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MECHANICAL PROPERTIES OF PETG-BASED MATERIALS DESTINED FOR 3D-PRINTING

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Abstract: *Polyethyleneterephthalate glycol (PETG) and poly (lactic acid) (PLA) stand out as two leading 3D printing filaments. PETG boasts exceptional strength, durability, chemical resistance, and UV light resilience. Meanwhile, PLA is celebrated for its ease of use and biodegradability. This research delves into a comparison of their mechanical attributes and 3D-printing performance, spotlighting PETG's advantages in various applications. PETG shines by withstanding higher temperatures, resisting chemicals and UV rays, and offering greater flexibility compared to PLA. Moreover, PETG showcases superior layer adhesion and reduced warping, resulting in top-notch prints. Our comprehensive study data underscores PETG's excellence in flexural strength (3 MPa), compression strength (61 MPa), and dimensional stability. PETG emerges as the superior choice for applications demanding robustness, endurance, and environmental resistance.*

Key words: *3D-printing, Polyethyleneterephthalate glycol, poly (lactic acid), mechanical properties.*

1. INTRODUCTION

With the rapid advancement of 3D printing technology, there has been a growing demand for high-quality filament materials that can produce durable and functional parts and also to present an ease of use in the additive manufacturing process [1-3]. Among the various materials available for Fused Filament Fabrication (FFF), besides poly (lactic acid) (PLA), which is the most used polymer in the industry, polyethyleneterephthalate glycol (PETG) has emerged as a popular choice due to its ease of use and versatility. While every material offers unique advantages, understanding their mechanical properties is crucial for selecting the most suitable filament for specific applications.

PETG is a thermoplastic copolyester known for its strength [4], durability, and resistance to chemicals and UV light. These properties make it an attractive option over PLA for applications that require structural integrity, such as industrial prototypes, mechanical parts, and functional objects. On the other hand, PLA, a biodegradable thermoplastic [5] derived from renewable resources like corn starch [6], or sugarcane [7], offers ease of printing, low emissions during printing process, and a wide range of vibrant colors, making it popular among hobbyists, educators, and designers.

Comparing different materials from the point of view of mechanical properties such as elasticity, strength, toughness, as well as melt flow rate (MFR), water absorption capacity, hygroscopicity and thermal properties is of paramount importance to determine the advantages and limitations of using of one polymer over another in different applications and to determine the necessary parameters for accomplish a good result during 3D printing process.

On the other hand, after the additive manufacturing process, is helpful to analyze the properties, such as tensile strength, flexural test, compression strength, of the resulting 3D printed object to be sure that the polymer used will suited for the intended application, additionally, layer adhesion, and dimensional stability contribute to the overall print quality and reliability. Overall, these factors are important in evaluating the structural integrity and performance of a polymer used in additive manufacturing.

In this paper, two types of materials, PETG and PLA have been used and tested. both in in the form of filament and 3D printed samples. Properties such as density, and tensile strength were considered for filaments. For 3D printed samples bending and compression has been analyzed.

Analyzing the distinctive strengths and weaknesses of these two materials offers valuable insights into identifying their optimal applications and the industries in which PETG or PLA exhibit superior performance.

2. EXPERIMENTAL METHODOLOGY

Several samples were 3D printed for each test, and in order to provide a repeatable process with similar outputs and validation, it has been opted for half of the samples to be with 100% rectilinear type infill, and half of them to be made fully out of perimeters (table 1). In this way it could be observed also which parameter is better for high mechanical properties for each polymer. The FFF 3D printer on which the samples were manufacture is a Prusa MK3S, made by Prusa Research s.r.o. Czech Republic.

Table 1

List of specimens.

Specimen	Type	Test
PETG	Infill	5 x Bending
PETG	Perimeters	5 x Bending
PETG	Infill	5 x Compression
PETG	Perimeters	5 x Compression
PLA	Infill	5 x Bending
PLA	Perimeters	5 x Bending
PLA	Infill	5 x Compression
PLA	Perimeters	5 x Compression

The samples are designed in accordance with the ISO standards (Figure 1, Figure 2), and geometry using Fusion 360 from Autodesk. ISO178 is considered for flexural tests [8], and ISO604 for Compression testing [9].

After the designs were made, the samples were 3D printed (Figure 3) with recommended temperatures by the producer of the filaments and with the most common used parameters in industry for the materials analyzed. (table 2)

Table 2

Printing parameters.

Parameter	Measurement
Layer height	0.3 mm
Nozzle diameter	0.4 mm
PLA printing temp.	215 °C
PETG printing temp.	250 °C
PLA bed temp.	60 °C
PETG bed temp.	85 °C
Printing speed	50 mm/s

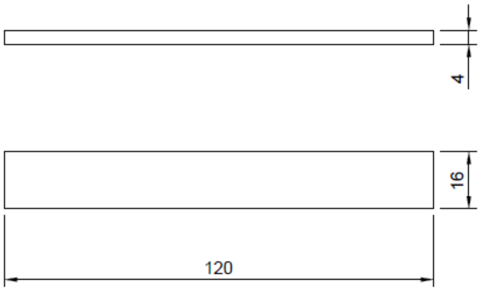

Fig.1. Dimensions of sample for bending test

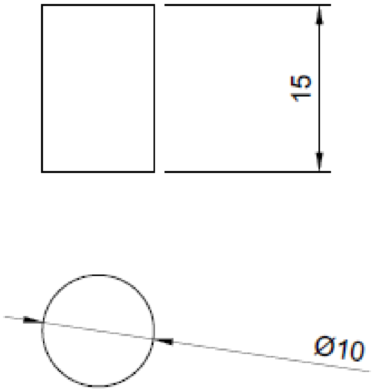

Fig.2. Dimensions of sample for compression test

The 3D-printed samples were equilibrated in an atmosphere of 32% relative humidity before mechanical testing.

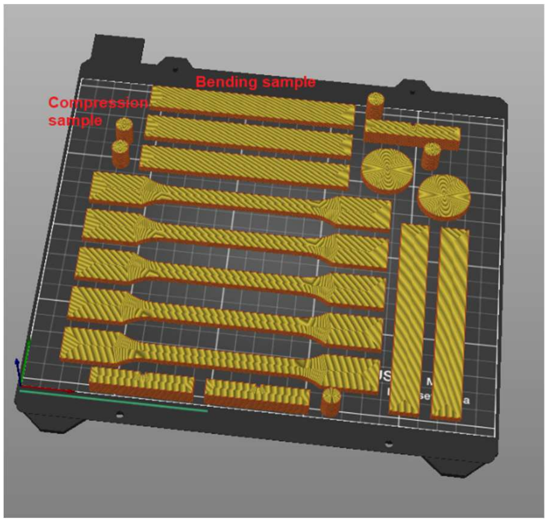

Fig.3. Samples with perimeters settings in 3D printer's software

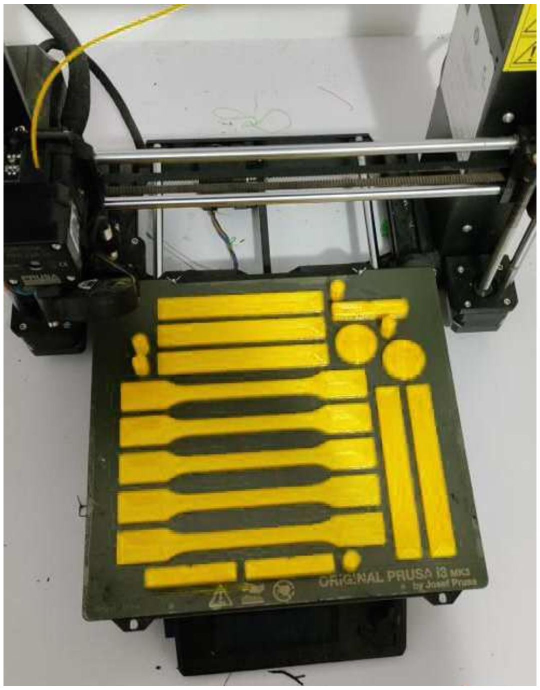

Fig.4. Samples of PLA with perimeters 3D printed on Prusa MK3S 3D printer

After 3D printing of the samples (Figure 4) was completed, a comprehensive measurement analysis was conducted to evaluate the dimensional accuracy and asses the deviation from the designed samples. This analysis aimed to determine how closely the printed samples aligned with the intended specifications and to identify any variations or discrepancies that occurred during the printing process. The obtained measurements were then compared to the predefined target measurements (standard dimensions) derived from the design specifications used to create the samples. These target dimensions served as the reference values representing the intended design and the desired geometric characteristics of the 3D printed objects.

The density of each material was measured with the help of Radwag weighing balance and calculated automatically with the Archimedean method (Figure 5), five measurements have been taken for each material.

Fig.5. Radwag weighing balance

This study included bending and compression tests to assess the mechanical properties of ReForm PETG from FormFutura and PolyTerra PLA from Polymaker.

The bending and compression tests were performed to assess the response of PETG and PLA polymers under different loading conditions. The bending test provides insights into the flexibility, stiffness and resistance to deformation of the materials, while the compression test evaluates their compressive strength and ability to withstand external forces.

The apparatus on which the tests were done is a Universal testing machine WDW 150S (Figure 6).

Understanding the mechanical properties of materials is crucial for determining their suitability and performance in various applications. In the realm of 3D printing, assessing the mechanical behavior of filaments is essential to ensure the functionality and structural integrity in printed objects [10].

Fig.6. Universal testing machine WDW 150S

3. RESULTS AND DISCUSSION

It can be observed that the PETG filament has a lower density (1.2426 g/cm^3) compared to PLA filament, which has a density of 1.2964 g/cm^3 (Figure 7), according to trends reported in reference literature for pure polymers [11]. After performing a One-Way ANOVA test on the density measurements for the two types of materials, Pearson's coefficient of variation *p* is equal to 0.05. At a 0.95 confidence level, the population means are significantly different.

The higher density of PLA may indicate that it is more compact and has a greater mass for a given volume compared to PETG. The density alone suggests that PLA may potentially be more rigid than PETG.

The lower density contributes to PETG's enhanced flexibility and impact resistance, as it offers a more lightweight and less rigid structure compared to PLA.

The density of the filament played an important role in the 3D printed process. PETG, known for its flexibility and elasticity, combined with lower density exhibits more dimensional changes due to its inherent mechanical properties. The samples printed had a dimensional deviation of 2.14% on the X-Y axis from standard.

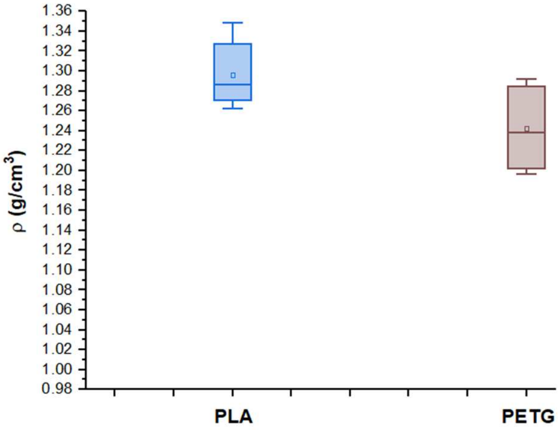

Fig.7. Density values for the PLA and PETG filaments

On the other hand, PLA, being more rigid due to higher density, is less prone to deformation and demonstrate relatively better dimensional stability. The smaller deviation in dimensions of 1.13% on the X-Y axis for PLA prints suggests that the material is less likely to experience significant dimensional changes during the printing process.

However, it's important to consider that other factors, such as printing parameters and structural design can also impact dimensional accuracy. The samples printed with 100% rectilinear infill had a greater dimensional deviation from the standard on the Z axis (3.5%) than when the samples were printed with no infill, but with concentrical perimeters.

The observed difference in compression strength between the samples printed with 100% rectilinear infill (52 MPa) and 100% perimeters (60 MPa) (Figure 8) suggests significant variations in the mechanical properties of the PLA printed objects.

When 3D printing with rectilinear infill, the interior of the printed object is filled with a pattern of crisscrossing lines, creating a grid-like structure. This infill pattern provides internal support and strength to the object while minimizing the material usage [12].

The difference in compression strength can be attributed to the variations in the structural integrity and density of the printed samples. The solid perimeters offer a more continuous and robust surface, enabling them to better withstand compressive forces. The uninterrupted outer perimeters and the absence of voids or gaps within the perimeters contributes to the enhanced compression strength compared to the rectilinear infill samples, which have a grid-like internal structure.

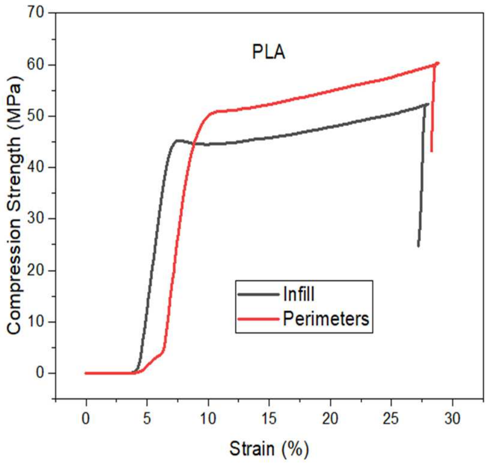

Fig.8. Compression Stress-Strain curves for PLA printed samples

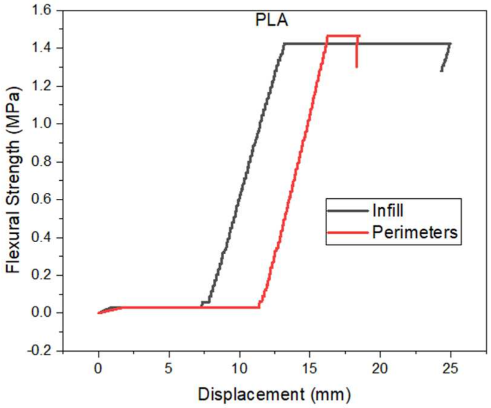

Fig.9. Flexural Stress-Strain curves for PLA printed samples

The bending tests were performed on the Z axis of the samples and the results are shown in figure 9 for PLA.

The samples printed with 100% perimeters exhibited a slightly higher flexural strength (1.47 MPa) compared to the samples printed with 100% rectilinear infill (1.42 MPa). This suggests that the solid perimeters contribute to increased rigidity and resistance to bending forces.

Moreover, the observed strain and displacement values for the PLA samples (Figure 8, Figure 9) suggests that samples with perimeters can undergo a slightly higher level of deformation at low stress values. In contrast, samples with 100% infill exhibit compression resistance at a lower deformation, indicating that the internal lattice pattern of the infill provides immediate resistance to deformation.

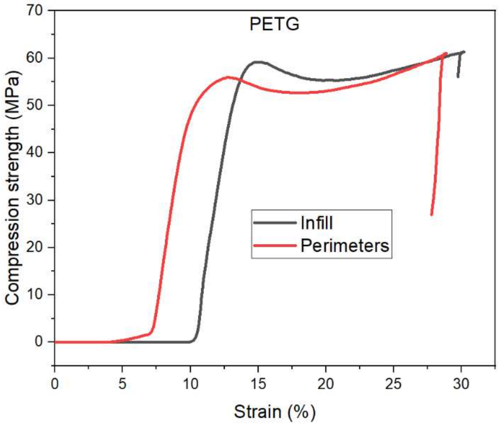

Fig.10. Compression Stress-Strain curves for PETG printed samples

Also, the characteristics of how the perimeters on the 3D printed sample for bending tests is constructed help the probe to withstand to higher elongation in comparison with the sample made with solid infill.

The compression strength results for PETG samples printed with 100% rectilinear infill (61 MPa) and perimeters (61 MPa) indicate that PETG performs consistently in terms of resisting compressive forces, regardless of the internal infill or outer perimeter structure.

Comparing these results to the PLA samples, where the compression strength of the samples printed with perimeters was higher compared to the samples with solid infill it can be observed that the behavior differs between the two materials.

The flexural strength of PETG samples printed with both, infill and perimeters, falls within a relatively narrow range, 2.91 MPa for infill, respectively 3 MPa for perimeters (Figure 11). This suggests that the choice of infill pattern has a limited influence on the flexural strength of PETG compared to other factors.

In contrast to PLA, where the flexural strength difference between the samples with 100% rectilinear infill and 100% perimeters was more pronounced, the difference in flexural strength between the PETG samples is relatively small. This indicates that PETG exhibits a more consistent flexural behavior regardless of the infill pattern or solid perimeters.

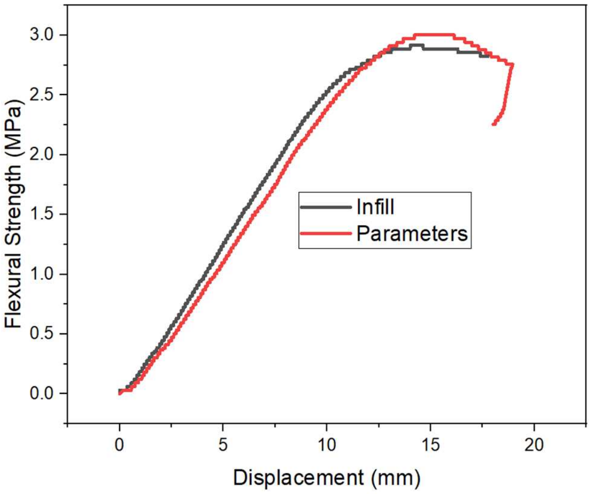

Fig.11. Flexural Stress-Strain curves for PETG samples

The similar flexural strength values for PETG samples printed with different structures settings may be attributed to the inherent material properties of PETG. Polyethyleneterephthalate glycol is known for its excellent flexibility, toughness, and resistance to deformation, the amorphous structure allows for better energy absorption and distribution, resulting in increased flexural strength. These characteristics contribute to its ability to withstand bending forces without significant variation based on the internal structures of the object printed.

Also, the displacement observed for the flexural Stress-Strain curves for PETG samples (Figure 11) are almost identical, which suggest that when a bending force is applied on an object made out of PETG the internal structure does not influence the resistance, as long as the part is 100% solid and has no internal air gaps, contrary to compression resistance of the PETG samples, where the samples printed with 100% have a greater deformation (Figure 10).

Taking into account these findings, the choice of infill density, pattern and outer shell thickens can contribute to achieving the desired balance of strength flexibility, and overall performance. Also, the specific influence of infill and outer perimeter characteristic on material properties can vary depending on the specific material being used. As is shown in the presented paper, the infill density or outer perimeter shell, did not have a greater influence on PETG samples as for PLA, resulting in a consistent results for PETG regardless of this parameters.

4. CONCLUSION

The paper focused on comparing the mechanical properties of polyethyleneterephthalate glycol and poly (lactic acid) filaments, with specific attention to their densities, dimensional accuracy, and performance in compression and flexural tests using samples with two different construction parameters, 100% infill and 100% perimeters.

PETG exhibited a density of 1.2426 g/cm^3, while PLA had a slightly higher density of 1.2964 g/cm^3. PLA is marginally denser than PETG, which can influence the 3D printing process.

When printed with solid infill, PETG samples showed no deviation from the standard dimensions in the Z-axis, whereas PLA exhibited a 2.75% deviation. However, when printed with perimeters, PETG demonstrated a higher deviation on the X-Y axis compared to PLA. These results suggest that the choice of infill pattern and material can influence dimensional accuracy differently.

PETG samples printed with 100% infill and perimeters exhibited the same compression strength, indicating that the infill pattern did not significantly impact the material's ability to withstand compressive forces. On the other hand, considering the densities of the two materials, 1.2426 g/cm^3 for PETG and 1.2964 g/cm^3, it is worth noting that PETG achieves higher compression strength to PLA while utilizing a slightly lower material mass. This suggests that PETG demonstrates an efficient use of material resources as it achieves higher compression strength with a lower density.

The flexural strength of PETG samples present a minimal increased in strength when those with perimeters were tested, indicating that 3D printing patterns has limited influence on the flexural behavior of PETG.

Overall, these findings suggest that PETG and PLA exhibit distinct mechanical characteristics in additive manufacturing process. PETG displays good dimensional accuracy with lower deviation than PLA when is 3D printed with rectilinear infill but higher deviations when printed with perimeters. PETG also demonstrate consistent compression strength regardless of the construction settings of the object. In terms of flexural strength, the impact of infill pattern is relatively small for PETG compared to PLA.

Understanding the mechanical properties of different filaments is crucial for selecting the appropriate material for specific applications. PETG demonstrates that is a good recyclable substitute material for PLA because demonstrates with his dimensional accuracy, consistent compression and flexural strength make it suitable for applications where durability and resistance are important.

Further research and experimentation can provide additional insights into the mechanical behavior of PETG and PLA, considering various printing parameters and sample designs. These findings contribute to the knowledge base surrounding 3D printing materials and assist in optimizing their use for diverse applications.

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Proprietățile mecanice a materialelor din PETG destinate printării 3D

Polyetilentereftalat glicol (PETG) și acidul polilactic (PLA) se evidențiază ca două dintre cele mai importante filamente pentru imprimantele 3D. PETG se distinge prin forța sa excepțională, durabilitate, rezistența chimică și capacitatea de a rezista la radiațiile UV. În schimb, PLA-ul este apreciat pentru ușurința sa în utilizare și biodegradabilitate. Acest articol se concentrează pe o comparație a proprietăților lor mecanice și performanței printării 3D, evidențiind avantajele PETG-ului în diverse aplicații. PETG-ul se remarcă prin capacitatea sa de a rezista la temperaturi mai ridicate, rezistența la substanțe chimice și radiațiile UV, precum și prin flexibilitatea sa mai mare în comparație cu PLA-ul. În plus, PETG-ul prezintă o aderență superioară între straturi și o reducere a deformării, ceea ce duce la imprimări de calitate superioară. Datele noastre cuprinzătoare din studiu subliniază excelența PETG-ului în ceea ce privește rezistența la încovoiere (3 MPa), rezistența la compresiune (61 MPa) și stabilitatea dimensională. PETG-ul se evidențiază ca alegerea potrivită pentru aplicațiile care necesită rezistență mecanică, durabilitate și rezistență la factorii de mediu.

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