From plastic waste to frugal products - Mechanical properties evaluation

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Abstract Plastic utilization has contributed to shocking waste generation numbers. Within the context of promoting sustainability and improving resources value, Circular Economy appears as an exciting solution to provide methodologies that can empower the connection of reducing environmental damages on the value chain of products and services. With new practices, new products concepts appear and Frugal Innovation is transforming the product and business concept. These affordable solutions can provide sustainable practices to preserve natural ecosystems and effectively use resources.

This research aims to provide a structure to prove the feasibility and possibility to explore plastic recycling to provide 3D printing feedstock and produce frugal products using all the approached concepts. It is assessed to a mechanical evaluation of five important mechanical properties of recycled ABS, PET and PLA. This evaluation provided a mechanical characterization and information that highlights a downgrade of the approached mechanical properties, comparing with virgin material. However, with the conclusions drawn from the obtained properties it was possible to produce three different frugal products. This proves the feasibility of recycling plastic waste to produce frugal products, taking advantage of new sustainable methodologies.

Keywords: Circular Economy; 3D Printing; Plastic Recycling, Frugal Products, Mechanical Properties

1. Introduction

One the most used materials in modern economy is plastic. Given the combination of a great versality and low acquisition cost, plastic use has grown exponentially over the past decades and is expected to continue this growth on the next 20 years (MacArthur, 2016). However, plastics products are, usually, associated with a short life spam and their intensive use is resulting on devasting ecological problems. For instance, greenhouse emissions in the production and after-use externalities costs related to plastic packaging have been estimated to be around 40 billion USD, by the UNEP. A major factor contributing to such problems is a shocking 32% of plastic packaging escaping from recycling systems, contributing to a terrific loss of 95% (between 80-120 billion USD) plastic packaging material value (MacArthur, 2016).

Additionally, the world population is consuming 1.6 times more than what can be sustained by our natural resources (Global Footprint Network, 2016). To preserve our planet and promote prosperity and development, a radical change in the current systems and practices is urgent. Circular Economy is a concept that intents to promote improvements on resource efficiency. It relies on reducing as much as possible waste and shifting the current take-make-waste model to a take-make-renew-take (Despeisse et al., 2017). Thus, circular economy can be stated as an economic system composed by business models where the 'end-of-life' concept is eliminated as possible by reducing, reusing, recycling and recovering materials, all over the production/distribution and consumption processes. These processes should be seen from a micro (products, companies, consumers), meso (eco-industrial parks) and macro (city, region, nation) perspectives, with the purpose of establishing an sustainable development, providing environmental quality, economic prosperity and social equity and bringing benefits to current and future generations (Kirchherr, Reike, & Hekkert, 2017).

It is important to introduce new technologies that sustain the practice of circular economy. 3D printing has proven to be a technology that has tremendous potential to minimize production costs and enables companies to serve mass customized demands (Berman, 2012). It has also been seen as a technology that allows companies to produce quality products and also embrace circular economy principles, as 3D printing technology minimizes resources waste. Indeed, the adaptation of this technology on the production of plastic products consuming plastic material waste is being seen as an efficient and cost effective practice to serve multiple industry sectors (Despeisse et al., 2017).

It has been explored a methodology to produce recycled plastic feedstock to 3D printers, using a shredder designed to shred plastic products into small pieces and an extruder to produce the 3D printer filament. With the plastic materials shredded, filament can be produced with commercial extrusion of plastic. In this process, plastic materials enter in a closed loop process to obtain recycled filament from post-consumer plastic. This concept intents to be a simple functional process to reduced plastic waste as possible (Kreiger, Mulder, Glover, & Pearce, 2014).

In addition, it has also been given importance to the investigation of FRUGAL products, that need to be extremely affordable and also sustainable, with high-quality offerings. Adopting frugality implies a development of a production practice that minimizes resources usage and align a design phase with reduction cost targets. It is also fundamental to align these methodologies with new technologies, to produce efficient and quality products (Maric, Rodhain, & Barlette, 2016; Roland Berger, 2015). Therefore, taking in account the aforementioned 3D printing features, it is totally justifiable the deployment of this technology to produce locally Frugal products.

In the past decade, it has been verified an arise of attention to explore these concepts. This research intents to emphasize the connection between them, proving the functional feasibility of a methodology to produce frugal products with plastic waste, taking advantage of the approached principles and technologies.

2. Methodology to evaluate the mechanical properties

In order to evaluate the quality assessment of recycled plastics Vilaplana and Karlsson (2008) developed a conceptual framework regarding three main axes. This framework aims to provide a holistic vision on the material degradation: degree of degradation, regarding the variation in mechanical properties and structural changes; degree of mixing, regarding the presence of polymeric impurities; low molecular weight compounds, regarding the presence of additives, contaminants and degradation products in the polymer structure. In the end it comes up to the researcher to decide the property/ies to study in his assessment (Vilaplana & Karlsson, 2008). This research aims to determine how can recycled plastic filament can be applied to produce functional frugal products, thus it was decided to evaluate the variation of the mechanical properties. It considered this mechanical variation, since it is necessary to determine the material characteristics to produce a functional frugal product. The mechanical tests performed were chosen based on similar researches on plastics mechanical properties (Cruz Sanchez, Boudaoud, Hoppe, & Camargo, 2017; Zander, Gillan, & Lambeth, 2018a). It was decided to perform a tensile, compression and torsion tests. The tensile test is a fundamental mechanical test and it can provide knowledge whether if the material is brittle or ductile. It also provides information to measure the material's stiffness (Instron, 2019). The compression test is important to define the material brittle or ductility when subjected to compressive forces (Instron, 2019). The torsion test provides knowledge to qualify the product resistance, until the rupture, to torsional forces (Instron, 2019).

It was chosen to investigate recycled ABS, PLA and PET, since ABS and PLA have been widely used in the production of products with 3D Printing and it has been verified an interest to study the viability of introducing PET in this industry (Zander, Gillan, & Lambeth, 2018b). The recycled filament was acquired from Refil, a company that provides numerous 3D printing filament solutions. The production of this plastic filaments is based on shredding and extrusion processes, using plastic waste as feedstock (Refil, 2019). With the conclusions withdrawn from the mechanical analysis done to the specimens, it was possible to determine possible applications for the studied materials. It was produced three different considered frugal products to test the materials performance and prove the functional feasibility of the approached methodology. **Figure 1** presents the methodology adopted in this research.

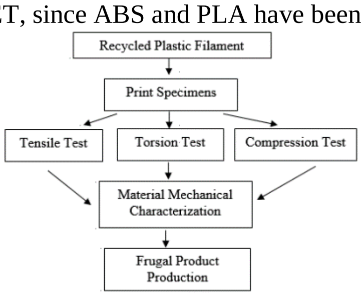

Figure 1 – Research Methodology

2.1. Printing Parameters and Specimens Characteristics

To assess the selected mechanical tests, it was necessary to define the printing parameters and print specific specimens for each mechanical test. The printing parameters were chosen taking under consideration work done by Miguel & Oliveira (2018), Fernandes (2016) and Cruz Sanchez, Boudaoud, Hoppe, & Camargo (2017a). The printing parameters were discussed with 3D Ways, a company specialized in 3D printing solutions, which collaborated with this research proving their headquarters and equipment to produce the specimens and products. It was chosen to print the specimens at four different printing temperatures to, with the mechanical analysis and dimensional analysis, define the best printing temperature ("sweet spot") for each studied filament. These printing temperatures were discussed with 3D Ways, regarding their custom printing temperatures and the advised printing temperatures from Refil (Refil, 2019). For the ABS it was chosen to print the specimens at 230ºC, 240ºC, 250ºC and 260ºC. For the PET it was chosen to print the specimens at 220ºC, 230ºC, 235ºC and 240ºC. For the PLA it was chosen to print the specimens at 200ºC, 205ºC, 210ºC and 215ºC. The printing parameters selected are presented in **table 1.**

Table 1 – Printing Parameters

	PET	PLA	ABS	
Parameters	Values	Values	Values	Units
Layer Thickness	0.2	0.2	0.2	mm
Bed Temperature	50	80	100	ºC
Nº Perimeters	4	4	4	
Top Solid Layers	6	6	6	20
Bottom Solid Layers	4	4	4	53
Fill Density	100	100	100	%
Travel Speed	100	100	100	mm/s
Nozzle Diameter	0.4	0.4	0.4	mm
Nozzle Speed	60	60	60	mm/s
G-code	Simplify 3D	Simplify 3D	Simplify 3D	

The selected ASTM international standards, which define the specimen's geometry and dimension, for the tensile, compression and torsion test were ASTM D638-02a, ASTM E143 – 13 and ASTM D 1621 – 00, respectively (ASTM, 2018; ASTM International, 2003; ASTM standard D1621, 2004). Starting from the tensile specimens, they were produced following the guidelines of the ASTM D638-02a, accordingly the Type I of the suggested specimens. This standard recommends these dimensions for the majority of tensile tests specimens' production (ASTM International, 2003). However, there were made some small modifications to promote more precise results. Since the tensile testing machine reveals to have some inconsistencies reading lower strength values, it is recommended to produce a sample with large dimensions of the area subjected to traction, promoting higher values of the strength. It is important to mention that the central rectangular section is thinner than extremities to avoid a fracture near the grips. The area subjected to traction has a 13mm width, 57mm length and a thickness of 3.2mm.

The torsion specimens were made accordingly the ASTM E143 – 13 standard test method. This standard recommends specimens in shape of cylinders, with a uniform diameter. Considering the same reasoning of the tensile specimens, the central cylindrical section is thinner than extremities to avoid a fracture near the grips. It is also important to guarantee that the specimens are solid in order to perform tests with credible results. In the determination of the shear modulus slight imperfections can produce errors on the values of this property. The area subject to torsion has 8 mm diameter and 30mm length

Finally, the compressions specimens were made accordingly the ASTM D 1621 – 00 standard test method. It is recommended to produce a cross section with a minimum of 25.8 cm^2 and maximum of 232 cm^2. These specimens were produced in a cubic geometry to promote stability during the compression test. The compression specimens were cubes of 12mm of edge.

2.2. Mechanical Tests Methodology

Starting from the tensile test, this test aims to provide mechanical properties regarding the resistance of the material to tensile loads and the elasticity or stiffness of the material (Instron, 2019). Thus, it will be used the collected data to state three important mechanical properties: Young Modulus, regarding the elastic/stiff property; Tensile Strength, regarding the maximum supported tensile stress; Yield Strength, regarding the maximum stress supported until the material passes through elastic to plastic deformation (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012).

Regarding the equipment used to perform this test, the testing machine used was an INSTRON 5566. This machine was setup with a load of 10 kN and a speed of testing of 2mm/min. It also necessary to introduce on the software the values of Thickness (T) and Width (W), allowing the machine to determine and collect instant data related to the Strength (F) and displacement (Δl). In this traction test there are some precautions to take in consideration. To start this tensile test, it is necessary to introduce some data on the software, such as the number of samples that will be tested (36) and the speed of testing. It is important to guarantee that the axis of the specimen is aligned with the direction of the application of the load. Thereafter, it is possible to start the tensile test. However, it is extremely important to reset to zero the value of the measured strength before starting every traction of a specimen. When starting the test, the machine reads a small negative load value, which has no implications in the results. However, if in the next test the load value is not reset, the machine will accumulate this value. If this procedure continues sample after sample, the starting read load will increase to values that will interfere with the reliability of the results. Resetting this load value to zero will prevent the machine from reading mistaken values. The data collected in the tensile test provides information to draw the Stress-Strain curve for the tested specimen. With such Stress-Strain diagrams it is possible to determine the desired mechanical properties.

This torsion test is conducted to determine torsional properties of the material. A wide range of products and components are exposed to torsional forces during their application. Performing this torsional test can provide information to simulate real life conditions and with the collected data it is possible to state an important mechanical property: Shear Modulus, an interesting property to calculate the compliance of structural materials in torsion.

Regarding the equipment used to perform this test, the testing machine used was an INSTRON 8874. The machine was set up with a rotation ratio of 5º/s. It is necessary to introduce on the Instron Fast Track 2 – MAX software the number of samples (36). Also, it is important to ensure that the grips are well positioned in order to produce the failure on the desired gauge of 50mm length. Thereafter, it is required to guarantee that the force applied by the grips does not fractures the specimen, to avoid inconsistent results. After this preparation, it is initiated the torsion test and the machine performs until the tested specimen fractures. The machine records the torque applied and the angle of twist, providing a Torque-Angle of Twist diagram. The machine collects the torque values in kN*m and the Angle of Twist in degrees. The standard test performed is directed to obtain the shear modulus, G, of the tested material.

This compression test is conducted to extract information of a material behavior under compression forces. It is also an essential mechanical test to explore the capacity of brittle materials to maintain their integrity under compressive loads. By performing this compression test it is possible to state an important mechanical property: Maximum strength in compression, a property that indicates the point where a brittle material fracture. However, given that the materials to be tested are known to be ductile, they will continue their deformation until the load is no longer being applied (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012).

A compression test is in fact comparable to a uniaxial tensile test. However, in the compression test the load is made in the opposite direction, to perform a compression on the specimen. Regarding the equipment used to perform this test, it was used an INSTRON 5566. The machine was set up with a speeding test of 1,5mm/m. The testing machine was assembled with two metal sheets on the grips zone, to promote a uniform force distribution. It is also important to ensure that the cube is well centered on the testing machine. It is necessary to introduce data on the software, such as the number of samples (36) and some specific dimensions, such as the width and length of the specimen. After this procedure, it is possible to initiate the compression test. The machine records the displacement and the load applied to the specimen.

3. Mechanical Tests Results

The pattern chosen for the presentation of the results was identical for all the three different mechanical tests. It can be traduced as: The presentation of the obtained Curves Diagrams, regarding the four different printing temperatures; The presentation of the tables relative to the obtained properties for the tested specimens, at each printing temperature; The presentation of the overall mechanical properties of the material, correspondent to an average of all the data collected for the material in matter. This presentation of the properties corresponding to an average of all the tested specimens, for the material in matter, intents to specify the material properties after the recycling and 3D Printing process, without considering the influence of the printing temperature.

3.1 Tensile Tests Results

Starting by the ABS samples, in **figure 2** it is presented the Stress-Strain curve correspondent to the average of the values collected, for each printing temperature.

The ABS samples revealed to have similar Strain-Stress curves, independently of the printing temperature. This can traduce similar values for the three properties in study. It is important to refer that all the ABS specimens fractured almost immediately after their maximum Tensile Strength values. The

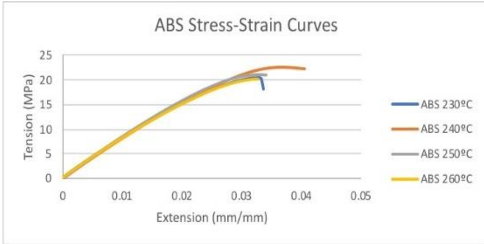

Figure 2 – ABS Stress-Strain diagram at each printing temperature

ABS mechanical properties obtained from the best printing temperature, 240ºC, are presented in **table 2.**

Table 2 – Mechanical properties obtained from the best printing temperature

240ºC	ABS 4	ABS 5	ABS 6	Average	SD	VC
Young Modulus [MPa]	792,29	776,63	781,21	783,38	8,05	1,03
Yield Strength [MPa]	19,46	19,44	19,42	19,44	0,02	0,11
Tensile Strength [MPa]	22,44	22,46	22,56	22,49	0,06	0,29

Regarding the collected data from all the samples and focusing on the ABS overall properties, setting aside the printing temperature influencing factor, the average values extracted from the tensile tests of ABS can be traduced as: Young Modulus 792,51 MPa; Yield Strength 18,63 MPa; Tensile Strength 21,21 MPa.

Considering the PET samples, in **figure 3** it is presented the Stress-Strain curve correspondent to the average values for each printing temperature.

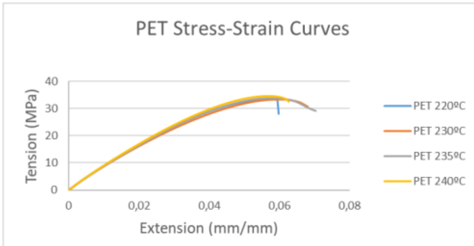

Figure 3 - PET Stress-Strain diagram at each printing temperature

It is notable that for all the printing temperatures, the Stress-Strain curves presented are, in fact, similar, presenting an identical behavior in the elastic and plastic deformation zones of the diagram. The PET mechanical properties obtained from the best printing temperature, 240ºC, are presented in **table 3.**

Table 3 – PET Mechanical properties obtained from the best printing temperature

240ºC	PET 10	PET 11	PET 12	Average	SD	VC
Young Modulus [MPa]	784,23	782,87	799,64	788,92	9,32	1,18
Yield Strength [MPa]	29,35	29,16	29,37	29,29	0,11	0,39
Tensile Strength [MPa]	34,43	34,43	35,09	34,65	0,38	1,10

Regarding the collected data from all the samples, the average values for the PET mechanical properties extracted from the tensile tests are: Young Modulus 761,91 MPa; Yield Strength 28,97 MPa; Tensile Strength 33,87 MPa.

Finally, in **figure 4** it is presented the PLA samples Stress-Strain curve correspondent to the average values for each printing temperature.

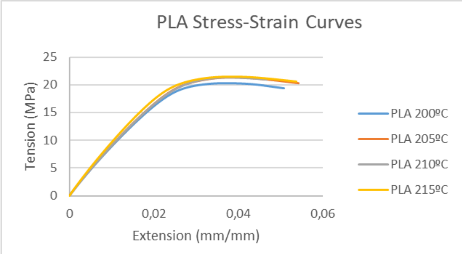

Figure 4 - PLA Stress-Strain diagram at each printing temperature

Once again, as the other recycled plastics, the PLA Stress-Strain curves presented a similar behavior. In the elastic deformation zone, it can be observed an identical pattern for all the printing temperatures. However, in the plastic deformation zone, the lowest printing temperature is highlighted by a smaller value to its maximum tension. The PLA mechanical properties obtained from the best printing temperature are presented in **table 4.**

Table 4 – PLA mechanical properties obtained from the best printing temperature

210ºC	PLA 7	PLA 8	PLA 9	Average	SD	VC
Young Modulus [MPa]	801,46	884,27	836,23	840,66	41,58	4,95
Yield Strength [MPa]	19,31	19,08	19,02	19,14	0,15	0,79
Tensile Strength [MPa]	21,82	21,18	21,18	21,40	0,37	1,72

The PLA mechanical properties extracted from the tensile tests are: Young Modulus 849,89 MPa; Yield Strength 19,02 MPa; Tensile Strength 21,18 MPa.

3.2 Torsion Tests Results

Starting by the ABS specimens, in **figure 5** it is presented the Torque-Angle of Twist curve correspondent to the average of values collected, for each printing temperature.

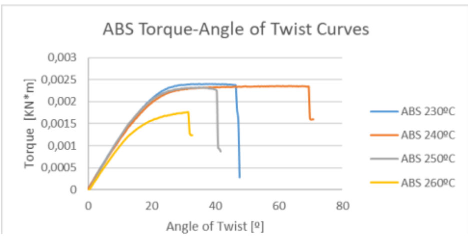

Figure 5 - ABS Torque-Angle of Twist diagram at each printing temperature

The behavior in elastic deformation zone is identical for the 230ºC, 240ºC and 250ºC printing. However, it can be verified some differences on the curves presented in the plastic deformation zone. The 230ºC and 250ºC printing temperatures reproduced similar curves, with a slightly greater angle of twist, until the collapse, for the specimens printed at 230º. The maximum Torque was similar for these both printing temperatures. The 240ºC printing temperature revealed the greater angle of twist, until the fracture and a similar maximum Torque to the 230ºC and 250ºC printing temperatures. The ABS mechanical property obtained from the best printing temperature, 240ºC, is presented in **table 5.**

Table 5 - ABS mechanical property obtained from the best printing temperature

240ºC	ABS 4	ABS 5	ABS 6	Average	SD	VC
Shear Modulus [MPa]	754,78	794,74	1058,44	869,32	165,00	18,98

The average of the ABS shear modulus from all the collected data, setting aside the influence of the printing temperature, can be traduced as: Shear Modulus 794,58 MPa.

Considering the research on the PET relative torsion properties, in **figure 6** it is presented the Torque-Angle of Twist curve correspondent to the average of values collected, for each printing temperature.

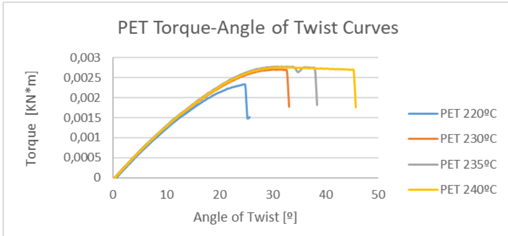

Figure 6 – PET Torque-Angle of Twist diagram at each printing temperature

Considering the plastic zone of the diagram, the curves obtained for three highest printing temperatures are, in fact, similar. The specimens produced at these printing temperatures revealed, approximately, equal values of maximum Torque applied by the machine. However, there is a slightly increase of angle of torsion until the fracture, as the printing temperature also increases. The lowest printing temperature, 220ºC, provided the lowest values of the Torque and Angle of Twist. The PET mechanical property obtained from the best printing temperature is presented in **table 6.**

Table 6 - PET mechanical property obtained from the best printing temperature

240ºC	PET 10	PET 11	PET 12	Average	SD	VC
Shear Modulus [MPa]	836,13	1057,92	795,50	896,52	141,25	15,75

The PET mechanical property obtained from the average of the torsion tests can be traduced as: Shear Modulus 890,63 MPa.

Finally, regarding the presentation of the PLA relative torsion properties, in **figure 7** it is presented the Torque-Angle of Twist curve correspondent to the average of values collected, for each printing temperature.

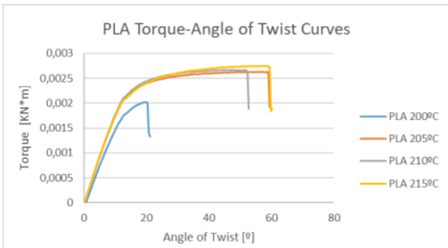

Figure 7 - ABS Stress-Strain diagram at each printing temperature

For the PLA specimens it was verified a significant difference on the curve obtained for the lowest printing temperature, when comparing with the curves of the other three printing temperatures. The 205ºC, 210ºC and 215ºC printing temperatures presented an almost equal linear region, correspondent to the elastic deformation. In the plastic deformation, the 205ºC and 215ºC printing temperatures also presented a very similar pattern, with a slightly higher value of angle of twist, until the fracture, when compared with the 210ºC printing temperature. The PLA mechanical property obtained from the best printing temperature is presented in **table 7.**

Table 7 - PLA mechanical property obtained from the best printing temperature

210ºC	PLA 7	PLA 8	PLA 9	Average	SD	VC
Shear Modulus [MPa]	833,95	1435,66	1574,63	1281,41	393,70	30,72

Finally, the average of the shear modulus from all the collected data of the PLA specimens is: Shear Modulus 1133,44 MPa.

3.3 Compression Tests Results

The Stress-Strain curves obtained for the ABS, PET and PLA specimens at each printing temperature, were, in fact, quite similar. Thus, it was opted to only present the results obtained from the mechanical analysis. The ABS mechanical properties obtained from the best printing temperature are presented in **table 8.**

Table 8 - ABS mechanical properties obtained from the best printing temperature

240ºC	ABS 4	ABS 5	ABS 6	Average	SD	VC
Young Modulus [MPa]	395,53	352,09	428,35	391,99	38,25	9,76
Yield Stress [MPa]	26,80	25,18	25,62	25,87	0,84	3,23

The ABS mechanical properties obtained from the average of the compression tests can be traduced as: Young Modulus 440,16 MPa; Yield Stress 25,32 MPa.

The PET mechanical properties obtained from the best printing temperature are presented in **table 9.**

Table 9 - PET mechanical properties obtained from the best printing temperature

240ºC	PET 10	PET 11	PET 12	Average	SD	VC
Young Modulus [MPa]	532,06	507,72	527,43	522,40	12,93	2,47
Yield Stress [MPa]	32,46	33,05	32,98	32,83	0,32	0,99

Regarding values of PET young modulus and yield stress from the average of all the data collected, the PET mechanical properties obtained from the compression tests can be traduced as: Young Modulus 536,97 MPa; Yield Stress 31,52 MPa.

The PLA mechanical properties obtained from the best printing temperature are presented in **table 10.**

Table 10 - PLA mechanical properties obtained from the best printing temperature

210ºC	PLA 1	PLA 2	PLA 3	Average	SD	VC
Young Modulus [MPa]	623,00	757,24	755,13	711,79	76,90	10,80
Yield Stress [MPa]	40,91	40,32	41,28	40,84	0,49	1,19

Finally, the value of PLA young modulus and yield stress from the average of all the data collected is: Young Modulus 639,22 MPa; Yield Stress 40,39 MPa.

4. Materials Mechanical Characterization

With the assistance of the software CES-EDUPACK, using with the information disposed by the software regarding the mechanical properties of the correspondent virgin material, it is possible to analyze the variation of the approached mechanical properties. It is also interesting to frame the mechanical properties of the recycled filaments accordingly scales relative to the mechanical properties available on the software.

Regarding the analysis of the recycled ABS mechanical properties, it can be compared the properties of virgin ABS presented in CES-EDUPACK with the recycled ABS properties, regarding the overall values obtained from all the ABS tested specimens. **In table 11** is presented the considered mechanical properties values displayed in CES-EDUPACK and the values obtained from the mechanical tests performed.

Table 11 - ABS theoretical values provided by CES vs Recycled ABS overall values

Mechanical Properties	Virgin ABS Range Values	Recycled ABS Values
Young's Modulus [GPa]	1,1 - 2,9	0,793
Shear Modulus [GPa]	0,319 - 1,03	0,869
Yield Strength [MPa]	18,5 - 51	18,63
Tensile Strength [MPa]	27,6 - 55,2	21,21
Compressive Strength [MPa]	31 - 86,2	25,32

It is possible to verify that the recycled ABS filament presents lower mechanical properties values when comparing with virgin material properties. For the recycled ABS, the shear modulus and yield strength are the only values inside their correspondent range of values presented for the virgin ABS. However, the yield strength value is situated on lower bound of the virgin ABS values range. The tensile strength and compressive strength are out of the range, still the values are near the lower bound of the range for the virgin material. The young modulus is also out the range and with a more accentuate difference compared with the tableted properties of the virgin material. Looking to this comparison, it can be stated that the mechanical properties ABS suffer a reduction with this recycling and 3D printing processes.

In **figure 8** it is represented the scales provided by CES-EDUPACK. The blue line corresponds to a density line of all the polymers. The red mark corresponds to the value of the recycled ABS of the concerning mechanical property.

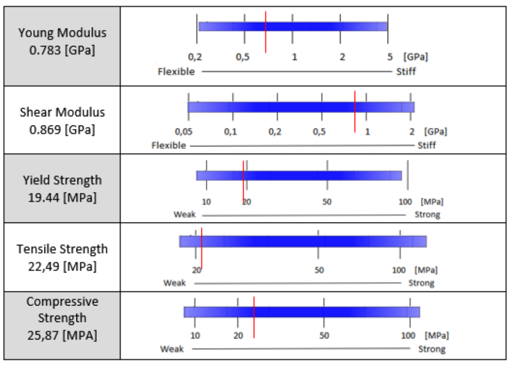

Figure 8 - Mechanical Properties Framework with Recycled ABS

Regarding the young modulus, with the best printing temperature (240ºC), this recycled ABS presented a value slightly lower from the medium term between a flexible or stiff material. The shear modulus presented a value corresponding to a stiffer material. These two properties present values near the densest zone of the polymer's density line. The yield strength presented a value in the weak zone of the scale, corresponding to low resistance to absorb elastically a tensile load. The tensile strength presented a value also in the weak zone, in bottom of the scale, corresponding to low resistance to tensile loads. The compressive strength presented a lower value present in the intermediate term between a weak or strong material, corresponding to a medium resistance to compressive loads. In general, these three properties presented values in more isolated zones of the polymer's density line. This framework can traduce this recycled ABS as a material with a weak resistance to tensile traction, a medium resistance to compressive loads, more flexible to tensile traction and with a stiffer property regarding torsion resistance.

Regarding the analysis of the recycled PET mechanical properties, in **table 12** is presented the considered mechanical properties values displayed in CES-EDUPACK and the values obtained from the mechanical tests performed.

Table 12 - PET theoretical values provided by CES vs Recycled PET overall values

Mechanical Properties	Virgin PET Range Values	Recycled PET Values
Young's Modulus [GPa]	2,76 - 4,14	0,762
Shear Modulus [GPa]	0,994 - 1,49	0,89
Yield Strength [MPa]	56,5 - 62,3	28,97
Tensile Strength [MPa]	48,3 - 72,4	33,87
Compressive Strength [MPa]	62,2 - 68,5	31,53

It is notable that the recycled PET presents a considerable downgrade of the mechanical properties when comparing with the virgin material properties. For the recycled PET, all the values of the properties are out the range of the values presented for the virgin PET. Considering the shear modulus scale presented in the recycled ABS characteristics section, this is the property, that even though it is out of range, presents the nearest value to the theorical range with a lower variance. The yield strength, tensile strength and compressive strength present values with substantial differences of approximately 30 MPa to the lower value of their correspondent virgin PET range values. The young modulus is the property which presents the greatest difference of approximately 2 GPa to the lower value of its correspondent virgin property range. With this, it can be stated that the PET mechanical properties suffer a accentuate reduction with this recycling process. **Figure 9** presents PET properties framed in the scales provided by CES.

Starting from the young modulus, with the best printing temperature (240ºC), this recycled PET presented a value near the medium term between a flexible or stiff material. The shear modulus presented a value corresponding to a stiffer material. The yield strength presented a value slightly lower from the

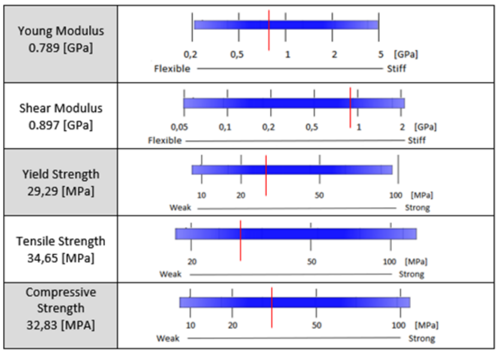

Figure 9 - Mechanical Properties Framework with Recycled PET

intermediate term between the weak and strong zones of the scale, corresponding to the average polymer's resistance to absorb elastically tensile loads. The tensile strength presented a value corresponding to the medium zone between a weak and medium strong material, corresponding to a material with a medium tensile resistance. The compressive strength presented a value a slightly lower from the intermediate term between a weak or strong material, corresponding to the average polymer's resistance to compressive loads. In general, these three properties presented values with better properties from the ABS properties. This framework can traduce this recycled PET as a medium strong material resistant to compressive and tensile loads, more flexible to tensile traction and with a stiffer property regarding torsion resistance.

Finally, it come the analysis of the recycled PLA mechanical properties, compared with the properties of virgin PLA presented in CES-EDUPACK. In **table 13** is presented the considered mechanical properties.

Table 13 - PLA theoretical values provided by CES vs Recycled PLA overall values achieved

Mechanical Properties	Virgin PLA Range Values	Recycled PLA Values
Young's Modulus [GPa]	3,3 - 3,6	0,849
Shear Modulus [GPa]	1,2 - 1,29	1,13
Yield Strength [MPa]	55 - 72	19,02
Tensile Strength [MPa]	47 - 70	21,18
Compressive Strength [MPa]	66 - 86	40,39

Once again it is notable a downgrade of the PLA mechanical properties when comparing with the virgin material properties. This PLA downgrade is similar to the one verified for recycled PET. For the recycled PLA, all the values of the properties are out the range of the values presented for the virgin PLA. However, the value of the shear modulus is near the theorical range and, accordingly the shear modulus scale, the variance is not accentuated. The yield strength and tensile strength present values with substantial differences of approximately 30 MPa bellow the lower bound of the range. The compressive strength presents a value bellow the lower bound of the range of around 25 MPa. Identical to the pattern verified in the recycled PET analysis, the young modulus is the property which presents the greatest difference of approximately 2,5 GPa. It can be concluded that the PLA mechanical properties suffer a accentuate reduction with this recycling process.

Moreover, identically to the analysis done for the ABS and PET mechanical characteristics, **figure 10** presents the scales provided by CES-EDUPACK. The blue line corresponds to a density line of all the polymers. The red mark corresponds to the value of the recycled PLA of the concerning mechanical property, obtained with the best printing temperature.

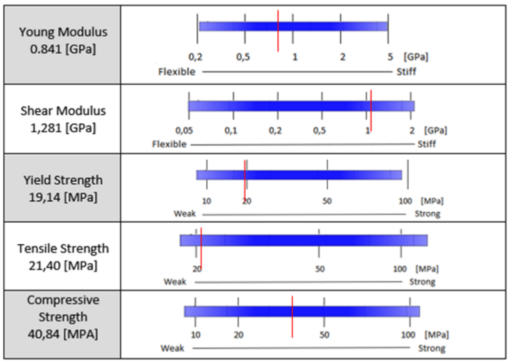

Figure 10 - Mechanical Properties Framework with Recycled PLA

With the best printing temperature (210ºC), the young modulus of the recycled PLA presented a value near the medium term between a flexible or stiff material. The PLA shear modulus presented the highest value, corresponding to a stiffer material. In fact, these two properties presented similar characteristics to the PET properties. The yield strength presented a value in weak zone of the scale, corresponding to a weak resistance to absorb elastically tensile loads. The tensile strength presented a value in the lower bound of the range, corresponding to a weak tensile resistance material. The compressive strength presented a value corresponding to the intermediate term between a weak or strong material, corresponding to a medium resistance to compressive loads. In general, the recycled PLA presented the first two properties of the scale with similar values to the recycled PET properties and the yield strength and tensile strength presented similar values to the recycled ABS respectively properties. This framework can traduce this recycled PLA as a material with weal resistance to tensile loads, however stronger than ABS, presenting a balanced flexibility and stiffness regarding tensile loads and stiffer concerning torsion loads.

5. Frugal Products Production

The products were chosen from two important open source web platforms, such as Thingiverse and MyMiniFactory. These platforms aim to expand the growth of 3D Printing by making possible to share and download 3D Printing files of a wide range of type of products. The information concerning the 3D printing files and design, regarding the selected products, is provided in the web platforms. To justify the frugality of the selected products it was created a table indicating seven fundamental frugal products characteristics. **Table 14** presents this information and it was sustained by a research done by Kuo (2017). To perform the decision of allocating each studied type of plastic to produce the products it was, firstly, considered the final application of each product. The final applications influence the type of loads that the product may be subjected and the necessities for resistance, flexibility or stiffness. Thereafter, it was taken under consideration the analysis performed to the recycled filaments. Accordingly each recycled plastic mechanical characteristics and the products "mechanical needs", it was allocated each recycled filament to produce each product.

Table 14 - Seven Fundamental Frugal Characteristics (Adapted from (Kuo, 2017)

1. Focusing on the fundamental needs
2. Eliminating non-essential functions of products
3. Trimming down the processes
4. Affordability
5. Functionality
6. Ease of Use
7. Sparing use of resources

Regarding the usability of the arm cast, it was not accessed to tests with real people since it was necessary to involve injured people and that requires other levels of bureaucracy. Thus, it was accessed to a research done by Fitzpatrick et al. (2017) on this printed arm cast, which tested the product and obtained some interesting feedback. The fit and the stiffness of the cast was considered excellent, however there were some concerns that proved space for improvement. The first and main concern was on the methods to closure the cast, which require a more robust and strength fixation and at the same time it needed to be thinner. Another problem was related with some restrictions in the ability to pinch and movement of the thumb. Finally, there was verified an interesting circumstance. The thumb joint diameter was not taken under consideration when modelling the product and it was not fitting well on the patient's hands. However, this problem was effectively solved by heating and soften the plastic, which allowed to modify the structure to widen the opening. This revealed the capacity to produce small modifications to the cast, which is not provided by the traditional methods (Fitzpatrick, Mohanned, Collins, & Gibson, 2017). Finally, as presented in figure 49, the 3D printed arm cast produced in this dissertation revealed a robust and clean geometry with the solid desired design. The product was tested to adapt to an arm of a children and it effectively responded to the arm adaptation desired format, as exposed in **figure 11**.

Figure 11 – Recycled PLA printed arm cast molded to a children arm

Regarding the usability of the fork and spoon support for disabled people, it was asked to a group of five users to perform three different tasks. The first task was to eat a soup with a spoon attached to the support. Thereafter, it was defined to the users eat a pasta and rice with a fork attached to the support. Finally, it was asked to users eat meat and fish with also using the fork in the support. **Table 15** presents the tasks assessed by the users and their success percentage.

Table 15 – Tasks assessed by the users

	Task description	Attached cutlery	Sucess
Task 1	Eat a soup	Spoon	100%
Task 2	Eat a pasta and rice	Fork	100%
Task 3	Eat meat and fish	Fork	100%

The feedback concerning the usability of the support given by the users was positive, with a fully successful task's performance. In general, the users described this support as comfortable robust product, with the potential to help disabled people. However, there are some aspects that need to be taken under consideration regarding this product evaluation. Firstly, unfortunately it was not possible to assess to people with hand mobility problems, which would give a more realist feedback on the product usability. Although, it was asked to the users to simulate as possible a hand mobility handicap. Secondly, the cutlery provided was of a unique size, and, given the numerous cutlery's designs and sizes, it seems important to develop an adapter to turn this support universal as possible. To conclude this overview on the support quality and usability, it is important to refer that the geometry of this support was not the most appropriate to work with PET filament as feedstock to the printer. The support presented some imperfections in the geometry due to the accentuate curvature, which could fixed by redesigning to a rectilinear shape. However, these imperfections did not influence the product usability performance and comfort. Thus, the PET filament seemed to be adequate to produce this product.

Figure 12 - 3D Printed support with recycled PET

Regarding the usability of the waterblock, it was asked to the users perform only the task of washing hands, as this is the unique purpose of this product function. This task was also performed with a fully successful rate, and, again, the feedback given by the users was truly positive. This product allowed users to wash their hands with a used plastic water bottle and, at the same time, saving water in this daily personal care task. However, there are some details, concerning the product design, that can be upgraded in this product. Firstly, it can be produced a complementing support to grab the bottle, allowing to attach a cable that makes possible to hang the bottle to any structure. Secondly, the necessity to drill a bottle lid is not interesting, since this product is directed to help people living with scarcity of resources. So, it seemed interesting to produce a bottle lid, already with this hole, making this product more functional and promoting its ease of use**. Figure 13** presents the product design, which presented an acceptable printing quality with negligible imperfections and, so, the ABS filament seemed to be adequate to produce.

Figure 13- 3D printed waterlock with recycled ABS

Figure 14 - Waterlock with the soap attached

6. Conclusions and Future Work

This work presents in several aspects a possible innovative concept. Firstly, it exposed the necessity to improve the methods and resources to response to a critical situation currently affecting our planet, the poor plastic recycling rates. Secondly, it is provided information regarding circular economy principles, 3D printing industry and technology and frugal products. These concepts can be connected, providing a convenient methodology regarding methods to recycle and reuse plastics, taking advantage of the 3D printing technology. Furthermore, it was studied recycled ABS, PET and PLA mechanical characteristics to put into practice an opportunity to explore possible applications of recycled plastic material to produce frugal products. The developed theoretical research alongside with the experimental research, provided a document that accomplished interesting objectives.

- The statement of the verified reduction of five important mechanical properties, triggered by the plastic recycled method and 3D printing technology.
- A functional interpretation of what the values of the approached mechanical properties define in terms of product mechanical performance.
- A mechanical resistance comparison between recycled ABS, PLA, two main types of plastics used in the plastic 3D printing industry, and recycled PET, one of the plastics that have the most armful impact on our ecosystems, which has recently raised the attention to explore it in the 3D printing industry.
- An analysis on the 3D printing temperature parameter, to provide information to define good setups to produce plastic 3D printed

recycled products with the most reliable quality.

- A real demonstration of possible frugal products applications, based on the concepts studied and experimental data collected, proving the functional feasibility of an entire innovative methodology, which starts from recycling plastics and ends on producing frugal products using circular economy principles and 3D printing.

To conclude this research, it is important to mention possible future work. To produce quality products, it seems important to explore other material variations, such as structure changes and the degree of contamination and traduce it into possible product applications. It also arises the possibility to combine different types of plastic to produce 3D printing filament, to understand if it is possible to take advantage of the best properties from each type of plastic, producing an even better recycled filament solution.

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