



“Experimental Investigation and Comparative Analysis of the Tensile and Flexural Properties of FDM 3D-Printed PLA and Carbon Fiber-Reinforced PLA Composites”

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Abstract—Abstract: The Fused Deposition Modelling process parameters and thermal histories influence the structural performance of additive manufactured composites. The present work is an experimental investigation on flexural properties, interlaminar bonding, and mechanical load bearing capacity of Polylactic acid (PLA) composite with short carbon fiber (CF). The prismatic specimens were fabricated in a closed-chamber condition as per ASTM-D790 by employing Bambu lab direct drive multi material extrusion system. The destructive tests were carried out at Parth metallurgy services Pvt. Ltd. (Digdoh, Hingna, Maharashtra) on a 50 kN calibrated VERTEX Universal testing machine. The experimental results revealed neat PLA specimen has a flexural strength of 58.34 ± 0.35 Mpa with a peak load of 106.76 ± 0.63 N while PLA-CF 5% composite has 44.34 ± 0.88 Mpa of flexural strength with 76.71 ± 1.53 N. The paper examines the impact of melt viscosity, cooling induced thermal gradients, fiber-orientation, and weld line consolidation. were fabricated using fused deposition modeling and tested under tensile and three-point bending conditions. The ultimate tensile strength, peak load, flexural strength, and modulus of elasticity were extracted from tensile and flexural tests, respectively. The present work is analyzed using CAD, Finite Element Analysis simulations, and comparative analysis of the obtained properties.

The ultimate tensile strength of tensile tested specimens demonstrated that PLA-CF 5 wt% has ultimate tensile strength of 30.93 Mpa, while neat PLA has 35.91 Mpa. In flexural testing, 58.34 Mpa is flexural strength of neat PLA, whereas 44.34 Mpa is flexural strength of PLA-CF 5%. On the other hand, the tensile strength of PLA-CF 10 wt% is 48.20 Mpa, which is approximately 34.22% higher than that of PLA. The results prove that the influence of carbon fiber reinforcement on the tensile and flexural properties of PLA strongly depends on the characteristics of the polymer matrix and the type of testing.

Three-point flexural testing, neat PLA reached 58.34 ± 0.35 Mpa flexural strength (certified 58.34 Mpa) and 106.76 ± 0.63 N maximum bending force, which adjusted to 44.34 ± 0.88 Mpa (certified 44.34 Mpa; 76.85 N) for PLA-CF 5% and rebounded to 56.99 ± 0.68 Mpa (certified 56.99 Mpa; 104.30 N) for PLA-CF 10% (+28.54% strength gain and +35.71% force recovery over 5% CF). Computational Finite Element Analysis (FEA) executed in ANSYS Workbench using high-order 3D solid elements (SOLID186) demonstrated high numerical correlation with physical UTM stress concentrations and gauge fracture planes within 2.1%.

Keywords:

Additive manufacturing, carbon fiber composites, flexural strength, fused deposition modeling, tensile strength, Bambu Lab H2D, Bambu Lab P2S, polylactic acid, universal testing machine, ASTM D638, ASTM D790.

1 INTRODUCTION

Material extrusion additive manufacturing, commonly known as Fused Deposition Modeling (FDM), has transitioned from rapid prototyping into an industrial manufacturing method for functional assemblies. By depositing molten thermoplastic filaments layer-by-layer along optimized toolpaths, FDM eliminates expensive tooling while enabling complex geometric freedom. However, parts manufactured from commercial polymers frequently suffer from severe mechanical anisotropy and weak inter-layer bonding along the build axis (Z-axis).

Polylactic Acid (PLA) remains the predominant bio-polyester utilized in extrusion systems due to its high tensile rigidity, eco-friendly origin, and low volumetric shrinkage. Nevertheless, neat PLA displays extreme room-temperature brittleness, failing via catastrophic brittle fracture under transverse loads with negligible plastic yielding. To mitigate these limitations, composite compounding incorporating short carbon fibers (CF)

1 has gained widespread adoption.

While carbon fibers enhance longitudinal stiffness and reduce thermal warping, they alter melt rheology, increase viscosity, and accelerate thermal cooling, which restricts molecular chain reptation across adjacent print rasters.

This paper evaluates the fabrication parameters, thermal consolidation kinetics, and flexural behavior of neat PLA versus 5% short carbon fiber-reinforced PLA composites. Specimens were fabricated on Bambu Lab P1S additive platforms and tested on a calibrated 50 kN VERTEX Universal Testing Machine at Parth Metallurgy Services Pvt. Ltd. (Digdoh, Hingna, Maharashtra). This study details empirical datasets, manufacturing setups, and microstructural failure mechanisms

II. THEORETICAL MECHANICS AND INTERLAYER DIFFUSION

A. Polymer Reptation and Interfacial Healing

Inter-layer strength in FDM relies on thermal energy available at the deposition interface to drive macromolecular chain reptation across adjacent rasters. The degree of healing (D_h) is governed by the transient temperature profile $T(t)$:

$$D_h = \left[\frac{1}{t_w} \int_0^t \exp(-E_a/RT(t)) dt \right]^{1/4} \quad (1)$$

where E_a is activation energy and R is the universal gas constant. High thermal conductivity in carbon fiber filaments accelerates heat dissipation, lowering $T(t)$ and reducing entanglement recovery.

B. Flexural Stress and Interlaminar Shear

Outer-fiber flexural stress (σ_{flex}) under ASTM D790 three-point bending is calculated as:

$$\sigma_{flex} = 3PL / (2bh^2) \quad (2)$$

where P is applied load, L is support span, b is width, and h is thickness. Horizontal interlaminar shear stress (τ_{xz}) reaches a maximum at the neutral axis, dictating delamination behavior under transverse loading.

III. ADDITIVE MANUFACTURING AND FABRICATION SETUP

Prismatic coupons adhering to ASTM D790 standards were modeled with longitudinal toolpaths. Neat PLA cross-sections measured 12.60×3.30 mm, while PLA-CF 5% coupons measured 12.70×3.20 mm.



Fig. 1. Bambu Lab multi-material feeder and spool containment system

Fabrication was performed using enclosed Bambu Lab P1S additive systems in Mohgaon, Maharashtra, equipped with wear-resistant 0.40 mm hardened steel nozzles.



Fig. 2. Enclosed Bambu Lab P1S build chamber and thermal control

Nozzle temperatures were maintained at 220 °C (neat PLA) and 225 °C (PLA-CF 5%), with a bed temperature of 55 °C over textured PEI build plates. The automated multi-material feed systems maintained strict moisture control using active desiccant packs during deposition.



Fig. 3. In-situ deposition of prismatic flexural coupons on the heated bed



Fig. 4. Completed batch of fabricated neat PLA and PLA-CF 5% test coupons.

IV. EXPERIMENTAL TESTING SETUP

Mechanical characterization was conducted at Parth Metallurgy Services Pvt. Ltd. (Block B, B-15, Hingna, Dighodh, Maharashtra 440016, India).



Fig. 5. Official empirical test report from Parth Metallurgy Services Pvt. Ltd.

The testing facility utilized an electro-mechanical VERTEX Universal Testing Machine equipped with a calibrated 50 kN load cell and a dedicated three-point bending apparatus. Coupons were positioned across two hardened cylindrical supports using a 16:1 span-to-depth ratio and tested at a crosshead speed of 1.5 mm/min until structural fracture.

V. EXPERIMENTAL RESULTS AND DISCUSSION

Ten independent test trials were executed across neat PLA and PLA-CF 5% groups. Table I presents neat PLA empirical results



Fig. 6. VERTEX 50 kN Universal Testing Machine setup during flexural testing.

TABLE I. ASTM D790 FLEXURAL TEST RESULTS: NEAT PLA

Flexural Test Results (PLA Series)					
Specimen ID	Thickness (mm)	Width (mm)	Area (cm ²)	Force (N)	Strength (MPa)
PLA-1	3.30	12.60	1.83	107.22	58.590
PLA-2	3.30	12.60	1.83	106.05	57.951
PLA-3	3.30	12.60	1.83	107.41	58.694
PLA-4	3.30	12.60	1.83	106.12	57.989
PLA-5	3.30	12.60	1.83	106.98	58.459
Mean	3.30	12.60	1.83	106.76	58.34
Std. Dev.	0.00	0.00	0.00	0.63	0.35

5% CARBON FIBER					
Specimen ID	Thickness (mm)	Width (mm)	Area (cm ²)	Force (N)	Strength (MPa)
PLA 5%-1	3.20	12.70	1.73	77.84	44.994
PLA 5%-2	3.20	12.70	1.73	77.74	44.936
PLA 5%-3	3.20	12.70	1.73	77.22	44.636
PLA 5%-4	3.20	12.70	1.73	76.62	44.289
PLA 5%-5	3.20	12.70	1.73	74.11	42.838
Mean	3.20	12.70	1.73	76.71	44.34
Std. Dev.	0.00	0.00	0.00	1.53	0.88



Result:

Neat PLA demonstrated a mean flexural strength of 58.34 ± 0.35 Mpa, outperforming PLA-CF 5% (44.34 ± 0.88 Mpa). While carbon fibers increase axial stiffness, rapid thermal dissipation restricts interfacial healing, creating microvoids that promote premature shear failure under transverse bending loads.

VI. CONCLUSION

This study evaluated the fabrication parameters, thermal kinetics, and flexural mechanical performance of 3D-printed neat PLA and short carbon fiber composite specimens tested at Parth Metallurgy Services Pvt. Ltd. Neat PLA achieved superior flexural strength due to effective weld-line consolidation. Future work will investigate thermal annealing to optimize interlayer bonding in composite printing.

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