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INFLUENCE OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF 3D PRINTED COMPONENTS

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ABSTRACT:
For prototype and production purposes, one of the most well-liked processes in additive manufacturing (AM) is fused deposition modelling (FDM). However, the quality of FDM items might vary depending on the 3D printing process choices. The data is entered into the device, preferably in STL format, and after that, the technology generates 3D digital drawings layer by layer. The PETG material product and technology may be employed right away in engineering applications after adequate mechanical property testing. Fused deposition, a kind of 3D printing, melts the material layer by layer using molten wire at a certain temperature before depositing it into the machine in accordance with design instructions. Numerous process variables, including screen angle, orientation, material deposition rate, layer thickness, and nozzle diameter, have an impact on the mechanical qualities of the produced item, such as tensile strength, elongation, shear strength, and flexural strength. In this method, the final result is produced using a 3D printer after a CATIA 3D CAD digital model is translated to STL file format and printed. In this experiment, PETG composite served as the initial raw material. Tensile and flexural tests were used to assess the mechanical characteristics of the PETG composite in line with ASTM D638 Type IV and ASTM D790 design specifications. The aforementioned mechanical qualities were investigated on samples with various screen orientations, layer thicknesses, and filler densities.

Keywords: 3D Printed Components, PETG, Raster angle, Layer thickness, Infill density, Tensile Strength, flexural strength.

1. INTRODUCTION

Three-dimensional models are produced from CAD models using additive manufacturing, one of Industry 4.0's production methods. When creating an item with additive manufacturing, as opposed to conventional machining, layers are added rather than material being removed. Examples of additive manufacturing processes include stereolithography (SLA), fused deposition modelling (FDM), selective laser melting (SLM), binder jetting, direct energy deposition, kinetic fusion, laminated object modelling (LOM), and others.

By layering the die head in the required direction while heating the polymer filaments to their melting temperature, fused deposition modelling is a material extrusion-based technique that produces the desired item.

The algorithms that regulate how the nozzle travels are created using a 3D model of the thing that will be printed. When producing items with complicated shapes, FDM decreases the number of assembly pieces. Fig. 1 displays a schematic of the FDM 3D printer. It is distinguished by a broad range of materials, simplicity, accessibility, robustness, affordability, and usefulness. Some of the thermoplastic materials used in fused deposition modelling are ABS (acrylonitrile butadiene styrene), PETG (polyethylene terephthalate glycol), PLA (polylactic acid), TPU (thermoplastic polyurethane), and PC (polycarbonate).

 ISSN: 2278-4632
Vol-13, Issue-04, No.03, April : 2023

The usage of FDM is widespread, including applications in the tooling, aerospace, automotive, and medical fields. Fig. 2 depicts the procedure for printing any component using fused deposition modeling. He begins by creating the CAD model and finishes by cleaning the component.

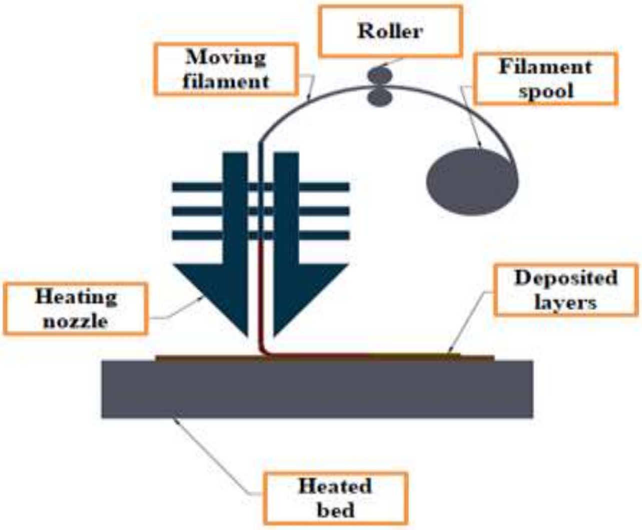


Figure 1: FDM layers deposition mechanism

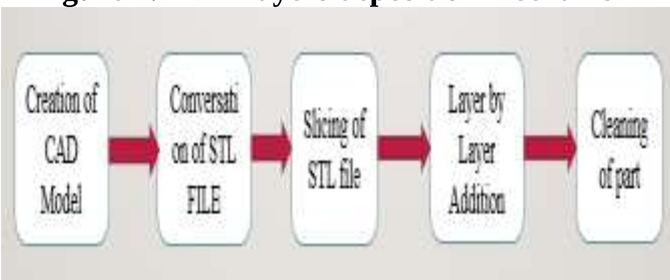


Figure 2: Steps involved in FDM

Thermoplastic polyester polyethylene terephthalate glycol (PETG) is utilised in a wide range of commercial applications, including the production of bottles and containers, packaging of medical implant materials, and more due to its superior formability, durability, and chemical resistance. It is created by the copolymerization of the naturally colourless or transparent monomers glycol and PET. $(C_{10}H_8O_4)_n$ is mentioned as PETG's molecular make-up. The benefits of ABS and PLA are also present in PETG. It creates pieces that are significantly stronger and more flexible than other materials. For printing components and examining the various PETG material qualities, it is essential to choose the process settings carefully since they have an impact on the part's strength. The part's quality and dimensional correctness are also impacted. Among the various process variables are layer thickness, extrusion temperature, infill density, infill pattern, screen angle, line speed, air gap, etc. It is measured how thick the layer is that is placed on the printing bed. The extrusion temperature in fused deposition modelling refers to the temperature at which the thermoplastic filament is heated in the die before being extruded. The infill density reveals the amount of materials used to build a product. A material deposition technique known as infill patterning is used to produce the inside structure of an FDM printed product. The angular distance between the build platform and the x-direction of the extruded material is known as the grid angle.

2. LITERATURE REVIEW

R. Srinivasan et al. [1] Other parameters, such as B. layer thickness, filling pattern, screen angle, air gap, etc., are considered constants, while the filling density fluctuates between 20 and 100 percent. When the bulk density is 100% and the layer thickness is 0.1 mm, the maximum tensile strength is attained. At 100%, a bottom surface roughness rating of 2.87 m was attained. ASTM Standard D638 for SOLIDWORKS 2016 Software Tensile Specimen Preparation

K. Durgashyam et al. [2] PETG material tensile and flexural strength testing were carried out utilising fused deposition modeling. The sample was printed using a 1.75 mm-diameter filament with a density of 1.7 g/cm3 at a bed temperature of 235 °C. Layer thickness, filling density, and feed rate were thought of as variables. The parameter that has the most impact on the component's tensile strength may be found using ANOVA (Analysis of Variance).

T. Panneerselvam et al. [3] The study looked at the tensile, flexural, and hardness properties of 3D-printed PETG material using FDM. Hexagonal patterns were found to have a greater influence on the tensile strength of PETG parts. The highest mean values were obtained at 80% infill density, 0.3 mm layer height, and a hexagonal pattern. The failure mode was brittle fracture, as there were no signs of yielding during the testing.

Muammel M. Hanon et al. [4] Using PETG as the build material, the researchers looked at the anisotropy prediction of various screen angles, print orientations, and infill percentages. A Bq Witbox 2 3D printer was used to produce a total of 36 samples in accordance with ISO 527-2:2012 standard 1B type. PETG outperformed PLA because it produced better stretching outcomes.

R. Srinivasan et al. [5] Finding the ideal filler design for PETG components is the goal of this research. Triangular, cubic, lattice, concentric, honeycomb, rectangular, staggered, and octet are among the complementing designs taken into consideration in this research. Lattice specimens, honeycomb specimens, and rectangle specimens all had the greatest tensile strengths. This is because the grid layout makes the printed pieces' bonding stronger. The intermolecular membranes of honeycomb fillers are preserved.

Juan M. Barrios et al. [6] The characteristics of PETG 3D-printed self-cleaning components were investigated by the researchers. They discovered that flow rate and pressure acceleration had a greater impact than the other factors. Layer height, printing temperature, speed, acceleration, and flow rate are all considered changeable factors, with a maximum of three levels for each. The section's ability to maintain a constant compression load is also due to compression acceleration.

Arda Özen et al. [7] JICB formats are based on ISO, ISO 527-2, and ASTM D3039. To explain early failure, a digital twin of the lab test utilising FEM analysis is shown. It was discovered that the PETG material's macroscopic structure had become more homogenous.

Prajwal P. Agarwal et al. [8] An experimental investigation of the tensile strength, dimensional correctness, and printing speed of PETG material pieces created on an FDM 3D printer was done by a Japanese research team. Printing uses the honeycomb design because it provides the most strength. The number of samples was decreased by using Taguchi's orthogonal L9 array.

Jorge Manuel Mercado-Colmenero et al.[9] PETG material was analysed experimentally and numerically using Ansys Mechanical Limited to determine its properties under pure uniaxial compressive stress. The mechanical behaviour is discovered to be entirely linear up to the elastic limit. The observed fracture for specimens made in the Z-direction is brittle, while the X- and Y-directions exhibit persistent plastic deformations.

S. Swetha et al. [10] By fixing one end, static structural analysis was carried out on the Ansys 16.2 workbench. With an increase in layer height and a drop in filler percentage, a considerable decrease was seen. The verification of experimental tensile and compression tests is consistent. The difference between the experimental and simulated findings may be seen at 5% inaccuracy.

3. PROBLEM IDENTIFICATION AND OBJECTIVES:

The following goals of the proposed study should be taken into account while evaluating and optimising 3-DP FDM process parameters for fabricating PETG-based products employing screen angle, layer thickness, and bulk density:

Using an FDM 3D printer and different input parameters to produce a test item in accordance with ASTM specifications, the creation of a workable design-of-experiment (DOE) approach to assess the performance of DOE-compliant FDM-printed samples evaluated on the UTM machine and to identify the key process parameters and number of experimental runs.

ISSN: 2278-4632
Vol-13, Issue-04, No.03, April : 2023

4. METHODOLOGY

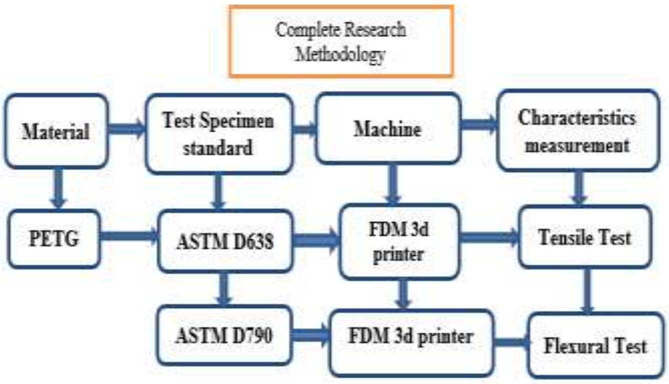


Fig4.1: Methodology

4.1 MATERIALS

4.1.1 PETG

PETG, also known as polyethylene terephthalate glycol, is a thermoplastic polyester with good chemical resistance and great industrial moldability. PETG is easy to vacuum form, pressure form, and heat bend because of the low forming temperatures. As a result, it is frequently used for consumer and commercial applications that make use of 3D printing or other thermoforming manufacturing techniques. Additionally, PETG is compatible with industrial techniques including milling, bending, and stamping. As a copolymer, PETG blends the qualities of PET with glycol.

4.1.2 CHEMICAL COMPOSITION

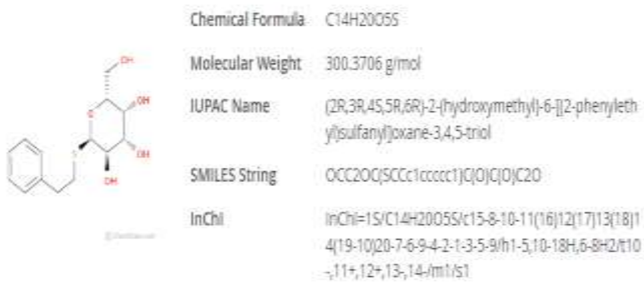


Fig4.2 chemical composition of PETG

4.1.3 MECHANICAL PROPERTIES:

Table4.1 Material Properties of Thermoplastic PETG

Property	Metric	units	English	units
General				
Density	1.26e3 - 1.28e3	kg/m^3	0.0455 - 0.0462	lb/in^3
Mechanical				
Yield Strength	4.79e7 - 5.29e7	Pa	6.95 - 7.67	ksi
Tensile Strength	6e7 - 6.6e7	Pa	8.7 - 9.57	ksi
Elongation	1.02 - 1.18	% strain	102 - 118	% strain
Hardness (Vickers)	1.41e8 - 1.56e8	Pa	14.4 - 15.9	HV
Impact Strength (un-notched)	1.9e5 - 2e5	J/m^2	90.4 - 95.2	ft.lbf/in^2
Fracture Toughness	2.11e6 - 2.54e6	Pa/m^0.5	1.92 - 2.31	ksi/in^0.5
Young's Modulus	2.01e9 - 2.11e9	Pa	0.292 - 0.306	10^6 psi
Thermal				
Max Service Temperature	51 - 64	°C	124 - 147	°F
Melting Temperature	81 - 91	°C	178 - 196	°F
Insulator or Conductor	Insulator		Insulator	
Specific Heat Capability	1.47e3 - 1.53e3	J/kg °C	0.352 - 0.366	BTU/lb.°F
Thermal Expansion Coefficient	1.2e-4 - 1.23e-4	strain/°C	66.8 - 68.1	µstrain/°F
Eco				
CO2 Footprint	3.22 - 3.56	kg/kg	3.22 - 3.56	lb/lb
Recyclable	Yes		Yes	

4.2 PARAMETER SELECTION

The printing circumstances have a little impact on the moulding process of 3D-printed items. To assure the quality of the samples, consideration of the screen angle and layer thickness of both components is required. Halftone analysis is used to investigate how print speed, temperature, layer thickness, and other process variables impact sample quality as well as how these factors impact the mechanical characteristics of the sample. The two most crucial factors that affect pattern generation are the two-component screen angle and layer thickness.

4.2.1 RASTER ANGLE

The raster angle describes the angle created by FDM between the build platform's x-axis and the nozzle's path. Two nearby layers' raster angles are 90° different from one another. The raster angle has an impact on the form correctness and mechanical performance of the printed pattern. Typically, a screen angle between 0° and 90° may be used. Three raster angle values were chosen as a result: $0^0/90^0$, $30^0/60^0$, and $+45^0/45^0$.

4.2.2 LAYER THICKNESS:

"Layer thickness" refers to the thickness of each layer of material deposited by the FDM die. The outer profile of a layered structure becomes increasingly vulnerable to the influence of steps as layer thickness rises due to an increase in surface roughness, a loss in surface accuracy of the printed pattern, and an increase in surface roughness. On the other hand, increasing the layer thickness lengthens the printing process and reduces the printed sample's accuracy, efficiency, and smoothness of the surface. The nozzle diameter, the material's characteristics, and the form precision all affect the layer thickness. Four levels of typical layer thickness were employed in the experiment: 0.2, 0.3, 0.32, and a nozzle diameter of 0.4 mm.

4.2.3 INFILL DENSITY:

The fill % represents the interior model density. from zero percent, which symbolises a totally hollow thing, to one hundred percent, which symbolises a fully solid model. The infill has a significant impact on compressive strength since it supports the model's interior.

S. No	Raster angle	Layer thickness(mm)	Infill density
1	$0/90^0$	0.2	30
2	$30^0/60^0$	0.2	30
3	$+45^0/45^0$	0.2	30
4	$0/90^0$	0.3	30
5	$30^0/60^0$	0.3	30
6	$+45^0/45^0$	0.3	30
7	$0/90^0$	0.32	30
8	$30^0/60^0$	0.32	30
9	$+45^0/45^0$	0.32	30

Table4.2. DATA SET FOR SPECIMENS

4.3 SPECIEMEN PREPARATION

The American Society for Testing and Materials (ASTM) standard was followed while printing the tensile specimens and the flexural specimens.

4.3.1 TENSILE SPECIMEN PREPARATION

The **ASTM D638** standard is the most familiar, universally accepted testing method to find out the tensile strength of different materials. Dog bone and dumbbell are two shapes for test specimens' fabrication up to 14mm material thickness. Figure 4.3 represents the **ASTM D638 Type IV** standard having a dumbbell shape. Using the **FIE UTE HGFL** model UTM (universal testing Machine) test machine (Figure 3.7), test specimens were checked for the tensile strength as per **ASTM D638 Type IV** customary test stipulations. During test runs, 5mm/min as the machine speed was tuned and the test piece was fixed correctly between upper and lower jaw.

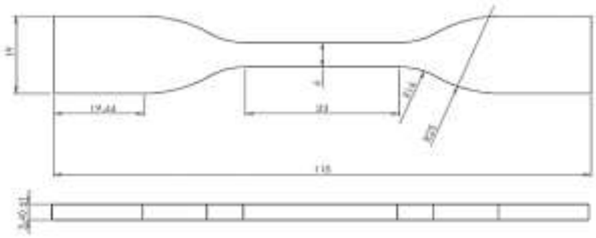


Figure 4.3: Test sample for tensile strength

ISSN: 2278-4632
Vol-13, Issue-04, No.03, April : 2023

4.3.2 FLEXURAL SPECIMEN PREPARATION

The **ASTM D790** standard is the most familiar, universally accepted testing method to find out the Flexural Test of different materials. Figure 3.8 represents the **ASTM D790** standard having a rectangular shape.

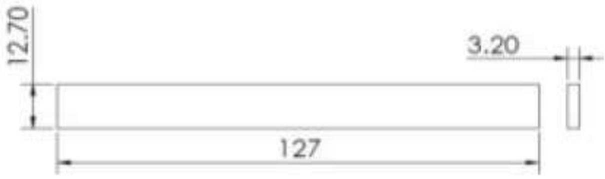


Fig4.4. ASTM D790 Bending test specimen dimension

5. EXPERIMENTAL SETUPMENT

ASTM standard for tensile test and flexural test specimens and manufacturing steps, a) Dimensions of the tensile test specimens according to ASTM D638-14 Type IV, View of the specimens in slicing program

Angle: 0/90^0

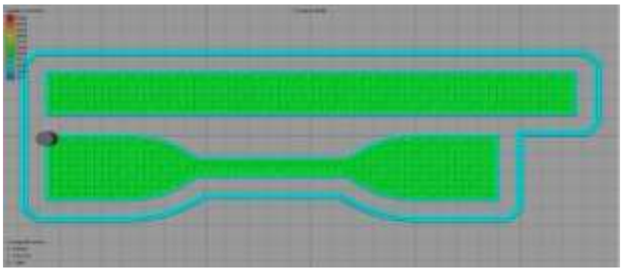


Fig5.1: Real view of the 3D printing process

Angle: 30/60^0

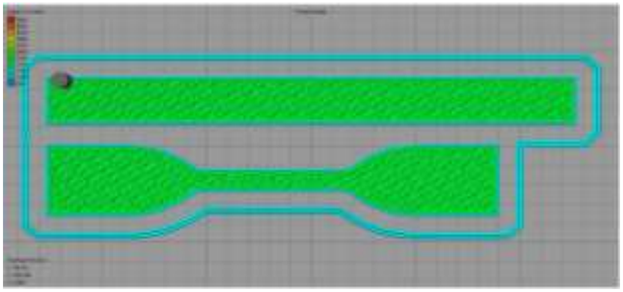


Fig5.2: Real view of the 3D printing process

Angle: +45^0/45^0

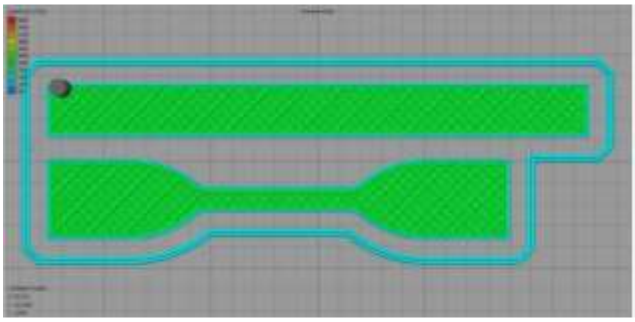


Fig5.3: Angle +45^0/45^0 Real view of the 3D printing process

Fig5.4: Machining process

5.1 TENSILE TEST SPECIMENS

Tensile strengths of test specimens built with various layer thickness and screen angle parameter values are evaluated to ascertain the impact of these parameter values on the mechanical characteristics of tensile and flexural strengths.

Fig5.5: ASTM D638 Type IV specimen

5.2 FLEXURAL SPECIMENS

Flexural strengths of test specimens built with various layer thickness and screen angle parameter values are evaluated to ascertain the impact of these parameter values on the mechanical characteristics of tensile and flexural strengths.

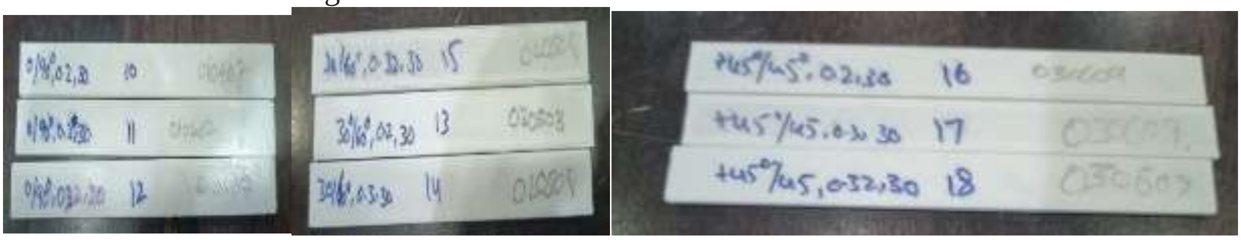


Fig5.6: ASTM D790 Specimen

6. RESULTS AND DISCUSSIONS

6.1 RESULTS FOR TENSILE STRENGTH

Figure 6.1 displays the mechanical tensile strength data mentioned above for nine sets of specimens. The strength of the specimen is also increased by thickening the layers. Intralayer bonding's function might be one cause. The maximum layer thickness rises from 0.2, 0.3, and 0.32 mm with a fixed raster angle. Compared to 0.2 mm and 0.32 mm, which both need extra layers to attach to one another and provide the appropriate total layer height, a solid layer thickness of 0.3 mm has much better strength. With a layer thickness of 0.3 mm and a 0/90° raster angle, the maximum tensile strength was discovered.

Fig6.1 Tensile test specimens

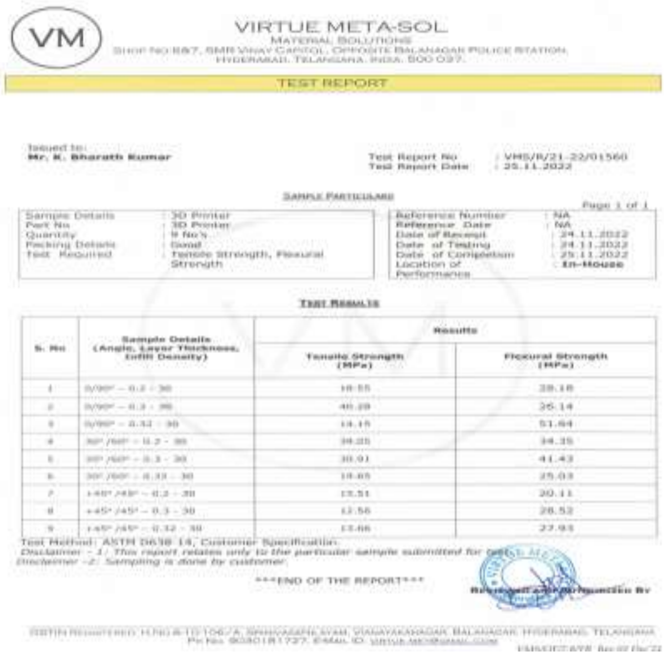
6.2 RESULTS FOR FLEXURAL STRENGTH

Figure 6.2 displays the mechanical flexural strength values mentioned above for nine sets of specimens. The strength of the specimen is also increased by thickening the layers. Intralayer bonding's function might be one cause. The maximum layer thickness rises from 0.2, 0.3, and 0.32 mm with a fixed raster angle. In contrast to 0.2 mm and 0.3 mm, which both need extra layers to connect to one another and provide the appropriate total layer height, a solid layer thickness of 0.32 mm has a much better flexural strength. The layer thickness of 0.32 mm and a 0/90° raster angle were determined to have the maximum flexural strength.

ISSN: 2278-4632
Vol-13, Issue-04, No.03, April : 2023

Fig6.2 Tensile test specimens

6.3 TEST RESULTS:



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SHOP NO 8&7, SMR VINAY CAPITOL, OPPOSITE BALANAGAR POLICE STATION, HYDERABAD, TELANGANA, INDIA, 500 037.

TEST REPORT

Issued to:
Mr. K. Bharath Kumar

Test Report No : VMS/R/21-22/01560
Test Report Date : 25.11.2022

SAMPLE PARTICULARS

Page 1 of 1

Sample Details	3D Printer	Reference Number	NA
Part No	3D Printer	Reference Date	NA
Quantity	9 No's	Date of Receipt	24.11.2022
Packing Details	Good	Date of Testing	24.11.2022
Test Required	Tensile strength, Flexural Strength	Date of Completion	25.11.2022
		Location of Performance	In-House

TEST RESULTS

S. No	Sample Details (Angle, Layer Thickness, Infill Density)	Results	
		Tensile Strength (MPa)	Flexural Strength (MPa)
1	0/90° – 0.2 – 30	18.55	28.18
2	0/90° – 0.3 – 30	40.29	36.14
3	0/90° – 0.32 – 30	14.15	51.64
4	30° /60° – 0.2 – 30	39.25	34.35
5	30° /60° – 0.3 – 30	30.91	41.43
6	30° /60° – 0.32 – 30	18.65	25.03
7	+45° /45° – 0.2 – 30	13.51	20.11
8	+45° /45° – 0.3 – 30	12.56	28.52
9	+45° /45° – 0.32 – 30	13.66	27.93

Test Method: ASTM D638 14, Customer Specification.
Disclaimer – 1: This report relates only to the particular sample submitted for test.
Disclaimer – 2: Sampling is done by customer.

END OF THE REPORT

Reviewed and Authorized By

Fig6.3: The above Test report shows that tensile and flexural strength results

7. CONCLUSION

The aforementioned research employed PETG raw materials to make the 3D-printed components, and the tensile and flexural strengths of the parts were mechanically assessed using a UTM machine to ascertain the effects of layer thickness, raster angle, and infill density. The research led to the following finding:

1. According to all of the experiment findings, changing the layer thickness, raster angle, and infill density has a noticeable impact on the tensile and flexural characteristics.

2. According to tensile tests, layer thicknesses of 0.3 mm and 0°/90° have higher tensile strengths than those of 0.2 mm and 0.32 mm and $+45^0/-45^0$ and $30^0/60^0$ raster angles, respectively.

3. Flexural testing showed that layer thickness of 0.32 mm and a raster angle of 0°/90° had higher flexural strength than layer thicknesses of 0.2 mm and 0.3 mm and raster angles of $+45^0/-45^0$ and $30^0/60^0$.

4. To produce superior mechanical qualities compared to other mechanical values, the ideal layer thickness was 0.3 mm, and the ideal raster angle was 0°/90°.

8. REFERENCES:

1. R. Srinivasan, W. Ruban, A. Deepanraj, R. Bhuvanesh, and T. Bhuvanesh, "Effect on infill density on mechanical properties of PETG part fabricated by fused deposition modelling," in Materials Today: Proceedings, Jan. 2020, vol. 27, pp. 1838–1842. doi: 10.1016/j.matpr.2020.03.797.

2. R. Srinivasan, K. Nirmal Kumar, A. Jenish Ibrahim, K. v. Anandu, and R. Gurudhevan, “Impact of fused deposition process parameter (infill pattern) on the strength of PETG part,” in Materials Today: Proceedings, Jan. 2020, vol. 27, pp. 1801–1805. doi: 10.1016/j.matpr.2020.03.777.
3. R. Srinivasan, P. Prathap, A. Raj, S. A. Kannan, and V. Deepak, “Influence of fused deposition modeling process parameters on the mechanical properties of PETG parts,” in Materials Today: Proceedings, Jan. 2020, vol. 27, pp. 1877–1883. doi: 10.1016/j.matpr.2020.03.809.
4. K. Durgashyam, M. Indra Reddy, A. Balakrishna, and K. Satyanarayana, “Experimental investigation on mechanical properties of PETG material processed by fused deposition modeling method,” in Materials Today: Proceedings, 2019, vol. 18, pp. 2052–2059. doi: 10.1016/j.matpr.2019.06.082.
5. T. Panneerselvam, S. Raghuraman, and N. Vamsi Krishnan, “Investigating Mechanical Properties of 3D-Printed Polyethylene Terephthalate Glycol Material Under Fused Deposition Modeling,” Journal of The Institution of Engineers (India): Series C, vol. 102, no. 2, pp. 375–387, Apr. 2021, doi: 10.1007/s40032-020-00646-8.
6. J. M. Barrios and P. E. Romero, “Improvement of surface roughness and hydrophobicity in PETG parts manufactured via fused deposition modeling (FDM): An application in 3D printed self-cleaning parts,” Materials, vol. 12, no. 15, Aug. 2019, doi: 10.3390/ma12152499.
7. A. Özen, D. Auhl, C. Völlmecke, J. Kiendl, and B. E. Abali, “Optimization of manufacturing parameters and tensile specimen geometry for fused deposition modeling (Fdm) 3d-printed petg,” Materials, vol. 14, no. 10, May 2021, doi: 10.3390/ma14102556.
8. P. P. Agarwal, T. S. Dadmode, M. R. Kadav, A. P. Ogale, and P. P. Mangave, “Experimental Analysis of Mechanical properties of PETG Material 3D Printed Material by Using Fused Deposition Modelling Technique,” 2020, doi: 10.5281/zenodo.3739793.
9. J. M. Mercado-Colmenero, M. Dolores La Rubia, E. Mata-Garcia, M. Rodriguez-Santiago, and C. Martin-Doñate, “Experimental and numerical analysis for the mechanical characterization of petg polymers manufactured with fdm technology under pure uniaxial compression stress states for architectural applications,” Polymers (Basel), vol. no. 10, pp. 1–25, Oct. 2020, doi: 10.3390/polym12102202.
10. S. Swetha, P. Morampudi, K. Aruna, P. & Putha, and P. Kumar, “Evaluation of Tensile Properties of 3D Printed Petg Specimen as per ASTM Standards.” [Online]. Available: www.tjprc.org
11. M. M. Hanon, R. Marczis, and L. Zsidai, “Anisotropy evaluation of different raster directions, spatial orientations, and fill percentage of 3d printed petg tensile test specimens,” in Key Engineering Materials, 2019, vol. 821 KEM, pp. 167–173. doi: 10.4028/www.scientific.net/KEM.821.167.
12. A. Jaisingh Sheoran and H. Kumar, “Fused Deposition modeling process parameters optimization and effect on mechanical properties and part quality: Review and reflection on present research,” in Materials Today: Proceedings, 2020, vol. 21, pp. 1659–1672. doi: 10.1016/j.matpr.2019.11.296.
13. D. Yadav, D. Chhabra, R. K. Gupta, A. Phogat, and A. Ahlawat, “Modeling and analysis of significant process parameters of FDM 3D printer using ANFIS,” in Materials Today: Proceedings, 2020, vol. 21, pp. 1592–1604. doi: 10.1016/j.matpr.2019.11.227.
14. Popescu, D., Zapciu, A., Amza, C., Baciu, F., Marinescu, R., “FDM process parameters influence over the mechanical properties of polymer specimens: A review”, Polymer Testing, Vol. 69, Pages 157-166, 2018.
15. M. H. Hsueh et al., “Effect of printing parameters on the thermal and mechanical properties of 3d-printed pla and petg, using fused deposition modeling,” Polymers (Basel), vol. 13, no. 11, Jun. 2021, doi: 10.3390/polym13111758.

