Effects of Printing Parameters on the Mechanical Strength of Thermoplastics 3D Printed Specimens

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ABSTRACT

3D printing is increasingly adopted in the biomedical field, particularly for developing adaptive assistive devices. Common materials for Fused Deposition Modelling (FDM) include Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate Glycol (PETG). With the growing demand to identify the best materials and parameter settings for these applications, our project focuses on creating a 3D model of tensile test specimens with varying infill densities, wall perimeters, and layer heights for both ABS and PETG materials. Our goal is to evaluate how these parameter settings affect the tensile properties of each material. We fabricated the 3D specimen model following ASTM D638-14 Type I dimensions and conducted tensile tests using a Universal Testing Machine at a 5mm/min feed rate. Our results indicate that increasing infill density enhances Young's modulus and tensile strength for both ABS and PETG materials. Young's modulus for ABS shows marginal improvement with different wall perimeters. A similar trend is observed in Young's modulus and tensile strength for ABS

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and PETG at different layer heights. PETG exhibits higher tensile strength, while ABS demonstrates greater stiffness.

Keywords: *3D Printing; ABS; PETG; Young's Modulus; Tensile Test*

Introduction

Additive manufacturing, commonly known as 3D printing, has gained widespread acceptance since its inception and has become particularly popular in the DIY online community [1]. This innovative technique offers numerous advantages, including the rapid fabrication of intricate models. Among the various methods within additive manufacturing, Fused Deposition Modelling (FDM) stands out as one of the most well-known. FDM involves the precise layering of polymeric filament on a heated bed to create 3D objects [2]. The popularity of this method is attributed to the ongoing reduction in the cost of materials and equipment [3]. Filament materials and spare parts for 3D printers are readily available online, and their affordability has improved significantly over the past decade.

The widespread adoption of additive manufacturing extends to various industries, including automotive manufacturing, construction, and even everyday domestic use. However, one of its most significant contributions lies in its ability to produce customized products at a relatively low cost, particularly within the biomedical field. 3D printing has revolutionized the creation of patient-specific knee replacements that mirror the patient's anatomy [4]. With the capacity to adjust the size and shape of these parts using CAD software, it becomes easier to cater to the diverse needs of different patients. In the past, surrogate body parts were expensive for individuals with disabilities, but 3D printing has drastically reduced these costs [5]. This is largely due to the accessibility of filament materials and the simplicity of producing 3D components.

An essential consideration when using the FDM method is the selection of the appropriate material for the process. FDM 3D printers can utilize various filament materials to create 3D models, such as Acrylonitrile Butadiene Styrene (ABS) and Polyethylene Terephthalate Glycol (PETG). ABS, a polymer composed of acrylonitrile, butadiene, and styrene, is valued for its robust mechanical and physical properties [6]. On the other hand, PETG, a thermoplastic polyester, is chosen for its chemical resistance and strong mechanical performance [7]. Both materials exhibit distinct mechanical properties and behave differently when used as filaments in 3D printing. Therefore, a comprehensive study of the tensile properties of these materials is crucial for direct comparison before selecting one for 3D printing. Previous studies have shown that different materials significantly affect the performance of 3D-printed parts, as revealed through finite element analysis. Static analysis reveals variations in mechanical properties, such as ductility, von Mises stress, and operating temperature, among different materials [8]. It's worth noting that finite element analysis (FEA) offers a cost-effective, less hazardous, and practical approach, although it may not always yield optimal results [9].

Despite all these benefits that 3D printing possesses, there are many parameters that need to be considered before a good 3D printed part can be fabricated using FDM. How precise and accurate the printed parts are dependent on the method and scale of printing used [10]. These parameters include infill density, wall perimeter, and layer height, which can be adjusted in a slicer software such as Ultimaker Cura. These three main key factors control the mechanical characteristics of the printed parts [11]. Infill density refers to the volume of material inside the 3D-printed object. Meanwhile, the wall perimeter is the thickness of the shell at the outermost layer of the 3D-printed model. Finally, layer height is the distance between each layer of plastics during the printing process. It is first assumed that as all three parameter values increase, the mechanical property of the part is also increased. Srinivasan et al. [12] reported that increasing the infill density will increase the tensile strength of PETG material. The same effect can also be seen in other materials [13]. The wall perimeter also has a great impact on the tensile strength of a printed part [14]. Meanwhile, a lower layer height is usually associated with higher tensile strength [15].

However, it's important to acknowledge that prior studies were conducted under diverse methodologies and environmental conditions, and there is a notable absence of direct comparative research on the tensile properties' response to variable infill density, layer height, and wall perimeter for ABS and PETG materials. Consequently, this research has been undertaken to fabricate 3D models for a tensile test experiment, varying infill density, wall perimeter, and layer height according to ASTM D638-Type I standards, using an Ender 3 printer. This investigation aims to identify how infill density, wall perimeter, and layer height affect the tensile properties of the model and to compare the tensile behaviour of both ABS and PETG materials.

Although numerous parameters require adjustment when preparing to 3D print a model, this study specifically centres on three key parameters: infill density, wall perimeter, and layer height, while allowing Ultimaker Cura software to automatically generate other settings. A rectilinear infill pattern is uniformly used for each specimen (as depicted in Figure 3a). The findings of this research serve as a valuable reference for manufacturers seeking to anticipate the mechanical behavior of their 3D-printed products under tensile loads. This is particularly relevant for biomedical applications in the creation of prosthetic limbs.

Methodology

Development of CAD model

3D models for both ABS and PETG materials are designed by using CATIA V5 21 software. The design dimension followed the ASTM D638 Type-I standard measurement. Figure 1 shows the ASTM D638-Type I standard dimension used to design the CAD model for both specimens. The sample is created into a dumbbell shape for the tensile test experiment [16], as shown in Figure 2. The thickness, width, and gauge length of the CAD model are 3 mm, 13 mm, and 57 mm, respectively.

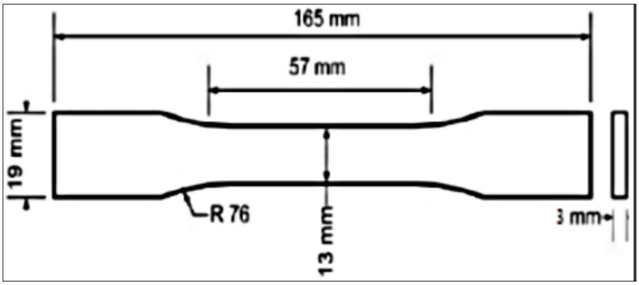


Figure 1: ASTM D638-Type I standard dimension

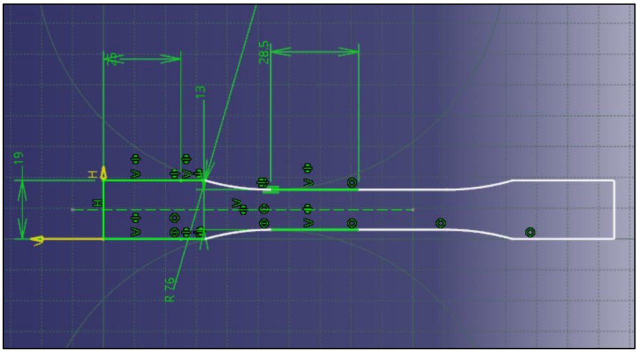
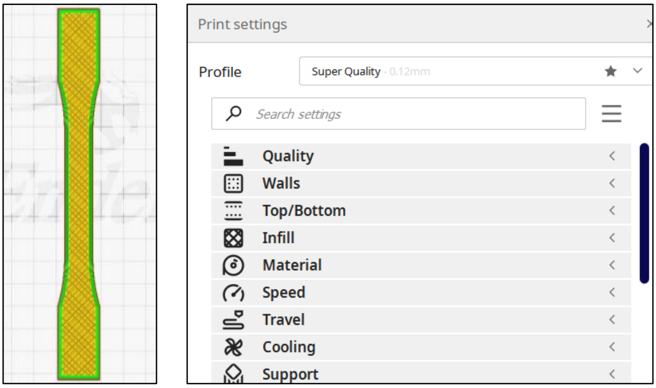


Figure 2: 3D CAD model designed using CATIA V5 21

Slicing of the 3D CAD model

Slicing stands as a pivotal step in the 3D printing process, converting a 3D model from CAD software in Stereolithography (STL) format into g-code, a language comprehensible by the 3D printer. Within this phase, the critical parameters of infill density, wall perimeter, and layer height are fine-tuned, with the entire process executed using Ultimaker Cura software. The specifics of this control encompass three key parameters, as depicted in Figure 3b. The outcome of this slicing process is illustrated in Figure 3a. Furthermore, Table 1, Table 2, and Table 3 offer a comprehensive breakdown of the parameter settings for the infill density test, wall perimeter test, and layer height test performed during the slicing process in Ultimaker Cura.

In the infill density test, parameters were systematically adjusted in 20% increments, ranging from 0% to 100%, while maintaining a constant wall perimeter of 2 mm and a layer height of 0.20 mm. The wall perimeter test, on the other hand, involved varying the wall parameter across 1 mm, 2 mm, and 3 mm settings, with infill density and layer height consistently set at 10% and 0.20 mm, respectively. Lastly, in the layer height test, the layer height was manipulated to 0.12 mm, 0.20 mm, and 0.28 mm, with infill density and wall perimeter held constant at 10% and 2 mm, respectively. These parameter selections are based on fundamental adjustments for 3D printer slicer programs, aligning with similar settings employed by other researchers [17]-[20].



(a) (b)

Figure 3: (a) The slicing result of the ASTM D638-Type I model; and (b) print settings options in Ultimaker Cura

Table 1: Parameter settings for infill density test

Specimen no.	Infill density	Wall perimeter	Layer height
1	0	2	0.20
2	20	2	0.20
3	40	2	0.20
4	60	2	0.20
5	80	2	0.20
6	100	2	0.20

Table 2: Parameter settings for wall perimeter test

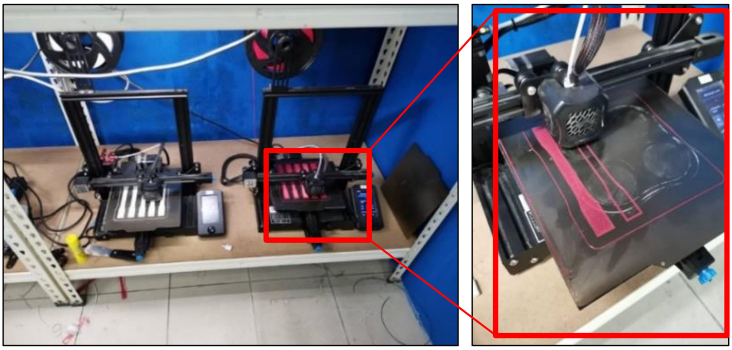
Specimen no.	Infill density	Wall perimeter	Layer height
7	10	1	0.20
8	10	2	0.20
9	10	3	0.20

Table 3: Parameter settings for layer height test

Specimen no.	Infill density	Wall perimeter	Layer height
10	10	2	0.12
11	10	2	0.20
12	10	2	0.28

3D printing of ABS and PETG specimens

The specimens for ABS and PETG materials were manufactured using Fused Deposition Modelling (FDM) technology. A total of 96 specimens were fabricated using four units of 3D printer model Ender 3 at AA3D Technology Sdn. Bhd.'s facility with 4 mm nozzle diameter. Each test or parameter setting number has four pieces of specimen. The ABS and PETG filaments were obtained from AA3D Technology Sdn. Bhd. Figure 4a and Figure 4b show the 3D printer model Ender 3 units used to print the specimen for ABS and PETG materials. Each specimen number takes around 7 hours to complete the printing process. Figure 5a and Figure 5b show the completed ABS and PETG specimens, respectively. Every finished printed specimen was stored at room temperature before the tensile test experiment.



(a) (b)

Figure 4: (a) Ender 3 printer units; and (b) specimen being printed on the heating bed

(a) (b)

Figure 5: (a) Specimen for ABS material; and (b) specimen for PETG material

Tensile test experiment

The effect of variable infill density, wall perimeter, and layer height on ABS and PETG materials 3D printed models were investigated using a tensile test experiment. The experiment is done according to the ASTM D638 standard test method for the tensile properties of plastics. The test was done using a unit of the Universal Testing Machine model Servopulser Shimadzu at the Advance Strength of Material Laboratory in UiTM Shah Alam, as shown in Figure 6a and Figure 6b. The feed rate was set to 5 mm/min, and the test was done at room temperature. The test produced a table of force and deformation. The stress and strain values were calculated using Equation (1) and Equation (2) in Excel software. A stress-strain graph is produced, and Young's Modulus is calculated by identifying the slope of the linear line of the stress-strain graph, as shown in Figure 7, using Equation (3).

$$\sigma = F/A \tag{1}$$

$$\varepsilon = \Delta L/L \tag{2}$$

$$E = \sigma/\varepsilon \tag{3}$$

where:

σ = Uniaxial stress (Pa)
ε = Strain (mm/mm)
F = Force (N)
A = Cross sectional area of specimen (m^2)
ΔL = Change in length of specimen (m)
L = Original length of the specimen (m)
E = Young's Modulus (Pa)

(a) (b)

Figure 6: (a) Tensile test was done using Universal Tensile Testing machine model Servopulser Shimadzu; and (b) each end of the specimen were attached on the testing machine machine

Results and Discussion

Effects of infill density in predicting the tensile properties of ABS and PETG materials

This experiment focused on assessing the impact of different infill percentages on the elastic modulus of ABS and PETG specimens. The initial hypothesis posited that decreasing infill density would lead to a reduction in the elastic modulus [17] for both ABS and PETG materials. Figure 7 illustrates the effect of infill density on the Young's modulus of 3D specimens for these materials, confirming the anticipated trend. The graph depicts a linear increase in the elastic modulus with higher infill density for ABS material. Specifically, specimen 1 (0% infill) exhibits the lowest Young's modulus at 995.53 MPa, while specimen 6 (100% infill) demonstrates the highest elastic modulus at 1083.45 MPa. These findings align with Ali et al.'s observations [19], which also noted that the highest infill density results in the highest elastic modulus for ABS material. This phenomenon occurs because at 100% infill density, the raster structures are closely packed, forming stronger interconnections that demand greater force to break. However, it's worth noting that there's only a marginal 8.83% improvement in the elastic modulus when infill density is increased from 0% to 100%. Additionally, there's a mere 0.3% enhancement in the elastic modulus when infill density is raised from 40% to 60% and from 60% to 80%.

For PETG material, the results mirror those observed for ABS. Young's modulus increases in PETG 3D printed material with higher infill density. A comparison between 0% infill density and 100% infill density reveals a 17% improvement in the elastic modulus for PETG material. The highest Young's modulus is recorded at 991.59 MPa with 100% infill density, while the lowest elastic modulus value stands at 841.01 MPa with 0% infill density. Lower infill densities result in more distant raster structures, leading to weaker bonds that require minimal force to break.

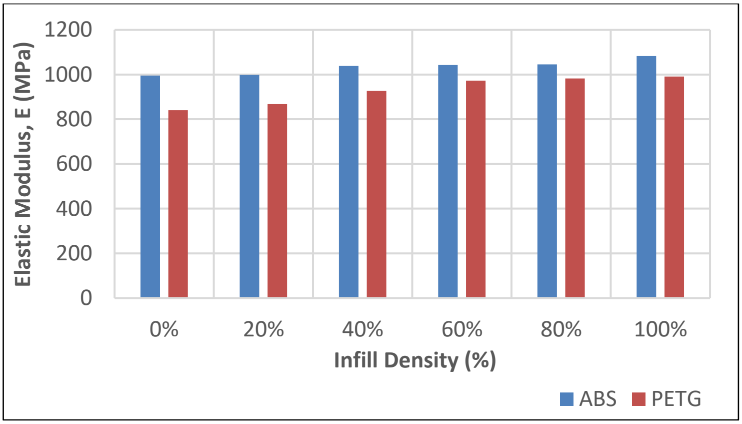


Figure 7: Comparison of Young's modulus at different ABS and PETG infill density

Figure 8 provides a comparison of the ultimate tensile strength at various infill densities for both ABS and PETG materials. In the case of ABS material, the results reveal the highest tensile strength, reaching 36.42 MPa at a 60% infill density, while the lowest tensile strength is recorded at 32.87 MPa with 0% infill density. The tensile strength of ABS increases progressively as infill density rises from 0 to 60%. However, when infill density is increased further from 60 to 80%, the tensile strength experiences a decrease of 7.7%, declining from 36.42 to 33.62 MPa. Subsequent increases in infill density, from 80 to 100%, result in a 7.3% improvement in tensile strength, reaching 36.09 MPa.

Conversely, for PETG material, the highest tensile strength recorded stands at 39.94 MPa with 100% infill density, while the lowest tensile strength is noted at 35 MPa with 20% infill density. The tensile strength of PETG material consistently improves as infill density increases from 20 to 100%. These findings align with the general observation that the tensile characteristics of 3D specimens tend to enhance as infill percentage rises [20]. Dave et al. [21] have also reported a similar pattern where, in most cases, increasing infill density leads to an improvement in tensile strength. This improvement is attributed to stronger atomic bonds at higher infill percentages, as well as the increased density of the 3D printed specimen at greater infill ratios.

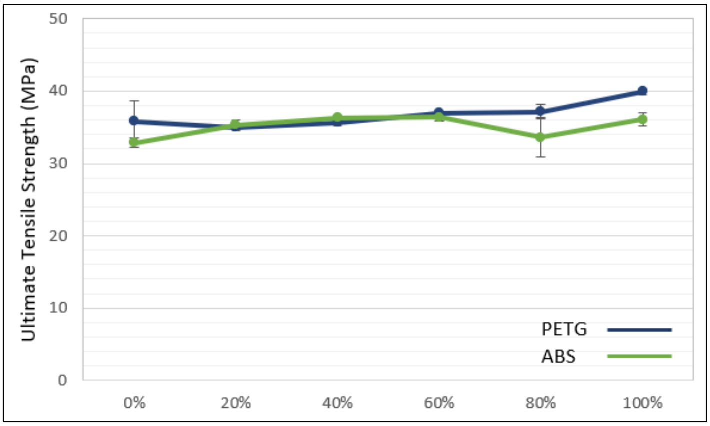


Figure 8: Comparison of ultimate tensile strength at different ABS and PETG infill density

Effects of wall perimeter in predicting the tensile properties of ABS and PETG materials

Figure 9 presents a comparison of the influence of wall perimeter on Young's Modulus for ABS and PETG materials. The results indicate that increasing the wall perimeter from 1 to 3 mm, with increments of 1 mm, has no significant impact on the elastic modulus of ABS material. For ABS, the elastic modulus experiences a slight increase, progressing from 980.09 MPa for 1 mm wall thickness to 985.05 MPa for 2 mm and further to 986.02 MPa for 3 mm wall thickness. However, a different pattern emerges for PETG material. At 1 mm wall thickness, the recorded experimental Young's modulus is 607.93 MPa. When the wall thickness is increased to 2 mm, the Young's modulus undergoes an approximate 58% increase, reaching 959.63 MPa. Further increases in wall thickness result in an approximately 2% rise in Young's modulus, reaching 979.81 MPa. The highest recorded elastic modulus for both materials is observed with the thickest wall perimeter.

Cwikla et al. [3] have suggested that increasing wall thickness is advisable when aiming for maximum strength in 3D printed models. This is because augmenting the wall thickness replaces the hollow infill of the 3D-printed part with a solid layer of filament, thereby enhancing the overall strength of the specimen.

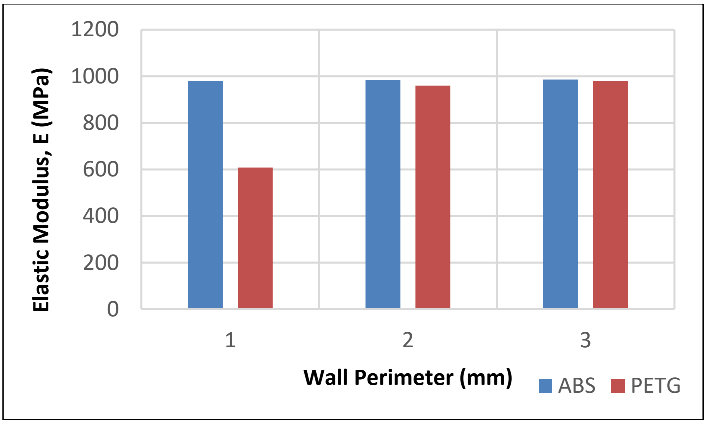


Figure 9: Comparison of wall perimeter effect on Young's modulus of ABS and PETG materials

Figure 10 provides a comparison of the tensile strength of ABS and PETG materials under varying wall perimeters. For ABS material, increasing the wall perimeter results in an improved tensile strength of the specimen. At 1 mm wall thickness, the tensile strength is recorded at 31.25 MPa. Increasing the wall thickness to 2 mm leads to an approximate 8% enhancement in the tensile strength, reaching 33.72 MPa. Further increments in the wall perimeter yield an approximately 3.6% improvement in tensile strength, reaching 34.95 MPa. Similarly, PETG material exhibits a corresponding trend. The tensile strength of PETG material improves as the wall thickness increases. At 1 mm wall thickness, the tensile strength is 22.40 MPa. Expanding the wall thickness to 2 mm results in an approximate 84% improvement in the tensile strength of PETG material, reaching 41.24 MPa. Further increases in the parameter to 3 mm only slightly raise the tensile strength to 41.27 MPa. This finding aligns with Lubombo and Huneault's observations [22], where it is acknowledged that a higher shell number enhances the specimen's strength under uniaxial tensile loading. The thicker wall replaces the hollow infill and bears most of the load applied to the specimen.

Effects of layer height in predicting the tensile properties of ABS and PETG materials

Figure 11 compares the effect of layer height on the Young's modulus of ABS and PETG materials. The graph reveals that increasing the layer height for both ABS and PETG materials enhances the elastic modulus, thereby improving the specimen's resistance to deformation within the elastic region. For ABS material, an elastic modulus of 736.72 MPa is recorded at a 0.12 mm layer height. The elastic modulus improves by approximately 27% when the layer height is increased to 0.20 mm. A further increase in layer height to 0.28 mm results in an approximately 7% improvement in the elastic modulus, reaching 996.27 MPa. Meanwhile, for PETG material, the elastic modulus is recorded at 754.19 MPa at a 0.12 mm layer height. The result shows a 34% improvement (1010.91 MPa) when increasing the layer height to 0.20 mm. Increasing the layer height further to 0.28 mm only results in an approximately 5% improvement (1062.37 MPa) in the elastic modulus of PETG material. Overall, increasing the layer height parameters yields better mechanical properties [23]. Printing the specimen at a higher layer height results in fewer but thicker extrusions. Using a higher layer height setting when printing a specimen in a horizontal orientation increases the cross-sectional area of the filament that resists the tensile load.

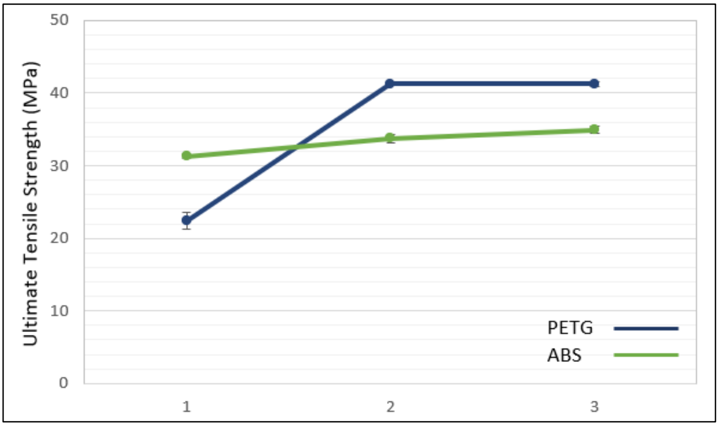


Figure 10: Comparison of wall perimeter effect on ultimate tensile strength of ABS and PETG materials

Figure 12 provides a comparison of the effect of layer height on the ultimate tensile strength of ABS and PETG materials. The results show that increasing the layer height settings improves the tensile strength of the 3D-printed specimen. For ABS material, the tensile strength is recorded at 26.65 MPa at a 0.12 mm layer height. The tensile strength increases by approximately 20% (32.02 MPa) when increasing the layer height to 0.20 mm. Further increasing the layer thickness to 0.28 mm results in approximately a 9% improvement in the tensile strength (35.06 MPa). Similarly, for PETG material, the same trend can be observed, with an improvement in tensile strength as the layer height increases. At a 0.12 mm layer height, the tensile strength is recorded at 33.22 MPa. Increasing the layer height to 0.20 mm improves the tensile strength by approximately 28% (42.43 MPa). About an 8% improvement (45.72 MPa) in tensile strength is observed when increasing the layer height to 0.28 mm. Chokshi et al. [24] investigated the process parameters' effect on mechanical properties for FDM processing and found that the tensile strength increased with an increase in the layer height up to a certain limit. Increasing the distance between each layer allows the filament to remain hot for a longer time, providing better adhesion.

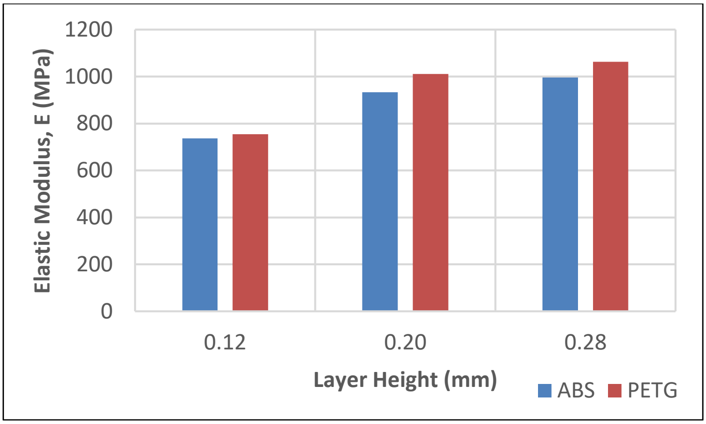


Figure 11: Comparison of layer height effect on the Young's modulus of ABS and PETG materials

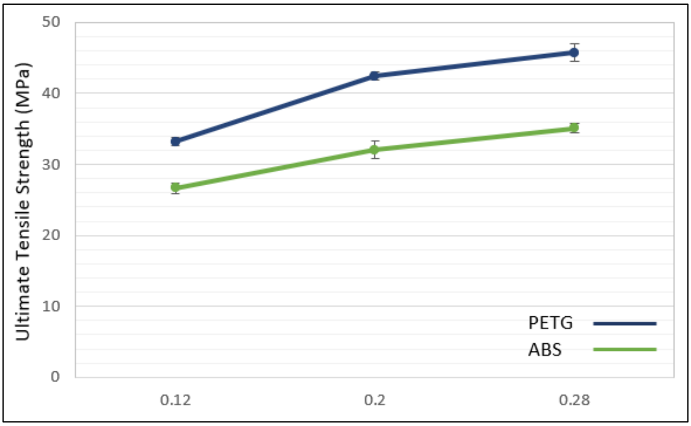


Figure 12: Comparison of layer height effect on the ultimate tensile strength of ABS and PETG materials

Conclusion

The study investigated the effects of infill density, wall perimeter, and layer height on the tensile properties of ABS and PETG materials. A total of 120 specimens were created, and the experiment was conducted using a Uniaxial tensile test machine. It was observed that increasing the values of infill density, wall perimeter, and layer height improved the tensile properties of both ABS and PETG materials. However, some parameters were found to have an insignificant impact on improving the mechanical properties of the printed parts. For example, increasing the wall thickness only slightly improved the elastic modulus for ABS material. Consequently, it's more desirable to print a 3D part with a lower wall thickness, reducing printing time without compromising the part's tensile properties. Similarly, the difference in tensile properties between printing PETG material with 2 mm and 3 mm wall thickness was found to be insignificant. Therefore, it is more rational to print a 3D part with a 2 mm wall thickness to save both printing time and filament material. The study also revealed that ABS material is stiffer compared to PETG material, while PETG material exhibits higher tensile strength than ABS material. Based on this finding, ABS material should be chosen when stiffness is a requirement for the printed part, while PETG should be preferred when high tensile strength is needed. These research findings are important for determining the tensile properties of 3D printed parts using ABS and PETG materials. They serve as a valuable reference for manufacturers and the DIY community when deciding to use ABS and PETG as filament options. Taking these parameter settings into consideration can help reduce the overall cost of filament and the time required for 3D printing.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest

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