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DEVELOPMENT OF EQUIPMENT FOR FILAMENT PRODUCTION FROM PET BOTTLES FOR ADDITIVE MANUFACTURING: PARAMETER ANALYSIS AND COMPARISON WITH COMMERCIAL PRODUCTS

Jorge Henrique de Souza Marques Alves
Matheus Oliveira Mazetto
Daniel Alberto Flórez Morales
Marcio Peres de Souza
Diego Augusto Costa Alves
Cleudmar Amaral Araújo
Arthur Alves Fiocchi
Federal University of Uberlandia, Mechanical School. Uberlandia (MG), Brazil. Av. Joao Naves de Avila, 2121.
jorgehsm02@gmail.com
matheus.mazetto@ufu.br
esdanielflorez@gmail.com
marcioperes@ufu.br
diegoaugusto@ufu.br
cleudmar.araujo@ufu.br
arthurfiocchi@ufu.br

Abstract. *With the increasing concern for the environment and the need to recycle materials, the development of equipment that enables the production of filament for additive manufacturing from PET bottles has gained prominence. These devices transform PET bottles into filaments that can be used in 3D printers, although filament production is currently done manually, and the obtained results are not well understood. In addition to being a sustainable solution, this practice can also generate cost savings for users of 3D printers, as filament produced from PET bottles can be cheaper than pre-purchased filament. This article describes the development of equipment capable of producing filaments for additive manufacturing from PET bottles. Furthermore, the study analyzes the influence of parameters such as motor rotation speed, cut filament width, pre-heating, and heating temperatures in the equipment, and compares the strength of the final material with commercial products. The goal is to evaluate the feasibility of using PET bottles as a low-cost alternative to produce filaments for additive manufacturing, as well as to understand how equipment parameters affect the quality of the resulting filament. Solidworks software was used to create the CAD model for equipment design. Additionally, a PID control strategy was implemented for its operation using Arduino. In the evaluation process of filament produced from PET bottles and its comparison with commercial products, tensile tests were performed. The results showed that lower temperatures result in filaments with higher mechanical strength. Furthermore, the results indicate that it is possible to produce high-quality filaments from recycled plastic waste while maintaining suitable mechanical and thermal properties for additive manufacturing. These findings are important for the sustainability and environmental impact reduction in the additive manufacturing industry.*

Keywords: *Filament, additive manufacturing, recycling, PET, strength*

1. INTRODUCTION

Additive manufacturing (AM), specifically 3D printing, is playing an increasingly important role in industrial manufacturing and is primarily used in prototyping and tool fabrication. Its technological advancements are bringing forth new design possibilities, products, and production paradigms (Thompson et al., 2016).

Recently, competitive and low-cost AM methods have been studied, which can simultaneously achieve high-quality printing. Innovators can now easily conceive and create 3D ideas, as AM/3D printing significantly streamlines prototype production (Dizon et al., 2018).

FDM printer filaments are often made from widely used plastics such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), high-impact polystyrene, and polyethylene terephthalate (PET). These materials are commonly chosen due to their suitable properties for 3D printing. However, the cost of these filaments is relatively high, ranging from 19 to 80 USD/kg. Table 1 presents a comparison of the typical properties of some filament materials used in 3D printing, such as PLA, ABS, HDPE, and PET, which are four widely used plastic materials in various applications (Chong et al., 2016).

The production of plastics has reached 322 million tons due to its versatility, low cost, and ease of manufacturing. However, this massive production and consumption of plastics generate a large volume of waste and have caused a considerable environmental impact, both in land and water pollution, as plastics tend to decompose very slowly and occupy landfills and beaches. There is an urgent need to address the environmental issues that currently cast a shadow over the production, use, and consumption of plastics. The millions of tons of plastic waste ending up in the oceans every year are one of the most visible and alarming signs of these problems, causing growing public concern (Turku et al., 2018; Awaja and Pave, 2004; Arenda et al., 2019).

Table 1. Comparison of typical properties of commercial PLA, ABS, HDPE, and PET values.

Properties	PLA	ABS	HDPE	PET
Melt Flow Rate, g/10min	2.4 - 4.3	22 - 48	4 - 8	5 - 30
Tensile Strength, MPa	50 - 55	30 - 52	20 - 40	50 - 80
Strain at yield, %	10 - 100	3 - 75	> 100	3 - 6
Young’s modulus, MPa	3500	1700 - 2800	200 - 1200	2000 - 4000
Melting Temperature, ºC	120 -170	200 - 230	120 - 190	240 - 260
Glass Transition Temperature, ºC	50 - 60	100	80 - 110	70 - 80
Extruding Temperature, ºC	160 - 220	210 - 230	130 - 190	240 - 280
Cooling Time	Long	Medium	Medium	Long

Plastic recycling has been beneficial to us, humans, and to the environment, at least to some extent, but there is still much to be done to improve it. Plastic recycling, or plastic reprocessing, is the process by which waste or used plastics are reprocessed and transformed into new useful products, processed into the same products, or processed into completely different products (Turku et al., 2018). “Figure 1” presents a schematic diagram of the Resource Circulation Loop.

Figure 1. Resource Circulation Loop Source: Kefyalew (2023)

As mentioned earlier, 3D printing technology has been widely known for its various applications and is used in many fields. However, there is a concern about how the filament can be more environmentally friendly and produced from recycled materials. The issue of high cost of materials in FDM 3D printing and the large amount of plastic waste generated can be mitigated by utilizing plastic waste in the production of 3D printing filaments (Kefylew, 2023). Among recyclable plastics, polyethylene terephthalate (PET) is a popular raw material for filament extrusion due to its wide availability in common consumer products such as soda bottles and food packaging (Kefylew, 2023).

In this work, the material for the 3D printer filament will be manufactured from recycled PET (Polyethylene Terephthalate) waste. This would reduce the expensive cost of FDM filament materials and minimize environmental pollution caused by these plastic wastes. PET filament material is cost-effective, environmentally friendly, and easy to use.

2. Methodology

The methodology employed in this study consisted of five distinct stages, each aimed at achieving the proposed objectives. Firstly, the construction project of the testing bench was carried out, establishing the foundation for conducting the experiments. Subsequently, the materials were processed, adequately preparing the components used in the study. The next step involved the production of PET filaments, following a specific procedure to ensure consistency and quality of the analyzed materials. Following that, the tensile strength test and evaluation of the filament quality were conducted. Finally, the usability test was performed to analyze the practical applicability of the filaments in real-life situations. Through this comprehensive approach, the study sought to obtain a comprehensive and in-depth understanding of PET filaments and their viability for potential industrial and commercial applications. Figure 2 presents the flowchart of the methodology, highlighting the five key stages involved in this study.

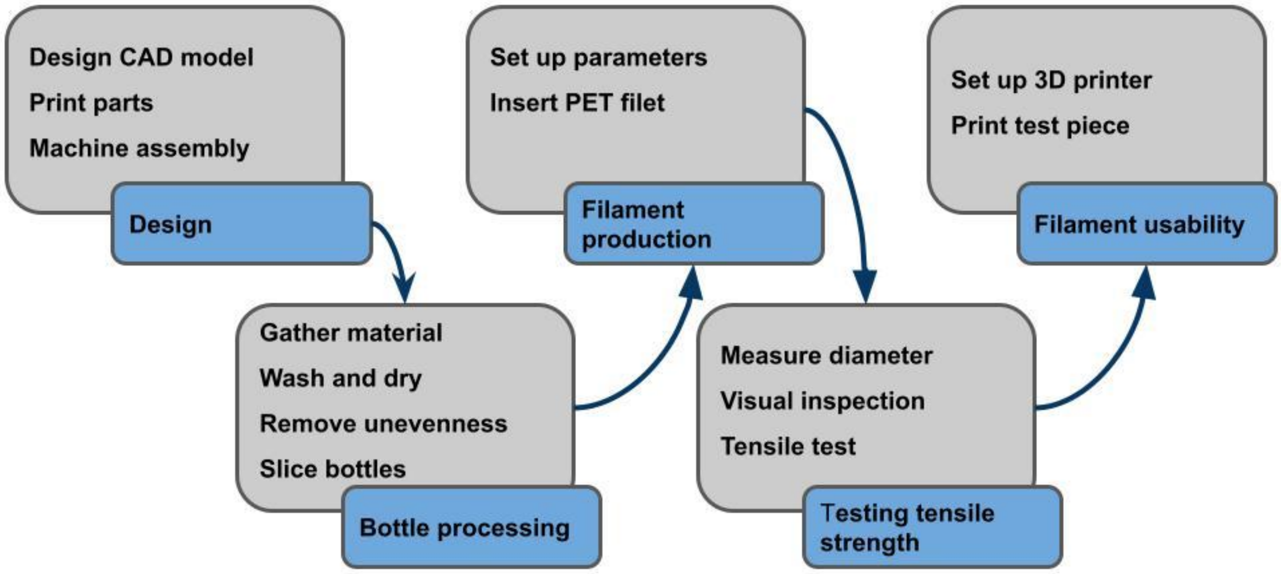

Figure 2. Methodology Flowchart

2.1 Bench construction project

In this stage of the study, the design of the experimental testing bench aimed at filament production from PET bottles was conceived. The project was meticulously developed to allow controlled variation of the parameters considered most relevant in the filament manufacturing process, including material thickness, extrusion temperatures, and drawing speeds.

Initially, CAD modeling was employed to ensure the proper functionality of the equipment. Specific parts for the testing bench were designed using Solidworks software, which were subsequently manufactured through additive manufacturing, specifically 3D printing, using the GTMax Core A3 3D printer and PLA filament. A PET cutter was developed, consisting of a 3D-printed structure and a utility knife blade, to perform precise cutting of PET bottles, preparing them for the subsequent filament manufacturing process.

The testing bench comprised the following key components: a heated aluminum block responsible for material fusion, a brass extruder nozzle used for filament extrusion, and a NEMA 23 stepper motor employed to control filament drawing speed. A 24V 40W heating cartridge was utilized to heat the aluminum block, monitored by a NTC 100K thermistor for precise temperature control.

The bench's control system was developed using an Arduino NANO microcontroller, a stepper motor driver, potentiometers, and an LCD. This configuration enabled automated control of crucial parameters such as drawing speed and extrusion temperatures. Additionally, a 24V 240W power supply was employed to provide the necessary power to the bench's components. The physical construction of the testing bench involved metal profiles, 3D-printed connectors, and an MDF board, ensuring a robust and stable structure for the integrated assembly of all components.

As a result, the development of the testing bench facilitated the creation of an adequate and controlled experimental system for PET filament production, allowing a detailed examination of the key variables involved in the manufacturing process. In Figure 3, a schematic diagram of the constructed filament production bench is presented.

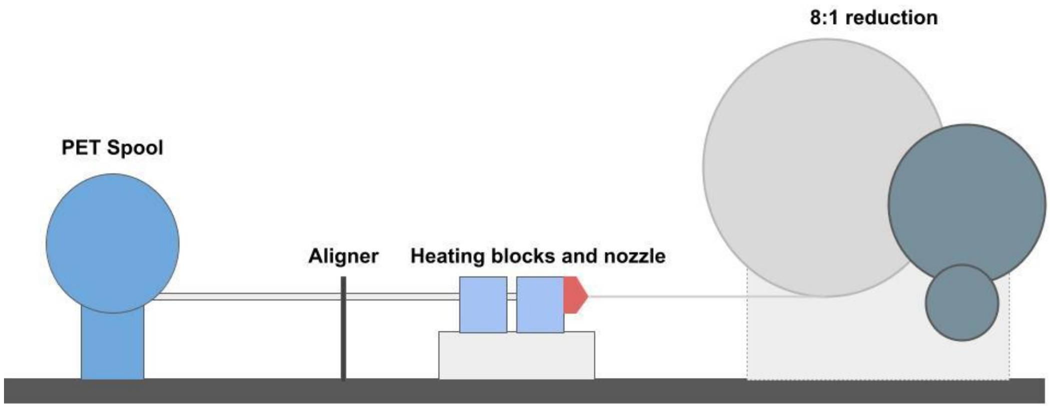

Figure 3. Schematic diagram of the constructed filament production bench

2.2 Material processing

The processing of the raw material begins with the collection of PET bottles that will be used, followed by cleaning, standardization, and subsequent slicing. In order to achieve homogeneity of the raw material, this study employs empty 2-liter soda bottles, of a single commercially available type. The washing process is carried out to remove contaminants from the plastic, such as dust, grease, labels, oil, among others. The plastics are washed with surfactants (detergents) or a sodium hydroxide (NaOH) solution. To remove labels and adhesive, the plastics are immersed in water for 10 minutes while being simultaneously washed, with manual removal of the labels. The bottle standardization phase is essential to ensure a constant width of the PET filament. This is achieved by pressurizing the inside of the bottle and using a heat gun to remove any irregularities. In order to use the bottles for filament production, they need to be cut into a continuous strip of uniform width. For this purpose, a PET bottle slicer was developed, consisting of a 3D-printed structure that holds a utility knife blade.

2.3 Filament production

Once the material is cut to the desired size, it is necessary to insert the tip of the strip into the heating block and then secure it to the spool with a radius of 0.035 m, which is connected to the stepper motor through an 8:1 reduction system. Next, the desired temperature is selected in the control system, and the blocks are allowed to heat up. Then, the desired drawing speed is chosen. At the end of the process, the produced filament is stored on the spool. In this work, two strip widths are used for three different drawing speeds, with the nozzle temperature fixed at 250°C. Therefore, six different filaments are obtained for analysis.

2.4 Tensile strength test and filament quality

In this step, the diameters of all the produced filaments were measured at 10 different positions, and they all underwent visual inspection for internal and external finish qualities. Subsequently, tensile tests were conducted on all the produced filaments, as well as on a commercial PETG filament from the GTMax3D brand.

2.4.1 Diameter measurement

The measurement of the diameter of the produced filaments is an important step to ensure their quality and uniformity. For each filament sample, 10 measurements were taken at different points, ensuring an accurate representation of the diameter. Additionally, the variation between individual measurements and the mean was evaluated to assess diameter uniformity. This methodology allowed for monitoring the quality and ensuring compliance of the produced filaments with the desired specifications.

2.4.2 Visual inspection

The visual inspection of the filaments involved careful and detailed observation of the selected samples. The samples were examined in a well-lit area, allowing for the identification of possible visual defects such as scratches, deformations, or irregularities on the surface. These defects were recorded and classified according to their severity, considering the established specifications and acceptance criteria. In case defects beyond acceptable limits were identified, corrective measures were taken, such as adjustments in the production parameters. Sections of the filament with visible defects were discarded and not used in the tensile tests. This visual inspection methodology provided a comprehensive evaluation of the surface quality of the filaments, contributing to ensuring compliance and improving the quality of the final product.

2.4.3 Tensile strength test

The methodology for the tensile strength test of the filaments consisted of several well-defined steps. Initially, filament samples were prepared by cutting them into appropriate length segments for the 1000 mm (± 2 mm) test, following the ASTM D638-22 standard. During this stage, it was important to ensure that the samples were free from visible defects such as cracks, bubbles, or deformations.

Next, the test equipment setup was conducted, involving the use of a BME-10kN Universal Testing Machine (UTM) from the manufacturer Oswaldo Filizola, an S-type load cell from Berman Load Cells model BTSI with a maximum capacity of 1000 kg, and a pair of custom-made clamps, as shown in Figure 4. The UTM and all accessories were properly calibrated according to the NBR ISO 7500-1 standard. The clamps were correctly installed on the equipment to ensure proper fixation and alignment of the samples during the test.

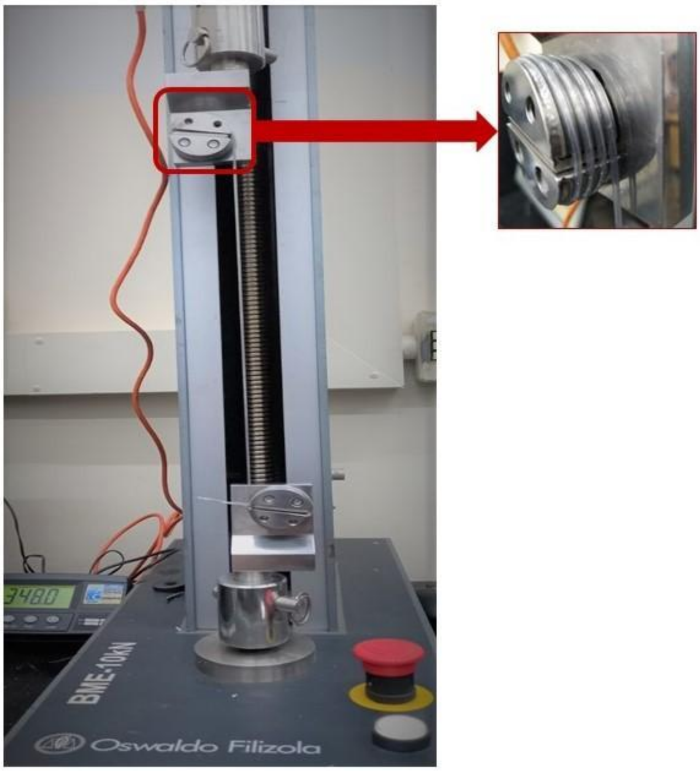

Figure 4. Experimental arrangement for tensile tests

The experimental procedure was modeled with a useful length of the specimens of 165 mm, as performed by Rodrigues S. et al. (2023). With the specimens properly mounted, the testing machine was adjusted to initiate the tensile test at a displacement rate of 5 mm/min. The stopping criterion for the test was the specimen rupture.

The stress-strain data were automatically recorded by the testing machine's control software. These data were recorded in real-time, and once the rupture occurred, the test was terminated, and the data were subsequently exported to a spreadsheet for analysis.

After the completion of the tests, the recorded data were analyzed. Parameters of interest, such as rupture stress and elastic modulus, were calculated. The results were compared with the expected values for reference filaments. Statistical analyses were performed to assess the consistency of the results and identify possible variations among the samples. Three tensile tests were conducted for each type of filament, with six being manufactured and one commercial (total number of samples = 21). Finally, environmental conditions were kept consistent throughout all the tests to avoid temperature and humidity-related variations.

2.5 Usability test

In addition to the tensile test, to evaluate the usability of the filament produced from recycled PET bottles, a simple cube was selected as a test object and printed using a GTMAX Core A3 printer. The printing settings were adjusted using a nozzle temperature of 255°C, a bed temperature of 70°C, and an extrusion speed of 80 mm/s, within the manufacturer's recommended range.

During the cube printing process, aspects such as layer adhesion, detail resolution, and dimensional stability were observed. The printing process was carefully monitored to verify if the produced filament exhibited good flowability and proper fusion during extrusion.

Once the cube printing was completed, a qualitative visual analysis was performed. Possible defects such as adhesion failures, deformations, or irregularities on the printed surfaces were observed. The analysis also included checking the dimensions of the cube and comparing them to the specifications of the original 3D model.

The results obtained from the cube printing provided valuable insights into the usability of the filament produced from recycled PET bottles. The visual analysis allowed for the identification of surface defects and evaluation of print quality.

Based on the results of these tests, the feasibility and quality of the filament produced from recycled PET bottles for use in 3D printing were assessed. This direct analysis of the functionality of the printed filament contributed to understanding its usability in real additive manufacturing applications. In conclusion, printing the cube using the filament produced from recycled PET bottles provided valuable insights into its properties and characteristics. This stage of the study expanded the evaluation of the filament beyond the tensile tests, providing a more comprehensive understanding of its behavior during the 3D printing process.

3. Results

The results are presented in three distinct stages: Manufacturing results, tensile strength results, and usability results.

3.1 Manufacturing results

A total of 6 different filaments were produced, using a combination of 2 widths of PET strips and 3 drawing speeds. For the analysis of manufacturing quality, the diameters and the surface and internal finishes of the filaments were evaluated.

3.1.1 Dimensional quality

Table 2 contains the results of the final diameters of the filaments relative to the parameters used.

Table 3.1. Manufacturing parameters of recycled PET filaments

Filament	Velocity, m/s	Filet's average width, mm	Width standard deviation, mm	Average filament diameter, mm	Diameter standard deviation, mm
A	0,0005	8,55	0,568	1,71	0,032
B	0,0005	9,24	0,207	1,74	0,034
C	0,0016	8,80	0,714	1,72	0,024
D	0,0016	9,00	0,236	1,72	0,021
E	0,0043	8,26	0,628	1,72	0,042
F	0,0043	9,07	0,194	1,73	0,022

Observing the table, it is evident that the drawing speed does not have a significant influence on the final diameter of the filament. However, filaments D, F, and C exhibited the smallest variations. Other parameters that may influence the final diameter, such as nozzle diameter and drawing temperature, still need to be tested.

3.1.2 Filament finish

All filaments produced under the specified conditions in this study exhibited a tubular shape, as shown in Figure 5.

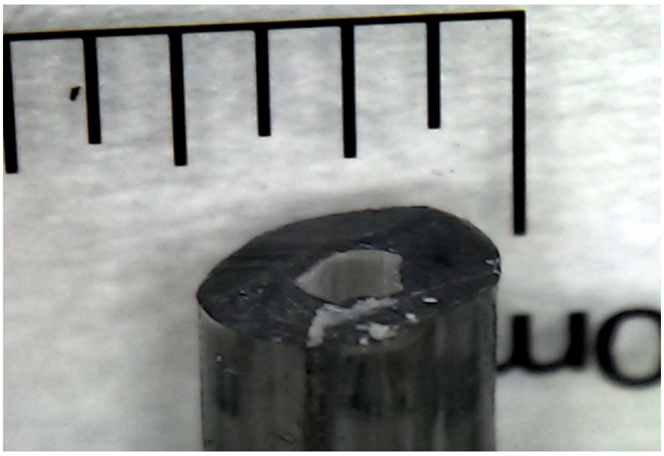

Figure 5. Enhanced visualization of the tubular section in the filament

The finish quality of the filament was assessed qualitatively. In this regard, all filaments exhibited a good finish and visual homogeneity, making them considered suitable for use. It is important to note that due to the observed variations in the tubular section fill, the tensile strength values may be higher than reported. In Figure 6, the observed fill variations can be seen, warranting further investigation for a more comprehensive understanding of the mechanical properties of the filaments.

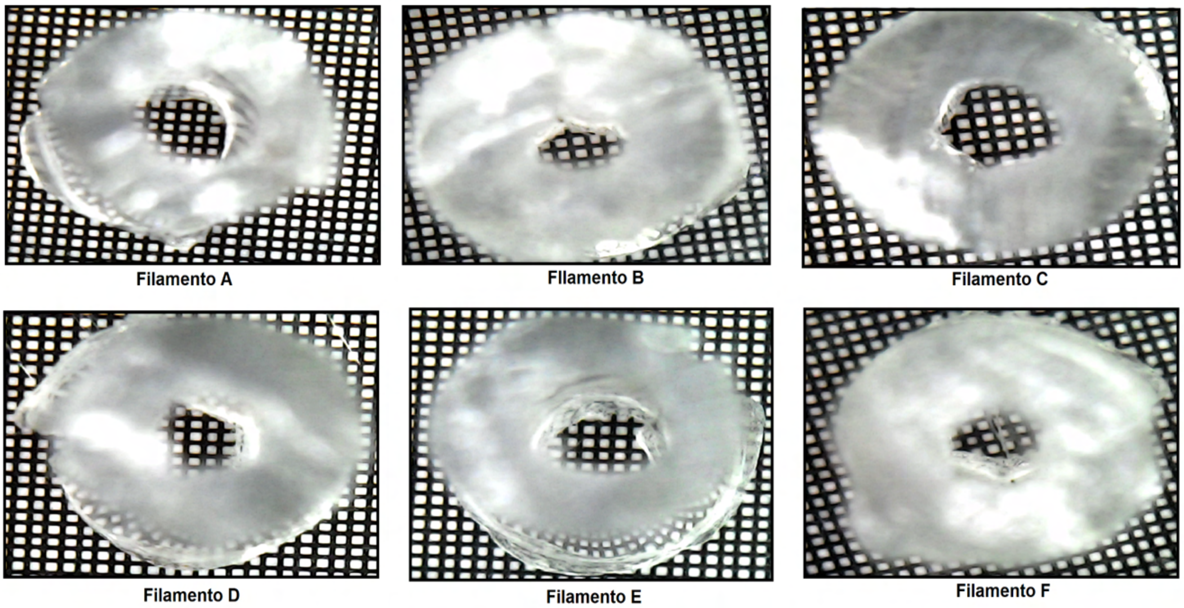

Figure 6. Hollow recycled PET filament

3.2 Tensile strength results

The results obtained from the tensile strength assessments are presented. Tensile tests were performed on all the produced filaments and one commercial PETG filament from the brand GTMAX. Three specimens were used for each filament type analyzed. However, during the tests with filament A, one specimen was lost, resulting in only two specimens for this filament.

All the tensile test graphs exhibited similar behavior, as exemplified in Figure 7, which shows the results of the tests conducted with filament B. It is possible to observe the presence of stress drop and recovery points, possibly due to filament adjustment in the grips, as the filament deformation levels were high.

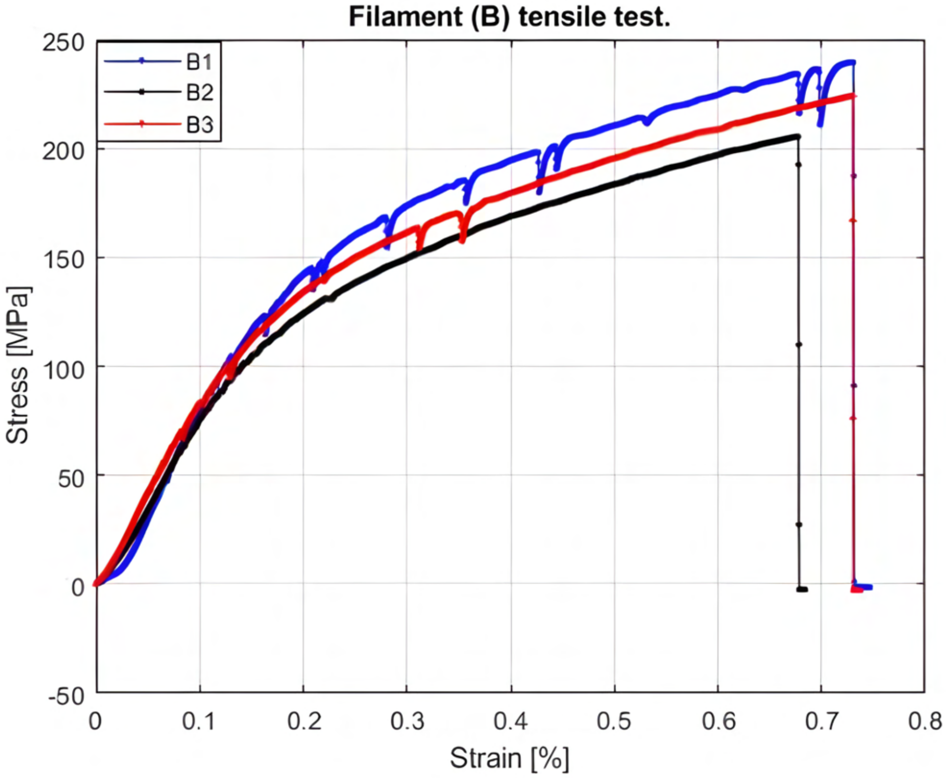

Figure 7. Average behavior between stress and strain

Figure 8 illustrates the fitting curves of the average behavior between stress and strain for the material.

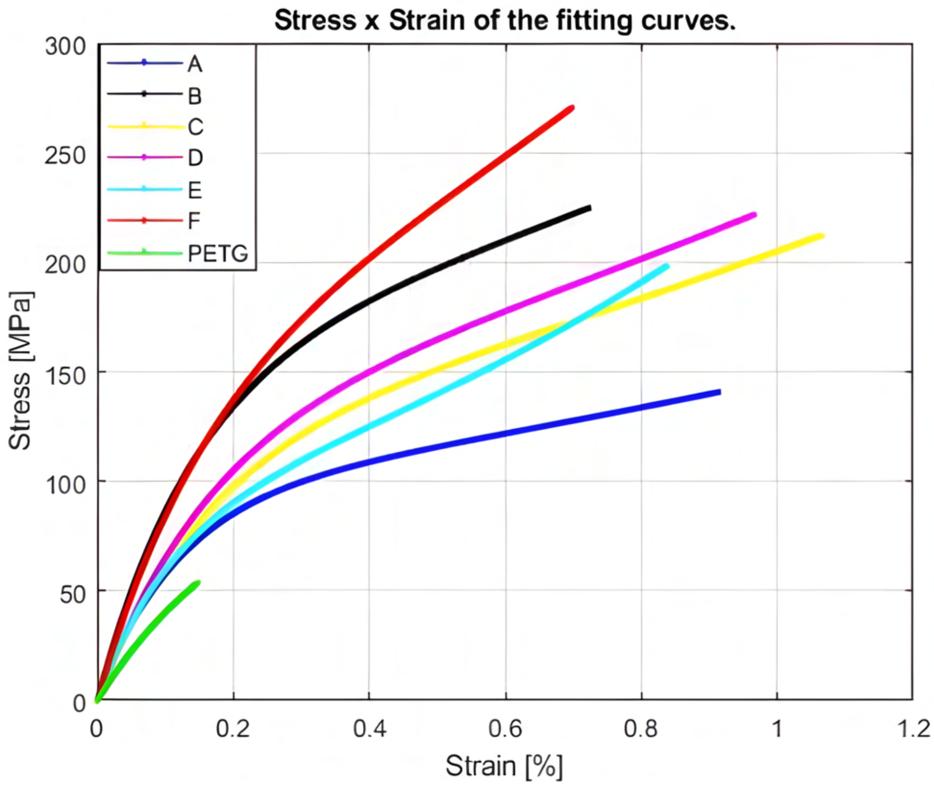

Figure 8. Stress-Strain Curves

In all the tests, the modulus of elasticity, maximum deformation, and rupture stress of each filament were determined, as shown in Table 3.

Table 3. Tensile Test Results

	Rupture Stress	Standard Deviation	Mean Deformation	Standard Deviation	Average Elastic Modulus	Standard Deviation
A	144.74	6.148	0.91356	0.257540	698.25	141.7749
B	222.96	17.104	0.72265	0.033597	862.97	64.3377
C	205.48	5.332	1.06340	0.138661	594.00	49.0433
D	217.74	20.463	0.96555	0.137350	611.97	14.0532
E	177.82	36.343	0.83686	0.193180	576.23	71.7191
F	260.67	21.207	0.69787	0.143609	849.17	44.9889
PET G	43.53	0.812	0.14761	0.018447	396.30	50.2046

The coefficient of determination R^2 was utilized to assess the quality of the fits obtained in our experiment. The results revealed that the regression models exhibited R^2 values ranging from 0.9903 (minimum) to 0.9984 (maximum).

Upon examination of Table 3, it becomes evident that the filaments produced from recycled PET displayed significantly higher tensile strength compared to the commercial filaments, indicating their potential suitability for manufacturing structurally oriented components. However, it is important to note that this investigation solely focused on analyzing filament strength, and further tests on the printed specimens are warranted to ascertain whether components fabricated with recycled PET filament also exhibit superior strength in comparison to those created with commercial filament.

The elastic moduli and maximum deformations of the recycled PET filaments were found to be 260.67 MPa and 1.06%, respectively.

The deviations presented in Table 3 correspond to the standard deviations of the estimated means within each analyzed group. It is crucial to acknowledge that each group was subjected to testing with only three specimens, and obtaining more robust statistical outcomes would necessitate conducting tests on a larger number of specimens per group

3.3 Usability results

To assess the usability of the produced filaments, solid 10 mm cubes were printed using a GTMAX Core A3 printer. The results indicate that the use of filaments made from recycled PET is feasible in conventional printers. However, further in-depth studies are still needed to determine the optimal printing parameters for this type of filament.

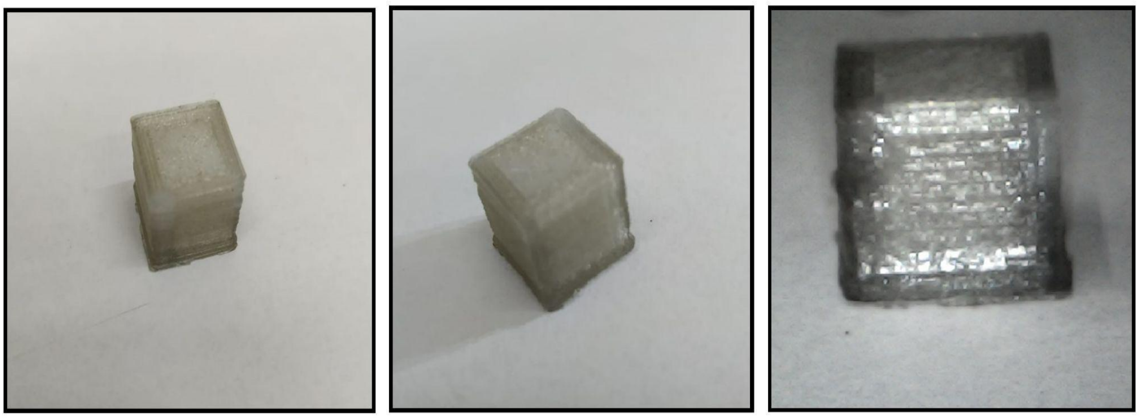

Figure 3.3. 3D printed with recycled PET filament.

4. Conclusion

The objective of this work, which was to produce filaments using PET bottles, was successfully achieved, resulting in high-quality filaments suitable for 3D printing. Furthermore, it was observed that parameters such as drawing speed and fillet width did not significantly affect the final filament diameter.

It was also found that the manufacturing method resulted in tubular-shaped filaments with an internal void. This void was present in all manufactured filaments, regardless of the analyzed parameters. However, filaments produced with a wider fillet exhibited a visibly smaller void, as seen in the enlarged photos. It is important to note that this void was not considered in the rupture stress calculations, implying that the actual rupture stress is expected to be higher than the obtained results. The desired goal for future research is to produce solid filaments, thus achieving even greater strength and improved print quality.

Regarding tensile strength tests, it was evident that all filaments made from recycled PET exhibited significantly higher tensile strength compared to commercially available PETG filaments. However, the tensile strength of 3D printed specimens was not evaluated in this study. The strength of printed specimens is expected to depend on other parameters, but it is anticipated that using filaments with higher strength will result in stronger printed parts.

It is important to note that the material analyzed has an unknown chemical composition since it is obtained from recycled material, thus variations between samples are expected. Additionally, the obtained results for filaments manufactured with the same parameters showed deviations, which are also anticipated due to the methodology used in the tests, such as filament settling in the grips used.

For future studies, it is recommended to conduct further analysis of the material's chemical composition and perform a larger number of tests to obtain more precise and representative results.

5. Acknowledgments

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6. References

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7. Responsibility notice

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