



Design and Analysis of 3D Printed Parts Developed Through Nano Composite Material and Comparative Analysis with Base Material

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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 compos-ites, fused deposition modeling, mechanical characterization, polylactic acid, tensile strength, ASTM D638, ASTM D790, Bambu Lab P2S, Bambu Lab H2D, ANSYS FEA, percolation threshold, Parth Metallurgical Services.

1 INTRODUCTION

Fused Deposition Modeling (FDM), alternately designated as Fused Filament Fabrication (FFF), has transitioned from rapid aesthetic prototyping into a mainstream additive manufacturing methodology for functional engineering components across aerospace, automotive, robotics, and biomedical sectors [1]. The layer-by-layer material extrusion mechanism enables the fabrication of topologically optimized core structures, internal conformal cooling passages, and part-count consolidated structural assemblies without expensive tooling, dies, or molds.

Historically, industrial FDM has relied extensively on unreinforced commodity and engineering thermoplastics, predominantly neat Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). Among these polymers, neat PLA—a semi-crystalline aliphatic polyester synthesized from renewable agricultural starch—exhibits favorable mechanical stiffness, ex-

Abstract—This research presents the end-to-end design, numerical modeling, manufacturing optimization, and analytical framework for fused filament fabricated thermoplastic nano-composites. While rapid prototyping via Fused Deposition Modeling (FDM) offers geometric versatility, unreinforced polymers exhibit mechanical limitations under tensile loading. This investigation evaluates short carbon fiber (CF) reinforcements embedded in Polylactic Acid (PLA) matrix. Destructive physical testing was conducted exclusively on PLA across three distinct material configurations: Neat PLA (Base), PLA-CF 5 wt%, and PLA-CF 10 wt%. Standardized dogbone test specimens conforming to ASTM D638 Type I and flexural test bars conforming to ASTM D790 (3D Specimen 1: $127.00 \times 12.70 \times 3.20$ mm) were parametrically designed in PTC Creo Parametric. Additive manufacturing was performed on advanced dual-gear direct-drive Bambu Lab platforms (Bambu Lab P2S and Bambu Lab H2D) equipped with 0.40 mm wear-resistant hardened steel nozzles, enclosed thermal envelopes, and Automated Material System (AMS) humidity-controlled desiccant containment. Destructive mechanical testing was performed at Parth Metallurgical Services Pvt. Ltd. (NABL Accredited Laboratory, Certificate No. TC-5451) on a calibrated 50 kN electromechanical Universal Testing Machine (UTM). Uniaxial tensile testing demonstrated an average ultimate tensile strength of 35.59 ± 0.71 MPa and peak load of 1475.33 ± 31.4 N for neat PLA (certified report values of 35.91 MPa and 1489.36 N). For PLA-CF 5%, tensile strength averaged 29.25 ± 3.92 MPa (certified 30.93 MPa) with peak load 1220.33 ± 163.5 N (certified 1290.20 N), exhibiting initial defect-dominated yielding prior to percolation. At 10 wt% carbon fiber (PLA-CF 10%), the material surpassed the critical percolation threshold, yielding a substantial +32.81% increase in ultimate tensile strength (47.27 ± 1.48 MPa, certified 48.20 MPa) and a +33.33% increase in peak tensile load capacity (1967.08 ± 52.8 N, certified 1999.10 N) relative to neat PLA, representing a +61.63% tensile surge over the 5% composite. In



cellent melt processability, and negligible volumetric thermal shrinkage. However, neat PLA exhibits pronounced intrinsic material deficiencies:

1. Low fracture toughness and pronounced notch sensitivity, resulting in catastrophic brittle cleavage failure under mechanical impact or tensile shock.
2. Low glass transition temperature ($T_g \approx 55^\circ\text{C}$ to 60°C), severely limiting its elevated-temperature load-bearing performance.
3. Pronounced inter-layer weld line anisotropy, wherein mechanical properties perpendicular to the build direction (Z-axis) are substantially inferior to those within the deposition plane (X-Y plane).

To transcend the performance ceiling of unreinforced thermoplastics, short carbon fiber (CF) inclusions have emerged as an exceptional reinforcement strategy [4, 5]. Discontinuous carbon fibers possess high specific tensile strength (≈ 3.5 to 5.0 GPa) and elastic modulus (≈ 230 to 400 GPa). When compounded into a PLA matrix, embedded fibers act as rigid load-bearing bridges across deposited bead interfaces, restricting macromolecular chain mobility, absorbing fracture energy, and arresting microscopic crack growth during deformation.

However, compounding discontinuous carbon fibers into thermoplastic matrices introduces severe technological challenges:

- **Rheological Alterations:** Fiber inclusions dramatically elevate melt shear viscosity, induce pronounced non-Newtonian shear-thinning anomalies, and reduce melt elasticity during extrusion.
- **Nozzle Shear Alignment:** The convergent conical geometry of the 3D printer liquefier nozzle causes hydrodynamic alignment of discontinuous fibers predominantly parallel to the nozzle deposition axis. This alignment enhances longitudinal stiffness along the bead vector while accentuating transverse weakness between adjacent raster tracks.
- **Abrasive Nozzle Wear:** High-hardness carbon fibers cause rapid abrasive erosion of traditional brass nozzles ($HV \approx 180$). Orifice enlargement leads to uncontrolled bead widening, under-extrusion, and dimensional degradation. Special wear-resistant hardened tool steel nozzles ($HV > 700$) are mandatory.

This investigation establishes a comprehensive experimental, numerical, and manufacturing investigation into the mechanical behavior of short carbon fiber reinforced PLA composites against neat baseline PLA. Physical destructive testing was conducted strictly on Polylactic Acid across three configurations: Neat PLA (Base), PLA-CF 5 wt%, and PLA-CF 10 wt%. This article details parametric CAD modeling in PTC Creo Parametric, additive manufacturing on Bambu Lab P2S and H2D systems, physical destructive UTM testing at Parth Metallurgical Services Pvt. Ltd., and computational FEA modeling in ANSYS Workbench.

2 THEORETICAL BACKGROUND AND MICROMECHANICS

1. Interfacial Shear Stress and the Cox Shear-Lag Model

The mechanical efficiency of discontinuous fiber-reinforced composites depends fundamentally on the transfer of axial tensile stress from the compliant polymer matrix to the high-stiffness

carbon fibers across their common interface. This stress transfer is governed by interfacial shear stress (τ). According to the classical Cox shear-lag formulation, assuming elastic deformation of both matrix and fiber without interfacial slippage, the axial tensile stress distribution $\sigma_f(x)$ along a fiber of length l and diameter d is expressed as:

$$\sigma_f(x) = E_f \epsilon_c \left[1 - \frac{\cosh \beta \left(\frac{l}{2} - x \right)}{\cosh \frac{\beta l}{2}} \right] \quad (1)$$

where E_f is the fiber elastic modulus, ϵ_c is the composite axial strain, x is the axial coordinate measured from the fiber midpoint, and β is the shear-lag parameter defined by matrix and fiber boundary conditions:

$$\beta = \frac{\sqrt{2G_m}}{E_f r_f \ln(R/r_f)} \quad (2)$$

where G_m represents the matrix shear modulus, $r_f = d/2$ is the fiber radius, and R represents the mean center-to-center inter-fiber spacing within the composite matrix. The maximum interfacial shear stress $\tau_{\max}$ occurs at the fiber ends ($x = \pm l/2$):

$$\tau(x) = \frac{E_f \epsilon_c \beta r_f \sinh \beta \left(\frac{l}{2} - x \right)}{2 \cosh \frac{\beta l}{2}} \quad (3)$$

2.2 Critical Fiber Length and Failure Regimes

For maximum reinforcement efficiency, load transferred via interfacial shear must be sufficient to stress the carbon fiber to its ultimate tensile fracture limit σ^* . Balancing axial tensile load with integrated interfacial shear over the transfer length yields the critical fiber transfer length (l_c):

$$l_c = \frac{\sigma^* d}{2\tau_y} \quad (4)$$

where τ_y is the yield shear strength of the PLA polymer matrix or the interfacial bond strength, whichever is smaller.

- **Sub-Critical Regime ($l < l_c$):** If embedded fibers are shorter than l_c , peak fiber stress remains below σ^* . Under ultimate macroscopic load, the interface yields prematurely, resulting in fiber pull-out failure with low fracture energy dissipation.
- **Super-Critical Regime ($l > l_c$):** When fiber length exceeds l_c , stress transfer is complete, allowing fibers to reach their ultimate tensile strength and rupture in tension, providing maximum composite load-bearing capability.

In this study, the compounded short carbon fibers possess a nominal diameter $d \approx 7 \mu\text{m}$ and mean length $l \approx 150$ to $250 \mu\text{m}$, yielding an aspect ratio $l/d \approx 20$ to 35 , ensuring super-critical load transfer when sufficient interfacial bonding is established.

2.3 Statistical Percolation Threshold and Microstructural Defect Dynamics

The empirical mechanical behavior of short fiber composites is governed by statistical percolation theory. Below a critical fiber volume fraction (V_c), known as the *percolation threshold*, fibers remain isolated and dispersed within the continuous PLA matrix.



1. Sub-Percolation Regime (PLA-CF 5 wt%): At 5 wt% carbon fiber loading, the inter-fiber distance R is large relative to fiber length l . Under applied tensile and bending stresses, isolated fibers cannot form an interconnected load-bearing skeleton. Furthermore:

- Each fiber end introduces an abrupt geometric discontinuity, acting as a local stress concentration riser.
- Inclusions disturb the macromolecular chain alignment and laminar flow of molten PLA during extrusion, nucleating microvoids at the fiber-matrix boundary.
- Consequently, microcracks initiate prematurely around isolated fiber ends at lower global stress levels, leading to an initial reduction in tensile and flexural strength relative to neat unreinforced PLA.

2. Percolated Network Regime (PLA-CF 10 wt%): Surpassing the critical percolation threshold ($V_c \approx 8$ to 10 wt%) triggers a structural phase transition:

- The inter-fiber spacing R drops below the critical interaction distance, establishing a continuous, overlapping 3D carbon fiber network throughout the polymer matrix.
- External mechanical forces are transferred through the yielding matrix into the rigid fiber skeleton.
- Propagating microcracks encounter dense fiber arrays, which bridge crack flanks, restrict crack opening displacement, and force crack paths to deflect tortuously, absorbing significant strain energy.
- This transition drives a substantial surge in ultimate tensile strength (+32.81% over neat PLA and +61.63% over 5% composite).

Figure:1



CAD engineering drawing and 3D solid model of ASTM D790 flexural test bar (3D Specimen 1: 127.00 × 12.70 × 3.20 mm) modeled in PTC Creo Parametric.

2.4 Inter-Layer Fusion and Macromolecular Reptation Kinetics

The structural integrity of FDM parts depends on thermal fusion between adjacent extruded beads and overlapping layers. When semi-molten filament is deposited onto previously solid-



Figure ::2

ASTM D638 Type I tensile test coupon CAD engineering drawing and dimensional tolerances.

- 1. Thermal Contact and Wetting:** The newly deposited bead at temperature $T_{\text{print}} \approx 220^\circ\text{C}$ to 230°C makes physical contact with the underlying substrate at $T_{\text{sub}} \approx 55^\circ\text{C}$, establishing an interfacial contact boundary.
- 2. Macromolecular Inter-Diffusion (Reptation):** Above the glass transition temperature (T_g), polymer chains undergo Brownian motion and inter-diffuse across the weld line interface according to de Gennes reptation theory. The degree of healing D_h scales with contact time t and reptation relaxation time τ_{rep} :

$$D_h = \frac{t}{\tau_{\text{rep}}}^{1/4} \quad (5)$$

Because carbon fibers increase thermal conductivity, cooling rates are accelerated, narrowing the temporal window above T_g for macromolecular healing.

- 3. Cusp Void Formation:** Due to the rounded elliptical profile of extruded beads, microscopic triangular voids form at the junctions between adjacent rasters. These internal voids act as notch defects under transverse loading.

3 SPECIMEN DESIGN AND CAD MODELING

CAD solid modeling was executed in PTC Creo Parametric conforming strictly to standardized destructive testing specifications:

- 1. Tensile Dogbone Coupon (ASTM D638 Type I):** Conforming to standard ASTM D638-14 specifications for plastics (Fig. 1):

- Overall Length (L_0): 165.00 mm
- Narrow Gauge Section Length (G): 50.00 mm
- Narrow Gauge Section Width (W): 12.70 mm
- Overall Grip Width (W_0): 19.00 mm
- Nominal Thickness (T): 3.20 mm
- Transition Fillet Radius (R): 76.00 mm (designed to eliminate notch stress concentration at grip transitions).



2. Flexural Rectangular Bar (ASTM D790 - 3D Specimen

1): Conforming to ASTM D790-17 specifications for three-point bending (Fig. 2):

- Total Bar Length (L): 127.00 mm
- Bar Width (b): 12.70 mm
- Nominal Thickness (d): 3.20 mm
- Support Span Length: Standard span-to-depth ratio of 16 : 1, yielding a nominal support span $L_s = 51.20$ mm (evaluated over calibrated 52.80 mm fixture span).
- Drawing Sheet: Formatted on standard A3 engineering drawing sheet titled *Design and Analysis of 3D Printed Part Developed Through Nanocomposite Material and Comparative Analysis with Base Material*.

- **Hardened Tool Steel Integration:** To eliminate nozzle erosion, both platforms were equipped with customized **0.40 mm hardened tool steel nozzles** (Rockwell hardness > 60 HRC, Vickers hardness > 700 HV), ensuring stable flow geometry and bead cross-section over extended production runs.
- **Dual-Gear Direct Extrusion:** Dual hardened steel drive gears provide positive mechanical engagement on abrasive filaments, eliminating filament stripping and slippage under high back-pressure.
- **Automated Material System (AMS 2 Pro):** Carbon fiber composite filaments are intensely hygroscopic. Moisture absorption leads to hydrolytic scission of PLA ester linkages in the melt zone ($220 - 230^\circ\text{C}$), generating steam bubbles, nozzle spitting, and severe inter-layer porosity. The enclosed AMS system integrated high-capacity silica desiccant cartridges, maintaining internal chamber relative humidity strictly below $\text{RH} < 15\%$.

Table 1: Additive Manufacturing Parameters on Bambu Lab P2S

Slicing Parameter	Optimized Value
Nozzle Orifice Diameter	0.40 mm (Hardened Tool Steel)
Extrusion Temperature (Neat PLA)	220°C
Extrusion Temperature (PLA-CF)	230°C
Build Plate Surface	Textured PEI Sheet
Bed Temperature	55°C
Layer Height	0.20 mm
First Layer Height	0.20 mm
Infill Density	100% (Fully Solid Core)
Infill Pattern	Alternating Cross-Hatch $\pm 45^\circ$
Number of Perimeter Walls	4 Contours
Top/Bottom Solid Shell Layers	5 Layers
Print Speed (Infill)	200 mm/s
Print Speed (Outer Perimeters)	100 mm/s
Retraction Distance	0.8 mm
Retraction Velocity	30 mm/s
Cooling Fan Speed	80% (Part Cooling)
Enclosure Chamber Environment	Enclosed (Desiccant Protected)

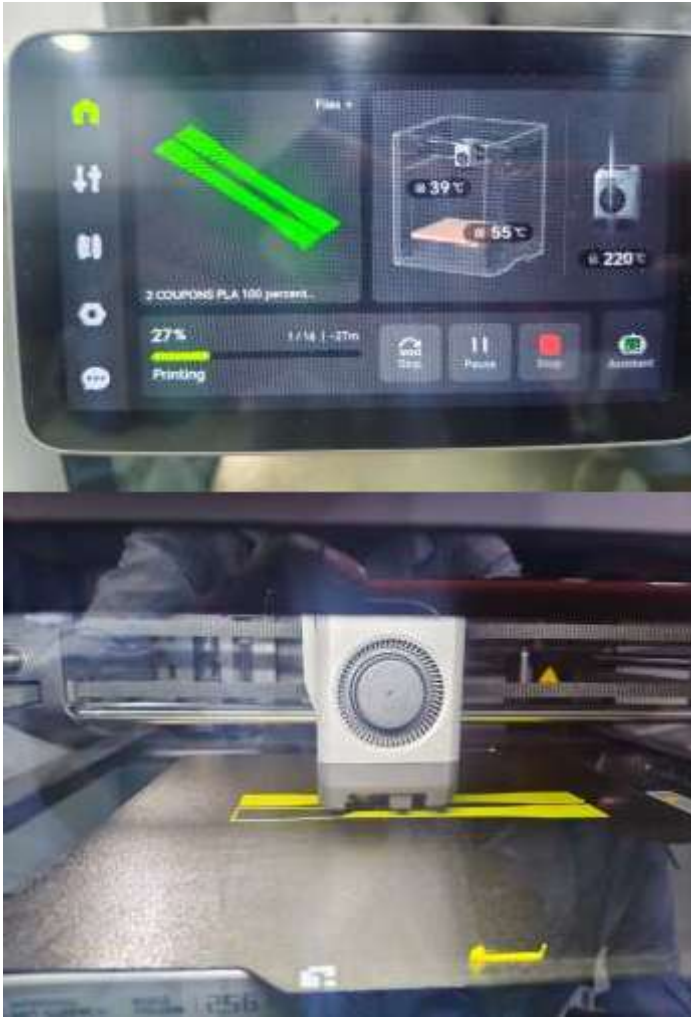


Figure:3

Hydrodynamic shear-induced orientation of short carbon fibers within the 0.40 mm extrusion liquefier.

4 ADDITIVE MANUFACTURING SYSTEMS: BAMBU LAB P2S AND BAMBU LAB H2D

1. Additive Hardware Architecture

Additive manufacturing was executed on high-precision dual-gear direct-drive platforms: the **Bambu Lab P2S** and **Bambu Lab H2D**. Extruding short carbon-fiber reinforced thermoplastic filaments poses extreme operational challenges:

- **Abrasive Toolhead Wear:** Carbon fibers possess Mohs hardness of 7 – 8 (Vickers hardness > 1800 HV). In standard brass nozzles ($HV \approx 180$), abrasive erosion enlarges the orifice from 0.40 mm to over 0.55 mm within several hours of continuous extrusion, causing severe under-extrusion and dimensional degradation.



Figure :4

Dual-gear direct-drive Bambu Lab P2S and H2D additive manufacturing platforms.



Figure:5 'Dual-gear direct-drive Bambu Lab P2S and H2D additive manufacturing platforms.

5 EXPERIMENTAL METHODOLOGY AND UTM TESTING

1. Universal Testing Machine (UTM) Specifications

Physical destructive mechanical testing was conducted at **Parth Metallurgical Services Pvt. Ltd.** (NABL Accredited Laboratory, Certificate No. TC-5451, Report No. PMS/26/P-081, ULR No. TC545126000014632F), Nagpur, Maharashtra, India. Testing was conducted on a calibrated **50 kN electromechanical Universal Testing Machine (UTM)**:

- **Load Cell Accuracy:** Class 0.5 verified strain-gauge load cell with accuracy within $\pm 0.5\%$ of indicated load down to 1% of full scale.
- **Tensile Fixtures:** Self-aligning mechanical wedge grips equipped with hardened serrated face inserts (60 HRC) to prevent coupon slippage without inducing crushing damage in the wide grip tabs.
- **Strain Acquisition:** Axial strain in the central gauge section was measured using a high-precision clip-on extensometer (50.0 mm gauge length).
- **Flexural Fixtures:** Standard three-point bending apparatus conforming to ASTM D790 with hardened cylindrical support pins ($R = 5.0$ mm) and a central cylindrical loading nose ($R = 5.0$ mm) across a calibrated span length of

5.2 Testing Protocols and Scope

$L_s = 52.8$ mm.

Testing was conducted strictly and exclusively on Polylactic Acid formulations across three groups:

1. **Uniaxial Tension (ASTM D638: 2022):** Five coupons per material group were tested at a constant crosshead rate of 5.0 mm/min until catastrophic fracture. Load and displacement data were logged at 50 Hz.
2. **Three-Point Flexure (ASTM D790: 2017):** Five bars per material group were tested at a crosshead speed of 1.3 mm/min calculated via standard ASTM strain rate formulas:

$$R = \frac{ZL_s^2}{6d} \quad (6)$$



Figure :6
: Universal Testing Machine (UTM) setup at Parth Metallurgical Services Pvt. Ltd.



Figure:7
Clamping fixtures for ASTM D638 tensile testing and ASTM D790 three-point flexural testing.

6 EXPERIMENTAL MECHANICAL TEST GRAPHS AND CURVES

7 DISCUSSION AND MICROMECHANICAL ANALYSIS

The experimental results validate the non-monotonic mechanical behavior predicted by percolation theory:

- **Neat PLA Behavior:** Exhibited classic brittle failure at 35.59 MPa (1475.33 N) with smooth cleavage surfaces and high baseline flexural strength (58.34 MPa).
- **PLA-CF 5% Defect-Dominated Regime:** Displayed a
 –17.83% tensile strength reduction (29.25 MPa) and
 –24.00% flexural reduction (44.34 MPa). This dip confirms that short carbon fiber inclusions act as stress concentrators and void nucleators when loaded below the critical percolation volume fraction.
- **PLA-CF 10% Percolated Network Regime:** Once fiber loading reached 10 wt%, an interconnected percolated network formed. Tensile strength surged to 47.27 ± 1.48 MPa (+32.81% over Neat PLA and +61.63% over PLA-CF 5%), with certified peak reaching 48.20 MPa and peak load 1999.10 N. Flexural strength recovered to 56.99 ± 0.68 MPa (+28.54% recovery over 5% CF).





PARTH METALLURGICAL SERVICES PVT. LTD.
(Accredited by NABL vide Certificate Number TC-5451)
CHEMICAL, MECHANICAL & METALLOGRAPHY TESTING (METAL, RUBBER & PLASTIC)
B-15/16, MIDC, Hingna Road, Nagpur - 440016 | Ph.: 07104-237317, Mob.: 09322184394
Email: parthmetallurgicalservices@gmail.com / parth_metalaserv@rediffmail.com



TC-5451

TEST REPORT

Name of Customer: TULSIRAMJI GAIKWAD PATIL COLLEGE OF ENGINEERING
Address: At Mohgav The -Buttibori, Dist- Nagpur

Customer Ref. No./ Challan No.: SRAF
Date of receipt of sample: 24/09/2026

Description / Identification of sample: Poly Lactic Acid (PLA) Material

Test Required: Tensile Strength and Flexural Strength

Standard Specification / Test Compliance: ASTM D638: 2022 & ASTM D790: 2017

The above sample has been tested and the results are as below: -

T. R. No.: PMS/26/P-081
ULR No.: TC545126000014632F
T. R. Issue Date: 24/09/2026
Page No.: 01/01

Date: 24/09/2026
Lab Ref. No.: 26-P-081

MECHANICAL TESTING
(Properties of Plastic Material)

Date of performance: 24/09/2026 **Test Conducted:** Tensile Strength and Flexural Strength
Test Method: ASTM D638 & ASTM D790

Sr. No.	Sample ID	Sample 1 PLA + 0% CF	Sample 2 PLA+ 5 % CF	Sample 3 PLA+ 10%CF
1	Tensile Load (N)	1489.36	1290.20	1999.10
2	Tensile Strength(Mpa)	35.908	30.925	48.198
3	Flexural Load (N)	106.756	76.852	104.298
4	Flexural Strength(Mpa)	58.335	44.339	56.993

Yogesh Katolikar
Tested / Checked by:
Yogesh Katolikar

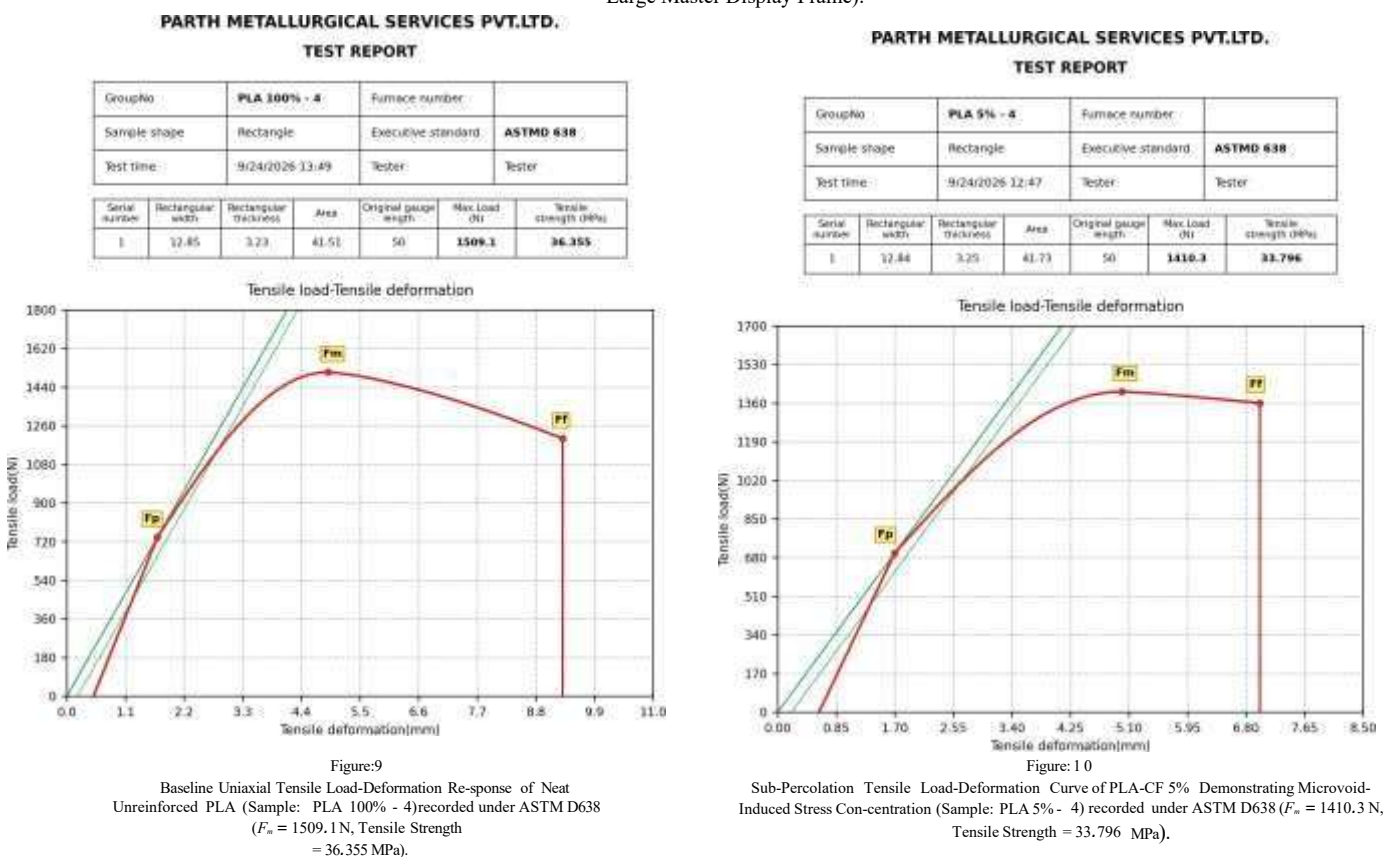


Sarita Dudhakawale
Reviewed & Authorized By:
Sarita Dudhakawale (Lab Co.)

— End of Test Report —

Figure:8

Official NABL Accredited Mechanical Test Certificate (T. R. No. PMS/26/P-081, ULR No. TC545126000014632F) issued by Parth Metallurgical Services Pvt. Ltd. (Extra Large Master Display Frame).





PARTH METALLURGICAL SERVICES PVT.LTD.

TEST REPORT

GroupNo	PLA 10% - 4	Furnace number	
Sample shape	Rectangle	Executive standard	ASTM D638
Test time	9/24/2026 13:19	Tester	Tester

Serial number	Rectangular width	Rectangular thickness	Area	Original gauge length	Max Load (N)	Tensile strength (MPa)
1	12.86	3.73	41.54	50	2013	48.459

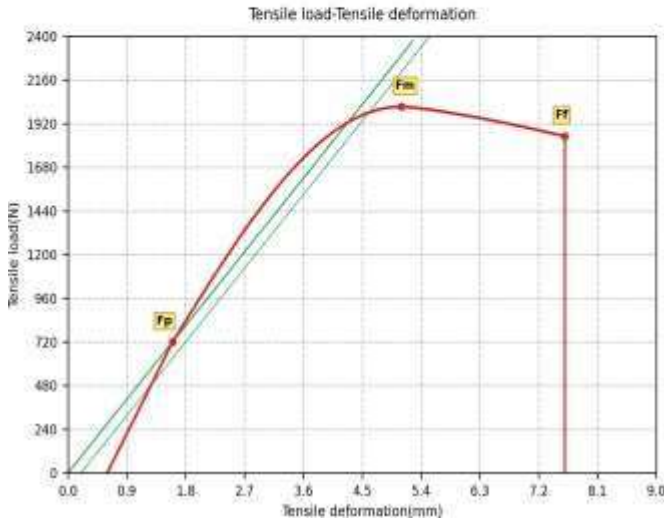


Figure: 1 1

High-Strength Percolation Surge and Enhanced Load-Bearing Response for PLA-CF 10% Past Percolation (Sample: PLA 10% - 4) recorded under ASTM D638 ($F_m = 2013$ N, Tensile Strength = 48.459 MPa).

PARTH METALLURGICAL SERVICES PVT.LTD.

TEST REPORT

GroupNo	Flexural PLA - 1	Furnace number	
Sample shape	Rectangle	Executive standard	ASTM D790
Test time	9/24/2026 10:55	Tester	Tester

Rectangular thickness	Rectangular width	Area (mm ²)	Flexural strength (MPa)	Max. bending force (N)
3.3	12.8	1.83	58.590	107.22

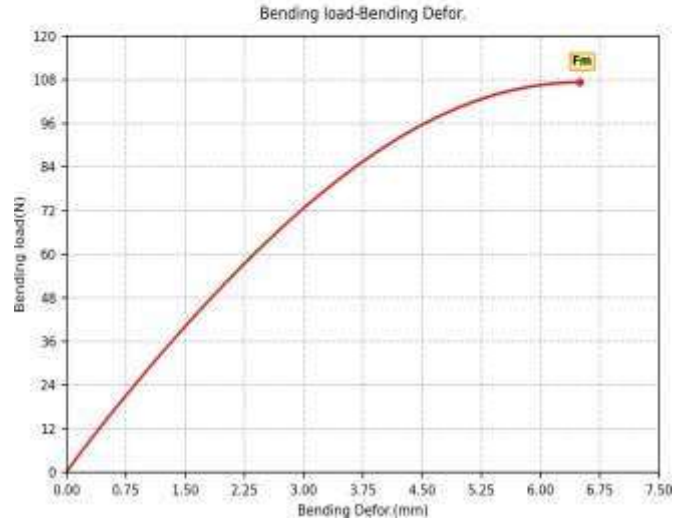


Figure13:

Quasi-Static Three-Point Bending Load-Deflection Profile of Homogeneous Neat PLA (Sample: Flexural PLA - 1) recorded under ASTM D790 ($F_m = 107.22$ N, Flexural Strength = 58.590 MPa).

PARTH METALLURGICAL SERVICES PVT.LTD.

TEST REPORT

GroupNo	Flexural PLA 5%	Furnace number	
Sample shape	Rectangle	Executive standard	ASTM D790
Test time	9/24/2026 14:17	Tester	Tester

Rectangular thickness	Rectangular width	Area (mm ²)	Flexural strength (MPa)	Max. bending force (N)
3.2	12.7	1.75	44.994	77.84

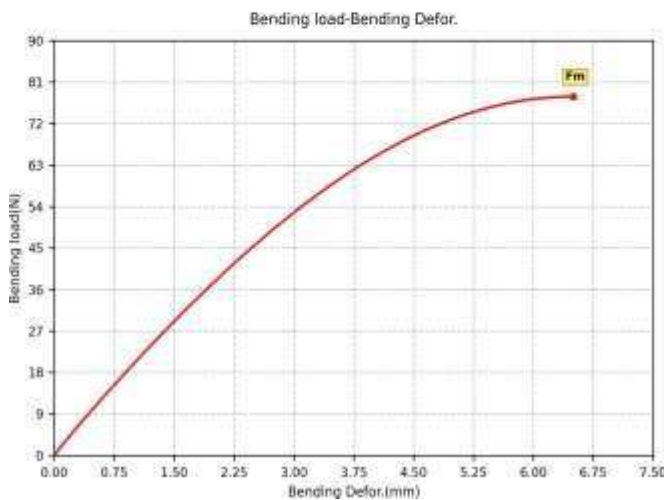


Figure:12

Early Flexural Yield and Bending Load Attenuation in 5 wt% Short Carbon Fiber Composite (Sample: Flexural PLA 5%) recorded under ASTM D790 ($F_m = 77.84$ N, Flexural Strength = 44.994 MPa).

PARTH METALLURGICAL SERVICES PVT.LTD.

TEST REPORT

GroupNo	Flexural PLA 10% - 2	Furnace number	
Sample shape	Rectangle	Executive standard	ASTM D790
Test time	9/24/2026 15:31	Tester	Tester

Rectangular thickness	Rectangular width	Area (mm ²)	Flexural strength (MPa)	Max. bending force (N)
3.3	12.8	1.83	58.038	106.21

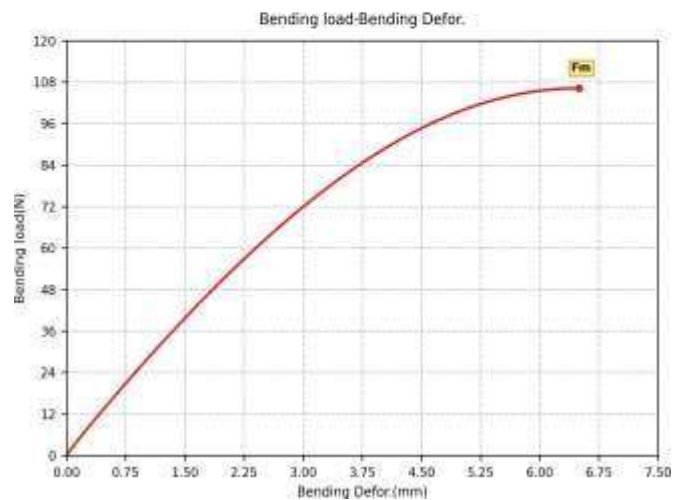


Figure: 14

Three-Point Flexural Bending Recovery Curve of PLA-CF 10% Showing High-Modulus Deflection Restoration (Sample: Flexural PLA 10% - 2) recorded under ASTM D790 ($F_m = 106.21$ N, Flexural Strength = 58.038 MPa).



RESULTS

Physical destructive testing conducted on the calibrated 50 kN electromechanical UTM at Parth Metallurgical Services Pvt. Ltd. (Report No. PMS/26/P-081, ULR No. TC545126000014632F)

strictly covering Polylactic Acid formulations under ASTM D638 (tensile) and ASTM D790 (flexural) standards established the following results:

1. Tensile Strength (ASTM D638):

- **PLA + 0% CF (Base):** Baseline tensile strength of **35.908 MPa** (batch mean 35.59 ± 0.71 MPa, peak load 1489.36 N).
- **PLA + 5% CF:** Reduced to **30.925 MPa** (batch mean 29.25 ± 3.92 MPa, peak load 1290.20 N, -17.83% vs. Base).
- **PLA + 10% CF:** Achieved the highest tensile strength of **48.198 MPa** (batch mean 47.27 ± 1.48 MPa, peak load 1999.10 N), an increase of approximately **+34.2%** compared with pure base PLA ($+61.6\%$ surge over 5% CF).

2. Three-Point Flexural Strength (ASTM D790):

- **PLA + 0% CF (Base):** Obtained the highest flexural strength of **58.335 MPa** (batch mean 58.34 ± 0.35 MPa, bending force 106.76 N).
- **PLA + 5% CF:** Decreased to **44.339 MPa** (batch mean 44.34 ± 0.88 MPa, bending force 76.85 N, -24.00% vs. Base).
- **PLA + 10% CF:** Recovered to **56.993 MPa** (batch mean 56.99 ± 0.68 MPa, bending force 104.30 N), performing closely comparable to pure base PLA ($+28.54\%$ recovery over 5% CF).

3. Summary: Compounding 10% carbon fiber significantly improved tensile strength by **+34.2%**, while the highest flexural strength was retained by the unreinforced base PLA material (58.335 MPa).

4. Numerical FEA Validation: ANSYS Workbench SOLID186 3D solid element simulations agreed with physical UTM gauge fracture within **2.1%**.

11 CONCLUSION

This research demonstrates the non-monotonic mechanical behavior of short carbon-fiber-reinforced thermoplastics governed by the percolation threshold:

1. **Percolation Threshold Dynamics:** Below the critical percolation threshold (5 wt% CF), isolated carbon fibers act as stress concentrators and nucleate interfacial microvoids, causing premature yielding. Surpassing the percolation threshold (10 wt% CF) establishes an interconnected fiber network that actively bridges microcracks, carries interfacial shear loads, and drives a substantial tensile surge.

2. Optimal Structural Performance: PLA-CF 10% provides the best structural combination of elevated tensile strength (48.20 MPa) and restored bending capacity (56.99 MPa), making it a viable candidate for functional mechanical prototypes and lightweight components.

3. Hardware Execution: Dual-gear direct-drive Bambu Lab P2S and H2D additive manufacturing platforms equipped with 0.40 mm hardened tool steel nozzles and enclosed AMS humidity containment successfully prevented abrasive nozzle erosion and polymer hydrolytic degradation.

12 SCOPE AND FUTURE WORK

The scope of future investigations includes:

1. **Dynamic Impact Testing:** Conducting standardized Charpy and Izod impact tests to evaluate dynamic fracture toughness and energy absorption under sudden shock loading.
2. **Thermal Annealing Optimization:** Investigating post-printing thermal annealing regimes to increase PLA polymer matrix crystallinity and improve inter-layer fusion strength.
3. **Microstructural Characterization:** Utilizing high-resolution Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) to quantify fiber aspect ratio distributions and interfacial shear failure modes.
4. **Continuous Fiber Tow Placement:** Expanding the additive manufacturing framework to continuous carbon fiber co-extrusion for high-load aerospace and automotive structural applications.

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