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Article

Sustainable 3D Printing with Recycled PETG: Mechanical Characterization and Process Optimization in FDM Technology

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Abstract: As additive manufacturing becomes increasingly relevant for sustainable production, the mechanical reliability of parts made from recycled materials remains a subject of concern. In single-piece or low-volume manufacturing, the ability to predict part quality and structural behavior is crucial, especially when rework or failure incurs high costs. This study explores the feasibility of using recycled PETG filament in FDM (Fused Deposition Modeling) 3D printing, comparing its mechanical properties to those of virgin PETG. Standardized test specimens are designed and fabricated for tensile, bending, and impact testing. All samples are produced on a Creality Ender 3 printer and evaluated using universal testing machines under controlled conditions. The results reveal that recycled PETG demonstrates comparable elastic behavior to virgin material, though slightly lower maximum strength. Differences in performance under tensile and impact stress are most notable, with virgin PETG showing higher resistance to rupture. The findings highlight the potential of recycled PETG for non-critical load-bearing applications and emphasize the importance of optimized printing parameters to enhance material performance. This work contributes to broader efforts in sustainable additive manufacturing by demonstrating the viability of recycling in functional part production.

Keywords: recycled PETG; fused deposition modeling (FDM); mechanical properties; tensile testing; bend testing; impact resistance; 3D printing; sustainable materials; additive manufacturing; polymer recycling

1. Introduction

The demand for sustainable and cost-effective production methods has driven interest in 3D printing technologies, especially in Fused Deposition Modeling (FDM). FDM is widely used due to its affordability, material variety, and accessibility. However, the environmental impact of using virgin polymer materials remains a challenge (Figure 1). Recycled plastics, including PETG, offer a promising alternative, but concerns persist about their mechanical integrity when reused in additive processes.[1–4]



Figure 1. Schematic of FDM process or Creality Ender 3 printer.

Previous research has indicated variability in the performance of recycled filaments, often influenced by thermal degradation, contamination, and changes in polymer structure. In this context, evaluating the mechanical behavior of recycled PETG compared to virgin PETG under standardized conditions becomes essential for understanding its practical applications in engineering and prototyping.[4–7]

This study focuses on characterizing the bending, tensile, and impact properties of 3D printed PETG samples using both recycled and virgin materials. It aims to determine whether recycled PETG can be reliably used in technical applications and what trade-offs may exist.[5–8]

2. Materials and Methods

2.1. Tensile Test Specimen

This testing method is intended for generating tensile property data for the control and specification of plastic materials. These data are also valuable for quality characterization, as well as for research and development purposes. For many materials, there may be specifications that require the use of this method, although certain procedural modifications may take precedence when conforming to a specific standard.[9,10]

Specimens of type 1A, as defined in DIN EN ISO 527-2 (Figure 2), are selected for determining the tensile properties of plastics intended for molding and extrusion applications.

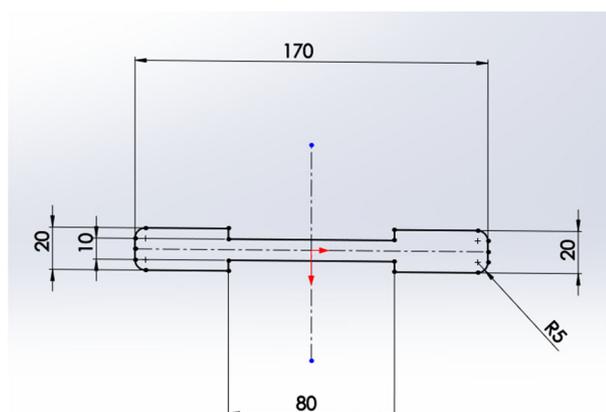


Figure 2. Dimensions of tensile test specimen type 1A from DIN EN ISO 527-2.

The 3D-printed specimen quality is set to the highest accuracy level, given that the specimen features rounded corners, which necessitate high dimensional precision (Figure 3).

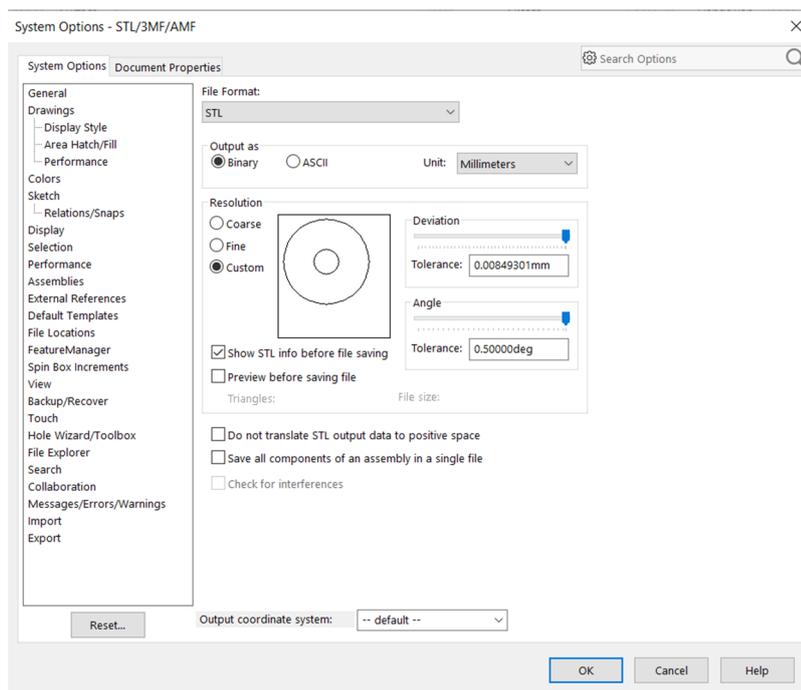


Figure 3. Quality settings of STL file for 3D printing.

2.2. Tensile Test Specimen

Flexural tests may involve subjecting the specimen to a defined loading limit and evaluating the resulting load response against specified criteria (pass/fail), or bending the specimen until failure occurs and determining the load and deflection required to initiate fracture.[11–13]

Various specimen geometries can be used for this test; however, the most commonly employed dimensions are:

ASTM standard: 3.2 mm × 12.7 mm × 125 mm (0.125" × 0.5" × 5.0")

ISO standard: 10 mm × 4 mm × 80 mm (Figure 4)

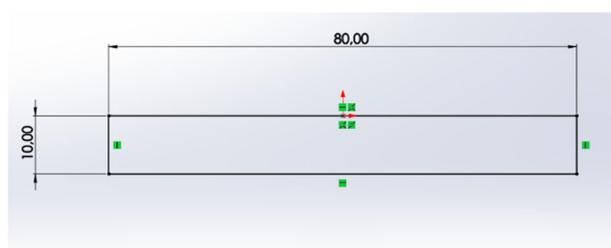


Figure 4. Dimensions of flexural test specimen from ISO178.

2.3. Impact Test Specimen

Impact testing is conducted to observe the mechanical behavior that materials exhibit when subjected to sudden impact loads, which may cause them to deform, tear, or fracture completely and/or instantaneously.[14–16]

The primary purpose of such tests is to determine the material's ability to absorb energy during a collision. This absorbed energy can then be used to evaluate parameters such as impact strength, hardness, fracture toughness, and overall impact resistance, depending on the specific test method employed and the material properties being assessed.[17]

The impact energy per unit area required to fracture a specimen under flexural loading conditions is also determined. In this method, the test specimen is mounted as a simply supported beam and struck by a swinging pendulum. The energy lost by the pendulum is considered equivalent to the energy absorbed by the specimen during fracture.

In this study, the first specimen type ($80 \times 10 \times 4$ mm), shown in Figure 5, is selected for the impact testing.

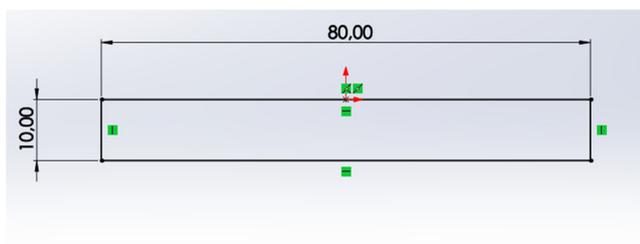


Figure 5. Dimensions of impact test specimen from ISO179.

3. Results

3.1. Build up processing

The specimens are positioned on the print bed of the slicing software, where their placement and estimated print time can be visualized (Figure 6). Once the necessary settings have been configured, the next step is to proceed with printing the specimens.

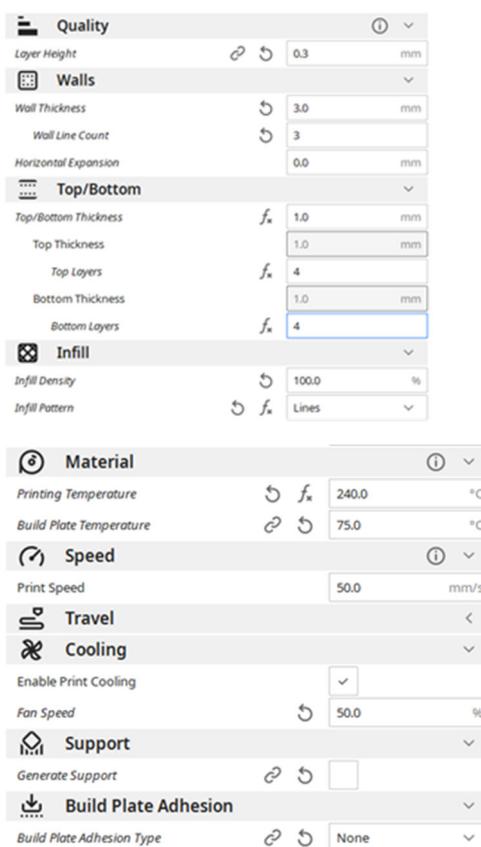


Figure 6. Print Quality Settings.

The specimens are shown in Figure 7 are produced from non-recycled PETG material.

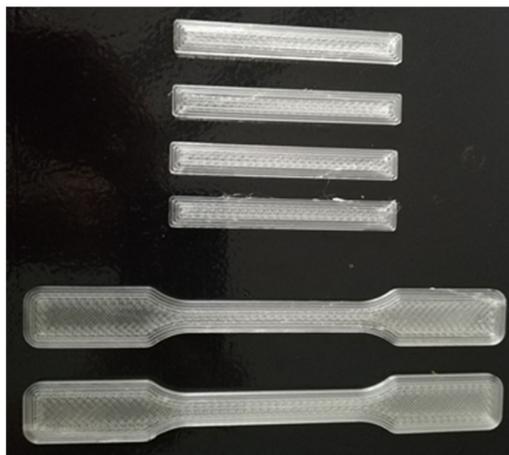


Figure 7. Six Finished Specimens Made from Non-Recycled PETG Material.

3.2. Mechanical Testing of the Fabricated Specimens and Comparative Analysis

3.2.1. Bending Testing of Non-Recycled Material

For the bend testing, a total of three specimens per material type are used — three specimens made from PETG and three specimens made from recycled PETG. A schematic representation of the bend testing setup is provided (Figure 8). Based on the measurement results, stress-strain curves are generated to illustrate the behavior of the specimens during testing.[18,19]

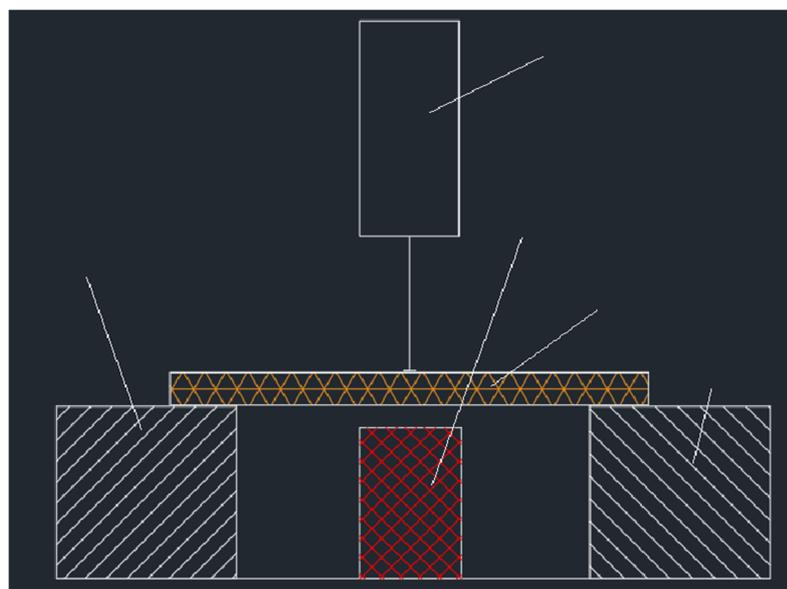


Figure 8. Schematic of the experimental setup.

The data is recalculated from N to MPa for a more accurate representation of the applied stress (Table 1). One Pascal (Pa) corresponds to a force of one Newton (N) applied over a surface area of one square meter. Therefore, the data presented in MPa is independent of the sample's cross-sectional area, in contrast to the data presented in Newtons.

Table 1. Results of Bend Testing (non-recycled PETG Material).

Deformations (mm)	Applied force (N)	Stress (MPa)
1.5	51.9	2.076

4.5	132.7	5.308
7.5	197.5 (crack)	7.9 (crack)
10.5	182.4	7.296
13.5	162.6	6.504
16.5	156.6	6.264
19.5	136.9	5.476

Plastic deformation (Figure 9) is observed at 7.5 mm and 7.9 MPa (third row of Table 1).



Figure 9. Plastic Deformation (Cracking) of Non-Recycled Material Samples.

A graph (Figure 10) is constructed based on the data from the table (table 1).

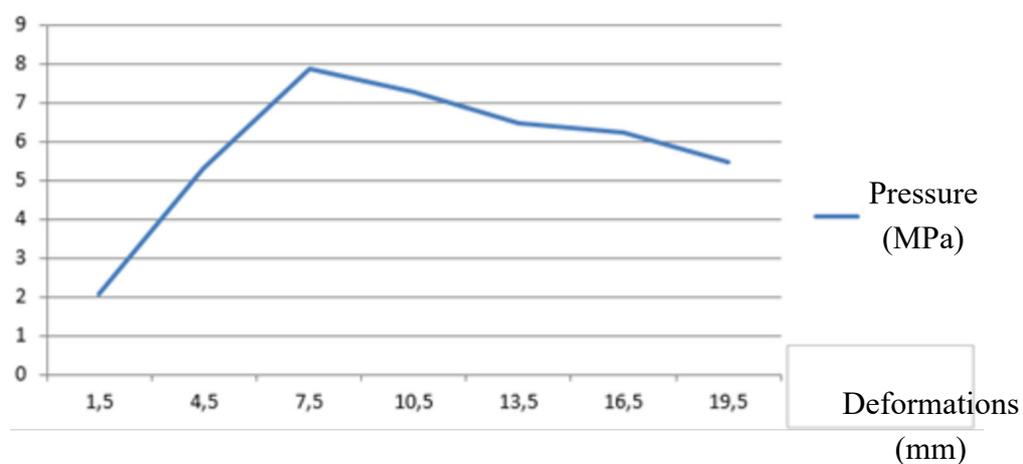


Figure 10. Graph for the bending test of non-recycled material.

3.2.2. Bend Testing of Recycled PETG Material

In Table 2, the arithmetic mean results of three measurements are shown in Newtons (N).

Table 2. Results of Bend Testing (recycled PETG Material).

Deformations (mm)	Applied force (N)	Stress (MPa)
1.5	46.3	1.852
4.5	123.3	4.932
7.5	171.7 (crack)	6.868 (crack)
10.5	171.1	6.844
13.5	167.65	6.706

16.5	154.4	6.176
19.5	117.75	4.71

A graph (Figure 11) is constructed based on the data from Table 2.

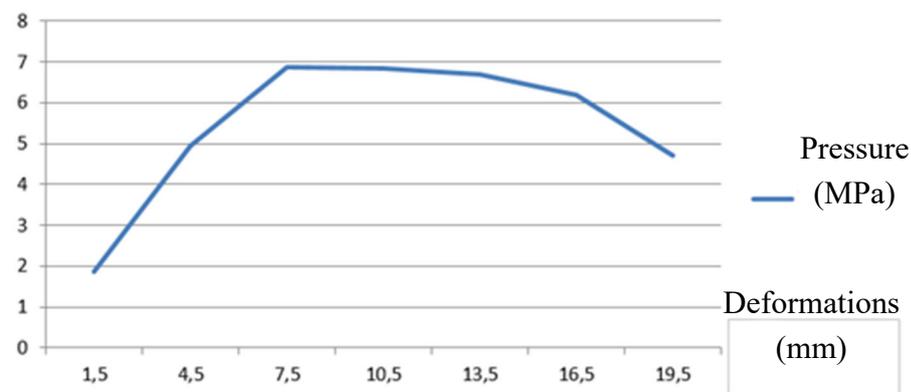


Figure 11. Bend Test Graph for Non-Recycled Material.

Plastic deformation (Figure 12) is observed at 7.5 mm and 6.868 MPa.



Figure 12. Plastic Deformation (Cracking) of Recycled Material Samples.

3.2.3. Tensile Testing

The **Instron MODEL 1185** machine, shown in (Figure 13), is used for this test.



Figure 13. Instron MODEL 1185.

The sample is placed between the two grips as shown in (Figure 14) and subjected to tensile stress until failure.



Figure 14. Sample Setup Before Testing.

The failure of the non-recycled PETG sample occurs with minimal elongation (Figure 4.8), while the recycled PETG sample does not fail but instead elongates. This is because, during recycling, there are unknown materials mixed with PETG, which make it more elastic, as shown in (Figure 15). It should be noted that the recycled PETG samples did not fail within the maximum load capacity of the testing equipment. This observation does not imply infinite ductility but rather indicates that the samples withstood the applied tensile load without fracturing, possibly due to a higher proportion of elastic or non-homogeneous phases introduced during the recycling process.

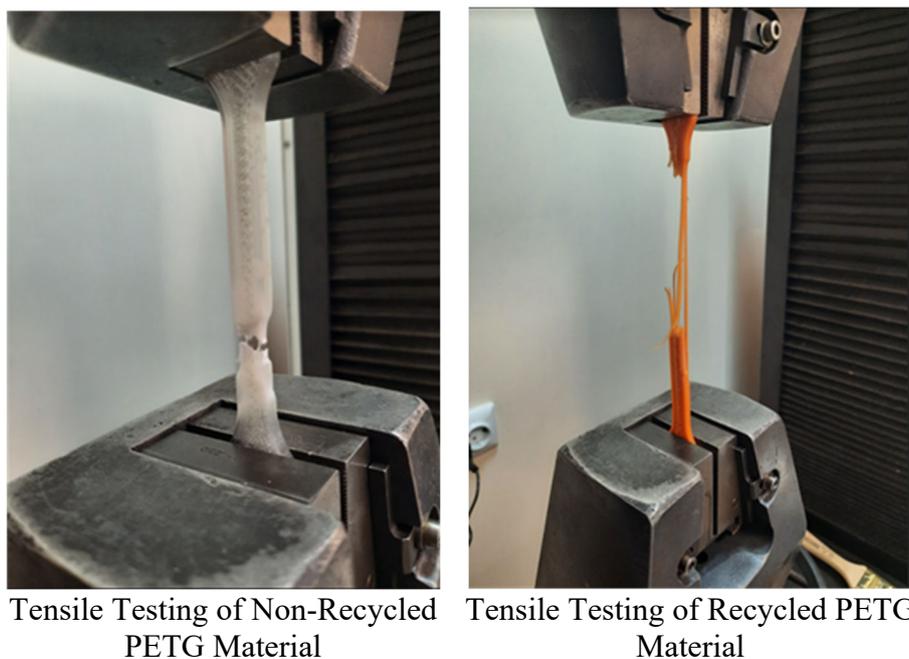


Figure 15. Tensile Testing.

Results of tensile testing of non-recycled PETG Material is shown in table.

Table 3. Results of Tensile Testing of Non-Recycled PETG Material.

Parameter	Value	Unit
Samplingrate	10	Hz
FullScaleLoad	5000	N
CrossheadSpeed	10	mm/min
Resolution	0,0167	mm/meas
Diameter		mm
X	10,53	mm
Y	3,5	mm
Crosssection	36,855	mm ²
GageLenght		mm
StartZero (Manual)	50	row
ForceZero	129,4	auto
TensileStrenght	59,10	MPA
MaxForce	2178,1	N

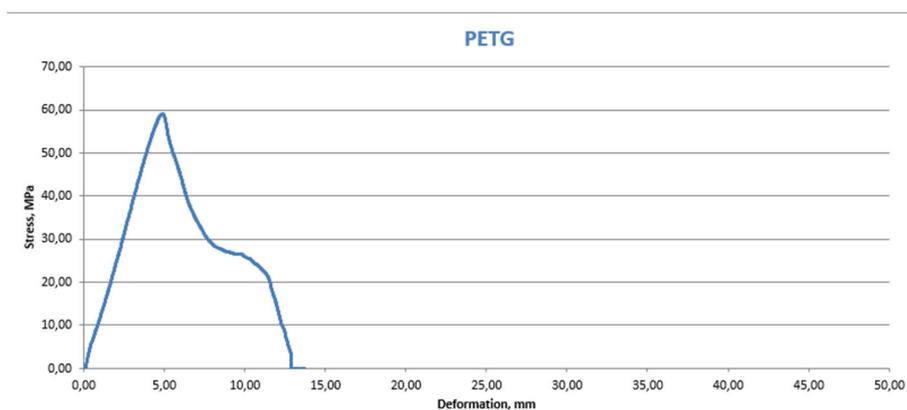


Figure 16. Graph for Non-Recycled PETG Material.

Results of tensile testing of non-recycled PETG Material is shown in Table 4.

Table 4. Results of Tensile Testing of Non-Recycled PETG Material.

Parameter	Value	Unit
Samplingrate	10	Hz
FullScaleLoad	5000	N
CrossheadSpeed	10	mm/min
Resolution	0,0167	mm/meas
Diameter		mm
X	10,75	mm
Y	3,8	mm
Crosssection	40,85	mm ²
GageLenght		mm
StartZero (Manual)	50	row
ForceZero	226,05	auto
TensileStrenght	46,54	MPA
MaxForce	1901,2	N

From Figure 17, it can be observed that the highest point occurs when the necking begins, and this is where the tensile force is at its maximum. For the non-recycled material, a higher force is applied, while for the recycled material, no fracture occurs.

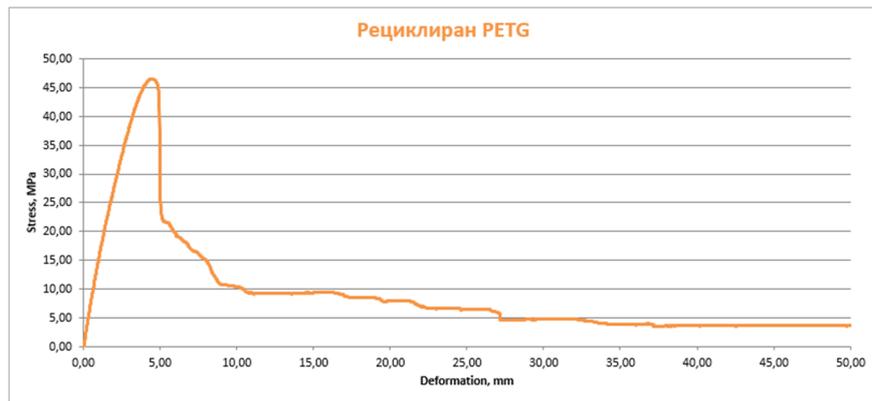


Figure 17. Graph for Recycled PETG Material.

3.2.4. Impact Bending Test Using the Izod Method

For this test, an impact bending machine using the Izod method - "Gotech GT-7045-HMH" is used, as shown in figure.



Figure 18. Gotech GT-7045-HMH.

During testing of various samples of non-recycled PETG material (Table 5), the stress values differ by no more than 2 MPa. The shown values are the arithmetic mean of three measurements.

Table 5. Impact Bending Test Using the Izod Method of Non-recycled PETG Material.

Parameter	Unit	Value
Cap	J	1
Rising angle		220,38
Speed	M/sec	3,46
Width	mm	10
Thickness	mm	4
Area	mm ²	40

Break		C
E/A	J/M ²	8141,44

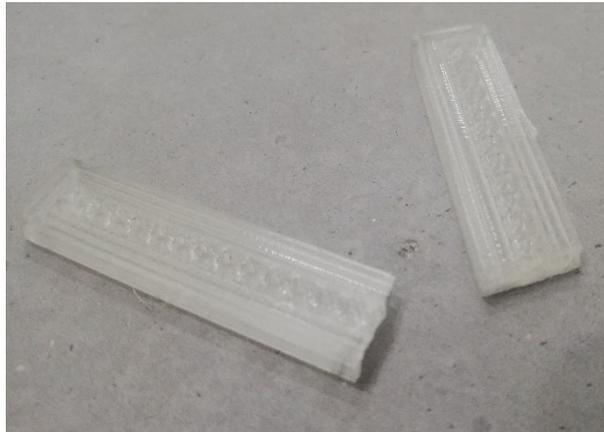


Figure 19. Non-Recycled PETG Material Sample.

The measurements for the recycled material consist of four samples, and no arithmetic mean is taken, as the values differ.

The first sample undergoes complete break at a higher calculated fracture energy, as shown in (Table 6).

Table 6. First Impact Bending Test Using the Izod Method of Recycled PETG Material.

Parameter	Unit	Value
Cap	J	1
Rising angle		228,67
Speed	M/sec	3,46
Width	mm	10
Thickness	mm	4
Area	mm ²	40
Break		C
E/A	J/M ²	8489,63
Cap	J	1



Figure 20. Recycled PETG Material Sample.

The second and third samples did not fracture during testing.

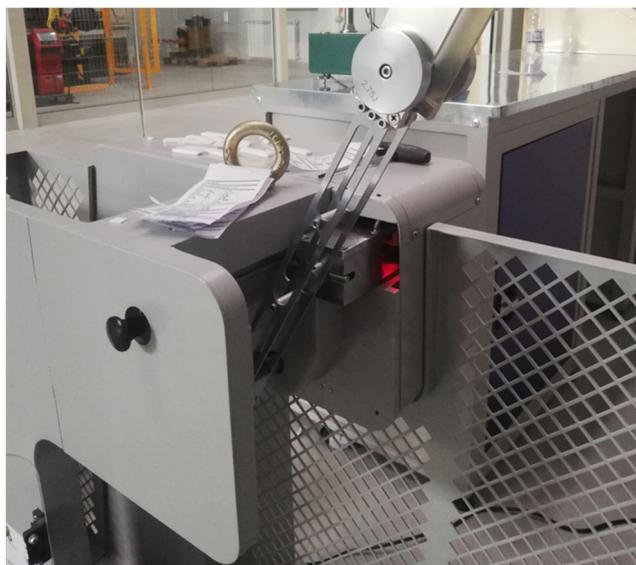
Table 7. Second Impact Bending Test Using the Izod Method of Recycled PETG Material.

Parameter	Unit	Value
Cap	J	1
Rising angle		152,57
Speed	M/sec	3,46
Width	mm	10
Thickness	mm	4
Area	mm ²	40
Break		N
E/A	J/M ²	8027,79
Cap	J	1

Table 8. Third Impact Bending Test Using the Izod Method of Recycled PETG Material.

Parameter	Unit	Value
Cap	J	1
Rising angle		152,79
Speed	M/sec	3,46
Width	mm	10
Thickness	mm	4
Area	mm ²	40
Break		N
E/A	J/M ²	7615,1
Cap	J	1

Due to the absence of fracture in the second and third trials, a weight of 2.75 J is applied in the fourth test.

**Figure 21.** Weight of 2.75 J.

Once again, the sample remained intact, exhibiting elastic deformation with minor residual plastic deformation (Table 9).

Table 9. Forth Impact Bending Test Using the Izod Method of Recycled PETG Material.

Parameter	Unit	Value
Cap	J	2,75
Rising angle		216,83
Speed	M/sec	3,46
Width	mm	10
Thickness	mm	4
Area	mm ²	40
Break		P
E/A	J/M ²	8384,17
Cap	J	2,75

Figure 22 illustrates the post-impact condition of the recycled PETG sample subjected to a 2.75 J impact. Unlike the previous trials, no complete fracture is observed, which supports the hypothesis of enhanced energy absorption through elastic deformation. This finding suggests that recycled PETG may be suitable for applications requiring moderate impact resistance and ductility, provided that the variability in recycled filament quality is accounted for.



Figure 22. Recycled PETG Material Sample.

4. Discussion

The mechanical characterization revealed that while virgin PETG exhibits more consistent and predictable performance across all tests, recycled PETG shows a wider range of behavior due to material inhomogeneities introduced during the recycling process.

In bending and tensile testing, virgin PETG consistently demonstrated higher maximum stress values and brittle fracture modes. Recycled PETG, however, exhibited greater elongation and plastic deformation under tensile loading, which may be attributed to the presence of plasticizers or other polymer blends introduced during recycling.

Impact testing further highlighted this variability. Although one recycled PETG sample absorbed more energy than virgin PETG before fracturing, others resisted fracture altogether, pointing to inconsistencies in energy dissipation mechanisms. These outcomes underline the

importance of quality control and the need for thorough pre-processing when employing recycled materials in functional applications.

Ultimately, while recycled PETG may not be suitable for high-load or safety-critical parts, it shows promise for cost-effective, environmentally conscious use in non-critical components, especially where ductility and energy absorption are beneficial.

5. Conclusions

The findings of this study demonstrate that recycled PETG, while not equivalent to virgin PETG in terms of mechanical consistency and maximum load-bearing capacity, can still perform adequately in a variety of functional applications. The results from tensile, bending, and impact tests reveal acceptable levels of elasticity and strength, especially for non-critical use cases.

The increased variability and occasional nozzle clogging observed during the printing of recycled PETG specimens highlight the importance of implementing quality assurance protocols for filament processing. Future work should explore standardized pre-treatment or filtration methods to improve the homogeneity of recycled materials.

From a sustainability perspective, the ability to reuse PETG filament effectively contributes to circular economy practices within additive manufacturing. Continued research and optimization may expand its usability even further, bridging the gap between environmental responsibility and engineering performance.

The objective of the thesis has been achieved by 3D printing samples made of PETG and recycled PETG material. These printed specimens are used for mechanical testing, including tensile, bending, and impact testing.

The results of the tests show consistent and repeatable behavior among the samples printed from non-recycled material. In contrast, the samples made from recycled PETG exhibited significant variations and differences in mechanical behavior across individual specimens.

These deviations are attributed to the recycling process and contamination with various unknown additives and impurities, which lead to a non-homogeneous filament structure. This inhomogeneity also complicates the 3D printing process, causing frequent nozzle clogging due to inconsistent filament composition.

A notable trend observed from the mechanical tests is the increased elasticity of the recycled material, accompanied by lower peak load values when compared to the non-recycled material.

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