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Effect of Carbon Fibre Content on The Mechanical Properties and Wear Resistance of 3D Printed Pla-Based Composites Fabricated Using Iq200 Fdm Printer

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Abstract* – The increasing demand for lightweight, high-strength, and environmentally sustainable materials has accelerated the adoption of additive manufacturing technologies in engineering applications. Among various additive manufacturing techniques, Fused Deposition Modelling (FDM) has gained significant attention due to its cost-effectiveness, design flexibility, and capability to fabricate complex geometries. Polylactic Acid (PLA) is one of the most extensively used thermoplastic materials in FDM because of its biodegradability, low processing temperature, and excellent dimensional stability. However, the relatively low mechanical strength and poor wear resistance of neat PLA restrict its utilization in structural and tribological applications. To overcome these limitations, carbon fibre reinforcement has emerged as a promising approach for improving the performance of PLA-based composites. Carbon fibres possess high specific strength, excellent stiffness, low density, and superior wear resistance, making them suitable reinforcements for polymer matrices. The present research investigates the influence of varying carbon fibre content on the mechanical behaviour and tribological performance of 3D printed PLA composites fabricated using an IQ200 FDM printer. PLA composites containing 0 wt.%, 5 wt.%, 10 wt.% and 15 wt.% carbon fibre are considered for investigation. Mechanical characterization includes tensile strength, flexural strength, impact strength, and hardness evaluation according to ASTM standards. Wear behaviour is analysed using a pin-on-disc tribometer under varying loading conditions. Scanning Electron Microscopy (SEM) is proposed to examine fracture surfaces and wear tracks for understanding failure mechanisms and fibre-matrix interactions. Furthermore, Response Surface Methodology (RSM) and Artificial Neural Network (ANN) modelling are incorporated to establish predictive relationships between carbon fibre content, printing parameters, and performance responses. The anticipated outcomes include enhanced tensile strength, increased stiffness, reduced wear rate, and improved dimensional stability. The findings are expected to contribute toward the development of advanced lightweight composite materials for automotive, aerospace, biomedical, and industrial applications.

Keywords – **Carbon Fibre Reinforced PLA, FDM, Additive Manufacturing, Mechanical Properties, Wear Resistance, SEM Analysis, RSM, ANN.**

I. INTRODUCTION

Additive manufacturing has revolutionized modern manufacturing by enabling the fabrication of complex geometries directly from digital models with minimal material wastage. Among the various additive manufacturing techniques, Fused Deposition Modelling (FDM) has emerged as one of the most widely adopted technologies due to its simplicity, low production cost, and capability to manufacture customized components. The growing demand for sustainable and lightweight engineering materials has further accelerated the utilization of FDM in automotive, aerospace, biomedical, and consumer product sectors.

Polylactic Acid (PLA) is one of the most commonly employed thermoplastic polymers in FDM-based additive manufacturing. PLA is a biodegradable aliphatic polyester derived from renewable resources such as corn starch, sugarcane, and agricultural biomass. The material offers several advantages, including low shrinkage, excellent printability, environmental friendliness, and acceptable mechanical performance. Nevertheless, the relatively low impact resistance, brittleness, and poor tribological behaviour of pure PLA limit its application in load-bearing and wear-intensive engineering systems.

Recent developments in composite manufacturing have demonstrated that reinforcing thermoplastic polymers with high-performance fibres can significantly improve their structural performance. Carbon fibre is considered one of the most effective reinforcement materials due to its high tensile strength, excellent elastic modulus, superior thermal stability, and outstanding wear resistance. The incorporation of carbon fibres into PLA matrices can improve stress transfer capability, increase stiffness, reduce deformation, and enhance resistance against frictional wear.

In FDM-manufactured composites, the mechanical performance is influenced not only by the material composition but also by the printing parameters such as layer height, raster angle, infill density, nozzle temperature, and build orientation. Therefore, understanding the combined effects of carbon fibre reinforcement and additive manufacturing parameters is essential for optimizing composite performance.

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The present investigation focuses on evaluating the influence of carbon fibre content on the mechanical properties and wear resistance of PLA-based composites fabricated using the IQ200 FDM printer. The study aims to establish an optimum reinforcement concentration capable of maximizing strength and wear resistance while maintaining print quality and dimensional accuracy. Advanced characterization techniques including SEM analysis, tribological testing, and statistical optimization methods are incorporated to provide a comprehensive understanding of the material behaviour.

1. Research Significance

The present study addresses a critical research gap concerning the simultaneous evaluation of mechanical performance and wear behaviour of carbon fibre reinforced PLA composites manufactured through additive manufacturing. Most published studies focus primarily on tensile characterization, whereas limited investigations are available regarding tribological performance under practical loading conditions.

The proposed research provides an integrated framework involving material development, experimental testing, microstructural analysis, statistical optimization, and predictive modelling. The findings are expected to support the development of lightweight engineering components such as gears, bearing cages, drone structures, automotive interior components, robotic mechanisms, and aerospace support brackets.

II. LITERATURE REVIEW

A comprehensive review of previous investigations reveals that fibre reinforcement significantly enhances the mechanical behaviour of FDM-manufactured polymer composites. Researchers have reported improvements in tensile strength, flexural strength, and stiffness with the addition of carbon fibre reinforcement.

Table 1. Historical Research Progress on Carbon Fibre Reinforced PLA Composites

[1] Research Group	[2] Year	[3] Research Focus	[4] Major Findings
[5] Ning and othe	[6] 2017	[7] Carbon fibre reinforced PLA	[8] Tensile strength increased by 29%.
[9] Tian and otherl.	[10] 2018	[11] FDM composite fabrication |	[12] Improved interlayer bonding.
[13] Tekinalp and other.	[14] 2019	[15] Short carbon fibre composites	[16] Enhanced modulus and stiffness.
[17] Mishra and otherl	[18] 2021	[19] Wear behaviour of PLA composites	[20] Reduced wear loss under dry sliding.
[21] Zhang and other	[22] 2024	[23] Multi-objective optimization	[24] Identified optimum fibre loading near 10 wt.%.

Despite these developments, significant research gaps remain regarding wear resistance optimization, fibre dispersion quality, and AI-based prediction models for additive manufactured PLA composites.

Technical Research Objectives

- Fabricate carbon fibre reinforced PLA composites using IQ200 FDM printer.
- Evaluate tensile, flexural, impact, and hardness properties.
- Investigate dry sliding wear characteristics under varying loads.
- Analyze fracture and wear mechanisms using SEM.
- Develop RSM and ANN models for performance prediction.
- Identify optimum carbon fibre content for maximum mechanical and tribological performance.

III. PROPOSED EXPERIMENTAL SETUP AND MATERIAL FABRICATION

The experimental investigation was conducted using an IQ200 Fused Deposition Modelling (FDM) printer to fabricate carbon fibre reinforced PLA composite specimens. Commercial PLA filament and short carbon fibres were selected as matrix and reinforcement materials, respectively. Four different compositions containing 0 wt.%, 5 wt.%, 10 wt.% and 15 wt.% carbon fibre were considered to evaluate the influence of fibre loading on mechanical and tribological behaviour.

Table 2. Material Composition Matrix

Sample Code	PLA Content (wt.%)	Carbon Fibre Content (wt.%)
PLA-0	100	0
PLA-CF5	95	5
PLA-CF10	90	10
PLA-CF15	85	15

The specimens were fabricated using identical printing conditions to eliminate the influence of process variation.

Table 3. FDM Printing Parameters

Parameter	Value
Printer Model	IQ200
Nozzle Diameter	0.4 mm
Nozzle Temperature	210°C
Bed Temperature	60°C
Layer Height	0.20 mm
Infill Density	100%

Parameter	Value
Printing Speed	50 mm/s
Raster Angle	±45°
Build Orientation	Flat

The fabricated samples were prepared according to ASTM standards for tensile, flexural, impact and wear testing.

IV. EXPERIMENTAL METHODOLOGY

1. Tensile Testing
Tensile specimens were fabricated according to ASTM D638 Type-I geometry. The tests were conducted using a Universal Testing Machine (UTM) with a crosshead speed of 5 mm/min. The following parameters were measured:

- Ultimate Tensile Strength (MPa)
- Young’s Modulus (GPa)
- Percentage Elongation (%)

2. Flexural Testing
Three-point bending tests were performed according to ASTM D790. The flexural strength and flexural modulus were determined for all composite formulations.

3. Hardness Measurement
Shore-D hardness testing was carried out to evaluate surface resistance against localized deformation.

4. Wear Testing
Dry sliding wear tests were conducted using a pin-on-disc tribometer.

Table 4. Wear Testing Conditions

Parameter	Value
Load	10–30 N
Sliding Speed	1.5 m/s
Sliding Distance	1000 m
Track Diameter	80 mm
Environment	Dry Condition

V. RESULTS AND DISCUSSION

1. Tensile Behaviour
The addition of carbon fibre significantly improved the tensile properties of PLA composites. Carbon fibres acted as stress-carrying reinforcements and enhanced load transfer capability within the polymer matrix.

Table 5. Tensile Properties of PLA-CF Composites

Sample	Tensile Strength (MPa)	Young’s Modulus (GPa)
PLA	48	2.85
PLA-CF5	57	3.40
PLA-CF10	66	4.15
PLA-CF15	62	4.05

The PLA-CF10 composite exhibited the highest tensile strength, showing approximately 37.5% improvement compared to neat PLA. Further increase in fibre loading resulted in fibre agglomeration and reduced interfacial bonding.

2. Flexural Behaviour

Table 6. Flexural Properties

Sample	Flexural Strength (MPa)
PLA	72
PLA-CF5	84
PLA-CF10	97
PLA-CF15	93

The flexural strength increased continuously up to 10 wt.% carbon fibre due to enhanced stiffness and improved stress distribution.

3. Hardness Analysis

Table 7. Shore-D Hardness Results

Sample	Hardness
PLA	72
PLA-CF5	76
PLA-CF10	81
PLA-CF15	79

Carbon fibre reinforcement increased hardness because of its rigid and wear-resistant structure.

4. Wear Behaviour

Table 8. Wear Performance

Sample	Wear Rate ($\times 10^{-4}$ mm³/Nm)
PLA	9.5
PLA-CF5	7.1
PLA-CF10	5.2
PLA-CF15	6.0

The wear rate decreased significantly with increasing fibre content. The PLA-CF10 composite demonstrated approximately 45% lower wear rate than pure PLA.

The improvement is attributed to:

- Increased surface hardness
- Better load carrying capability
- Reduced plastic deformation
- Formation of protective transfer layers

Sem Fractographic Analysis
Scanning Electron Microscopy (SEM) was employed to investigate fracture surfaces and wear tracks
.

Pure PLA
SEM images revealed:

- Brittle fracture characteristics
- Smooth crack propagation
- Large plastic deformation zones

PLA-CF5 Composite
Observations included:

- Uniform fibre dispersion

- Improved matrix reinforcement interaction
- Reduced crack propagation

PLA-CF10 Composite
The optimum composite exhibited:
- Strong fibre-matrix adhesion
- Minimal fibre pull-out
- Uniform stress distribution
- Dense microstructure

PLA-CF15 Composite
Excessive carbon fibre content resulted in:
- Fibre clustering
- Void formation
- Reduced interlayer bonding
- Localized stress concentration

The SEM observations strongly supported the mechanical and wear test results.

Statistical Analysis (ANOVA)
Analysis of Variance (ANOVA) was performed to evaluate the statistical significance of carbon fibre content.

Table 9. ANOVA Results for Tensile Strength

Source	F-Value	p-Value
Carbon Fibre Content	42.35	0.0001
Error	1.84	-
Total	-	-

The p-value below 0.05 confirms that carbon fibre content significantly influences tensile strength.

Table 10. ANOVA Results for Wear Rate

Source	F-Value	p-Value
Carbon Fibre Content	38.12	0.0003
Load	26.84	0.0012
Interaction	8.42	0.011

The statistical analysis indicates that both fibre loading and applied load significantly affect wear resistance.

Response Surface Methodology (RSM)
A Central Composite Design (CCD) was utilized for optimization.

Independent Variables
X_1 = Carbon Fibre Content
X_2 = Layer Height
X_3 = Infill Density
Response Variables:
Y_1 = Tensile Strength
Y_2 = Wear Rate
Second-order regression equation:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_{12}X_1X_2 + \beta_{23}X_2X_3 + \beta_{13}X_1X_3 + \beta_{11}X_1^2 + \beta_{22}X_2^2 + \beta_{33}X_3^2$$

Optimization Results Indicated
- Carbon Fibre Content = 10 wt.%
- Layer Height = 0.20 mm
- Infill Density = 100%

Predicted Responses
- Tensile Strength = 67.2 MPa
- Wear Rate = 5.1×10^{-4} mm^3/Nm

Artificial Neural Network (ANN) Model
A Multi-Layer Perceptron (MLP) neural network was developed in MATLAB.

Network Architecture
Input Layer
- Carbon Fibre Content
- Layer Height
- Infill Density

Hidden Layer
- 12 Neurons

Output Layer
- Tensile Strength
- Wear Rate

Training Algorithm
- Levenberg–Marquardt Backpropagation

Model Performance
Table 11. ANN Prediction Accuracy

Response	R^2 Value
Tensile Strength	0.993
Wear Rate	0.989

The ANN model demonstrated excellent prediction capability and can be utilized for real-time optimization of 3D printed composite fabrication.

Expected Engineering Applications
The developed carbon fibre reinforced PLA composites can be utilized in:
- Automotive dashboard supports
- UAV and drone structural components
- Lightweight robotic mechanisms
- Aerospace interior structures
- Bearing cages
- Low-load gears
- Biomedical assistive devices

VI. CONCLUSIONS

The present investigation evaluated the effect of carbon fibre content on the mechanical and tribological performance of 3D printed PLA composites fabricated using an IQ200 FDM printer.

Major conclusions are summarized as follows:

- Carbon fibre reinforcement significantly enhanced the tensile, flexural and hardness properties of PLA.
- The tensile strength improved from 48 MPa to 66 MPa with 10 wt.% carbon fibre loading.
- Wear resistance improved considerably, achieving approximately 45% reduction in wear rate.
- SEM analysis revealed superior fibre-matrix bonding at 10 wt.% carbon fibre content.
- Higher fibre loading (15 wt.%) resulted in fibre agglomeration and localized defects.
- ANOVA confirmed the statistical significance of carbon fibre reinforcement on composite performance.
- RSM optimization identified 10 wt.% carbon fibre as the optimum composition.
- ANN modelling achieved prediction accuracy exceeding 98%.
- PLA-CF10 exhibited the best balance between mechanical strength and wear resistance.
- Carbon fibre reinforced PLA composites fabricated through FDM possess significant potential for advanced lightweight engineering applications.

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