Experimental Investigation of Mechanical Properties of PLA 3D Printing Material using Fused Deposition Modelling Technique

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***Abstract*—This study experimentally investigates the mechanical properties of Polylactic Acid (PLA) 3D printing material using the Fused Deposition Modelling (FDM) technique. Tensile, compressive, and flexural tests were conducted on PLA specimens printed with varying parameters, including layer thickness, infill density, and printing orientation. The results show that the mechanical properties of PLA are significantly influenced by the printing parameters. Specifically, the tensile strength and modulus of PLA specimens increased with decreasing layer thickness and increasing infill density. The compressive strength and flexural strength also showed similar trends. The printing orientation was found to have a significant effect on the mechanical properties, with specimens printed in the longitudinal direction exhibiting higher strength and stiffness compared to those printed in the transverse direction. The findings of this study provide valuable insights into the mechanical behavior of PLA 3D printing material and can be used to optimize the printing parameters for specific applications.**

Keywords—Additive Manufacturing; PLA; Infill Density; Mechanical Properties

I. INTRODUCTION

Additive manufacturing (AM) has revolutionized the field of manufacturing by enabling the rapid production of complex geometries and customized products [1]. Among various AM techniques, Fused Deposition Modeling (FDM) has gained significant attention due to its simplicity, affordability, and versatility [2]. FDM uses melted plastic to create objects layer by layer, allowing for the production of complex shapes and structures [3].

Polylactic Acid (PLA) is a biodegradable and renewable thermoplastic that has become a popular material for FDM due to its low cost, ease of processing, and environmental sustainability [4]. PLA is widely used in various applications, including rapid prototyping, model making, and production of end-use parts [5]. However, the mechanical properties of PLA parts printed using FDM are highly dependent on the printing parameters, such as layer thickness, infill density, and printing orientation [6].

Understanding the mechanical properties of PLA is crucial for its application in various fields, including aerospace, automotive, and biomedical engineering [7]. Several studies have investigated the mechanical properties of PLA printed using FDM, but most of these studies have focused on the tensile properties of PLA [8-10]. There is a need for a comprehensive study that investigates the mechanical properties of PLA, including tensile, compressive, and flexural properties, and their dependence on printing parameters.

This study aims to experimentally investigate the mechanical properties of PLA 3D printing material using the FDM technique. The effects of layer thickness, infill density, and printing orientation on the tensile, compressive, and flexural properties of PLA will be studied. The findings of this study will provide valuable insights into the mechanical behavior of PLA and can be used to optimize the printing parameters for specific applications.

II. EXPERIMENTAL DETAILS

FDM as one of the most popular but also complex additive manufacturing (AM) technology that provides a number of advantages over conventional manufacturing processes. FDM process, also known as "Fused Filament Fabrication, FFF" and "Material

Extrusion", is based on the extrusion of molten material layer by layer on working bed and producing part on working print bed, showed on picture bellow. The 3D printing parts fabrication with FDM technology begins with the material also known as a filament, most often the material is thermoplastic, that is conveyed into the extrusion head via a feeder. In the extrusion head, the filament is melted in a heating element and through the nozzle it is applied in the form of deposited lines on the printing bed, where the final geometry of the product is formed.

Fused Deposition Modeling (FDM) relies on thermoplastic materials in filament form, which are melted and extruded layer by layer to create 3D objects. The choice of material significantly impacts the properties, applications, and performance of the final part. Below is the flowchart of materials commonly used in FDM printing.

The printer used to fabricate the specimens are Ender-3 V3 and Bambu Lab P1S printers.

The Ender-3 V3 is designed for speed, precision, and compatibility with a wide range of materials, making it an excellent choice for hobbyists and professionals alike.

The Bambu Lab P1S is a high-speed 3D printer designed for fast, precise, and reliable printing. The P1S incorporates features like an enclosed chamber and enhanced components, making it suitable for printing more demanding materials like ABS and PETG. It has advanced technology, including multi-material printing capability when paired with an AMS unit.

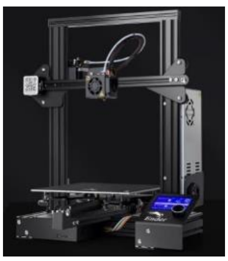

Fig 1 : Ender-3 V3 Printer

Fig 2 : Bambu Lab P1S Printer

Tensile test conducted for all the specimens according to ASTM D638 Type 1 standards.

Table 1 : Tensile Specimen

SL.No	Patterns	Infill Density	Layer Thickness
1	Gyroid	80%	0.2
2	Concentric	80%	0.2
3	Cubic Sub-division	80%	0.2
4	Triangles	80%	0.2

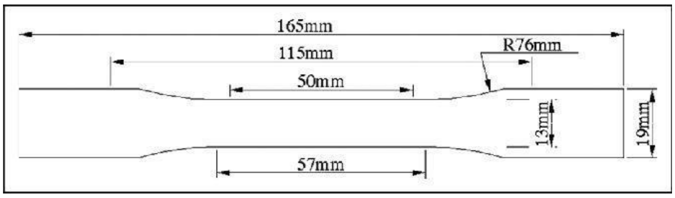

Fig 3 : 2D sketch of Tensile specimen

Fig 4 : CAD model of Tensile specimen

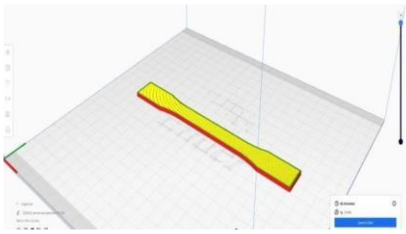

Fig 5 : Slicing of Tensile specimen using Ultimaker Software

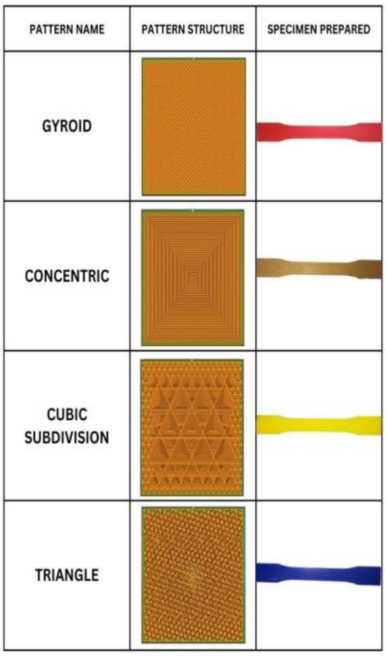

Fig 6 : Tensile specimens of Different patterns

Compression test conducted for all the specimens according to ASTM D695 Type 1 standards.

Table 2 : Compression Specimen

SL. No	Patterns	Infill Density	Layer Thickness
1	Gyroid	80%	0.2
2	Concentric	80%	0.2
3	Cubic Sub-division	80%	0.2
4	Triangles	80%	0.2

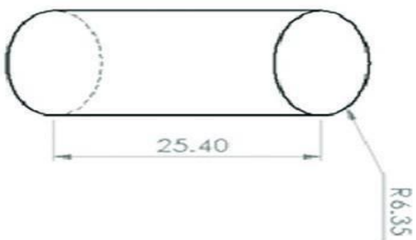

Fig 7 : 2D sketch of Compression Specimen

Fig 8 :CAD model of Compresion Specimen

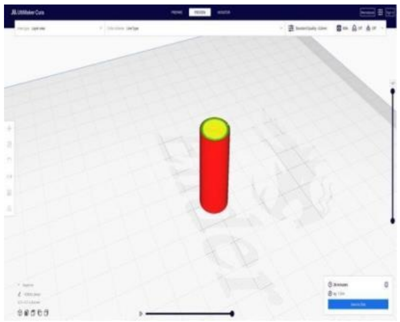

Fig 9 : Slicing of Compression specimen using Ultimaker Software

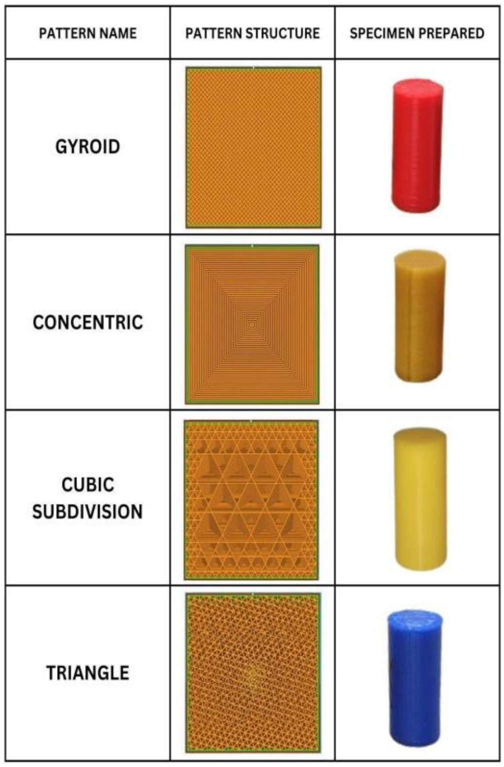

Fig 10 : Fig 3.10 :- Compression specimens of Different patterns

Impact test conducted for all the specimens according to ASTM D256 Type 1 standards.

Table 3 : Impact Specimen

SL. No	Patterns	Infill Density	Layer Thickness
1	Gyroid	80%	0.2
2	Concentric	80%	0.2
3	Cubic Sub-division	80%	0.2
4	Triangles	80%	0.2

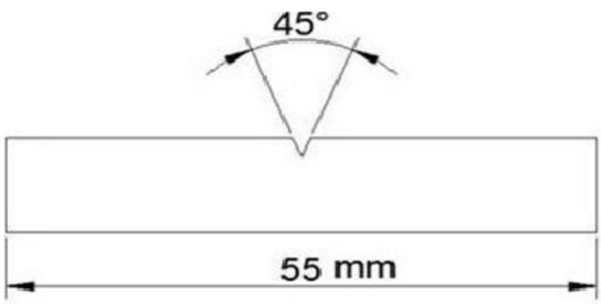

Fig 11 : 2D sketch of Impact specimen

Fig 12 : CAD Model of Impact Specimen

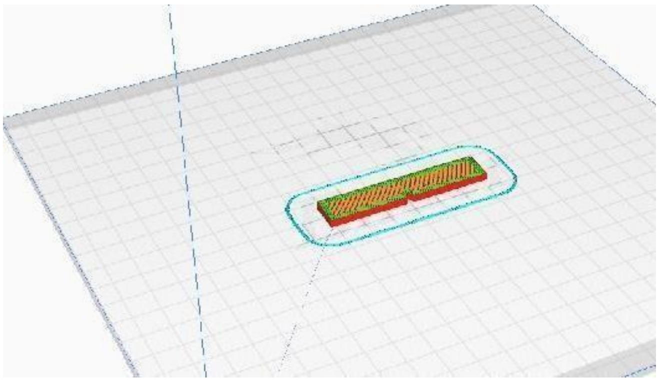

Fig 13 : Slicing of Impact specimen using Ultimaker Software

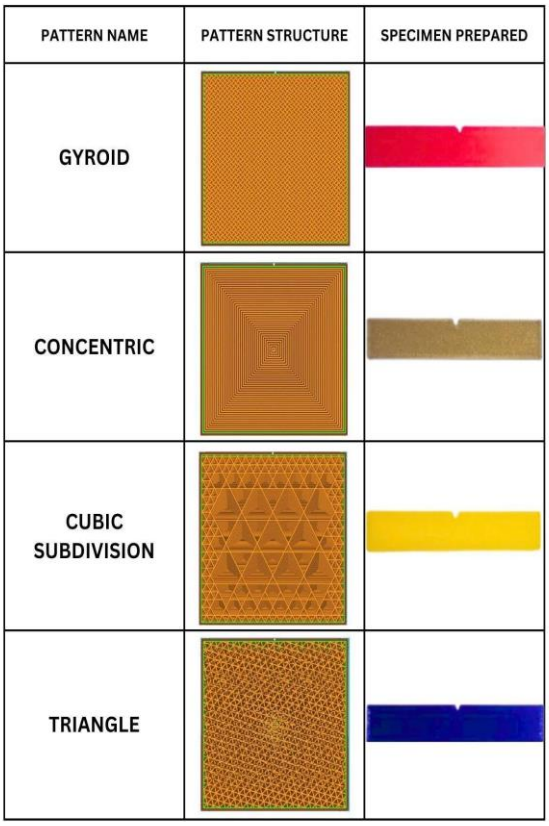

Fig 14 : Impact specimens of Different patterns

III. RESULTS AND DISCUSSIONS

Ultimate Tensile Strength :

A thorough examination of the ultimate tensile strength of diverse lattice structures, including Gyroid, Cubic Subdivision, Concentric and Triangle, has been performed.

The findings indicate considerable variations in ultimate tensile strength across the analysed structures, underscoring the significance of internal geometry, surface area-to-volume ratio, and deformation mechanisms in influencing tensile resistance. The Concentric Lattice Structure displays the highest ultimate tensile strength of 30.16 MPa, owing to its radial, concentric configuration, superior radial stiffness, effective stress distribution, and elevated stiffness-to-weight ratio.In contrast, the Gyroid Lattice Structure exhibits a moderate ultimate tensile strength of 22.9 MPa, resulting from its intricate internal architecture, high surface area-to-volume ratio, and balanced stiffness and toughness. and Cubic subdivision and triangle lattice structures have reduced ultimate tensile strengths (16.97 MPa and 16.16 MPa, respectively), presumably attributable to their simpler configurations, diminished surface area-to-volume ratios, and restricted deformation mechanisms. These discoveries have substantial implications for the design and development of lattice structures across diverse industries, including aeronautical, automotive, and biomedical engineering. By choosing the ideal lattice configuration, engineers can develop materials with customised mechanical properties, thereby improving their performance and efficiency. The ultimate tensile strength of lattice structures is significantly affected by their internal geometry, surface area-to-volume ratio, and deformation mechanisms. The Concentric lattice structure demonstrates enhanced ultimate tensile strength owing to its distinctive amalgamation of radial stiffness, stress distribution, and stiffness-to-weight ratio. These findings offer significant insights for the design and optimisation of lattice structures across many applications.

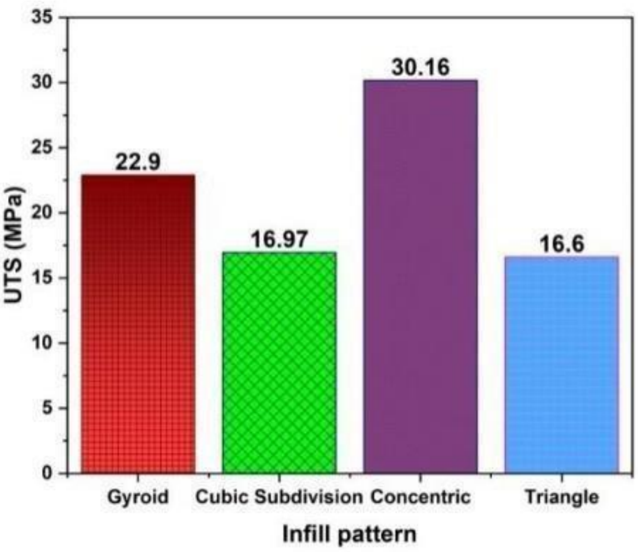

Fig 15 : comparative studies of the UTS of different lattice structures

Yeild Strength :

A thorough examination of the yield strength of different lattice structures, namely Gyroid, Cubic Subdivision, Concentric, and Triangle, has been performed. The findings indicate notable variations in yield strength across the analyzed structures, underscoring the significance of internal geometry, surface area-to-volume ratio, and deformation mechanisms in influencing resistance to plastic deformation. The Concentric Lattice Structure demonstrates the maximum yield strength (24.82 MPa), owing to its radial, concentric configuration, superior radial stiffness, effective stress distribution, and elevated stiffness-to- weight ratio.The Gyroid Lattice Structure exhibits moderate yield strength of 22.04 MPa, attributed to its intricate internal architecture, elevated surface area-to-volume ratio, and optimal balance of stiffness and toughness. Cubic Subdivision and Triangle Lattice Structures have reduced yield strengths (16.09 MPa and 13.03 MPa, respectively), presumably attributable to their simpler configurations, diminished surface area-to-volume ratios, and restricted deformation mechanisms. The yield strength of lattice systems is significantly.

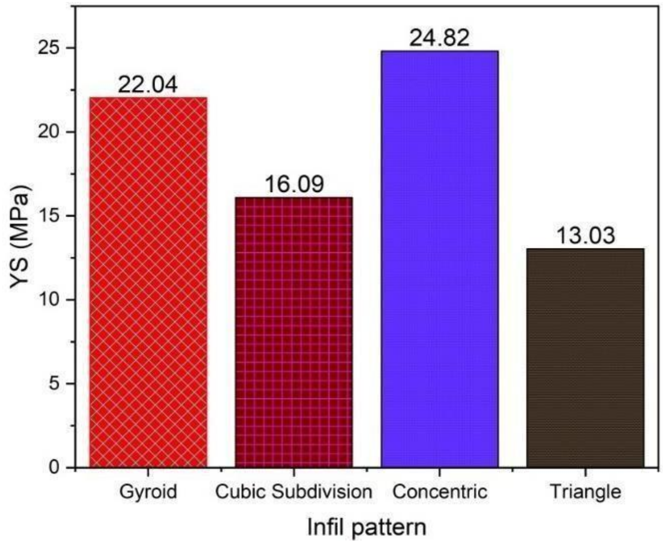

Fig 16 : comparative studies of the YS of different lattice structures

Compression strength :

A thorough examination of the compressive strength of diverse lattice structures, including Gyroid, Cubic Subdivision, Concentric, and Triangle, has been performed. The findings indicate notable variations in compressive strength across the analysed structures, underscoring the significance of internal geometry, surface area-to-volume ratio, and deformation mechanisms in influencing compressive resistance. Triangle Lattice Structure: Displays superior compression strength (79.13 MPa), resulting from its triangular lattice configuration, elevated angular stiffness, substantial surface area-to-volume ratio, and effective deformation mechanisms. In contrast, Concentric Lattice Structure: Shows considerable compression strength (63.59 MPa), owing to its radial, concentric design, remarkable radial stiffness, optimal stress distribution, and high stiffness-to-weight ratio. The Gyroid Lattice Structure exhibits moderate compressive strength (55.12 MPa) because to its intricate internal configuration, elevated surface area-to-volume ratio, and optimal balance of stiffness and toughness. The Cubic Subdivision Lattice Structure exhibits the lowest compressive strength (19.24 MPa), presumably because to its simplistic, orthogonal configuration, reduced surface area-to- volume ratio, and constrained deformation process. The compressive strength of lattice systems is significantly affected by their internal geometry, surface area-to-volume ratio, and deformation mechanisms. The triangular lattice structure demonstrates exceptional compressive strength owing to its distinctive amalgamation of angular rigidity, surface area- to-volume ratio, and deformation processes. These findings offer significant insights for the design and enhancement of lattice structures across diverse applications.

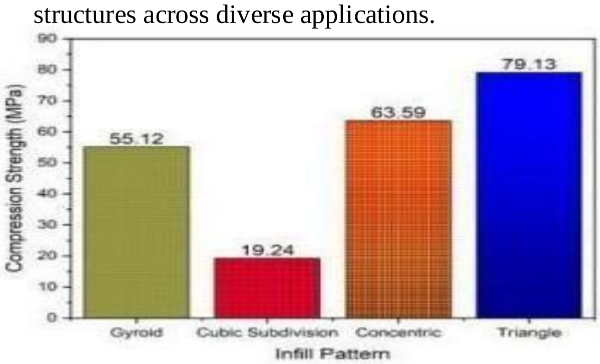

Fig 16 : Comparative studies of the Compression Strength of different lattice structures

Impact Strength :

A comparative analysis of the impact strength of different lattice structures, namely Gyroid, Cubic Subdivision, Concentric, and Triangle, has been performed. The results indicate considerable discrepancies in impact strength among the various constructions. Concentric lattice structures provide superior impact strength (27.6 MPa), owing to their radial, concentric configuration that offers exceptional radial stiffness and impact force resistance. Gyroid lattice structures exhibit moderate impact strength of 23.12 MPa, attributable to their intricate internal architecture, elevated surface area-to-volume ratio, and optimal balance of stiffness and toughness. Triangular lattice structures exhibit somewhat reduced impact strength (22.74 MPa) due to their triangular configuration, elevated surface area-to-volume ratio, and superior deformation mechanisms. Cubic Subdivision lattice structures exhibit the lowest impact strength (21.34 MPa), presumably because to their simplistic, orthogonal configuration, reduced surface area- to-volume ratio, and constrained deformation mechanisms. These discoveries have considerable significance for the design and development of lattice structures across diverse industries, including aeronautical, automotive, and biomedical engineering. By choosing the ideal lattice configuration, engineers can develop materials with customised mechanical properties, thereby improving their performance and efficiency.

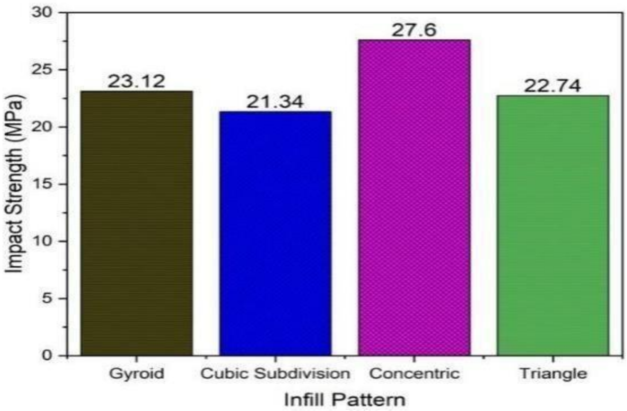

Fig 17 : Comparative studies of the Impact Strength of different lattice structures

IV. CONCLUSIONS

Studies on the influence of variable patterns on mechanical properties are successfully carried out.

Maximum Ultimate Tensile Strength of 21.26 is observed on Concentric pattern compared to Triangle, Gyroid and Cubic Subdivision pattern.

Maximum Compression Stength of 79.13MPa is observed on Triangle pattern,compared to Cubic Subdivision, Gyroid and Concentric pattern.

Maximum Impact Strength of 27.60 J/m is observed on Concentric pattern compared to Triangle, Gyroid and Cubic Subdivision pattern.

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