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Effects of Nanofillers on the Wear and Frictional Properties of Cellulosic Fibre-reinforced Composites Under Varying Applied loads

This study explores the impact of nanofillers on the wear and frictional characteristics of Cellulosic fibre-reinforced composites. With increasing demand for lightweight and durable materials in various industries, understanding the effects of nanofillers on composite performance is crucial. In this research, pin-on-disc trials were conducted under applied loads ranging from 80 N to 140 N, maintaining a constant 50% fibre volume fraction, a sliding distance of 3000 m, and a velocity of 1 m/s. The incorporation of 5 phr graphite powder was systematically investigated, compared to a graphite-absent control group, to elucidate the nanofiller's influence. Experimental results revealed a notable decrease in the Coefficient of Friction (COF) by 2.63 % to 9.09 % across different applied loads. Moreover, the Specific Wear Rate (SWR) exhibited a significant reduction at all loads, with the most substantial decrease of 61.45 % observed at 80 N. SEM analysis provided further insights, indicating a shift in wear mechanisms towards less damaging interactions. These findings highlight the potential of these composites for high-stress tribological applications in industries.

Keywords: *cellulosic fibre, graphite powder, epoxy composites, wear resistance, coefficient of friction, scanning electron microscopy.*

1. INTRODUCTION

The development and optimization of composite materials, especially in enhancing wear and frictional properties for engineering applications, are key areas of research in materials science. Composite materials play a vital role in engineering applications, particularly in improving wear and frictional properties, driving on–going research in materials science. Notably, natural fibres have gained attention for their environmental benefits and mechanical properties as reinforcements in composites [1–6]. Concurrently, the use of nanofillers, such as graphite powder, has emerged as a promising avenue for reducing wear in polymer composites [7].

Building on this foundation, the research focuses on investigating the influence of graphite powder on the wear and frictional properties of Cellulosic fibre-rein–forced composites. Previous studies have undersco-red the importance of nanofillers, like graphite powder, in enhancing wear performance. For instance, Yousif et al. demonstrated the positive impact of nanofillers on the tribo-performance of composites, leading to improved wear resistance [8]. Similarly, Aravindh et al. highlighted the potential of nanofillers to augment the mechanical properties of fibre-reinforced composites, suggesting enhanced wear characteristics [1].

Moreover, Sumithra et al.'s review of tribological behaviour in natural reinforced composites provides valuable insights into the role of additives like graphite powder in influencing friction, wear, and lubrication [9]. Recent advancements in high-performance graphene-based natural fibre composites have further showcased the potential of graphite and similar materials in improving wear resistance and durability [10].

However, many studies have investigated the tribo–logical behaviour of synthetic fibre-reinforced compo–sites but have not delved deeply into natural fibres like Furcraea foetida. Additionally, recent reviews have noted a gap in research regarding the detailed study of natural fibre composites with varied orientations and the inclusion of nanofillers such as graphite powder [11, 12]. These limitations highlight the need for a compre–hensive study that evaluates the tribological perfor–mance of natural fibre composites, particularly Furcraea foetida fibre, under varying conditions.

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The experimental approach involves pin-on-disc tests under various loads, a methodology validated by previous studies for assessing wear properties of com–posites [13]. By maintaining a consistent fibre volume fraction and fixed graphite powder content, we aim to align with established methodologies for accurate wear analysis [14]. This body of literature collectively sup–ports the hypothesis that the addition of graphite powder to Cellulosic fibre-reinforced composites could signi–ficantly improve their wear performance, thereby alig–ning with the objectives and expected outcomes of the current study.

Comparative analysis with composites without graphite powder is also conducted, similar to previous studies on the impact of nanofillers [15]. The results are expected to offer significant contributions to the under–standing of the wear mechanisms in composite mate–rials, with detailed analysis using scanning electron microscopy [16].

This research seeks to understand the specific influ–ence of graphite powder and also aims to advance the broader knowledge of dynamic interactions within com–posite materials. By offering insights into wear mecha–nisms through detailed scanning electron microscopy analysis, our research is poised to inform the develop–ment of more efficient, wear-resistant engineering com–ponents, meeting the increasing demand for sustainable and high-performing materials.

2. METHODOLOGY

In the methodology section, the experimental proce–dures employed to investigate the wear and frictional properties of the composite materials has been exp–lained. This includes a detailed description of the composite material preparation, graphite powder incor–poration, pin-on-disk setup, and surface analysis techni–ques utilized in the study.

2.1 Composite Material Preparation

In the investigation that formed the basis of this article, the primary matrix material utilized was an epoxy resin, specifically the EpoxAmite™ 100 series combined with 103 slow hardeners, sourced from Mecha Solve Engi–neering. This low-viscosity epoxy resin was selected for its properties conducive to impregnation and penetration into the fibre matrix, enhancing wetting and distribution within the fibre network.

In this study, the focus is on Furcraea Foetida fibres, a type of cellulosic fibre that has been underexplored in tribological research. Despite its limited study in this field, preliminary evidence suggests that these fibres possess significant potential to enhance tribological performance [17], [18]. For composite fabrication, a 50/50 volume fraction of Furcraea Foetida fibres to resin was maintained. The vacuum infusion technique employed ensured a homogenous mixture of the resin and fibres. An acrylic mould, designed specifically for this purpose and measuring 125 mm in length, 80 mm in width, and 7.87 mm in thickness, was prepared by applying a release agent to its surfaces. The fibres, tailored to the mould's dimensions, underwent a 24-hour compression process under a hydraulic press to achieve the requisite thickness and density before being positioned in the mould.

Prior to the resin infusion, a strategic approach was taken to preserve the fibre orientation. Threads were used to secure the fibres, maintaining their alignment, and ensuring uniform resin distribution. The mould was then meticulously sealed with screws and adhesive tape to prevent air intrusion and connected to a vacuum setup, which included a pump and resin trap, facilitating the resin infusion process.

Finally, the composite, with the fibres oriented unidirectionally and maintaining a consistent 50% volume fraction, was allowed to cure. Samples for tribological examination were subsequently extracted from the composite plate using a diamond cutter, following ASTM Standards for precision and consistency. Figure 1 shows the images of sample that is ready to undergo pin on disc test with a dimension of 8 mm x 8 mm x 34 mm.

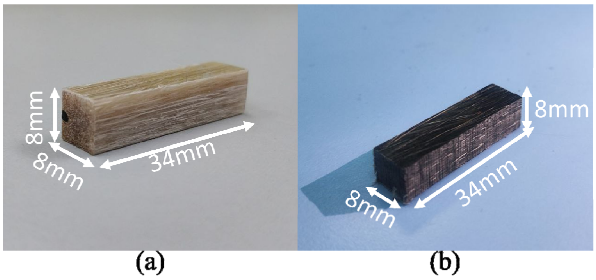

Figure 1. Sample for pin on disc test: (a) Cellulosic fibre reinforced composites, (b) Graphite powder infused cellulosic fibre reinforced composites.

2.2 Graphite Powder Incorporation

A critical enhancement in the composite fabrication was the incorporation of graphite powder. For this purpose, 5 parts per hundred resin (PHR) of graphite powder were meticulously weighed, ensuring precise propor–tionality to the total weight of the epoxy resin. This ratio was determined to optimize the balance between the mechanical properties of the composite and the func–tional benefits of the graphite. The Table 1 shows the detail properties of the graphite powder.

Table 1. Properties of graphite powder

Properties	
Form	Solid
Impurities	≤0.2% Substances soluble in Ethanol
Density	2.2 g/cm3 at 20 °C
Size	≤50nm

The integration of graphite into the epoxy matrix required careful attention to detail. Prior to the addition of the 103 slow hardener, the graphite powder was thoroughly blended with the epoxy resin. This mixing process was performed with a focus on achieving a homogenous mixture, thereby ensuring that the graphite was uniformly dispersed throughout the resin. Such uniformity is pivotal for maintaining the composite's structural integrity and enhancing its wear and frictional properties.

As the epoxy-graphite mixture was prepared, particular care was taken to stir the mixture gently. This cautious approach was essential to prevent the introduction of air bubbles, which can adversely affect the composite's final characteristics. The stability and consistency of the mixture were critical factors in this phase of the process.

During the vacuum infusion process, the epoxy-graphite mixture was carefully introduced into the mould. The objective here was to ensure that the resin-graphite mixture permeated evenly throughout the fibre network. Achieving a uniform distribution was vital for maintaining the desired mechanical properties of the composite.

Post-infusion, the curing process was adjusted to accommodate the specific characteristics of the graphite-epoxy mixture. Monitoring and maintaining the recommended curing parameters, such as temperature and pressure, was essential, particularly given the modified behaviour of the resin due to the presence of graphite.

Upon completion of the curing process, a detailed examination of the composite material was undertaken. This examination aimed to identify any potential alterations in the composite's appearance or texture attributable to the graphite content. Insights gained from this assessment informed adjustments in subsequent fabrications, ensuring the refinement of the composite's quality.

Finally, the prepared composite was processed further for tribological testing. Samples were extracted with precision, using a diamond cutter, conforming to the stringent requirements of ASTM G99 standards. This final step marked the transition from fabrication to the evaluation phase of the study.

2.3 Pin-on-Disc Test Setup

An essential component of the research involved conducting pin-on-disc tests to evaluate the wear and frictional properties of the Cellulosic fibre-reinforced composites with and without graphite powder.

The Koehler K93500 pin-on-disc apparatus used for this study was calibrated to meet the precision requirements for wear and friction testing. The disc was composed of a standardized wear-resistant material (ground hardened steel disc (EN-31, 60HRC)), ensuring consistent wear interaction with the test samples. The pin, fabricated from the composite material, was machined to the specified dimensions as per ASTM G-99 standards. The Figure 2 shows the pin-on-disc tribometer.

The tests were conducted under a range of applied loads (80 N, 100 N, 120 N, and 140 N) to simulate different operational stress conditions. The sliding velocity was set at a constant 1m/s, and the total sliding distance for each test was maintained at 3000 m.

Throughout the testing process, real-time data on frictional force and wear were collected using sensors integrated into the pin-on-disc setup. The coefficient of friction (COF) for each test run was calculated by measuring the frictional force and normal load. Additionally, the specific wear rate was determined by quantifying the material loss from the composite pin post-test, using a high-precision balance.

Each test commenced with the composite pin brought into contact with the rotating disc under the predetermined load. The system was enclosed to minimize external environmental effects. The duration of each test was calibrated to ensure the completion of the 3000m sliding distance.

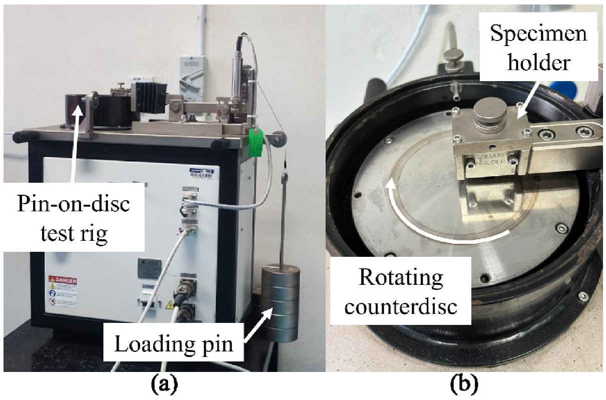

Figure 2. (a) Pin-on-disc tribometer, (b) Pin-on-disc test rig.

2.4 Surface Analysis Technique

The primary technique employed for surface analysis was Scanning Electron Microscopy (SEM). This method provided high-resolution images of the wear tracks on the composite surfaces, allowing for a detailed examination of wear patterns, debris formation, and potential microstructural changes due to friction and wear.

For SEM analysis, samples were carefully extracted from the wear tracks post pin-on-disc testing. These samples were then coated with a thin conductive layer to prevent charging under the electron beam. SEM imaging was conducted at various magnifications to capture both the overview and the detailed features of the wear tracks. Figure 3 shows the specimen coated with a conductive layer and positioned within the Scanning Electron Microscope's stage for SEM analysis.

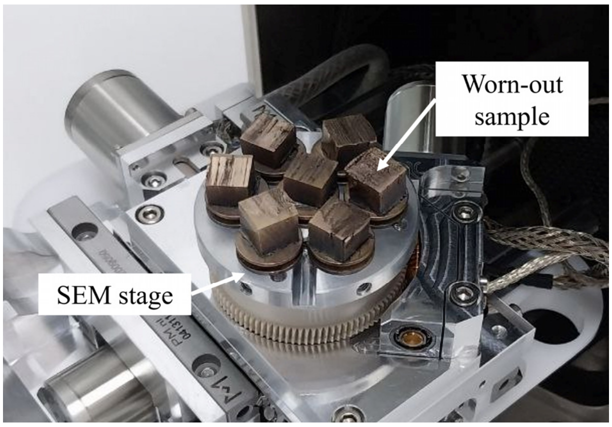

Figure 3. The specimen positioned on the SEM stage before analysis.

The SEM images were systematically analysed to identify wear mechanisms such as abrasion, adhesion, or fatigue. Special attention was given to the differences in wear mechanisms between the graphite-enhanced and control samples. The presence of graphite was expected to influence the wear morphology, which could be revealed through this microscopic examination.

3. RESULT AND DISCUSSION

3.1 Frictional Force vs Sliding Distance

Figure 4 presents a comparative analysis of the tribo–logical performance of cellulosic fibre reinforced epoxy composites with a variation in graphite powder content under a consistent applied load. The data exhibit two distinct trends corresponding to 0 PHR (blue) and 5 PHR (orange) graphite powder content.

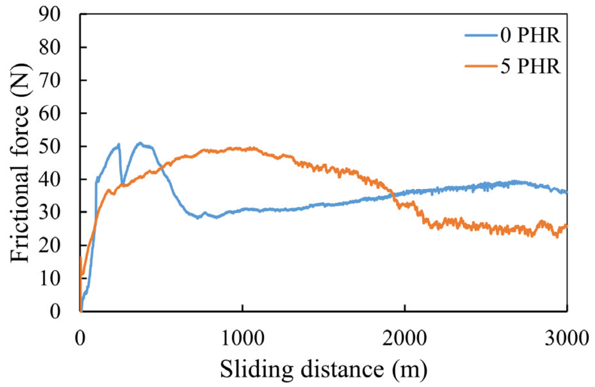

Figure 4. Frictional force vs Sliding distance of composite with 0PHR and 5PHR graphite powder under 80N applied load.

Initially, both composites experience a peak in frictional force, indicative of the breakaway friction as motion commences. Notably, the composite without graphite powder (0 PHR) exhibits a higher peak at 231 m with frictional force of 50 N suggesting greater resistance to motion, due to increased interaction bet–ween fibre and matrix, as well as fibre and counterface [18–21].

As sliding distance increases, the frictional force for the 0 PHR composite demonstrates higher variability and overall force. This is attributed to the absence of graphite, which, in other composites, acts as a solid lubricant, reducing direct fibre-counterface contact and distributing stress more evenly.

Conversely, the addition of 5 PHR graphite powder appears to stabilize the frictional force over the sliding distance with highest peak at 1070 m with frictional force 49.6 N. The lubricating properties of graphite reduce the wear of the composite surface, resulting in a more consistent and lower frictional force. This is aligned with the findings from other research indicating the beneficial role of graphite in enhancing tribological properties [22], [23].

The plateau observed post-peak in both composites signifies a transition to steady-state wear. For the 0 PHR composite, the higher and fluctuating frictional force suggests a more aggressive wear mechanism, due to debonding. In contrast, the steadier force profile of the 5 PHR composite suggests the formation of a transfer film of graphite, which can offer a protective layer to the composite surface.

In short, the graph demonstrates the advantageous role of graphite powder in the tribological performance of cellulosic fibre reinforced composites. The presence of graphite not only decreases the frictional force but also contributes to a more stable tribological behaviour over an extended sliding distance, underlining its importance in composite design for applications where wear resistance is critical.

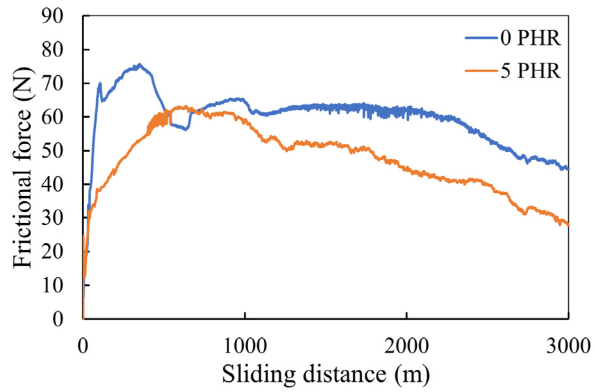

Figure 5. Frictional force vs Sliding distance of composite with 0PHR and 5PHR graphite powder under 100N applied load.

Based on the Figure 5, the composite without grap–hite powder (0 PHR) demonstrated a higher initial peak in frictional force at 351 m with 75.7 N which is an indicative of higher initial asperity engagement and a more aggressive wear-in period [24]. This was followed by a fluctuating yet gradually stabilizing trend, which may represent the formation and disruption of a transfer film [25].

Conversely, the inclusion of 5 PHR graphite powder exhibited a lower peak at 639 m with 63.2 N and overall reduced frictional force over the entirety of the sliding distance. This attenuation in frictional force is attributed to the intrinsic lubricating properties of graphite, which facilitate a smoother interaction between the composite surface and the counterface [22], [26].

From the analysis, it can be inferred that the addition of graphite powder to the cellulosic fibre reinforced epoxy composites results in a notable decrease in frictional force, suggesting an improved wear resistance. Such findings are consistent with existing literature that emphasizes the efficacy of graphite as a solid lubricant in composite materials [27].

The reduction in frictional force with the incor–poration of graphite powder not only enhances the ma–terial's longevity but also optimizes its performance under operational conditions. In short, this investigation sheds light on the potential of graphite powder to en–hance the wear resistance of cellulosic fibre reinforced epoxy composites.

Based on the Figure 6, it can be observed that the composite with 0 PHR shows a higher initial peak in frictional force at 203 m with 78.2 N, which is an indicative of a higher initial resistance to motion, due to asperities or surface irregularities engaging more intensively at the onset of sliding [28]. As sliding continues, the force exhibits a decreasing trend until stabilizing, which suggests a wear-in period where the mating surfaces adapt to each other due to the smoothening of asperities or the formation of a transfer film.

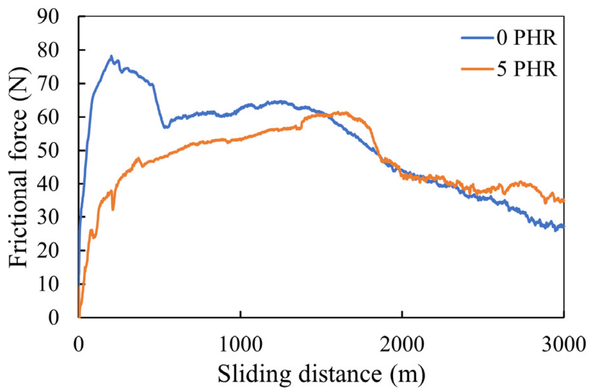

Figure 6. Frictional force vs Sliding distance of composite with 0PHR and 5PHR graphite powder under 120N applied load.

Conversely, the composite with 5 PHR graphite powder, which shows a more gradual increase to a lower peak frictional force at 1602 m with 61.4 N followed by a more stable behaviour. The presence of graphite, a well-known solid lubricant, appears to miti–gate the initial peak and promote a steadier state of friction. This behaviour can be attributed to the forma–tion of a lubricious graphite film on the contact surface, which reduces interfacial adhesion and shear strength, leading to lower friction.

These observations align with the tribological beha–viour of fibre-reinforced polymer composites as repor–ted in the literature. Graphite is often added to such composites to enhance their tribological performance, particularly to lower the coefficient of friction and wear rate under various loading conditions [29]. The wear mechanisms at play here can range from adhesive and abrasive wear without graphite to more lubricated wear with graphite, impacting the overall durability and efficiency of the material in practical applications.

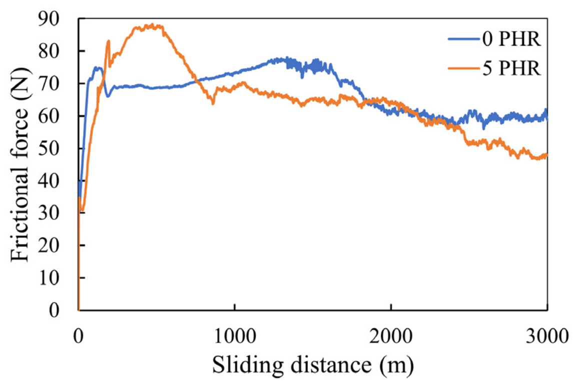

Figure 7. Frictional force vs Sliding distance of composite with 0PHR and 5PHR graphite powder under 140N applied load.

Figure 7 shows that initially, both composites dis–play a sharp peak in frictional force for composite with–out graphite powder (at 110 m with 75 N) and for composite with 5PHR graphite powder (at 473 m with 88.3 N) which is attributed to the 'stick-slip' pheno–menon common in the early stages of wear tests [30]. As sliding progresses, the composite without graphite (0 PHR) shows a slightly higher frictional force compared to the composite with graphite (5 PHR), suggesting that the addition of graphite powder contributes to a reduction in friction.

Moreover, Figure 7 reveals a more stable frictional behaviour in the composite with 5 PHR graphite powder. The lower and steadier frictional force suggests that the graphite acts as a solid lubricant, distributing the contact stress and providing a protective layer that reduces direct fibre-matrix contact.

The SEM images in Figure 13(b) revealing fibre-matrix debonding at 140 N for the composite with graphite powder suggest that while graphite reduces friction, it may also affect the mechanical interlocking between the fibre and the matrix. This might lead to a compromised load transfer efficiency and possibly a lower wear resistance under higher loads. In contrast, the presence of transfer layer and matrix cracking in the composite without graphite under the same load could indicate higher internal stress concentrations leading to material failure.

3.2 Coefficient of Friction vs Sliding Distance

Figure 8 describes the correlation between the Coef–ficient of Friction (COF) and the applied loads ranging from 80 N to 140 N for composites with 0 and 5 PHR graphite powder concentrations. As the applied load increases from 80 N to 140 N, there is a corresponding increase in the COF for both types of composites.

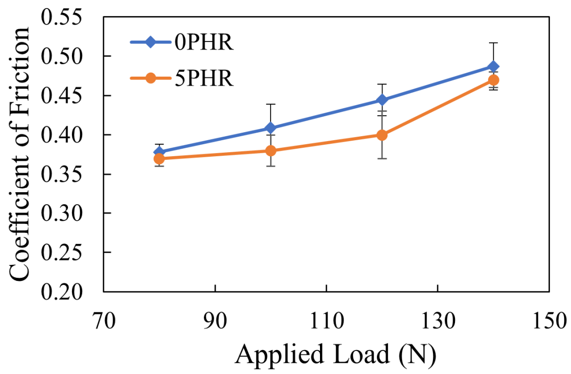

Figure 8. Coefficient of friction against Applied load of composites with 0PHR and 5PHR graphite powder.

Specifically, the composite without graphite powder (0 PHR) exhibits a starting COF of 0.38 at 80N, which progressively increases to 0.49 at 140 N. This is a indicative of the standard load-dependent frictional be–haviour, where the contact area and asperity defor–mation typically augment with higher loads, leading to increased friction [31].

The composite with 5 PHR graphite powder starts at a slightly lower COF of 0.37 at 80 N and increases to 0.47 at 140 N. The rate of increase in COF with the load is similar for both composites; however, the composite with graphite powder maintains a consistently lower COF across all loads. This substantiates the role of graphite as a solid lubricant, which likely forms a tran–sfer film between the contact surfaces, thus diminishing the frictional force [32]. Notably, the disparity in COF between the two composites widens with escalating loads, suggesting that the effectiveness of graphite as a friction modifier is more pronounced under higher loading conditions.

It is also noteworthy that the difference in COF between the two composites diminishes with increasing load, starting from a 0.01 difference at 80 N and reducing to a 0.02 difference at 140 N. This could imply that the lubricating effect of graphite becomes more pronounced under higher load conditions, potentially due to more effective transfer and distribution of the graphite particles between the contact surfaces during sliding.

3.3 Coefficient of Friction vs Sliding Distance

Figure 9 presents an insightful exploration into the wear behaviours of Cellulosic fibre-reinforced epoxy composites, differentiated by the inclusion of graphite powder at 0 PHR and 5 PHR. The specific wear rate (SWR), measured in mm^3/Nm, serves as a quantitative gauge for the material's resistance to wear under a tribological load. As the applied load escalates from a moderate 80 N to a substantial 140 N, an upward trend in SWR is observed for both types of composites, indicating that wear rate amplifies with the increasing load. This trend is consistent with tribological principles where increased load can escalate the contact pressure and thus intensify wear [33]–[35].

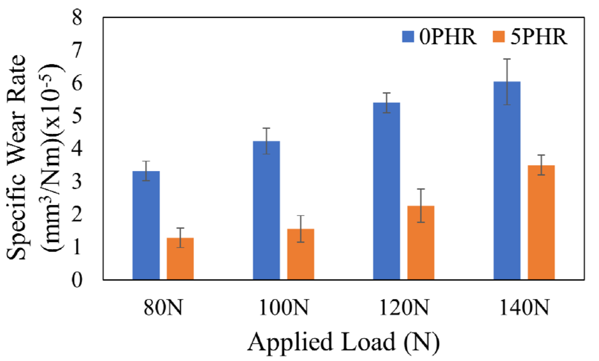

Figure 9. Specific Wear Rate against Applied load of composites with 0PHR and 5PHR graphite powder.

However, the extent of wear rate acceleration is not identical for the two composites. The composite without graphite powder (0 PHR), consistently shows a superior SWR at all levels of applied load, signifying a lower wear resistance when compared to the 5 PHR compo– site. On the other hand, the 5 PHR composite exhibits a SWR that increases less steeply, hinting at a more robust wear resistance, due to the self-lubricating nature of graphite. At the applied load of 80 N, SWR decreased by 61.45 %, and at 100N, it reduced by 63.36 %. Even at higher loads of 120 N and 140 N, the 5PHR com– posite maintained substantial SWR reductions of 58.15 % and 42.22 %, respectively. This demonstrates the consistent and effective enhancement of wear resistance with the addition of graphite powder.

3.4 SEM Analysis and Wear Mechanism Insight

Analysing the SEM images in Figure 10, there are dis– tinct wear mechanisms of cellulosic fibre reinforced epoxy composites with different graphite powder con– tents under a specific applied load. In Figure 10(a), the composite with 0 PHR graphite powder shows visible signs of debris, suggesting abrasive wear. This debris are a result of the hard particles plowing the material surface during sliding [36]. Moreover, the resinous and fibrous regions indicate regions of material removal and fibre exposure, respectively. The debonding circles indicate areas where the fibre has detached from the matrix, implying weak interfacial bonding which is crucial for load transfer and wear resistance [37].

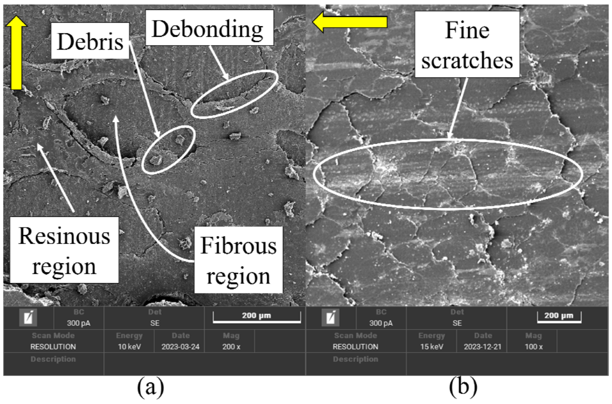

Figure 10. SEM pictures of worn-out samples under applied load of 80N: a) 0PHR, b) 5PHR.

In contrast, Figure(b), representing the composite with 5 PHR graphite powder, exhibits fine scratches without significant debris. This suggests a smoother wear process, potentially due to the lubricating effect of graphite which reduces the abrasion between the sliding surfaces. The absence of heavy debris and large exposed fibrous regions implies that graphite may enhance the wear resistance by forming a transfer film that protects the surface.

From these observations, it's evident that the addi– tion of graphite powder alters the wear behaviour signi– ficantly. While the composite without graphite shows more aggressive wear features, the addition of graphite seems to mitigate the material loss, presenting a potential for improving the lifespan and performance of composites in tribological applications.

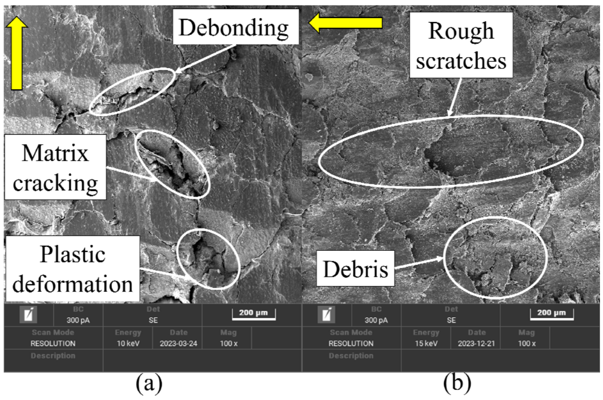

Figure 11. SEM pictures of worn-out samples under applied load of 100N: a) 0PHR, b) 5PHR.

The Scanning Electron Microscope (SEM) images provided in Figure 11 depict the wear mechanisms on cellulosic fibre reinforced epoxy composites subjected to a pin-on-disk test under an applied load of 100 N. For worn out sample in Figure11(a) without graphite pow– der, the SEM image shows visible signs of debonding, matrix cracking, and plastic deformation. This indicates that the material has undergone significant mechanical stress, leading to separation at the fibre-matrix interface, cracks through the matrix material, and permanent de–formation due to the higher load compared to the 80 N test.

In contrast, worn out sample in Figure 11(b) with 5PHR graphite powder shows rough scratches and debris but less severe damage, suggesting that the grap–hite acts as a solid lubricant, reducing friction between the contact surfaces. Graphite can form a transfer film on the counterpart surface, decreasing direct contact and thus wear on the composite material.

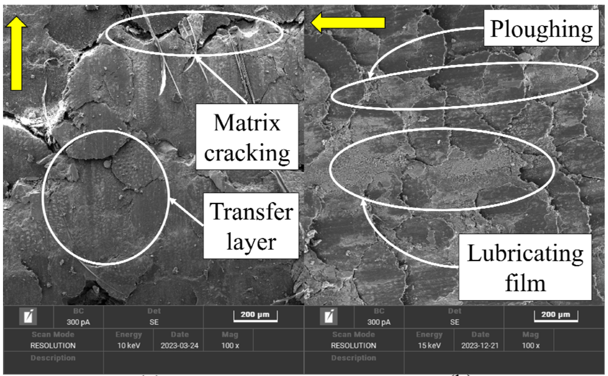

Figure 12. SEM pictures of worn-out samples under applied load of 120N: a) 0PHR, b) 5PHR.

Analysing the SEM images provided for the cellulosic fibre reinforced epoxy composites subjected to a pin-on-disk test under an applied load of 120 N in Figure 12, it can be observed that there are distinct wear mechanisms between the composites with 0 PHR and 5 PHR graphite powder.

In Figure 12(a), which represents the composite with 0 PHR graphite powder, there is a clear presence of matrix cracking and a transfer layer. The matrix crac–king indicates a brittle failure mode within the epoxy matrix, due to the stress concentration exceeding the material's tensile strength [38]. The transfer layer sug–gests that material from the composite or counterface has been smeared across the surface during the wear process, which can act as a protective layer reducing further wear.

In contrast, Figure 12(b) shows the composite with 5 PHR graphite powder. Here, there is evidence of ploughing and the formation of a lubricating film. Ploughing indicates a more ductile wear mechanism where material is displaced to form ridges adjacent to grooves [39]. The presence of a lubricating film, which is often comprised of graphite and other debris, can significantly reduce the coefficient of friction and protect against severe wear [40].

The addition of graphite in the composite of Figure 12(b) appears to promote the formation of a lubricating film, which can dissipate energy and accommodate deformation more effectively than the brittle matrix observed in Figure 12(a). This may explain the absence of matrix cracking in the composite with 5 PHR graphite powder. Graphite's intrinsic lubricity is well-documented and can enhance the wear resistance of composites significantly under tribological stress.

Figure 13 provided the scanning electron micro–scope (SEM) images for the cellulosic fibre reinforced epoxy composite present distinctive wear mechanisms under a substantial applied load of 140N. For the com–posite with 0 PHR graphite powder (Figure 13a), dela–mination is a prominent failure mode, manifesting as a peeling away of the composite layers. This occurrence typically arises from inadequate interfacial bonding strength between the fibres and the matrix or from an applied stress that surpasses the material's interlaminar threshold [41]. Additionally, the presence of cracks within the matrix indicates stress concentration effects which may originate from either the external load surpassing the material's intrinsic flaw tolerance or from inherent material imperfections that become critical under load [42].

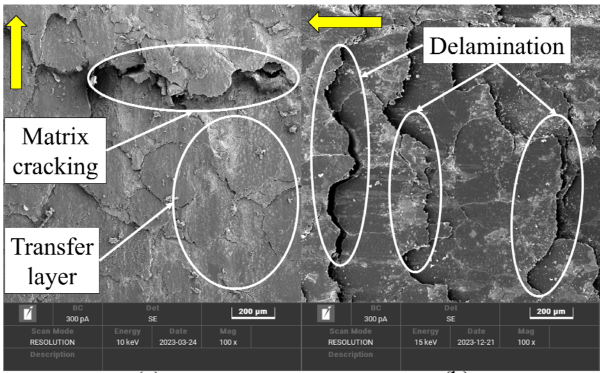

Figure 13. SEM pictures of worn-out samples under applied load of 140N: a) 0PHR, b) 5PHR.

Conversely, Figure 13(b), representing the compo–site infused with 5 PHR graphite powder, showcases debonding of fibres from the matrix. This detachment is possibly a consequence of the differing thermal expan–sion coefficients of the fibre and matrix or the exertion of a stress exceeding the interfacial adhesion capacity [43]. Interestingly, despite this debonding, the wear distribution appears more homogeneous, possibly hin–ting at the beneficial role of graphite. The self-lubri–cating nature of graphite is reducing frictional interac–tions, leading to more even wear across the composite surface, which is a desirable trait for applications demanding high wear resistance [44].

4. CONCLUSION

In summary, the integration of 5PHR graphite powder into Cellulosic fibre-reinforced epoxy composites markedly improves their tribological performance. The SEM analysis and wear tests elucidate that with graphite enhancement, the composites demonstrate stabilized fri–ctional behaviour over extended sliding distances, with a notable peak frictional force of 49.6 N at 1070 m for an 80 N load—a significant improvement over the 50 N peak at 231 m observed in the 0 PHR composites. This trend of improved stability with the addition of graphite is consistent even at increased loads.

The Specific Wear Rate (SWR) analysis supports this finding, indicating that the 5PHR composites experience significantly reduced wear, with a reduction of 61.45 % at an 80 N load and maintaining a consi–derable reduction of 42.22 % even at a 140 N load. Concurrently, the Coefficient of Friction (COF) is con–

sistently lower in the graphite-infused composites across all loads, dropping by 2.63 % at 80 N and by as much as 9.09 % at 120 N.

The SEM studies provide microscopic confirmation of the wear mechanisms, revealing that the 5 PHR composite exhibits less severe damage, such as reduced debonding and matrix cracking, and suggests the for–mation of a protective lubricating film, which is absent in the 0PHR composite. At the highest applied load of 140 N, while the 0 PHR composite shows delamination and cracks, the 5 PHR composite maintains more uni–form wear, indicating the resilience imparted by the graphite powder.

These empirical findings demonstrate that the incorporation of graphite into Cellulosic fibre-reinforced epoxy composites significantly enhances wear resistance and reduces friction across a spectrum of applied loads, validating the use of graphite as an effective solid lubricant. The research underscores the potential of graphite-reinforced composites for industrial applications where durable and low-friction materials are essential, potentially transforming practices in sectors like automotive and aerospace engineering and contributing to the advancement of sustainable material technology.

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NOMENCLATURE

COF	Coefficient of Friction
PHR	Parts per Hundred Resin
SEM	Scanning Electron Microscope
SWR	Specific Wear Rate

УТИЦАЈ НАНОПУНИЛА НА ХАБАЊЕ И СВОЈСТВА ТРЕЊА КОМПОЗИТА ОЈАЧАНИХ ЦЕЛУЛОЗНИМ ВЛАКНИМА ПОД РАЗЛИЧИТИМ ПРИМЕЊЕНИМ ОПТЕРЕЋЕЊИМА

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Ова студија истражује утицај нанопунила на хабање и карактеристике трења композита ојачаних целу–лозним влакнима. Са све већом потражњом за лага–ним и издржљивим материјалима у различитим индустријама, разумевање ефеката нанопунила на перформансе композита је кључно. У овом истра–живању, пин-он-дисц тестови су спроведени под примењеним оптерећењима у распону од 80 Н до 140 Н, уз одржавање константног 50% запреминског удела влакана, растојање клизања од 3000 м и бр–зину од 1 м/с. Уградња 5 пхр графитног праха је систематски испитивана, у поређењу са контролном групом без графита, да би се разјаснио утицај нанопунила. Експериментални резултати су открили значајно смањење коефицијента трења (ЦОФ) за 2,63 % до 9,09 % при различитим примењеним оп–терећењима. Штавише, специфична стопа хабања (СВР) је показала значајно смањење при свим опте–рећењима, са највећим смањењем од 61,45 % приме–ћеним на 80 Н. СЕМ анализа је пружила даље увиде, што указује на померање механизама хабања ка мање штетним интеракцијама. Ови налази нагла–шавају потенцијал ових композита за триболошку примену високог напрезања у индустрији.