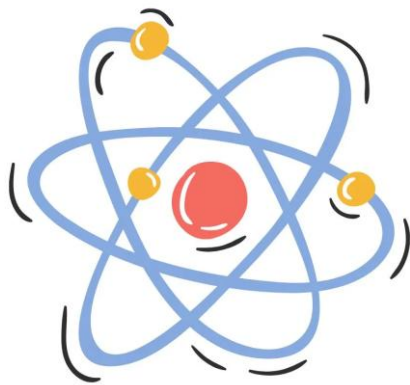




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**Abstract:** This study investigates the tribological performance of epoxy-based hybrid composites reinforced with ramie woven fabric and organically modified montmorillonite (OMMT) nanoclay. The composites were fabricated by incorporating different concentrations of OMMT nanoclay (3, 6, and 9 wt%) into the epoxy matrix containing ramie woven fabric. The tribological behaviour of the developed composites was evaluated using a pin-on-disc tribometer under a constant sliding distance of 800 m. Experiments were conducted at different applied loads of 5, 10, and 15 N and sliding velocities of 1, 2, and 3 m/s to examine their effects on the coefficient of friction (COF) and specific wear rate (SWR). Among the investigated compositions and test conditions, the composite containing 9 wt% OMMT nanoclay exhibited the best tribological performance, achieving a minimum SWR of 0.0158 ( $10^{-3} \text{X mm}^3/\text{Nm}$ ) and a COF of 0.0681 at 5N load and 1 m/s velocity. The optimum tribological conditions were further validated using Taguchi-based statistical analysis. SEM was engaged to examine the worn surfaces and identify the dominant wear mechanisms. The improved tribological performance with increasing OMMT content can be attributed to enhanced filler–matrix interfacial bonding and the formation of a protective tribofilm during sliding, which reduced material loss and friction. The findings demonstrate that incorporating OMMT nanoclay into ramie woven fabric-reinforced epoxy composites is an effective approach for developing lightweight composite materials with improved wear resistance and frictional performance.

**Keywords:** Ramie fiber, nanoclay(OMMT), Taguchi analysis, dry sliding wear testing, and hybrid polymer composites

## 1. Introduction

Introduction Natural fibers are not used in structural uses, because of their poor mechanical strength and lack of bonding with resins, it is generally considered as a non-structural application [1]. Research suggests that natural fibers like jute and coir are not good and have insufficient tensile strength and stiffness for structural use. Besides, the low bonding between the fiber and matrix also reduces the load transmission ability [2]. Over the past few years, several research studies have been undertaken in an effort to address this problem by incorporating other fillers in the composites [3–4]. A large volume of literature has revealed that the use of micro and nano fillers in polymer composites can enhance the load-bearing and tensile property and surface hardness of the composites [5–7]. Hybrid and nanofiller systems offer the best available evidence, but the exact level of enhancement is dependent on the level of filler in the composite, the bonding between the filler and the polymer and dispersion [8]. Carbon, glass, asbestos, Kevlar are often used reinforcing materials in polymer due to the advantage they possess, such as excellent availability, good mechanical properties, and high strength; however, they have high cost, poor degradability and energy requirement. This (Taguchi technique and Grey Wolf Optimization) appeared to be the most ideal method for investigating the sliding wear phenomena of epoxy composites with micro sized Kota stone dust. The composites results revealed that addition

of Kota stone dust [10] increased the wear resistance of the composites. However, enhancement of tribological properties, particularly in terms of wear and frictional resistance, of epoxy composites may lead to considerable improvement by employing natural waste fibers and fillers as reinforcement [11]. Biodegradability, low weight, low cost, easy supply and so on, show that natural fiber-reinforced polymer composite is used widely in the construction industry as well as the fields of automobiles, aviation, and shipbuilding [12]. Most studies indicate that natural fibers are the reinforcement materials that play an important role in producing composites. Mechanical properties of stacking order of reinforcing layers was found to be playing a significant role in improving the mechanical performances of jute/Kevlar reinforced polymer composites by scientifically appraising these parameters [13]. Natural fiber-reinforced polymer composites are sustainable and light-weight, with poor mechanical performance as a result of poor fiber-matrix bonding, but this can be improved through the addition of fillers, hybridization and surface treatments [14-15]. The research results also indicate that the properties of the fillers such as their type, concentration and dispersion can have a great impact on the industrial applicability, thermal stability, resistance to moisture, stiffness and strength [16-18]. One experimental study has shown that a natural-fiber epoxy system with the introduction of nano fillers resulted in an enhancement of tensile, flexural and compressive properties, and the researcher is currently investigating using natural fibers combined with natural nano fillers and interfacing layers [19]. The strong theme that the set has, is that the combination of natural fibers and the addition of the filler to realise the performance benefit, comes with great challenges regarding the compatibility between the interface of the fiber and the filler, [20]. Strengthen, be resistant to heat, moisture or a combination of both with additives like montmorillonite, graphene, aluminium and silica [21]. Based on many studies of the mechanical and tribological behavior of polymer composites reinforced with natural fibers, it can be concluded that natural-fiber reinforcement generally enhances the properties with optimization of fiber loading, orientation, surface treatment, and interfacial bonding [22]. For wear, flexural and general mechanical properties, composite systems containing fillers such as graphite or silica fume are more effective [23] but results are not univocal for the same type of material. Concrete that has been treated with silica fume for flexural and strength increases, as well as carbon fabric-epoxy composites filled with graphite for wear, are the best direct mates [24-25]. The way the composites of glass fiber reinforced with PA-6, with various contents of graphite, PTFE and UHMWPE behaved mechanically as a result of tests was investigated. The results showed that the mechanical property for the composite were extensively improved by the use of graphite fillers [26]. Optimization of the fiber loading can improve mechanical property of bi-directional carbon fiber incorporated composite such as tensile, flexural, hardness, impact, and interlaminar shear [27-28]. Carbon fiber reinforced PEEK has proven to have a significant enhancement in tribology research. Abrasion and sliding wear under various temperature, load and sliding conditions have been studied extensively. Friction and wear resistance properties of manufactured composites are usually lowered when using PEEK with carbon fiber reinforcement; with appropriate hybrid fillers, the resistance to friction and wear can be further improved [29]. The study on epoxy composite filled with red brick dust showed that at optimum fillers amount and during optimum test condition, the rate of erosion and sliding wear can reduce by adding red brick dust to the composites [30,31]. Research into the tribological properties of polymers has indicated that there are many mechanisms that control the control of abrasive wear, the most important of which are: cutting, ploughing, fatigue, particle removal and surface transfer. The most significant mode depends on the system experiencing two-body or three-body abrasion [32-34]. Polymer tribological reactions depend on the differences in the mechanical properties and transfer-film behaviour, in 2-body (abrasive) wear hard asperities or an abrasive particle often results in material removal from a softer polymer surface due to localised plastic deformation, cutting, ploughing, or fracture. Virgin polymers are not suitable in tribological environment and thus many researches have been done on polymer composites. It has been found that correct type, content and alignment of reinforcement material (such as fibers, fillers,

internal lubricants) significantly improve the performances of these materials in terms of friction and wear [35]. Polymer nano composites, as studied, can lead to enhancements in mechanical, tribological, thermal and optical properties. The effectiveness of such improvements is strongly affected by such aspects as loading, processing environment, dispersion of the nano filler in the polymer, and the adhesion between the nano filler and the polymer [36]. The investigation focused on the effect of nano-graphene filler on the sliding and coarse wear behavior of bidirectional CFRP composite, which proved improvement in wear resistance at optimal contents of nano-graphene filler by reducing the rate of wear, friction and abrasive loss [37-39].

The Taguchi technique, developed by the Japanese Genichi Taguchi, is a statistical design-of-trials method which allows optimizing parameters in a robust manner with a small number of tests [40–41]. Uses orthogonal arrays and the S/N ratios. Taguchi studies have shown that polymer composites can have their wear properties optimized by heat treating pultruded ramie fiber-reinforced polyester to 140°C. In this instance, roots' surface roughness turned out to be one of the key issues in obtaining optimum wear performance [42-43]. The mechanical characteristics and the abrasive wear resistance of silk/basalt hybrid epoxy composites with halloysite nanotubes. The most effective data is favorable about the hardness, apparent effect resistance and specific effect wear rate that are reached in lower to moderate HNT concentrations, while optimal performance can be attained with higher concentrations of HNT [44-46].

It is evident from the review of literature that the utilization of nanoclay filler for polymer composite materials has received very little attention, particularly for its effect on the tribological properties under various operating condition. For this reason, using the Taguchi method to optimize the tribological parameters, the tribological behavior of ramie woven fiber-reinforced epoxy composites is investigated by varying the nanoclay contents in 3%, 6%, and 9% by weight. The scanning electron microscopy was used to examine the wear tracks obtained from the pin-on-disc wear testing, thereby determining the tribological performance of the materials and gaining insight of the behaviour of the hybrid composites.

## 2. Materials and Methods

### 2.1 Reinforcement and Polymer matrix

The composite material is manufactured with the mixture of epoxy resin (LY556) and curing agent (HY951) and using woven ramie fibers (250 GSM) for reinforcement. The characteristics of the composite, namely the use of a particulate filler, was improved by adding OMMT nanoclay. The epoxy resin (LY556), the curing agent (HY951), and nanoclay were supplied by Ultrananotech India Ltd., Bengaluru, India and woven ramie fiber mats were supplied by Vruksha Composites, Guntur, Andhra Pradesh, India. Due to their outstanding compatibility with epoxy resins, fabric mat made of 0 degree/90 degree woven ramie fiber was used for the reinforcement materials. The following physical properties of the resin and reinforcement (Table 1) might be helpful in this regard.

**Table 1. Physical properties of reinforcement and matrix**

| Property                     | Ramie | Epoxy | Nanoclay |
|------------------------------|-------|-------|----------|
| Density (g/cm <sup>3</sup> ) | 1.50  | 1.15  | 2.1      |
| Tensile strength(MPa)        | 650   | 35    | 100      |
| Young's modulus(GPa)         | 8.0   | 3.1   | 40       |
| Elongation Failure (%)       | 2-4   | 1-8.5 | 5        |

## 2.2 Ramie fiber

The fibers of the stems from the ramie plant are called ramie fibers. It is very valued for its resistance to heat and moisture resistance, its low density and great tensile strength. The properties of these materials render them attractive as a component for textiles and polymer composites, as depicted in figure 1a, when woven. Renewable, bio-degradable, Ramie fiber is an environmentally friendly alternative to synthetic fibers. Its low weight and strong weight-to-strength ratio and sustainability properties can also apply to a number of technical and industrial applications.



Figure 1. a) Ramie fiber and b) Nanoclay

## 2.3 Nanoclay(OMMT)

A layered silicate filler often used in polymer composites is OMMT nanoclay (100 nm), also known as organically modified montmorillonite. By appropriate dispersion of the matrix, its thermal stability, wear resistance, mechanical and barrier properties can all be improved. Figure 1 b illustrates that the OMMT has a nanoscaled structure with huge specific surface area, which is useful for improving filler-polymer interface. There has been considerable interest in research into its potential use to enhance the functionality of composites such as polyethylene, nylon and epoxy.

## 2.4 Hand layup process

The hand lay-up method and hydraulic compression moulding were used to create ramie woven fabric incorporate into epoxy with nanoclay filler. The mats, which measured( 300 X 300) mm, were mixed with matrix epoxy that had 23 wt% of fabric and 77% matrix (resin-hardener mixture) by weight. The epoxy resin content in the matrix was 90%, and hardener 10%.The composites were compressed in the hydraulic compression moulding machine with 500 kN capacity of hydrostatic pressure, 300 mm square moulding chamber and a height of 20 mm into 3 mm thickness plates. During manufacturing, three layers of woven ramie fiber mat were sandwiched in between four layers of resin mixture, obtaining a composite structure.

For comparing the wear behaviour with different amount of nanoclay filler, three different formulations were prepared as presented in table 2. The concentration of the fillers was 3%, 6% and 9% by weight. Resin, hardener and filler were thoroughly mixed together prior to the application to ensure consistency. The composites were post cured for three hours at 70°C following a 24 hour ambient temperature cure to achieve a higher level of mechanical performance and cross linking density.

Table 2. Wt % of ramie/nanoclay ,epoxy and nano composites

| Sl No | Wt% of ramie fabric (.R+R+R) | Wt % of Nanoclay | Wt % of epoxy | Ttl wt of Composites Wt <sub>c</sub> (%) |
|-------|------------------------------|------------------|---------------|------------------------------------------|
| 1     | 23                           | 3                | 74            | 100                                      |
| 2     | 23                           | 6                | 71            | 100                                      |
| 3     | 23                           | 9                | 68            | 100                                      |

## 2.5 Experimental details

Composite plates were manufactured according to the specifications for two-body abrasive wear test design and then prepared as wear test specimens shown in Figure 2(b) with cylindrical shape of 3 mm thickness and 10 mm diameter, based on the specification shown in Figure 2(a). These samples were precisely cut by a single-head laser cutting machine in a BS6040 Model by an Indian company BSM Pvt. Ltd. This kind of equipment is calibrated for operation under specific conditions. For further secure attachment to the tribotester, laser-cut polymer sample discs have been glued onto the end of AISI D3 Steel pin specimens with a 10 mm diameter and 30mm in length as shown in Figure 2(c). The samples were tested using the ASTM G-99 standard on an AISI D3 steel disk in a pin-on-disc tribotester (DUCOM -TR-20LE) as illustrated in Figure 2(d & e). Abrasion loss of pin specimen was done to determine the initial volume loss ( $V_{int}$ ) and final volume loss ( $V_{fnl}$ ) were measured. The SWR ( $\text{mm}^3/\text{Nm}$ ) was used to determine it by using equations (1) and (2) [47].

$$\text{Specific wear rate} = \frac{V_{int} - V_{fnl}}{F * L} \quad (1)$$

$V_{int}$  and  $V_{fnl}$  are the initial and final volume of the specimen in this experiment, respectively, and  $L$  is the sliding distance, applied force is applied,. Friction force in Newtons was calculated from the direct reading of the friction monitor and COF was calculated using equation (2).

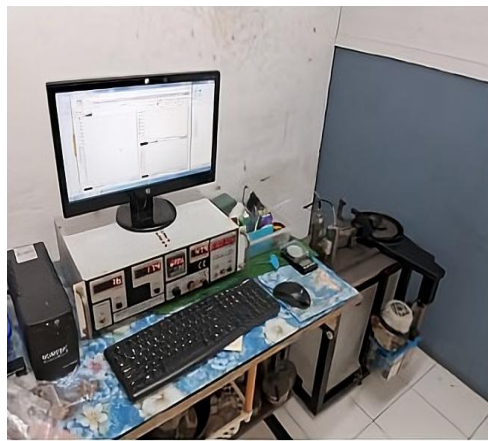
$$\text{Coefficient of friction} = \frac{\text{Frictional force}}{\text{Applied load}} \quad (2)$$



a) Fabricated composite plate

b) Laser cut for wear test

c) sample fixed to steel rod



d) DUCOM pin-on-disc equipment



e) Top view of pin-on-disc setup

Fig.2 Pin and Disc equipment with fabricated sample

## 2.6 Taguchi Analysis

As the number of process parameters increases, the complexity of the experimental procedure and the effort required for parameter optimization also increase. Conventionally, the number of experimental trials increases with the number of influencing parameters, resulting in greater time and resource requirements. This limitation can be addressed by employing statistical design-of-experiments techniques, such as the Taguchi method, which utilizes orthogonal arrays to systematically reduce the number of experimental trials while maintaining reliable information about the effects of individual parameters. In the present investigation, the primary control factors considered were filler content (wt%), applied load (N), and sliding velocity (m/s). The selected control factors and their corresponding levels are presented in Table 3. The Taguchi L27 orthogonal array was employed to investigate the influence of these input parameters on the output responses, namely, the coefficient of friction (COF) and specific wear rate (SWR). The primary objective was to minimize both COF and SWR for the selected composite formulations. Accordingly, the “smaller-the-better” signal-to-noise (S/N) ratio was adopted for the optimization of the tribological responses using Minitab 16 software

$$SN \text{ ratio} = -10 \log \left[ \frac{1}{n} \sum_{i=1}^n (y_i)^2 \right] \quad (3)$$

Table 3. Control-factors and their levels

| Control-factors             | levels |    |    |
|-----------------------------|--------|----|----|
|                             | 1      | 2  | 3  |
| Filler add (wt%)            | 3      | 6  | 9  |
| Load in (N)                 | 5      | 10 | 15 |
| Sliding velocity in (m/sec) | 1      | 2  | 3  |

## 2.7 SEM Analysis

The worn surfaces of the ramie fibre/nanoclay composite specimens were characterized using scanning electron microscopy (SEM). Prior to SEM examination, the specimen surfaces were sputter-coated with a thin layer of gold to enhance electrical conductivity and minimize charging effects during imaging. The transfer

layer formed on the 320-grit abrasive paper was also examined using SEM to evaluate the material deposited on the counterface during the wear test.

### 3. Result and Discussion

#### 3.1 Specific wear rate (SWR) and Coefficient of friction (COF) of ramie/nanoclay nanocomposite

The wear testing parameters adopted in the experiments were filler add, sliding speeds (1, 2 and 3 m/s), load (5, 10 and 15 N) and stable sliding distance (800 m) to ensure entire surface contact between pin and disc through each trial. The results of some of the experiments performed with the load parameter, sliding velocity and filler adding are shown in table 4. Testing conducted by the information collecting method of tribo-tester measured wear (micrometres) and the forces of friction (Newtons). The tribological characteristics have been calculated from these readings, which are presented in Table 4. The specific wear rate (SWR) was found to be as low as  $0.0158 (10^{-3} \text{X mm}^3/\text{Nm})$  for the composite containing 9 wt% filler under a load of 5 N and a velocity of 1 m/s. The lower wear rate under these conditions can be attributed to the reduced depth of penetration of the counterpart surface irregularities and the limited interaction of abrasive particles with the composite surface.

The incorporation of OMMT nanoclay improves the filler–matrix interfacial bonding and contributes to the formation of a protective tribolayer, thereby reducing material removal during sliding. In contrast, an increase in sliding velocity to 3 m/s, 6 wt% of filler addition and applied load to 15 N contributed in a considerable enhance in the SWR ( $0.1314 (10^{-3} \text{X mm}^3/\text{Nm})$ ) of the nanocomposites. The combined effect of higher interface pressure and velocity increased the depth of penetration of the counterpart surface irregularities into the composite surface, leading to the formation of deeper and more pronounced wear grooves. Furthermore, the increased frictional energy generated at the contact interface resulted in a rise in localized temperature, promoting plastic deformation and softening of the epoxy-rich exterior level. The repeated mechanical-thermal stresses at the sliding interface weakened the filler–matrix interfacial region, causing debonding and subsequent removal of the matrix and reinforcement particles. Consequently, greater material loss and an increased specific wear rate were observed under the higher load and sliding-velocity conditions.

The coefficient of friction (COF) exhibited a minimum value of 0.0901 for the composite containing 9 wt% filler under a load of 5 N and a sliding-velocity of 1 m/s. The lower COF under these conditions can be attributed to the relatively low frictional heat generation at the contact interface between the composite specimen and the counterface disc. The incorporation of OMMT nanoclay also contributes to improved interfacial bonding and the development of a stable shift layer, which reduces direct asperity-to-asperity contact and facilitates smoother descending. In contrast, increasing the load to 15 N, reducing the filler content to 6 wt%, and increasing the sliding-velocity to 3 m/s resulted in a substantial increase in the COF to 0.5252. The higher load and velocity increased the frictional energy generated at the sliding interface, resulting in localized temperature rise and softening of the polymer matrix. The softened surface undergoes plastic deformation and increased adhesion with the counterface, while the disruption of the protective transfer layer promotes direct contact between the composite and disc surfaces. These combined thermal and mechanical effects increase the interfacial resistance to sliding, thereby resulting in a higher coefficient of friction.

**Table 4. Experimental results of wear rate and COF by using parameters**

| Sl no. | Filler add<br>in wt % | Load in<br>N | Sliding velocity<br>in m/s | SWR<br>( $10^{-3} \times \text{mm}^3/\text{Nm}$ ) | COF    |
|--------|-----------------------|--------------|----------------------------|---------------------------------------------------|--------|
| 1      | 3.0                   | 5            | 1                          | 0.0302                                            | 0.1653 |
| 2      | 3.0                   | 5            | 2                          | 0.0337                                            | 0.2324 |
| 3      | 3.0                   | 5            | 3                          | 0.0399                                            | 0.2763 |
| 4      | 3.0                   | 10           | 1                          | 0.0560                                            | 0.35   |
| 5      | 3.0                   | 10           | 2                          | 0.0607                                            | 0.41   |
| 6      | 3.0                   | 10           | 3                          | 0.0678                                            | 0.4685 |
| 7      | 3.0                   | 15           | 1                          | 0.0833                                            | 0.5223 |
| 8      | 3.0                   | 15           | 2                          | 0.0991                                            | 0.582  |
| 9      | 3.0                   | 15           | 3                          | 0.1196                                            | 0.6525 |
| 10     | 6.0                   | 5            | 1                          | 0.0255                                            | 0.1325 |
| 11     | 6.0                   | 5            | 2                          | 0.0293                                            | 0.1752 |
| 12     | 6.0                   | 5            | 3                          | 0.0373                                            | 0.2306 |
| 13     | 6.0                   | 10           | 1                          | 0.0540                                            | 0.2725 |
| 14     | 6.0                   | 10           | 2                          | 0.0573                                            | 0.3255 |
| 15     | 6.0                   | 10           | 3                          | 0.0615                                            | 0.3856 |
| 16     | 6.0                   | 15           | 1                          | 0.0757                                            | 0.3987 |
| 17     | 6.0                   | 15           | 2                          | 0.0951                                            | 0.4792 |
| 18     | 6.0                   | 15           | 3                          | 0.1314                                            | 0.5252 |
| 19     | 9.0                   | 5            | 1                          | 0.0158                                            | 0.0901 |
| 20     | 9.0                   | 5            | 2                          | 0.0217                                            | 0.1288 |
| 21     | 9.0                   | 5            | 3                          | 0.0269                                            | 0.1657 |
| 22     | 9.0                   | 10           | 1                          | 0.0416                                            | 0.1981 |
| 23     | 9.0                   | 10           | 2                          | 0.0456                                            | 0.241  |
| 24     | 9.0                   | 10           | 3                          | 0.0495                                            | 0.3054 |
| 25     | 9.0                   | 15           | 1                          | 0.0510                                            | 0.2972 |
| 26     | 9.0                   | 15           | 2                          | 0.0655                                            | 0.3735 |
| 27     | 9.0                   | 15           | 3                          | 0.0768                                            | 0.4166 |

### 3.2 Taguchi analysis

The specific wear rate and coefficient of friction were statistically analyzed using the Taguchi design-of-experiments (DOE) approach based on the “smaller-the-better” signal-to-noise (S/N) decisive factor. The primary objective was to identify the optimum combination of process parameter and evaluate their influence on the tribological performance of the ramie fiber-reinforced hybrid polymer composites containing spent abrasive particle filler. The main-effects plots presented in Figures 3 and 4 illustrate the effects of filler content, applied load, and velocity on SWR and COF, respectively. The analysis indicated that the optimum parameter combination for minimizing the SWR was filler content of 9 wt%, 5N load, and 1 m/s sliding velocity. The same combination of parameters also produced the minimum COF, as shown in Figure 4. These results demonstrate that the higher filler concentration, combined with a lower applied load and sliding velocity, provides favourable tribological conditions by reducing material removal and interfacial resistance during sliding.

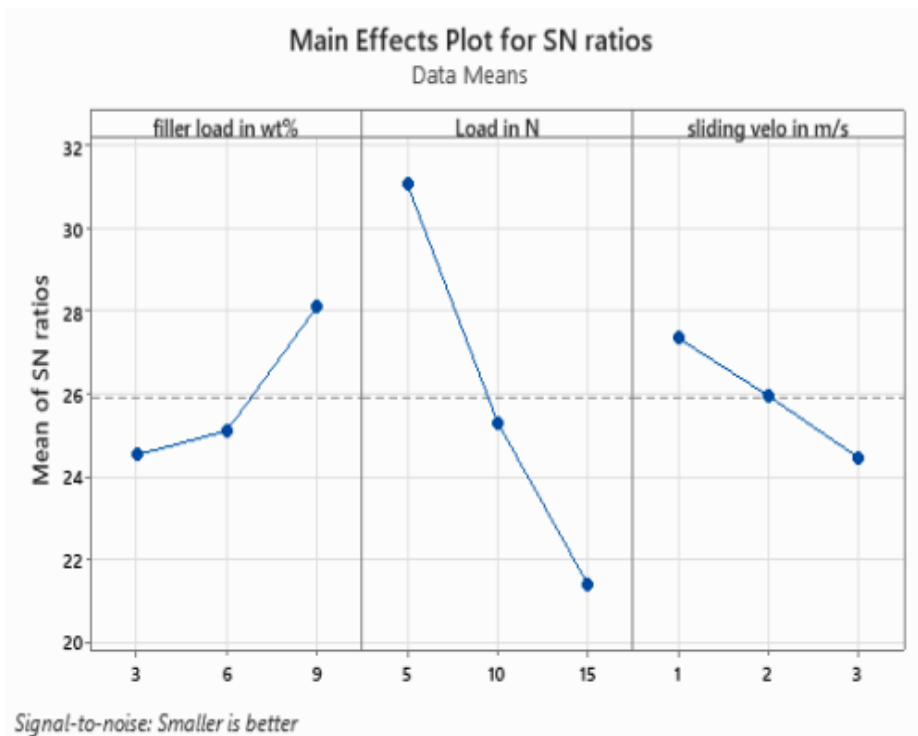


Figure 3. Main effect plot for Wear rate

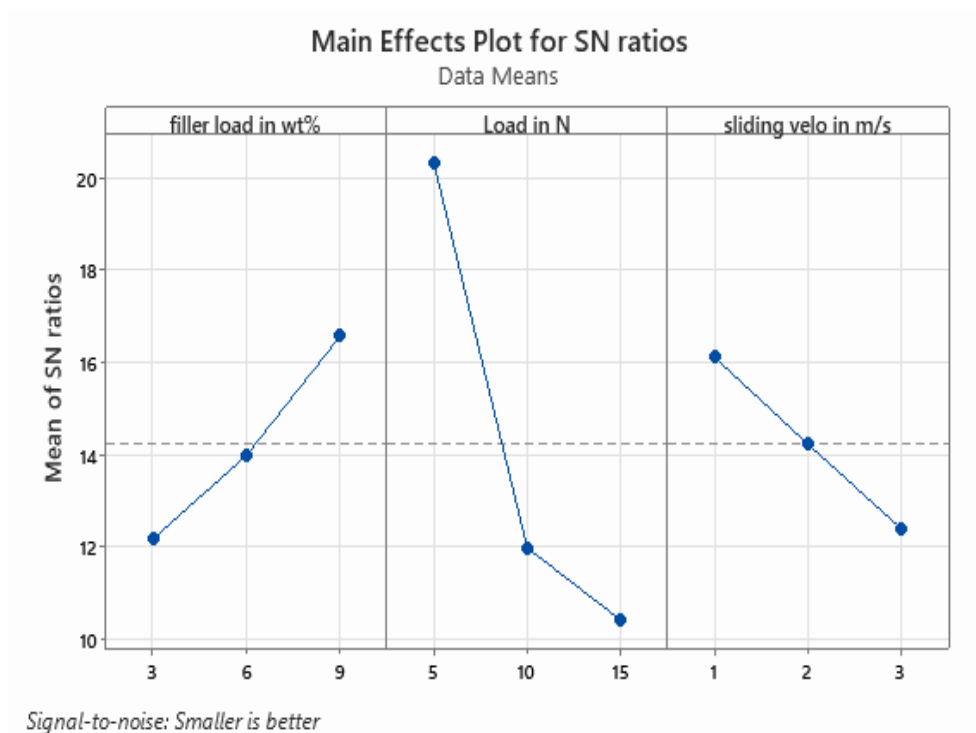


Figure 4. Main effect plot for Coefficient of friction

The analysis indicated that the optimum parameter combination for minimizing the SWR was a filler content of 9 wt%, 5N load, and 1 m/s sliding velocity. The same combination of parameters also produced the minimum COF, as shown in Figure 4. These results demonstrate that the higher filler concentration, combined with a lower applied load and

sliding velocity, provides favourable tribological conditions by reducing material removal and interfacial resistance during sliding.

### 3.3 Load effect on Wear Behaviour and Frictional Characteristics

The normal load exhibited the most pronounced influence on both SWR and COF compared with sliding velocity and filler content. This trend is marked from the response tables presented in Tables 5 and 6, where the applied load exhibited the highest delta values and was consequently assigned the highest rank for both tribological responses. The delta values for SWR and COF were 9.69 and 9.94, respectively, indicating the dominant contribution of normal load to the tribological behaviour of the composite. The analysis of variance (ANOVA) results presented in Table 7 further confirmed the significant contribution of the investigated parameters to the specific wear rate. The applied load accounted for 72.15% of the total variation in SWR, followed by filler content, which contributed 11.39%. Similarly, the ANOVA results for COF in Table 8 indicated that the load was the mainly influential parameter, accounts for 69.05% of the total variation, while filler content contributed 17.93%. These results demonstrate that the normal load governs the contact conditions at the sliding interface and consequently has a substantial effect on material removal and frictional behaviour.

All three investigated factors—filler content, applied load, and sliding velocity—were found to have statistically significant effects on the tribological responses within the selected experimental range. Among these factors, the applied load was identified as the dominant parameter. The raise in load enhances the contact pressure between the composite specimen and counterface, resulting in greater penetration of surface asperities and increased real area of contact. Consequently, higher mechanical stresses and frictional energy are generated at the interface, promoting matrix deformation, fiber–matrix debonding, and progressive material removal.

**Table 5. Signal-to-Noise Response Analysis of Wear Performance**

| Level | Filler-load in wt % | Load in N | Sliding-velocity in m/s |
|-------|---------------------|-----------|-------------------------|
| 1     | 24.52               | 31.07     | 27.35                   |
| 2     | 25.11               | 25.30     | 25.95                   |
| 3     | 28.12               | 21.38     | 24.45                   |
| Delta | 3.60                | 9.69      | 2.90                    |
| Rank  | 2                   | 1         | 3                       |

**Table 6. Signal-to-Noise Response Analysis of co efficient of friction**

| Level | Filler-load in wt % | Load in N | Sliding-velocity in m/s |
|-------|---------------------|-----------|-------------------------|
| 1     | 12.16               | 2.34      | 16.11                   |
| 2     | 13.98               | 11.97     | 14.22                   |
| 3     | 16.57               | 10.40     | 12.38                   |
| Delta | 4.40                | 9.94      | 3.73                    |
| Rank  | 2                   | 1         | 3                       |

The observed increase in wear with applied load is consistent with the fundamental wear relationship described by Archard's wear law, according to which wear volume is relative to the applied load under otherwise comparable conditions. The dominance of normal load therefore confirms its critical role in controlling the wear and friction behaviour of the ramie fiber-reinforced polymer composites.

### 3.4 Filler load effect on Wear Behaviour and Frictional Characteristics

Filler content also exerted a significant influence on the specific wear rate (SWR) and coefficient of friction (COF) of the ramie fiber-reinforced hybrid polymer composites. Although its contribution was lower than that of the applied normal load, filler content was identified as the second most influential parameter within the investigated range. As shown in Table 5, the delta value associated with filler content for SWR was 3.60, indicating a measurable effect on the wear response. The ANOVA results further revealed that filler content accounted for 12.63% of the total variation in SWR, confirming its statistically significant contribution to the wear behaviour. A similar trend was observed

**Table 7. ANOVA-Based Evaluation of Wear Rate**

| Source                                  | DF | Seq SS   | Adj SS   | Adj MS   | F      | P     | Contribution |
|-----------------------------------------|----|----------|----------|----------|--------|-------|--------------|
| filler load in wt%                      | 2  | 0.002546 | 0.002546 | 0.001273 | 57.08  | 0.000 | 11.39        |
| Load in N                               | 2  | 0.016123 | 0.016123 | 0.008061 | 361.48 | 0.000 | 72.15        |
| sliding velo in m/s                     | 2  | 0.001767 | 0.001767 | 0.000883 | 39.61  | 0.000 | 7.91         |
| filler load in wt%*Load in N            | 4  | 0.000771 | 0.000771 | 0.000193 | 8.65   | 0.005 | 3.45         |
| filler load in wt%* sliding velo in m/s | 4  | 0.000095 | 0.000095 | 0.000024 | 1.07   | 0.432 | 0.43         |
| Load in N*sliding velo in m/s           | 4  | 0.000868 | 0.000868 | 0.000217 | 9.73   | 0.004 | 3.88         |
| Residual Error                          | 8  | 0.000178 | 0.000178 | 0.000022 |        |       | 0.8          |
| Total                                   | 26 | 0.022348 |          |          |        |       | 100          |

**Table 8. ANOVA-Based Evaluation of Friction**

| Source                                  | DF | Seq SS   | Adj SS   | Adj MS   | F       | P     | Contribution |
|-----------------------------------------|----|----------|----------|----------|---------|-------|--------------|
| filler load in wt%                      | 2  | 0.107014 | 0.107014 | 0.053507 | 353.96  | 0.000 | 17.93        |
| Load in N                               | 2  | 0.411986 | 0.411986 | 0.205993 | 1362.68 | 0.000 | 69.01        |
| sliding velo in m/s                     | 2  | 0.052125 | 0.052125 | 0.026062 | 172.41  | 0.000 | 8.73         |
| filler load in wt%*Load in N            | 4  | 0.020264 | 0.020264 | 0.005066 | 33.51   | 0.000 | 3.39         |
| filler load in wt%* sliding velo in m/s | 4  | 0.000984 | 0.000984 | 0.000246 | 1.63    | 0.258 | 0.16         |
| Load in N*sliding velo in m/s           | 4  | 0.003388 | 0.003388 | 0.000847 | 5.60    | 0.019 | 0.57         |
| Residual Error                          | 8  | 0.001209 | 0.001209 | 0.000151 |         |       | 0.2          |
| Total                                   | 26 | 0.596970 |          |          |         |       | 100          |

for the coefficient of friction, as presented in Table 6, where filler content exhibited a delta value of 4.40. The ANOVA results in Table 8 indicated that filler content contributed approximately 17.93% to the total variation in COF, demonstrating a more pronounced influence on frictional behaviour than on the wear rate. The combined effects of filler content and applied load further modified the interfacial contact conditions and

consequently influenced the frictional response of the composites. The incorporation of filler particles improved the resistance in wear rate of the ramie fiber incorporated polymer hybrid composites up to an optimum filler concentration. This improvement can be attributed to the effective dispersion of organically modified montmorillonite (OMMT) nanoclay within the polymer matrix and the resulting enhancement of the filler–matrix interfacial interaction. The layered silicate structure of OMMT can restrict localized matrix deformation and improve the load-bearing capacity of the composite. During sliding, the well-dispersed nanoclay particles can also contribute to the formation of a relatively stable protective transfer layer at the contact interface, thereby reducing direct contact between the composite surface and counterface. Consequently, material removal and frictional resistance are reduced, leading to enhanced tribological performance. However, beyond the optimum filler concentration, particle agglomeration and non-uniform dispersion may occur, potentially creating localized stress concentrations and weakening the matrix–filler interface, which can adversely affect wear resistance.

### 3.5 Sliding velocity effect on Wear Behaviour and Frictional Characteristics

The sliding velocity influence on the tribological behaviour of the ramie fiber-reinforced hybrid polymer composites was comparatively lower than that of the applied normal load and filler content. As shown in Table 5, sliding velocity exhibited a delta value of 2.90 for the specific wear rate (SWR), indicating a measurable but relatively limited influence on material wear. The ANOVA results presented in Table 7 further confirmed that sliding velocity accounted for approximately 7.91% of the total variation in SWR, demonstrating its comparatively minor contribution to the overall wear behaviour. A similar trend was observed for the coefficient of friction (COF). As indicated in Table 6, sliding velocity exhibited a delta value of 3.73, ranking third among the investigated control factors. The ANOVA results in Table 8 showed that sliding velocity had a statistically significant effect on COF; however, its contribution to the total variation was relatively small, accounting for approximately 8.71%. The relatively lower contribution of sliding velocity compared with applied load and filler content suggests that the contact pressure and composite composition play more dominant roles in governing the interfacial friction and wear mechanisms under the investigated experimental conditions. An increase in sliding velocity generally increases the pace of frictional generation at the contact boundary, which can result in localized temperature rise, matrix softening, and changes in the stability of the transfer layer. However, the extent of these effects depends strongly on the applied load and filler concentration. Therefore, within the selected experimental range, sliding velocity was identified as a statistically significant but comparatively less influential parameter affecting both SWR and COF.

### 3.6 Validation of results

A general linear regression approach was employed to establish empirical mathematical models for predicting the specific wear rate (SWR) and coefficient of friction (COF) of the ramie fiber-reinforced hybrid polymer composites as a function of the selected control parameters. The independent variables considered in the regression analysis were filler content, applied normal load, and sliding velocity, while SWR and COF were treated as the corresponding response variables. The developed regression equations, presented as equations (4) and (5), respectively, provide a quantitative relationship between the input

**Table 9. Comparison of Experimental and Predicted tribological Responses**

| Sl no.  | Filler add in wt % | Load in N | Sliding velocity in m/s | Experiment Wear rate in ( $10^{-3}$ X $\text{mm}^3/\text{Nm}$ ) | Prediction for Wear rate in ( $10^{-3}$ X $\text{mm}^3/\text{Nm}$ ) | Error in % | Accuracy in % | Experiment Co-efficient of friction (COF) | Prediction for Co-efficient of friction (COF) | Error in % | Accuracy in % |
|---------|--------------------|-----------|-------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------|------------|---------------|-------------------------------------------|-----------------------------------------------|------------|---------------|
| 1       | 3                  | 5         | 1                       | 0.0302                                                          | 0.0288                                                              | 4.53       | 95.47         | 0.1653                                    | 0.1634                                        | 1.14       | 98.86         |
| 2       | 3                  | 5         | 2                       | 0.0337                                                          | 0.0327                                                              | 2.94       | 97.06         | 0.2324                                    | 0.2124                                        | 9.38       | 90.62         |
| 3       | 3                  | 5         | 3                       | 0.0399                                                          | 0.0389                                                              | 2.57       | 97.43         | 0.2763                                    | 0.2615                                        | 5.66       | 94.34         |
| 4       | 3                  | 10        | 1                       | 0.056                                                           | 0.0542                                                              | 3.32       | 96.68         | 0.35                                      | 0.3306                                        | 5.86       | 94.14         |
| 5       | 3                  | 10        | 2                       | 0.0607                                                          | 0.0578                                                              | 5.02       | 94.98         | 0.41                                      | 0.389                                         | 5.4        | 94.6          |
| 6       | 3                  | 10        | 3                       | 0.0678                                                          | 0.0658                                                              | 3.04       | 96.96         | 0.4685                                    | 0.4473                                        | 4.72       | 95.28         |
| 7       | 3                  | 15        | 1                       | 0.0833                                                          | 0.0801                                                              | 4          | 96            | 0.5223                                    | 0.4977                                        | 4.92       | 95.08         |
| 8       | 3                  | 15        | 2                       | 0.0991                                                          | 0.0972                                                              | 1.95       | 98.05         | 0.582                                     | 0.5655                                        | 2.91       | 97.09         |
| 9       | 3                  | 15        | 3                       | 0.1196                                                          | 0.1156                                                              | 3.46       | 96.54         | 0.6525                                    | 0.6332                                        | 3.04       | 96.96         |
| 10      | 6                  | 5         | 1                       | 0.0255                                                          | 0.0248                                                              | 2.6        | 97.4          | 0.1325                                    | 0.1238                                        | 6.98       | 93.02         |
| 11      | 6                  | 5         | 2                       | 0.0293                                                          | 0.0276                                                              | 6.09       | 93.91         | 0.1752                                    | 0.1679                                        | 4.31       | 95.69         |
| 12      | 6                  | 5         | 3                       | 0.0373                                                          | 0.0363                                                              | 2.75       | 97.25         | 0.2306                                    | 0.2120                                        | 8.74       | 91.26         |
| 13      | 6                  | 10        | 1                       | 0.054                                                           | 0.0520                                                              | 3.81       | 96.19         | 0.2725                                    | 0.2587                                        | 5.32       | 94.68         |
| 14      | 6                  | 10        | 2                       | 0.0573                                                          | 0.0568                                                              | 0.88       | 99.12         | 0.3255                                    | 0.3122                                        | 4.26       | 95.74         |
| 15      | 6                  | 10        | 3                       | 0.0615                                                          | 0.0598                                                              | 2.84       | 97.16         | 0.3856                                    | 0.3656                                        | 5.45       | 94.55         |
| 16      | 6                  | 15        | 1                       | 0.0757                                                          | 0.074                                                               | 2.3        | 97.7          | 0.3987                                    | 0.3936                                        | 1.29       | 98.71         |
| 17      | 6                  | 15        | 2                       | 0.0951                                                          | 0.0912                                                              | 4.28       | 95.72         | 0.4792                                    | 0.4564                                        | 4.99       | 95.01         |
| 18      | 6                  | 15        | 3                       | 0.1314                                                          | 0.1293                                                              | 1.62       | 98.38         | 0.5252                                    | 0.5192                                        | 1.15       | 98.85         |
| 19      | 9                  | 5         | 1                       | 0.0158                                                          | 0.0152                                                              | 3.95       | 96.05         | 0.0901                                    | 0.0842                                        | 6.94       | 93.06         |
| 20      | 9                  | 5         | 2                       | 0.0217                                                          | 0.0209                                                              | 3.83       | 96.17         | 0.1288                                    | 0.1234                                        | 4.34       | 95.66         |
| 21      | 9                  | 5         | 3                       | 0.0269                                                          | 0.0258                                                              | 4.26       | 95.74         | 0.1657                                    | 0.1626                                        | 1.89       | 98.11         |
| 22      | 9                  | 10        | 1                       | 0.0416                                                          | 0.0377                                                              | 10.08      | 89.92         | 0.1981                                    | 0.1868                                        | 6.03       | 93.97         |
| 23      | 9                  | 10        | 2                       | 0.0456                                                          | 0.0445                                                              | 2.47       | 97.53         | 0.241                                     | 0.2354                                        | 2.38       | 97.62         |
| 24      | 9                  | 10        | 3                       | 0.0495                                                          | 0.0475                                                              | 4.21       | 95.79         | 0.3054                                    | 0.2839                                        | 7.56       | 92.44         |
| 25      | 9                  | 15        | 1                       | 0.051                                                           | 0.0498                                                              | 2.41       | 97.59         | 0.2972                                    | 0.2894                                        | 2.67       | 97.33         |
| 26      | 9                  | 15        | 2                       | 0.0655                                                          | 0.0635                                                              | 3.15       | 96.85         | 0.3735                                    | 0.3473                                        | 7.53       | 92.47         |
| 27      | 9                  | 15        | 3                       | 0.0768                                                          | 0.0753                                                              | 1.99       | 98.01         | 0.4166                                    | 0.4052                                        | 2.8        | 97.2          |
| Average |                    |           |                         |                                                                 |                                                                     | 3.49       | 96.51         |                                           |                                               | 4.73       | 95.27         |

parameters and the tribological responses within the investigated experimental range. The adequacy and predictive capability of the developed models were evaluated using the coefficient of determination ( $R^2$ ). The regression model developed for SWR exhibited an ( $R^2$ ) value of 93.68%, indicating that approximately 93.68% of the observed variation in specific wear rate could be explained by the selected input parameters. Similarly, the regression model for COF yielded an ( $R^2$ ) value of 91.54%, demonstrating that approximately 91.54% of the variation in the COF was accounted for by the predicted model. The relatively high ( $R^2$ ) values obtained for both responses indicate a strong correlation between the experimented observations and the predicted dimensions, thereby confirming the suitability of the regression models for describing the tribological behaviour of the developed composites. These results also demonstrate that filler content, applied load, and sliding velocity collectively provide a substantial contribution to the variation in wear and friction characteristics under the specified test conditions.

$$\begin{aligned} \text{Wear rate} = & 0.0008 + 0.00094 * \text{fillerload} + 0.00544 * \text{Load} - 0.00217 * \\ & \text{Slidingvelocity} - 0.000385 * \text{fillerload} * \text{Load} - 0.000361 * \text{fillerload} * \\ & \text{Slidingvelocity} + 0.001420 * \text{Load} * \text{Slidingvelocity} \end{aligned} \quad (4)$$

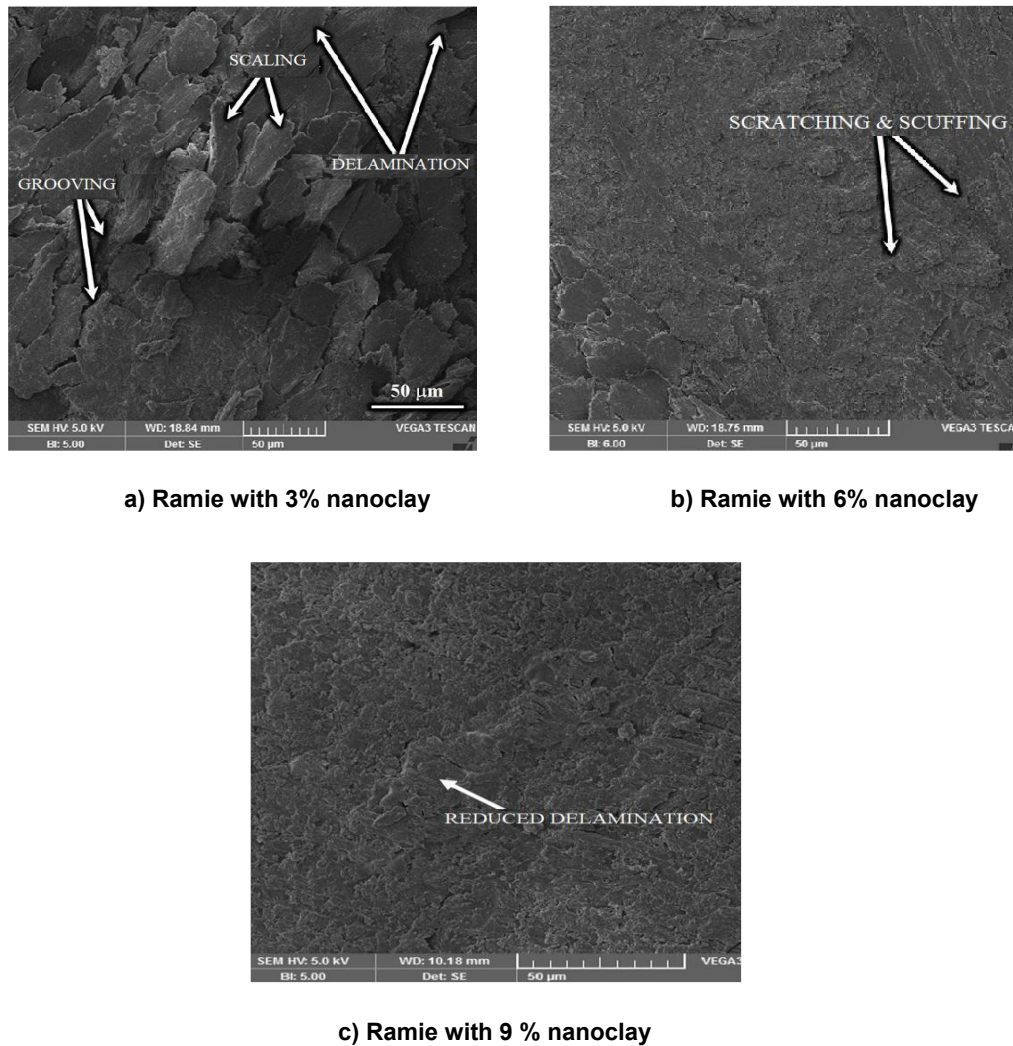
$$\begin{aligned} \text{Coefficient of friction} = & -0.041 - 0.0008 * \text{fillerload} + 0.03802 * \text{Load} + \\ & 0.0446 * \text{Slidingvelocity} - 0.002152 * \text{fillerload} * \text{Load} - 0.00164 * \text{fillerload} * \\ & \text{Slidingvelocity} + 0.00187 * \text{Load} * \text{Slidingvelocity} \end{aligned} \quad (5)$$

The experimental results for the specific wear rate (SWR) and coefficient of friction (COF) were compared with the corresponding values predicted by the developed regression models, as presented in Table 9. The comparison demonstrated a good agreement between the experimental and predicted results. The average deviation between the experimented observation and predicted SWR values was approximately 3.49%, while the corresponding average deviation for COF was 4.73%. The relatively low percentage deviations indicate that the developed regression models provide satisfactory predictive accuracy and can effectively represent the tribological behaviour of the investigated hybrid polymer composites within the selected experimental range.

### 3.7 SEM analysis of worn surfaces

The SEM micrographs of the wear-affected surface obtained after abrasive wear testing of the ramie fiber-reinforced hybrid polymer composites are presented in Figures 5(a–c). Figure 5(a) depicts the worn surface of polymer hybrid composite containing 3 wt.% nanoclay, tested under a normal load of ( $W = 5$ ) N, a sliding velocity of ( $v = 1$ ) m/s, and a sliding distance of ( $L = 800$ ) m. The micrograph reveals distinct tribological damage features, including surface delamination, material pull-out, and scaling, which are characteristic of abrasive wear mechanisms. Pronounced grooves and scratches are also observed along the sliding direction, indicating ploughing and micro-cutting of the composite surface. These defects can be attributed to inadequate interfacial adhesion between the ramie fibers and polymer matrix, which facilitates fiber pull-out and localized material removal, thereby reducing the abrasive wear resistance of the composite. Figure 5(b) presents the wear-affected surface morphology of the hybrid polymer composite containing 6 wt.% nanoclay under the same test conditions. The worn surface exhibits comparatively reduced damage, although features such as delamination, scuffing, and abrasive scratches are still evident. The incorporation of nanoclay improves the resistance of the composite to abrasive material removal by enhancing the load-bearing capability of the polymer matrix and improving the fiber–matrix interfacial bonding. Consequently, the propagation of surface cracks and detachment of reinforcement from the matrix are suppressed. However, the higher nanoclay concentration may promote localized filler agglomeration or alter the filler–matrix interaction, resulting in some degree of interfacial

discontinuity. Nevertheless, the overall wear resistance of the 6 wt.% nanoclay composite is superior to that of the composite containing 3 wt.% nanoclay



**Fig 5 .Worn surfaces of Ramie with wt% of nanoclay at 5 N load, 1 m/sec sliding velocity**

As shown in Figure 5(c), the incorporation of 9 wt.% nanoclay provides the most significant improvement in the abrasive wear resistance of the ramie fiber-reinforced hybrid polymer composite. The worn surface exhibits substantially fewer and less severe delamination regions, indicating improved resistance to abrasive material removal. In addition, the extent of interlaminar failure and fiber pull-out is considerably reduced. Under the applied mild abrasive conditions, the composite containing 9 wt.% nanoclay exhibits the lowest wear rate compared with the composites containing 3 wt.% and 6 wt.% nanoclay. This improvement can be attributed to the relatively uniform dispersion of the nanoclay within the epoxy matrix, which promotes stronger interfacial interactions among the ramie fibers, nanoclay particles, and polymer matrix. The enhanced interfacial bonding improves stress transfer across the composite constituents and restricts crack initiation and propagation during sliding. Furthermore, the well-dispersed nanoclay particles act as micro-scale barriers against abrasive penetration and material removal, thereby reducing the formation of severe grooves, delamination, and fiber pull-out. Consequently, the composite containing 9 wt.% nanoclay demonstrates superior resistance to abrasive wear and exhibits a more stable and less severely damaged worn surface.

## 4. Conclusion

The tribological behaviour of ramie fiber-reinforced hybrid polymer composites incorporating different concentrations of organically modified montmorillonite (OMMT) nanoclay was systematically investigated under varying normal loads and sliding velocities. The results demonstrated that the incorporation of OMMT significantly influenced the wear resistance and frictional characteristics of the composites.

- The incorporation of OMMT improved the wear resistance of the composites, with the optimum performance obtained at 9 wt.% nanoclay.
- The effect of nanoclay was more significant under mild conditions of load 5N, and sliding velocity 1 m/s, whereas its influence was relatively limited at higher load and higher sliding velocity.
- The best parameters of load 5 N, sliding velocity 1 m/s, and 9 wt.% OMMT resulted in a low SWR (0.0158 mm<sup>3</sup>/Nm) and low COF (0.0681).
- The S/N response analysis shows that applied load has the greatest influence on the tribological behaviour of the ramie fiber-reinforced polymer composites, followed by filler content and sliding velocity, ranked first, second, and third, respectively.
- The developed mathematical model showed approximately 96% prediction accuracy, confirming its reliability for estimating the tribological responses. The developed mathematical model exhibited approximately 96% predictive reliability during validation, indicating a strong correlation between the experimentally measured and model-predicted tribological responses. This confirms the suitability of the developed model for predicting SWR and COF within the investigated range of operating parameters.

Overall, the ramie fiber-reinforced epoxy/OMMT hybrid polymer composites demonstrated enhanced wear resistance, reduced friction, and improved tribological stability. The optimized composite has potential for lightweight and wear-resistant applications in automotive, aerospace, marine, sporting goods, sustainable packaging, wind-energy systems, and consumer-electronics components, where reduced weight, improved wear resistance, and environmentally conscious material selection are desirable.

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