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Article

The Effect of Infill Variation on the Tensile, Bending, Impact, Hardness, and Density Properties of PLA and ABS Materials Produced by FDM

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Abstract

Additive Manufacturing (AM) or 3D printing using the Fused Deposition Modelling (FDM) method offers high flexibility in producing polymer components through process parameter settings, one of which is the infill percentage that affects mechanical performance. This study analyzes the effect of infill variations (25%, 50%, 75%, 100%) on the mechanical properties of two popular thermoplastic materials, Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). Testing was conducted according to ASTM standards, including tensile strength, bending strength, impact strength, hardness, and density. The results show that PLA has higher tensile strength (47–53 MPa), bending strength, and hardness than ABS (33–38 MPa). Conversely, ABS demonstrates better toughness through higher impact values, while the difference in density is relatively small and insignificant. Increasing the infill percentage is proven to enhance strength and hardness in both materials, but an increase in material consumption accompanies this. These findings indicate a trade-off between stiffness and toughness, so material selection must be tailored to application requirements. PLA is more suitable for precision components requiring dimensional stability, while ABS is recommended for applications with dynamic loads and impact risks. This study provides a practical foundation for optimizing FDM parameters in engineering, medical, and consumer product applications, particularly material and infill.

Keywords: Additive manufacturing; FDM; Infill density; PLA; ABS

INTRODUCTION

Additive Manufacturing (AM) or 3D Printing is a modern manufacturing technology that enables the creation of three-dimensional objects based on digital models. This technology can produce complex designs that are difficult to achieve using conventional methods [1]. One of the advantages of 3D printing is its ability to accelerate prototype development while optimizing material and energy usage, thereby enhancing manufacturing efficiency [2][3]. Additive manufacturing has been widely applied across various sectors, including

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aerospace, energy, automotive, healthcare, and consumer products [4]. The most commonly used method is Fused Deposition Modeling (FDM), where thermoplastic filament is heated until it melts, then extruded through a nozzle and layered according to the CAD model [5][6]. Layer thickness typically ranges from 0.1–0.3 mm, controlled by the distance between the nozzle and the bed and the ratio of filament flow rate to print speed [7]. The two most commonly used thermoplastic materials are PLA and ABS, with PLA being more widely chosen due to its biocompatibility and environmental friendliness [8].

One of the crucial parameters in FDM is infill, as it determines the density of the internal structure, which affects mechanical properties, specimen mass, and the amount of material used. Several studies have reported that variations in infill and print patterns significantly affect mechanical performance, particularly tensile strength, and elastic modulus [9][10][11][12][13][14]. However, the main challenge is determining the optimal infill configuration to balance mechanical performance and material efficiency.

Previous studies have reported mixed trends. Syrlybayev et al. (2021) [15] reported that an increase in infill is directly proportional to an increase in tensile strength, although an increase in mass accompanies it. Cahyati and Putra (2023) [16] confirmed that higher infill increases printing time and material consumption. Gunasekaran et al. (2021) [17] found that variations in infill density affect hardness, tensile strength, impact strength, and flexural strength in PLA, while Syaefudin et al. (2023) [18] demonstrated that printing orientation significantly affects tensile strength, yield strength, and elastic modulus in PLA and ABS. Collectively, these studies highlight a knowledge gap: a comprehensive cross-material comparison of thermoplastic materials under varied infill conditions across multiple mechanical properties remains limited.

Based on this review, most studies have focused on only one type of material (PLA or ABS) or other parameters such as layer thickness and print orientation. To address this gap, the present study aims to experimentally analyze the effect of infill variation on the mechanical properties of both PLA and ABS simultaneously, including tensile strength, bending strength, impact toughness, surface hardness, and relative density. By conducting a side-by-side comparison, this work highlights the trade-offs between stiffness and toughness in these widely used polymers, providing a clearer basis for selecting material–infill combinations in practical applications. The findings are expected to contribute novelty by offering a more integrated understanding of how infill density influences two structurally different materials, PLA with its semi-crystalline domains and ABS with its amorphous structure, thereby providing a scientific foundation for optimizing FDM parameters in engineering, biomedical, and consumer product contexts.

METHODS

Materials and Specimens

The materials used in this study were Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) filaments with a diameter of 1.75 mm, which were chosen because they are the most commonly used thermoplastic materials in Fused Deposition Modeling (FDM) technology due to their wide availability and representative mechanical properties. The specimen design was created using SolidWorks software in accordance with relevant ASTM standards to ensure dimensional accuracy and the validity of mechanical test results. The digital model was then exported in STL format for processing using FlashPrint software, where print parameters were set and the model was sliced into thin layers ready for production. The printing process was carried out using a Flashforge Dreamer 3D printer, which operates on the FDM principle through melting thermoplastic filaments and layered deposition. The machine's technical specifications are shown in Table 1, which includes key parameters such as print resolution, extruder temperature, build plate temperature, and print speed. The technical specifications summarized in Table 1 serve as a reference for experimental replication and cross-study comparisons.

Table 1. Flashforge Dreamer printer specifications

Flashforge Dreamer	Specification
Printing Technology	FFF (Fused Filament Fabrication)
Printer Dimensions	480 x 335 x 410 mm
Print Dimensions	230 L x 150 W x 140 H
Layer Resolution	100 - 500 microns
Position Precision	XY: 11 microns, Z: 2,5 microns
Software and Firmware	FlashPrint
Number of Extruders	2
Connectivity	Wi-Fi, USB Cable, SD Card
Heated Bed	*Yes*
AC input	100-240 V, ~2amps. 50-60Hz, 350W

The printing process was carried out with constant parameters to ensure consistency of results and validity of comparisons. The nozzle diameter was set at 0.4 mm, with a layer height of 0.18 mm and a printing speed of 60 mm/s. The extrusion temperature is set differently for each material, namely 210 °C for PLA and 240 °C for ABS. In comparison, the heated bed temperature is set at 60 °C for PLA and 110 °C for ABS to minimize warping and ensure optimal adhesion of the initial layer. The main variation applied was the infill percentage of 25%, 50%, 75%, and 100% with a hexagonal pattern, chosen because it produces a more even stress distribution than other infill patterns. Meanwhile, other parameters such as wall thickness, print orientation, and print speed were kept constant, so that the research variables were focused solely on material type

(PLA and ABS) and infill variations. The detailed printing parameter configurations for each material are shown in Table 2, which can serve as a reference for replicating the experiment or comparing it with previous studies.

Table 2. Printing parameter configuration

Settings	Material	
	PLA	**ABS**
Nozzle Temperature (°C)	210	240
Bed Temperature (°C)	60	110
Layer Height (mm)	0,18	0,18
First Layer Height (mm)	0,27	0,27
Infill Shape	Hexagon	Hexagon
Infill Percentage (%)	25, 50, 75, 100	25, 50, 75, 100
Print Speed (mm/s)	60	60
Travel Speed (mm/s)	80	80
Enclosure	no	yes
Fan	All On	Nozzle Only

The test specimens in this study were produced based on ASTM standards to ensure compliance with internationally applicable mechanical testing procedures. Tensile strength testing was performed using ASTM D638 Type I, which is widely used in evaluating the tensile properties of polymer materials because it provides accurate data on elastic modulus, maximum tensile strength, and elongation at break. Bending testing refers to ASTM D790, which is designed to determine the flexural properties of thermoplastic materials through the three-point bending method. To assess resistance to impact loads, impact testing was conducted in accordance with ASTM D256. Additionally, surface hardness was characterized based on ASTM D2240 Shore D, suitable for medium to high hardness polymer materials. Meanwhile, density testing refers to ASTM D792, which is based on the principle of mass comparison in air and water. The dimensions of the test specimens used for each test are shown in detail in Figures 1–5, with units in millimeters.

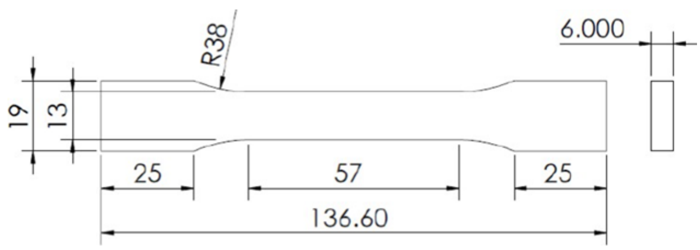

Figure 1. Dimensions of bending test specimens

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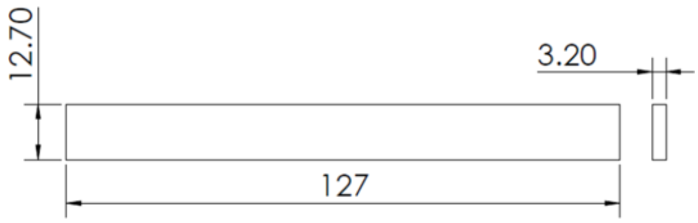

Figure 2. Dimensions of bending test specimens

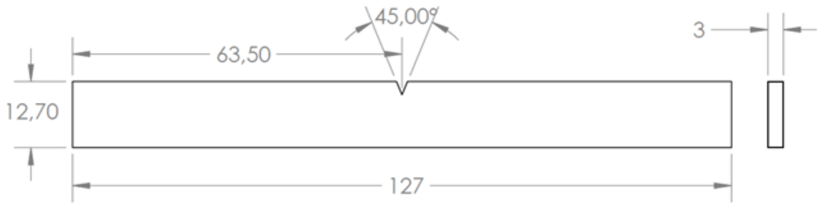

Figure 3. Dimensions of impact test specimens

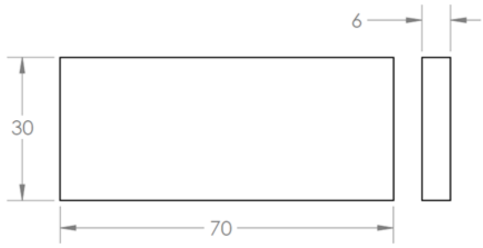

Figure 4. Dimensions of hardness test specimens

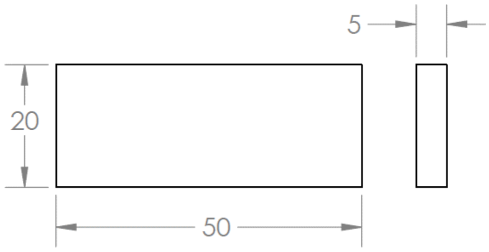

Figure 5. Dimensions of density test specimens

Each test condition, which combines material type and infill percentage, was printed five times to ensure data reliability and reduce the influence of printing process variability. Thus, 40 specimens were obtained for each type of mechanical test (2 materials × 4 infill variations × 5 replications). This approach aligns with experimental statistical practices that emphasize the importance of sufficient replication to reduce random errors and enhance the validity of analysis results. A visual representation of the printed test specimens is shown in Figure 6, illustrating the physical form and dimensional consistency of the specimens used in this study.

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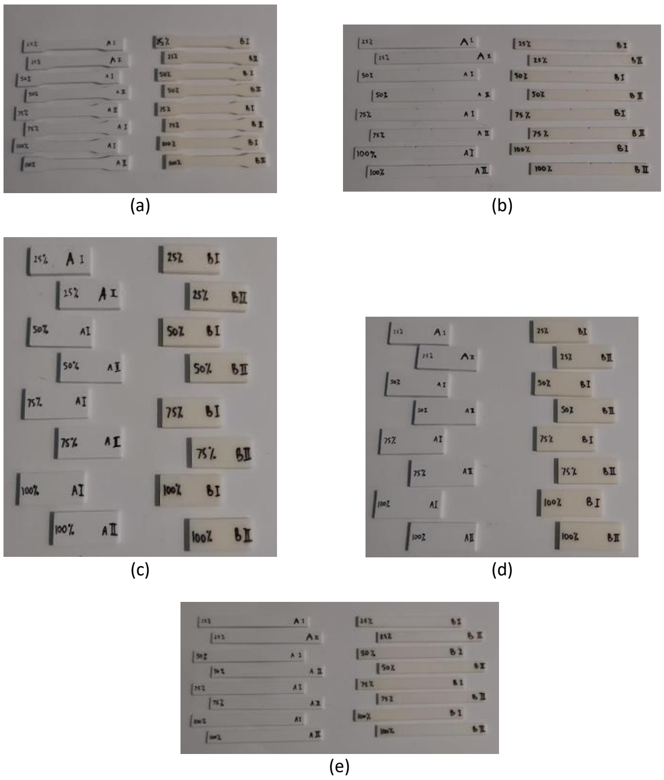

Figure 6. Material test specimens (a) tensile test specimen, (b) impact test specimen, (c) density test specimen, (d) hardness test specimen, and (e) bending test specimen

Mechanical Testing Procedures

Mechanical testing was performed using several standard methods to characterise the material comprehensively. Tensile testing was performed using a Universal Testing Machine (UTM) with a capacity of 50 kN at a crosshead speed of 5 mm/minute in accordance with ASTM D638, with parameters analyzed including maximum tensile stress (UTS), elongation at break, and elastic modulus. Bending tests were performed using the three-point bending method in accordance with ASTM D790, with the span distance set at 16 times the specimen thickness, thereby yielding data on flexural strength and flexural modulus. Meanwhile, material toughness was tested using a pendulum impact tester with a capacity of 2 J in accordance with ASTM D256, where the absorbed energy per cross-sectional area of the fracture was calculated as an indicator of toughness. To measure surface properties, hardness testing was performed using a Shore D durometer based on ASTM D2240, with three test points on each specimen, and the average value was used as the final result. Additionally, the material density was analyzed according to ASTM D792 using Archimedes' principle, which involves comparing the mass of the specimen in air and when submerged in water. Prior to all testing, calibration of measuring instruments and testing machines was performed to ensure the accuracy and consistency of the results.

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Data Analysis

The test results for each experimental condition are presented as average values from five replications to obtain representative data and minimize the influence of individual specimen variations. These mean values, consistent across replications, are the basis for comparing material performance across different infill variations. The analysis was conducted descriptively by observing trends in tensile strength, elastic modulus, impact toughness, surface hardness, and material density. This approach enables a quantitative explanation of the performance differences between PLA and ABS. Although the study is limited to descriptive statistics, the use of replication enhances the reliability of the observed trends. The absence of inferential statistical tests (e.g., ANOVA or t-tests) is acknowledged as a limitation, and future research should incorporate such analyses to validate the statistical significance of the observed differences. Nevertheless, the descriptive trends presented in this work provide a clear picture of the influence of infill variation on the mechanical characteristics of both materials, without requiring additional error bar representation.

RESULT AND DISCUSSION

Tensile Test

The tensile test results (Table 3) show that PLA exhibits higher tensile strength than ABS—47–53 MPa for PLA versus 33–38 MPa for ABS—indicating that PLA can withstand tensile loads approximately 30–40% greater. This difference is attributable to PLA's semi-crystalline morphology, which confers stronger intermolecular interactions and a stiffer structure, whereas amorphous ABS tends to exhibit lower tensile strength. The trend in Figure 7 shows that an increase in infill is directly proportional to an increase in tensile strength for both materials, with PLA consistently outperforming ABS. On the deformation side, Figure 8 shows that the average strain of PLA ranges from 10.20–14.81%, while ABS remains relatively stable at 10.19–11.74%. Interestingly, PLA, which is known for its stiffness, still shows an increase in strain at 100% infill, while ABS exhibits constant plasticity despite its lower strength. Therefore, it can be concluded that PLA is more suitable for applications requiring structural strength and dimensional stability. At the same time, ABS is more appropriate for applications demanding moderate flexibility and consistent deformation.

Table 3. Average results of tensile testing

Specimen	Width (mm)	Thickness (mm)	Δl (mm)	Pmax (KN)	Stress (MPa)	Strain (%)
A - 25%	13.28	6.03	6.91	1.4	17.61	12.12
A - 50%	13.24	5.97	7.51	2.1	26.02	13.18
A - 75%	13.26	6.05	5.82	2.4	29.73	10.20
A - 100%	13.38	6.39	8.44	5.1	59.49	14.81

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Specimen	Width (mm)	Thickness (mm)	Δl (mm)	Pmax (KN)	Stress (MPa)	Strain (%)
B - 25%	13.13	6.18	6.15	1.0	12.90	10.79
B - 50%	13.11	6.08	6.12	1.3	16.06	10.73
B - 75%	13.17	6.08	5.81	1.6	19.51	10.19
B - 100%	13.29	6.34	6.69	3.3	38.72	11.74

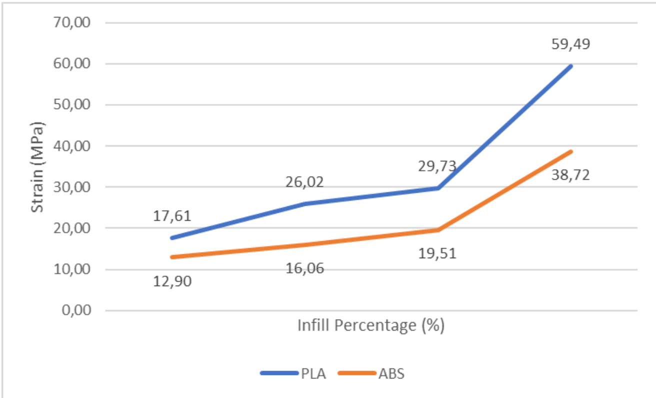

Figure 7. Average stress graphs

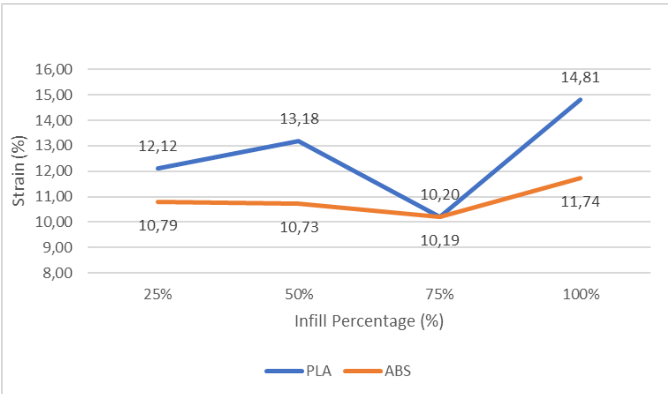

Figure 8. Average strain graphs

Bending Test

The bending test results (Table 4) show that the bending stress of PLA is higher than that of ABS, indicating that PLA has stiffer properties and better resistance to elastic deformation. The trend in Figure 9 shows an increase in bending stress as the infill percentage increases, with PLA consistently showing higher values than ABS. These findings confirm the potential of PLA for use in applications requiring stiffness and dimensional stability, such as precision prototypes or medical components. Conversely, the lower flexural modulus of ABS makes it more flexible, making it more suitable for applications requiring flexibility and tolerance to deformation.

Table 4. Average results of bending tests

Specimen	Width	Thickness	ΔL Broken	Pmax	Bending Stress
	(mm)	(mm)	(mm)	(KN)	(Mpa)
A - 25%	12.71	3.25	9.43	0.105	58.82
A - 50%	12.73	3.16	8.69	0.110	64.92
A - 75%	12.68	3.25	10.68	0.135	75.86
A - 100%	12.76	3.37	11.71	0.165	85.64
B - 25%	12.48	3.36	10.36	0.065	34.87
B - 50%	12.58	3.27	9.57	0.075	41.93
B - 75%	12.49	3.24	8.91	0.090	51.68
B - 100%	12.59	3.44	12.77	0.115	58.06

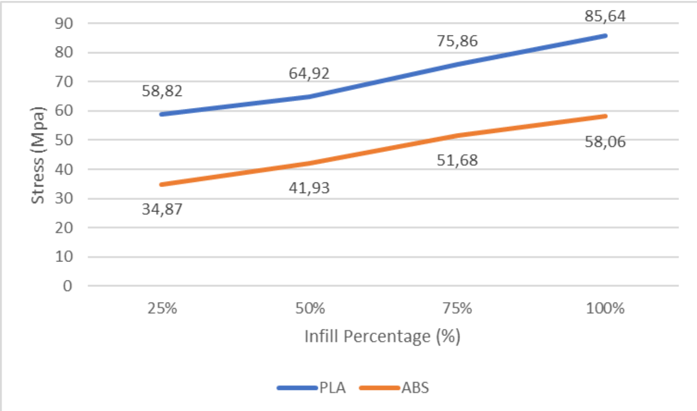

Figure 9. Average bending stress graphs

Impact Test

The impact test results show a tendency opposite to the tensile and bending tests. ABS has higher energy absorption than PLA, as shown in Table 5 and Figure 10, indicating that ABS has better toughness, while PLA tends to be more brittle. This mechanism is related to the amorphous nature of ABS, which allows for greater plastic deformation before fracture, enabling more effective absorption of impact energy. Conversely, the semi-crystalline structure of PLA makes the material stiffer but less capable of distributing shock energy. These findings highlight the potential of ABS for application in products susceptible to impact, such as automotive components and everyday consumer products.

Table 5. Average results of impact testing

Specimen	Angle α (°)	Energy (J)	Angle β (°)	Absorbed Energy (J)	Area (mm^2)	Impact strength (J/mm^2)
A - 25%	30	21	29.5	0.7	36.09	0.019

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Specimen	Angle α (°)	Energy (J)	Angle β (°)	Absorbed Energy (J)	Area (mm^2)	Impact strength (J/mm^2)
A - 50%	31	21	29	1.4	35.21	0.039
A - 75%	32	21	29	1.4	36.10	0.038
A - 100%	33	21	29	1.4	38.04	0.036
B - 25%	34	21	29.5	0.7	37.0	0.019
B - 50%	35	21	29.0	1.4	36.3	0.038
B - 75%	36	21	29.0	1.4	36.6	0.038
B - 100%	37	21	28.5	2.0	39.2	0.052

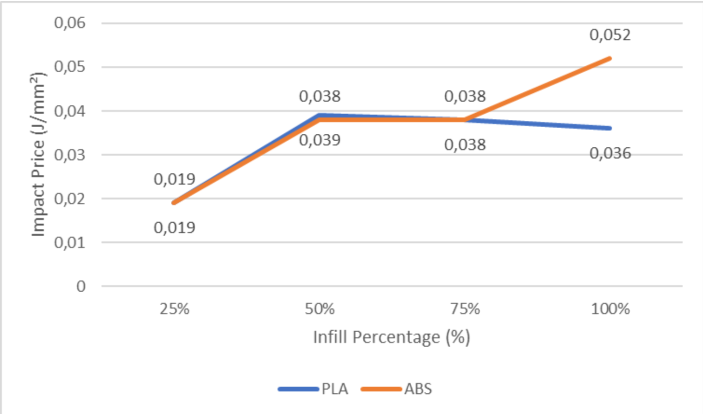

Figure 10. Average impact strenght graphs

Hardness Test

The hardness test results (Table 6) show that PLA has a higher value than ABS, indicating that PLA is more resistant to scratches and penetration. Figure 11 shows that an increase in infill percentage directly contributes to an increase in hardness for both materials, with PLA consistently outperforming ABS. The higher hardness of PLA aligns with its rigid and semi-crystalline nature, but also makes the material more prone to brittle failure when subjected to impact energy. Conversely, the softer ABS demonstrates better ability to absorb impact energy, making it more resistant to damage from dynamic loads. These findings highlight the trade-off between stiffness and toughness that must be carefully considered when selecting materials for specific applications.

Table 6. Average results of hardness testing

Specimen	Average Hardness (HD)
A - 25%	80.75
A - 50%	82.83
A - 75%	86.33
A - 100%	87.50
B - 25%	60.67
B - 50%	77.83

Specimen	Average Hardness (HD)
B - 75%	82.92
B - 100%	84.17

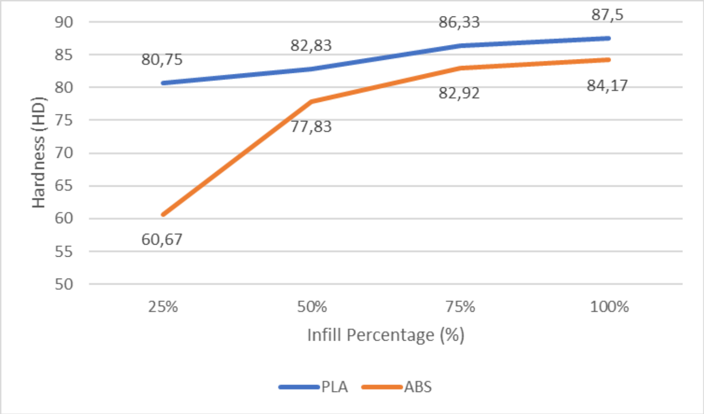

Figure 11. Graph of average hardness

Density test

The density measurement results (Table 7) show that PLA has a slightly higher value than ABS, but the difference is relatively small. It does not significantly affect mechanical performance, as shown in Figure 12. This finding indicates that variations in mechanical properties between the two materials are more predominantly influenced by microstructure and intrinsic polymer properties, such as the crystallinity level in PLA and the amorphous nature of ABS, rather than solely by density differences. Thus, density is not the primary determining factor in distinguishing the mechanical performance of PLA and ABS, but rather serves as a supporting parameter in material characterization.

Table 7. Average results of density testing

Specimen	Average Density (g/cm³)
A - 25%	0.67
A - 50%	0.88
A - 75%	1.03
A - 100%	1.15
B - 25%	0.54
B - 50%	0.72
B - 75%	0.83
B - 100%	1.00

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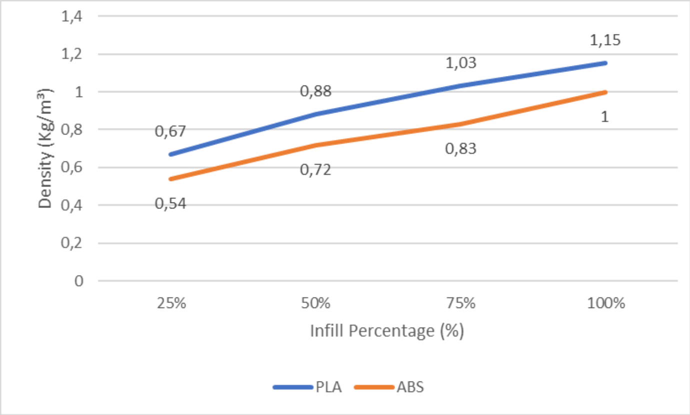

Figure 12. Average density graphs

Discussion (Implications)

The experimental findings consistently demonstrate clear differences between PLA and ABS across various mechanical aspects. PLA, with its semi-crystalline structure, shows superior tensile strength, bending strength, and hardness. The ordered crystalline regions in PLA contribute to stronger intermolecular bonding, which enhances stiffness and dimensional stability. However, this rigidity makes PLA more susceptible to brittle failure under impact loading. In contrast, ABS, which is predominantly amorphous, exhibits lower stiffness but greater plastic deformability, enabling higher impact resistance and improved toughness. At lower infill percentages, both materials are more prone to void formation, which acts as a stress concentrator and accelerates crack initiation. As infill density increases, voids are reduced and crack propagation is better restrained, improving strength and hardness.

From a practical perspective, these characteristics suggest different application domains for each material. With its stiffness and dimensional accuracy, PLA is more suitable for biomedical prototypes, surgical guides, and precision consumer products. On the other hand, ABS, with its superior impact resistance and tolerance to deformation, is better suited for automotive interior components, protective casings for electronic devices, and consumer goods subjected to repeated dynamic loads. The efficiency aspect is also noteworthy: while higher infill percentages enhance mechanical performance, they require longer printing times and greater material consumption. Therefore, the optimal configuration should be selected based on the intended application's specific functional requirements and economic considerations.

This study highlights the importance of infill configuration in optimizing mechanical performance, but it also opens avenues for further research. Future studies should consider the combined influence of infill with other process parameters, such as printing orientation, raster angle, and layer height, to develop a more comprehensive optimization framework. Such approaches could further improve the balance between mechanical performance, material efficiency, and manufacturing cost in additive manufacturing.

CONCLUSION

This study shows that infill variation significantly affects the mechanical properties of PLA and ABS printed using the FDM method. PLA consistently has higher tensile and bending strengths (47–53 MPa compared to 33–38 MPa for ABS) and greater surface hardness, making it superior in stiffness and dimensional stability. Conversely, ABS exhibits higher impact absorption energy, reflecting better toughness for dynamic or impact-prone applications. The difference in density between the materials is relatively small and does not significantly affect overall mechanical performance. Increasing the infill percentage improves the mechanical properties of both materials, but impacts print time and material consumption. PLA is recommended for applications requiring stiffness and wear resistance, while ABS is more suitable for conditions involving shock loads or repeated impacts. These findings provide a scientific basis for selecting the optimal material–infill combination in the FDM process and support its application in engineering, medical, and consumer products. A limitation of this study is that the analysis relied on descriptive statistics without applying inferential tests. Future investigations are recommended to include statistical analyses to validate the significance of differences between materials and infill variations, thereby strengthening the generalizability of the findings.

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