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EVALUATING THE TRIBOLOGICAL PERFORMANCE OF FIBER-REINFORCED COMPOSITES FOR ORTHOPEDIC FIXATION SYSTEMS

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ABSTRACT

This study investigates the tribological performance of epoxy-based polymer composites reinforced with flax, carbon fiber (CF), Kevlar, and hybrid Kevlar-Carbon fibers to assess their suitability for orthopedic implant applications. The research focuses on two key parameters: the coefficient of friction (COF) and surface roughness, both of which are crucial for implant durability and functionality. A reciprocating wear test was conducted under varying normal loads (2 N, 4 N, 6 N and 8 N) and fiber volume fractions (8 %, 16 % and 24 %) to evaluate frictional behavior. The results indicate a significant reduction in COF with increasing fiber content across all reinforcement types, demonstrating the beneficial effects of fiber incorporation. Among the tested composites, CF exhibited the lowest COF due to its self-lubricating properties and smoother surface, whereas flax fiber composites consistently showed the highest COF, attributed to their rougher texture and higher adhesion with stainless steel. Hybrid Kevlar-Carbon composites demonstrated intermediate COF values, balancing Kevlar's toughness with CF's friction-reducing characteristics. Additionally, surface roughness was measured using a Mitutoyo Surftest SJ-210 after tribological testing to analyse the effect of wear on the composite surfaces. The findings revealed an increase in surface roughness with higher fiber volume fractions, particularly in flax and Kevlar composites. These results highlight the importance of optimizing fiber selection and volume fraction to achieve favorable tribological properties, ensuring reduced friction while maintaining adequate wear resistance. The study provides valuable insights into the potential application of fiber-reinforced epoxy composites in biomedical implants, emphasizing their ability to enhance durability, minimize wear-related complications, and improve implant longevity.

KEYWORS

Orthopaedic implants, Kevlar fibers, carbon fibers, epoxy composites, coefficient of friction, surface roughness.

INTRODUCTION

Orthopaedic implants are critical in restoring function and mobility to patients suffering from bone fractures, degenerative diseases, or trauma-related injuries, [1, 2]. Traditionally, metallic implants made from stainless steel, titanium, and cobalt-chromium alloys have been the standard due to their high mechanical strength, durability, and biocompatibility, [3]. However, despite their widespread use, these materials present several challenges that can compromise the long-term success of the implant, [4]. One of the most significant issues is stress shielding, where the high stiffness of metal implants alters the natural load distribution in the bone, leading to bone resorption and eventual implant loosening, [5-7]. Additionally, metallic implants are susceptible to corrosion and wear, particularly in physiological environments, which can lead to the release of metal ions into surrounding tissues, potentially causing inflammation and adverse biological responses, [3, 5, 7]. Another drawback of metallic implants is their incompatibility with modern imaging techniques, such as MRI and CT scans, where their high density creates artifacts that obscure diagnostic imaging, making postoperative monitoring more challenging, [8 - 12].

To address these challenges, polymer-based fiber-reinforced composites (FRCs) have gained attention as promising alternatives for orthopedic applications, [13 - 15]. These materials offer several advantages, including lower stiffness, which better matches that of natural bone, thereby reducing stress shielding effects. Moreover, polymer composites are lightweight, corrosion-resistant, and radiolucent, ensuring improved imaging capabilities compared to metal implants [15 - 17]. By incorporating high-strength reinforcing fibers such as flax, carbon fiber, Kevlar, or hybrid fiber combinations, these composites can achieve optimized mechanical properties while maintaining flexibility and durability [13 - 15, 17 - 20]. Flax fibers, being biodegradable and derived from natural sources, offer sustainability and biocompatibility, whereas carbon fibers provide superior strength and wear resistance, and Kevlar fibers contribute toughness and energy absorption [15, 20]. The strategic combination of these reinforcements allows for the development of materials that balance strength, fatigue resistance, and wear performance for enhanced orthopedic applications, [15, 20].

Despite the promising mechanical properties of FRCs, their tribological behavior remains a crucial aspect that requires thorough investigation, particularly regarding their interaction with fixing screws, which are essential for implant stability [21-23]. In orthopedic applications, implants are commonly fixed to the bone using stainless steel screws, which introduces a dynamic contact interface that undergoes repeated loading and frictional wear, [24 - 26].

Over time, poor tribological performance between the implant material and the fixing screws can result in increased wear, surface degradation, and micro-movements, ultimately leading to loosening of the fixation and implant failure. Therefore, understanding the coefficient of friction (COF) and surface roughness characteristics of these composites in contact with stainless steel is vital to predicting their long-term stability and optimizing their design for enhanced durability [20, 25, 27 - 31].

This study aims to evaluate the tribological performance of epoxy-based fiber-reinforced composites by conducting reciprocating wear tests to measure the COF and assess surface roughness both before and after wear testing. The experimental analysis will examine how different fiber types (flax, carbon, Kevlar, and hybrid), fiber volume fractions (8 %, 16 %, and 24 %), and normal loads (2N, 4N, 6N, and 8N) influence the frictional response and wear behavior of the composites. The findings of this study will provide critical insights into the suitability of these composites for orthopedic applications, ensuring enhanced wear resistance, improved fixation durability, and a longer service life for polymer composite implants.

EXPERIMENTAL

Epoxy Resin

Epoxy resins, valued for their mechanical strength, chemical resistance, and ease of processing, were initially restricted to non-biological applications due to safety concerns. However, advancements in composition have enabled their adaptation for biomedical use. Modified epoxy resins now interact safely with biological tissues, avoiding cytotoxic or immune responses. This compatibility is achieved through safer raw materials, removal of harmful additives, and optimized curing processes, see Table1.

Table 1 Mechanical properties of epoxy

Property	Value
Tensile Strength (MPa)	179
Tensile modulus (GPa)	10.4
Elongation at Break (%)	Low (brittle)
Density (g/cm³)	1.1

200 g 2×2 Twill Carbon Fiber with 3000 filaments per fiber.

The tensile strength and stiffness of carbon fibers are outstanding, see table 2, surpassing a variety of traditional materials like metals and ceramics. Carbon fibers consist of slender filaments of high-strength carbon. When integrated into polymer matrices, carbon fibers enhance the strength of composites, boosting their ability to bear loads and resulting in impressive strength-to-weight ratios.

Table 2 mechanical properties of CF provided from manufacturer

Property	Value
Tensile Strength (MPa)	3100
Tensile modulus (GPa)	230
Elongation at Break (%)	1.8
Density (g/cm³)	1.79

200 g 2×2 Twill Kevlar Fibers with 3000 filaments per fiber

Kevlar is a heat endurance and powerful artificial fiber, associated to other Traditional metallic implants often exert excessive weight and pressure on the adjacent bone, leading to an in-creased likelihood of issues such as stress shielding, implant failure, and bone resorption. Kevlar fiber composites present a solution by

reducing the weight of the implant while maintaining or potentially improving its mechanical properties, as seen in table 3.This alleviates bone stress, enhances patient comfort, and facilitates more efficient rehabilitation.

Table 3 mechanical properties of Kevlar provided from manufacturer

Property	Value
Tensile Strength (MPa)	3800
Tensile modulus (GPa)	131
Elongation at Break (%)	2.4
Density (g/cm^3)	1.44

200 g 2×2 Twill Hybrid CF-Kevlar with 3000 filaments per fiber.
Carbon-Kevlar hybrid woven fabric is a type of composite material that merges the attributes of both carbon fiber and Kevlar fiber. This fabric is created by interlacing strands of carbon and Kevlar fiber in a specific ar-rangement, resulting in a fabric with enhanced mechanical properties.

200 g 2×2 Twill Flax
Flax-woven fiber is a versatile and sustainable material. It is appreciated for its environmentally friendly farming practices, ability to decompose, and unique aesthetic appeal, despite its mechanical strength being lower than some other options as seen in table 4. Research efforts are focused on overcoming performance limitations while maintaining its inherent advantages, positioning flax-woven fiber as a promising candidate for a sustainable future across various industries.

Table 4 mechanical properties of Flax provided from manufacturer

Property	Value
Tensile Strength (MPa)	61
Tensile modulus (GPa)	7
Elongation at Break (%)	1.5
Density (g/cm^3)	1.45

Fabrication method
The lay-up process was used to fabricate the suggested composites. The epoxy resin's low viscosity made it easier for it to penetrate the woven fabric. Furthermore, trapped air bubbles were able to rise to the surface and disperse more effectively due to the epoxy's low viscosity property. In order to prevent the development of stress concentration zones, which could jeopardize the material's integrity and mechanical performance, the composite structure must be free of voids and air bubbles.

Tribological test
The tribological behavior of orthopedic implants plays a critical role in their long-term performance. When implants are fixed to bone using stainless steel screws, friction and wear at the interface can influence their stability, mechanical integrity, and overall lifespan. Excessive wear may lead to loosening of the implant, while an

inappropriate coefficient of friction (COF) can cause undesirable stress concentrations, potentially affecting the healing process and implant success.

To evaluate the frictional interaction between the proposed polymer composite implants and stainless steel screws, a reciprocating wear test was conducted. This test provides crucial insights into the COF of different composite materials under varying loading conditions. Understanding the tribological properties of these materials ensures that they meet the necessary mechanical requirements for orthopedic applications while minimizing wear-related complications.

Reciprocating Wear Test

The tribological tests were performed using a reciprocating wear test rig illisturated in Fig.1, designed to simulate the frictional contact between the composite implants and stainless steel screws. The test rig consists of a stainless steel plate mounted on a reciprocating platform, while the composite specimen is held against the plate with a controlled normal force. A reciprocating sliding motion was applied to simulate real-life loading conditions.

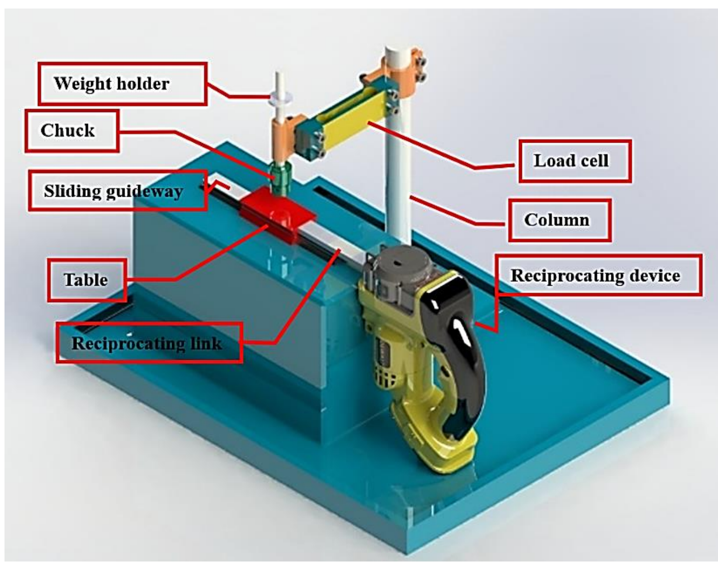

Fig. 1 Reciprocating friction and wear test machine.

The test parameters were carefully chosen to replicate physiological conditions and assess the impact of fiber reinforcement on frictional performance. The composite specimen was positioned such that both the epoxy matrix and the fiber reinforcements came into direct contact with the stainless steel plate. The following parameters were maintained throughout the experiment, see table 5.

Table 5. Reciprocating friction and wear test parameters

Property	Value
Matrix	Epoxy
Reinforcement	Flax, Carbon Fiber, Hybrid, Kevlar Fiber
Volume Fraction (VF) (%)	(8, 16, 24)
Normal Force (N)	2, 4, 6, 8
Condition of sliding	Dry

Each test was repeated multiple times to ensure repeatability and accuracy of the results. The COF was continuously monitored throughout the test using force sensors integrated into the test rig, allowing for real-time data collection and analysis. The results from this test will help determine the optimal composite formulation for orthopedic applications by identifying materials that exhibit favorable frictional properties, reduced wear, and enhanced mechanical stability.

Surface Roughness

Surface roughness is a critical parameter in evaluating the tribological performance of composite materials, as it directly influences wear behavior and friction characteristics. To assess the surface texture of the fabricated composites, a Mitutoyo Surftest SJ-210 Portable Surface Roughness Tester was employed, seen in Fig.2. The device utilizes a stylus-based contact method to measure surface irregularities across the composite specimens. Measurements were conducted on both the woven reinforcement fibers and the surrounding epoxy matrix to capture variations in roughness within the composite structure.

Fig. 2 Mitutoyo Surftest SJ-210 Portable Surface Roughness Tester.

The roughness test was performed after the composite specimens had been subjected to an 8N normal load against a stainless steel plate to evaluate the effect of repeated contact and rubbing on surface texture. The roughness values were recorded in terms of the arithmetic mean roughness (Ra) to quantify the topographical differences between the fiber and matrix regions. This analysis provides essential insights into the role of surface texture in frictional interactions, complementing the COF

measurements and enhancing the overall tribological assessment of the composite implants.

RESULTS AND DISCUSSION

Reciprocating Wear Test

The tribological performance of the composite materials is a key factor in assessing their suitability for orthopedic implant applications. The following charts, Fig3, illustrate the variation in coefficient of friction (COF) and wear characteristics across different reinforcement types, fiber volume fractions, and applied normal loads.

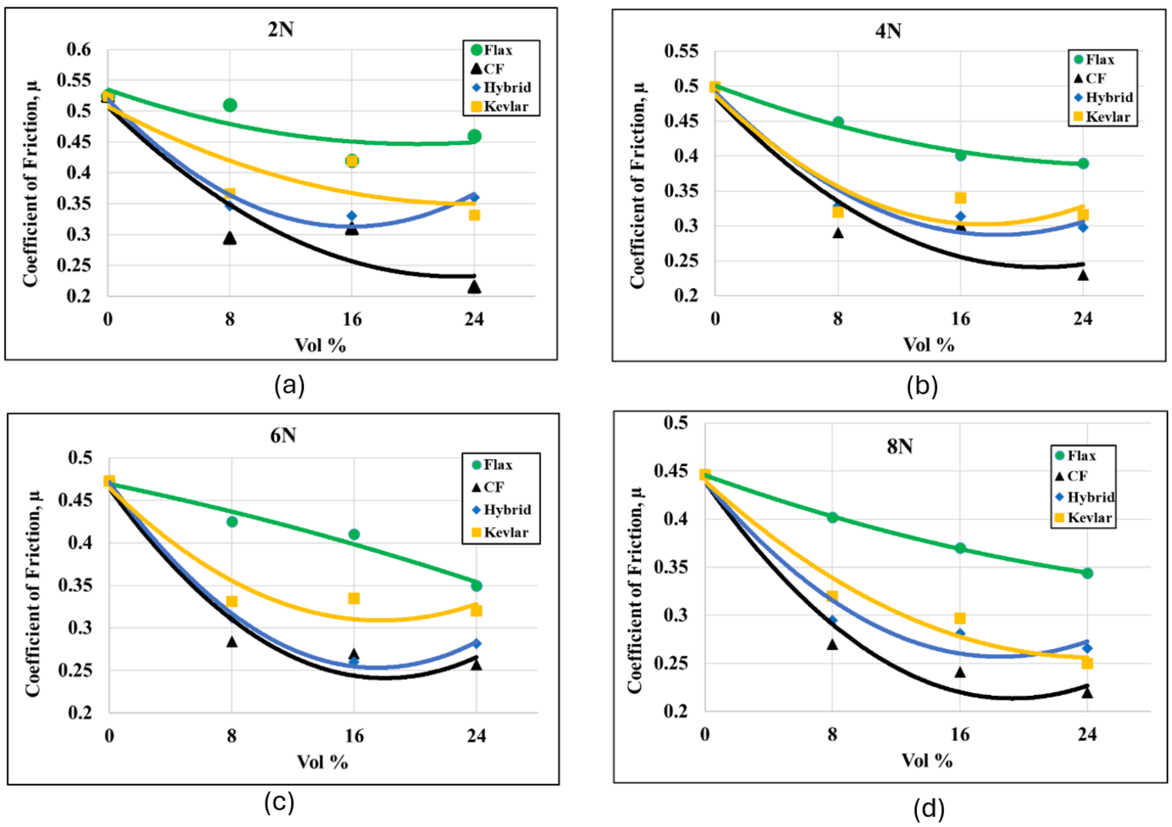

Fig. 3 Coefficient of friction displayed by the tested composites at different normal loads (a) 2 N, (b) 4 N, (c) 6 N, (d) 8 N.

The coefficient of friction (COF) results for the polymer composite materials reinforced with flax, carbon fiber (CF), Kevlar, and hybrid Kevlar-Carbon fibers under varying normal loads (2 N, 4 N, 6 N, and 8 N) and fiber volume fractions (8 %, 16 %, and 24 %) reveal significant trends regarding the tribological performance of these materials. Flax fiber composites exhibit the highest COF values across all normal loads, which can be attributed to their rougher surface and greater adhesion with stainless steel. In contrast, carbon fiber composites consistently demonstrate the lowest COF, benefiting from their self-lubricating properties due to graphite particles generated from wear that act as a lubricant, in addition to their smoother surface characteristics that reduce adhesive interactions. Kevlar composites show intermediate COF values, higher than carbon fiber but lower than flax, due to their tendency to form micro-fibrils under load, which increases surface contact and

friction. Hybrid Kevlar-Carbon composites display COF values between those of Kevlar and carbon fiber, benefiting from the combination of Kevlar's toughness and carbon fiber's low-friction properties.

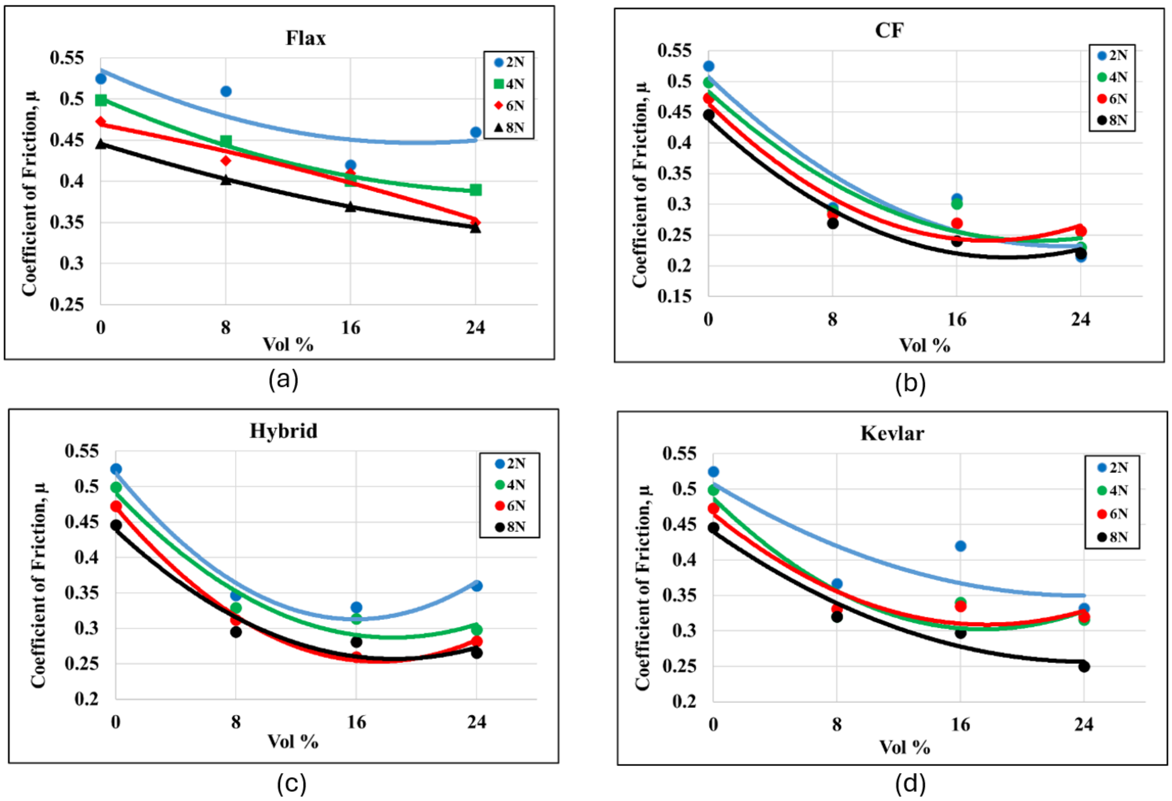

Fig. 4 Coefficient of Friction displayed by the tested composites at reinforcement types (a) Flax, (b) CF, (c) Hybrid, (d) Kevlar.

The alternative representation, shown in Fig. 4, of the dataset provides a clearer visualization of the COF trends for each reinforcement type, emphasizing the influence of increasing normal load at each fiber type. The separation of individual material responses highlights the consistent reduction in COF with load, particularly for carbon fiber and hybrid composites, which maintain the lowest friction values across all conditions. Additionally, the refined graphical representation reinforces the observation that flax composites exhibit the highest COF, while Hybrid Kevlar-Carbon reinforcements offer a balanced performance.

Increasing the normal load results in a general decrease in COF across all reinforcement types, as seen in Fig. 4 (a), (b), (c) and (d) , this can be attributed to the increased real contact area and improved load distribution. Similarly, increasing the fiber volume fraction leads to a consistent reduction in COF, with the most significant improvement occurring between 0% and 8%, as fiber reinforcement reduces the matrix-dominated friction. Beyond 16%, further reductions in COF become less pronounced, suggesting a threshold beyond which additional fiber content has diminishing returns.

Overall, carbon fiber reinforcement offers the most favorable tribological performance, making it an optimal choice for minimizing friction in orthopedic applications, while hybrid composites provide a balance between frictional performance and material toughness.

Surface Roughness

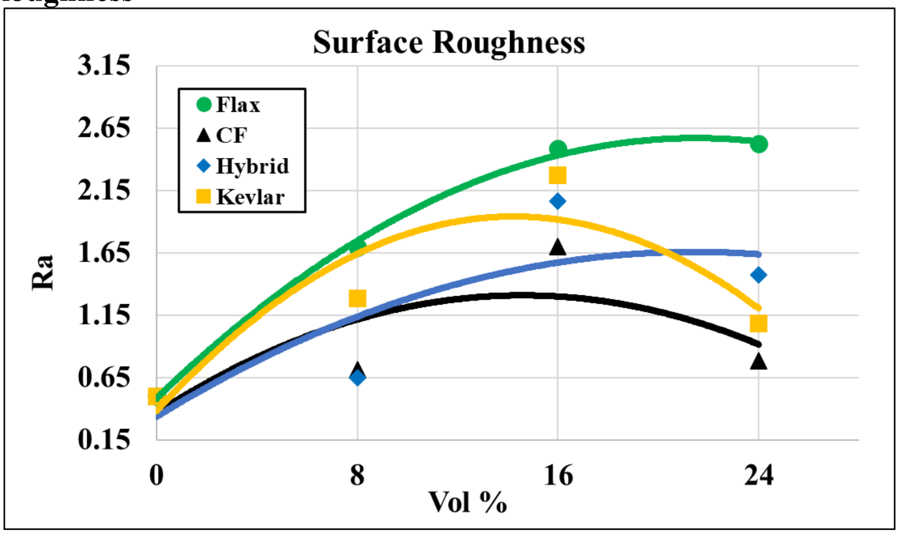

Fig. 5 Effect of volume fraction on Surface Roughness of the tested composites.

While observing Fig. 5, the surface roughness (Ra) of the composite specimens exhibits a clear increasing trend with higher fiber volume fractions, reflecting the greater exposure of the woven reinforcement on the surface. The epoxy-only specimens initially exhibit the lowest roughness but become progressively rougher as fiber content increases, indicating that the resin alone contributes to a smoother finish while reinforcement fibers introduce additional texture.

Flax fiber composites consistently demonstrate the highest roughness values reaching 2.6 Ra due to the intrinsic texture of natural fibers and their tendency to create irregular surface features. As the fiber content increases, the epoxy matrix becomes less dominant, leading to a more pronounced surface texture. Carbon fiber composites, in contrast, exhibit the lowest roughness among the reinforced specimens with a Ra value of 0.8 , benefiting from their inherently smoother surface and compact weave structure. However, even carbon fiber composites experience a gradual increase in Ra with higher fiber volume fractions due to reduced resin coverage. Hybrid Kevlar-Carbon composites show intermediate roughness values, as the presence of Kevlar fibers introduces additional surface irregularities compared to pure carbon fiber reinforcement. Kevlar-reinforced composites also exhibit increasing roughness with fiber volume fraction, largely due to Kevlar's tendency to fibrillate under mechanical interaction, creating a more textured surface. Overall, these findings suggest that fiber selection and volume fraction significantly influence the surface characteristics of the composites, which in turn may impact their tribological behavior, particularly in terms of wear resistance and frictional interaction.

CONCLUSIONS

1. The coefficient of friction (COF) varies with fiber type, volume fraction, and applied load, with carbon fiber composites showing the lowest COF and flax composites the highest.

2. Increasing the fiber volume fraction generally reduces COF, particularly at lower reinforcement levels, but this effect seems less effective beyond 16 %.

3. Surface roughness measurements indicate that fiber reinforcement increases initial roughness, with post-wear analysis revealing further changes due to frictional interactions with stainless steel.

4. The findings highlight the potential of hybrid Kevlar-carbon composites as a balanced solution, offering improved tribological properties while maintaining mechanical integrity.

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