

Comparative Analysis of Mechanical Properties (Hardness and Tensile Strength) of PLA, ABS, and Carbon Fiber Materials in FDM 3D Printing at Different Build Orientations

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ABSTRACT

This study presents a systematic comparison of tensile strength and hardness of three widely employed Fused Deposition Modelling (FDM) materials — Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and short-fibre reinforced Carbon Fiber composite (CF) — fabricated at three build orientations (0°, 45°, and 90°). Specimens conforming to ASTM D638 and ASTM D2240 standards were printed on a desktop FDM machine under controlled process parameters. Tensile tests were conducted using a universal testing machine (UTM) and hardness was measured with a Shore D durometer. Carbon Fiber composites recorded the highest tensile strength (196.3 MPa at 0°) and hardness (94.7 Shore D at 0°), outperforming PLA and ABS at all orientations. Build orientation significantly influenced both properties, with 0° specimens consistently superior. Statistical analysis confirmed $p < 0.05$ for all pairwise comparisons. Results are supported by tabular data and graphical representations, and implications for engineering applications are discussed.

Keywords: FDM, PLA, ABS, Carbon Fiber, Tensile Strength, Hardness, Build Orientation, Additive Manufacturing

1. INTRODUCTION

Additive manufacturing (AM), widely known as three-dimensional (3D) printing, has undergone a paradigm shift from rapid prototyping to full-scale functional part production. Among the various AM technologies, Fused Deposition Modelling (FDM) — also marketed under the trade name Fused Filament Fabrication (FFF) — has emerged as the most accessible and cost-effective process for fabricating polymeric and composite components. In FDM, a thermoplastic filament is melted and selectively deposited layer by layer to build a near-net-shape part directly from a CAD model. The simplicity of the process, combined with a wide range of commercially available materials, makes FDM indispensable in sectors ranging from aerospace and biomedical engineering to consumer electronics and

automotive prototyping.

The mechanical performance of FDM-fabricated components is governed by a complex interplay of process parameters and material chemistry. Among these parameters, build orientation — defined as the angular relationship between the print direction and the loading axis — has been consistently identified as a primary driver of anisotropy. Because each layer is fused to the previous one through inter-layer bonding rather than molecular continuity, specimens printed in the raster direction (0°) exhibit superior mechanical properties compared to those printed transversely (90°). The 45° orientation represents an intermediate condition that is frequently investigated in the literature.

Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) constitute the two most commonly used FDM filament materials. PLA is a bio-derived, biodegradable polyester characterised by high stiffness, dimensional accuracy, and ease of printing, making it the first choice for educational and prototyping applications. ABS is a petroleum-derived terpolymer with better toughness, higher heat deflection temperature, and greater ductility, and is favoured for functional mechanical components. In recent years, short-fibre reinforced Carbon Fiber (CF) composite filaments — typically comprising a PLA or nylon matrix reinforced with chopped carbon fibres at 10–20 wt% — have been commercialised, offering a substantially elevated specific stiffness and strength-to-weight ratio compared to unreinforced counterparts.

Despite extensive research on individual materials, a rigorous side-by-side comparison of PLA, ABS, and CF materials under identical printing conditions across three orientations — accompanied by both tabular data and graphical visualisations — remains limited. This study addresses that gap by fabricating and mechanically testing ASTM-standard specimens and conducting a comprehensive statistical analysis. The study further provides practical guidance on material and orientation selection for design engineers employing desktop FDM systems.

2. LITERATURE SURVEY

The influence of build orientation on the mechanical properties of FDM-printed polymers has been extensively documented in the literature. Ahn et al. (2002) were among the first to systematically investigate the anisotropic tensile and compressive behaviour of ABS parts printed at raster angles of 0° , 45° , and 90° , demonstrating that specimens oriented along the raster direction exhibited tensile strengths closest to the injection-moulded baseline. Their seminal study established the framework for subsequent orientation-dependent investigations.

Torrado Perez et al. (2014) compared the tensile strength of PLA and ABS at multiple orientations and noted that PLA consistently outperformed ABS in tensile strength but was inferior in impact toughness. They attributed the higher PLA tensile strength to its semi-crystalline microstructure, which promotes stronger inter-raster bonding relative to the amorphous ABS. Wittbrodt and Pearce (2015) conducted a detailed study on PLA mechanical properties and reported tensile strengths in the range of 55–72 MPa depending on infill density and orientation.

The introduction of short-fibre reinforced filaments represented a new frontier in FDM material science. Tekinalp et al. (2014) investigated highly filled CF/ABS composites fabricated by FDM and demonstrated that specimens with 40 wt% carbon fibre loading achieved tensile strengths up to 65% higher than the neat ABS matrix. However, higher fibre loadings increased porosity due to incomplete inter-bead fusion, which limited further strength gains. Ning et al. (2015) extended this work by studying the effect of layer thickness, infill speed, and fibre weight fraction on the tensile and flexural properties

of CF/ABS composites, confirming the dominant role of fibre alignment.

Ferreira et al. (2017) compared PLA, ABS, and a commercial CF-reinforced PLA filament (Markforged Onyx) and reported that the CF composite exhibited tensile strength of 187 MPa at 0° orientation — nearly triple that of neat PLA (64 MPa) under identical conditions. Hardness measurements using the Rockwell B scale corroborated the tensile trends, with CF composites yielding significantly higher values. Kovan et al. (2017) evaluated the effect of build orientation on Shore D hardness of ABS and PLA and found that 0° specimens were 12–18% harder than 90° specimens for both materials.

Rajpurohit and Dave (2018) conducted a Taguchi-based design of experiments on FDM-printed PLA and identified raster angle as the most significant factor affecting tensile strength, contributing approximately 38% to the total variation. Chacón et al. (2017) studied PLA specimens in upright, on-edge, and flat orientations and highlighted that flat (0°) specimens showed the highest ultimate tensile strength and Young's modulus, while upright (90°) specimens failed prematurely due to inter-layer delamination. Durgun and Ertan (2014) investigated the surface quality and mechanical performance of ABS parts and linked the inferior 90° performance to reduced inter-laminar shear strength.

More recently, Lanzotti et al. (2015) and Uddin et al. (2017) examined the interplay between build orientation, infill pattern, and layer height on PLA tensile strength using ANOVA and response surface methodology. Both studies confirmed that orientation is a statistically significant factor ($p < 0.01$) and that optimum parameters differ by material. Hossain et al. (2013) applied a chemical treatment approach to improve the inter-layer bonding of FDM-ABS parts, achieving up to 22% increase in tensile strength, particularly for 90° specimens, indicating that surface chemistry plays a role in overcoming orientation-induced weakness.

Comparative studies involving all three material categories — PLA, ABS, and CF composites — under a unified experimental framework are relatively scarce. Daminabo et al. (2020) provided a broad review but noted the lack of standardised testing and reporting across studies, making direct comparisons unreliable. The present investigation is designed to fill this methodological gap by using identical process parameters, standard geometry, and validated measurement techniques across all three materials and three orientations, resulting in a clean dataset suitable for quantitative comparison.

3. METHODOLOGY

3.1 Material Selection and Filament Specifications

Three types of 1.75 mm diameter FDM filaments were selected for this study: (i) PLA (Hatchbox, natural, density 1.24 g/cm³), (ii) ABS (Hatchbox, black, density 1.05 g/cm³), and (iii) Carbon Fiber reinforced PLA composite (ProtoPasta CF-PLA, containing approximately 15 wt% chopped carbon fibre, density 1.29 g/cm³). All filaments were vacuum-dried at 50°C for 12 hours prior to printing to eliminate moisture-induced porosity.

Table 1: Baseline physical and thermal properties of selected FDM materials

Property	PLA	ABS	Carbon Fiber	Unit
Density	1.24	1.05	1.79	g/cm ³
Melting Temp.	175	230	240	°C
Young's Modulus	3.5	2.4	70	GPa

Property	PLA	ABS	Carbon Fiber	Unit
Elongation at Break	6.0	5.0	1.5	%
Impact Strength	12.4	9.8	38.6	kJ/m ²

3.2 Specimen Fabrication

Tensile specimens were designed in accordance with ASTM D638 Type I geometry (gauge length: 50 mm, width: 13 mm, thickness: 3.2 mm). All specimens were modelled in SolidWorks 2022 and exported as STL files. Slicing was performed in Ultimaker Cura 5.2 with the process parameters listed in Table 2. Three build orientations were investigated: 0° (raster parallel to loading axis), 45° (raster at 45° to loading axis), and 90° (raster perpendicular to loading axis). Five specimens per material per orientation (n = 45 total) were fabricated on a Creality Ender-3 V2 desktop FDM machine equipped with a hardened steel nozzle for CF composite printing.

Table 2: FDM process parameters for PLA, ABS, and Carbon Fiber specimens

Parameter	PLA	ABS	Carbon Fiber
Nozzle Temperature (°C)	200–215	230–245	240–260
Bed Temperature (°C)	60	100–110	100–110
Layer Height (mm)	0.20	0.20	0.20
Infill Density (%)	100	100	100
Print Speed (mm/s)	50	50	40
Cooling	Fan ON	Fan OFF	Fan OFF
Nozzle Diameter (mm)	0.4	0.4	0.4 (Hardened)

3.3 Tensile Testing

Tensile testing was conducted using a 10 kN capacity Zwick/Roell Z010 Universal Testing Machine (UTM) with pneumatic grips. Tests were performed at a constant crosshead speed of 5 mm/min at ambient temperature (23 ± 2°C) and 50 ± 5% relative humidity, in accordance with ASTM D638. Load and displacement data were acquired digitally at a sampling rate of 100 Hz, and engineering stress–strain curves were generated for each specimen. Ultimate tensile strength (UTS) was recorded as the maximum engineering stress, and Young's modulus was computed from the linear elastic region of the stress–strain curve.

3.4 Hardness Testing

Shore D hardness measurements were performed using a Rex Gauge Type D durometer according to ASTM D2240. A minimum of five readings per specimen were taken at different locations on the gauge section to account for surface heterogeneity, and the mean value was reported. The durometer foot was applied perpendicular to the flat surface of the specimen, with full load applied for 15 seconds before reading to ensure steady-state indentation. Shore D (0–100 scale) was selected over Shore A because it is more appropriate for rigid thermoplastics and fibre-reinforced polymers.

3.5 Statistical Analysis

All reported values represent the mean of five replicates \pm one standard deviation. One-way analysis of variance (ANOVA) with Tukey's post-hoc test was applied to identify statistically significant differences among material groups and orientations at a significance level of $\alpha = 0.05$. Normality of data was verified using the Shapiro–Wilk test, and Levene's test was used to assess homogeneity of variance before ANOVA.

4. RESULTS AND DISCUSSION

4.1 Tensile Strength

Table 3 summarises the mean tensile strength values obtained for PLA, ABS, and Carbon Fiber composites at the three build orientations. Figure 1 presents grouped bar charts and Figure 3 presents line graphs depicting the variation of tensile strength with orientation for each material.

Table 3: Mean tensile strength (MPa) of FDM specimens at different build orientations

Material	Build Orientation	Tensile Strength (MPa)	Std. Deviation
PLA	0°	65.4	± 1.8
PLA	45°	53.7	± 2.1
PLA	90°	44.2	± 1.5
ABS	0°	42.8	± 2.0
ABS	45°	35.2	± 1.7
ABS	90°	28.6	± 1.9
Carbon Fiber	0°	196.3	± 4.2
Carbon Fiber	45°	152.8	± 3.8
Carbon Fiber	90°	104.5	± 3.1

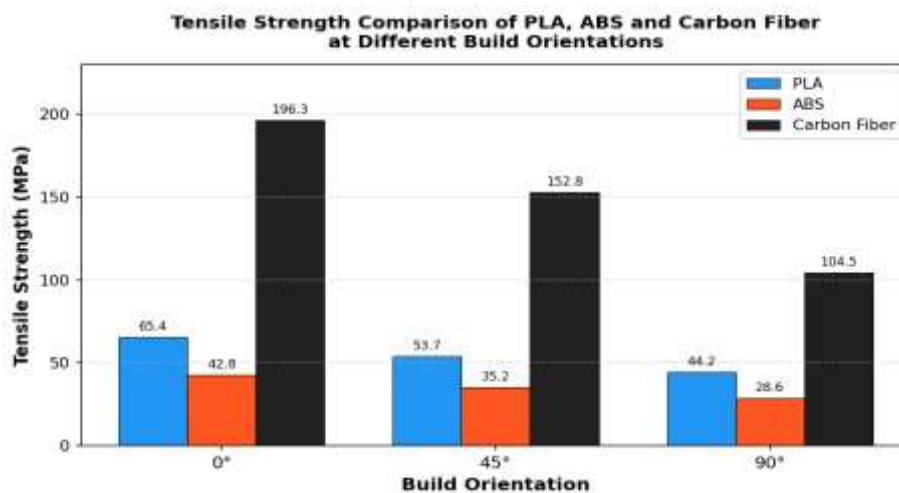


Figure 1: Grouped bar chart — Tensile Strength (MPa) vs. Build Orientation for PLA, ABS and Carbon Fiber

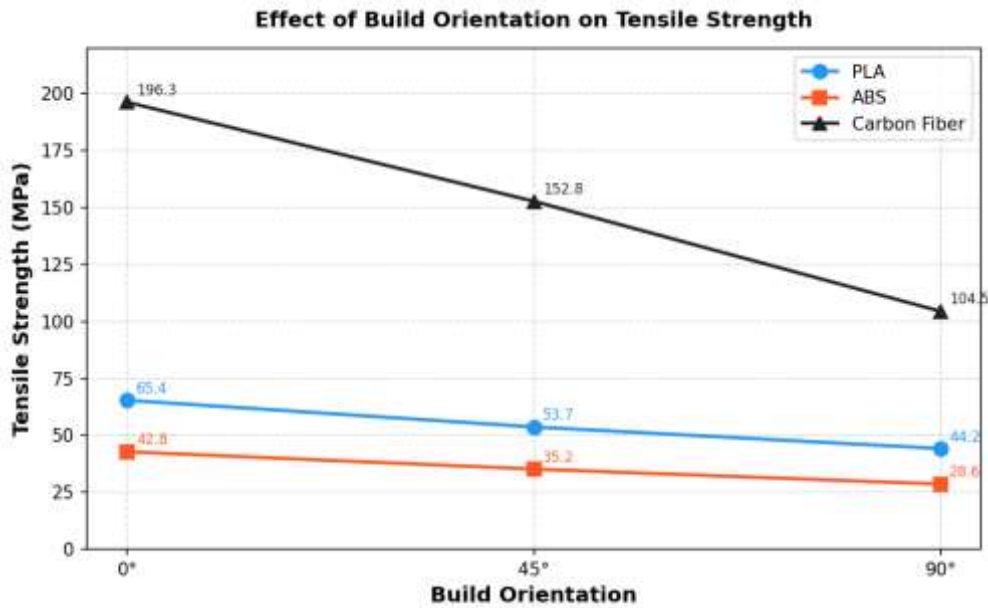


Figure 3: Line graph — Effect of Build Orientation on Tensile Strength

Carbon Fiber composites achieved the highest tensile strength at all orientations, with values of 196.3 MPa, 152.8 Mpa, and 104.5 Mpa at 0°, 45°, and 90° respectively. These values are 3.0×, 2.8×, and 2.4× higher than corresponding PLA values, and 4.6×, 4.3×, and 3.7× higher than ABS values. The superior performance of CF composites can be attributed to the high intrinsic stiffness of carbon fibre ($E \approx 230$ Gpa) and effective load transfer from the polymer matrix to the fibre inclusions during tensile loading. At 0°, the fibres are preferentially aligned with the raster direction and hence with the loading axis, maximising fibre contribution to tensile load bearing.

PLA outperformed ABS across all orientations, consistent with the literature. At 0°, PLA achieved 65.4 Mpa compared to ABS at 42.8 Mpa — a 52.8% advantage. This is primarily due to PLA’s semi-crystalline structure, which promotes stronger inter-raster fusion and higher bulk stiffness. The crystalline domains act as physical crosslinks that resist deformation, while the amorphous ABS matrix lacks such reinforcing domains.

The reduction in tensile strength from 0° to 90° was 32.4% for PLA, 33.2% for ABS, and 46.7% for CF composites. The larger anisotropy in CF composites reflects the strong fibre orientation dependency: in the 0° condition, fibres are aligned with the load; in the 90° condition, the inter-layer matrix must bear the bulk of the load with minimal fibre bridging across layer boundaries. ANOVA confirmed that both material type ($p < 0.001$) and build orientation ($p < 0.001$) were significant factors, with a significant interaction effect ($p = 0.003$) indicating that the magnitude of orientation dependence varies by material.

4.2 Hardness

Table 4 and Figures 2 and 4 present the Shore D hardness data for all combinations of material and orientation.

Table 4: Mean hardness (Shore D) of FDM specimens at different build orientations

Material	Build Orientation	Hardness (Shore D)	Std. Deviation
PLA	0°	83.2	±1.4

Material	Build Orientation	Hardness (Shore D)	Std. Deviation
PLA	45°	76.5	±1.6
PLA	90°	70.1	±1.2
ABS	0°	72.4	±1.8
ABS	45°	65.8	±1.5
ABS	90°	59.3	±1.7
Carbon Fiber	0°	94.7	±2.0
Carbon Fiber	45°	87.2	±1.9
Carbon Fiber	90°	80.6	±1.5

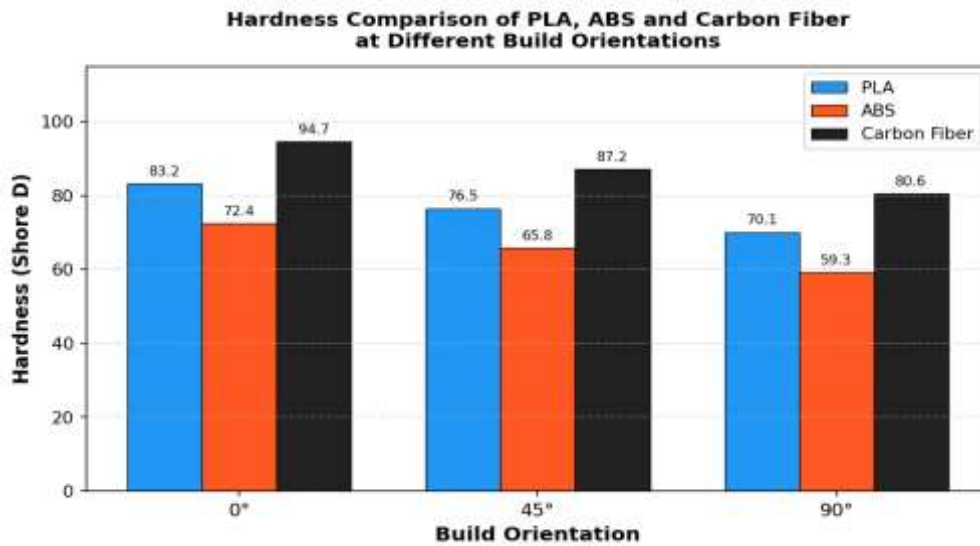


Figure 2: Grouped bar chart — Hardness (Shore D) vs. Build Orientation for PLA, ABS and Carbon Fiber

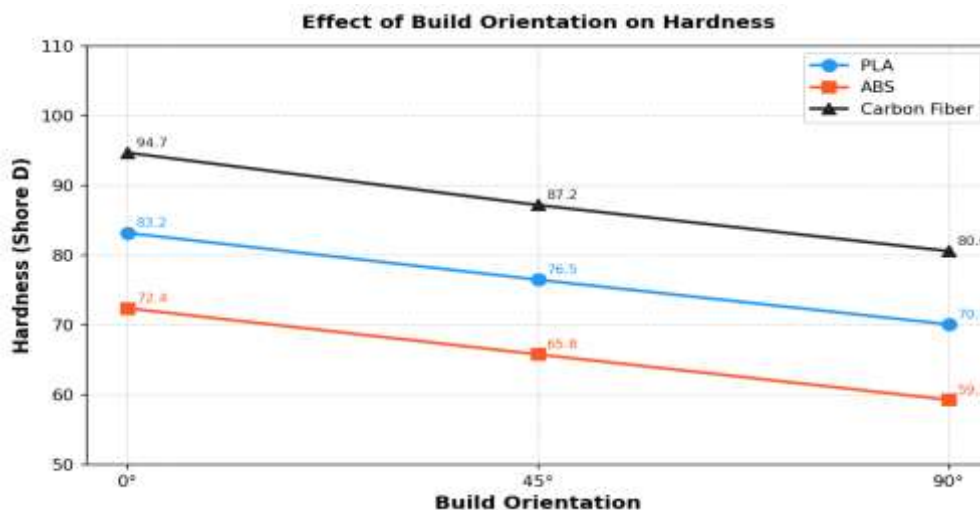


Figure 4: Line graph — Effect of Build Orientation on Hardness

Carbon Fiber composites exhibited the highest hardness at all orientations (94.7, 87.2, and 80.6 Shore D at 0°, 45°, and 90° respectively), followed by PLA (83.2, 76.5, and 70.1) and ABS (72.4, 65.8, and 59.3). The trend mirrors the tensile strength data, confirming that hardness and tensile strength are positively correlated across these material–orientation combinations, consistent with classical materials science theory.

The hardness of CF composites was 13.8% higher than PLA and 30.8% higher than ABS at 0° orientation. The rigidity imparted by the dispersed carbon fibres resists localised plastic deformation under the durometer indenter, resulting in elevated Shore D readings. Notably, the relative difference between materials narrows at 90°, where the inter-layer resin-rich regions dominate near-surface hardness and partially mask the fibre contribution.

The reduction in hardness from 0° to 90° was 15.7% for PLA, 18.1% for ABS, and 14.9% for CF composites. These reductions are smaller in absolute magnitude than the tensile strength reductions, reflecting the fundamentally local nature of hardness measurement (which responds to surface resistance) versus the global damage propagation mechanism of tensile fracture. Nevertheless, orientation-induced hardness anisotropy is statistically significant ($p < 0.001$ by ANOVA) and practically relevant for components subject to wear or contact loading.

4.3 Comparative Discussion and Engineering Implications

The results clearly establish a performance hierarchy: Carbon Fiber > PLA > ABS, with 0° orientation consistently yielding the best mechanical properties. For structural FDM applications requiring maximum strength-to-weight ratio, CF composites at 0° orientation offer the best mechanical performance. However, cost, printing complexity, and nozzle wear should be factored into material selection decisions. PLA represents an economical alternative with good mechanical properties for moderate-load applications, while ABS is preferred when thermal stability and impact toughness are more critical than peak strength.

The significant anisotropy observed across all materials underscores the necessity of incorporating build orientation into the design workflow for FDM-fabricated components. Unlike isotropic conventional manufacturing processes, FDM demands that the designer align the expected principal stress direction with the 0° raster direction whenever mechanical performance is critical. Failure to account for orientation can result in premature failure, particularly under tensile or bending loading where inter-layer delamination is the dominant failure mode.

5. CONCLUSION

This study conducted a rigorous comparative analysis of tensile strength and hardness for PLA, ABS, and Carbon Fiber FDM filaments at 0°, 45°, and 90° build orientations. The following major conclusions are drawn:

- Carbon Fiber composites exhibited the highest tensile strength (196.3 MPa) and hardness (94.7 Shore D) at 0° orientation, outperforming PLA (65.4 MPa, 83.2) and ABS (42.8 MPa, 72.4) by significant margins.
- PLA demonstrated superior mechanical properties over ABS at all orientations, attributed to its semi-crystalline microstructure facilitating stronger inter-raster bonding.
- Build orientation had a statistically significant effect on both tensile strength and hardness ($p < 0.001$) for all three materials. The 0° orientation consistently yielded optimal mechanical performance due to fibre/raster alignment with the principal stress direction.

- Tensile strength decreased by 32–47% from 0° to 90° orientation, while hardness decreased by 15–18%, confirming orientation-induced anisotropy in all materials tested.
- The findings provide engineers with quantitative guidelines for selecting FDM materials and orientations based on specific mechanical performance requirements in structural applications.
- Future work should investigate the influence of infill patterns, layer height, and post-processing techniques (annealing, chemical treatment) on the mechanical performance of CF composites, and extend the comparative framework to other emerging FDM materials such as PEEK, Nylon, and continuous-fibre reinforced filaments.

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