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EXPERIMENTAL STUDY ON OPTIMIZING THE FUSED DEPOSITION MODELING PARAMETERS FOR POLYETHYLENE TEREPHTHALATE GLYCOL MATERIAL USING TAGUCHI METHOD

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SUMMARY

In many different manufacturing techniques, additive manufacturing technologies have proven to be quite useful for developing a prototype model in wide range of applications. In that technique, Fused Deposition Modeling (FDM) is one of the concern favorite methods used in industries, because it can create complex structures at a low cost. FDM uses the polymer ingredients that are melted, extruded, and layered on top of one another to create the desired product, independent of design intricacy. This examination analyzes the effects of several process variables on the flexural and impact characteristics of parts produced of polyethylene terephthalate glycol (PETG)material, including infill structure, layer thinness, infill multi-layering, and infill concentration. The L9 orthogonal array was developed by the Taguchi method to be employed in this design of experiment. Through the analysis of variance (ANOVA), the study elucidated the relative substance and percentage effort of each process parametric quantity to the desired outcomes. The results obtained through the Taguchi method revealed optimal parameters for both impact strength and flexural tests. For impact strength, the optimum factor was determined as a layer thinness of 0.12-millimeter, quarter cubic infill structure, 30% infill denseness (density), and a multi-layering of 3. Conversely, for the flexural test, the optimal factor was found to be a layer thinness of 0.12-millimeter, cross 3D infill structure, 60% infill denseness, and a multi-layering of 4 respectively.

Key words: *additive manufacturing, fused deposit modeling, process factor, polyethylene terephthalate glycol, mechanical properties.*

INTRODUCTION

Additive manufacturing involves the creation of parts step by step addition layers of materials that correspond to the three-dimensional model outlines of the components [1,2]. Since their inception, additive manufacturing profession have undergone continuous advancement, witnessing the introduction of new methods and materials, enhancements in the mechanical and considerable belongings of 3D printed components, among other improvements [3–9] [31]. Among the other manufacturing process the easy and affordable processes is fused deposition method, It stands out for its versatility in material options including PLA, PET-G, ASA, ABS, TPU, and nylon, as well as its user-friendly nature and cost-effectiveness in terms of both materials and equipment [11–18]. Polyethylene terephthalate glycol (PETG) is widely favored for its robustness, flexibility, and exceptional thermal stability benefits, contributing to its popularity [19, 20] [27]. Its ease of handling and suitability for food-related purposes further enhance its appeal. Moreover, PETG's recyclability contributes to waste reduction efforts and environmental sustainability. Its ability to withstand vacuum forming and high temperatures without fracturing adds to its versatility. Additionally, PETG's natural transparency makes it an ideal choice for aesthetic applications [21, 22] [25].

Among these characteristics, infill density (Id) revealed as the most significant factor influencing the mechanical properties of the fused deposit modeling parts under examination. In [8] an assessment was undertaken to analyze the effect of fabrication parameters on the mechanical attributes and numerical analysis of fused deposit modeling-printed components. The study found that PET-G components made with a triangular fill pattern and the highest infill percentage had the best compressive properties. When compared to other designs, such as grid, linear, honeycomb, and coaxial, the compressive results for the triangle pattern ranged from 6.45% to 35.16% higher.

In, researchers investigated the optimal process component to increase the tensile properties of nylon and Acrylonitrile Butadiene Styrene (ABS) parts. There were three things that were looked at: the infill pattern (Ip), which could be triangular, hexagonal, or octet-shaped; the infill density (Id) at 10%, 50%, or 100%; and the printing speed (Ps) at 60, 65, or 70 mm/s. The results showed that infill density (Id), out of all the characteristics looked at, had a major impact on tensile strength, with strength rising noticeably with larger infill densities.

Hanon et al. [19] investigated how the infill density, construction position, and raster angle affect the ductile characteristics of PETG and discovered that a 0° raster angle gives excellent strength. A different study [32] looked at the impact characteristics of PETG sections with corresponding infill structures while keeping the raster angle constant at 0° for each of the eight patterns. They determined that the grid pattern offered the best impact properties. Among these, inter-layer bonding, layer thinness, infill structure, and raster angle emerge as critical design elements [29]. Nonetheless, FDM encounters significant challenges in producing operational or serviceable parts, notably including incompatible surfaces, subpar mechanical properties and limited exactness [30]. Daminabo et al. [23] conducted a study to assess how different infill patterns affect the strength of PETG parts. They discovered that the grid pattern, followed by the honeycomb and rectilinear patterns, significantly enhanced tensile strength. The grid pattern's strong bonds contribute to this increased strength, while the honeycomb pattern effectively maintains its inter molecular layers. Among the patterns tested, the grid pattern had the highest tensile characteristics, while the coaxial pattern had the lowest. In another work, Bhandari et al. [21] discovered that ductile property rises with higher infill concentration and declines with layer thickness.

EXPERIMENTAL SETUP

In this article shows as a experimental and methodology, which include the selection of a filament material, specify process parameters, fabricate specimen and evaluating the mechanical properties. Figure 1 that displays the method used to study of the effects of fused deposition modeling parameters on a flexural and impact behavior of a Polyethylene Terephthalate Glycol components [24].

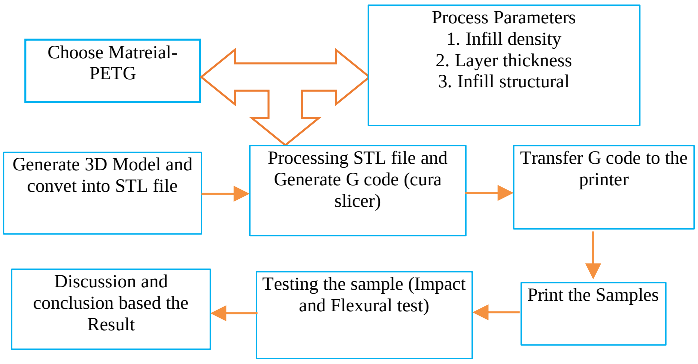

Figure 1. These Phases of Approach that has Investigating the Outcome of Fused Deposition Method Settings in Mechanical Properties of PET-G Components

Fused Deposit Modeling

Fused Deposition Modeling (FDM) is a 3D printing technique that involves heating a thermosetting filament and squeezing it out through a nozzle in layers [26] [28].

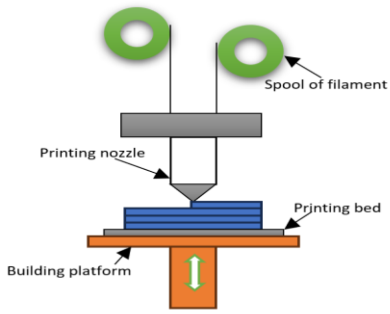

Figure 2. Schematic of Fused Deposit Modeling Process

The technique starts with a computerized 3D model, which is then divided into tiny horizontal layers using specialist software. The printer heats the filament to a molten state and deposits it onto the build platform, adhering to the pattern set by the sliced model. As each layer is laid down, it cools and bonds with the previous one. The build platform usually moves vertically to allow for the addition of new layers. Critical factors that affect FDM include nozzle temperature, print rate, layer thinness, and infill denseness. While in figure 2 represents the schematic diagram of fused deposit modeling was represented.

Precise adjustment of these parameters is essential to achieve the desired mechanical attribute and overhead quality of the printed product. It is popular for prototyping, tool creation, and manufacturing end-use parts due to its flexibility and range of material choices.

Filament Material

Polyethylene Terephthalate Glycol (PETG) was chosen for fabricating the specimens. PETG is a thermoplastic resin known for its low shrinking, high strength, excellent layer adhesion, and durability without brittleness. The attributes of PETG material under the specified printing conditions are detailed below.

Filament dia: 1.75 mm

Density: 1.27 g/cc

Melt Temperature: 235^{o} C

Bed Temperature: 60^{o} C.

Process Parameters

The mechanical attribute of the printed component is strongly affected by the parameters were chosen for printing process in fused deposit modeling method. In order to have desired mechanical strength, optimal selection of the process parameter has to be carried out. Hence, in the experimental investigation, four process factors viz., Layer height, Infill density, Infill structure and Infill multiple layers have been chosen for impact analysis and flexural analysis. The process parameters of the FDM process are described as shown below:

Layer Thickness

Layer thickness, sometimes known as layer dimension, is a measurement of the FDM head's ultra-thin layers. This thinness is dictated by the material used and the extruder nozzle tip diameter.

Infill Density

Infill density is the quantity of plastic utilized to fill the inside of a print. Higher infill density leads to a longer print time, whilst lower infill density shortens the print time.

Infill Pattern

Infill structure refers to the internal structure of a print, which affects the material's properties and overall strength. It show a essential function in deciding the quality and durability of the manufactured object and its section is shown in figure 3.

- *Cubic Structure:* The cubic infill type constructs cubic volumes within the part by layering a pattern akin to a triangular infill. However, each successive layer is offset, creating enclosed cube-shaped volumes with a corner oriented downward.

- *Cross 3D structure:* The cross pattern generates multiple cross shapes as infill, making it ideal for flexible parts that need to bend and twist. It is less effective for rigid plastics. A 3D version of the cross pattern can be used to enhance strength.

- *Tri- Hexagon structure:* The tri-hexagon infill stands out as the most robust pattern. It features a hexagonal structure interspersed with triangles, resembling the grid and triangular infill types, achieved by intersecting lines within the same layer. However, this overlapping occasionally leads to potential nozzle clogging during printing.

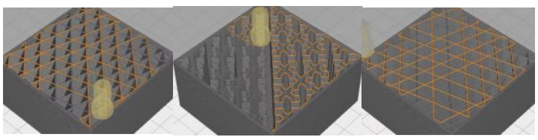

Figure 3. Infill Pattern (a) Cubic, (b) Cross 3D and (c) Tri-Hexagon

Table 1. Process Invariable and their Levels

S.No	Process Parameters	Level 1	Level 2	Level 3
1	Layer thinness (mm)	0.12	0.16	0.20
2	Infill structure	Quarter-cubic	Tri-Hexagon	Cross 3D
3	Infill density (%)	30	45	60
4	Infill multiplayer	2	3	4

Infill Multilayer

Line infill consists of parallel lines per layer that cross at a 90-degree angle with the preceding layer. Unlike certain designs, these lines do not overlap within the corresponding layer, resulting in increased two-dimensional strength. The primary function of infill is to furnish internal support for top layers, which would otherwise need to bridge over empty spaces.

Table 2. Full Factorial Experimental Design

Exp.No	Layer Thickness (mm)	Infill Structure	Infill Density (%)	Infill Multi layer
1	0.12	Quarter Cubic	30	2
2	0.12	Tri-Hexagon	45	3
3	0.12	Cross 3D	60	4
4	0.16	Quarter Cubic	45	4
5	0.16	Tri-Hexagon	60	2
6	0.16	Cross 3D	30	3
7	0.20	Quarter Cubic	60	3
8	0.20	Tri-Hexagon	30	4
9	0.20	Cross 3D	45	2

Additionally, infill influences printing speed, structural integrity, filament usage, and the visual appearance of the printed object. After the identification of process parameters, detailed experiments were performed. The process invariable and the levels of the FDM operation are described in Table 1.

Ross (1996) has stated that experiments should be designed in such a way that it can help to improve some performance characteristics to an acceptable or optimum value with a nominal amount of scientific research. In the current study, four process factors were determined for conducting an experiment with three levels of variation.

In the current study, the complete factorial design was employed to execute an experiment at each factor level combination. In a complete factorial experimental design, trials are done with all potential factor settings combinations. A full-factorial experimental pattern allows for the prediction of all conceivable interactions. For each experiential run, the process parameters were set according to full factorial experimental design in table 2.

Fabrication of Specimen

The fabrication procedure was executed using an Ender 3 Pro printer, as illustrated in Figure 4. In any manufacturing process, the initial step is design. The design was created using SolidWorks software, and the resulting computer aided design model is displayed in Figure 4.

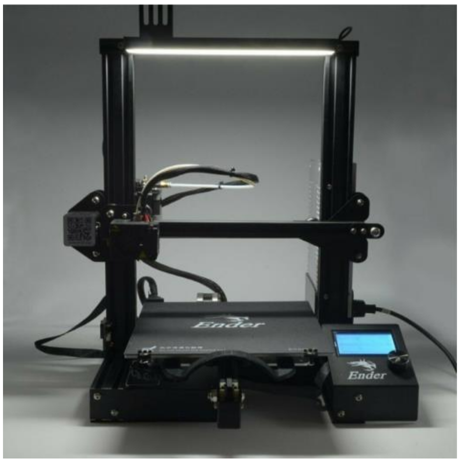

Figure 4. Ender 3pro 3D Printer

This CAD file was then converted into an STL format. Ultimaker CURA was utilized for slicing, where optimal situation for all factor were set. Subsequently, the printer was prepared to print the needed part. The printing time period may alter based on the given factor and the part's sizing, but not the design quality. For this study, impact and flexural specimens were printed using the FDM process with the Ender 3 Pro 3D printer.

The American Society for Testing and Materials (ASTM) standard was followed to develop a model, the sample piece dimension are in the standard of D6110 and D 738 type for impact and flexural as shown in Figure 5. a and 5.b.

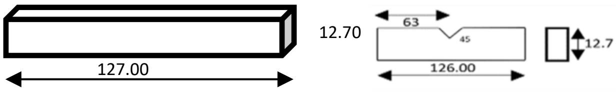

Figure 5. a. Flexural Specimen b. Impact Specimen

This CAD file was then converted into an STL format. Ultimaker CURA was utilized for slicing, where optimal situation for all factor were set. Subsequently, the printer was prepared to print the needed part. The printing time period may alter based on the given factor and the part's sizing, but not the design quality. For this study, impact and flexural specimens were printed using the FDM process with the Ender 3 Pro 3D printer. CAD model of impact and flexural specimen shown in fig. 6.

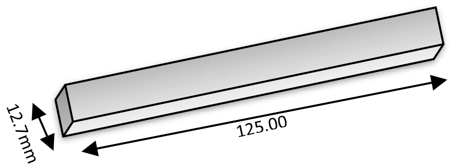

Figure 6. CAD Model of Impact and Flexural Specimen

The final fabricated specimen is displayed in Figure 7.a and 7.b.

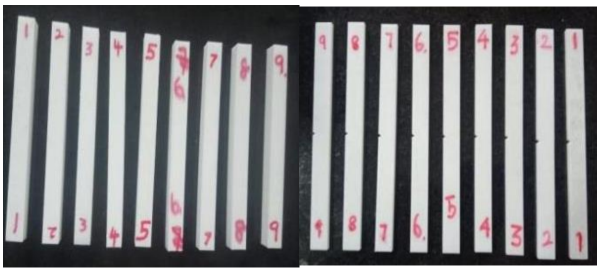

Figure 7. Fabricated Specimen a) Flexural b) Impact

Properties of Printed Specimen

The structural properties of the material instance will be determined through impact and flexural tests conducted on a impact test and bend test.

Impact Test

The mechanical characteristics of PETG material will be assessed using the results of impact and flexural tests conducted under appropriate process parameters. During the impact test, the initial contact line was maintained at a fixed distance from the specimen clamp and notch centerline, aligning with the notch itself. The pendulum's swing during testing-initiated contact with the specimen at a distance of 22 millimeter higher up the upper surface of the vice [10]. The built-in software system of the testing machine taped the energy spent by the apparatus in fracturing the specimen.

Flexural Test

For the flexural test, the maximum flexural strength was noted for investigation. The test utilized a span length of 53 mm, with a machine experiment movement set at 10 millimeter/min as shown in the Figure 8.

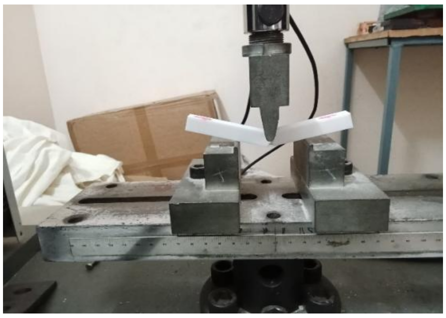

Figure 8. Flexural Test Machine

RESULTS AND DISCUSSION

The mechanical properties of PETG material will be revealed through results exist from impact and flexural tests conducted at specific process factor as mentioned in the table 3. To evaluate the outcome of the process inconsistent, the impact intensity at the highest level is going to be noted. Simultaneously, flexural tests will be performed, and the flexural capability at the peak point will be used for further analysis.

Table 3. Experimental Values of Impact and Flexural Strengths of Specimens

Exp.No	**Layer Thickness (mm)**	**Infill Structure**	**Infill Density (%)**	**Infill Multi layer**	**Impact Strength (J)**	**Flexural Strength (MPa)**
1	0.12	Quarter Cubic	30	2	2.40	26.488
2	0.12	Tri-Hexagon	45	3	2.50	36.848
3	0.12	Cross 3D	60	4	1.30	49.814
4	0.16	Quarter Cubic	45	4	1.90	34.058
5	0.16	Tri-Hexagon	60	2	2.25	30.082
6	0.16	Cross 3D	30	3	1.80	36.142
7	0.20	Quarter Cubic	60	3	1.90	32.722
8	0.20	Tri-Hexagon	30	4	2.00	42.981
9	0.20	Cross 3D	45	2	1.40	30.152

Modeling and Validation

The ANOVA test serves as the primary approach for examining factors influencing a given dataset. By enabling simultaneous comparison of multiple groups, it aims to ascertain potential relationships among them. In the context of studying the mechanical properties of PETG material, Analysis of Variance (ANOVA) is employed to find out the factor with the most significant impact. Utilizing Minitab 18 software, ANOVA analysis is conducted on both impact and flexural strengths. Subsequently, main effects plots are generated to visualize contributions to mechanical property enhancement, and the parameter value with the most substantial impact is determined. The ensuing analysis and discussion delve into the interpretation of main effects plots and resultant findings.

ANOVA for the Intensity of Impact

The main effect plot (Figure 9) illustrates the impact strength concerning layer thickness, infill density, infill structure, and infill multiple layers. At lower layer thicknesses, the material exhibits higher impact strength, but as thickness increases, there's a decline in impact strength. As a result, Taguchi categorizes needed qualitative components into forms to attain optimum conditions, The larger the better.

$$\text{SNi} = -1og10\sum_{i=1}^{n} 1/\,Yi$$

SNi is utilised to increase the response value.

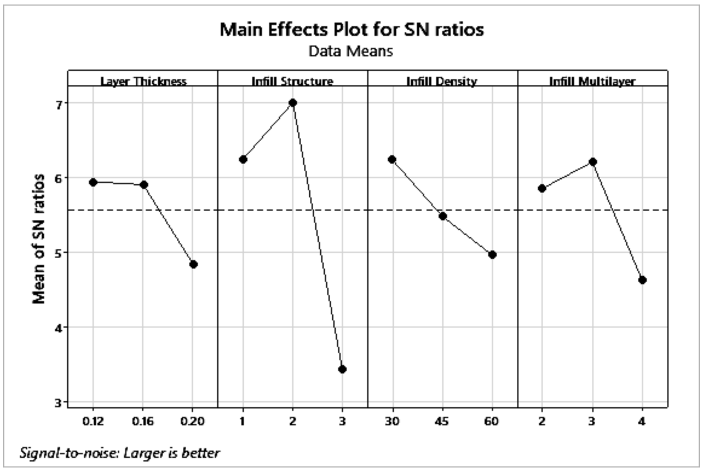

Figure 9. Main Impact Plot: S/N Ratio for Impact Strength

Similarly, moderate infill multiple layers result in good impact strength, but a further increase lead to decreased strength. Consequence table for signal to noise ratio - Impact strength shown in table 4.

Table 4. Consequence Table for Signal to Noise Ratio - Impact Strength

Level	Layer Thickness	Infill Structure	Infill Density	Infill Multilayer
1	5.947	6.251	6.243	5.857
2	5.908	7.008	5.485	6.213
3	4.839	3.436	4.966	4.625
Delta	1.108	3.572	1.278	1.588
Rank	4	1	3	2

Regarding infill density, higher initial values correspond to higher impact strength, but a subsequent increase result in reduced strength. After analyzing the impact strength data using ANOVA, the following table will likewise provide the results indicated in Table 5.

The optimal parameters for impact strength were identified as a layer thinness of 0.12 mm, a quarter cubic infill structure, 30% infill density, and a multi-layering of 3.

Table 5. Results of ANOVA for Impact Strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Layer Thickness	2	0.14389	10.67%	0.14389	0.07194
Infill Structure	2	0.91722	68.00%	0.91722	0.45861
Infill Density	2	0.09389	6.96%	0.09389	0.04694
Infill Multilayer	2	0.19389	14.37%	0.19389	0.09694
Error	0	*	*	*	*
Total	8	1.34889	100.00%		

Based on Table 5, it is evident that infill structure, out of all the characteristics, has the most significance, accounting for 68.00% of the total. Thus, infill multi-layer was 14.37%, layer thickness was 10.67% and infill density was 6.96% of the total.

AANOVA for the Intensity of Flexural

The main effect plot (Fig. 10) illustrates the flexural strength concerning layer thickness, infill density, infill structure, and infill multiple layers.

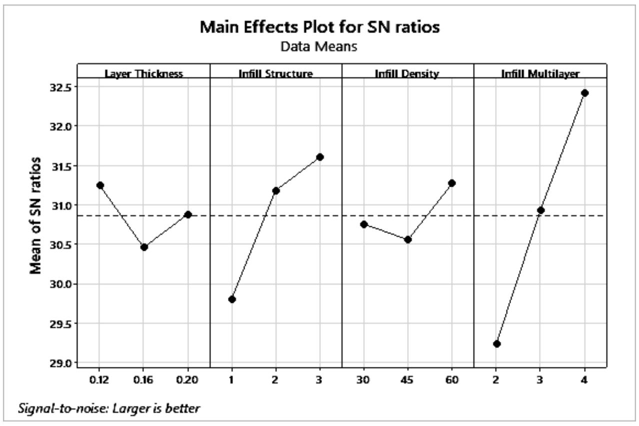

Figure 10. Main Impact Plot: S/N Ratio for Flexural Strength

At lower layer thicknesses, the material exhibits higher flexural strength, but as thickness increases, there's a decline in flexural strength. Similarly, for infill multiple layers, and infill density higher values result in good flexural strength, but a further decrease leads to decreased strength. Consequence table for signal to noise ratio - Flexural strength shown in table 6.

Table 6. Consequence Table for Signal to Noise Ratio - Flexural Strength

Level	Layer Thickness	Infill Structure	Infill Density	Infill Multilayer
1	31.25	29.8	30.76	29.24
2	30.46	31.18	30.55	30.93
3	30.88	31.6	31.27	32.41
Delta	0.79	1.8	0.72	3.17
Rank	3	2	4	1

Regarding infill structure, tri-hexagon corresponds to higher flexural strength, but a subsequent increase result in reduced strength. After analyzing the flexural strength data using ANOVA, the following table will likewise provide the results indicated in Table 7.

Table 7. Results of ANOVA for Flexural Strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS
Layer Thickness	2	27.68	6.80%	27.68	13.84
Infill Structure	2	95.16	23.38%	95.16	47.58
Infill Density	2	21.40	5.26%	21.40	10.70
Infill Multilayer	2	262.76	64.56%	262.76	131.38
Error	0	*	*	*	*
Total	8	406.99	100.00%		

Based on Table 7, it is evident that infill multiple layer, out of all the characteristics, has the most significance, accounting for 64.56% of the total. Thus, infill structure was 23.38%, layer thickness was 6.80% and infill density was 5.26% of the total.

For the flexural test, the best factor was determined to be a layer thinness of 0.12 mm, a cross 3D infill structure, 60% infill denseness, and a multi-layering of 4.

CONCLUSION

The consequence of activity factor on the mechanical attribute of Polyethylene Terephthalate Glycol (PETG) material was thoroughly examine by conducting impact and flexural tests using a testing machine. The test samples were made-up by using an Ender 3 Fused Deposition Modeling (FDM) printer and the following results were reached during mechanical testing are:

- Layer thickness and infill density of the PETG material must be minimal and have a modest amount of multilayer infill in order to demonstrate the material's strong impact properties.
- Conversely, with a minimum layer thickness, multiple layers at maximum infill, and a lower infill density percentage, the material demonstrates excellent flexural properties.
- The tri-hexagon infill pattern demonstrated the highest impact strength among all infill patterns, while the cross-3D infill pattern exhibited the greatest flexural strength compared to the others.
- Overall, the contribution of the infill multiple layers is greater compared to infill density, layer thickness, and infill structure. Specifically, the infill multiple layers contributed 14.37% to impact strength and 64.58% to flexural strength.

Therefore, among the various process element such as infill structure, layer thinness, and infill denseness, the infill multiple layers exhibited the most significant consequence on the mechanical attribute of Polyethylene Terephthalate Glycol (PETG) material.

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