

Experimental Characterization of the Mechanical Properties of 3D Printed Structures with Polylactic Acid

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ABSTRACT

Additive manufacturing, also known as 3D printing, has significantly transformed the manufacturing industry by offering cost-effective, rapid, and versatile production methods. Fused Deposition Modeling (FDM), also referred to as Fused Filament Fabrication (FFF), is among the most widely used additive manufacturing techniques, particularly for processing a broad range of thermoplastics. Key printing parameters in FDM such as infill density, print orientation, and layer thickness play a critical role in determining the mechanical properties of printed structure. Polylactic acid (PLA) is one of the most extensively used biodegradable thermoplastics for FDM printing due to its ease of processing and environmental benefits. While pure PLA is dielectric, the incorporation of conductive nanomaterials such as carbon black, significantly enhances its electrical conductivity. This study investigates the influence of 3D printing parameters on the mechanical properties of structures printed with both pure PLA and conductive PLA composite containing carbon black. 3D printed samples with varying solid infill ratios of 15%, 45%, 75%, and 100% were tested under tensile loadings with two different strain rates. Results showed that increasing solid infill density from 15% to 100% led to notable improvement in ultimate tensile strength, rising from 36.9 ± 0.35 MPa to 55.7 ± 0.12 MPa. In addition, infill orientation was also found to have a significant impact on mechanical performance. In addition, while had a significant impact on mechanical properties. Furthermore, while the incorporation of carbon black improved the electrical properties, we found that it results in a reduction in mechanical properties compared to pure PLA. This study highlights the importance of optimized printing parameters and material composition on the mechanical properties of FDM printed structures.

Keywords: 3D printing; fused deposition modeling; polylactic acid (PLA); mechanical properties; anisotropy

INTRODUCTION

Additive manufacturing (i.e., 3D printing) has been rapidly changing the manufacturing industry over the past few decades. 3D Printing has reshaped the manufacturing process as a sustainable process due to numerous advantages such as less material waste, ease of manufacturing complex structures, less

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human involvement, less post-processing, and energy efficiency (1-5). Unlike the traditional subtractive manufacturing, which is the method where layers of materials are removed to produce the desired product, in Additive Manufacturing (AM), desired parts are developed additively layer by layer. The continuous and increasing growth experienced since the early days and the successful results up to the present time allow for optimism that additive manufacturing has a significant place in the future of manufacturing (6). AM covers a wide range of processes for creating 3D prototypes and structures from digital files. According to the American Society for Testing and Materials (ASTM), AM has been divided into seven processes, which include VAT Photopolymerization, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, and Direct Energy Deposition (7, 8).

Fused Deposition Modeling (FDM) is a widely used additive manufacturing technology for the fabrication of complex geometric parts using thermoplastic polymers such as Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Polylactic Acid (PLA), and Thermoplastic Polyurethane (TPU) (3, 5, 9). The FDM method works by a heated nozzle laying down molten material in layers to produce a desired part (10). The material is a filament, generally a thermoplastic with a low melting point, pulled by a drive wheel, and then put into a temperature-controlled nozzle head and heated to a semiliquid phase. The filament is the primary material used in the FDM process (11-14).

The advantages of FDM are mainly the ability to optimize both the external and the internal geometry of the components, allowing for a more efficient material distribution. Thus, complex parts can be produced with high precision and at a relatively low cost compared to traditional manufacturing processes. However, the downside of FDM includes the limitation of the print size and material choice since this 3D printing method mainly uses thermoplastics that are dielectric (15).

PLA is one of the most widely used thermoplastics in FDM printing with various applications. PLA is biodegradable and can be produced from non-toxic, renewable feedstock, and it is a naturally occurring organic acid (16). The synthesis of recyclable and degradable polymers having a highly cross-linked three-dimensional network structure, such as PLA, is imperative for polymer science and green technology (17). PLA has higher mechanical properties (particularly Young's modulus, ultimate tensile strength, and flexural strength) compared to other polymers, such

as polypropylene, polystyrene, and polyethylene (18). However, PLA suffers from some shortcomings, such as low ductility and toughness, high sensitivity to moisture, and fast degradation by hydrolysis (19).

Additive Manufacturing offers flexibility in customizing, designing, reducing waste, faster prototyping, and manufacturing complex objects. The printing parameters play a significant role in the mechanical properties of the 3D printed product. Numerous researchers have investigated the mechanical properties of 3D printed polymers. Their findings indicated that the orientation of the raster (30°, 45°, and 60°) and the thickness of each layer have a notable impact on the mechanical characteristics (20). Layer thickness refers to the slice height of the STL model for building the part, which can affect the surface quality and accuracy. Infill ratio determines how much the inside of a part will be filled. It can make a part either fully or partially solid, impacting the mechanical properties of the 3D printed part. The infill pattern controls the motion of the nozzle or platform in filling the area of the layer. Both infill ratio and infill pattern (i.e., shape) affect the build time, amount of utilized material, and strength of the FDM parts (21).

Among the different parameters affecting the mechanical properties of fabricated parts, the build orientation is often one of the most influential and one of the few factors prevalent in almost all 3D printing processes. Build orientation refers to which orientation a printed part is placed on the print platform. The build orientation impacts the accuracy, build time, cost, surface finish, and mechanical properties. Therefore, it is essential to analyze the effect of orientation on the mechanical properties of 3D printed structures (22, 23).

In this work, we studied the impact of solid infill ratio, print orientation, pull rate, and addition of conductive nanoparticles on the mechanical properties of 3D printed structures using PLA. The results show that increasing the aligned rectilinear solid infill density from 15% to 100% leads to approximately 51% enhancement in the ultimate tensile strength (UTS) of PLA samples printed according to ASTM-D638 type I. In addition, 3D printed samples with 90 degrees (i.e., patterns perpendicular to the stretching direction) lead to ~30% decrease in UTS compared to 0 degrees (patterns aligned with the stretching direction). Furthermore, PLA-based conductive filament with carbon black shows higher elasticity despite a 55% lower UTS. This work paves the way for a better understanding of the process-microstructure-properties relationship in FDM printed structures using thermoplastics for broad applications.

MATERIALS AND METHODS

The polylactic acid (PLA) filament used for printing the samples in this study was acquired from Prusa directly with a diameter of 1.75 mm and a recommended nozzle temperature of 190-220 °C. The samples were printed by a Prusa Mk4 3D printer, with a 400 μm diameter nozzle, and print bed temperature of 65 °C as shown in Figure 1(a). The tensile samples were designed in SolidWorks following the ASTM-D638 standard type I samples, with a thickness of 3.2 ± 0.4 mm. The dimensions of the samples are shown in Figure 1(b). The print speed was 20 mm/s, and printed type I samples with two different infill densities are shown in Figure 1(c).

In 3D printing using the FDM method, solid infill refers to the filled content inside the printed object with various patterns, such as gyroid, cubic, rectilinear, aligned rectilinear, etc. Each pattern and the ratio directly impact the printing process as well as the mechanical properties. In this work, we adopted aligned rectilinear patterns to investigate the impact of solid infill density on mechanical properties, as shown in Figure 2(a). We used Prusa slicer for generating the G-codes. Figure 2(a) illustrates the type I samples with 15%, 45%, 75%, and 100%, respectively. As shown, the 100% sample means the inside of the printed object is filled with materials, whereas in 15%, it is partially filled. Figure 2(b) shows half-way printed samples with corresponding infill densities. In addition, to investigate the impact of nanoparticles on the mechanical properties of PLA-based nanocomposites, we tested

mechanical properties of electrically conductive PLA. The conductive PLA was purchased from Protopasta (SKUCDP1170). This filament has an electrical resistance of 2-3.5 kΩ for 10 cm length and 1.75 mm diameter. The PLA based nanocomposites contain around 20 wt% CB nanoparticles as the conductive element with a density of approximately 1.24 g/cc. The recommended nozzle temperature is 210-230 °C which is implemented on the same printer (Prusa MK4).

A Shimadzu AGS-X tensile machine with a 10 kN load cell was used for tensile testing of 3D printed standard samples (ASTM D638, type I) as shown in Figure 3(a).

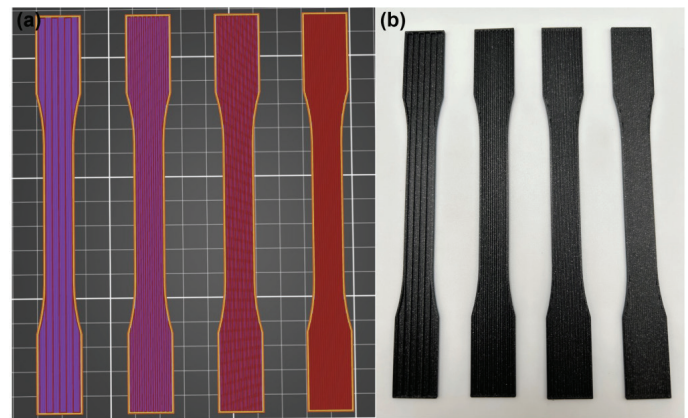


Figure 2. 3D printed samples with solid infill ratios of 15%, 45%, 75%, and 100% (left to right). (a) schematic of slicing, (b) printed samples showing various infill densities.

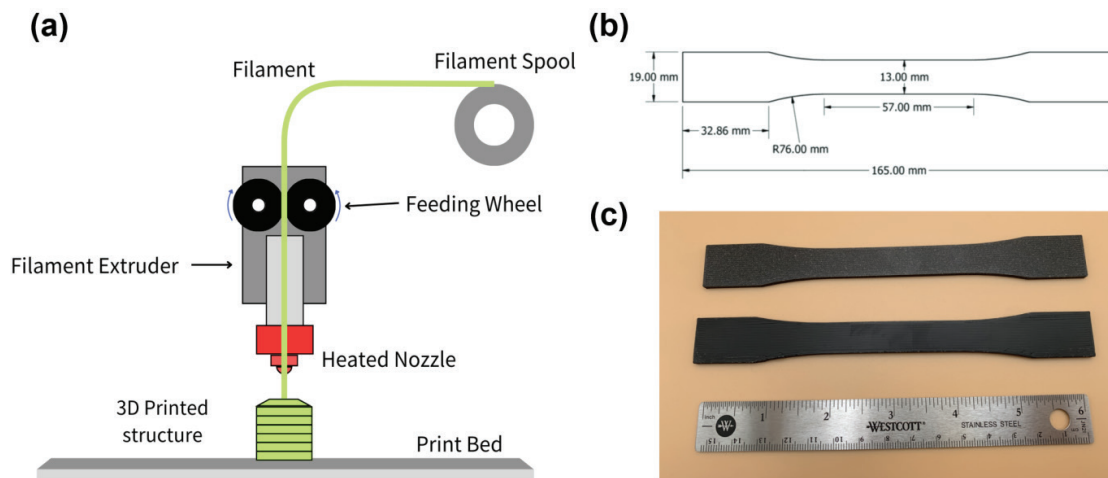


Figure 1. Schematic illustration of (a) Fused Deposition Modeling (FDM) printing, (b) standard samples according to ASTM-D638 type I, and (c) printed samples with different solid infill densities.

Two pull rates of 1 mm/min and 12 mm/min were tested to study the influence of testing parameters on mechanical properties. For each condition, we tested three samples to ensure the repeatability and accuracy of the result. The calculated uncertainty is ~2% due to cross sectional area measurement and sensitivity of the load cell. Figure 3(b)

demonstrates the failed samples after tensile test. It is worth noting that in this study we present stress versus displacement representing the distance between lower and upper clamps.

RESULTS

Figure 4 shows the stress-displacement for 3D printed PLA samples with aligned rectilinear infill pattern with densities of 15%, 45%, 75%, and 100% respectively. As shown in Figure 4(a), samples with 15% solid infill density showed an UTS of 36.9 ± 0.35 MPa, where increasing the infill density to 45% resulted in 23.5% enhancement in UTS to 45.6 ± 0.06 MPa. Further increasing the infill density to 75% yielded a UTS of 50.9 ± 0.6 MPa. Finally, the 100% infill density samples displayed the highest UTS at 55.7 ± 0.12 MPa, representing a 51% increase compared to the 15% infill samples.

Additionally, the displacement of samples at breakage which represents ultimate tensile strain is higher for the 100% infill samples compared to 15% infill samples. As shown in Figure 4, the 100% infill samples exhibited a displacement at breakage of 4.10 ± 0.16 mm which is 8.7%, and 9.3% higher than the displacement of 75%

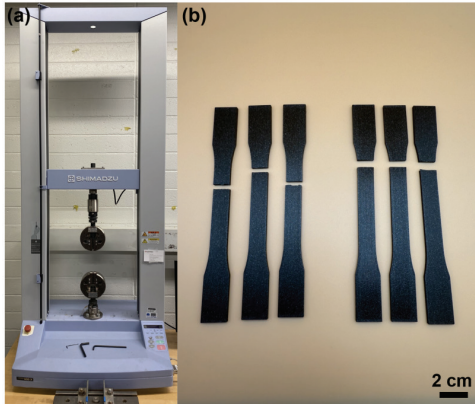


Figure 3. (a) Shimadzu AGS-X tensile machine, (b) 3D printed samples with 15%, and 100% solid infill density after testing.

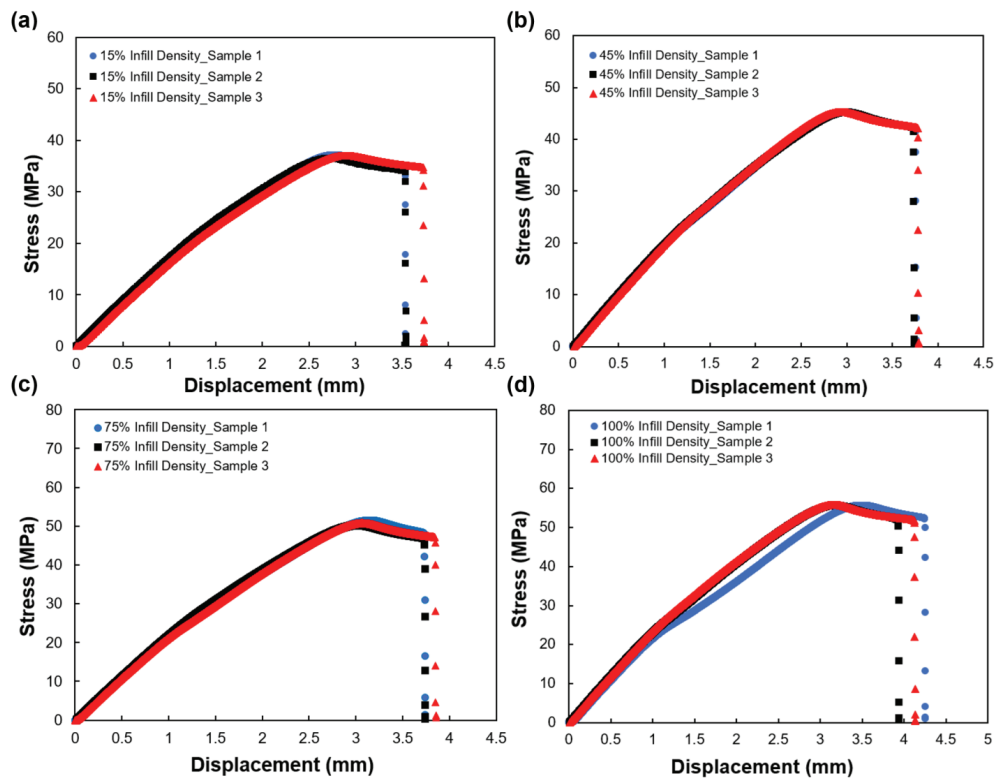


Figure 4. Impact of solid infill density ratio on mechanical properties of 3D printed samples.

infill (3.77 ± 0.66 mm) and 45% infill (3.75 ± 0.02 mm) samples, respectively. Furthermore, the 15% infill samples showed a 3.9% lower displacement at failure compared to 100% infill samples.

Another important parameter that plays a key role in the mechanical properties of 3D printed structures is print orientation. Print orientation refers to how a 3D model is positioned on the build plate during printing. Also, the print orientation is determined to minimize support, print time, surface finish, interlayer bonding, etc. We examined the effect of two print orientations—horizontal (0 degrees) and vertical (90 degrees)—on the mechanical properties of aligned rectilinear solid infill samples, all printed with 45% infill density, as shown in Figure 5(a).

Two samples from each orientation were tested under identical condition. The results reveal that the samples printed at 0 degree exhibited a UTS of 45.6 ± 0.06 MPa, while those printed at 90 degrees showed an average UTS of 32.1 ± 0.5 MPa. Additionally, the samples printed with aligned layers (i.e., 0 degrees) displayed approximately 26% higher elongation at failure compared to the samples printed with perpendicular layers (i.e., 90 degrees). Figure 5(b) shows the cross-section view of the printed samples for both orientations.

The strain rate (i.e., pull rate)—the speed at which a sample is stretched—has significant effect on its mechanical properties. Notably, some thermoplastics exhibit greater sensitivity to changes in strain rate than others. Figure 6

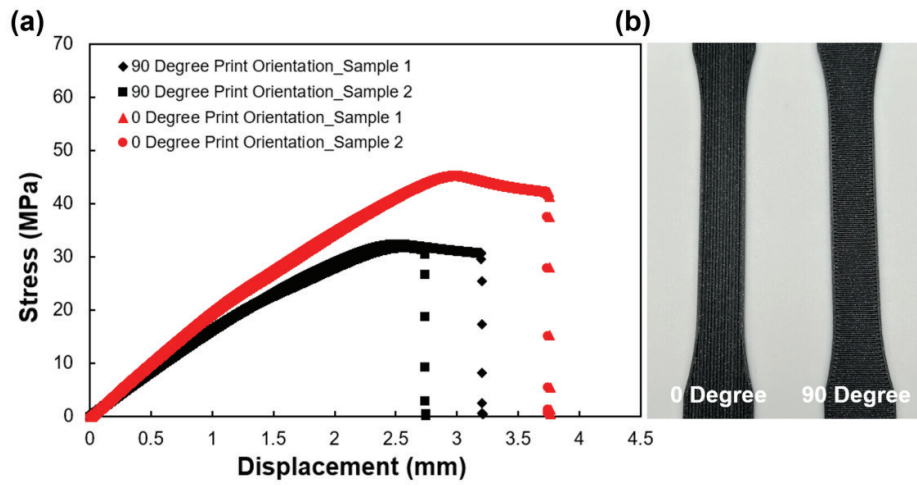


Figure 5. (a) Impact of print orientation on mechanical properties, (b) 3D printed samples with 0-degree and 90-degree orientations for 45% infill density.

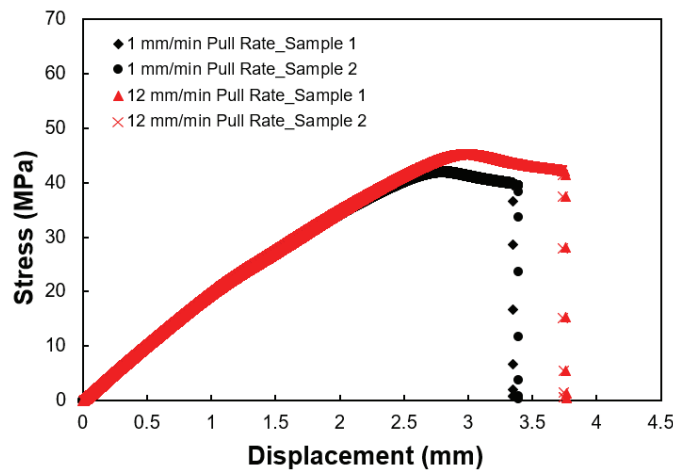


Figure 6. Influence of pull rate on mechanical properties of 3D printed PLA samples.

presents the stress-displacement for PLA samples with 45% infill and layers aligned with the loading direction tested at pull rates of 1 mm/min, and 12 mm/min. As shown, the sample tested at 12 mm/min achieved a higher UTS of 45.6 ± 0.06 MPa, compared to 41.8 ± 0.35 MPa for the 1 mm/min samples—a 9.1% increase. Furthermore, samples pulled at 12 mm/min exhibited 8.4% greater elongation than those tested at the lower rate.

Polymer nanocomposites containing conductive nanoparticles such as carbon black (CB), graphene nanoplatelets (GnP), and carbon nanotubes (CNT) have received extensive interest to replace rare materials such as copper. Conductive polymeric nanocomposites have numerous applications including sensors to electromagnetic shielding, electrochemical energy storage devices, light emitting diodes, etc. (24, 25). However, addition of nanoparticles to thermoplastic comes at the cost of mechanical properties. Conductive PLA is one of the most popular conductive filaments due to its ease of use and relatively low cost. Figure 7 shows stress-displacement test of pure PLA samples and conductive PLA with 45% solid infill tested under the same pull rate. The conductive PLA filament used in this study was purchased from Protopasta (SKUCDP1170). According to the manufacturer, the filament exhibits an electrical resistance of 2-3.5 k Ω over a 10 cm length with diameter of 1.75 mm. The PLA-based filament incorporates carbon black as the conductive filler. Carbon black is 0-dimensional spherical nanoparticles with an average diameter of less than 50 nm, depending on the synthesis

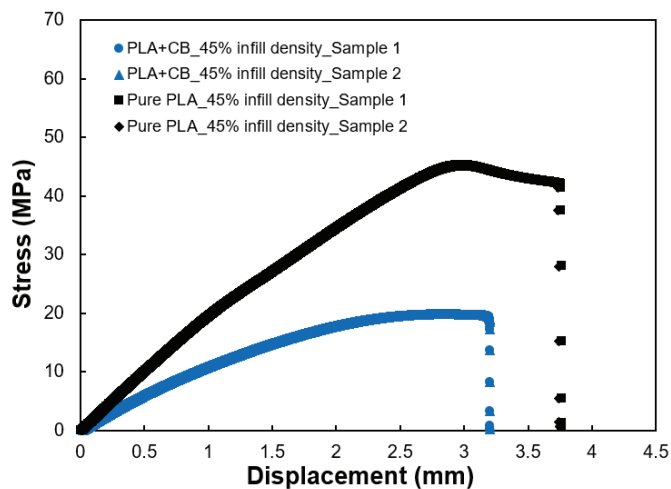


Figure 7. Comparison of mechanical properties of 3D printed pure PLA samples and PLA nanocomposites with Carbon Black nanoparticles with 45% infill density.

method. Printing was carried out on the same Prusa MK4 printer, using the recommended nozzle temperature range of 210-230 °C.

A comparison between pure PLA samples and PLA-based nanocomposites containing carbon black (CB) nanoparticles—both printed with a 45% infill ratio—revealed a significant disparity in mechanical performance. Pure PLA samples exhibited an ultimate tensile strength (UTS) of 45.6 ± 0.06 MPa, significantly higher than the 20.3 ± 0.70 MPa recorded for the conductive PLA nanocomposites, representing an approximate 125% increase. Similarly, the elastic modulus of the conductive samples was lower (11.65 ± 0.20 MPa) compared to that of pure PLA (20.13 ± 0.26 MPa). This reduction in both stiffness and strength is primarily attributed to the inclusion of CB nanoparticles, which alter the microstructure and load transfer behavior within the polymer matrix.

From a materials science perspective, polymeric nanocomposites are formed by dispersing nanoscale fillers into a polymer matrix to enhance or tailor specific properties. In the case of conductive PLA, carbon black is introduced to impart electrical conductivity. However, the incorporation of CB—while beneficial for electrical performance—can compromise mechanical integrity if not uniformly dispersed or properly bonded with the matrix. CB particles tend to agglomerate due to their high surface energy, creating stress concentration sites and microstructural defects that hinder effective stress transfer during mechanical loading.

Moreover, nanofillers can interfere with the polymer chain mobility and reduce crystallinity, which typically weakens the mechanical performance. In the absence of strong interfacial adhesion between the PLA matrix and CB particles, the applied stress cannot be efficiently distributed, resulting in premature failure under tensile loading. Thus, while the presence of CB enables the development of electrically conductive filaments suitable for functional applications (e.g., sensors, circuitry), it does so at the expense of tensile strength and stiffness when compared to pure PLA.

DISCUSSION

As shown in Figure 4, the enhanced ultimate tensile strength at higher infill densities is attributed to the increased load-bearing capacity of the samples prior to failure. A higher infill ratio introduces more material along the primary load path, which effectively distributes the applied stress and reduces stress concentrations within the gauge section. In contrast, samples with lower

infill densities contain a greater number of internal voids and gaps, which act as stress concentrators and serve as initiation sites for cracks, ultimately leading to premature failure.

Furthermore, increased infill density results in greater overlap and contact between adjacent extruded paths and layers. This enhanced interfacial contact promotes stronger interlayer adhesion, which is critical for mechanical integrity in 3D-printed parts. Improved bonding between layers not only increases the resistance to delamination but also enables more uniform stress distribution throughout the structure under tensile loading. The observed increase in displacement (i.e., strain at failure) with higher infill density, also evident in Figure 4, can be attributed to the more continuous and cohesive thermoplastic network. A denser infill structure allows the material to deform more uniformly and stretch further before fracture. This ductile behavior arises from improved load transfer between layers and a reduction in internal defects, both of which delay crack propagation and enable the sample to absorb more energy prior to breaking.

The results presented in Figure 5 indicate that samples printed with a 90-degree orientation exhibit higher UTS compared to those printed at 0 degrees. This difference in mechanical performance is closely related to the nature of layer orientation and interlayer bonding in fused deposition modeling 3D printing.

In the 90-degree orientation, the printed filament paths are aligned parallel to the direction of the applied tensile load, allowing the stress to be carried more effectively along the continuous extruded strands. This configuration enables the material to utilize the intrinsic strength of the polymer within each printed filament, resulting in higher load-bearing capacity. Conversely, in the 0-degree orientation, the tensile load is applied perpendicular to the printed layers, meaning that the load must be transferred across interlayer interfaces. These interfaces rely on thermal fusion during the printing process, which is inherently weaker than the polymer's intralayer strength due to limited diffusion and adhesion between layers. As a result, tensile stress in this configuration tends to promote delamination and failure at the interlayer boundaries, leading to a significantly lower UTS. In summary, when the applied tensile force acts along the weak axis (as in the 0-degree orientation), the mechanical performance is governed primarily by interlayer adhesion, which is less robust than the material's bulk strength. This leads to reduced tensile strength and lower overall load-carrying capacity

compared to orientations where the filament paths are aligned with the loading direction.

As illustrated in Figure 6, the effect of pull rate on the tensile strength of PLA is closely linked to its inherently brittle nature. At higher strain rates, such as 12 mm/min, there is less time for the polymer chains—particularly the crystalline lamellae—to undergo molecular relaxation or reorientation in response to the applied stress. This limited chain mobility results in a stiffer mechanical response and an apparent increase in ultimate tensile strength. The material is essentially “locked” into a more rigid configuration, enabling it to withstand greater loads before failure. Typically, lower pull rates (e.g., 1 mm/min) are expected to promote higher ductility, as the extended deformation time allows for gradual stress redistribution and energy dissipation through chain movement and yielding mechanisms. However, contrary to this expectation, the samples tested at the higher pull rate demonstrated greater elongation at break. This counterintuitive result may be attributed to enhanced strain localization or microstructural changes induced by rapid deformation, which can delay the onset of catastrophic failure and enable the material to stretch further before breaking.

The reduced mechanical properties of the conductive PLA-based nanocomposite, as shown in Figure 7, can be attributed primarily to a decrease in the effective load-bearing cross-sectional area of the PLA matrix due to the presence of carbon black nanoparticles. Additionally, poor interfacial adhesion between the CB fillers and the PLA matrix likely impairs stress transfer efficiency, weakening the composite under tensile loading. Furthermore, the conductive nanocomposite samples exhibit more brittle behavior, characterized by a rapid increase in stress followed by sudden failure. This brittleness arises because the addition of CB nanoparticles restricts the mobility and orientation of PLA polymer chains, limiting their ability to undergo plastic deformation. Consequently, the elongation at break is reduced, as illustrated in Figure 7, reflecting a transition to a more brittle failure mode in the nanocomposite compared to pure PLA.

CONCLUSION

Additive manufacturing, commonly known as 3D printing, has revolutionized the manufacturing industry by offering cost-effective production and enabling the optimization of internal component structures. Fused deposition modeling is one of the most widely used

additive manufacturing techniques, which fabricates objects by melting thermoplastic polymers such as PLA, ABS, PC, etc. and depositing them layer by layer. The mechanical properties of FDM-printed parts are highly influenced by printing parameters such as infill density, layer thickness, print orientation, and so on. This study investigated how infill density and print orientation, along with pull rate and the addition of carbon black (CB), affect the mechanical performance of PLA-based printed structures. Our results showed that the ultimate tensile strength increased significantly from 36.9 ± 0.35 MPa to 55.7 ± 0.12 MPa as the infill ratio was raised from 15% to 100%. Furthermore, samples printed with a 90-degree orientation exhibited a UTS of 32.1 ± 0.51 MPa, which is 42.1% lower than the 45.6 ± 0.06 MPa observed in samples printed at 0 degrees. Additionally, the incorporation of carbon black nanoparticles into PLA negatively impacted the mechanical properties despite enhanced electrical properties. Pure PLA samples demonstrated a UTS of 45.6 ± 0.06 MPa, which was approximately 125% higher than that of the PLA/CB nanocomposite samples. These findings highlight the critical influence of printing parameters and filler content on the structural integrity of FDM-printed components.

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DECLARATION OF CONFLICT OF INTERESTS

The author declares that there are no conflicts of interest regarding the publication of this article.

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