PLA Mechanical Performance Before and After 3D Printing

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***Abstract*—PLA or polylactic acid is a thermoplastic made from renewable sources. Thanks to its environmental value compared to petroleum sourced materials, it is widely used in 3D printing industry. Due to the advantages of additive manufacturing in terms of cost and time consumption, many industries are using these technologies to re-engineer parts or assemblies to optimize their products. However, the properties given by the supplier are not conforming to the final printed product. This issue can be dangerous, especially when these products are used in the biomedical fields or toys for children or other sensitive areas. The aim of this paper is to outline the difference between the final properties and the primary ones. The samples are tested in traction following the ASTM D638 Standard. The specificities of the standard in terms of specimen dimensions and test methodologies have been respected. The results demonstrated that there is a difference between the performance of the material before and after using a 3d printer.**

Keywords—Additive manufacturing; PLA; test sample; traction; 3D printing

I. INTRODUCTION

With the affordable price of 3D printers and the rise of local and industrial Fablabs (fabrication laboratory), the study of the mechanical behavior of the material becomes important. People start printing any broken object in their homes and replace it without thinking in the possible damage that it can do to the assembly. Even the industries start prototyping products to replace missing pieces using the technical data sheet of the material as reference. These technical sheets of commercial plastics are available on the internet and give the mechanical, physical and thermal properties [1]. These properties may vary depending on the supplier and the specific grade of the resin in question. They may also vary depending on the process and manufacturing parameters during the implementation of the products. For example, the morphology/structure of semi-crystalline used in 3D printing can be very sensitive to small variations in implementation parameters such as build plate temperature, temperature of the nozzle, etc. Therefore, manufacturers of products made of plastic materials are led to carry out their own mechanical tests when developing a new product to make sure it meets the design parameters. Mechanical tests are essential to determine the mechanical properties [2] of materials needed for a given application or for other reasons such as quality control or research and development.

The most common thermoplastics used in 3D printing are ABS (acrylonitrile butadiene styrene) and PLA (poly lactic acid) [3][4]. Due to its environment friendly properties [5] and its performances [6], PLA is the subject of our research.

The study targets the following objectives:

- Test in traction the targeted material PLA (polylactic acid).
- Determine the effect of movement speed on the mechanical properties in traction.
- Compare the mechanical behavior of the material before and after being processed on a 3D printing machine.

The first step was to analyze the technical data sheet of the used PLA before printing it. Then the test conditions of an ASTM Standard were followed, which resulted in the shape and dimensions of the test samples, in addition to all the details of the test machining and procedure.

The 3D printer and the test machine used in the study are adequate to the scope of the standard, thus, a specific methodology was followed to test the samples and to calculate the mechanical performance after 3D printing. Then the results were compared to the original data of the supplier.

The rest of the paper contains information about the tested material, the test methodology and the manufactured test specimens. The following section is about the results of the mechanical properties [7] before and after 3D printing. Then, a discussion is presented to analyze the results.

II. TESTED MATERIAL: PLA

PLA or Polyactid acid is thermoplastic polyester “Fig. 1” widely used in 3D printing. Thanks to the fact that it is produced from renewable resources (such as corn starch, tapioca roots or sugar cane), it is the second most used bio plastic in the world [8], even if it’s not a commodity polymer. In 3D printing it’s by far the most used plastic filament, especially for the FDM (Fused Deposition Modeling) processes [9]. The main applications are the proof of concept in architecture, games or cinema.

PLA polymers range from amorphous glassy polymer to semi-crystalline and highly crystalline polymer with a glass transition 60–65 °C, a melting temperature 130-180 °C, and a tensile modulus 2.7–16 GPa [10][11]. Heat-resistant PLA can withstand temperatures of 110 °C.[12] The basic mechanical properties of PLA are between those of polystyrene and PET.

The PLA is used in food packaging and in many objects injected, extruded or thermoformed. It is also used in surgery as the stitches are made of biodegradable polymers to decompose under water and enzymes. In addition to being one of the most used material in 3D printing, thanks to its affordability and performance.

Physical Properties

Property	Testing Method	Typical Value
Density(g/cm³ at 21.5 ℃)	ASTM D792 (ISO 1183, GB/T 1033)	1.17-1.24
Glass transition temperature(℃)	DSC, 10 ℃/min	50-60
Softening temperature of filament(for 1.75 mm; ℃)	Custom method	146-150
Melt index(g/10 min)	210 ℃, 2.16 kg	7-11
Moisture content[1](%)	Thermogravimetric	≤0.1%
Odor	/	Almost odorless
Solubility	/	Insoluble in water; soluble in chloroform, toluene, and tetrahydrofuran(THF)

Mechanical Properties[1]

Property	Testing Method	Typical Value
Young's modulus(MPa)	ASTM D638 (ISO 527, GB/T 1040)	2636±330
Tensile streght(MPa)	ASTM D638 (ISO 527, GB/T 1040)	46.6±0.9
Elongation at break(%)	ASTM D638 (ISO 527, GB/T 1040)	1.90±0.21
Bending modulus(MPa)	ASTM D790 (ISO 178, GB/T 9341)	3283±132

Fig. 1. Technical Data Sheet of the used PLA.

III. Test Conditions

A. *ASTM D638*

The official name of the standard is "D638 – 10 Standard Test Method for Tensile Properties of Plastics" "Fig. 2".

This test method covers the determination of tensile properties of reinforced and unreinforced plastics in the form of dumbbell-shaped test samples standards. These samples are tested under defined condition in terms of pretreatment, temperature, humidity and movement speed.

It is used to test materials with a thickness up to 14mm. However, for the analysis of samples in the form of thin sheets less than 1.0 mm thick, the ASTM D882 is the preferred test method. If the thickness is greater than 14mm, it must be reduced by machining.

1. Scope 2. Referenced Documents 3. Terminology 4. Significance and Use 5. Apparatus 6. Test Specimens 7. Number of Test Specimens 8. Speed of Testing 9. Conditioning 10. Procedure 11. Calculation 12. Report 13. Precision and Bias5 14. Keywords	ANNEXES (Mandatory Information) A1. TOE COMPENSATION A2. DEFINITIONS OF TERMS AND SYMBOLS RELATING TO TENSION TESTING OF PLASTICS A3. MEASUREMENT OF POISSON'S RATIO A3.1 Scope A3.2 Referenced Documents A3.3 Terminology A3.4 Significance and Use A3.5 Apparatus A3.6 Test Specimen A3.7 Number of Test Specimens A3.8 Conditioning A3.9 Procedure A3.10 Calculation A3.11 Report A3.12 Precision and Bias A3.13 Keywords SUMMARY OF CHANGES

Fig. 2. Scope and Content of the ASTM Standard.

This standard is designed to provide tensile properties of plastic material, in order to characterize it in a research and development aim.

All the samples must be made in exactly the same environment with the same printing conditions.

The testing machine must respect the following details:

- A fixed or a stationary grip.
- A Movable member with a second grip.
- Valid grips to ensure that the specimen is correctly inserted and aligned with the z axis so that no rotary motion in necessary to avoid slippage. The grips must be held clean at all time.
- A drive mechanism with a regulated speed.
- A load indicator to follow and retrieve the stress data.
- The material of the grips must be adaptable to the thermoplastic samples.
- An extension indicator to show the strain.
- A micrometer to measure the width and thickness of the specimen.

The specimens used in this standard are also normalized following these criteria:

- There are five types of dumbbell shaped specimens. The shape and the dimensions are determined for a specific material with a specific thickness range. It also depends on how does the material break. For example, if it's in the narrow section a specific type is advised.
- The standard has different dimension criteria for rigid plastics, non-rigid ones and reinforced composites.
- The standard also gives preparation methods, depending on the process [13] used to manufacture the specimen.
- The gage marks on the specimen must be done in a way that does not affect the material behavior.

The number of test specimens is five for each sample for isotropic materials.

The speed of testing depends on the type of material; a table is given by the standard to choose within a range.

The test procedure is also detailed in the standard, starting with the measures of width and thickness of the specimen before testing it. This procedure also depends on the machining used to manufacture the test, and the shape and dimensions of the specimen.

All specimens must be held by the grips in the same way and shall be tightened firmly, but without crushing the sample. Then, the record of the load-extension curve must be done with a specific extension indicator.

The calculation takes into account the toe compensation that occur in the beginning of the test, then the calculation method is specified in the norm to determine the adequate data.

B. Test Machine

The universal tensile test machine (DELTALAB EM 550) “Fig. 3” used in this study is shown below. It has a load cell capacity of 50kN. It submits test samples to efforts and measures the deformation in order to establish constitutive laws of the sample’s material. The machine is designed to be used in many materials and structural testing applications. It performs tensile test, compression, bending, fatigue, creep, hardness, friction as well as tests on assemblies and structures.

The machine is connected to a control part consisting of a computer, a printer, DELTALAB software and a software / machine interface to control, acquire and process data.

General characteristics

- Maximum force on the cross member: 50 kN.
- Maximum stroke: 1 m.
- Drive: Direct current servomotor with tachometric generator.
- Transmission: Wheel and worm gear reducer, pulleys, toothed belt and ball screw.
- Displacement measurement: Optoelectronic encoder for resolution 500 positions per revolution.
- Force measurement: Sensor with deformation gauges.
- Power supply: 240 V single phase / 50 Hz at 1 kW max.
- Maximum servomotor torque: 3 N.m.
- Load range: 0 to 50 kN in tension and compression.
- Height under cross member: 1000 mm.
- Distance between columns: 400 mm.
- Travel speed of the cross member: 0.5 mm / min at 350 mm / mn.
- Drive device by 2 screws with double row of balls.
- Resolution of the displacement measurement sensor: 0.01 mm.
- Resolution of the force sensor of 50 kN: 25 N.
- Display of force and displacement on screen DC electric motor with tacho generator.

Fig. 3. Test Machine DELTALAB Serie EM550.

C. Test Samples

For our study, the ASTM D638 standard for tensile testing of plastics is used. Here is the geometry “Fig. 4” determined from the standard:

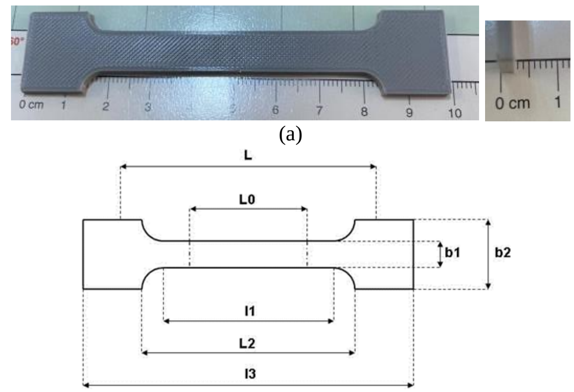

Fig. 4. Test Sample from the ASTM Standard: a-Printed Sample b-ASTM Standard.

Among the samples geometries proposed by the ASTM D638, the dumbbell shaped geometry shown above was chosen. To facilitate the results analysis, the necessary dimensions were listed for the requested calculations “Table I”. These dimensions are necessary to transform the load into stress. The effective length is the length which is assumed to take the entire measured displacement. Thus, in dividing the displacement on this length, the strain can be estimated and consequently, the data displacement (mm) – load (Newtons) can be transformed into strain (%) – stress (MPa).

The sample has been designed using SOLIDWORKS 2018, following the ASTM D638 dimensions.

The process parameters “Fig. 5” have been set using Ultimaker Cura, with an infill pattern of 100% to respect the volume of a sample made by injection molding.

TABLE I. TEST SAMPLE DIMENSIONS FROM THE ASTM STANDARD

Dimension	Symbol	Value[mm]
Thickness	T	3
Width in the reference length area	b1	10±0.5
Length of the narrow calibrated part	l1	60 ± 0.5
Width in the shoulder area	b2	20±0.5
Reference length	L0	50±0.25
Distance between tools	L	115±5

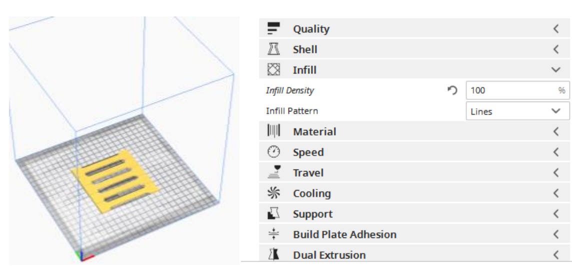

Fig. 5. 3D Printing Parameters.

D. 3D Printer

The 3D printer used "Fig. 6" to manufacture the samples in the ENDER-3.

Fig. 6. 3D Printing Machine ENDER-3.

The chosen printer is one of the best fused deposition modeling with a low price range, thanks to its performance and polyvalence. Its functionalities are comparable with high cost printers. The print volume is 220*220*250mm, with a heated build plate, a pick-up detector and a tight filament path that facilitates printing of flexible filaments.

The Ender-3 is an open-source printer is commonly used in local fabrication laboratories to manufacture small parts or to learn about robotics and mechanics. This technology is mature and stable, which allow a 200 hour work flow. In addition, it allows completing a print after a power outage for example, with thermal runaway protection. Thanks to this stability and a high precision pulley, this printer affords more resistance and lower noise. With an extrusion mechanism MK8, it reduces the clogging risk and it can print almost any filament in the market. The rails made with CNCs provide precise positioning and a solid frame to ensure a good quality and a high printing precision. The build plate can reach 110°C in 5 minutes.

This is the technical specifications of the printer:

- Modeling Technology: FDM (Fused Deposition Modeling).
- Printing Size: 220x220x250mm.
- Printing Speed: 180mm/s.
- Filament: 1.75mm PLA, TPU, ABS.
- Working Mode: Online or SD offline.
- File Format: STL,OBJ,G-code.
- Machine Size: 440x440x465mm.
- Net Weight: 8KG.
- Power Supply: 100-265V 50-60HZ.
- Output: 24V 15A 270W.
- Layer Thickness: 0.1-0.4mm.
- Nozzle Diameter: 0.4mm.
- Printing Accuracy: ±0.1mm.
- Nozzle Temperature: 255°C.
- Hotbed Temperature: 110°C.

IV. Methodology

A. Test Method

Here are the followed steps to test the sample "Fig. 7", according to the ASTM standard:

- Measure the width and thickness of each sample at 0.025 mm near.
- Place the sample in the handles of the test machine.
- Tighten the handles evenly as necessary to prevent the sample from slipping during the test.
- Adjust the test speed.
- Perform the test and record the results.

Five tests were carried out for two different speeds, which give us a total of 10 test specimens tested.

Fig. 7. Tested Samples after Traction.

B. Calculation Method

The calculation method used is simple and systematic. First of all, the raw data of the results were analyzed and then converted it into more practical units in terms of stress and strain.

Due to the initial clearance in the assembly, the first portion of the graph curve before the linear domain must be discarded since it is not representative of displacement as a function of force. Indeed, this small part of the curve very often represents the movement of the sample in the jaws of the universal traction machine. Thus, to normalize the curves, the linear domain is extended up to the intersection with the abscissa and the graph is shifted to obtain the point of intersection of the extension with the x axis at the origin.

In this case, in order to find the yield point, only the point where the applied force is maximum is determined. Then a conversion to MPa is necessary to obtain the yield point.

There are two types of conversions required, converting force to stress and converting displacement to strain.

Force (kN) to Stress (MPa)

$$\sigma(\mathrm{MPa}) = \frac{\mathrm{Force\ (N)}}{\mathrm{Surface\ (mm^2)}} \tag{1}$$

Surface = Ti Wi

"Ti" represents the thickness and "Wi" the width of the specified sample "i".

Once the coordinate of the first maximum stress found, the associated displacement in mm are found and transformed it into strain.

$$\varepsilon(\%) = \frac{\text{Displacement (mm)}}{\text{length (mm)}} \quad (2)$$

V. Results

A. *Data*

After realizing the ten tensile tests for the two travel speeds, the calculations explained above were carried out and the obtained curves and the results are shown in the following tables and graphs: "Fig. 8", "Table II", "Fig. 9", and "Table III".

B. *Speed Test Effect*

The bibliographical analysis shows that the stress rate modifies the mechanical properties [14][15] of the material tested. Young's modulus and elastic limit increase with increasing stress speed. The deformation of the material at the elastic limit is lower. However, the resistance to flow is higher with increasing speed.

This is explained by the fact that when the speed is higher, the material spends less time to deform elastically and therefore begins its plastic deformation more quickly. As the speed is faster, there is less time for the polymer chains to move through the material under tension. On the other hand, the mechanical properties [16][17] at the yield point are increased, in particular since a greater load can be applied due to the resistance which is stronger.

However, the results obtained in our case are almost identical between the speed of 50 mm / min and 25 mm / min. This is explained by the difference between these speeds which is not very large. In the research cited [18], the ratio between the speeds is 1/10 while in our case the ratio is ½.

C. *Mechanical Properties*

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The table "Table IV" shows the comparison of the data provided by the supplier and the data found experimentally.

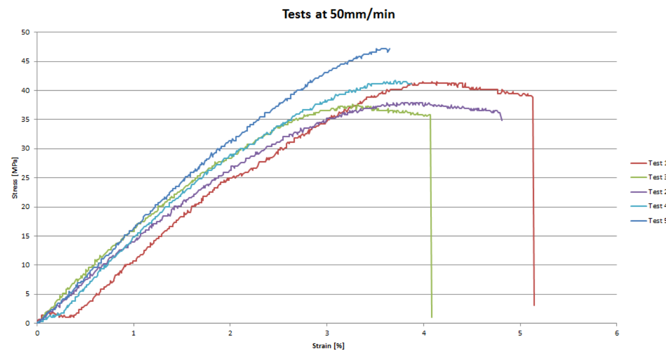

Fig. 8. Stress / Strain Graph for the 5 Tests at 50mm/min.

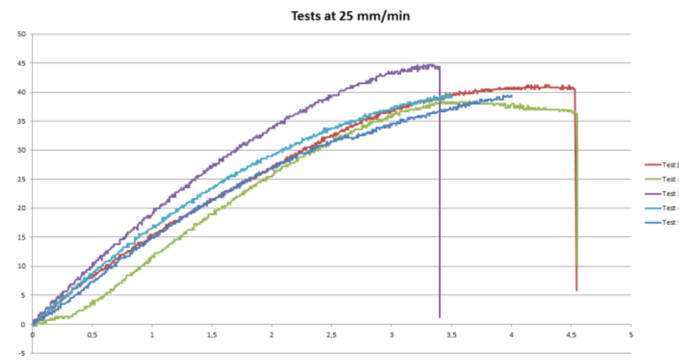

Fig. 9. Stress / Strain Graph for the 5 Tests at 25mm/min.

TABLE II. Results of the 5 Tests at 50 mm/min

Measured properties	Symbol	Unit	Test1	Test2	Test3	Test4	Test5	Average	SV	CV
Thickness	T	mm	2,86	2,9	2,92	2,88	2,88	2,888	0,023	0,008
Length	L	mm	60,45	59,7	59,7	60,45	59,8	60,02	0,395	0,007
Width	W	mm	10,095	10,095	10,02	10,05	10,07	10,07	0,032	0,003
Surface	S	mm²	28,872	29,276	29,258	28,94	29	29,07	0,185	0,006
Load at yield point	Py	N	1190	1110	1100	1210	1370	1196	108,5	0,09
Load at elastic limit	Pe	N	1180	1010	1070	1170	1290	1144	108,1	0,094
Travel to Py	dy	mm	2,61	2,42	1,98	2,24	2,1	2,27	0,251	0,111
Displacement to Pe	de	mm	2,32	1,78	1,76	2	1,88	1,95	0,229	0,117
Elastic modulus in tension	E	MPa	1147,3	1277,3	1394,7	1344	1455	1324	118,3	0,089
Resistance to yield point	sy	MPa	41,21	37,9	37,6	41,8	47,2	41,14	3,88	0,094
Elastic limit	se	MPa	40,87	34,S	36,6	40,4	44,S	39,37	3,91	0,099
Strain at yield point	ey	%	4,33	4,054	3,317	3,706	3,512	3,78	0,41	0,108
Strain at the elastic limit	ee	%	3,83	2,982	2,948	3,309	3,144	3,24	0,36	0,111

TABLE III. RESULTS OF THE 5 TESTS AT 25 MM/MIN

Measured properties	Symbol	Unit	Test1	Test2	Test3	Test4	Test5	Average	SV	CV
Thickness	T	mm	2,89	2,925	2,4	2,845	2,857	2,78	0,21	0,078
Length	L	mm	60,3	59,951	60,251	60,841	60,24	60,30	0,32	0,005
Width	W	mm	10,1	10,078	10,245	10,095	10,11	10,12	0,06	0,007
Surface	S	mm²	29,2	29,478	24,588	28,72	28,90	28,16	2,02	0,072
Load at yield point	Py	N	1200	1130	1100	1130	1140	1140	36,74	0,032
Load at elastic limit	Pe	N	1160	1120	1030	1080	1010	1080	62,04	0,057
Travel to Py	dy	mm	2,49	2,22	2,02	2,12	2,41	2,25	0,19	0,087
Displacement to Pe	de	mm	2,19	2,01	1,73	1,86	1,88	1,93	0,17	0,09
Elastic modulus in tension	E	MPa	1257	1223	1543	1317,4	1271,9	1322,4	127,9	0,097
Resistance to yield point	sy	MPa	41,2	38,333	44,752	39,345	39,43	40,60	2,53	0,062
Elastic limit	se	MPa	39,8	37,994	41,904	37,604	34,93	38,44	2,59	0,068
Strain at yield point	ey	%	4,13	3,703	3,3526	3,4845	4,00	3,73	0,33	0,089
Strain at the elastic limit	ee	%	3,63	3,3527	2,8713	3,0571	3,12	3,20	0,29	0,092

The first observation is that the young modulus of the tested specimens is 50% compared to that given by the supplier.

As regards the tensile strength, it is 12.3% lower for the test specimens tested.

As for the deformation at break, it is greater for the material tested by 200% compared to the supplier's data.

D. Synthesis

From the results detailed in the previous section, it is shown that the mechanical properties of the test specimens are completely different from those given by the supplier. The mechanical strength of 3D printed specimens is significantly lower than that of the material before it is printed (50% lower Young's modulus, 12% lower tensile strength, and 200% higher strain).

This difference is explained by the micrographic structure “Fig. 10” of the material after printing. Indeed, despite entering 100% infill in the printer management software, this rate is not achievable with this type of process. In Fig. 10, the micrographic structure of a sectional view of a 3D printed test specimen is shown. This structure clearly shows voids between the printed filaments. This implies two changes in mechanical performance.

The first is that the strain is greater because the cracks propagate less quickly inside the specimen. This is because the crack stops when it encounters a void, so the specimen continues to deform until a new crack appears which in turn stops etc.

The second change is in the mechanical resistance which is significantly lower. Indeed, because of the voids, the density of the material is less important, which implies a lower resistance compared to a solid specimen made by injection molding.

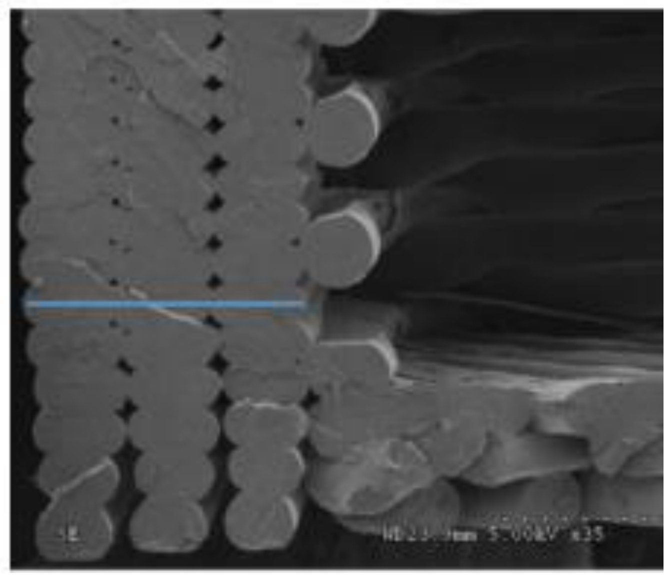

Fig. 10. Scanning Electron Micrograph of the 3D Printed Samples Perimeters [19].

TABLE IV. PROPERTIES COMPARISON BETWEEN THE TECHNICAL DATASHEET AND THE TESTED PLA

Property	PLA datasheet	Tested PLA
Young’s modulus (MPa)	2636 ± 330	1323±123
Tensile strength (MPa)	46.6±0.9	40.87±3.2
Elongation at break (%)	1.9±0.21	3.75±0.37

VI. CONCLUSION

PLA is the most used material in 3D printing, especially for the fused deposition modeling process, which is the most used process because it is the cheapest and easiest process to use. Knowledge of the mechanical properties of parts printed in PLA is very important, as these parts are increasingly used in proof of concept for important applications, especially in the biomedical field, such as implants etc.

This study allowed to test in traction specimens designed in PLA with a 3D printer, all while following the details of ASTM D638 [20]. Then w a comparison between the results obtained and the data provided by the supplier was detailed. The results have shown that there is a huge lag in the mechanical performance of the specimen before and after printing. This information is very important because most researchers use the data provided by the material supplier to justify the strength of manufactured parts. This can be dangerous especially for applications in the biomedical or industrial field.

This study therefore allowed outlining the importance of testing parts after manufacture to ensure their mechanical properties. That said, other studies can be carried out to enrich the latter. In particular by using different types of filling to find which type provides better resistance. Studies can also be carried out on other manufacturing parameters such as printing direction to study the influence of each parameter.

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