Investigating the Mechanical Properties of 3D Printed Components

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***Abstract*— Additive manufacturing (AM) has acquired an increasing interest from industrial, academic, and research fields in the last few decades. One of the AM techniques that is overgrowing and gripping more attention is Fused Deposition Modeling (FDM). 3D printed parts with FDM are being considered in replacing traditionally manufactured parts made with traditional materials. Hence, comes the need for understanding the mechanical behavior of printed parts to evaluate its eligibility for any given application. However, knowledge established is lacking information about 3D printing materials mechanical properties. From here comes the aim of this paper, which is to investigate the compression properties of PLA 3D printed samples. Furthermore, to examine the consistency of mechanical behavior over duplicated 3D printed samples. Specimens would be 3D printed by the FDM technique under the same 3D print conditions to minimize and -or if possible- eliminate the impact of unwanted factors on compressive properties of the material.**

Keywords—mechanical properties, 3D printed parts, fused deposition modeling

I. INTRODUCTION

The revolution of the additive manufacturing technology has changed the world in many directions due to its remarkable benefits to the industrial sector that has a significant impact as well on the sectors [1,2]. Moreover, this revolution has been extended to other applications, like in prototyping, simulations, and failure mechanism [3,4], whereas the aerospace sector is one of the promising sectors due to the vast and numerous applications that could be adopted of using 3D printing technology [5]. However, the 3D printing technology started being embraced in schools [6] for the learning purposes [7], as well as implemented in different university levels [8].

In this work, we investigated the impact of different printing parameters on the mechanical properties of the final produced parts, since many factors affect the performance of the printed parts eventually, which would affect positively or negatively on the functionality and even the safety of the product. This section is divided into five subsections that describe in detail the fused deposition modeling in A, the mechanical properties and the related parameters that affect the printing process in B, the compressive test procedure, and standardization in C, whereas D and E cover the mechanical properties of the material.

A. Fused Deposition Modeling

There are several techniques of additive manufacturing that are based on different printing processes. One method is Fused deposition modeling (FDM) or Fused Filament Fabrication (FFF) which is based on filament extrusion. In general, the FDM process can be described as follows: first, the STL file is created from the 3D CAD model, then G-code generated in a slicer software [9]. The functioning process of FDM printing starts with heating the liquefier to the desired temperature to melt the thermoplastic filament [10]. After heating up the filament, it is extruded continuously through the nozzle onto the printer's build platform [10]. By gradual layer-by-layer deposition, the full sample is produced. The process illustrated in Fig. 1.

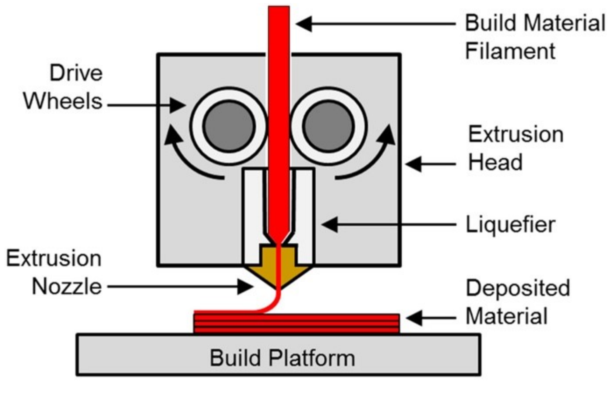

Fig. 1. Schematic illustration of FDM printing process [11].

B. Mechanical Properties and Print Parameters

As the replacement of traditionally manufactured parts by 3D printed parts is taken into consideration, it becomes essential to study the mechanical properties of the 3D printed parts. Mechanical property tests provide such information about material properties (e.g., tensile strength, compressive strength). However, it is not easy to define these mechanical properties for fused deposition modeled parts because of several reasons. The main problem is that the printed samples of mechanical properties are anisotropic [10].

Moreover, they depend on print parameters knowing that there is a large number of print parameters (e.g., material, infill pattern, layer resolution, print speed, ...), which makes it difficult to analyze [12]. Some print parameters can play a critical role in determining the mechanical behavior of the printed samples [13]. These parameters, like material type, infill pattern, and infill density. Materials, such as PLA and ABS, for example, have different tensile strengths with typical values of 37 MPa and 27 MPa, respectively [14]. Different Infill patterns affect the strength of the printed model as well as the weight of the model [15], [16]. For example, a gyroid infill pattern provides the model with higher strength than a triangular infill pattern [15]. Besides, some infill patterns require less print time to finish the model than others.

Infill density is the ratio of the material's mass to the volume inside the printed object. A higher ratio means a stiffer produced object, but a higher cost as expected. Fig. 2 represents different types of 3D printing infill patterns and varying percentages of infill density.

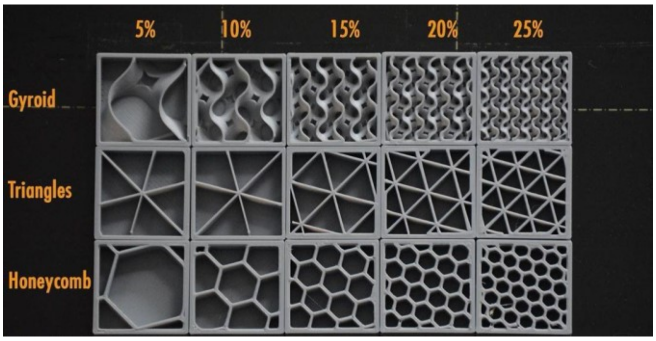

Fig. 2 Different infill patterns and densities [17].

C. PLA 3D Printing Material and Compression Testing

One of the most used thermoplastic materials in FDM is PLA because of its advantages over other thermoplastic 3D printing materials [20]. It is essential to examine its mechanical behavior to evaluate its capability of replacing traditional materials. Several studies focused on PLA mechanical property testing. Most of them determined tensile strength by conducting tensile testing in accordance with ASTM D638-14 Standard Test Method for determining Tensile Properties of Plastics [24], [25].

Moreover, they studied the effect of layer thickness, infill pattern and density, raster orientation and other variable parameters on tensile strength, flexural strength, impact strength, and elastic modulus. However, the compressive properties of PLA are not enough investigated like other mechanical properties. Compressive testing is considered one of the testing methods that provide with vital information about materials' compressive properties. This would help to estimate whether the material is suited for the nominated applications or is going to fail under the applied load. It allows us to observe the material's reaction when being compressed. Furthermore, compression tests are used to measure several mechanical properties and help to determine others like elastic modulus and compressive strength [21]. Many standards are used for carrying out compression tests on polymer additive manufactured parts, one of them is ASTM D695-Standard test method for estimating compressive properties of rigid plastics [18], and the other one is ISO 604 Plastics, for determining of the compressive properties [22].

D. Toughness

Toughness or impact strength of a plastic is defined as the material's ability to resist deformation. It can also be defined as the amount of energy absorbed by the material when stressed [19]. Izod and Charpy impact tests are ASTM standard methods to measure toughness [26], [27]. They are based on the principle of determining the amount of energy absorbed by a material during fracture. A way to determine the toughness of the material without measuring it directly through tests is by taking the integration of the stress vs. strain curve of the particular material, which is the area under the curve. Relate to Fig. 3.

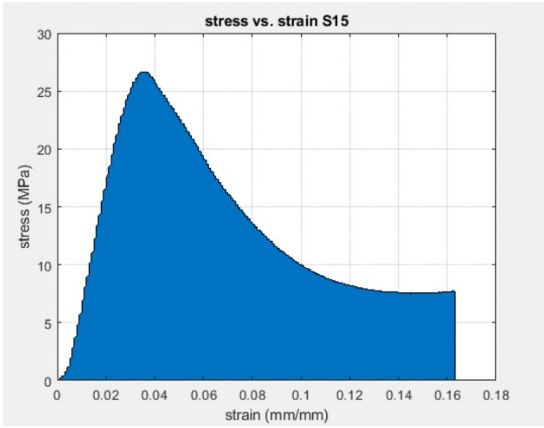

Fig. 3. Relating toughness to Stress vs. Strain curve. Toughness is the blue shaded area under the curve.

E. Specific Strength

The specific strength of a material is defined as the ratio of the material's strength to its density. Higher specific strength means that the material has higher strength and lighter weight [28]. Fig. 4. represents a diagram showing the specific strength for some materials. It shows that polymers' specific strengths range between 7-70 kNm/kg approximately.

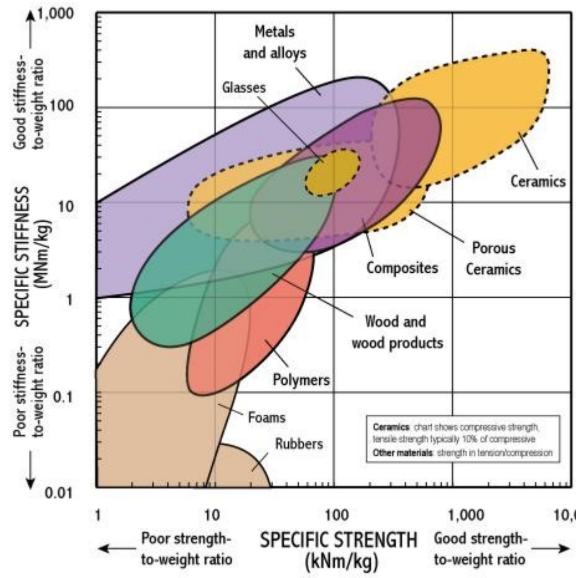

Fig. 4. Specific stiffness-specific strength diagram for various materials [29].

II. PRINTING SPECIFICATIONS AND CONDITIONS

The printer used to print the test specimens was Ultimaker 2 Extended+ printer, which works by FFF technology. Test specimens were designed in a cuboidal shape with dimensions of 20mm in length and width, 40mm in height using Catia software. Then, they were sliced in Ultimaker Cura software. The used print parameters are stated in TABLE I. The printer has a maximum build volume of 223 × 223 × 305 mm. It has a heating bed, glass build platform with a temperature range 20 - 100 °C. The material used for printing specimens was PLA thermoplastic filament with a diameter of 2.85mm. Mechanical properties with test methods of PLA 3D printed test specimens as Ultimaker supplier stated in the technical data sheet of PLA are stated in TABLE II. A top view image showing the triangular infill pattern was taken during the printing process and is shown in Fig. 5.

TABLE I. PRINT PARAMETERS FOR COMPRESSION TEST SPECIMENS

PARAMETER	VALUE
Material	PLA (Polylactic acid)
Infill pattern	Triangular
Filament diameter	2.85 mm
Layer resolution	150 microns
Print head travel speed	30 mm/s
Build speed	< 8 mm^3/s
Nozzle diameter	0.25 mm
Nozzle temperature	180 °C

TABLE II. MECHANICAL PROPERTIES OF PLA TEST SPECIMENS AS STATED FROM THE SUPPLIER [23]

PROPERTY	VALUE	TEST METHOD
Tensile modulus	2,346.5 MPa	ISO 527 (1 mm/min)
Tensile stress at yield	49.5 MPa	ISO 527 (50 mm/min)
Tensile stress at break	45.6 MPa	ISO 527 (50 mm/min)
Elongation at yield	3.3%	ISO 527 (50 mm/min)
Elongation at break	5.2%	ISO 527 (50 mm/min)
Flexural strength	103 MPa	ISO 178
Flexural modulus	3,150 MPa	ISO 178

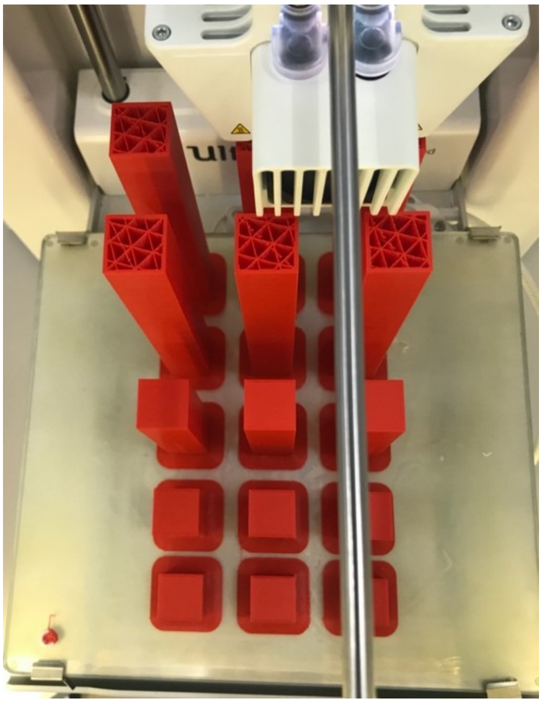

Fig. 5. Top view of test specimens while being 3D printed.

III. COMPRESSION TESTING

Compression tests were performed to determine material's behavior of printed samples while subjected to compressive loads by measuring fundamental variables like stress and strain. They were conducted in accordance with ASTM D695 – 15 Standard Test Method for Compressive Properties of Rigid Plastics [18]. Fig. 6. shows an image of one sample while being tested. Fig. 7. shows images of the three specimens before and after the compression tests. The machine used for the test was MTS compression test machine. The specimens were tested under a test speed of 1.30mm/min. During the test, the applied force was recorded with a load sensor. Elongation at peak data was collected, which was used in later discussed calculations. Modulus of Elasticity was recorded as well. Load-Extension diagrams were obtained from the test.

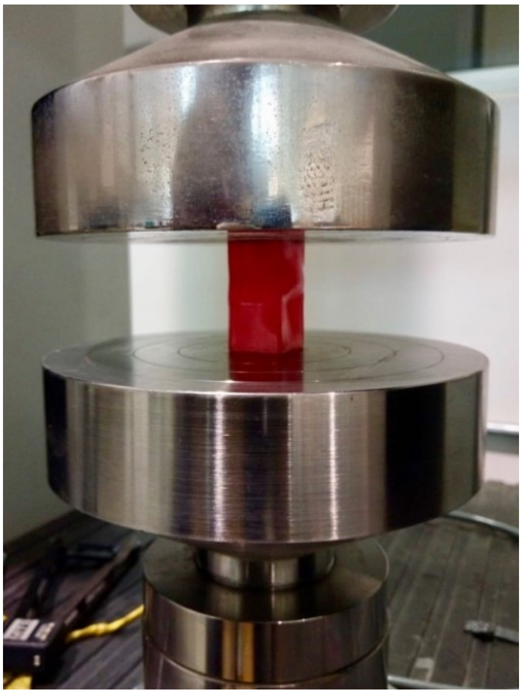

Fig. 6. Compression testing of one sample.

Fig. 7. Samples before and after compression testing.

IV. RESULTS AND DISCUSSION

Before compression testing, masses of the three specimens were measured by Mettler PE1600 analytical balance and determined to have an average mass of 8.1 grams with a sample standard deviation of 0.11. The density of each specimen was calculated using measured mass and theoretical volume of the cuboids. The average density is 0.000506 g/mm^3 while the sample standard deviation is 7×10^{-6}. Mass and density values for each specimen are depicted in TABLE III.

TABLE III. MASS AND DENSITY OF EACH SPECIMEN

Specimen #	Mass (g)	Volume (mm^3)	Density (g/mm^3)
1	7.99	20 × 20 × 40	0.000499
2	8.1	20 × 20 × 40	0.000506
3	8.2	20 × 20 × 40	0.000513

Compression tests were performed for the three test specimens. In this experiment, the change in length due to applied load onto each specimen was plotted and is illustrated by the Load vs. Extension graph in Fig. 8. It shows that cuboid no. 3 sustained the higher value of maximum applied load than the rest two cuboids.

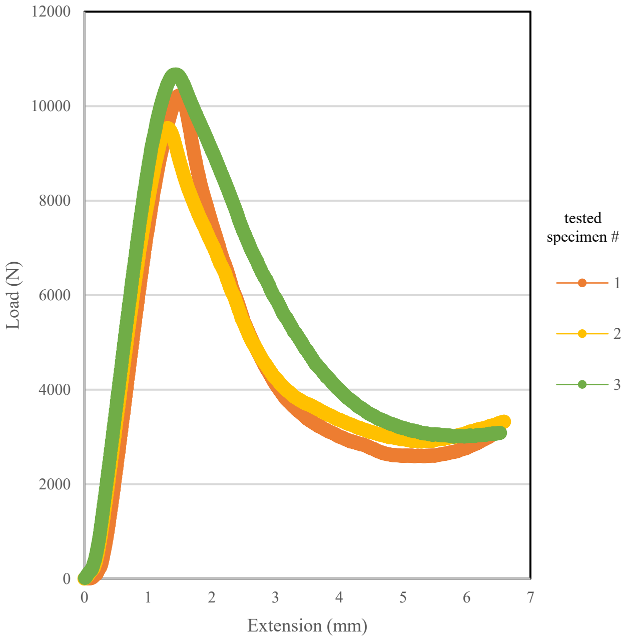

Fig. 8. Load vs. Extension diagram obtained from compression tests.

Other collected and calculated data are summarized in TABLE IV. Recorded change in length was used to calculate peak strain by dividing it over the theoretical height 40 mm of each specimen. The average elastic modulus is 1066.1 MPa and the average peak stress is 25.4 MPa, while the average peak strain is 0.0352. The sample standard deviation for modulus, stress, and strain are 24.5, 1.46 and 0.0024 respectively.

TABLE IV. ELASTIC MODULUS, PEAK STRESS AND PEAK STRAIN OF EACH SPECIMEN

Specimen #	Modulus (MPa)	Peak Stress (MPa)	Peak Strain
1	1074.6	25.6	0.0374
2	1038.4	23.8	0.0325
3	1085.2	26.7	0.0356

The data collected from the test allowed us to calculate the toughness of the printed samples. It was estimated by evaluating the area under stress vs. strain curve and was determined to have an average value of 1.8985 MPa with sample standard deviation of 0.21066. The toughness of each specimen is stated in TABLE V. Stress vs. strain for specimen #1, #2 and #3 graphs are illustrated in Fig. 9., 10. and 11. respectively.

TABLE V. TOUGHNESS OF EACH SPECIMEN

Specimen #	Toughness (MPa)
1	1.7356
2	1.8235
3	2.1364

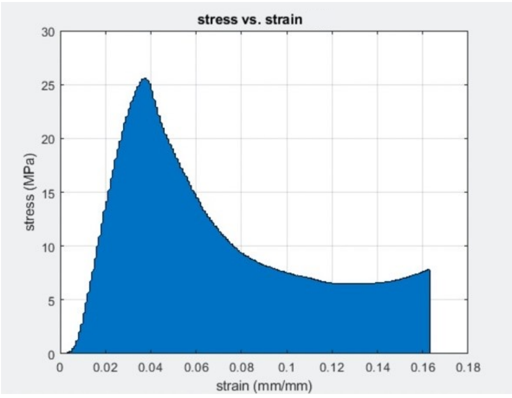

Fig. 9. Stress-strain curve for specimen 1.

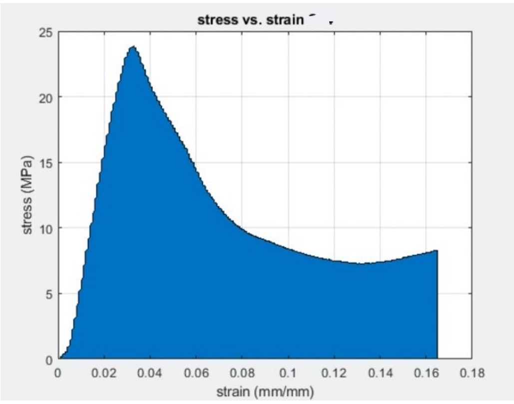

Fig. 10. Stress-strain curve for specimen 2.

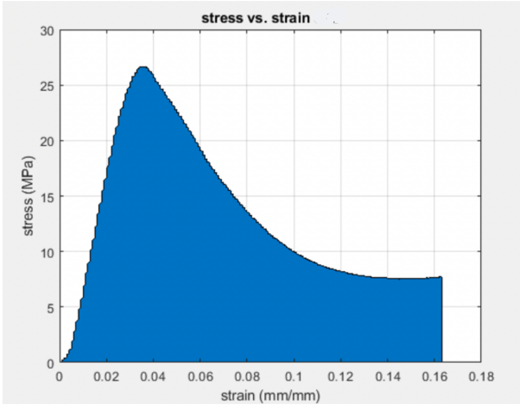

Fig. 11. Stress-strain curve for specimen 3.

MATLAB code was used to plot the stress vs. strain graph in order to calculate the area underneath it which gives the value of the toughness [31]. Stress and strain data collected during the test were imported to MATLAB first, then they were plotted. After that, the area was calculated. The code used in MATLAB to plot the graph and calculate the area for one sample is shown in Fig. 12.

```
clear all;
close all;
clc;

A=dlmread('15.txt');
x=A(:,5);
y=A(:,4);

z=trapz(x,y)
area(y)
area(x,y)

grid on


title 'stress vs. strain S15'

ylabel("stress (MPa)")
xlabel("strain (mm/mm)")

```

Fig. 12. MATLAB input

Toughness and density values were used then to find Specific strength or strength-to-weight ratio of printed parts. The average specific strength is 3748.81 MPa mm^3/g with a sample standard deviation of 365.45. As shown in TABLE VI. Specimen no. 3 has the highest strength-to-weight ratio.

TABLE VI. SPECIFIC STRENGTH FOR EACH SPECIMEN

Specimen #	Specific strength (MPa mm^3/g)
1	3478.16

2	3603.75
3	4164.52

Young’s modulus, peak stress, peak strain, and toughness of PLA material were obtained experimentally by compression tests on three identical fused filament fabricated parts. Experimental values of young’s modulus, ultimate stress, and ultimate strain are 1066 MPa, 25.4 MPa, and 3.5%, respectively. Typical values of young’s modulus, ultimate stress and ultimate strain for PLA are 1280 MPa, 21 MPa and 2.5% respectively [30]. By comparing experimental values obtained in this study to typical values, young’s modulus typical value is higher than the experimental value. In contrast, experimental values of maximum stress and strain are higher than typical values.

V. CONCLUSION

FDM parts or 3D printed parts are being considered in replacing traditionally manufactured parts. Hence, studying 3D printing materials’ mechanical properties is essential. They should match or at least be similar to the mechanical properties of replaced materials. From this point, this study was conducted. The paper presented experimental results about elastic modulus, compressive yield point, compressive yield strength, and compressive strength of 3D printed samples with PLA. Material’s response and behavior were determined by conducting the compression tests. The results obtained provide some information and add to the existing knowledge in the field of mechanical properties of fused deposition modeled parts, which is not enough explored yet.

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