A Project Report on

Experimental Investigation of 3D Printed Parts for Different Infill Patterns and Infill Densities

Submitted in partial fulfilment of the requirements for the award of the Degree of

Bachelor of Technology

In

Mechanical Engineering.

Submitted by

Bhukya Divya 20011A0304

Adarsh Golla 20011A0347

Bagade Naveen Kumar 21015A0305

Merugu Chaitanya 21015A0314

Under the esteemed guidance of

Dr. G. Krishna Mohana Rao

Senior Professor

DEPARTMENT OF MECHANICAL ENGINEERING

UNIVERSITY COLLEGE OF ENGINEERING SCIENCE AND TECHNOLOGY HYDERABAD

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY HYDERABAD -500085

TELANGANA

UNIVERSITY COLLEGE OF ENGINEERING SCIENCE ANDTECHNOLOGY HYDERABAD

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY

HYDERABAD -500 085

TELANGANA

DECLARATION

We, the undersigned declare that the project report entitled "**EXPERIMENTAL INVESTIGATION OF 3D PRINTING PARTS FOR DIFFERENT INFILL PATTERNS AND INFILL DENSITIES** " has been carried out and submitted by us in partial fulfilment of the requirements for the award of the Bachelor of Technology in Mechanical Engineering at JNTUH University College of Engineering Science & Technology Hyderabad is an authentic work carried out under Guidance of **Dr. G. Krishna Mohana Rao**, Senior Professor of Mechanical Engineering Department and has not been submitted to any other university.

Bhukya Divya 20011A0304

Adarsh Golla 20011A0347

Bagade Naveen Kumar 21015A0305

Merugu Chaitanya 21015A0314

UNIVERSITY COLLEGE OF ENGINEERING SCIENCE ANDTECHNOLOGY HYDERABAD

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY

HYDERABAD -500 085

TELANGANA

CERTIFICATE

This is to certify that the project entitled **"EXPERIMENTAL INVESTIGATION OF 3D PRINTING PARTS FOR DIFFERENT INFILL PATTERNS AND INFILL DENSITIES"** is a Bonafide record of a project work carried out by

Bhukya Divya	**20011A0304**
Adarsh Golla	**20011A0347**
Bagade Naveen Kumar	**21015A0305**
Merugu Chaitanya	**21015A0314**

The Department of Mechanical Engineering, Jawaharlal Nehru Technological University Hyderabad, University College of Engineering Science and Technology Hyderabad, submitted in partial fulfilment of the requirement for the award of Degree of Bachelor of Technology in Mechanical Engineering.

Project Guide
Dr. G. Krishna Mohana Rao
Senior Professor
Mechanical Engineering
JNTUH UCESTH

Head of the Department
Dr. E. Ramjee
Professor
Mechanical Engineering
JNTUH UCESTH

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Bhukya Divya 20011A0304

Adarsh Golla 20011A0347

Bagade Naveen Kumar 21015A0305

Merugu Chaitanya 21015A0314

ABSTRACT

Additive manufacturing, particularly through Fused Deposition Modelling (FDM), has revolutionized industrial applications by enabling the production of lightweight and intricate designs with enhanced strength. Tensile strength tests, conducted according to ASTM standards, were employed to evaluate the mechanical properties of the printed samples. The results highlight the significant influence of infill patterns and densities on both tensile and impact strength. Infill pattern selection, such as rectilinear, honeycomb, triangular, and gyroid, played a crucial role in determining the structural integrity of the printed parts.

This study focuses on investigating the impact of infill patterns (rectilinear, honeycomb, triangular, and gyroid) and infill densities (30%, 60%, and 90%) on the mechanical properties of 3D printed parts using Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) materials.

The study reveals that ABS and PLA materials exhibit distinct responses to varying infill patterns and densities. Optimal mechanical properties were achieved under specific conditions, showcasing the potential for customization based on material and infill parameters. This research contributes valuable insights into tailoring the mechanical characteristics of 3D printed parts for diverse industrial applications, emphasizing the importance of careful material and infill pattern selection in FDM-based additive manufacturing.

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CHAPTER 1

INTRODUCTION

1.1. History and Development

Hideo Kodama initially introduced the concept of Additive Manufacturing (AM) in 1981. Later, in 1984, Charles Hull invented the stereolithography technique, which developed as the first commercial technology. Additive manufacturing is the process of creating or fabricating a 3D object directly from a CAD model through layer-by-layer manufacturing. In recent years, AM has attracted industrialists and researchers, and much effort has been put into this sector to develop faster and cheaper AM techniques that will help us get better print quality. These techniques produced critical and intricate products with comparatively lesser manufacturing cost and time. The significant advantage of AM techniques is the design freedom for the development of new products, which is one of the limitations in the conventional manufacturing process. The application of AM methods drastically reduces the lead time of product development.

1.2. Additive Manufacturing

Additive manufacturing, also known as 3D printing, revolutionizes production by fabricating three-dimensional objects layer by layer from digital models, typically created using Computer-Aided Design (CAD) software. This innovative process offers versatility, speed, and cost-effectiveness, enabling the production of intricate geometries and customized products across various industries. A CAD model is modelled using any 3D modelling platform in the conventional process. The mould development is done using the dimensional data of the CAD model. The finished part is manufactured by using the developed mould. In AM techniques, the final piece is created immediately through the CAD 3D model by eliminating the in-between processes like mould development. Ziemian [35] discussed the factors involved while converting the CAD 3D model into a 3D printed part through FDM. Fig. 1 shows the steps involved to create a 3D model with AM techniques. Various available CAD platforms are used to create 3D models. The CAD data is converted into STL (Standard Tessellation Language) format, which the 3D printer interface understands. Slicing software like Repetier®, Cura® are used to slice the STL file into subtle layers. 3D part is produced layer-by-layer by AM technologies with set process parameters. Post-processing is performed if needed after the printing is done to improve the surface finish of the final product.

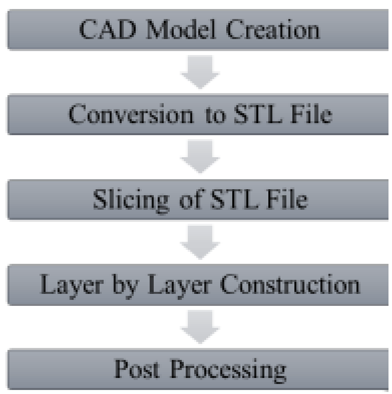


Fig. 1: General steps involved in additive manufacturing.

AM techniques are classified based on different methods and raw materials. The various techniques are differentiated based on the binding or sintering techniques. The raw materials are in the form of powder, liquid, and solid.

1.3. Fused Deposition Modelling

Fused Deposition Modelling (FDM) or Free Form Fabrication (FFF) is used extensively due to less expensive methods and raw materials. In the FDM technique depicted in Fig. 2, a polymer filament is fed to a heated extruder to melt the filament to a semi-molten temperature which is further deposited and cools down to develop a 3D structure. The degree of freedom of the extruder and platform depends on the fabrication of the printer. Generally, the extruder has movement in the z-directions, whereas the build platform moves in x and y-directions. The movement of the extruder and build platform is guided by the G-code generated by the slicing software. In some FDM systems (3D printers), multiple extrusion nozzles feed polymer components, especially when composite gradient components are required. The frequency, adjustment and performance of extrusion are highly dependent on the thermoplastic filament structures, and as a result, different 3D printers are designed for specific filament materials. The polymers filaments of Acrylonitrile butadiene styrene (ABS) and Polylactic Acid (PLA) is mainly used due to lower melting points. In contrast, polymers like Polyethylene terephthalate glycol (PETG), Polyether ether ketone (PEEK) are rarely used due to their higher melting point, which is difficult to handle.

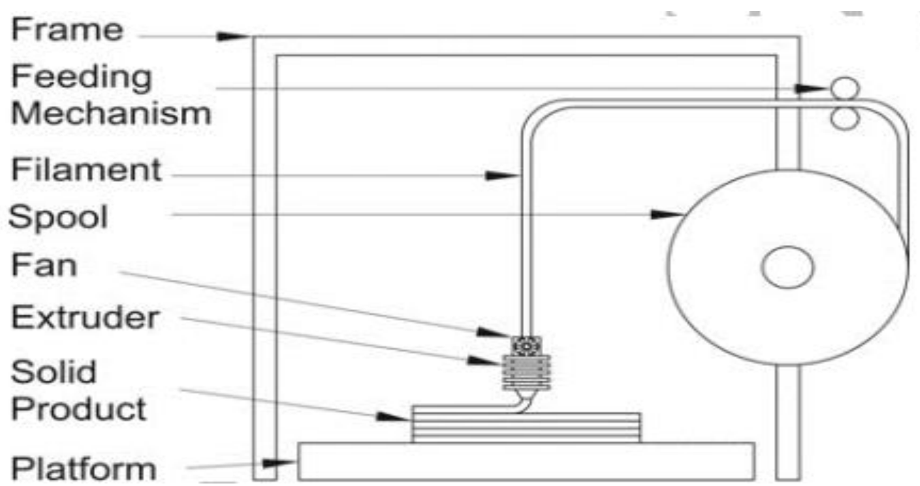


Fig. 2: Parts of Fused Deposition Modelling technique.

The various process parameters in FDM include air gap, layer thickness, raster width, infill pattern, raster angle, infill density, etc. These parameters are essential in influencing the physical properties of the 3D printed component. These process parameters also affect the lead time and the cost of the 3D printed part. In the initial years, the 3D printed products were used for the aesthetic purpose or feel a prototype, but with the change in time, the technology has been developed considerably, giving the freedom to replace the conventional manufacturing parts with 3D printed parts. It is essential to understand the influence of the respective process parameter on the physical behaviour of the 3D printed product, which is the objective of the review. Two process parameters, mainly infill density and infill pattern, are studied to understand the strength-to-weight performance of the 3D printed specimens.

1.4. Process Parameters

Process parameters play a vital role in controlling the physical behaviour, including part strength, surface quality and accurateness of the FDM printed part. The parameters control the size, shape, build time and interior structure. The user needs to set the parameters before creating the slicing of the STL file. The primary process parameters include layer thickness, model build temperature, infill pattern, infill density, raster width, raster air gap, shell thickness, raster angle, and build orientation depicted in Fig. 3.

1.4.1. Layer Thickness

Layer thickness can be defined as the slice height of the STL model for the part building. Layer thickness controls the motion of the nozzle or platform in the z-direction to build the next subsequent layer. The surface quality and accuracy are inversely dependent on the layer thickness.

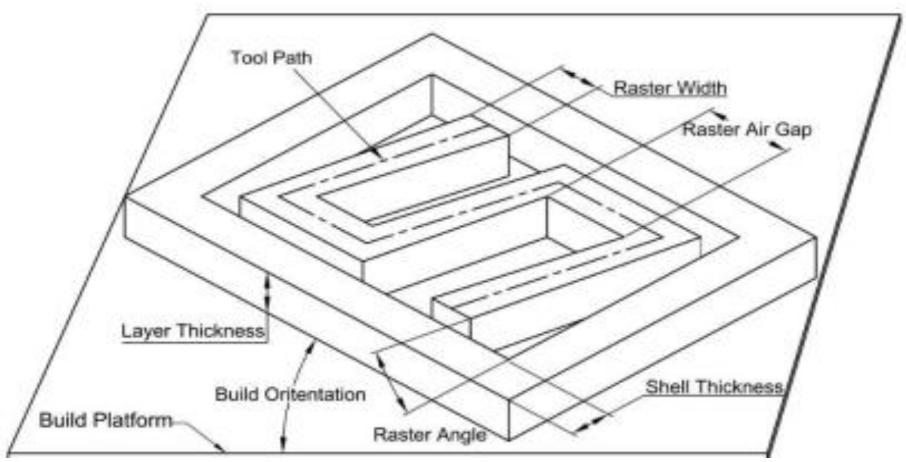


Fig. 3: Process parameters of FDM technique.

1.4.2. Model Build Temperature

The temperature at which the liquefier is set to feed the semi-liquid material to the nozzle to extrude on the previous layer is called a model build temperature. These temperatures influence the nature of bonding between the layers.

1.4.3. Infill Pattern

Infill pattern controls the motion of the nozzle or platform along the XY direction in filling the area of the layer. The infill pattern controls the build time, amount of raw material and strength of the FDM part depicted in Fig. 4.

1.4.4. Infill Density

Infill density is the amount of material used to fill the layer's inner area. This setting can make a part either fully or partially solid. The setting of the infill density is fed in the form of percentages like 25%, 50%, 75% or 100%. It again affects the build time, amount of raw material and strength of the FDM part. The various infill patterns are shown in Fig. 4.

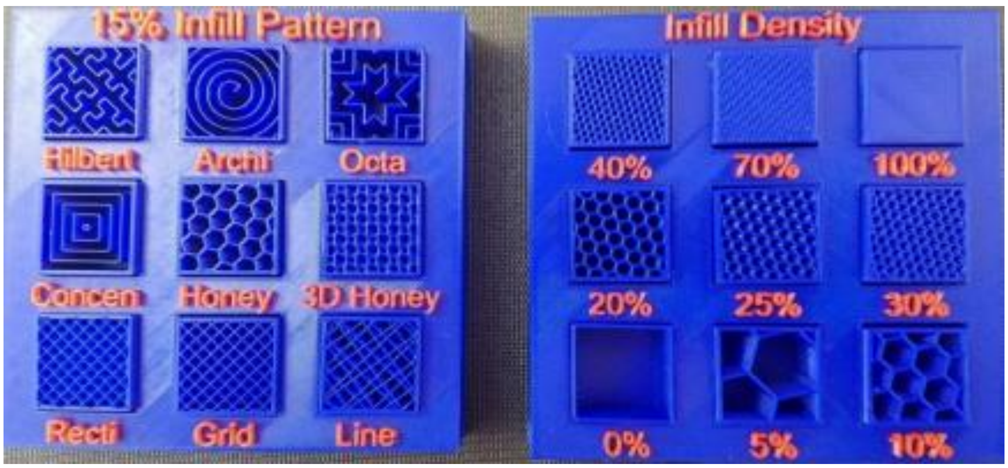


Fig. 4: Sample of various infill densities and infill patterns.

1.4.5. Raster Width

Raster width can be defined as the width of the infill pattern used to fill the interior regions of the part. It is dependent on the tip size of the nozzle. Raster width inversely affects the part accurateness and surface finish of the specimen.

1.4.6. Raster Air Gap

The distance between the two adjacent rasters is defined as a raster air gap. The gap between the shell boundary from the raster fill inside the contour perimeter is called the raster air gap. If the raster air gap is negative, the two adjacent rasters will overlap.

1.4.7. Raster Angle

Raster angle is the direction of the tool path motion concerning the x-axis of the platform. The range of raster angles is between 0° to 90°, set according to requirement. If the setting of the raster angle is fixed as ±45°, then in one layer, the direction of the tool path will be +45°, and in the next layer, it will be -45°. Raster angle is one of the reasons that the FDM part behaviour is anisotropic in nature.

1.4.8. Shell Thickness

When the nozzle or platform moves in z-direction for a new layer, the nozzle creates the boundary before filling it. Shell thickness defines the number of turns the tool will take around the edge of the layer. It is generally defined as one, two or three, i.e., the number of perimeters to be made before filling.

1.4.9. Build Orientation

Build orientation is the position inclination of the part to be made. Build orientation is one of the critical parameters because it decides the support material, which eventually affects the build time, amount of support material, the surface finish, and mechanical properties. Fig. 5 displays a different build orientation of the same 3D printed specimen, where Fig. 5 (a) and (b) are oriented without a support structure, while Fig. 5(c) consists of the support structure.

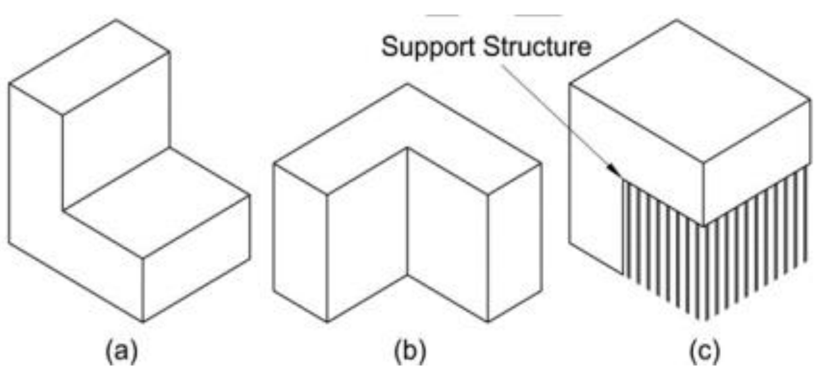


Fig. 5: Positioning of the 3D printed part with different build orientation (a) and (b) without support structure as well as (c) with the support structure.

The article's objective is to present the effect of infill density and infill pattern on the physical properties of the 3D printed specimen developed by the FDM technique. The literature selection is based on process parameters comprising infill density and infill patterns. If any other parameters are considered, it is also discussed along with it.

1.5 Testing

Universal Testing Machine (UTM) has long been a cornerstone in materials testing, playing a pivotal role in assessing the mechanical properties of various materials. As Fig. 6 illustrates, a typical UTM comprises essential components such as a load cell, grips, and a crosshead, allowing for the precise application of controlled forces to specimens. These forces induce deformation, enabling the measurement of crucial mechanical characteristics.

Fig.6: Universal tensile test machine.

The versatility of UTM lies in its ability to conduct a wide range of mechanical tests, including tensile, compressive, and flexural tests, which provide insights into parameters such as tensile strength, compressive strength, and modulus of elasticity. These tests are essential for understanding material behaviour under different loading conditions.

The significance of UTM extends across various industries, including manufacturing, construction, and research laboratories. In manufacturing, UTM is indispensable for quality control, ensuring that materials meet specified standards and exhibit the desired mechanical properties. In research, UTM aids in the development of advanced materials by providing a detailed understanding of their structural integrity.

This project focuses on utilizing the capabilities of a UTM to investigate the mechanical properties of 3D printed parts. The integration of UTM testing with additive manufacturing processes, such as FDM, allows for a comprehensive assessment of materials like Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). The study specifically explores the influence of infill patterns and densities on tensile and impact strength, shedding light on the customization potential of 3D printed components for diverse industrial applications.

In the following chapters, we will delve into the experimental setup, methodology, and results, presenting a detailed analysis of the mechanical behaviour of 3D printed parts under the scrutiny of UTM testing. Through this investigation, we aim to contribute valuable insights to the evolving landscape of additive manufacturing, highlighting the synergy between UTM and 3D printing technologies in advancing our understanding of material performance.

1.5.1. Universal Testing Machine Specifications (M-30)

Maximum Load Capacity: 30KN

Maximum Elongation: 1000mm (for tensile testing)

Maximum Deflection: 1000mm (for bending testing)

Software: Windows based software with data acquisition and analysis capabilities.

Speed Range: 0.1-400mm/min

1.6 Specimen Standards

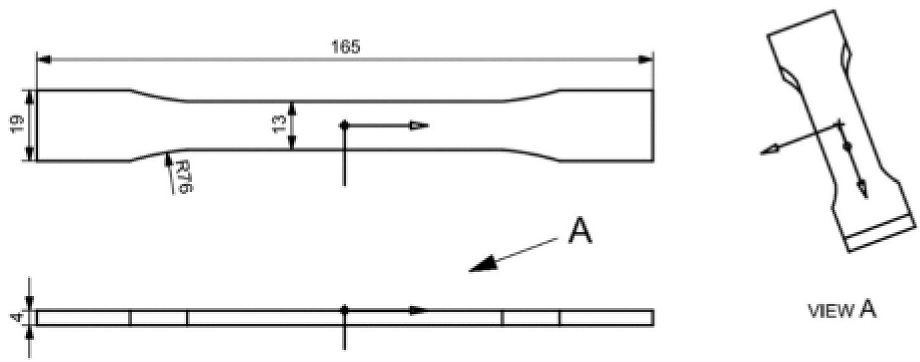


Fig. 7: Geometrical view of tensile test sample conferring ASTM 638

The tensile test specimens, designed in accordance with ASTM D638-I standards as depicted in Fig.7, embody meticulous attention to detail to ensure accurate and reliable testing outcomes. Sample Type 1 adheres strictly to a standardized configuration, featuring a precisely defined gauge length of 50 mm. This meticulous measurement section consistency is essential for accurate strain analysis. The gripping distance, extending precisely to 165 mm, aligns with ASTM specifications, emphasizing uniformity in the testing setup. These well-defined dimensions play a crucial role in guaranteeing the consistency and reproducibility of tensile test results. The adherence to such standardized parameters establishes a solid foundation for a comprehensive examination of the mechanical properties of materials under controlled loading conditions.

The commitment to precision in specimen design underscores the reliability of the tensile testing process, contributing to the validity and comparability of results across various studies or material assessments. The detailed adherence to ASTM standards reflects a dedication to methodological rigor, providing a basis for meaningful comparisons and evaluations in the field of materials science. By ensuring these stringent criteria are met, researchers can confidently draw insights into the mechanical behaviour of materials, facilitating advancements in materials characterization and engineering applications.

Fig. 8: Tensile Test Specimens Printed from PLA and ABS with Various Infill Patterns and Densities

This image depicts the 24 specimens used in the tensile tests, with an equal number printed from PLA and ABS. Each set includes specimens featuring different infill patterns (rectilinear, triangular, honeycomb, and gyroid) and varying infill densities (30%, 60%, and 90%).

CHAPTER 2

LITERATURE

2.1 Literature Review

Md. Qamar Tanveer et al. [1] showed that the complex profile customization, design, and production are made flexible with additive manufacturing (AM). The Fused Deposition Method (FDM) is a fundamental additive manufacturing technique. The mechanical strength of 3D printed parts is greatly influenced by the infill pattern and density. The article talks about the benefits of AM over traditional manufacturing methods, such as the FDM technique and its parameters. The strength-to-weight ratio of 3D printed parts is impacted by the density and pattern of the infill. The strongest pattern is rectilinear, and the printed specimens behave better physically when there is more infill density. Mechanical properties are also affected by the way infill patterns are designed during printing.

Adi P et al. [2] examined the effects of infill densities (100%, 80%, 60%, and 20%) on the 3D printed ABS-X, tough PLA, and PLA antibacterial nanocomposite materials' tensile mechanical properties. Through an understanding of the impact of infill design, the study seeks to optimize the advantages of 3D printed products with infill structures. The investigation also looks at the orientation, angle, and pattern of the infill in relation to loads. The findings imply that optimizing the advantages of infill structures requires a thorough understanding of the impact of infill design in 3D printed materials. The study also recommends developing a model to characterize printed materials with an infill structure for plastic and elastic deformation in FEM/FEA analyses.

Virendra K et al. [3] investigated the effects of 3-D printing over a wide a range of industrial applications. It looks at how various infill densities and patterns affect lightweight geometric designs. Using fused filament fabrication (FFF) technology, test samples were made and their mechanical characteristics evaluated. The impact and tensile strength were both strongly impacted by the infill pattern, according to the results.

Gabriel A. Johnson et al. [4] found that the surge in additive manufacturing has resulted in a notable rise in the number of 3D printers available for consumers; however, their ability to obtain material characterization data has been restricted. By performing ASTM Tensile (D638) tests on samples made by two commercially available 3D printers, this paper seeks to close this gap. Tensile strength, modulus, elongation, and failure mode are all strongly impacted by the infill percentage, according to the study, which evaluated seven materials from three polymer filament manufacturers. With the use of this data, components with precise loading requirements can be designed.

Shabana et al. [5] attempted the creation of complex shapes layer by layer without the need for human intervention. In contrast to multilayer structures, this study examines the mechanical performance of 3D printed ABS and PLA thermoplastics. With a higher flexural strength and elongation before breaking, PLA outperforms ABS and multilayer specimens in mechanical tests. By using this layered thermoplastic, the environmental impact can be minimized while meeting flexural strength requirements.

The objective of Sridharan K et al. [6] is to examine the mechanical properties and free vibration analysis of three different types of 3D printed engineering plastic materials: PC, PC-ABS, and AC-ABS (polycarbonate-butadiene styrene). The findings indicate that, in comparison to ABS and PC, PC-ABS material has a higher elastic modulus and load carrying capacity. The study also discovered that the PC-ABS thermoplastic blend offers better mechanical properties; however, more investigation is required to examine thermoplastic blends with various machine configurations and characteristics.

Adrian R.P et al. [7] used FDM additive manufacturing techniques to compare the mechanical properties of PLA and ABS. The study focuses on how the mechanical performance of PLA and ABS test specimens is affected by layer height, layer orientation, and infill density. ABS has less variability according to the results, with the infill percentage having the greatest impact. Compared to ABS, PLA specimens function more stiffly and have a higher tensile strength. Because PLA's layer bonds well, it can be used with additive technologies.

Aleska M et al. [8] have studied the process of FDM 3-D printing of thermoplastic materials like PLA and ABS. Prototypes and parts requiring greater dimensional accuracy are best served by PLA, while ABS offers superior mechanical qualities, faster printing rates, and greater heat resistance. PLA-X is a novel material that has higher toughness values than PLA but a mechanical behaviour similar to PLA due to the addition of second-phase particles. There is a price associated with adding second-phase particles, though.

Mohammed A et al. [9] shows the ability to create intricately shaped parts quickly and efficiently has made FDM a popular technique in additive manufacturing. Nonetheless, a number of FDM parameters, including raster angle, layer thickness, infill percentage, and printing speed, affect the mechanical characteristics of printed parts. Four FDM materials—PLA, ABS, PEEK, and PETG—are the subject of the study. The findings emphasize how crucial it is to choose the right process parameters in order to get better outcomes.

A. Nugroho et al. [10] used FFF and FDM to investigate the mechanical properties of materials printed through 3D printing. It is centered on the mechanical properties of materials made of PLA. The results of the study showed that flexural strengths are highly influenced by layer thickness. According to the study, as layer thickness increases, tensile strength first decreases and then increases. Additional factors like build orientation, feed rate, and tool patch will be investigated in future studies.

Mahmoud M et al. [11] investigated how FDM parts' mechanical properties are affected by infill patterns. Tests were conducted on six different infill patterns: full honeycomb, rectilinear, triangular, fast honeycomb, grid, and wiggle. The findings indicated that wiggle patterns had the highest ductility and elongation, while triangular infill patterns had the highest ultimate tensile strength and E-module.

Muammel M. Hanon et al. [12] explored the possibility of manufacture of anisotropic bodies through the prevalent 3D printing method, FDM, this study delves into the mechanical characteristics of two widely used plastics PLA and High-Temperature PLA (HT-PLA). Over seventy test specimens were fabricated with diverse settings for a comprehensive comparison of tensile strength values, elongation at break, and stress-strain curves. The optimal configuration, determined as X orientation, crossed 45/−45° raster direction, and 100% fill factor, revealed that HT-PLA exhibited superior elongation and tensile strength compared to PLA.

Marco L et al. [13] looked into the effect of parameters of 3D printing on the mechanical characteristics of PLA during production. Analysis of variance (ANOVA) is used in the study to assess how each parameter affects the mechanical properties. The results indicate that experiment with 60% infill, 220ºC extrusion temperature, 0º/90º raster angle, and 0.1 mm layer thickness has the best values for σUTS, σY, and E. The study also discovered that the best protection was given by materials like polyurethane and acrylic.

V.D. Sagias et al. [14] proposed a novel approach to understanding how printing factors influence the mechanical properties of 3D printed parts. The Taguchi methodology was used to optimize the combination of manufacturing parameters and their values. The study found that the main factor causing fractures was plastic deformation due to higher applied load than ultimate tensile strength.

Jose C.C et al. [15] examined the cost-effective additive manufacturing technique called FDM to create complex products with effective production and delivery processes. This study used FDM technology and PLA-graphene raw material to investigate the mechanical properties of 3D printed parts. The mechanical properties improved as the linear layer thickness parameters increased, according to the results. Impact energy reduced with infill, but tensile and flexural strengths rose. The study also assessed the connection between printing time/weight and mechanical properties. The outcomes supported designers' decision-making and complied with ASTM requirements.

Ei E.C et al. [16] evaluated the influence of layer thickness and infill density on PLA material's mechanical strength in a three-dimensional printing device. The Taguchi Method was used to test nine samples using the FDM technique. Regression functions, DOE, and optimization tools were used in the study to analyse data and raise machine productivity and product quality.

Md Algarni, [17] examined the mechanical characteristics of 3D printed PLA material and their effect on raster angle and moisture content. Three raster angles (0, 45, and 90) were tested in the study, and the PLA material's moisture content was changed. Tensile tests were performed on twenty-seven specimens; the results indicated that the best strength and strain mechanical properties were found in specimens with a 90% raster angle and 10% moisture content.

Samykano M et al. [18] explored the common additive manufacturing technique for producing robust, dimensionally stable parts is FDM. This work investigates how three key process variables affect the mechanical characteristics of 3D printed ABS. Young's modulus and tensile strength both significantly improved, while elongation at break decreased with increasing infill density, according to the results. It was discovered that an 80% infill percentage, a 55° raster angle, and a layer thickness of 0.5 mm produced the best mechanical properties.

S.T Dwiyati et al. [19] examined the tensile characteristics of ABS material that was printed in both axial and lateral directions. Tensile tests were performed on printed specimens of different thicknesses using a Zwick Roell Series Z 021 machine. The best outcomes were discovered in the axial direction of a layer with a thickness of 0.3 mm, a maximum load of 551.13 N, and a tensile strength of 30.60 MPa. The maximum force and tensile strength were greater in the axial direction. The study found that a tight structure is formed by additional layers.

S. Raja et al. [20] optimized printing parameters for FDM production using PLA filament, focusing on extruder temperature, bed temperature, layer height, printing speed, travel speed, infill, and shell count. Five ASTM D638 tensile specimens were produced using modern 3D printers. The study found that specimen I withstands more weight and moderate extension, making it the best printing parameter.

Rhoda A.M et al. [21] the investigated the process of 3D printed PLA components with different infill densities behave when it comes to fire. The findings indicate that as infill density rises, fuel load rises as well, maintaining combustion. While the flammability rating stays constant, the peak heat release rate and total heat release increase with infill density. Density increases tensile strength and ductility because porous materials are more prone to failure.

N. Mohan et al. [22] ensured that layers of material are deposited in a computer-controlled environment to create three-dimensional objects. One essential technique in AM is FDM. Its limitations, however, are limited use for functional parts and a limited range of materials. With an emphasis on composite materials like metal matrix composites, ceramic composites, natural fiber reinforced composites, and polymer matrix composites, researchers are currently trying to expand the variety of materials available for FDM. To enhance the FDM process and product quality, environmental and noise factors should be investigated in future research.

Saquib R et al. [23] observed that industrial component manufacturing is revolutionized by 3D printing, which has both technical and financial benefits. Its mechanical strength is being studied, especially in polymeric materials. The fatigue, tensile, and bending strength of 3D printed parts are all impacted by the process parameters. The technology is regarded as a sustainable replacement for traditional manufacturing processes and is employed in the aerospace, automotive, and medical industries.

Marton T.B et al. [24] examined the relationship between mass, pattern, and manufacturing time in 3D printed parts by comparing infill patterns and volume percentages using FDM technology. According to the study, printing time is influenced by the intricacy of the toolpath needed to create a pattern, with minor variations in mass for distinct patterns. Simple Grid patterns are not as mechanically resistant as Honeycomb and Gyroid patterns. 2D infill structures are equally efficient because no pattern exhibits remarkable mechanical anisotropy. Layer orientation may have a minor impact on crack propagation if it is not significant.

Rajneesh K et al. [25] explored the use of normal filaments in polymer composites due to their biodegradability, eco-benefits, and mechanical properties. This paper surveyed the flexural and weakening properties of regular fiber-supported polymer composites, focusing on factors like layer thickness, infill density, extrusion temperature, print speed, and FDM. The study also highlights the importance of considering cycle boundaries, incorporating carbon fiber in PLA, and incorporating carbon fiber in PLA for better results.

Vigneshwaran S et al. [26] analysed the performance and mechanical testing of polymer-fibre composites made by FDM. It calls for more research on various synthetic and natural fiber reinforcements by highlighting the impact of processing parameters on mechanical and thermal properties.

Cristina V et al. [27] checked the tensile properties of 3D printed specimens using FDM, The investigation focuses on the influence of spatial printing direction and size effect on mechanical properties, utilizing PLA dog bone specimens. The results reveal that spatial orientation has a lesser impact on young modulus but a more significant influence on tensile strength.

Oisik D et al. [28] used a versatile method of additive manufacturing that is used to create materials based on polymers is FDM. Nonetheless, fatigue behaviour under cyclic loading scenarios is critical for structural uses. With a focus on biomedical applications, this article assesses the fatigue characteristics of 3D printed polymeric materials. Although there hasn't been enough research done on the fatigue mechanism of FDM-based composites, the fiber's characteristics may help extend their fatigue life.

S.G Hernandeza et al. [29] presented a methodology for predicting the mechanical properties and mesostructure of FDM polymers. It proposes a computational framework for simulation using manufacturing parameters and filament properties. A two-stage thermal and sintering model is developed to predict filament bond formation. The model predicts void density and mechanical properties, with layer height and environment temperature being the most relevant manufacturing parameters.

Aboma W.G et al. [30] looked at how the high-performance ULTEM 9085 polymeric material's tensile properties are affected by the parameters of the FDM process. According to the study, one important factor that greatly affected the material's tensile strength was the raster angle. Based on the results, it is recommended that more levels be included in future research in order to get more precise results.

Tomasz K et al. [31] investigated the effects of model orientation and location on mechanical characteristics during uniaxial compression tests, such as Young's modulus and stress relaxation. The Stratasys Dimension 1200es 3-D printer was utilized to create cylindrical samples through the application of EDM technology. The findings demonstrate that rheological properties are strongly influenced by print direction. An angle of 0° yielded the highest Young's modulus value, whereas an angle of 45° produced the highest elasticity modulus.

Wenzheng Wu et al. [32] used FDM to examine the mechanical properties of 3D-printed polyether-ether-ketone (PEEK). The findings indicate that PEEK outperforms ABS in terms of tensile, compressive, and bending strengths, with an average tensile strength that is 108% higher. The ideal mechanical characteristics were discovered at a layer thickness of 300 μm and a raster angle of 0″/90″. The study concludes that more investigation is required to enhance the 3D printing system's hardware precision and control accuracy.

Ismail D et al. [33] investigated the effects of part orientations and raster angles on the surface finish and mechanical characteristics of FDM components. The study discovered that orientation affects mechanical behaviour and surface roughness more so than raster angle. Additionally, the study discovered that the best mechanical characteristics and surface roughness were found in specimens with a 0° raster angle in the horizontal direction.

K.G.J Christiyan et al. [34] evaluated the mechanical characteristics of an ABS + hydrous magnesium silicate composite using ASTM D638 and ASTM D760 standards. Employing AM technologies, specifically desktop 3D printing, the research focused on varying printing parameters. Results indicated that the lowest printing speed and layer thickness yielded the highest tensile and flexural strength. The successful fabrication of the composite using desktop 3D printers underscores their efficacy in engineering component production.

Ziemian et al. [35] provided a detailed overview of Additive Manufacturing (AM) advancements, emphasizing the transition from traditional methods to direct CAD model-to-3D print processes like FDM. Her work highlights the critical factors in converting CAD models to 3D printed objects, including the impact of layer thickness and model build temperature on print quality and mechanical properties. Ziemian's study on tensile tests using various infill patterns and densities further illustrates the optimization of print settings for specific performance requirements.

2.2 Literature Summary

This study explores the mechanical properties of 3D printed parts using FDM technology, focusing on ABS and PLA. It examines the influence of infill patterns and densities on the tensile and impact strength of the printed components. The findings highlight the importance of tailored approaches in optimizing mechanical properties. The study identifies optimal conditions for enhanced tensile and impact strength, highlighting the potential for customization based on specific material and infill parameters. The findings highlight the critical role of careful material and infill pattern selection in achieving optimal mechanical characteristics, emphasizing the need for informed decision-making in the application of FDM technology for 3D printing. The research contributes to the ongoing dialogue on refining additive manufacturing techniques and emphasizes the need for a thoughtful approach to material and process parameter selection for superior mechanical properties in 3D printed parts.

2.3 Gap Identification

1.) Limited exploration of infill percentages in previous research suggests a need to investigate a broader range to understand their effects on mechanical properties and printing outcomes comprehensively.

2.) Previous studies have overlooked the influence of printing time and layer size, indicating a gap in understanding the optimization of printing efficiency and part quality.

3.) The neglect of ABS material 3D printing through FDM technology underscores gaps in knowledge regarding its printing characteristics, mechanical properties, and post-processing requirements compared to PLA.

4.) Further research is warranted to explore techniques for enhancing the surface finish of PLA and ABS parts without relying on chemical treatments, reducing the need for labour-intensive post-processing steps.

5.) Comprehensive cost-effectiveness analyses, considering factors beyond material prices such as processing parameters and post-processing requirements, are necessary for informed decision-making in PLA and ABS part production.

2.4 Problem Statement

This project aims to address this gap by investigating the impact of infill patterns and densities on the mechanical strength of 3D printed PLA and ABS parts, providing valuable insights for improving print quality and performance.

2.5 Assumptions

1. It is assumed that the mechanical properties of PLA and ABS materials are consistent and uniform across different batches from the same supplier.

2. The 3D printer (Creality Ender 3) is assumed to be properly calibrated before each print, ensuring that variations in the printing process are minimized.

3. The experiments are conducted under controlled environmental conditions, assuming that factors such as temperature, humidity, and air currents do not significantly affect the printing and testing processes.

4. It is assumed that the adhesion between printed layers is consistent and uniform, which directly impacts the tensile strength and other mechanical properties of the printed specimens**.**

5. The infill within the printed specimens is assumed to be evenly distributed according to the specified patterns and densities, ensuring that the internal structure of the specimens is consistent.

6. All test specimens are assumed to be printed and post-processed according to ASTM D638 standards for tensile testing, ensuring comparability and validity of the test results.

7. The performance of the 3D printer and slicing software (used to generate G-code) is assumed to be optimal, with no significant errors or deviations affecting the print quality.

8. It is assumed that the nozzle and bed temperatures remain stable throughout the printing process, avoiding any fluctuations that could affect the material properties.

9. The impact of different infill patterns (rectilinear, honeycomb, triangular, gyroid) on the mechanical properties is assumed to be significant and measurable.

10. It is assumed that varying the infill density (30%, 60%, 90%) will have a noticeable impact on the tensile strength and elongation at break of the printed parts.

2.6 Methodology

The methodology employed in this study encompasses the selection and characterization of two thermoplastic materials, PLA and ABS, chosen for their distinct properties and common usage in 3D printing applications. With PLA offering ease of use and environmental friendliness and ABS providing toughness and impact resistance, the materials were subjected to a comprehensive analysis. Experimental parameters, including infill patterns (Rectilinear, Honeycomb, Triangular, Gyroid) and densities (30%, 60%, 90%), were meticulously chosen to investigate their influence on the mechanical properties of printed parts. Tensile Strength and Elongation at Break served as key output parameters, evaluated to understand the structural integrity and mechanical performance of the specimens. The experimental procedure, from printer calibration to mechanical testing using a UTM according to ASTM D638 standards, was rigorously followed to ensure consistency and accuracy. Leveraging Taguchi's method, the study optimized process parameters and minimized experimental runs while maintaining a balanced exploration of the parameter space.

2.7 Objectives

1. To study how different materials, specifically PLA and ABS, and the FDM process influence the mechanical properties of 3D printed parts. This includes examining the impact of infill density on properties such as strength.

2. To investigate key mechanical properties of 3D printed materials, focusing on tensile strength. This objective aims to understand how material choices affect the robustness and structural integrity of the printed objects.

3. To explore the effects of various infill patterns, including rectilinear, honeycomb, gyroid, and triangular, on the tensile properties of 3D printed parts. The objective is to determine which infill patterns exhibit the highest tensile strength.

CHAPTER-3

EXPERIMENTAL DETAILS

3.1 Materials Used

In this study, two types of thermoplastic materials were utilized: PLA and ABS. These materials were selected for their distinct properties and widespread use in various 3D printing contexts.

3.1.1 Polylactic Acid (PLA)

PLA is a biodegradable thermoplastic derived from renewable resources like corn starch or sugarcane. It is one of the most popular materials used in 3D printing due to its ease of use and environmentally friendly nature. PLA is known for its good surface finish, minimal warping, and ability to print fine details.

Characteristics:

- Easy to print with
- Low warping tendency
- Available in a variety of colours and blends
- Biodegradable and environmentally friendly

Properties:

- Tensile Strength: 50-70 MPa
- Density: 1.25 g/cm^3
- Melting Point: 180-220°C
- Young's Modulus: 3.5-4 GPa
- Elongation at Break: 3-6%

Applications: Commonly used for prototyping, consumer goods, and biomedical devices. It is suitable for applications where biodegradability and a good surface finish are important.

3.1.2 Acrylonitrile Butadiene Styrene (ABS)

ABS is a petroleum-based thermoplastic known for its toughness, impact resistance, and ability to withstand higher temperatures compared to PLA. It is widely used in 3D printing for applications that require durability and mechanical strength. ABS parts generally exhibit better mechanical properties but can be more challenging to print due to issues like warping and odors during printing.

Characteristics:

- High impact resistance
- Good mechanical strength
- Can be post-processed (sanded, machined, glued)
- Requires higher printing temperatures
- More prone to warping and odors during printing

Properties:

- Tensile Strength: 40-50 MPa
- Density: 1.04 g/cm^3
- Melting Point: 220-250°C
- Young's Modulus: 2-2.5 GPa
- Elongation at Break: 10-30%

Applications: Widely used in automotive parts, electronic housings, and toys (e.g., LEGO bricks). It is suitable for applications that demand high impact resistance and durability.

3.2 Experimental Parameters

3.2.1 Input Parameters

Input parameters are the controllable factors that influence the outcome of the experiments. In this study, the following input parameters were considered:

- Infill Pattern: Rectilinear, Honeycomb, Triangular, Gyroid
- Infill Density: 30%, 60%, 90%

These parameters were selected based on their significant impact on the structural integrity and mechanical properties of 3D printed parts.

3.2.2 Output Parameters

Output parameters are the measurable responses or characteristics of the printed parts. The following output parameters were evaluated in this study:

- Tensile Strength: The maximum stress endured by the specimen before failure occurred during the tensile test. This parameter provides insight into the material's ability to withstand tensile loading.
- Elongation at Break: The percentage of deformation the specimen undergoes before fracture, indicating its ductility or ability to deform plastically before failure.

These parameters were chosen to assess the mechanical performance and structural integrity of the printed parts under different experimental conditions.

3.3 Experimental Methodology Overview

A flowchart outlining the experimental procedure is provided below:

The experimental methodology for this study is designed to systematically investigate the effects of different infill patterns and densities on the mechanical properties of 3D printed PLA and ABS parts using FDM technology. The following steps outline the comprehensive process, from material selection to data analysis.

1. Start: The process begins with the initial planning and setup of the experimental study.

2. Material Selection: Two widely used materials PLA and ABS, are selected for their distinct mechanical properties and common usage in 3D printing.

3. Parameter Selection: The primary input parameters chosen for this study are the infill patterns (Rectilinear, Honeycomb, Triangular, Gyroid) and infill densities (30%, 60%, 90%). The output parameters to be measured include tensile strength and elongation at break.

4. 3D Printer Setup: The 3D printer (Creality Ender 3) is calibrated to ensure precision and consistency in the printing process and Printer settings are configured according to the selected process parameters for each experimental run.

5. Design of Experiments (Taguchi Method): The Taguchi method is employed using an orthogonal array (L9) to design the experiments. This approach ensures a balanced and efficient exploration of the parameter space while minimizing the number of experimental runs.

6. Specimen Fabrication: Test specimens are fabricated using the selected infill patterns and densities. The printing process is closely monitored to ensure consistency and quality.

7. Post-Processing: Printed specimens are allowed to cool down and solidify properly and a visual inspection is conducted to identify any defects or inconsistencies in the specimens.

8. Mechanical Testing Preparation: Specimens are prepared for mechanical testing according to ASTM D638 standards and the UTM is set up for conducting tensile strength tests.

9. Mechanical Testing: Tensile tests are conducted on the specimens to measure tensile strength and elongation at break. Data from these tests are recorded for further analysis.

10. Data Analysis: The collected data is analysed using statistical methods to understand the effects of different infill patterns and densities on the mechanical properties and Taguchi's method is used to identify the optimal combination of parameters for achieving the best mechanical properties.

11. Result Interpretation: Results are interpreted to draw conclusions about the impact of infill patterns and densities on the mechanical properties of PLA and ABS parts and findings and insights from the experiments are documented for reporting.

12. Conclusion: Key findings and implications of the study are summarized and potential areas for further research and improvement are suggested.

13. End: The experimental process concludes with the finalization of the report and sharing of results.

3.4 Experimental Setup

The experimental procedure involved the following steps:

1. Preparation of Printer: The Creality Ender 3 3D printer shown in fig.9 was calibrated and configured according to the specified process parameters for each experimental run.

2. Fabrication of Test Specimens: Test specimens were fabricated using the selected infill patterns, infill densities, and other process parameters. The printing process was monitored to ensure consistency and accuracy.

3. Mechanical Testing: The fabricated specimens were subjected to tensile strength tests using a Universal Testing Machine (UTM) according to ASTM D638 standards. The tests were conducted to evaluate the mechanical properties of the printed parts, including tensile strength, elongation at break, and Young's modulus.

Fig.9: Creality Ender 3 3D Printer

3.5 Fabrication Processes

The fabrication process for this study was meticulously planned and executed to ensure the production of high-quality 3D printed specimens. The process began with the design of the specimens using CAD software, followed by slicing the designs with slicing software like Cura to generate the necessary G-code for printing. This slicing software enabled the precise setting of parameters such as infill pattern, infill density, layer height, and print speed. Next, the 3D printer, specifically the Creality Ender 3, was prepared by cleaning and prepping the print bed with adhesive, if needed, to enhance bed adhesion. The appropriate filament, either PLA or ABS, was loaded into the printer, and it was preheated to the suitable temperature for the chosen material.

Calibration was a critical step in the process, involving the levelling of the printer bed and alignment of the nozzle to ensure accurate layer deposition and prevent print failures. Once the printer was calibrated, the G-code was uploaded, and the printing process began. The specimens were printed layer by layer according to the specified parameters, with continuous monitoring to avoid issues such as warping or clogging. Upon completion of the printing, the specimens were allowed to cool and solidify fully before removal from the print bed, which helped maintain dimensional accuracy and prevent warping.

Each printed specimen underwent a thorough inspection for visible defects like layer separation or incomplete structures. Specimens found to be defective were discarded, and replacements were printed as necessary. The post-processing required was minimal, typically involving the careful removal of support structures to avoid damaging the specimens. The finished specimens, each weighing approximately 8 to 10 grams, were then stored in a controlled environment to prevent moisture absorption and degradation until they were ready for mechanical testing. This comprehensive fabrication process ensured that the specimens were of high quality and suitable for subsequent testing, as depicted in Fig.10.

Fig.10: 3-D Printed Specimen

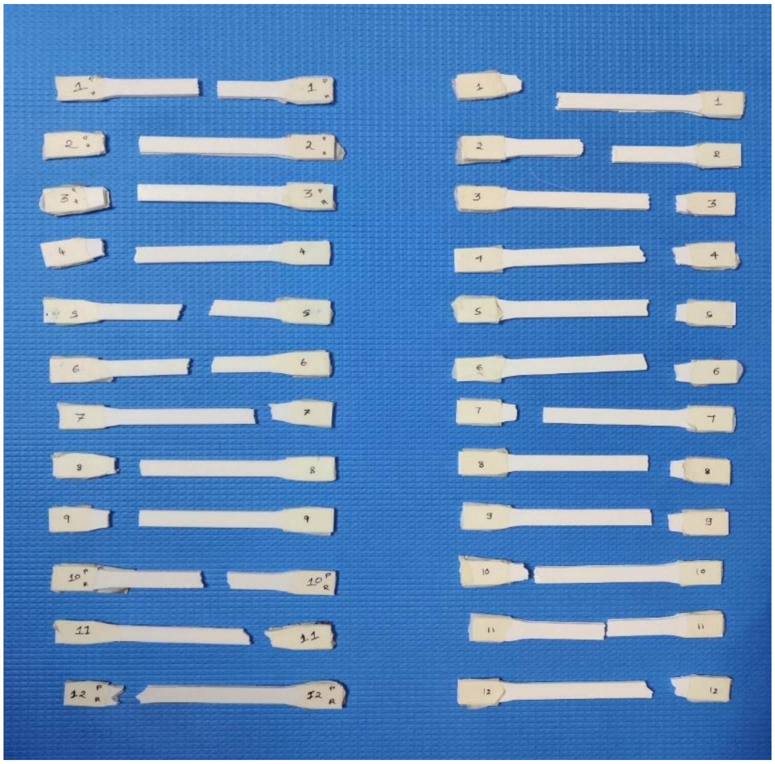
3.6 Design of Experiments

To systematically investigate the effects of various infill patterns and densities on the mechanical properties of 3D printed parts, an experimental design matrix was developed. This matrix outlines the combination of input parameters used to fabricate the test specimens.

Table 1: Experimental Design Parameters.

Run	Infill Pattern	Infill Density (%)
1	Rectilinear	30
2	Rectilinear	60
3	Rectilinear	90
4	Honeycomb	30
5	Honeycomb	60
6	Honeycomb	90
7	Triangular	30
8	Triangular	60
9	Triangular	90
10	Gyroid	30
11	Gyroid	60
12	Gyroid	90

Table 1 represents the systematic variation of infill patterns and infill densities used to fabricate the test specimens. Each combination is tested to analyse its effect on the mechanical properties of the printed parts, providing valuable insights into optimizing the FDM process.



(a) **(b)**

Fig.11: Post-Tensile Test Samples of 12 PLA (a) and 12 ABS (b) Specimens.

The specimens exhibit various degrees of fracture and deformation, demonstrating the impact of different infill patterns (rectilinear, triangular, honeycomb, and gyroid) and infill densities (30%, 60%, and 90%) on mechanical properties.

CHAPTER-4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results of the tensile strength tests performed on the 3D printed PLA and ABS specimens with varied infill patterns and densities. The results are analysed to determine the effects of these parameters on the mechanical properties of the printed parts. Additionally, the findings are discussed in the context of existing literature and potential applications.

4.2 Tensile Strength Results of PLA

The tensile strength tests were conducted using a UTM according to ASTM D638 standards. The results for each combination of infill pattern and infill density are summarized in Table 2.

Table 2: Tensile Test Results of PLA

Specimen Number	Specimen Code	Tensile Strength (N/mm^2)	Elongation at peak (mm)	Elongation at break (mm)	Elongation (%)
1	PR30	14.619	4.88	5.31	8.55
2	PR60	17.654	4.71	6.02	8.26
3	PR90	27.75	3.24	4.38	5.68
4	PH30	17.642	5.72	7.37	10.03
5	PH60	23.048	4.02	5.91	7.04
6	PH90	27.41	4.17	7.07	7.31
7	PT30	15.687	3.86	4.15	6.78
8	PT60	17.452	3.86	4.15	6.78
9.	PT90	20.96	3.39	4.98	5.94
10	PG30	17.21	3.47	3.49	6.08
11	PG60	22.46	4.2	4.57	7.37
12	PG90	26.66	3.37	4.2	5.91

The mechanical properties of PLA specimens were analysed using different infill patterns and percentages, including Rectilinear, Honeycomb, Triangular, and Gyroid, each at 30%, 60%, and 90% infill. The results shown in Fig. 12 indicated that increasing the infill percentage generally enhanced the tensile strength across all patterns. For instance, the rectilinear pattern exhibited a tensile strength increase from 14.619 MPa at 30% infill to 27.75 MPa at 90% infill. Similarly, the Honeycomb pattern showed significant improvements, with tensile strength rising from 17.642 MPa at 30% infill to 27.41 MPa at 90% infill. These patterns demonstrated substantial gains in tensile strength with higher infill percentages.

Conversely, the Gyroid pattern, while achieving high tensile strength values (17.21 MPa at 30% infill to 26.66 MPa at 90% infill), did not show as pronounced an increase as the Rectilinear and Honeycomb patterns. The Triangular pattern consistently exhibited lower tensile strength compared to the other patterns, regardless of the infill percentage, with values ranging from 15.867 MPa at 30% infill to 20.96 MPa at 90% infill. These findings highlight the importance of selecting the appropriate infill pattern and percentage to meet specific mechanical requirements, with the Honeycomb and Rectilinear patterns proving particularly effective for applications demanding high strength.

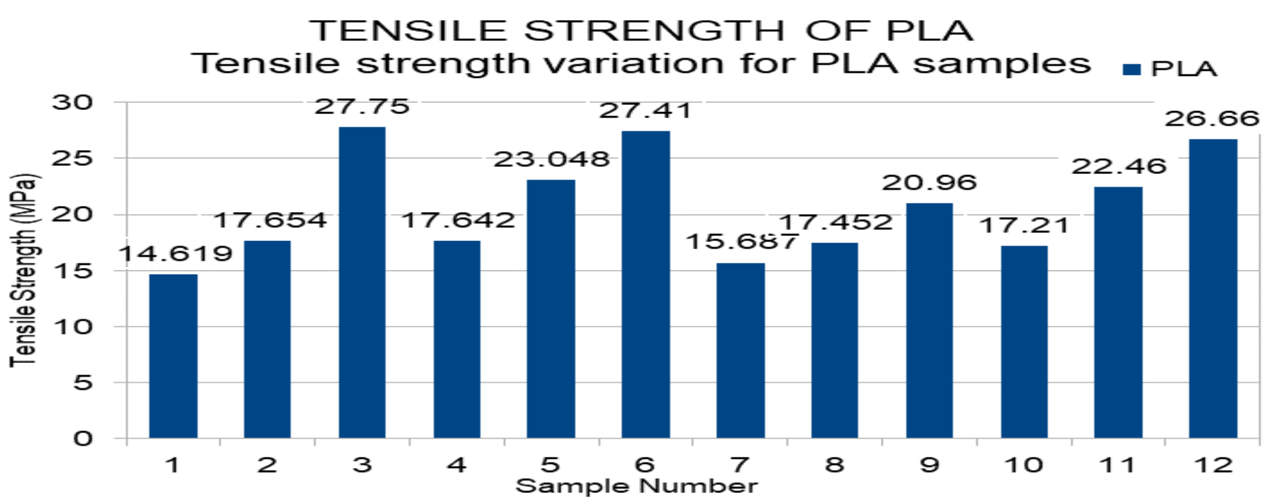


Fig. 12: Bar graph for Tensile Strength(N/mm^2) vs Specimen number (PLA).

From Tensile Test Of PLA:

- The properties of the specimens are interpreted from the graph which is plotted between the load and elongation.
- The specimen 3 of PLA has the highest tensile strength of all PLA samples at 27.75 Mpa which has rectilinear infill pattern at 90 % infill pattern.
- And specimen 1 of PLA has the lowest tensile strength of all PLA samples at 14.619 Mpa, which also has rectilinear infill pattern at 30 %.
- The relation of tensile strength and infill percentage for rectilinear infill pattern is not linear as there is a sharp jump for Sample 2 and 3 that is from 17.654 Mpa to 27.75 Mpa
- There is a consistent linear relationship of infill percentage and tensile strength in honeycomb (4,5,6) and gyroid (10,11,12) infill pattern for PLA.

4.2.1 Tensile Test Results of PLA

The tensile test results highlight the influence of different infill patterns and infill densities on the mechanical properties of PLA specimens. Tensile test results of PLA samples are depicted in Fig. 13 to Fig. 24. The following sections present a detailed analysis of these findings.

- **Specimen number: 1**

  Material – PLA

  Infill pattern - Rectilinear

  Infill Density – 30%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 98_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

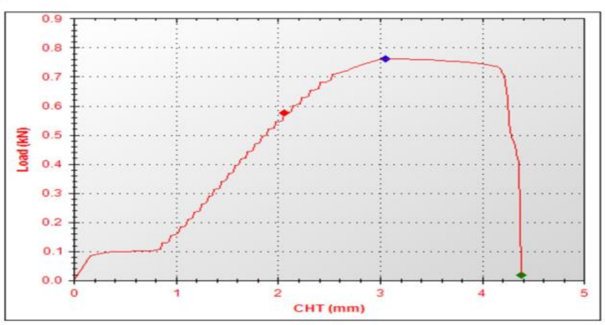
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.574	kN
Elongation At Yield	: 2.062	mm
Yield Stress	: 11.037	N/mm2
Load at Peak	: 0.760	kN
Elongation at Peak	: 3.236	mm
Tensile Strength	: 14.619	N/mm2
Load At Break	: 0.017	kN
Elongation At Break	: 4.383	mm
Breaking Strength	: 0.329	N/mm2
% Elongation	: 5.68	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 13: Tensile Test Report for PLA with Rectilinear Infill Pattern at 30% Infill Density.

• **Specimen number: 2**

Material – PLA

Infill pattern - Rectilinear

Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 97_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

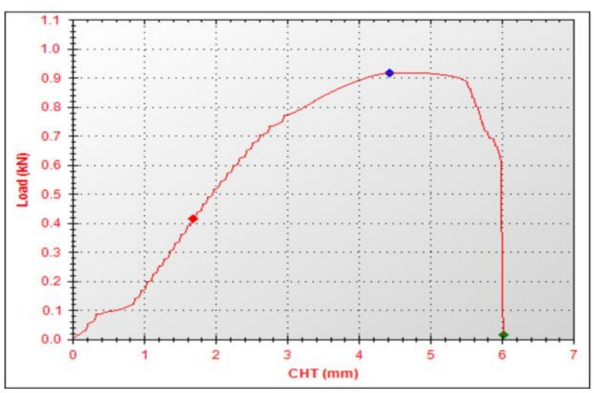
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.413	kN
Elongation At Yield	: 1.686	mm
Yield Stress	: 7.95	N/mm2
Load at Peak	: 0.918	kN
Elongation at Peak	: 4.710	mm
Tensile Strength	: 17.654	N/mm2
Load At Break	: 0.015	kN
Elongation At Break	: 6.017	mm
Breaking Strength	: 0.288	N/mm2
% Elongation	: 8.26	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 14: Tensile Test Report for PLA with Rectilinear Infill Pattern at 60% Infill Density.

• **Specimen number: 3**

Material – PLA

Infill pattern - Rectilinear

Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 96_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

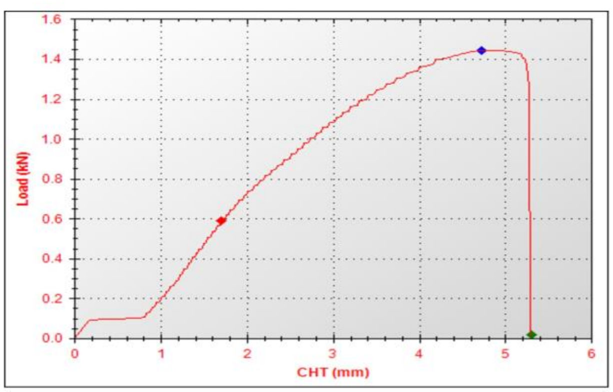
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.59	kN
Elongation At Yield	: 1.705	mm
Yield Stress	: 11.342	N/mm2
Load at Peak	: 1.443	kN
Elongation at Peak	: 4.876	mm
Tensile Strength	: 27.750	N/mm2
Load At Break	: 0.015	kN
Elongation At Break	: 5.309	mm
Breaking Strength	: 0.288	N/mm2
% Elongation	: 8.55	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 15: Tensile Test Report for PLA with Rectilinear Infill Pattern at 90% Infill Density.

- **Specimen number: 4**

  Material – PLA

  Infill pattern - Honeycomb

  Infill Density – 30%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 101_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

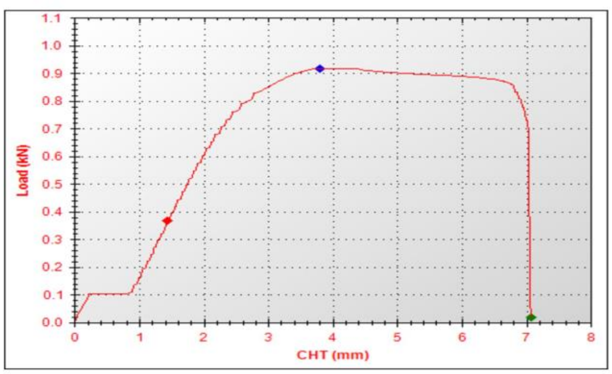
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.368	kN
Elongation At Yield	: 1.443	mm
Yield Stress	: 7.079	N/mm2
Load at Peak	: 0.917	kN
Elongation at Peak	: 4.166	mm
Tensile Strength	: 17.642	N/mm2
Load At Break	: 0.017	kN
Elongation At Break	: 7.071	mm
Breaking Strength	: 0.323	N/mm2
% Elongation	: 7.31	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 16: Tensile Test Report for PLA with Honeycomb Infill Pattern at 30% Infill Density.

- **Specimen number: 5**

  Material – PLA

  Infill pattern - honeycomb

  Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 100_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

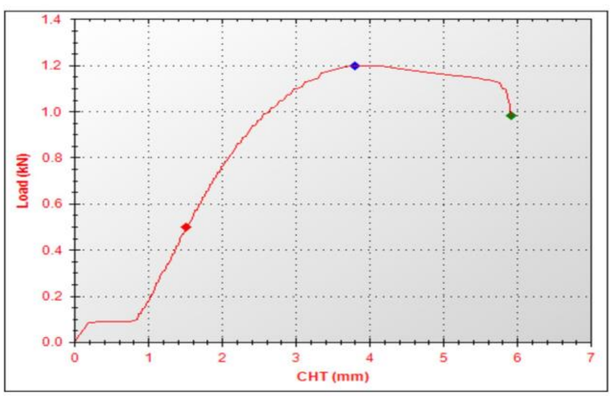
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.496	kN
Elongation At Yield	: 1.512	mm
Yield Stress	: 9.548	N/mm2
Load at Peak	: 1.199	kN
Elongation at Peak	: 4.015	mm
Tensile Strength	: 23.048	N/mm2
Load At Break	: 0.980	kN
Elongation At Break	: 5.913	mm
Breaking Strength	: 18.854	N/mm2
% Elongation	: 7.04	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 17: Tensile Test Report for PLA with Honeycomb Infill Pattern at 60% Infill Density.

• **Specimen number: 6**

Material – PLA

Infill pattern - honeycomb

Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 99_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

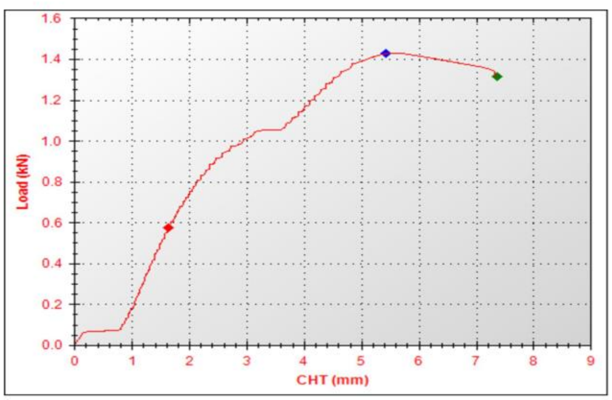
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.574	kN
Elongation At Yield	: 1.634	mm
Yield Stress	: 11.048	N/mm2
Load at Peak	: 1.425	kN
Elongation at Peak	: 5.717	mm
Tensile Strength	: 27.410	N/mm2
Load At Break	: 1.315	kN
Elongation At Break	: 7.366	mm
Breaking Strength	: 25.292	N/mm2
% Elongation	: 10.03	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 18: Tensile Test Report for PLA with Honeycomb Infill Pattern at 90% Infill Density.

- **Specimen number: 7**

  Material – PLA

  Infill pattern - Triangular

  Infill Density – 30%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 94_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

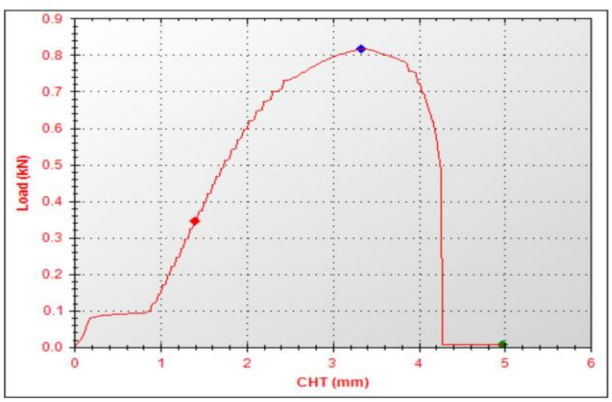
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.346	kN
Elongation At Yield	: 1.391	mm
Yield Stress	: 6.658	N/mm2
Load at Peak	: 0.816	kN
Elongation at Peak	: 3.385	mm
Tensile Strength	: 15.687	N/mm2
Load At Break	: 0.007	kN
Elongation At Break	: 4.977	mm
Breaking Strength	: 0.133	N/mm2
% Elongation	: 5.94	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 19: Tensile Test Report for PLA with Triangular Infill Pattern at 30% Infill Density.

• **Specimen number: 8**

Material – PLA

Infill pattern - Triangular

Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 91_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

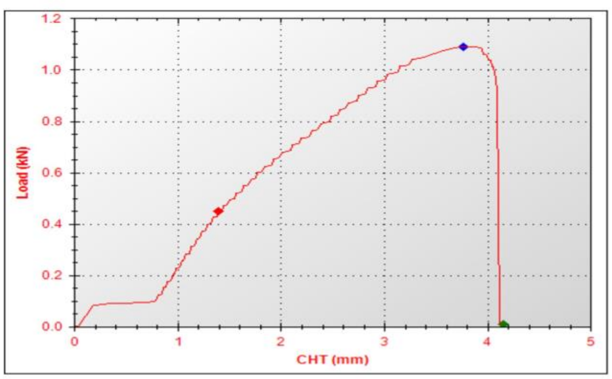
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.448	kN
Elongation At Yield	: 1.394	mm
Yield Stress	: 8.613	N/mm2
Load at Peak	: 1.090	kN
Elongation at Peak	: 3.864	mm
Tensile Strength	: 20.960	N/mm2
Load At Break	: 0.007	kN
Elongation At Break	: 4.151	mm
Breaking Strength	: 0.138	N/mm2
% Elongation	: 6.78	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 20: Tensile Test Report for PLA with Triangular Infill Pattern at 60% Infill Density.

• **Specimen number: 9**

Material – PLA

Infill pattern - Triangular

Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 91_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

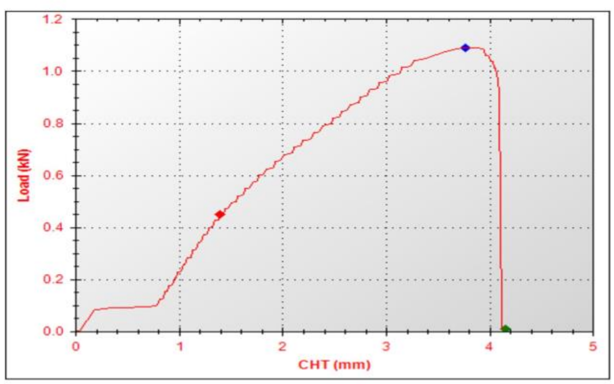
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.448	kN
Elongation At Yield	: 1.394	mm
Yield Stress	: 8.613	N/mm2
Load at Peak	: 1.090	kN
Elongation at Peak	: 3.864	mm
Tensile Strength	: 20.960	N/mm2
Load At Break	: 0.007	kN
Elongation At Break	: 4.151	mm
Breaking Strength	: 0.138	N/mm2
% Elongation	: 6.78	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 21: Tensile Test Report for PLA with Triangular Infill Pattern at 90% Infill Density.

• **Specimen number: 10**

Material – PLA

Infill pattern - Gyroid

Infill Density – 30%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 104_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

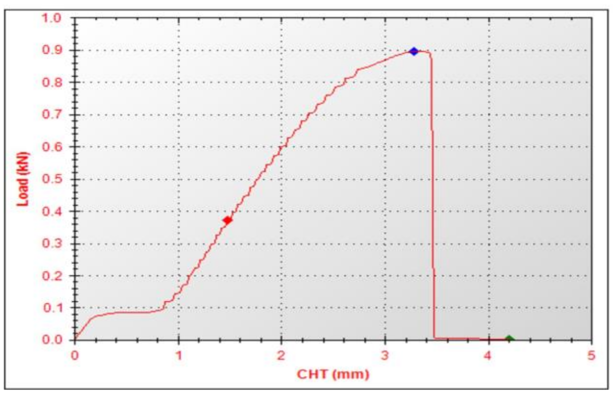
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.372	kN
Elongation At Yield	: 1.477	mm
Yield Stress	: 7.154	N/mm2
Load at Peak	: 0.895	kN
Elongation at Peak	: 3.369	mm
Tensile Strength	: 17.210	N/mm2
Load At Break	: 0.002	kN
Elongation At Break	: 4.200	mm
Breaking Strength	: 0.046	N/mm2
% Elongation	: 5.91	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 22: Tensile Test Report for PLA with Gyroid Infill Pattern at 30% Infill Density.

• **Specimen number: 11**

Material – PLA

Infill pattern - Gyroid

Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 103_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

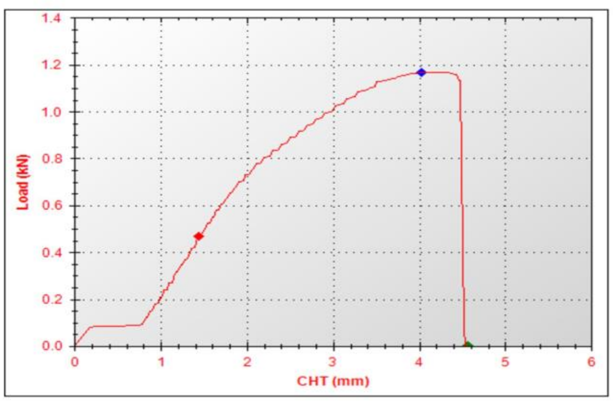
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.468	kN
Elongation At Yield	: 1.445	mm
Yield Stress	: 9.006	N/mm2
Load at Peak	: 1.168	kN
Elongation at Peak	: 4.199	mm
Tensile Strength	: 22.460	N/mm2
Load At Break	: 0.002	kN
Elongation At Break	: 4.566	mm
Breaking Strength	: 0.040	N/mm2
% Elongation	: 7.37	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 23: Tensile Test Report for PLA with Gyroid Infill Pattern at 60% Infill Density.

• **Specimen number: 12**

Material – PLA

Infill pattern - Gyroid

Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 102_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

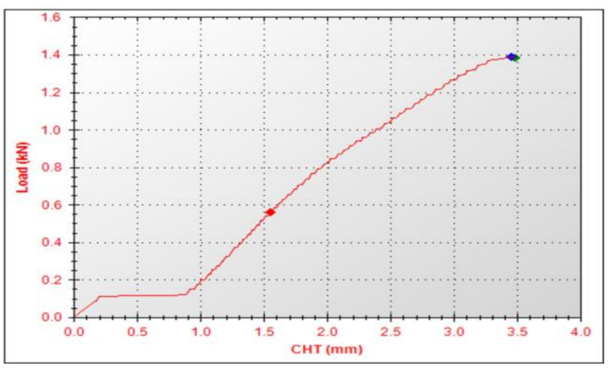
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.56	kN
Elongation At Yield	: 1.547	mm
Yield Stress	: 10.771	N/mm2
Load at Peak	: 1.386	kN
Elongation at Peak	: 3.468	mm
Tensile Strength	: 26.660	N/mm2
Load At Break	: 1.385	kN
Elongation At Break	: 3.485	mm
Breaking Strength	: 26.631	N/mm2
% Elongation	: 6.08	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 24: Tensile Test Report for PLA with Gyroid Infill Pattern at 90% Infill Density.

4.3 Tensile Strength Results of ABS

The tensile strength tests were conducted using a Universal Testing Machine (UTM) according to ASTM D638 standards. The results for each combination of infill pattern and infill density are summarized in Table 3.

Table 3: Tensile Test Results for ABS

Specimen Number	Specimen Code	Tensile Strength (N/mm²)	Elongation at Peak (mm)	Elongation at Break (mm)	Elongation (%)
1	AR30	17.43	3.88	5.5	6.81
2	AR60	22.34	4.51	7.11	7.92
3	AR90	31.82	3.91	4.02	6.86
4	AH30	17.54	4.46	4.63	7.83
5	AH60	22.29	4.14	4.99	7.25
6	AH90	28.16	4.32	4.54	7.57
7	AT30	20.83	2.92	2.99	5.12
8	AT60	21.94	3.15	3.17	5.53
9	AT90	20.8	2.5	2.55	4.38
10	AG30	18.82	3.09	3.22	5.41
11	AG60	17.74	2.54	2.59	4.45
12	AG90	28.39	3.69	3.71	6.46

The mechanical properties of ABS specimens were analysed using different infill patterns and percentages, including Rectilinear, Honeycomb, Triangular, and Gyroid, each at 30%, 60%, and 90% infill. The results shown in Fig.25 indicated that increasing the infill percentage generally enhanced the tensile strength across most patterns. For the Rectilinear pattern, the tensile strength increased from 17.429 N/mm² at 30% infill to 31.823 N/mm² at 90% infill, demonstrating significant improvement with higher infill. Similarly, the Honeycomb pattern showed a rise in tensile strength from 17.538 N/mm² at 30% infill to 28.16 N/mm² at 90% infill, indicating substantial gains in tensile strength as the infill percentage increased.

Conversely, the Gyroid pattern, while achieving some improvement in tensile strength, showed less pronounced increases compared to the Rectilinear and Honeycomb patterns. The tensile strength for Gyroid increased from 18.819 N/mm² at 30% infill to 28.39 N/mm² at 90% infill. The Triangular pattern consistently exhibited lower tensile strength compared to the other patterns, with values ranging from 20.883 N/mm² at 30% infill to 20.798 N/mm² at 90% infill, indicating minimal change with varying infill percentages. These findings highlight the importance of selecting the appropriate infill pattern and percentage based on the specific mechanical requirements, with the Rectilinear and Honeycomb patterns proving particularly effective for applications demanding high tensile strength.

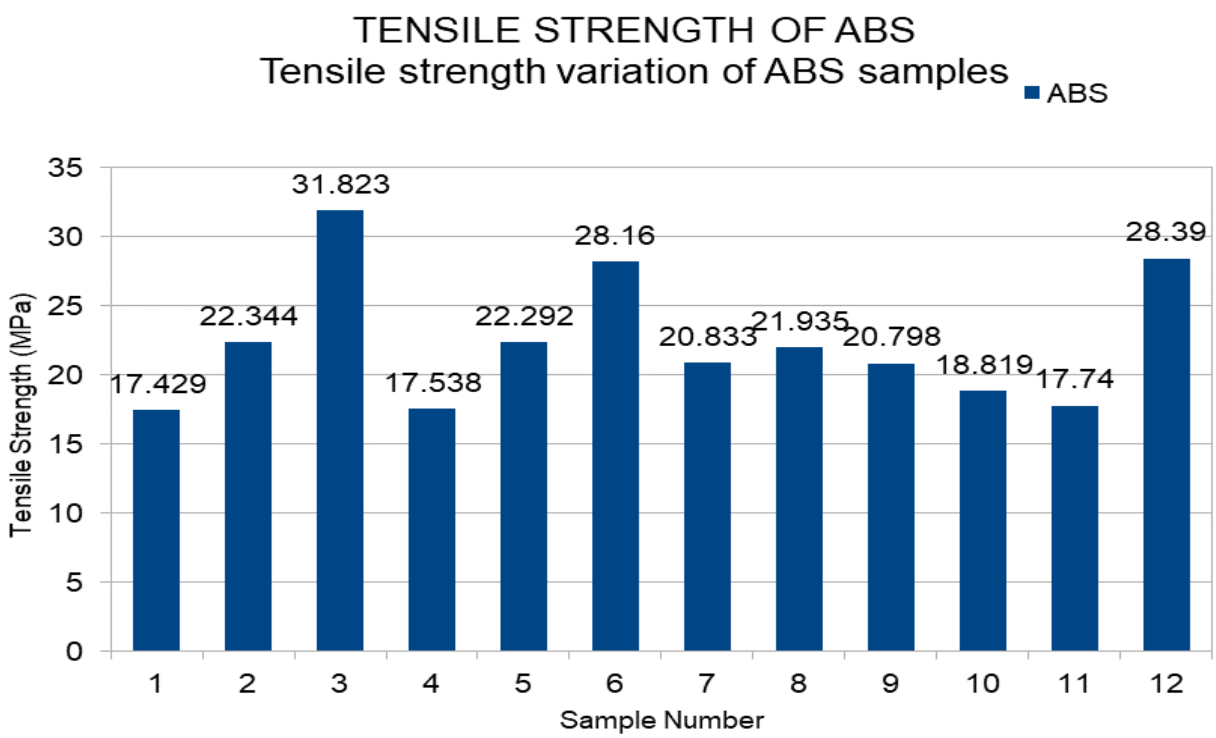


Fig. 25: Bar graph for Tensile Strength(N/mm^2) vs Specimen number (ABS).

From Tensile Test of ABS:

- The properties of the specimens are interpreted from the graph which is plotted between the load and elongation.
- The specimen 3 of ABS has the highest tensile strength of all samples at 31.823 Mpa, which has rectilinear infill pattern at 90% infill.
- The specimen 1 of ABS has the lowest tensile strength at 17.429 Mpa which has rectilinear infill pattern at 30% infill, but it is close to other pattern of same percentage like Honeycomb at 17.538 Mpa and gyroid at 18.819 Mpa.
- In triangular infill pattern (Num 7,8,9) shows constant tensile strength for ABS is 21.18 Mpa.
- There is a consistent linear relationship of infill percentage and tensile strength in honeycomb infill pattern for ABS.
- Gyroid has the least predictable relationship in the set as there is decrease in tensile strength when infill percentage increases from 30% to 60% and then it suddenly increases to a high value at 90%.

4.3.1 Tensile Test Results Of ABS

The tensile test results highlight the influence of different infill patterns and infill densities on the mechanical properties of ABS specimens. Tensile test results of PLA samples are depicted in Fig. 26 to Fig. 37. The following sections present a detailed analysis of these findings.

• **Specimen number: 1**

Material –ABS

Infill pattern - Rectilinear

Infill Density – 30%

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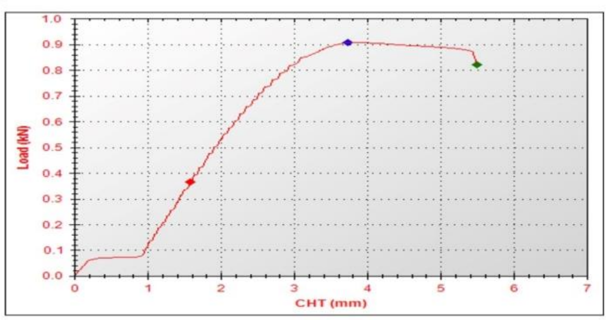
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 115_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

Input Data			Output Data		
Specimen Shape	: Flat		Load At Yield	: 0.365	kN
Specimen Type	: Composite Material		Elongation At Yield	: 1.581	mm
Specimen Description	:		Yield Stress	: 7.015	N/mm2
Specimen Width	: 13	mm	Load at Peak	: 0.906	kN
Specimen Thickness	: 4	mm	Elongation at Peak	: 3.884	mm
Initial G.L. For % elong	: 57	mm	Tensile Strength	: 17.429	N/mm2
Pre Load Value	: 0.00	kN	Load At Break	: 0.820	kN
Max. Load	: 30.00	kN	Elongation At Break	: 5.502	mm
Max. Elongation	: 1000.00	mm	Breaking Strength	: 15.767	N/mm2
Specimen Cross Section Area	: 52.000	mm2	% Elongation	: 6.81	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 26: Tensile Test Report for ABS with Rectilinear Infill Pattern at 30% Infill Density.

• **Specimen number: 2**

Material –ABS

Infill pattern - Rectilinear

Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 116_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

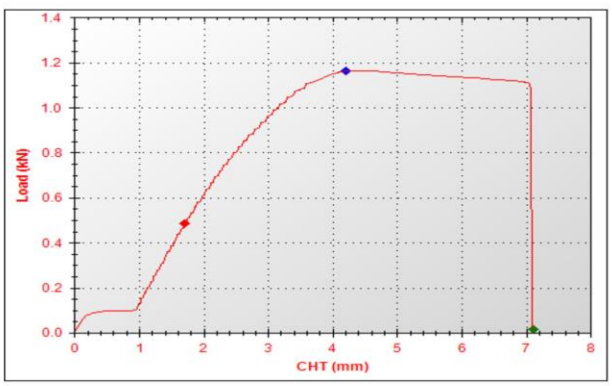
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.484	kN
Elongation At Yield	: 1.702	mm
Yield Stress	: 9.306	N/mm2
Load at Peak	: 1.162	kN
Elongation at Peak	: 4.513	mm
Tensile Strength	: 22.344	N/mm2
Load At Break	: 0.014	kN
Elongation At Break	: 7.107	mm
Breaking Strength	: 0.260	N/mm2
% Elongation	: 7.92	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 27: Tensile Test Report for ABS with Rectilinear Infill Pattern at 60% Infill Density.

- **Specimen number: 3**

  Material –ABS

  Infill pattern - Rectilinear

  Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 117_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

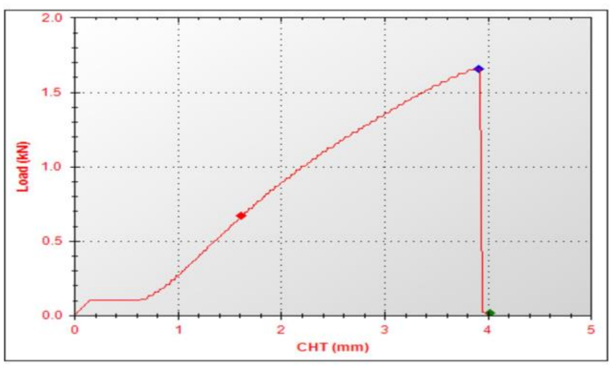
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.669	kN
Elongation At Yield	: 1.618	mm
Yield Stress	: 12.865	N/mm2
Load at Peak	: 1.655	kN
Elongation at Peak	: 3.913	mm
Tensile Strength	: 31.823	N/mm2
Load At Break	: 0.016	kN
Elongation At Break	: 4.018	mm
Breaking Strength	: 0.306	N/mm2
% Elongation	: 6.86	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 28: Tensile Test Report for ABS with Rectilinear Infill Pattern at 90% Infill Density.

• **Specimen number: 4**

Material –ABS

Infill pattern - Honeycomb

Infill Density – 30%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 105_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

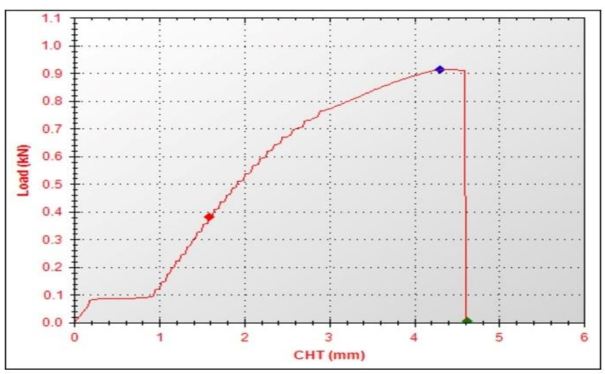
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.381	kN
Elongation At Yield	: 1.582	mm
Yield Stress	: 7.321	N/mm2
Load at Peak	: 0.912	kN
Elongation at Peak	: 4.463	mm
Tensile Strength	: 17.538	N/mm2
Load At Break	: 0.005	kN
Elongation At Break	: 4.630	mm
Breaking Strength	: 0.092	N/mm2
% Elongation	: 7.83	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 29: Tensile Test Report for ABS with Honeycomb Infill Pattern at 30% Infill Density.

- **Specimen number: 5**

  Material –ABS

  Infill pattern - Honeycomb

  Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 106_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

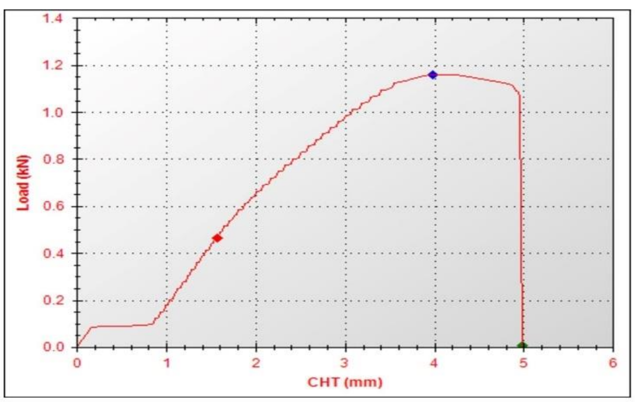
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.464	kN
Elongation At Yield	: 1.565	mm
Yield Stress	: 8.925	N/mm2
Load at Peak	: 1.159	kN
Elongation at Peak	: 4.135	mm
Tensile Strength	: 22.292	N/mm2
Load At Break	: 0.007	kN
Elongation At Break	: 4.993	mm
Breaking Strength	: 0.138	N/mm2
% Elongation	: 7.25	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 30: Tensile Test Report for ABS with Honeycomb Infill Pattern at 60% infill Density.

• Specimen number: 6

Material –ABS

Infill pattern - Honeycomb

Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 107_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

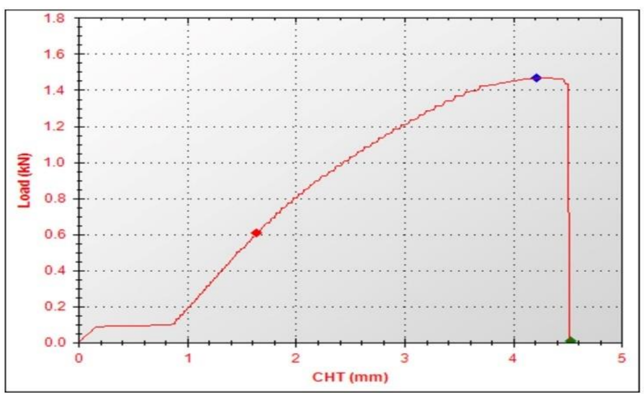
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.607	kN
Elongation At Yield	: 1.632	mm
Yield Stress	: 11.677	N/mm2
Load at Peak	: 1.464	kN
Elongation at Peak	: 4.315	mm
Tensile Strength	: 28.160	N/mm2
Load At Break	: 0.010	kN
Elongation At Break	: 4.535	mm
Breaking Strength	: 0.190	N/mm2
% Elongation	: 7.57	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 31: Tensile Test Report for ABS with Honeycomb Infill Pattern at 90% infill Density.

• **Specimen number: 7**

Material –ABS

Infill pattern - Triangular

Infill Density – 30%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 108_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

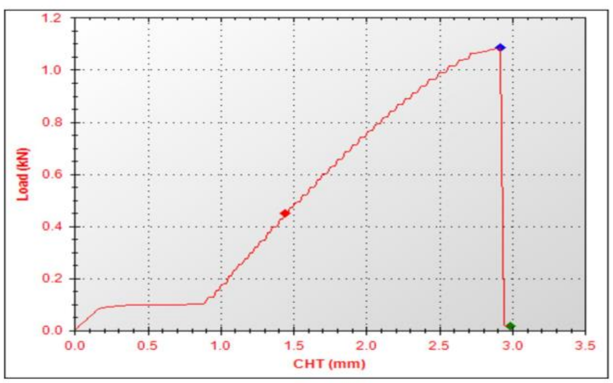
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.448	kN
Elongation At Yield	: 1.444	mm
Yield Stress	: 8.608	N/mm2
Load at Peak	: 1.083	kN
Elongation at Peak	: 2.920	mm
Tensile Strength	: 20.833	N/mm2
Load At Break	: 0.015	kN
Elongation At Break	: 2.989	mm
Breaking Strength	: 0.283	N/mm2
% Elongation	: 5.12	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 32: Tensile Test Report for ABS with Triangular Infill Pattern at 30% Infill Density.

• **Specimen number: 8**

Material –ABS

Infill pattern - Triangular

Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 109_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

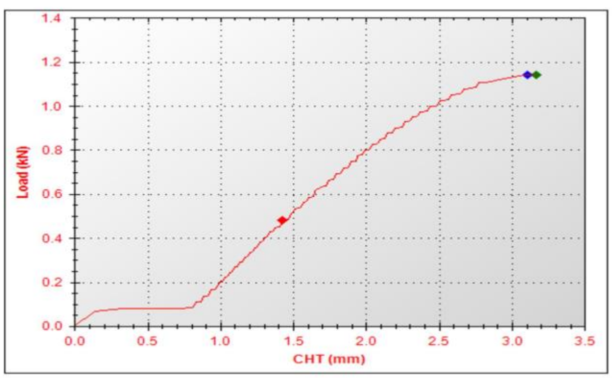
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.48	kN
Elongation At Yield	: 1.430	mm
Yield Stress	: 9.231	N/mm2
Load at Peak	: 1.141	kN
Elongation at Peak	: 3.154	mm
Tensile Strength	: 21.935	N/mm2
Load At Break	: 1.139	kN
Elongation At Break	: 3.171	mm
Breaking Strength	: 21.912	N/mm2
% Elongation	: 5.53	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 33: Tensile Test Report for ABS with Triangular Infill Pattern at 60% Infill Density.

• **Specimen number: 9**

Material –ABS

Infill pattern – Triangular

Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 110_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

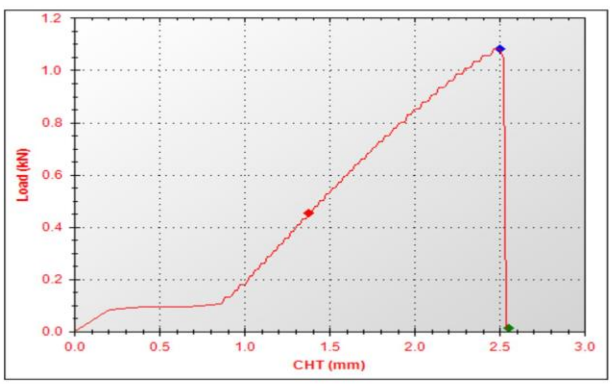
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.453	kN
Elongation At Yield	: 1.377	mm
Yield Stress	: 8.706	N/mm2
Load at Peak	: 1.082	kN
Elongation at Peak	: 2.499	mm
Tensile Strength	: 20.798	N/mm2
Load At Break	: 0.012	kN
Elongation At Break	: 2.554	mm
Breaking Strength	: 0.237	N/mm2
% Elongation	: 4.38	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 34: Tensile Test Report for ABS with Triangular Infill Pattern at 90% Infill Density.

• **Specimen number: 10**

Material – ABS

Infill pattern - Gyroid

Infill Density – 30%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 111_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

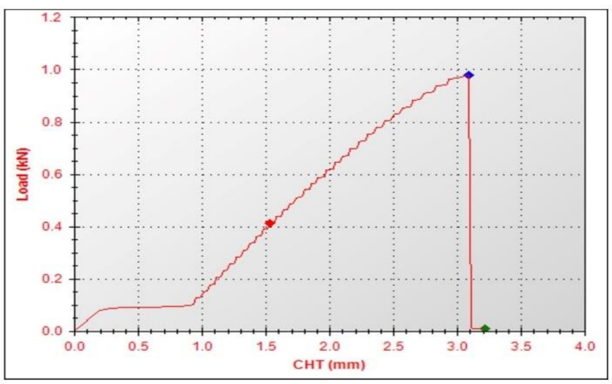
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.412	kN
Elongation At Yield	: 1.532	mm
Yield Stress	: 7.921	N/mm2
Load at Peak	: 0.979	kN
Elongation at Peak	: 3.086	mm
Tensile Strength	: 18.819	N/mm2
Load At Break	: 0.010	kN
Elongation At Break	: 3.222	mm
Breaking Strength	: 0.190	N/mm2
% Elongation	: 5.41	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 35: Tensile Test Report for ABS with Gyroid Infill Pattern at 30% Infill Density.

• **Specimen number:11**

Material – ABS

Infill pattern - Gyroid

Infill Density – 60%

M/s.RAGHAVA DURGA TECHNOLOGIES

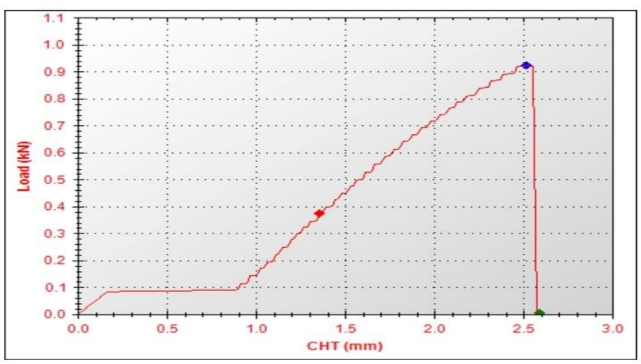
HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 112_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

Input Data			**Output Data**		
Specimen Shape	: Flat		Load At Yield	: 0.373	kN
Specimen Type	: Composite Material		Elongation At Yield	: 1.355	mm
Specimen Description	:		Yield Stress	: 7.177	N/mm2
Specimen Width	: 13	mm	Load at Peak	: 0.923	kN
Specimen Thickness	: 4	mm	Elongation at Peak	: 2.535	mm
Initial G.L. For % elong	: 57	mm	Tensile Strength	: 17.740	N/mm2
Pre Load Value	: 0.00	kN	Load At Break	: 0.004	kN
Max. Load	: 30.00	kN	Elongation At Break	: 2.590	mm
Max. Elongation	: 1000.00	mm	Breaking Strength	: 0.069	N/mm2
Specimen Cross Section Area	: 52.000	mm2	% Elongation	: 4.45	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 36: Tensile Test Report for ABS with Gyroid Infill Pattern at 60% Infill Density.

• **Specimen number: 12**

Material – ABS

Infill pattern - Gyroid

Infill Density – 90%

M/s.RAGHAVA DURGA TECHNOLOGIES

HYDERABAD 500072.

Tensile Test Report

Machine Model	: M-30	Test File Name	: 114_2024.Utm
Machine Serial No	: 2019 / 69		
Customer Name	: JNTUH College Of Engineering, Hyderabad	Date	: 15/05/2024
		Test Type	: Tensile
Customer Address	:	Heat No.	:
		OrderNo.	:
Sample	:	Test Refrence	:
Refrence	:		

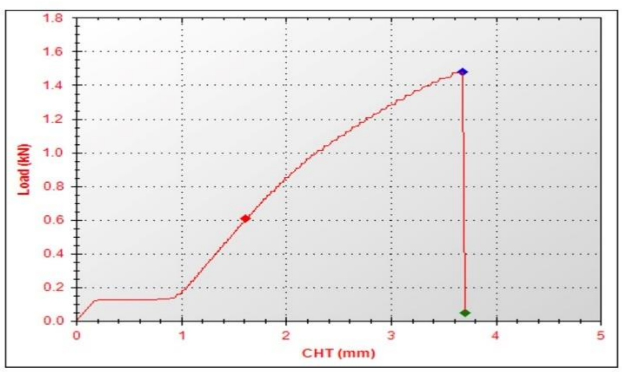
Input Data

Specimen Shape	: Flat	
Specimen Type	: Composite Material	
Specimen Description	:	
Specimen Width	: 13	mm
Specimen Thickness	: 4	mm
Initial G.L. For % elong	: 57	mm
Pre Load Value	: 0.00	kN
Max. Load	: 30.00	kN
Max. Elongation	: 1000.00	mm
Specimen Cross Section Area	: 52.000	mm2

Output Data

Load At Yield	: 0.604	kN
Elongation At Yield	: 1.614	mm
Yield Stress	: 11.625	N/mm2
Load at Peak	: 1.476	kN
Elongation at Peak	: 3.685	mm
Tensile Strength	: 28.390	N/mm2
Load At Break	: 0.048	kN
Elongation At Break	: 3.710	mm
Breaking Strength	: 0.917	N/mm2
% Elongation	: 6.46	%

Load Vs. Cross Head Travel



Tested By admin

Fig. 37: Tensile Test Report for ABS with Gyroid Infill Pattern at 90% Infill Density.

4.4 Discussion

4.4.1 Effect of Infill Pattern on Tensile Strength

The results indicate that the infill pattern significantly impacts the tensile strength of the 3D printed parts. Among the tested patterns, the Gyroid infill pattern generally produced the highest tensile strength for both PLA and ABS materials, particularly at higher infill densities. This can be attributed to the continuous and interconnected structure of the Gyroid pattern, which distributes stress more evenly throughout the part.

4.4.2 Effect of Infill Density on Tensile Strength

Increasing the infill density from 30% to 90% resulted in a notable increase in tensile strength for both PLA and ABS specimens. The denser infill structures provide more material to resist applied loads, thereby enhancing the overall strength of the parts. However, the rate of increase in tensile strength diminishes at higher densities, suggesting an optimal range for specific applications.

4.4.3 Comparison Between PLA and ABS

PLA specimens generally exhibited higher tensile strength compared to ABS specimens under the same infill conditions. This difference is likely due to the inherent material properties of PLA, which offers better rigidity and less flexibility than ABS. However, ABS showed greater elongation at break, indicating its superior toughness and ability to absorb impact without fracturing.

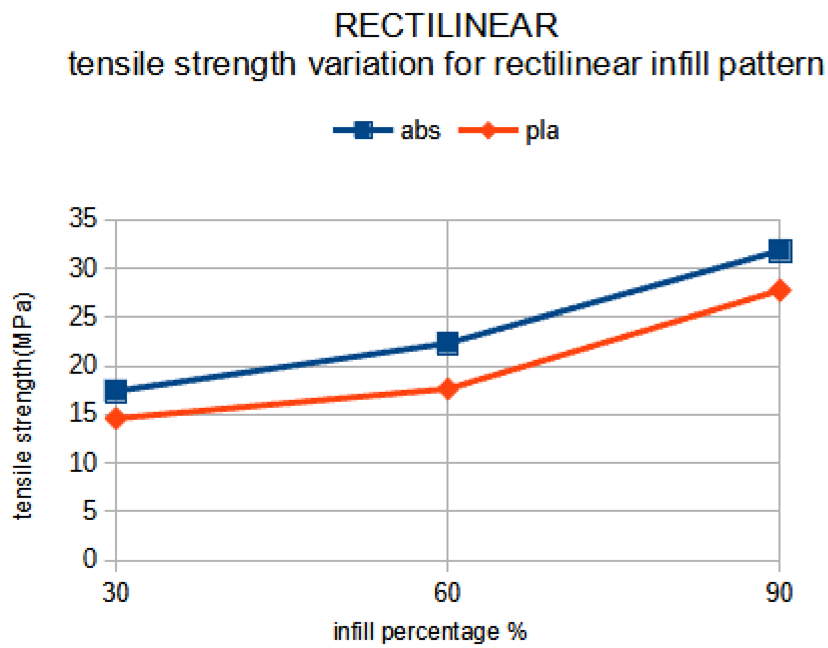


Fig. 38: Comparison of Tensile Strength for ABS and PLA Using Rectilinear Infill Pattern Across Different Infill Densities.

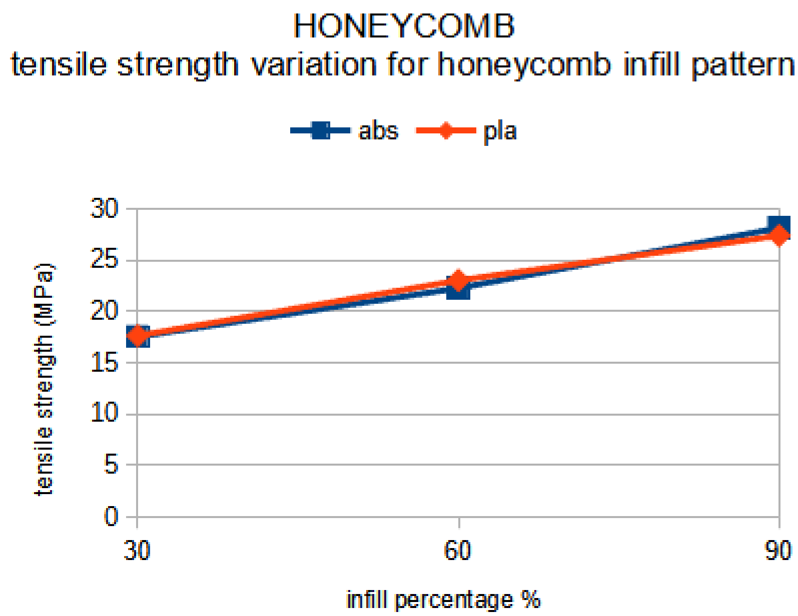


Fig. 39: Comparison of Tensile Strength for ABS and PLA Using Honeycomb Infill Pattern Across Different Infill Densities.

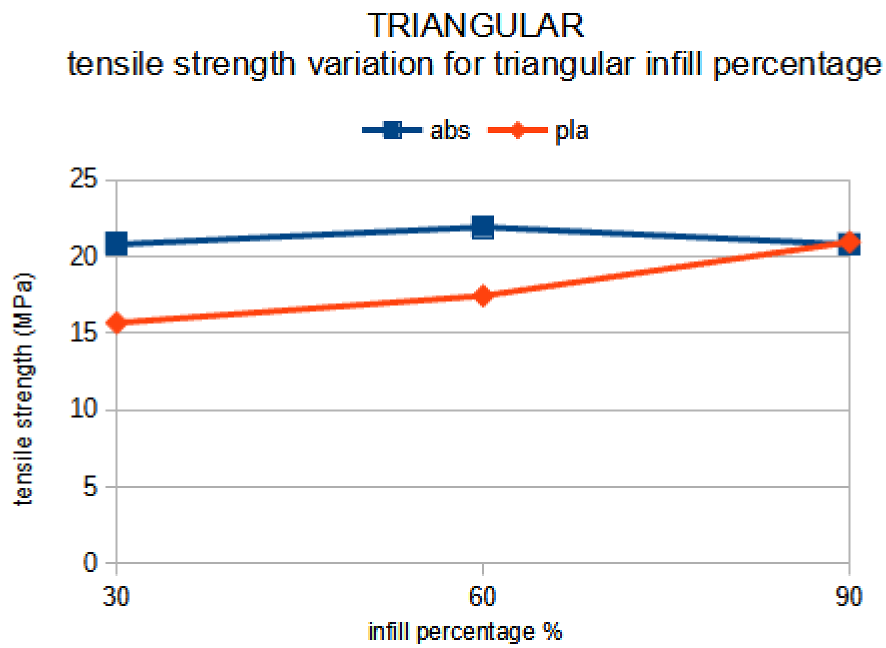


Fig. 40: Comparison of Tensile Strength for ABS and PLA Using Triangular Infill Pattern Across Different Infill Densities.

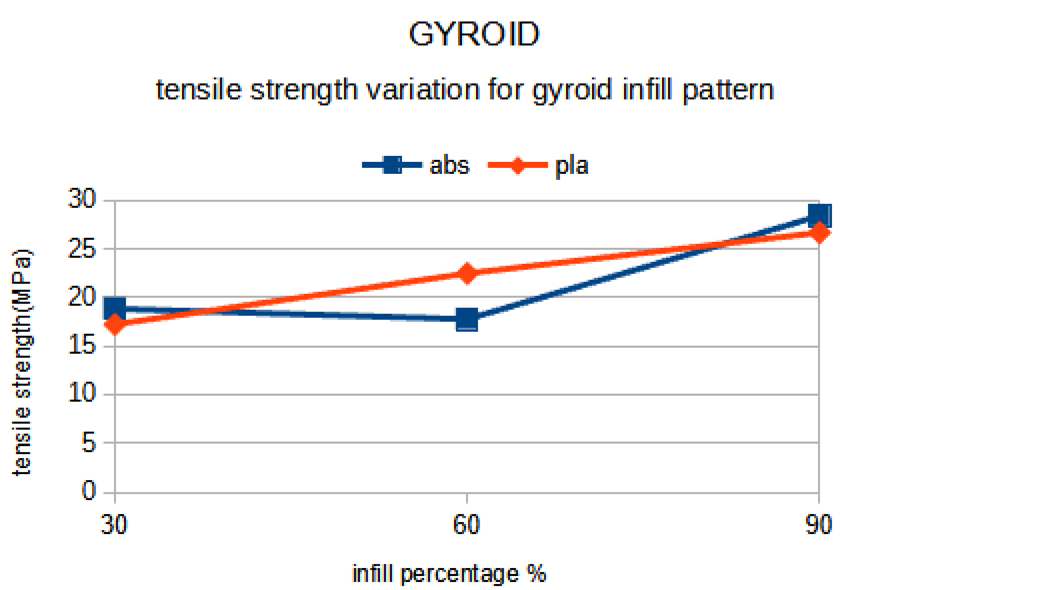


Fig. 41: Comparison of Tensile Strength for ABS and PLA Using Gyroid Infill Pattern Across Different Infill Densities.

- Fig. 38 showcases the tensile strength variation with infill percentage for the rectilinear pattern. Here, the strength varies almost linearly with infill percentage for both ABS and PLA, with ABS consistently stronger than PLA. This observation underscores the influence of infill pattern and percentage on the mechanical properties of 3D printed parts, with ABS demonstrating superior strength characteristics compared to PLA.
- In Fig. 39, the tensile strength variation with infill percentage for the honeycomb pattern is depicted. Surprisingly, both PLA and ABS exhibit nearly identical tensile strengths, indicating that the honeycomb structure is less influenced by material properties and more dependent on its inherent structure. The linear variation further underscores the structural robustness of the honeycomb pattern.
- Fig. 40 illustrates the tensile strength variation with infill percentage for the triangular pattern. Remarkably, ABS exhibits nearly consistent strength across all infill percentages, whereas PLA demonstrates lower strength at lower percentages, despite achieving similar strength levels at 90%. This observation suggests a transitional behaviour in PLA at lower percentages, highlighting the material's sensitivity to infill density.
- Fig. 41 presents the tensile strength variation with infill percentage for the gyroid pattern. The gyroid's curved surfaces distribute load uniformly in all directions but are prone to more deformation. This is evidenced by a decrease in strength at half infill percentages for ABS, while PLA, being stiffer, exhibits less susceptibility to deformation.

CHAPTER 5
CONCLUSIONS

5.1 Conclusions

This project investigated the effects of different infill patterns and densities on the mechanical properties of 3D printed parts using PLA and ABS materials. The study parameters included infill patterns (rectilinear, triangular, honeycomb, and gyroid) and infill densities (30%, 60%, and 90%).

Key findings include:

1. Strength and Durability: Honeycomb and gyroid patterns showed superior strength and durability for both PLA and ABS, distributing stress effectively and reducing fracture likelihood.

2. Material Efficiency: Lower density infill patterns, such as rectilinear and triangular at 30%, provided efficient material use while maintaining structural integrity.

3.Impact of Infill Density: Higher infill densities increased part strength for both materials but required more material and longer print times. PLA parts with higher densities showed higher tensile strength but were more brittle, while ABS parts maintained better ductility and impact resistance.

4. Tensile Test Results:

- PLA: Higher tensile strength but more brittle, suitable for applications requiring high stiffness.

- ABS: Lower tensile strength but higher elongation at break, better for applications needing durability and flexibility.

This study emphasizes the importance of selecting appropriate infill patterns, densities, and materials based on specific application needs. For high strength and stiffness, PLA with honeycomb or gyroid infill at higher densities is recommended. For durability and flexibility, ABS with similar infill patterns and optimized densities is preferable.

Future work could explore different materials, more complex infill geometries, and practical applications of these findings to enhance the performance and efficiency of 3D printed components, expanding the use of additive manufacturing technologies.

5.2 Limitations of Present Work

1.The study only explores a specific set of infill patterns (rectilinear, honeycomb, triangular, and gyroid) and three infill densities (30%, 60%, and 90%). Other patterns and densities might yield different results.

2. The research focuses exclusively on PLA and ABS materials. The findings may not be directly applicable to other 3D printing materials with different properties.

3. All specimens are printed using a Creality Ender 3 printer. Variations in printer models and settings might affect the reproducibility of the results.

4. The mechanical properties evaluated are limited to tensile strength and elongation at break. Other important properties like compressive strength, fatigue resistance, and thermal stability are not examined.

5. The test specimens are based on standard geometries defined by ASTM D638. Real-world applications often involve more complex geometries which might behave differently under similar conditions.

6. The study focuses on static tensile testing and does not include dynamic load or impact testing, which are crucial for applications involving fluctuating or shock loads.

5.3 Scope for Future Work

1.Investigate a broader range of infill patterns, densities, and printing materials to comprehensively understand their impact on part performance.

2. Explore the effects of post-processing methods on part properties to enhance surface finish and mechanical performance.

3. Evaluate part durability under dynamic loads through fatigue and impact testing to ensure suitability for real-world applications.

4. Develop computational models to predict part behaviour based on printing parameters and material properties for accurate design optimization.

5. Analyse the environmental sustainability of 3D printing processes and materials to minimize ecological footprint.

6. Explore multi-material printing techniques for fabricating parts with graded properties or embedded functionalities for advanced applications.

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[2] Adi P, Damir H and Edin K, “Experimental Investigation on Influence of Infill Density on Tensile Mechanical Properties of Different FDM 3D Printed Materials”, TEM Journal, Vol.: 10, Issue.: 3, pp.: 1195-1201.

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