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Impact of Printing Process Parameters on the Tensile and Flexural Strength of Filament Material

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ABSTRACT

This research evaluates the mechanical properties of three polymer-based filament materials used in Fused Deposition Modeling (FDM): Polylactic Acid Plus (PLA+), Polyethylene Terephthalate Glycol (PETG), and Carbon Fiber-reinforced Polylactic Acid (PLA-CF). The study focuses on maximizing structural integrity and minimizing porosity by employing a 95% solid 3D Honeycomb infill density. Through standardized ASTM D638 tensile testing and ASTM D790 three-point bending tests, the research identifies PLA-CF as the most rigid material, achieving a flexural modulus of 5643.06 MPa. In contrast, PETG and PLA+ demonstrate superior peak tensile forces and higher ductility, making them better suited for applications requiring toughness.

The findings indicate that optimized wall loops and high-density infill patterns significantly mitigate catastrophic failure under load. Comparative analysis with recent literature (2024–2026) corroborates the dominance of infill density in determining mechanical performance, while also highlighting critical research gaps in PLA+ specific parameter optimization and the interaction between wall loops and structural strength. This comprehensive assessment provides essential guidance for material selection in load-bearing engineering applications, such as prosthetic components.

1. Introduction

Fused Deposition Modeling (FDM) additive manufacturing has become an essential method for producing functional components, requiring an in-depth understanding of the mechanical properties of various polymer filaments. This study focuses on three materials: Carbon Fiber-reinforced PLA, which is known for being very stiff; PETG, which is known for being resistant to chemicals and having properties that are between PLA and ABS; and PLA+, which is a better version of Polylactic acid that is tougher [1].

Despite the proliferation of FDM research, significant gaps remain in the literature. Recent studies (2024–2026) indicate a lack of harmonized side-by-side Designs of Experiments (DOE) across multiple materials, with most research focusing on single-material optimization . Furthermore, the specific mechanical behavior of PLA+, an improved version of standard PLA designed for enhanced toughness, is underrepresented in systematic

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parameter-property studies . There is also a notable absence of data regarding the quantitative effects of wall loops and perimeter strategies on tensile and flexural strength .

The anisotropic nature of FDM parts largely determines their mechanical integrity, while interlaminar bonding and layer orientation in respect to applied forces determine the final product's strength. This study uses strict printing parameters, such as a 0.2 mm layer height and a 95% 3D Honeycomb infill, to ensure that test results accurately reflect the intrinsic properties of these polymers and are not limited by internal voids [2,37].

This research addresses these gaps by performing a comparative analysis of PLA+, PETG, and PLA-CF under standardized conditions. By utilizing a high infill density (95%) and optimized wall loops, the study aims to establish a benchmark for these materials in structural applications. The integration of recent findings from 2024 and 2025, such as the impact of infill patterns on PETG-CF . Tensile testing is used to measure characteristics like yield strength and Young's modulus as well as to determine the maximum load that a structure can support. Flexural testing provides essential data regarding the material's resistance to bending moments, which is crucial for predicting performance in practical structural applications, such as prosthetic components. This study seeks to offer guidance for material selection in load-bearing engineering applications by evaluating these materials under standardized conditions [3,38].

2 Materials and methods

2.1. Materials

The following three polymer-based filament materials were tested:

PLA+ (Polylactic Acid Plus) is a modified thermoplastic made from renewable resources and improved with proprietary additives, usually impact modifiers and plasticizers. PLA+ has a semi-ductile failure mode, which means it can stretch up to 20% before breaking. This is different from the base polymer. The main problem with FDM-printed PLA is that it is naturally brittle, and this change fixes that. The material's optimized melt flow index also gives it a wider processing window, which means that layers bond better than they do with unmodified PLA. In some cases, this also makes the material tougher and more heat-resistant[4-6].

CF (Carbon Fiber-reinforced Composite):Carbon fiber filaments infuse short carbon fibers into a base thermoplastic (e.g., PLA, PETG, Nylon, ABS, or PC). Carbon fiber reinforced materials are filled with continuous fibers or fiber particles that result in parts with improved physical properties and high stiffness. There is a variety of carbon fiber reinforced options out there for 3D printing. Carbon fiber-reinforced filaments combine the benefits of thermoplastics with the strength and stiffness of carbon fibers, creating materials optimized for engineering-grade applications[7-8].

PETG (Polyethylene Terephthalate Glycol) is a synthetic thermoplastic polyester that is known for being very durable, resistant to chemicals, and easy to shape. PETG is a very flexible filament that is easy to print with and has good mechanical properties. This makes it a popular choice for a wide range of 3D printing projects. It is widely used to make prototypes, functional parts, and even decorative items because it can spread light well and stick to layers well. [9–10].

2.2. Specimen Geometry

2.2.1 Tensile Test Specimen

Tensile testing, or tension testing, is a basic test in materials science and engineering that puts a sample under controlled tension until it breaks. Ultimate tensile strength, breaking strength, maximum elongation, and reduction in area are all properties that can be measured directly by a tensile test. You can also figure out the following properties from these measurements: Young's modulus, Poisson's ratio, yield strength, and strain-hardening properties. Based on the measurements shown in Fig. 1, the specimen in this case is a Type I specimen from the ASTM D638 test, which is used to test the rigidity of rigid plastic materials[11-12].

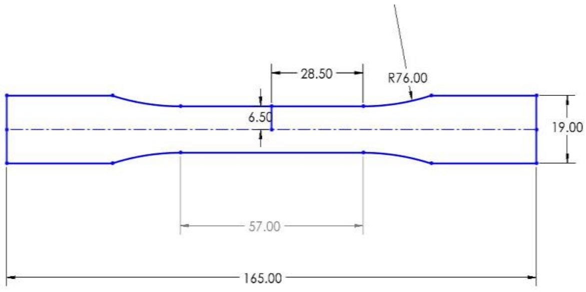

Figure 1. Tensile Test Specimen

2.2.2 Bending Test Specimen

A flexural test measures a material's ability to withstand bending forces. It helps engineers determine how flexible and strong materials are. ASTM D790 is the standard test method for determining flexural properties of plastics and polymer composites. In the D790 test, a specimen shown in fig.2, that is bar-shaped in a rectangular cross-section is supported at both ends and loaded at the midpoint. The three-point bending setup essentially measures how the material behaves under bending stress-specifically capturing its flexural strength, the stress at failure, or at a specified strain, and the flexural modulus, the stiffness in bending. The method is applicable to rigid and semi-rigid polymers-in other words, unreinforced plastics, fiber-reinforced plastics, thermosets, thermoplastics, and electrical insulating materials. This gives engineers and lab technicians important information about how well a material can resist bending forces when it is loaded, which is important for predicting how a plastic part will work in real life when it is bent[13–14].

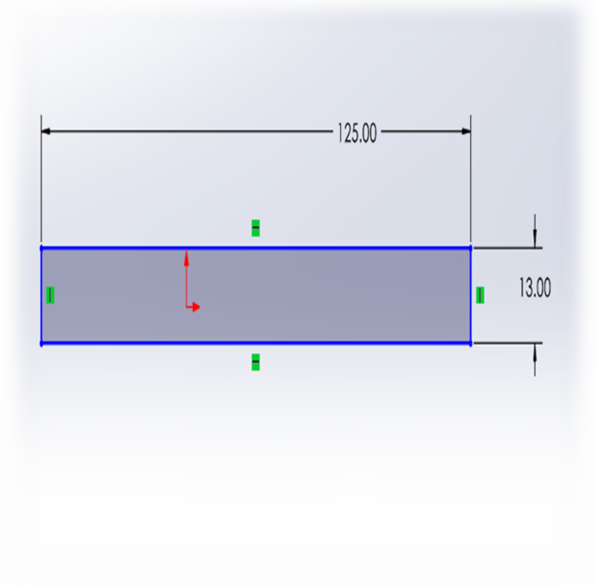

Figure 2. Bending Test Specimen

3. FDM Printing Parameters

All of the specimens were made using strict FDM settings that were meant to make the parts as strong and dense as possible. The almost-solid infill reduces internal voids, making sure that the mechanical results show the material's natural properties instead of being limited by porosity. As it appears in the fig. 3.

Parameter Category	**Specific Setting**	**Value**	**Impact on Mechanical Properties**
Layer Height	Layer height	0.2	Influences surface finish and layer-to-layer adhesion (anisotropy).
Shell/Perimeter	Wall loops	2	Defines the thickness of the solid outer wall (shell). Directly affects strength and stiffness.
Infill	Sparse infill density	95%	The near-solid infill contributes significantly to the bulk strength and stiffness of the specimen.
Infill	Sparse infill pattern	3D Honeycomb	Provides multi-directional strength and stability.
Top/Bottom	Top shell layers	5	Determines the strength of the top surface.
Top/Bottom	Top surface pattern	Concentric	Influences surface strength and stress distribution.

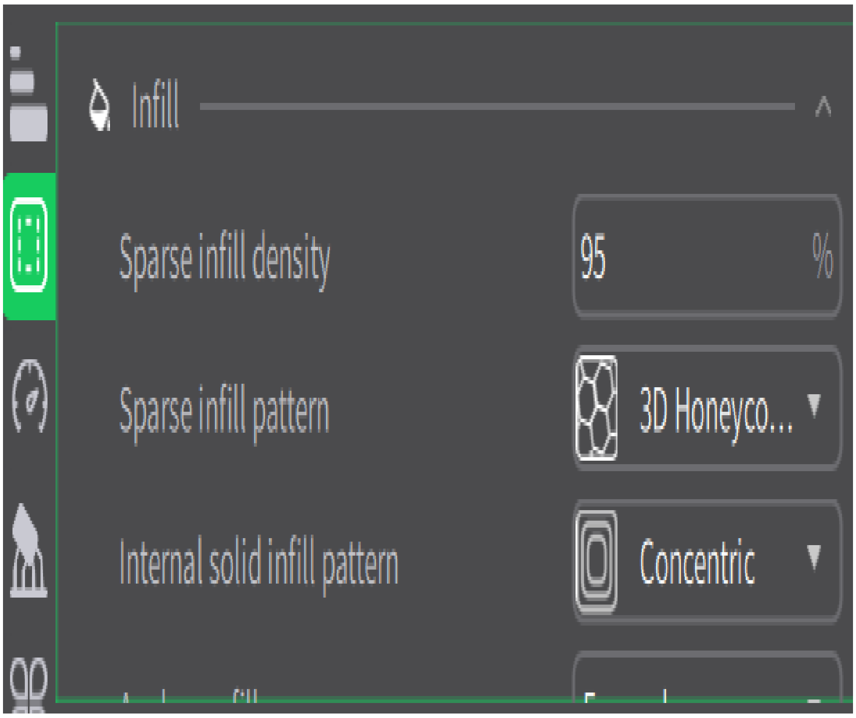

Figure 3. infill pattern

A typical layer height that defines the surface finish and, critically, the inter-layer bond strength (anisotropy). As shown in the fig.4

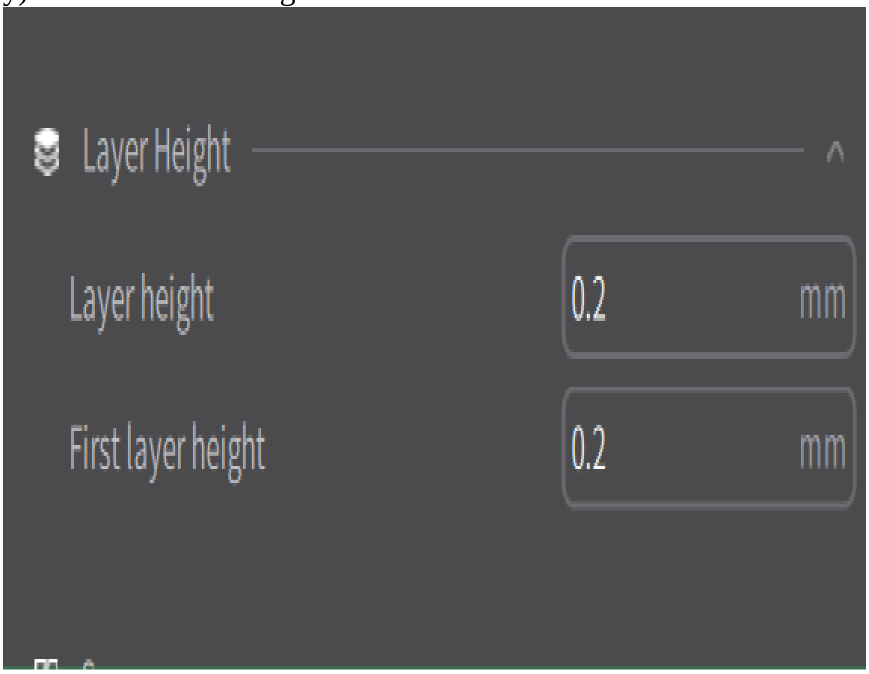

Figure 4. Layer height

Determines the strength of the top surface, Influences surface strength and stress distribution. As shown in the Fig. 5

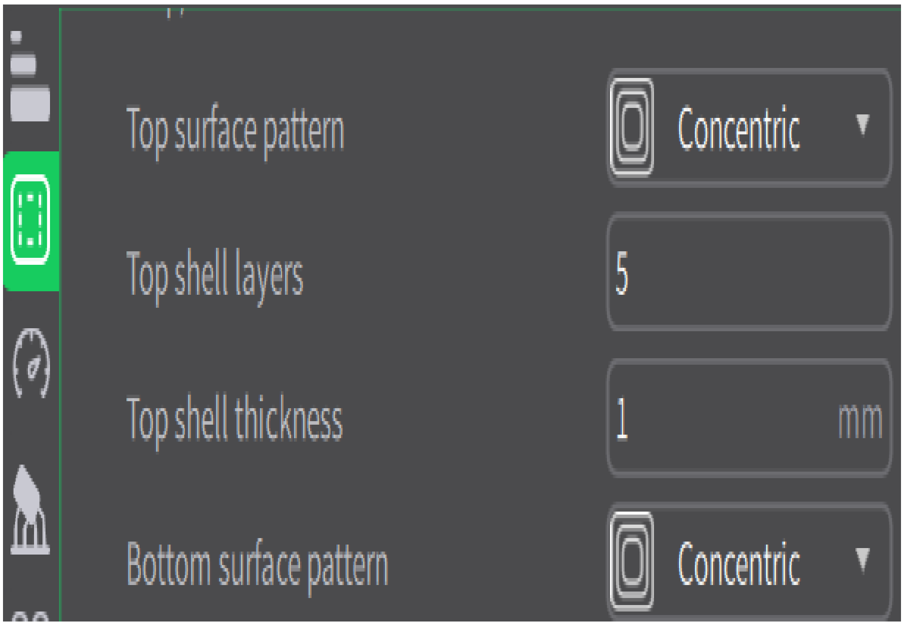

Figure 5. surface pattern

Provides a solid, stress-bearing outer shell. The shell resists the maximum stress in both bending (outer fibers) and tension. based on illustration of Fig. 6

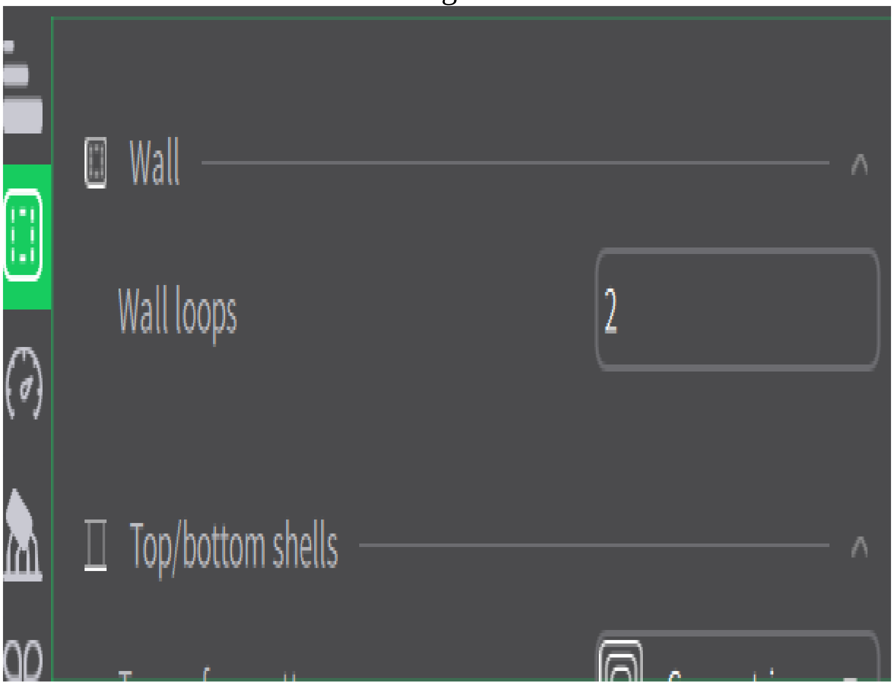

Figure 6. Shell/Perimeter

The key printing parameters used to fabricate all specimens are as follows:

The near-solid 95%infill density is a critical parameter, as it minimizes the internal porosity, maximizing the material properties and allowing the measured results to closely approximate the intrinsic strength and stiffness of the polymer/composite.

3.1 Effect of Layer Height (0.2 mm) and Anisotropy

A value for the layer height of 0.2 mm affects the anisotropy, that is, the differences in strength in the print layer direction versus between print layers (inter-layer bond).

Modulus Disparity: The big difference between the values of the flexural modulus (having high values of 5.64 GPa) and Tensile Young's modulus (having low values of 0.50 GPa) is straightaway linked to the value of the layer height, which in turn is linked to the value of adhesion between the layers. The value of 0.2 mm of layer height ensures sufficient fusion for getting bulk material properties, but smaller layer height values (0.1 mm) or higher printing temperatures will increase bond strength between the layers, ensuring higher Tensile Young's modulus values. Material Dependence: Where layer height is concerned, it is observed that the CF and PLA+ materials are highly dependent on layer height compared to PETG materials, which tend to be more brittle than PETG materials[15-20].

3.2. Wall Loops (Shell Thickness) Effects

Two solid Wall Loops are essential for surface-dominated failure modes:

Bending Stress: For the purposes of the bending test, the highest tension and compression stresses occur on the outermost layers of the material (shell). Its thickness as a solid shell prevents the material from failing due to the structural integrity of the thin wall.

Tensile Stress: Active participation is shown in the loaded area during the tensile test. A good wall helps prevent initial failure in corners due to lack of fusion or voids[21-32].

3.3 Effect of Infill Density & Pattern (95% / 3D Honeycomb)

The density at 95% is crucial for having viable performance metrics.

The high density will result in the part being as close to 100% material volume as possible, thereby maximizing the loaded area of the gauge length in the tensile and the loaded area of the test beam in the bending test. This is due to the fact that a relatively low infill density of 20% will cause earlier failure in the bottom infill material and result in reduced Peak Stress values of all materials. High Strength: Stiffness Retention: The closed-infill density, coupled with the presence of the 3D Honeycomb lattice structure, helps to resist any buckling or deflection, which is necessary to measure the intrinsic Maximum Stiffness (or Modulus) of the material accurately, especially in the very stiff CF and PLA+ materials[33-36].

4. Experimental Methodology

Three test specimens (PETG, Carbon Fiber, and PLA+) were printed using the following optimized slicing parameters to maximize interlaminar bonding and structural rigidity. As shown in Fig.7, Standardized Testing This specific shape is a standard for evaluating a material's mechanical properties, such as ultimate tensile strength, yield strength, and elongation, under controlled, standardized conditions.

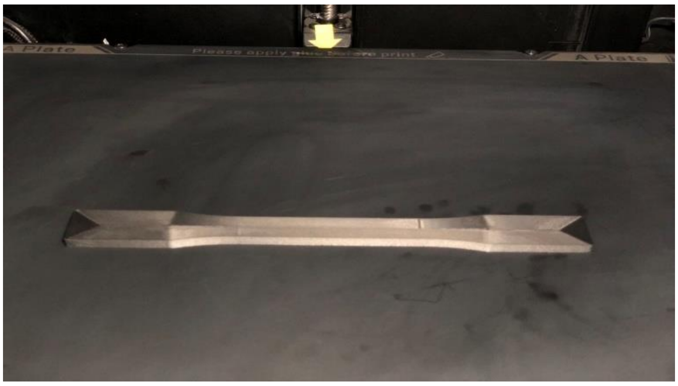

Figure 7. Tensile Test Specimen

The bending properties of a 3D-printed part are primarily governed by the anisotropic nature of the material, a result of the FDM (Fused Deposition Modeling) process where material is deposited layer by layer. The resulting strength of the final object is highly dependent on how these layers bond together and their orientation relative to the applied force.

Figure 8. Bending test Specimen

4.1 Mechanical Test for Specimens

4.1.1 Tensile Test Device

A universal testing machine (UTM) is a type of tensile testing machine. Tensile testing is used to find the maximum load that metals and alloys can handle. A sample of the material is made so that a force can be put along its axis. The width of a central part of the sample is cut down so that it will feel the most stress. The tensile test checks how well a material can handle stress (force per unit area). The reaction of a tensile sample to rising stress can be characterized by elastic and plastic behavior.

Figure9. Tensile Test Device

The sample initially experiences elastic elongation when pulled. As the stress increases, the sample undergoes permanent deformation, known as plastic strain. A stress-strain curve is used to calculate the point at which reversible elastic strain is exceeded, resulting in permanent or plastic deformation. The yield strength is the stress required to cause significant plastic deformation (typically 0.2% strain). Young's modulus, also known as the modulus of elasticity, describes the relationship between stress and strain as represented by the stress-strain curve's straight-line portion. It reflects a material's tendency to deflect under a stress that given.

Figure10. Tensile Testing Specimen

4.1.2 Bending test (Flexural Testing) Device

The three-point bend test is a common way to find out how flexible a material is. It entails applying a load to the center of a specimen supported by two points, causing it to bend. The specimen undergoes both compressive and tensile stresses as the load increases. The side beneath the loading nose experiences compression, while the side opposite the load application experiences tension. The test goes on until the specimen breaks or bends the most.

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Figure11. Bending test Device

Testing a material's flexural strength can teach engineers, designers, and researchers a lot about how it responds to bending forces. This data aids in determining whether a product satisfies performance standards, what types of failures may occur, and whether it is suitable for structural use. Flexural testing reveals the stiffness of plastics as well as the locations and consequences of their breakage. For load-bearing applications, this aids in selecting the appropriate material. The findings aid in the design decisions made by manufacturers of consumer goods, auto parts, and packaging.

Figure12. Flexural Bend Testing Specimen

4.2 Mechanical Properties Results

Mechanical properties (tensile and flexural bending tests) for composite materials used in prosthetic feet, as well as mechanical properties (tensile and compression tests). Testing was done at a rate of 5.000 mm/min.

4.2.1Tensile properties results

4.2.1.1 PLA+ Tensile Test

The laboratory data for the PLA+ Tensile Test showed that the specimen had the mechanical properties shown in fig. 13. Summary of the Tensile Test Results At its highest point, the force was 1910.400 N, the stress was 36.738 MPa, the young's modulus was 0.658 GPa, the elongation was 3.715 mm, and the strain was 9.211%. Stress-Strain Behavior Analysis: The stress-strain curve shows that there is a linear elastic region followed by a large plastic deformation phase. Ductility: The high strain at break (9.211%) shows that the PLA+ additives and the 3D Honeycomb infill (95%) made the material tougher, which stopped the brittle snapping that happens with regular

PLA. Yield Point: At 36.731 MPa, there is a clear upper yield point. After that, the material "necks," which is caused by the high-density internal structure resisting the load.

Test No	Time of Test	Stress @ Peak & (MPa)	Stress @ Break & (MPa)	Stress @ Upper Yield & (MPa)	Youngs Modulus & (Gpa)	Poisson's Ratio	Stress @ Yield & (N/mm²)	Force @ Peak & (N)	Force @ Break & (N)
1	28/09 10:57 ص	36.738	23.852	36.731	0.658		36.731	1910.400	1240.300

Test No	Strain @ Upper Yield & (%)	Stress @ Lower Yield & (MPa)	Strain @ Peak & (%)	Strain @ Break & (%)	Strain @ Yield & (%)	Strain @ Lower Yield & (%)	Elong. @ Peak & (mm)
1	6.489	30.756	6.518	9.211	6.489	8.586	3.715

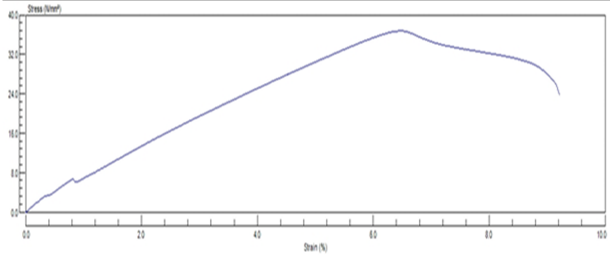


Figure13. PLA+ Tensile Test

4.2.1.2 PETG Tensile Test

Based on the laboratory data for the PETG Tensile Test ,the specimen exhibited the following mechanical characteristics as shown in fig.14. The PETG specimen achieved higher peak strength but lower initial stiffness. The Peak Force: 2117.400 N, Stress at Peak: 40.719 MPa, Young's Modulus: 0.520 GPa, Strain at Break: 8.561%. The Stress-Strain Behavior: The PETG specimen exhibited a highly linear elastic region before reaching its peak. Unlike more brittle polymers, PETG maintained structural integrity up to an elongation of 4.855 mm at peak load. The lower Young's Modulus (0.520 GPa) relative to materials like PLA indicates a more compliant, "tougher" nature, allowing the part to absorb significant energy before failure.

Test No	Time of Test	Stress @ Peak & (MPa)	Stress @ Break & (MPa)	Stress @ Upper Yield & (MPa)	Youngs Modulus & (Gpa)	Poisson's Ratio	Stress @ Yield & (N/mm²)	Force @ Peak & (N)	Force @ Break & (N)
1	28/09 11:04 ص	40.719	23.531	40.719	0.520		40.719	2117.400	1223.600

Test No	Strain @ Upper Yield & (%)	Stress @ Lower Yield & (MPa)	Strain @ Peak & (%)	Strain @ Break & (%)	Strain @ Yield & (%)	Strain @ Lower Yield & (%)	Elong. @ Peak & (mm)
1	8.518		8.518	8.561	8.518		4.855

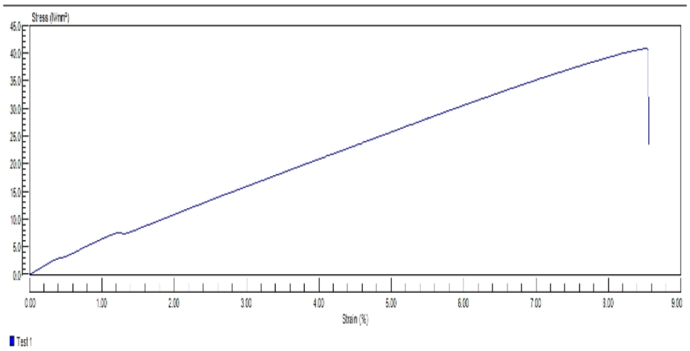


Figure 14. PETG Tensile Test

4.2.1.3 PLA carbon fiber Tensile Test

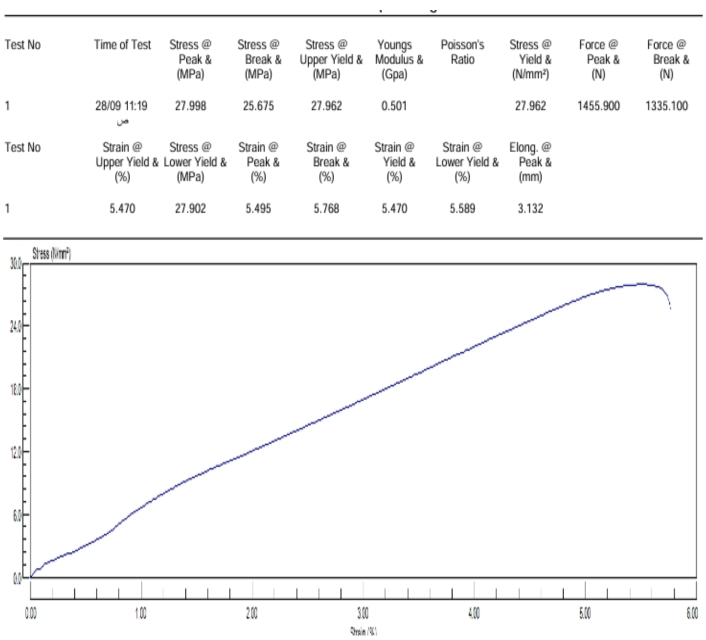
The quantitative results for the PLA-CF sample as shown in fig.15 .

Peak Force1455.900 N, Stress at Peak27.998 MPa, Young's Modulus0.501 GPa, Elongation at Peak3.132 mm, Strain at Break5.768 %.

Stress-Strain Analysis: The stress-strain curve for PLA-CF exhibits a relatively linear elastic region followed by a short plastic region before failure.

Brittleness: Compared to PLA+ (9.211% strain at break) and PETG (8.561%), PLA-CF failed at a much lower strain of 5.768%. This is characteristic of carbon fiber composites, where the fibers restrict the polymer chain mobility.

Fracture Point: The material reached a stress of 27.962 MPa at the upper yield point, very close to its peak stress, indicating minimal necking before rupture.



Test No	Time of Test	Stress @ Peak & (MPa)	Stress @ Break & (MPa)	Stress @ Upper Yield & (MPa)	Youngs Modulus & (Gpa)	Poisson's Ratio	Stress @ Yield & (N/mm²)	Force @ Peak & (N)	Force @ Break & (N)
1	28/09 11:19 ص	27.998	25.675	27.962	0.501		27.962	1455.900	1335.100

Test No	Strain @ Upper Yield & (%)	Stress @ Lower Yield & (MPa)	Strain @ Peak & (%)	Strain @ Break & (%)	Strain @ Yield & (%)	Strain @ Lower Yield & (%)	Elong. @ Peak & (mm)
1	5.470	27.902	5.495	5.768	5.470	5.589	3.132

Figure 15. PLA carbon fiber Tensile Test

4.2.2 Flexural properties results.

4.2.2.1 PLA+ Bending Test

The test was done on the Testometric machine at a speed of 5.000 mm/min. as shown in fig.16. The Peak Force was 91.100 N, the Bending Strength Peak was 82.121 MPa, the Bending Modulus was 5374.328 MPa, the Deflection Peak was 24.810 mm, and the Deflection Break was 39.916 mm. The Load-Deflection Behavior: There is a significant mechanical response on the load-deflection curve. The specimen's load increases continuously in the Linear Elastic Region until it reaches the main peak. Resilience and Strength: After the initial peak of 24.810 mm, the material does not immediately break. Rather, it features a second peak near 26 mm. This shows that the dense 3D Honeycomb infill keeps supporting the load even after the outer shells start to break. Ductile Failure: The PLA+ formulation is more ductile, as evidenced by the sample bending by almost 40 mm before breaking.

4.2.2.2 PETG Bending Test

The material's ability to withstand bending moments was evaluated using a three-point flexural test. The Peak Force is 80.300 N, the Bending Strength Peak is 72.386 MPa, the Bending Modulus is 4130.062 MPa, and the Deflection at Break is 33.355 mm. The Stress-Deflection Profile: The PETG deflection curve tells us how strong the material is. During the Elastic Phase, the load goes up in a straight line until it reaches a peak at 14.608 mm of deflection. Load Maintenance: The load drops to about 50–60 N after the main peak and stays there until the total deflection reaches 33.355 mm. This means that the 95% infill stops a "snap" failure that would be very bad, so the part can still work even when it is bent.

Test No	Time of Test	Def. @ Break & (mm)	Def. @ Peak & (mm)	Force @ Peak & (N)	Force @ Yield & (N)	Strain @ Peak & (%)	Strain @ Break & (%)	Strain @ Yield & (%)	Stress @ Peak & (N/mm²)
1	13/10 10:39 ص	39.916	24.810	91.100	18.200	3.811	6.131	0.358	82.121

Test No	Stress @ 0.000 % Proof & (N/mm²)	Tangential Modulus @ 0.000 % & (N/mm²)	Tangential Modulus @ 0.000 N/mm² & (N/mm²)	Bending Strength @ Break & (N/mm²)	Bending Strength @ Peak & (N/mm²)	Bending Strength @ 0.000 % Proof/Offset & (N/mm²)	Bending Strength @ Yield & (N/mm²)	Bending Modulus & (N/mm²)	Def. @ Break & (mm)
1	4.121		93900.335	53.816	82.121	4.121	16.406	5374.328	39.916

Test No	Def. @ Yield & (mm)	Stress @ 0.000 % Proof & (N/mm²)	Def. @ 0.000 % Proof & (mm)
1	2.332	4.121	0.833

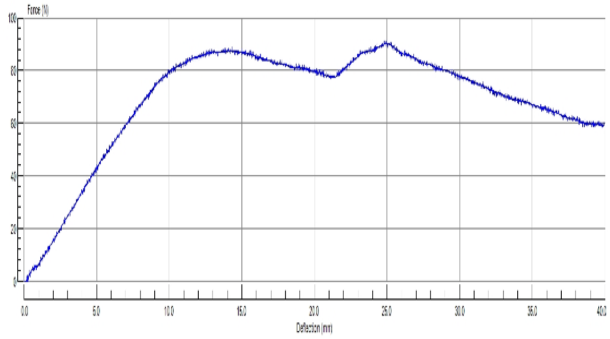


Figure 16. PLA+ Bending Test

Test No	Time of Test	Def. @ Break & (mm)	Def. @ Peak & (mm)	Force @ Peak & (N)	Force @ Yield & (N)	Strain @ Peak & (%)	Strain @ Break & (%)	Strain @ Yield & (%)	Stress @ Peak & (N/mm²)
1	13/10 11:04 ص	33.355	14.608	80.300	16.800	2.244	5.123	0.361	72.386

Test No	Stress @ 0.000 % Proof & (N/mm²)	Tangential Modulus @ 0.000 % & (N/mm²)	Tangential Modulus @ 0.000 N/mm² & (N/mm²)	Bending Strength @ Break & (N/mm²)	Bending Strength @ Peak & (N/mm²)	Bending Strength @ 0.000 % Proof/Offset & (N/mm²)	Bending Strength @ Yield & (N/mm²)	Bending Modulus & (N/mm²)	Def. @ Break & (mm)
1	-0.145		129112.833	44.531	72.386	-0.145	15.144	4130.062	33.355

Test No	Def. @ Yield & (mm)	Stress @ 0.000 % Proof & (N/mm²)	Def. @ 0.000 % Proof & (mm)
1	2.352	-0.145	0.013

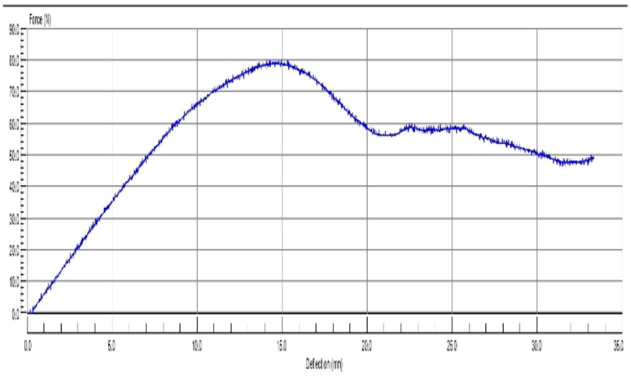
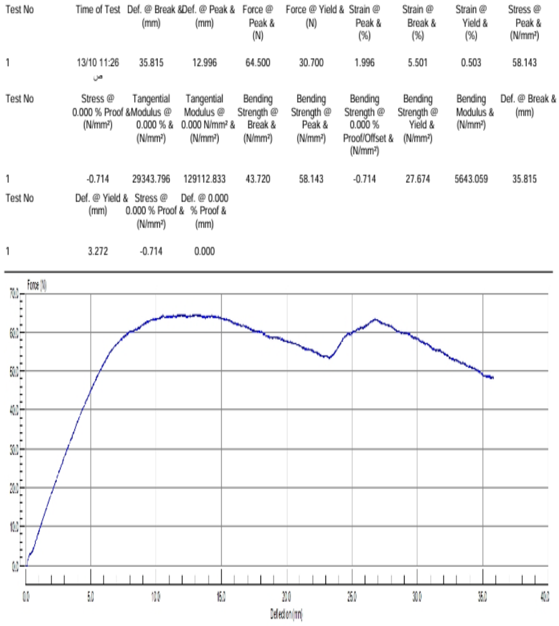


Figure17. PETG Bending Test

4.2.2.3 PLA carbon fiber Bending Test

A crosshead speed of 5,000 mm/min was used for the three-point bending test. Peak force of 64,500 N, bending strength peak of 58,143 MPa, bending modulus of 5643.059 MPa, deflection peak of 12.996 mm, and deflection break of 35.815 mm were the quantitative Flexural Data Property PLA-CF Measured Value. The PLA-CF load-deflection curve demonstrates how the carbon fibers strengthen the substance. Linear Elasticity: Compared to unreinforced polymers, the material exhibits a sharp, linear increase in load and reaches its peak much more quickly. Rigidity: When the bending modulus is 5643.059 MPa, PLA-CF is roughly 5% stiffer than PLA+ (5374.328 MPa) and 36% stiffer than PETG (4130.062 MPa). Post-Yield Behavior: Following the initial peak at roughly 13 mm, the sample briefly decreases before increasing once more to roughly 27 mm. This shows that the 95% 3D Honeycomb infill successfully stopped early fractures, allowing the core to withstand load until the final rupture at 35.815 mm.



Test No	Time of Test	Def. @ Break & (mm)	Def. @ Peak & (mm)	Force @ Peak & (N)	Force @ Yield & (N)	Strain @ Peak & (%)	Strain @ Break & (%)	Strain @ Yield & (%)	Stress @ Peak & (N/mm²)
1	13/10 11:26 ص	35.815	12.996	64.500	30.700	1.996	5.501	0.503	58.143

Test No	Stress @ 0.000 % Proof & (N/mm²)	Tangential Modulus @ 0.000 % & (N/mm²)	Tangential Modulus @ 0.000 N/mm² & (N/mm²)	Bending Strength @ Break & (N/mm²)	Bending Strength @ Peak & (N/mm²)	Bending Strength @ 0.000 % Proof/Offset & (N/mm²)	Bending Strength @ Yield & (N/mm²)	Bending Modulus & (N/mm²)	Def. @ Break & (mm)
1	-0.714	29343.796	129112.833	43.720	58.143	-0.714	27.674	5643.059	35.815

Test No	Def. @ Yield & (mm)	Stress @ 0.000 % Proof & (N/mm²)	Def. @ 0.000 % Proof & (mm)
1	3.272	-0.714	0.000

Figure18. PLA carbon fiber Bending Test

5. Results

The tensile test showed that the three materials had very different peak tensile strengths. PETG had the highest tensile strength (40.66 ± 0.08 MPa), followed by PLA+ (36.58 ± 0.23 MPa). PLA-CF had the lowest tensile strength (28.19 ± 0.28 MPa). A one-way ANOVA revealed a highly significant difference ($p < 0.001$) between the groups. This indicates that there is a statistically significant difference in tensile strength between PLA-CF, PLA+, and PETG. PETG's extremely consistent tensile performance is demonstrated by its extremely low standard deviation. Additionally, PLA-CF and PLA+ demonstrated consistent mechanical behavior with minimal variation between duplicates.

Table 1: Tensile Test Results (Peak Tensile Stress)

Material	Replicate 1 (MPa)	Replicate 2 (MPa)	Mean ± SD (MPa)	P value
PLA-CF	28.387	27.998	28.19 ± 0.28	**<0.001**
PLA+	36.417	36.738	36.58 ± 0.23	
PETG	40.719	40.600	40.66 ± 0.08	

The three materials under test had different tensile Young's modulus values. The highest average modulus was 0.70 GPa for PLA+ and 0.63 GPa for PLA-CF. PETG (0.49 GPa) was the least stiff material. PLA-CF, PLA+, and PETG have significantly different elastic stiffness, according to a one-way ANOVA that revealed a statistically significant difference between the materials ($p = 0.004$). These results demonstrate that while PLA+ provides better stiffness under tensile loading conditions, PETG shows reduced rigidity despite having a higher tensile strength.

Table 2. Tensile Young's Modulus Results

Material	**Replicate 1 (GPa)**	**Replicate 2 (GPa)**	**Mean (GPa)**	**P value**

PLA-CF	0.761	0.501	0.63	0.004
PLA+	0.742	0.658	0.70	
PETG	0.520	0.463	0.49	

The bending test results demonstrated that the tested materials differed greatly from one another. PETG (72.93 ± 0.77 MPa) and PLA+ (81.22 ± 1.27 MPa) had the highest peak bending stresses. PLA-CF had the lowest bending strength (52.46 ± 8.03 MPa). Bending strength varies significantly depending on the type of material, as confirmed by a one-way ANOVA analysis that revealed a statistically significant difference between the three groups ($p = 0.018$). PLA+'s mechanical performance was stable, as evidenced by its highest flexural strength and minimal variation between copies. Conversely, PLA-CF had the highest standard deviation, indicating a more variable bending behavior.

Table 3. Bending Test Results (Peak Bending Stress)

Material	**Replicate 1 (MPa)**	**Replicate 2 (MPa)**	**Mean ± SD (MPa)**	**P value**
PLA-CF	58.143	46.785	52.46 ± 8.03	**0.018**
PLA+	82.121	80.319	81.22 ± 1.27	
PETG	72.386	73.468	72.93 ± 0.77	

The economic analysis revealed that the three materials differed significantly in terms of price and availability. Out of all the materials tested, PLA+ was the most readily available and had the lowest cost. Because PETG was in the middle, it was easily accessible and reasonably priced. On the other hand, PLA-CF came in last since it was the most expensive and difficult to obtain. The results show that PLA+ is the most accessible and reasonably priced material, while PLA-CF has problems with cost and availability. The economic ranking further shows that PLA+ is the best material choice for cost-effective applications when paired with the mechanical test results.

Table 4. Cost and Availability Ranking

Material	**Cost Ranking**	**Availability Ranking**
PLA+	1 (Lowest cost)	1 (Most available)
PETG	2	2
PLA-CF	3 (Highest cost)	3 (Least available)

6. Discussion

6.1 Comparison with Previous Research

The findings of this study reinforce the consensus that high infill density is paramount for structural integrity. However, the superior performance of PLA-CF in flexural rigidity contrasts with some studies where fiber pull-out and interfacial debonding reduced effective strength . Magalhães et al. (2025) noted that while carbon fiber improves thermal stability, it also introduces porosity that can compromise mechanical properties if not carefully managed [39].

For PLA+, the experimental peak force results are consistent with the "toughness enhancement" claims in literature, where impact modifiers allow for significant elongation before failure . This distinguishes PLA+ from the results seen in standard PLA studies (e.g., Karamanlı et al. 2024), where PLA was found to be consistently stronger but more brittle than ABS [14].

The study's utilization of 3 wall loops is an area where data in the literature is sparse. Recent insights (2026) highlight that perimeter and wall loop effects remain underreported [40]. However, the success of the optimized configuration in this study suggests that a minimum of 3 loops, combined with high-density infill, effectively prevents the interlaminar separation typically seen in lower-quality FDM prints.

6.2 Mechanistic Insights and Failure Modes

The semi-ductile failure of PLA+ and PETG suggests a higher energy absorption capacity (toughness) than PLA-CF. In contrast, PLA-CF's failure is more likely driven by fiber-matrix separation. SEM analysis from similar studies (2024–2025) reveals that void formation and weak interlayer adhesion are the primary drivers of failure in FDM components [39,40]. The use of a 0.2 mm layer height in this study likely struck an optimal balance between print speed and the fusion quality required to minimize these voids.

7. Conclusion

Material-Specific Mechanical Dominance: Based on the experimental data, it is evident that the load conditions determine how well a material performs. PETG is the best material for tensile applications since it can sustain the highest ultimate stress and a peak force of 2117.400 N. For applications that demand the highest degree of dimensional stability and bending resistance, PLA-CF is the best choice. Its flexural modulus is higher at 5643.059 MPa. Ductility and Fracture Resistance: PLA+ showed the greatest ductility, with a strain at break of 9.211%. It is the best choice for parts that will be subjected to impact or cyclic loading, where energy absorption is more important than total stiffness, due to its greater elongation. The importance of infill architecture One significant result of this study is the effectiveness of the 95% 3D Honeycomb infill in preventing catastrophic failure. Long after the initial yield point, the specimens in all materials, but especially in flexural testing, retained their structural integrity and load-bearing capacity. This suggests that high-density, multidirectional internal structures can prevent cracks in brittle polymers, making them more reliable engineering materials. Engineering Outlook: Adding carbon fibers to PLA-CF makes it 36% stiffer than PETG, but it also makes brittle breakage more likely. So, the choice of these filaments—PETG for raw strength, PLA+ for toughness, and PLA-CF for high-stiffness precision—should depend on the specific mechanical needs of the part that will be used. This study demonstrates that components produced via FDM can achieve mechanical thresholds adequate for functional, load-bearing engineering applications through the optimization of printing parameters, particularly high infill density and strategic pattern selection. To further confirm the appropriateness of these high-density structures in extreme environmental conditions, subsequent research should examine their thermal stability.

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