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Wear Properties of Coated and Uncoated Glass and Basalt Fibre Reinforced Polyester Composites

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ABSTRACT

This research investigates the tribological behavior of polytetrafluoroethylene (PTFE) coated and uncoated synthetic glass fiber (GF) and basalt fiber (BF) polyester composites. It aims to enhance the wear resistance of GF and BF composites by applying a PTFE coating. The presence of thermoplastic coating is designed to improve the GF and BF composites durability and functionality, hence reducing maintenance costs by minimizing wear and tear. Physical and tribological tests were conducted, including sliding wear and abrasion tests to assess dry particle abrasive wear resistance, and also a pin-on-disk test to evaluate the coefficient of friction and roughness/smoothness of the materials surface. The tribological performance of the fibre reinforced polymer (FRP) composites with and without PTFE coatings was compared. The findings revealed that the Glass Fiber Reinforced Polymer (GFRP) composite exhibited the highest density, while the PTFE-coated Basalt Fiber Reinforced Polymer (BFRP) composite had the lowest density, with the PTFE-coated GFRP falling in between. In sliding abrasion tests, GFRP had a higher wear volume than BFRP, which demonstrated a 66% reduction in wear volume due to its superior hardness. PTFE-coated BFRP showed the lowest specific wear rate, decreasing by 56% compared to GFRP, which had the highest rate. In the dry particle abrasion test, PTFE-coated GFRP exhibited the lowest wear volume, reducing by 57% compared to BFRP. Overall, the study demonstrates that PTFE coatings significantly enhance the wear resistance and tribological performance of fiber-reinforced polymer composites. Hence, this will extend their lifespan and reduce the maintenance costs of the FRP structure.

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INTRODUCTION

Glass fiber-reinforced polymer (GFRP) composites are widely utilized across various industries due to their superior mechanical and chemical properties. Similarly, basalt fiber, which is derived from basalt rock and is naturally non-biodegradable, has been employed in many engineering applications, with its properties frequently evaluated in conjunction with polymer matrices (Boobalan et al., 2024; Antil et al., 2018; Vikas & Sudheer, 2017). The idea of incorporating PTFE thin film onto the FRP composite may enhance the performance by creating a protective layer. Polytetrafluoroethylene (PTFE) is a semi-crystalline thermoplastic known for its ability to form a uniform layer with consistent thickness on surfaces (Tóth et al., 2020). PTFE coatings are anticipated to offer benefits such as reduced friction, enhanced wear resistance, and improved surface properties, making them significant in tribological applications for fiber-reinforced composites.

These composites are extensively used in industrial, automotive, and manufacturing sectors, particularly in components like shafts and gears, which are subjected to various tribological loads, including adhesive, abrasive, and erosive forces (Mesri et al., 2023; Agrawal et al., 2016; Shuhimi et al., 2016). In applications such as water sports equipment, including rafts and surfboards, where composites are exposed to wear and erosion, it becomes crucial to investigate these factors. Marine and aerospace materials also face continuous exposure to corrosive fluids and hard element corrosion (Zhu & Li, 2024; Bender et al., 2022). To prevent corrosion and wear, it's essential to select the right combination of materials, including hard microparticles. Developing effective tribological components requires balancing low friction characteristics, as mentioned by Wei et al. (2024), with maintaining mechanical strength, which can be achieved by modifying the friction and strength properties of composites with functional additives like PTFE. Solid lubricants such as PTFE can serve as friction modifiers, with glass or basalt fibers used as reinforcement (Subramanian et al., 2016).

Wang et al. (2014) examined the two-body abrasive wear behavior of BFRP and GFRP using a pin-on-disc apparatus. The wear tests on BFRP and GFRP specimens were conducted under loads of 5, 10, and 15 N over an abrading distance of 100 m. BFRP exhibited the lowest specific wear rate across all loads, primarily due to its high hardness and the presence of iron (Fe) in its composition, which resists abrasive wear. Furthermore, Zhang et al. (2009) studied the friction and wear behavior of short basalt fibers (BF) reinforced with polyimide (PI) matrix composites using a ring-on-block test apparatus. These composites slid against GCr15 steel under dry conditions, and it was found that adding 10 wt.% of BFs improved the coefficient of friction and wear rate. A transfer layer formed on the counterpart surface during the friction process, which reduced both the friction coefficient and wear rate of the BF/PI composites. The tests revealed that BF/PI composites demonstrated better tribological properties at higher loads (200 N) and sliding speeds (0.862 m/s).

Besides, Birleanu et al. (2023) identified that an applied load of 10 N, a sliding velocity of 0.1 m/s, and a glass fiber content of 54% was the optimal combination for the multi-response properties of the tested friction composite, although increasing the GF content did not significantly enhance the tribological performance. Wang et al. (2021) explored the friction coefficient and surface roughness of samples with varying BF concentrations. They found that as the BF concentration increased, surface roughness also increased, while the friction coefficient initially rose to 0.39 before gradually decreasing to 0.3. Over time, the friction coefficient stabilized, although it was not directly proportional to surface roughness. The heat generated by friction between neat Polyether Ether Ketone (PEEK) and the steel ball increased adhesion and contact area, leading to a rapid increase in the friction coefficient, which eventually stabilized as the contact area reached its maximum (Lin & Schlarb, 2019; Díez-Pascual et al., 2013; Öztürk et al., 2007; Eriksson & Jacobson, 2000). Abu Talib et al. (2021) noted that the friction and wear characteristics of composites are highly dependent on testing conditions. In a 10-kilometer test, BFRP composites outperformed glass fiber-reinforced polymer (GFRP) composites in wear resistance against erosive sand. All the above research confirmed the effectiveness of basalt fiber in improving the tribological properties

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of FRP composites. Therefore, in this study the use of woven basalt fiber as reinforcement in composite was investigated.

According to Tóth et al. (2020), PTFE-filled samples showed the lowest coefficient of friction due to PTFE's superior lubricating properties, which also controlled frictional heating, resulting in the longest lifespan for PTFE-filled composites. Also, Huang et al. (2019) investigated the wear behavior of glass fiber-reinforced PTFE sliding against duplex steel at elevated temperatures using interrupted wear tests combined with worn surface observations. The results indicated that the coefficient of friction and wear rate changed with rising temperatures.

The analysis of GFRP and BFRP composites, particularly when enhanced with PTFE, reveals their substantial potential to enhance tribological performance across diverse applications. Consistent research findings highlight the importance of optimizing material composition and testing conditions to achieve superior friction and wear characteristics. As industries strive for more robust and efficient materials, ongoing research in this field will be essential for advancing composite technologies that can meet the demands of challenging operational environments. Therefore, the primary aim of this study is to evaluate the friction and wear characteristics of glass fiber and basalt fiber-reinforced polyester composites under three different wear tests: pin-on-disc testing, abrasive wear testing, and slurry erosion testing, to assess the physical and tribological performance of polyester-based composites with and without PTFE coating layer.

METHODOLOGY

Materials and composite fabrication

The matrix material, Liquid SHCP 3254 BQTN, an isophthalic polyester resin, was provided by Singapore High Polymer Chemical Product Pte Ltd, located in Jurong Industrial Estate, Singapore. Basalt and glass woven fibers, along with methyl ethyl ketone peroxide (MEPOXE M), a liquid organic peroxide used as a hardener, were supplied by Innovative Pultrusion Sdn. Bhd., Seremban, Negeri Sembilan. The polytetrafluoroethylene (PTFE) film used had a thickness of 0.025 mm with treated film surface.

The composites were fabricated using the hand lay-up technique followed by vacuum bagging. Layers of woven glass and basalt fibers were cut and prepared. A mixture of polyester resin and hardener was then applied to the layers of glass and basalt fibers, with each fiber ply being coated individually until a total of 10 plies was reached, achieving a minimum composite thickness of 4 mm. The composite was then vacuum bagged to eliminate any air trapped and enhance the interfacial bonding between the matrix and fibers.

Pin on disk test

A TR-20LE pin-on-disc tribometer was utilized to measure the coefficient of friction and sliding wear of the composite material, following the ASTM G99-95a. The samples were cut to a diameter of 75 mm and a thickness of 4 mm. A stainless-steel pin with a 6 mm diameter was used for the test. The samples were weighed before and after testing using an analytical balance. The test was conducted under dry conditions, applying a load of 30 N at a speed of 300 rpm for 25 minutes, with a wear track diameter of 20 mm.

Abrasion test

The TR-600 abrasion resistance tester was employed to evaluate the abrasive wear of the composite under dry conditions. Samples were prepared with a diameter of 125 mm and a thickness of 4 mm. The sample's weight was recorded both before and after testing. The test involved using two vitrified bonded silicon carbide discs, grade 46, which contacted the sample's surface to simulate the abrasive mechanism. The procedure adhered to the ASTM D3389 standard.

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Optical microscopy observation

Optical microscopy was employed to visualize the morphological surface structure or wear track after testing was conducted. A stereo-zoom microscope was used to capture detailed images of the sample surfaces. These images were then saved using software connected to the microscope.

RESULTS AND DISCUSSION

Density of FRP composites

The density of the polyester resin, BFRP, GFRP, PTFE-coated BFRP, and PTFE-coated GFRP composites is shown in Table 1.

Table 1. Density of FRP composite with and without PTFE

FRP Composite	Experimental density of composite (g/cm^3)	Theoretical density of composite (g/cm^3)	Percentage error (%)
GFRP	1.6644 ± 0.0245	1.8296	10.13
BFRP	1.6053 ± 0.0170	1.8519	12.26
PTFE-coated GFRP	1.6458 ± 0.0153	1.7994	8.64
PTFE-coated BFRP	1.5940 ± 0.0256	1.8014	11.42

As shown in Table 1, the density of GFRP is slightly higher than BFRP, with values of 1.6644 ± 0.0245 g/cm^3 and 1.6053 ± 0.0170 g/cm^3, respectively. Similarly, PTFE-coated GFRP also has a higher density compared to PTFE-coated BFRP, following the same pattern for both coated and uncoated composites. However, according to Sapuan et al. (2020) basalt fiber typically has a higher density than glass fiber and unsaturated polyester, and its use is expected to increase the density, tensile, and flexural properties of the composite. The observed variation could be due to insufficient compatibility at the interface between the matrix, filler, and fiber in the composites, as well as the presence of trapped porosity within the materials (Abu Talib, 2018).

When comparing the experimental density of the composites to theoretical values, the percentage error for GFRP and PTFE-coated GFRP is 10.13% and 8.64%, respectively, which are the lowest among the samples. In contrast, BFRP has the highest percentage error at 12.26%, with PTFE-coated BFRP showing an error of 11.42%. PTFE-coated GFRP is closest to the theoretical value, while BFRP deviates more from the expected value.

Sliding wear and coefficient of friction analysis

The wear volume of GFRP is higher than that of BFRP, with values of 0.08215 mm^3 and 0.05452 mm^3, respectively, as tabulated in Table 2. Similarly, PTFE-coated GFRP exhibits a higher wear volume compared to PTFE-coated BFRP, with values of 0.07803 mm^3 and 0.04581 mm^3, respectively. The use of PTFE coating results in an increased wear volume for both PTFE-coated GFRP and PTFE-coated BFRP. The lower wear volume observed in BFRP composites can be attributed to the higher hardness of the fiber-reinforced polymer (Abu Talib, 2018).

GFRP shows the highest specific wear rate, while PTFE-coated BFRP has the lowest, measured at 3 mm^3/Nm. The lower specific wear rate in PTFE-coated BFRP is due to the characteristics of the sample particles (Kanthraju & Suresha, 2016). A high specific wear rate indicates that the material is wearing away more rapidly relative to the applied load and sliding distance. Wear volume reflects the total material removed during the abrasion test, while specific wear rate provides a measure of material loss per unit load and per unit sliding distance during the test.

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Table 2. Wear volume of FRPs with and without PTFE coating film

Composite	Wear volume, ΔV (mm^3)	Specific wear rate, Ks (mm^3/Nm)
GFRP	0.08215	5.81103×10^{-6}
BFRP	0.05452	3.85654×10^{-6}
PTFE-coated GFRP	0.07803	5.51956×10^{-6}
PTFE-coated BFRP	0.04581	3.24007×10^{-6}

Fig 1 shows that GFRP has the highest coefficient of friction, followed by PTFE-coated GFRP, PTFE-coated BFRP, and BFRP. A higher coefficient indicates increased friction during sliding. Surface conditions after the pin-on-disc sliding test were analyzed under an optical microscope, as shown in Fig 2. The images reveal that coated composites have smoother surfaces than uncoated composites, which exhibit a lower coefficient of friction. Fig 2(a) shows visible scratches and material loss, which indicate significant wear. Likewise, Fig 2(b) shows visible areas where materials appear to have been removed. Contradicted to Fig 2(c) and Fig 2(d) present a smoother surface with minimal wear due to the protective layer of PTFE film onto the FRP composite surface.

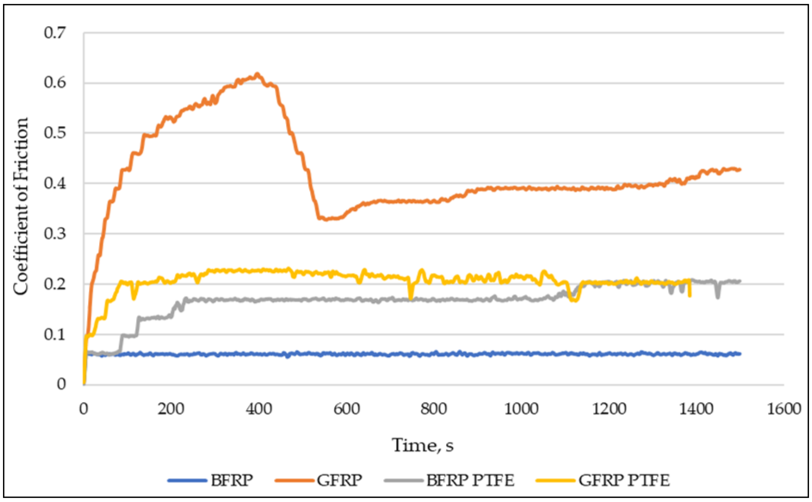
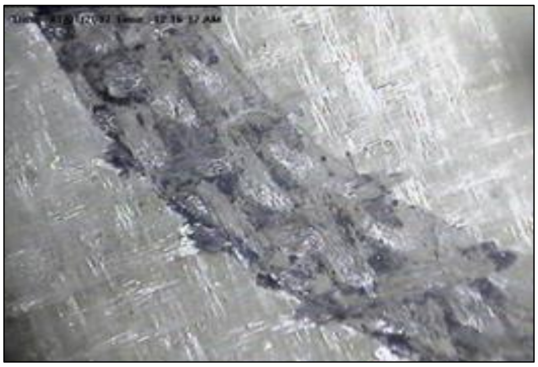
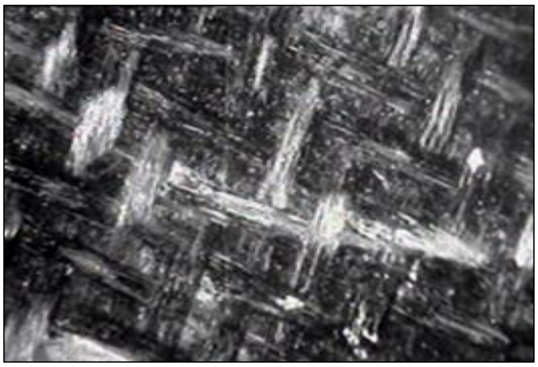


Fig. 1. Coefficient of friction against time during pin on disk test for coated and uncoated composite.



(a)



(b)

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(c) (d)

Fig. 2. Optical microscopic micrograph of (a) GFRP, (b) BFRP, (c) PTFE-coated GFRP, and (d) PTFE-coated BFRP after pin on disc test at 50x magnification.

Abrasion wear properties of FRP composites

Table 3 reveals that BFRP has the highest wear volume at 0.36317 mm^3, while PTFE-coated GFRP has the lowest at 0.20780 mm^3. PTFE-coated BFRP shows a wear volume comparable to that of PTFE-coated GFRP. After a distance of 2 km, the BFRP surface becomes more exposed to the wheel's counter-face, leading to increased abrasion due to frictional forces generated during contact, contributing to overall wear (Ray et al., 2021).

Table 3. Wear volume of FRP with and without PTFE

Composite	Wear volume, ΔV (mm^3)	Specific wear rate, Ks (mm^3/Nm)
GFRP	0.31523	2.22979 x 10^{-5}
BFRP	0.36317	2.56892 x 10^{-5}
PTFE-coated GFRP	0.20780	1.46990 x 10^{-5}
PTFE-coated BFRP	0.21393	1.51323 x 10^{-5}

Furthermore, BFRP has the highest specific wear rate, while GFRP has a lower rate. PTFE-coated GFRP shows the lowest specific wear rate, followed by PTFE-coated BFRP. A low specific wear rate reflects reduced friction and minimal material removal, whereas a high rate leads to increased contact with the abrasive wheel and greater material loss (Ray et al., 2021). Fig 3 demonstrates that coated composites have smoother surfaces than uncoated ones, which correlates with the lower coefficient of friction observed in PTFE-coated samples. Fig 3(a) demonstrates visible scratches and rough texture due to abrasion, which shows a significant impact on the composite's surface integrity. While Fig 3(b) shows visible wear and damage on the surface, the fiber is still intact, which affects the overall properties. Fig 3(c) reveals fewer scratches visible, which indicate a resilient surface that withstands wear better. Likewise, Fig 3(d) shows a visible wear line suggesting low material removal, but the surface remains intact.

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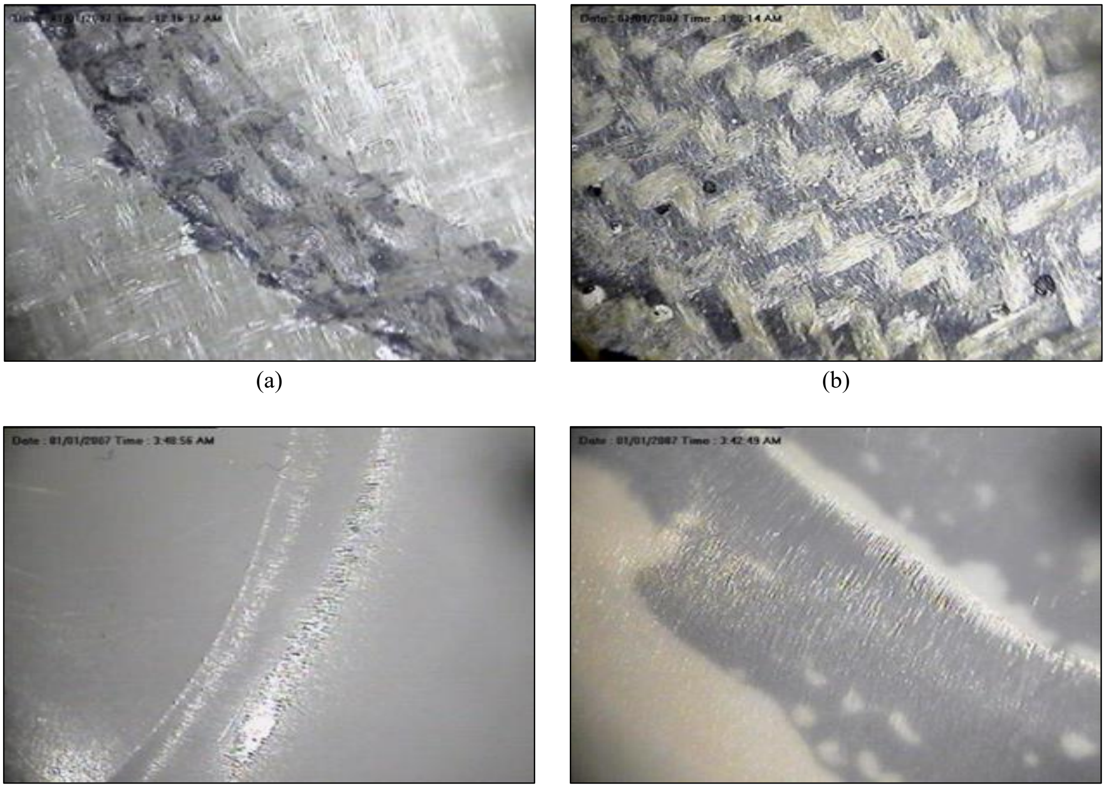

(a) (b) (c) (d)

Fig. 3. Optical microscopic micrograph of (a) GFRP, (b) BFRP, (c) PTFE-coated GFRP, and (d) PTFE-coated BFRP after abrasion test at 50x magnification.

CONCLUSION

In conclusion, this study investigated the density, wear properties, and morphological surface of FRP composites with and without PTFE coatings. The density analysis showed that GFRP has a higher density than BFRP, with PTFE-coated GFRP being closest to the theoretical value. Pin-on-disk tests revealed that GFRP exhibited a higher wear volume compared to BFRP, which experienced a 66.37% reduction in wear volume due to its hardness. Notably, PTFE-coated BFRP demonstrated the lowest specific wear rate, reducing it by 55.77% compared to GFRP. In abrasion tests, PTFE-coated GFRP had the lowest wear volume, decreasing by 57.22% compared to BFRP exhibited the lowest specific wear rate, decreasing by 57.21%. Optical microscopy confirmed that coated composites had smoother surfaces, correlating with lower coefficients of friction. This indicates that PTFE-coated GFRP is effective in minimizing friction and material removal. These findings highlight the effectiveness of PTFE coatings in enhancing the mechanical performance and durability of FRP composites, making them ideal for demanding applications such as antifouling coatings that inhibit barnacle growth on seawater-exposed structures, like glass composite boat hulls. Jeong et al. (2025) reported that polymer coatings show great potential in combating marine biofouling as more environmentally friendly alternatives. This reduces the cost of maintenance, effectively contributes to good cost-performance, and environmental sustainability.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: conceptualization, methodology, data curation writing-original draft preparation: M. F. Yusof; conceptualization, methodology, validation, supervision, writing-reviewing and editing: A. Jumahat; data curation, writing-original draft preparation, writing-reviewing and editing: Z. M. Zahib, N. L. A. Rahman, A. A. Maslan; conceptualization: M. Chalid. All authors reviewed the results and approved the final version of the manuscript.

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