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RESEARCH

Enhancement of Wear Resistance in 3D-Printed PLA and CF-PLA/Epoxy Composites via Taguchi Design and ANOVA

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A B S T R A C T

Due to the increasing importance of engineering plastics in diverse engineering fields, demand for these materials has grown alongside technological progress, driving the development of tailored properties for specific applications. This study evaluates the wear behavior of three polymer groups manufactured using additive manufacturing (Material Extrusion, MEX): polylactic acid and carbon fiber-reinforced polylactic acid, both fabricated by the deposition technique and reinforcement with epoxy resin. High-precision three-dimensional models were fabricated for each composite polymer to improve accuracy and performance. Samples were prepared as hollow cylinders with deposition thicknesses defined by diameter reduction ratios (wt.%) of 10%, 20%, and 40%, aiming to investigate the effect of epoxy reinforcement on wear behavior.Both wt.% and applied load during testing were considered as key factors influencing composite performance. Wear properties were assessed using a pin-on-disc device, following a systematic approach to examine the relationship between these parameters and the tribological behavior of the materials. Data analysis was conducted with MINITAB 19, employing the Taguchi method for experimental design and evaluation. Results demonstrated that the adopted design methodology enhanced adhesive wear resistance in all composites. Furthermore, the wt.% had a greater influence on wear performance than the applied load within the scope of this study.

1. INTRODUCTION

The wear behavior of polymers is a complex phenomenon that is difficult to predict due to the multiplicity of influencing factors, such as surface characteristics, applied load, temperature, environmental conditions, and the intrinsic properties of the material itself. These factors collectively affect the tribological performance and service life of polymers. The significance of the present study lies in its focus on improving these properties through material extrusion (MEX, formerly known as fused deposition modelling, FDM) and reinforcement techniques, aiming to enhance the tribological performance of the investigated polymers. Additive Manufacturing (AM), formerly referred to as Rapid Prototyping, is a well-established engineering approach that enables the fabrication of complex geometries and intricate designs with high flexibility. Rahul et al. [1] contributed to understanding and improving the application of AM in polymer-based materials, highlighting its versatility in engineering applications. Miquel et al. and Friedrich et al. [2,3] emphasized that computer-assisted 3D printing allows the production of complex models with varying thicknesses, unlike conventional methods. This capability has encouraged extensive research into the mechanical behavior of 3D-printed parts to develop products that meet engineering standards. Sofan-German et al. [4] demonstrated that PLA is an effective material for 3D printing UAV components due to its lightweight and strength, enabling the fabrication of durable and cost-efficient UAVs with stable flight performance. Subramaniyan et al. [5] analyzed the tribological properties of parts fabricated using MEX with PLA and its composites, including carbon fiber, ceramic fillers, and organic materials. Using pin-on-disc tests, they found that composite reinforcement reduced wear, whereas interlayer voids and z-axis printing increased it, highlighting the importance of material choice, layer thickness, and infill percentage. Revanka et al. [6] investigated epoxy–PLA composites reinforced with carbon fibers prepared via solution casting, demonstrating improvements in flexural strength and thermal stability. Similarly, Abdulla et al. [7] studied the dry sliding wear behavior of 3D-printed PLA, showing that higher infill density, applied load, and sliding speed contributed to reduced wear. Meena Pant et al. [8] optimized FDM process parameters—layer thickness, build orientation, and extrusion temperature—using the Taguchi method and validated the results via ANOVA, finding that build orientation was the most influential factor affecting wear. Other studies have investigated mechanical improvements in PLA through optimized nozzle temperature, 100% infill density, and printing speed [9], as well as reinforcement with metals [10] or embedding CFRP elements [11]. PLA/ABS composites reinforced with carbon fibers have also demonstrated improved wear resistance when printing parameters were optimized [12]. The effect of epoxy coating thickness on PLA and ABS printed parts has been reported, showing higher tensile strength and reduced surface roughness for PLA at a 0.06 mm layer thickness [13]. Mechanical testing of PLA, ABS, and epoxy samples further revealed that PLA is relatively brittle, ABS exhibits higher durability, and epoxy shows greater flexibility. Among these, ABS demonstrated superior impact resistance, while PLA exhibited higher fatigue resistance under rotational bending [14]. Studies on friction characteristics and epoxy reinforcement have confirmed that the epoxy weight ratio significantly enhances both mechanical and tribological performance [15-18]. Research on PLA composites reinforced with 3 wt.% graphene for 3D printing using FDM reported optimized process parameters that improved surface roughness and wear resistance. SEM analysis also revealed reduced defects, highlighting the potential of graphene-reinforced PLA for high-performance applications [19]. Perepelkina et al. demonstrated that 3D printing settings influence the tribological properties of polymers, including friction and wear, guiding the selection of optimal printing parameters [20]. Similarly, investigations into the sliding wear behavior of composites reinforced with 25% short carbon fiber and filled with potassium titanate whiskers (PIW) demonstrated that these additions substantially improved wear resistance [21]. Furthermore, nanofillers and fiber reinforcements in epoxy composites have been shown to enhance both wear resistance and overall mechanical properties [22,23]. A recent study focused on enhancing the properties of biodegradable plastics by blending PLA and polybutylene succinate (PBS) at a 90/10 wt.% ratio, with the addition of silicon carbide (SiC) in concentrations ranging from 10 to 40 phr. The mechanical, thermal, structural, and morphological properties of the resulting composites were evaluated. The results showed that incorporating SiC significantly improved the mechanical performance of the PLA/PBS blend, with Young's modulus increasing by 40% and impact strength by 76% compared to neat PLA [24]. These findings underscore the significant influence of reinforcement strategies on the mechanical and tribological behavior of polymers, including PLA. In light of this, the present study focuses on the fabrication of PLA specimens using ISO-standardized Material Extrusion (MEX), followed by epoxy resin reinforcement through casting, with the objective of improving tribological performance while retaining the inherent lightweight characteristics of PLA. The methodology involves the systematic reduction of cylindrical sample diameters to determine the optimal epoxy weight ratio that minimizes wear rate. Unlike previous research, which primarily addressed general reinforcement techniques, this study applies a novel approach by controlling epoxy content through hollow cylindrical designs. Despite progress in PLA reinforcement, there remains a lack of research employing controlled hollow cylindrical geometries with systematic diameter reductions to regulate the epoxy resin fraction within PLA and CF-PLA composites. The present study addresses this gap by fabricating hollow cylindrical samples with 10%, 20%, and 40% diameter reductions while maintaining constant MEX parameters. This design enables a precise evaluation of epoxy reinforcement effects on tribological behavior. The integrated approach highlights the originality of the research and its potential to advance the development of polymer composites for demanding engineering applications.

2. EXPERIMENTAL PART

2.1 Materials and methods

In this study, sample fabrication was carried out using 3D printing, specifically the ISO-standardized Material Extrusion (MEX) technique, in which thermoplastic material is extruded through a heated nozzle and deposited layer by layer. Using a 3D printer, three-dimensional samples were prepared separately from two types of polymers and subsequently enhanced with epoxy resin. Hollow cylinders with controlled diameter reductions were employed to regulate epoxy content, ensuring uniform distribution and consistent adhesion with the PLA and CF-PLA walls. This approach was intended to improve mechanical integrity, enhance wear resistance, and provide reproducible results across specimens. The samples were designed as hollow cylinders with a fixed outer diameter of 10 mm and a height of 50 mm, while the inner diameter was reduced by 10%, 20%, and 40% of the original diameter to achieve different wall thicknesses. Two types of thermoplastic polymers were selected for the outer walls: polylactic acid (PLA) and carbon fiber–reinforced polylactic acid (CF-PLA), due to their favorable mechanical properties and compatibility with MEX-based 3D printing technology. PLA filaments (printing temperature: 200–230°C) and CF-PLA filaments (190–220°C), both supplied by HELLO3D (Shenzhen, China; diameter: 1.75 mm), were used for sample fabrication. After printing, the samples were dried for 60 minutes, followed by epoxy casting into their cores. The specimens were then left at room temperature for two weeks to ensure complete epoxy curing. The epoxy resin used was SikaDur 3, with a mixing ratio of 2:1 and a density of 1.1 kg/L.

2.2 Selection of printing parameters

The 3D printer used in this study was the Creality Sermoon V1 Pro. Printing was carried out with a nozzle temperature of 195°C and a heated bed temperature of 50°C. The infill pattern was set to “Lines” with an infill density of 100%. A raster angle of 45°/135° was employed, while the layer thickness was maintained at 0.2 mm. The printing speed was set to 50 mm/s, and the build orientation was upright. All parameters were kept constant for all specimens. The selected printing parameters were based on the findings of previous studies [8-9], which reported favorable wear resistance under similar conditions. For the present study, the fabricated specimens were further evaluated under the influence of two additional variables: applied load and weight percentage of composite reinforcement materials. A total of nine samples were printed. The fundamental properties of the selected polymer materials are presented in Table 1, while Table 2 summarizes the fabrication parameters and sample configurations. Figure 1 shows the design of PLA and CF-PLA samples fabricated using the Creality Sermoon V1 Pro 3D printer prior to epoxy casting. The variation in internal diameter corresponds to the reduction in epoxy weight fraction, enabling the study of its effect on wear behavior. While Figure 2 illustrates the cylindrical specimens in their final form prior to the epoxy casting stage.

Table 1. Main properties of PLA and CF-PLA.

Terminologies	Tensile Strength (MPa)	Elongation at break	Density g/cm3	Printing temp. oC	Diameter (mm)	Diameter tolerance (mm)
Polylactic acid (PLA)	50-60	5-10%	1.24-1.3	200-230	1.75	±0.05
Carbon fiber-polylactic acid (CF-PLA)	Up to 60	1.5-3.5%	1.4	190-220	1.75	(±0.02) - (±0.05)

Table 2. Fabrication parameters of the samples.

No.	Samples	Epoxy (%)	PLA (%)	Carbon Fiber PLA (CF-PLA)
1	Epoxy (E)	100%	0	0
2	PLA	0	100%	0
3	Carbon Fiber-PLA (CF-PLA)	0	0	100%
4	10% PLAE	90	10	0
5	20% PLAE	80	20	0
6	40% PLAE	60	40	0
7	10% CF-PLAE	90	0	10
8	20% CF-PLAE	80	0	20
9	40% CF-PLAE	60	0	40

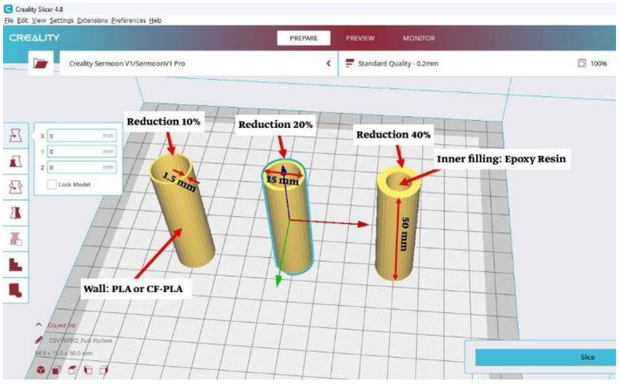

Fig. 1. Design stage of cylindrical PLA and CF-PLA samples with varying core diameters fabricated using the Creality Sermoon V1 Pro 3D printer.

Fig. 2. shows the final appearance of PLA and CF-PLA samples prior to the epoxy casting process.

2.3 Experimental procedures

All experimental data were obtained from tests conducted on composite specimens fabricated using 3D printing, corresponding to the ISO-standardized Material Extrusion (MEX) technique. A total of nine samples were evaluated according to ASTM G99 standards. Adhesive wear behavior was investigated using a pin-on-disc apparatus under controlled laboratory conditions, ensuring consistency across all specimens. The study focused on analyzing the effect of two factors—epoxy weight fraction (wt.%) and applied load—on the wear behavior of the composite samples. Printed samples with weight fractions of 10%, 20%, and 40% were subjected to three different load levels: 500 g, 1000 g, and 2000 g. These load levels were selected to assess the wear behavior under varying stress conditions while avoiding premature sample failure. Studying dry wear resistance provides insight into the bonding strength between the composite materials and their ability to withstand harsh operating conditions. The tests were conducted on three groups of samples, each group containing three sample types, under three load levels with a constant testing duration of 60 s, resulting in a total of 27 tests as detailed in Table 3**.** All experiments were performed under strictly controlled environmental conditions, maintaining a relative humidity of 2% and an ambient temperature of 15°C. Wear tests were conducted at a sliding speed of 1400 rpm along a circular track with a diameter of 14 cm, corresponding to a total sliding distance of 61,544 mm. The mass of each specimen was measured before and after testing using an HC-B Precision Balance electronic scale, with a maximum capacity of 500 g and a resolution of 0.0001 g, ensuring high accuracy in data acquisition. The specific wear rate of the specimens was calculated using the following formula:

$$W_{r(EXp)} = \frac{\Delta m}{FxLx\rho} \quad (1)$$

where $Wr_{(EXP)}$ represents the specific wear rate in mm^3/N.m, Δm is the mass loss of the specimen in grams, F is the applied normal load in Newton, L is the total sliding distance in meters (calculated as), and ρ is the density of the polymer composite in g/mm^3. This formulation provides a standardized evaluation of polymer material loss under controlled tribological conditions [16].

2.4 Theoretical methods

The Taguchi method was employed as an effective statistical tool to enhance system performance while minimizing experimental time and cost. In this study, the focus was on improving the signal-to-noise (S/N) ratio using the "smaller-the-better" criterion, which aims to reduce variability and improve result stability.

An L18 ($6^1 \times 3^1$) orthogonal array was selected in accordance with the experimental design requirements. The signal-to-noise ratio (S/N) was calculated using the following formula:

$$\frac{S}{N} = -10\ log_{10}\left(\frac{1}{n}\sum_{j=i}^{n} Y_{ij}^2\right) \quad (2)$$

where S/N is the signal-to-noise ratio, n is the number of repetitions for each variable combination, Yij denotes the observed value of the evaluation index for the i-th index and the j-th test, i = 1, 2, ..., n represents different evaluation indices, and j =1 ,2,...., n represents repeated measurements for each test condition. This formulation enables the systematic evaluation of experimental variability and the identification of optimal process parameters.

3. RESULT AND DISCUSSION.

The wear behavior of PLA and CF-PLA composites reinforced with epoxy was evaluated under controlled testing conditions. Table 3 presents the experimental mass loss data *(Δm_1, Δm_2, and Δm_3)* for the composite samples, measured in grams before and after wear testing at three applied load levels: 500 g, 1000 g, and 2000 g [7]. The table also includes the experimentally determined wear rates for the composite polymers. The first group of samples consists of unreinforced (pure) materials, including epoxy resin, PLA, and CF-PLA. The second and third groups represent composite samples reinforced with epoxy at different weight fractions, as detailed in Table 3. This grouping allows a comparative analysis of the effect of epoxy reinforcement on the wear behavior of PLA and CF-PLA composites.

Table 3. Experimental data of the adhesive wear rate of specimen composites.

Groups	Samples	Initial mass (g)	At load (500 g)		At load (1000 g)		At load (2000 g)	
			(Δm_1) g	$Wr_{(Exp)}$*10^{-4} (mm^3/N.m)	(Δm_2) g	$Wr_{(Exp)}$*10^{-4} (mm^3/N.m)	(Δm_3) g	$Wr_{(Exp)}$*10^{-4} (mm^3/N.m)
Group 1 (Pure material)	(E)	7.8526	0.006	42.161	0.0086	30.215	0.0149	26.174
	(PLA)	9.7474	0.0874	544.81	0.0785	244.66	0.176	274.273
	(CF-PLA)	9.8554	0.0839	463.22	0.0834	230.229	0.1911	263.77
Group 2 (PLA reinforced Epoxy)	10% PLAE	8.6678	0.0018	12.4895	0.0102	35.3865	0.0155	26.89
	20% PLAE	9.0151	0.0139	95.2484	0.0387	132.59	0.028	47.966
	40% PLAE	9.3947	0.0253	169.166	0.0315	105.3113	0.0191	31.927
Group 3 (CF-PLA) reinforced epoxy	10% CF-PLAE	8.5777	0.0243	166.22	0.0396	132.39	0.0286	48.821
	20% CF-PLAE	8.7606	0.0322	214.56	0.0134	131.934	0.0143	23.821
	40% CF-PLAE	9.7224	0.031	196.41	0.048	152.056	0.1334	211.294

Table 4 summarizes the wear data obtained from the 18-run experimental design, structured according to a two-factor, three-level layout using the Taguchi L18 ($6^1 \times 3^1$) orthogonal array. The analysis was performed by converting the results into signal-to-noise (S/N) ratios, using the "smaller-the-better" criterion, to identify the optimal control factor settings. This statistical evaluation, conducted using Minitab 19 software, aimed to minimize the influence of noise factors by maximizing the S/N ratio in decibels (dB). The S/N ratio data are further illustrated in Figure 3, which highlights the optimal conditions for the composite specimens and identifies the most influential factors affecting their wear behavior.

Table 4. Response of the signal-to-noise ratio (smaller-the-better).

Experimental run	Composite material	Load (g)	Wt.%	Wr $_{(Exp)}$ ×10-4	S/N ratio (dB)
1	10% PLAE	500	10	12.489	-41.4278
2	20% PLAE	500	20	95.248	-44.4019
3	40% PLAE	500	40	169.166	-45.2630
4	10% CF-PLAE	500	10	166.220	-41.43
5	20% CF-PLAE	500	20	214.560	-44
6	40% CF-PLAE	500	40	196.410	-45.3
7	10% PLAE	1000	10	30.215	-30.3446
8	20% PLAE	1000	20	244.660	-45.8793
9	40% PLAE	1000	40	230.229	-45.0580
10	10% CF-PLAE	1000	10	35.386	-30.345
11	20% CF-PLAE	1000	20	132.590	-45.88
12	40% CF-PLAE	1000	40	105.311	-45.1
13	10% PLAE	2000	10	26.174	-28.472
14	20% PLAE	2000	20	274.273	-45.8842
15	40% PLAE	2000	40	263.770	-45.4774
16	10% CF-PLAE	2000	10	26.890	-28.5
17	20% CF-PLAE	2000	20	47.966	-45.9
18	40% CF-PLAE	2000	40	31.927	-45.5

Figure 3 illustrates the average S/N ratio of the composite samples under the applied load conditions, aiming to identify the optimal weight fraction and allowable load. The results indicate that the ideal condition corresponds to A3B1, which represents a 10% reduction in the specimen's diameter under a 2000 g load. At this point, the optimal composition consists of 90% epoxy and 10% PLA or CF-PLA, providing the highest adhesive wear resistance and significantly enhancing the performance of the specimens. As shown for sample Nos. 13 and 16 in Table 4, epoxy reinforcement improved the wear resistance of PLA by approximately 90% compared with pure specimens, primarily by reducing friction and increasing hardness. For CF-PLA composites, the improvement was about 80%, reflecting the already high wear resistance contributed by the carbon fibers. The use of epoxy as a reinforcement agent effectively enhanced both the mechanical properties and wear resistance of the polymer composites, consistent with previous studies [13-18]. These results demonstrate the efficacy of epoxy reinforcement, particularly in materials with lower inherent hardness, such as PLA.

Figure 4 presents a set of residual plots used to assess the adequacy of the regression model for predicting Wr $_{(Exp)}$ ×10-4. The normal probability plot indicates that the residuals are approximately normally distributed, as most points closely follow the straight line, supporting the statistical assumptions of the model. In the residuals versus fitted values plot, no systematic

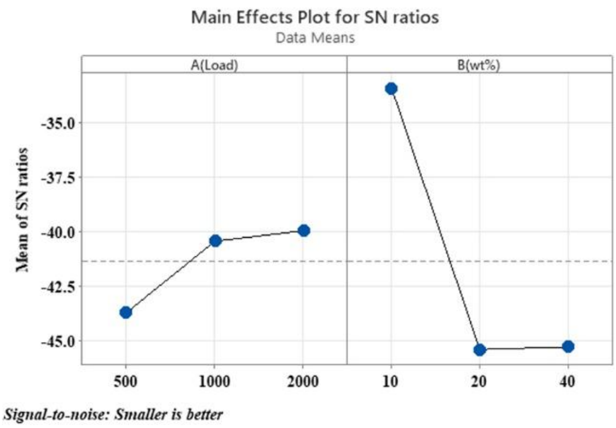

Fig. 3. Main effect plot for the S/N ratio of PLA and CF-PLA composites.

Patterns or correlations are observed between the residuals and predicted values, indicating homoscedasticity and the absence of structural bias. The histogram shows a generally symmetric distribution with slight skewness, confirming the statistical acceptability of the residual distribution. Finally, the residuals versus observation order plot displays scattered points without any sequential pattern or temporal trend, indicating independence of observations and no time-related effects. These residual analyses validate the regression model, confirming that the relationships between applied load, reinforcement content, and wear rate are adequately captured. This strengthens the reliability of the study's conclusions regarding the effectiveness of epoxy reinforcement. The regression model yielded an R^2 of 22.61% (adjusted=12.29% R^2) with a root mean square error (RMSE) of 87.5413, indicating a limited ability to explain the variability in wear rate while still providing relatively acceptable predictions. These results suggest that the model is sufficient to identify general trends, but future studies should consider additional variables, more complex modelling approaches, and larger sample sizes to improve predictive accuracy and reliability.

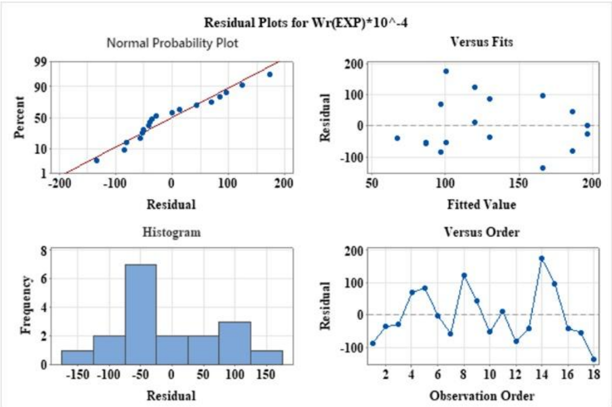

Fig. 4. Residual plots for the wear rate of PLA and CF-PLA composite specimens.

A multiple linear regression model was developed to describe the relationship between wear rate, applied load, and weight percentage of reinforcement:

$$W_{r(EXP)} = 73.9 - 0.02A + 3.32\,B \qquad (3)$$

Where A represents the applied load (g) and B represents the weight fraction of epoxy reinforcement (wt.%). The regression equation indicates that reducing the polymer content and increasing the applied load within acceptable limits enhances wear resistance. This finding confirms that epoxy performs better than polymer in terms of improving wear behavior, consistent with the observed performance of samples 13 and 16. The ANOVA results are presented in Table 5. The effect of load (A) on wear rate $Wr_{(EXP)}$ was not statistically significant (p = 0.555), while the effect of weight fraction (B) was close to significance (p = 0.063), highlighting its importance in controlling wear rate. The lack-of-fit test confirmed the adequacy of the model (p = 0.789). In experiments (1, 7, and 13) with 10% PLA, the wear rate exhibited a non-linear behavior; it increased from 12.489x10^-4 at a load of 500g to 30.215x10^-4 at 1000g, followed by a slight decrease to 26.174x10^-4 at 2000g. This reduction at higher loads is attributed to the formation of thin polymer layers on the surface, which act as a self-lubricating film, reducing effective shear stresses and limiting material removal. This highlights the significant role of surface phenomena in modifying wear behavior, as these transfer layers and the distribution of stresses collectively influence the material's overall performance. In contrast, the samples (2, 8, and 14) with 20% PLA, as well as (3, 9, and 15) with 40% PLA, showed a linear relationship with load, where the wear progressively increased with increasing load. This indicates that higher PLA content mitigates the non-linear effects of surface phenomena and promotes a more direct, load-dependent wear response. These findings suggest that the polymer system's weight fraction is a complex factor influencing wear behavior, as it governs the interaction between material properties—such as type, hardness, viscosity, and the ability to form transfer layers—and surface design features, including micro-textures, ultimately determining the material's wear performance.

These observations are consistent with the ANOVA results, which showed that the effect of load was not statistically significant (p = 0.555), while the effect of polymer content was close to the significance level (p = 0.063). This confirms that load alone does not dominate wear behavior. Similar mechanisms were reported in previous studies [25,26], confirming the combined role of composition and surface effects in modulating wear. The concept of this study can be applied to fabricate engineering components that require high strength and wear resistance at their core, with a polymeric surface offering greater flexibility, utilizing 3D printing technology to ensure design precision. It can serve as an inspiring concept for various engineering applications, such as unmanned aerial vehicles, robots, and more.

Table 5. Results of Analysis of Variance (ANOVA).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	33583	16792	2.19	0.146
A (Load)	1	2798	2798	0.37	0.555
B (Wt.%)	1	30785	30785	4.02	0.063
Error	15	114952	7663		
Lack-of-Fit	6	29068	4845	0.51	0.789
Pure Error	9	85884	9543		
Total	17	148535			

4. CONCLUSION

Additive manufacturing combined with reinforcement-based techniques is a rapidly evolving approach that significantly contributes to the advancement of composite polymer fabrication. Achieving high-quality materials and components requires a thorough understanding of process parameters and their influence on the final properties of composites. The main findings of this study are summarized as follows:

1. Epoxy reinforcement enhanced the wear resistance of PLA by approximately 90%, demonstrating its effectiveness as a reinforcing agent, particularly for polymers with low inherent hardness.
2. The multiple linear regression model indicated that the weight percentage of epoxy (B) has a greater impact on wear rate than the applied load (A).
3. Reducing the plastic content and increasing the applied load within acceptable limits improves wear resistance.
4. Samples 13 and 16 confirmed the superior wear performance of epoxy compared to pure plastic specimens.
5. ANOVA results showed that the effect of applied load was not statistically significant ($p = 0.555$), while the effect of weight percentage was near significance ($p = 0.063$).
6. The lack-of-fit test confirmed the adequacy of the regression model ($p = 0.789$).
7. It is recommended to focus on optimizing the epoxy weight percentage to enhance wear resistance and overall composite performance.

These findings highlight the effectiveness of controlled epoxy reinforcement in improving the tribological properties of PLA and CF-PLA composites and provide guidance for designing high-performance polymer-based materials in engineering applications.

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