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Experimental Study of Effect of Infill Density on Tensile and Compressive Behaviors of Poly Lactic Acid (PLA) Prepered by 3D Printed (FDM)

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ABSTRACT

One of the most advanced production techniques in the manufacturing sector is the Additive Manufacturing Process (AMP), commonly known as 3D printing. Among its various methods, Fused Deposition Modeling (FDM) is widely used for fabricating intricate geometries. Unlike CNC machining, injection molding, and sculpting techniques, which typically generate 70%-90% material waste, FDM is a more efficient process that significantly minimizes material loss. This study examines the impact of infill density on the tensile and compressive behavior of Poly Lactic Acid (PLA), as well as its mechanical and fracture properties. The research focuses on a hexagonal infill pattern with varying infill percentages of 25%, 50%, 75%, and 100%. In additive manufacturing (AM), prismatic closed-cell structures, commonly known as honeycomb infill, are frequently used to enhance the mechanical integrity of printed parts due to their uniform density and periodic nature. Additionally, the study evaluates the effect of print orientation at 0°, 45°, and 90°. The ASTM D638 standard was followed in designing the tensile test specimens. The findings indicate that tensile strength and elastic modulus increase with higher infill density. While variations in print orientation (0°, 45°, and 90°) result in only slight changes in tensile strength and elastic modulus, an increase in infill density reduces elongation at break. Furthermore, increasing the infill density also leads to higher compressive strength, demonstrating a direct correlation between structural integrity and material distribution in FDM-printed PLA components.

1. INTRODUCTION

In the industrial sector, additive manufacturing sometimes known as 3D printing, is a fast-expanding technology. Main benefit of AM is its ability to quickly and easily fabricate intricate designs from CAD models to fully working products [1]. It is being utilized more and more in engineering applications these days, including bespoke goods, the automobile sector, aviation, medical engineering, and more [2]. In AM, the entire product or individual components are produced and utilized as the final product [3]. Although it has been around since the 1980s, Fused Deposition Modeling (FDM™) is the most popular of the various AM techniques, including stereolithography, selective laser melting , selective laser sintering ,and laminated object manufacturing, to name a few [4]. A popular additive manufacturing technique for creating intricate geometric components for a range of engineering uses is FDM. To create a specific 3D structure, printers employ the FDM technology, which involves melting and extruding thermoplastic filament through a nozzle that follows a predetermined route. Polyamide (PA), polylactic acid , polycarbonate , acrylonitrile butadiene styrene , and thermoplastic [5]. PLA and ABS have a lower factor of thermal expansion and higher mechanical strength in FDM materials [6]. Three groups of specimens were created using PLA printing. The first group produced at 40 mm/s with an infill ratio of 50, 75, and 100. Additionally, the second group produced at 50 mm/s with an infill ratio of 50, 75, and 100. The third group produced at 60 mm/min with an infill ratio of 50, 75, and 100. The tensile test specimens were printed in compliance with ASTM D638. With an infill ratio of 100% and a print speed of 40 mm/min, specimen 3 from the first group produced the best results out of all the specimens [7]. Four distinct pore geometries for PLA bone scaffolds were created, and their mechanical characteristics were simulated. Four different pore geometries for PLA bone scaffolds were created, and their mechanical characteristics were simulated. The results demonstrate that, as a result of the stress distributions on the scaffold models, pore shape significantly influences mechanical characteristics [8]. The 3D-printed samples were created using the Fused Deposition Modeling process. Three specimens of each type were evaluated using specific infill patterns (trihexagon, gyroid, and line) and infill ratios (30, 50, and 70%).According to the ASTM D695 standard, an experimental research was conducted to calculate how infill pattern and ratio affected the 3D printed PLA's compressive strength. The compressive strength varies according on the infill design and ratio. According to findings of the investigation, the compressive strength increasing as the infill ratio increased. Interestingly, the maximum compressive strength was at 70% infill ratio with line pattern [9]. The purpose of this study is to use a low infill density to examine how the independent infill pattern affects the mechanical qualities and surface features of PLA, PETG, and PLA+ printed materials Printing with cubic, gyroid, and concentric patterns increased the ultimate tensile strengths of PLA, PETG, and PLA+, yielding maximum σu of 15.6, 20.8, and 16.5 MPa, respectively [10]. The tensile and fire characteristics of 3D-printed polylactide acid pieces with different infill levels were examined. According to the fire test results, a higher infill density resulted in a higher fuel load, which maintained combustion [11]. Both samples used zigzag patterns, and the three infill densities were adjusted by 30%, 60%, and 100%. The raster angles used were 0 and 90 degrees. Lastly, the research was performed using varying infill rates and raster angles. The tensile strength of pure PLA can be affected by the raster angle and infill density. Among the various infill densities and raster angles, PLA 0°100% exhibits the highest tensile strength and young moduli. In contrast to other parameters, the 90°30% pure PLA exhibits the maximum elongation of break. A higher infill density will result in less break elongation, which indicates more tightly packed clustered strands, limiting the polymer structure's ability to move The 0° raster angle, which was attained by aligning the raster with the printing direction, has the highest tensile strength and Young's moduli [12]. Utlizing Fused Deposition Modeling technology, 3D additive printing is utilized to examine the fatigue behavior of polylactic acid material with bamboo filler at various print nozzle diameters and infill densities The research findings indicate that infill density significantly affects the studied materials' fatigue characteristics. The examined material was strengthened as a consequence of the effect of cyclic testing, and its viscoelastic nature was also demonstrated [13]. To investigate the influance of build orientation on the material's tensile characteristics and build time, FDM 3D-printed PLA pieces were manufactured at various build orientations. Three construction orientations and three print angles were investigated in this context When the pieces' construction orientation was shifted from a flat to an upright printing angle, the tensile strength dropped [14]. Several common printing materials, such as Acrylonitrile Butadiene Styrene , Polylactic Acid ,and carbon fiber reinforced PLA composites (PLA-CF), have been used to study the effects of infill density and printing pattern on the mechanical characteristics of FDM 3D printing structures, The influance of infill density and printing patterns on the strength of the 3D printed structure [15]. Anisotropy is still a major worry despite additive manufacturing's (AM) numerous advantages, which include significant design flexibility for 3D-printed items. It was discovered that the construction orientation and material composition of the printed functional item had a significant impact on its mechanical performance [16]. Honeycomb infill pattern samples are produced using different infill densities of 20, 40, 60, and 80% to examine the mechanical and fracture behavior of MEX ABS/CF-ABS components. Significant gains in tensile strength, moduli, yield strength, and elongation are shown by CF-ABS samples with an 80% infill density and honeycomb fill pattern [17]. Using a nylon material reinforced with carbon fiber, the impact of infill pattern and density which are imparted to the mass of the standard sample on compressive strength is examined. Specimens with more mass have a higher compressive strength with the same infill pattern. Compared to samples with rectangular and gyroid fillings, those with triangular fills have a greater compressive strength with the like mass [18]. The Fused Deposition Modeling (FDM) technique constructs parts layer by layer by melting a thermoplastic filament and feeding it through a liquefier head. The material is then extruded through a computer-controlled nozzle, deposited onto the platform, and solidified [19].

In this study, Polylactic Acid (PLA) was used to fabricate tensile and compressive test samples with a hexagonal infill pattern at varying infill densities of 100%, 75%, 50%, and 25%, and with build orientations of 0°, 45°, and 90°. The objective of this research is to investigate the influence of infill density and build angle on the tensile and compressive behavior of FDM-printed samples.

2. MATERIAL AND METHOD

2.1 Material

The material is utilized in this work is polylactic acid (PLA) filament, the general characterization revealed in Table 1.

Table 1. Standard properties of PLA

Characteristic	Testing Criteria	Value
Density	ASTM D792	1.25 g/cm^3
Tensile strength	ASTM D638	31 Mpa
Glass transition temperture	DSC,10 C/min	61°C
Elongation at break	ASTM D638	7.3%

2.2 Methods

Tensile and compressive test samples were fabricated using an Ender 3 V2 3D printer equipped with a Sonic Pad Klipper, employing the Fused Deposition Modeling (FDM) method, as illustrated in Figure 1.

Figure 1. 3D printing machine

The tensile specimens were manufactured following the ASTM D638 standard, as shown in Figure 2, which details the specimen dimensions. Samples were printed with four different infill densities (25%, 50%, 75%, and 100%), with each infill percentage tested at three build orientations (0°, 45°, and 90°).

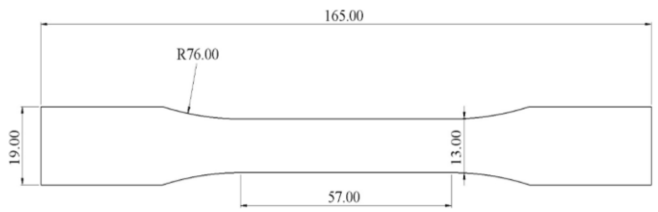


Figure 2. Diminution of specimen tensile [20]

Various infill patterns can be selected for FDM printing, including Hilbert curves, rectilinear, concentric, honeycomb, and Archimedean chords. This study specifically employs a hexagonal (honeycomb) infill pattern due to its ability to enhance mechanical performance while minimizing material usage.

Tensile tests were conducted using a Universal Testing Machine (UTM).

The compressive test specimens were designed in accordance with ASTM D695, as illustrated in Figure 3. The samples were fabricated using Fused Deposition Modeling (FDM) technology with infill densities of 100%, 75%, 50%, and 25%, utilizing a honeycomb infill pattern.

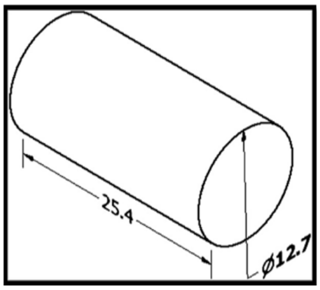


Figure 3. Diminution of specimen compressive [21]

2.2.1 The principle work of Fused Deposition Modeling

The first stage is to create a solid three-dimensional model. Numerous CAD applications allow for this to be accomplished. The 3D CAD model is exported to the FDM printer program in the stereolithography (STL) format. The STL file is exported to the printer software, where it is horizontally divided into numerous thin parts and process settings are adjusted. The slicing program then usages this information to generate a procedure plan, or G-code file, that governs the FDM machine's hardware.

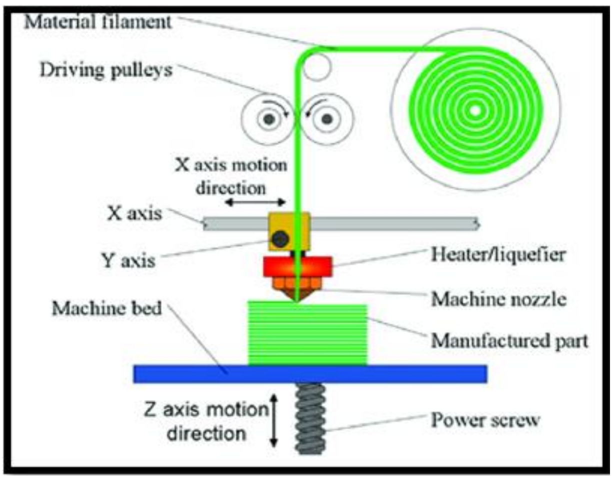


Figure 4. FDM technology

The FDM method creates two-dimensional patterns known as "slicing layers," which, when stacked on top of one another, roughly mimic the original three-dimensional component. The printing process is illustrated in Figure 4. According to a set of parameters that are constant for all samples as revealed in Table 2.

Table 2. The printing parameter

Parameter	Value
Nozzle size	0.4 mm
Temperture Extruder	200°C
Room temperature	37°C
Printing Speed	50 mm/s
Layer high	0.2 mm
First layer high	0.2 mm
Percentages of infill	100%, 75%, 50%, 25%
Wall thickness	1.4 mm

3. RESULTS AND DISCUSSION

3.1 Tensile test

As shown in Figure 5, the fracture patterns of the samples are presented for all infill densities and different raster angles.

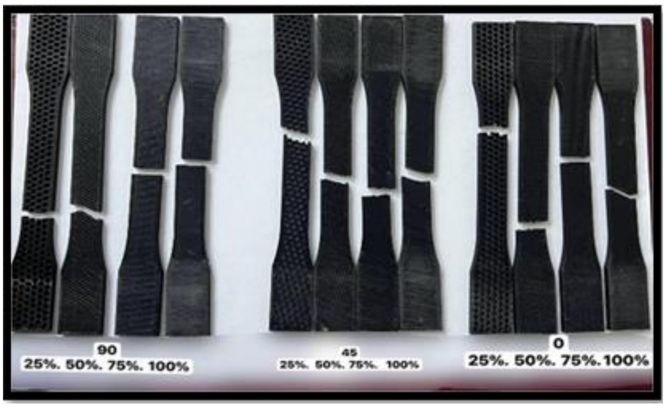


Figure 5. Specimen tensile after fracture

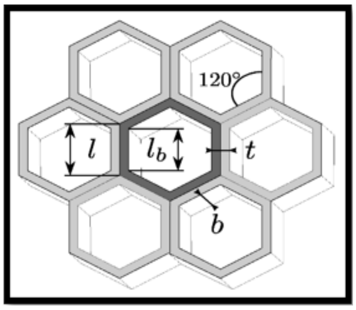


Figure 6. Dimensions of the hexagonal honeycombs [22]

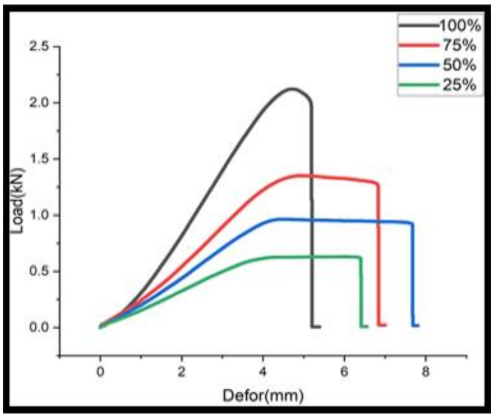
According to Eq. (1) (illustrated in Figure 6), this phenomenon demonstrates crack propagation through the honeycomb structure, where the applied load is distributed as a combination of distinct forces and moments acting on each cell wall. As a result, the material behavior transitions from ductile to brittle.

$$\sigma = \frac{2}{3} \cdot (\frac{t}{l})^2 \cdot \sigma_Y \quad (1)$$

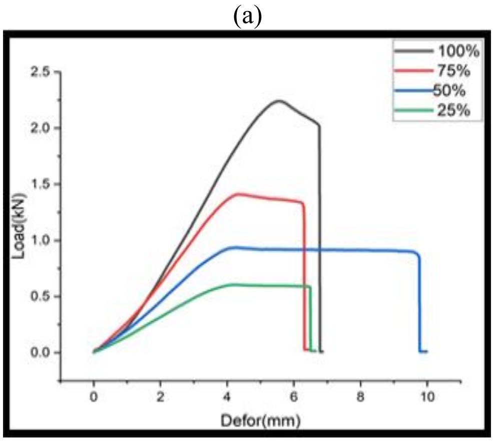
As shown in Figure 7(a)-(c), the load-deformation relationship is presented. An increasing trend from 25% to 100% infill density indicates a greater tolerance to applied load.

The findings suggest that samples with higher infill densities exhibit stronger interlayer bonding and greater resistance to deformation due to a reduction in air gaps. Additionally, the increase in tensile strength can be attributed to the greater number of honeycomb structures, which provide more hexagonal walls interconnected with faces, enhancing resistance to applied forces. This is also influenced by the higher material content relative to the cross-sectional area.

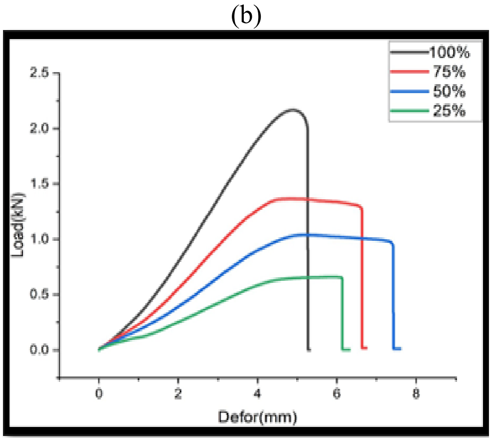
However, as shown in Figure 7(a)-(c), elongation increases as infill density decreases, reaching a peak at 25% infill density, before decreasing. This is because a lower infill density results in fewer honeycomb cells, reducing the material available to sustain deformation.



(a)



(b)



(c)

Figure 7. Load-deform curves of tensile test for all infill densities for a) 0°, (b) 90°, (c) 45°

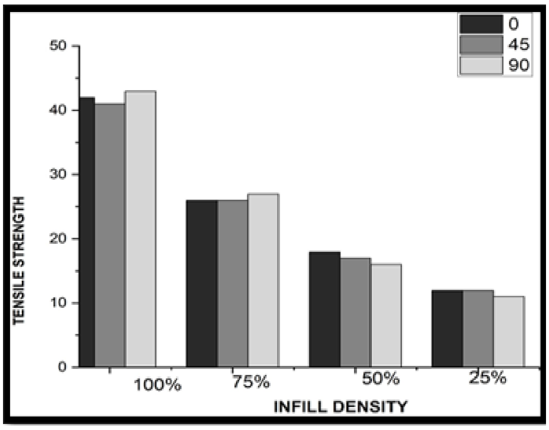


Figure 8. Infill density vs. tensile strength

As shown in Figure 8, the histograms of the maximum tensile strengths clearly indicate that the strength depends on the density of the samples and the orientation of the hexagonal cells relative to the load direction. Tensile strength refers to the maximum stress a material can resist while being stretched or pulled before failing. The orientation of the printed layers (0°, 45°, 90°). Although the effect is slight, these differences are a result of 0° Orientation. The highest tensile strength is usually obtained when printing along the loading direction. Inter-layer adhesion is maximized when the layers are in line with the applied force.

45-degree orientation Strength and flexibility can be balanced at this angle. In comparison to the 0° orientation, it permits some load distribution across layers, which may improve toughness but may also lower tensile strength.

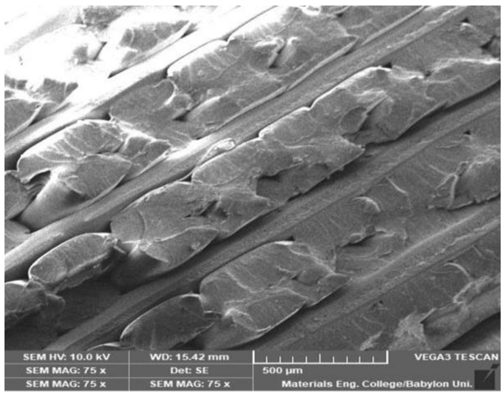
90-degree orientation Because inter-layer adhesion is less when printing perpendicular to the load direction, the tensile strength is often lower. Failure at the layer lines could result from the layers' ineffective stress transfer.

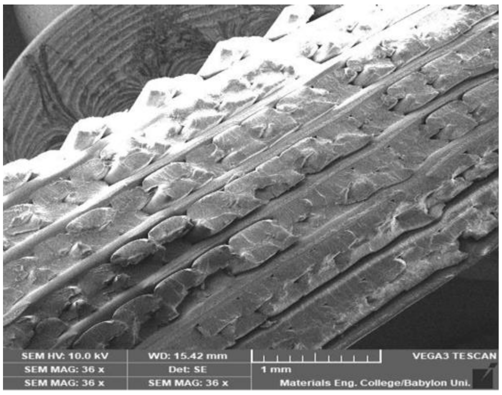
Inertia Across Sections Layer orientation affects the moment of inertia. The additional material can increase strength and stiffness at high densities, especially in the 90° form, which could offset the orientation's inherent drawbacks.

90-degree orientation Because of the reduced inter-layer adhesion, printing perpendicular to the load direction typically results in poorer tensile strength.

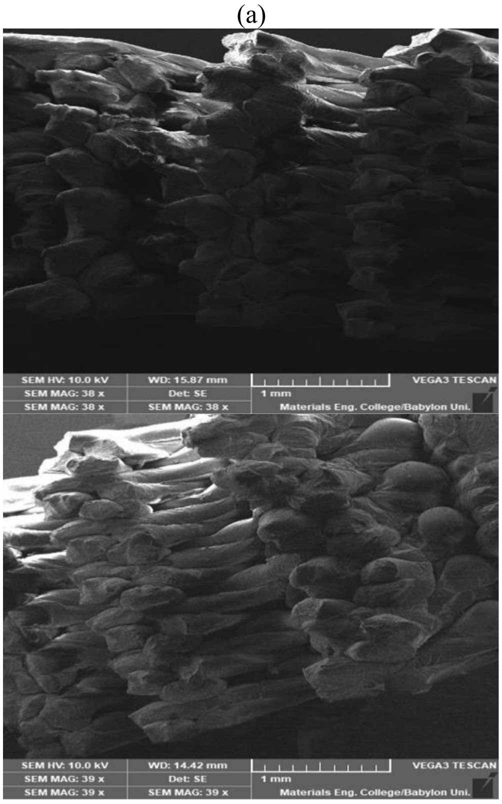
3.2 Microstructural analysis

The fracture surfaces of the samples were examined using a scanning electron microscope (SEM) to analyze the differences in mechanical properties. The validity of these differences was assessed by observing the fracture morphology in the SEM micrographs.





(a)



(b)

Figure 9. Fracture surfaces for (a) brittle 100% and (b) ductile 50% sample

Among all the infill densities, the most brittle (100%) and most ductile (50%) samples exhibited distinct fracture surfaces, as shown in Figure 9. For optimal mechanical performance, strong bonding at the polymer bead interfaces is crucial.

A detailed analysis revealed that a decrease in porosity levels was closely associated with an increase in infill density. SEM micrographs showed fewer voids in the 75% and 100% infill samples, which explains their superior mechanical properties at higher filling percentages. In contrast, the 50% infill specimens exhibited larger voids, resulting in lower strength compared to the 100% infill samples.

3.3 compressive test

As shown in Figure 10, the failure mechanism of the honeycomb structure is influenced by infill density. When the infill density increases, the size of the honeycomb cells also increases, leading to a change in the t/l ratio as described in following equation. The applied stress, σ, is given by:

$$\sigma = \frac{2}{3} \cdot \left(\frac{t}{l}\right)^2 \cdot \sigma_Y$$

where, σ_Y represents the flow stress of the material forming the cell walls. When the maximum stress in each face reaches σ_Y, a critical strain occurs, causing the cells to collapse through elastic buckling, brittle fracture, creep, or plastic yielding, depending on the material properties. At high strain levels, the contacting cell walls begin to fail, and further deformation leads to the compression of the cell wall material. Once the opposing cell walls completely touch, cell failure is complete, resulting in densification and a rapid increase in stiffness.

As shown in Figure 11, the maximum compressive strength was observed at a 100% infill ratio. The infill ratio is defined as the proportion of printed material to total volume, and increasing this ratio enhances compressive strength.

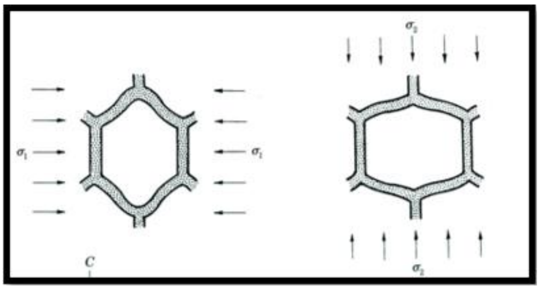


Figure 10. Structures subjected to two opposing forces [23]

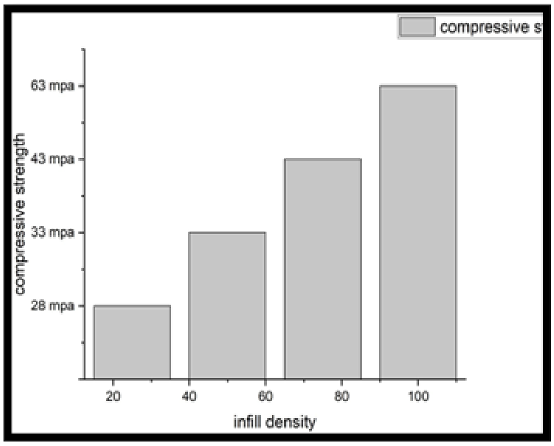


Figure 11. Relationship between infill density and compressive strength

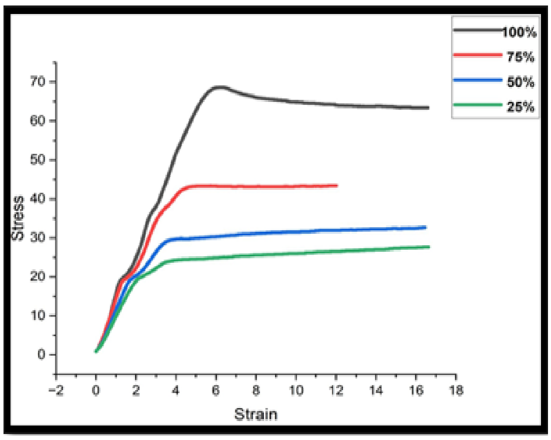


Figure 12. Stress-strain curves from compressive tests for all infill densities

From the stress-strain or load-deformation relationships presented in Figure 12, it is evident that stress (load) decreases as infill density decreases. This is due to the higher polymer content in specimens with greater infill density, leading to a smaller volume of empty space inside the printed structure. Smaller pores improve load-bearing capacity, resulting in a stronger material. In most cases, compressive strength is directly correlated with infill ratio, with specimens at 25%, 50%, 75%, and 100% infill densities demonstrating increasing compressive strength as the infill density increases.

4. CONCLUSION

The ability to build things with varying infill densities is one benefit of 3D printing FDM technology. Time, material, and final product costs can all be decreased with this advantage. This study investigated how a shift in the percentage of infill density affected the tensile and compressive proprieties for part FDM 3D printing made from poly lactic acid. The following conclusions:

•Increasing the infill density increases the tensile strength increases with a reduction in deformation magnitude (elongation) up to infill density to 25% Where the elongation or deformation will be reduced.

•In addition, increasing the infill density due A higher density and ultimately a smaller volume of empty space inside the printed specimen might result from the increased amount of polymer used in the printing process leads to increase compressive strength.

•Depends the tensile strength on the density of samples and orientation of hexagonal cells with load direction. Tensile strength refers to the maximum stress a material can resist while being stretched or pulled before failing. The orientation of the printed layers (0°, 45°, 90°), although the effect is slight. 0° Orientation Printing along the loading direction typically results in the highest tensile strength. 45° Orientation This angle can provide a balance between strength and flexibility. 90° Orientation Printing perpendicular to the load direction generally results in lower tensile strength due to weaker inter-layer adhesion.

Finally, increasing the infill density increases the strength of part to withstand deformation and stress. The minimum strength is 25% infill, while the maximum strength is 100 %.

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