiber and GNP particles with the epoxy matrix. Fiber reinforcement and its orientation in composites are more critical factors affecting composites’ tensile nature than nanofiller. Hence, load transfer from matrix to reinforcement is ineffective in composites with higher filler content.

3.2.2. Flexural strength

Figure 10 shows the value of strength and modulus of neat and GNP-filled polymer composites. According to the findings, the addition of GNP up to 0.5 wt% increased flexural modulus and strength. The maximum
Exural strength and modulus were observed for GFE-5, 720.25 MPa, and 40.5 MPa, respectively. There is a 2.1%, 4.2%, and 8.0% increment in flexural strength of GFE-1, GFE-3, and GFE-5 compared to GFE-0. This is the mechanical interlocking of GNP particles with the matrix. This is mainly due to the GNP particles’ surface geometry. This interlocking is present between the layers of the carbon fiber. It gives additional stiffness and flexural strength to the composites [38]. GNP nanoparticles avoid the mobility of fiber layers over the epoxy matrix and restrict the epoxy chain movements. After increasing the filler content beyond 0.5 wt%, the flexural properties reduced compared to GFE-0. Improper wetting, agglomeration of GNP particles, and higher void content are the leading cause of reducing properties for further increasing nanofiller content. Figure 11 shows the flexural stress versus strain graph of different composites.

3.3. Wear analysis

3.3.1. Taguchi design

Table 4 shows a Taguchi design that has been tested. Weight loss (mg) results are considered a variable response in a total of 16 experiments. The research is carried out with the ‘MINITAB 21’ program.
3.3.2. ANOVA prediction and analysis

ANOVA was used to assess the statistical significance of various control factors. The ANOVA results for abrasive wear for weight loss are shown in table 5. The ANOVA was performed using a 5% level of significance. The significance level is indicated in the last column of the ANOVA table. The major effects are more significant when the p-values are fewer than 5%. According to ANOVA, the weight percent of filler has a considerable effect on M at the 95 percent confidence level [29, 31]. Weight loss is highly considerable with a p-value of 0.000, followed by normal load (p = 0.001), sliding velocity (p = 0.0027) and sliding distance (p = 0.043) according to ANOVA data. Finally, the least considerable factor is the sliding distance, with a p-value of 0.043. According to table 5, the first-factor filler weight percent contributes the most to wear loss, accounting for approximately 70 percent of the total.

In contrast, the other factors like load and velocity also impact 17.82% and 6.90%, respectively. Although the factor sliding distance has generated just 4.83% contribution. At the 5% level of significance, two parameters, percent of filler, normal load, and sliding velocity, are meaningful, whereas the remaining components are negligible. Similarly, the higher the C-value, the larger the impact of that factor on M, and vice versa. Obviously, for GNP/Carbon fiber/Epoxy hybrid composites, with increasing weight percent of GNP wear reduces. It was emphasized that a stronger connection between epoxy, carbon fiber, and GNP has a large impact on wear, especially at 0.5 percent of GNP. The lubricating effect of GNPs in the hybrid composite is responsible for the lower friction coefficient. In summary, the ANOVA findings show that percentage of GNP has the greatest on wear. Sliding distance shows the least influence on wear.

3.3.3. Main effect plots analysis

ANOVA is performed on testing data using MINITAB to determine the significance of various parameters such as percentage of filler, normal load, sliding velocity, and sliding distance on wear for Carbon fiber-epoxy/GNP composite. The signal-to-noise ratios (S/N) serve as optimization objective functions [31], assisting in data analysis, predicting the best outcomes, and considering the mean and inconsistency of the experimental outcome [32]. Rank one indicates that factor (concentration) has the most significant impact on the response variable (M). Similarly, sliding distance has the least impact on wear. The means and S/N ratio and mean plot for M for various control parameters for two-body abrasive wear are shown in figure 12. In those graphs, the influence of the GNP weight percent on the weight loss is projected. Examining these statistics makes it possible to optimize the control elements that result in the least wear.
### 3.3.4. Regression equation, residual plot, and contour plots

Equation (1) is a regression equation that describes the link between weight loss and numerous input parameters.

\[ M = 32.58 - 51.23P + 1.005Q + 3.525R + 0.02325S \]  \hspace{1cm} (1)

Where \( M \) is the weight loss in mg, \( P \) is the weight percentage of filler, \( Q \) is the load in N, \( R \) is the velocity in m/s and \( S \) is the sliding distance in m. Equation (1) can estimate the anticipated values of weight loss by combining multiple input parameters. However, with the L16 orthogonal array, observed values have resulted in Table 4. The residual (observed error) is the discrepancy between observed and expected values. As a result, plotting the residual curve is required to interpret the observed further and predicted values, i.e., residual curves can be used to analyze the data.

Figure 13 shows the different residual plots for \( M \). The residuals are dispersed next to the equipped line, with just a minor deviation from the normal dispersion, according to the normal probability plot. This confirms that the residuals have a normal distribution, verifying the best linear connection between the response and control variables.

The plot shows the residual on the y-axis and the estimated response on the x-axis. Non-linearity, uneven error variances, and outliers can all be seen in this graph. The probability plot reveals that most of the data is contained within the curve, which better predicts the observed values [28, 29]. Furthermore, both axes are symmetrical, implying that the provided model accurately represents the obtained results. Furthermore, in all
residual plots, the variability of a variable is the same across the range of values that predict it. As a result, the best-fitting model for understanding the observed values in this investigation is the current regression equation (1) model.

Contour plots are used in this study to investigate the potential association between three process parameters. The contour plots of weight loss are shown in figure 14. In plots x and y, variables showed on the x and y-axes, and M (response values) showed on Z-axis. The dark green zone shows a higher weight loss value, which is a small area-wise. The contour planes illustrate numerous types of wear loss regions, which are represented by distinct colors. Wear in terms of weight loss larger than 80 mg was seen at longer sliding distances, higher loads, and lower concentrations in figure 4. The presence of 0.5 percent GNP reinforcement in the matrix has a lubricating effect, boosting wear resistance. Although, due to the filler at larger concentrations, a small region of weight loss of less than 40 mg has been recorded. All contour plots show the varied quality scores in the contour domain. The contour area also indicates that all factors have an interaction impact. Moreover, the higher the disorder in plots, the higher the interaction [29].

3.4. Wear rate and worn surfaces morphology
Figure 15 depicts the wear rate for different composites slides against 400 grits SiC paper under different operating conditions given in table 4. The result concluded that as the sliding distance increases, specific wear rates fall for all the samples. This table shows the optimum number of experiments. According to it, the wear test was performed under different operating conditions. A specific wear rate significantly decreased as the successive abrading distance increased. With increased abrading distance, the sleek wear track creation and blunt particle of SiC could be due to a steady decrease in specific wear rate. However, a GFE-0 had a greater specific wear rate, which dropped dramatically when GNP added up to 0.5 %. The highest decrement in particular wear rate was recorded when the composite was reinforced with 0.5 wt% of GNP. GNP acts as authentic reinforcement to prevent SiC particles from penetrating the epoxy matrix and carbon fibers from being pulled out due to their superior mechanical capabilities.

Figure 16 shows worn surfaces of different hybrid composite samples that contain different percent of GNP. This indicates that adding GNP to a Carbon fiber/Epoxy composite reduces abrasive wear and improves wear resistance. The specimens failed primarily due to matrix deformation and fiber fracture [20, 22]. Debonding results from a failure that started at one point in the fiber/matrix interface and continued along its length. Fiber
fracture and matrix deformation were found in the GFE-0 composite. Conversely, particles and fiber pullout agglomeration were seen in the 0.1% GNP/carbon fiber/epoxy composites. The mass loss results are supported by morphology findings, which show that damage to fiber and matrix increases as the applied normal load increases. At higher loads, substantial fiber and matrix damage was seen. Matrix deformation has occurred at lower applied loads. The figure shows that composites’ weight loss is higher at a higher load. Carbon fiber reinforcing also regulates the M. Due to sliding action at lower loads, the weak van der Waals forces between the GNPs in the epoxy matrix are overcome by shear forces [19]. GNPs that had become dislodged dispersed throughout the sliding surface, minimizing direct contact between the composite and paper surfaces. As a result, they shield the specimen’s surface from additional damage.

The matrix begins to distort as the stress increases to a certain level, and fiber is detached from the matrix. At higher loads, debris dislodged from the specimen surface forms a layer between the sliding surfaces consisting of a mixture of epoxy and GNP. This aids in the reduction of wear under higher loads. Most of the applied pressure is carried by the fibers during the sliding phase. As a result, interfacial fatigue and interface debonding occur in areas where fibers are heavily pressured. SEM images show a large crack that is an indication of fiber fracture. The fiber and matrix have relatively strong adhesion, resulting in a low wear rate. As surface morphology demonstrates, wear is caused by ploughing and debris entrapment mechanisms, resulting in wear mitigation and a low wear rate [12, 19].

### 3.5. Optimum conditions prediction

The optimum values of each factor are listed in table 6, and the confirmation test was performed using a set of optimum parameters. For GNP/Carbon fiber/epoxy composites, the combination of variables P4Q1R1S1 provides the lowest weight loss. Following that, three sets of experiments are carried out using this set of control parameters. The experimental value of weight loss is closer to the predicted value. It is validated via confirmation experiments which were conducted under the same conditions.

### 4. Conclusions

The present investigations conclude following points:

1. It was observed that 0.5 wt% GNP-filled carbon fiber/epoxy composite shows higher tensile and flexural strength than another composite. The addition of GNP reduces the mobility of the epoxy–fiber interface, resulting in a stiffer structure.

2. The addition of GNPs to the carbon fiber reinforced epoxy composites improves the sliding wear behavior significantly. In each composite, the filler weight percent and load have a greater effect on wear. The weight loss for GNP/Carbon fiber/epoxy composites lowers as the percentage of GNP increases.

3. Fiber pullout and cracking occur when stresses at the interface of matrix and fiber exceed the interfacial strength, according to the microscopic examination of worn-out sample fracture surfaces.

4. The optimal control variables for reducing composite wear have been determined. According to the ANOVA results, the sliding distance and velocity are less prominent for wear in GNP/Carbon fiber/epoxy composites.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of interest

This research work is genuine. There is no conflict of interest.

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