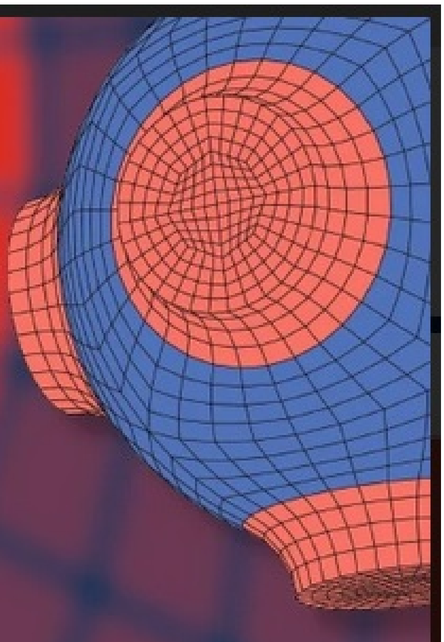
Advanced Structured Materials



Lucas F. M. da Silva *Editor*

Materials Design and Applications IV

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About This Book

This volume of *Advanced Structured Materials* contains selected papers presented at the 4th International Conference on Materials Design and Applications 2022 (MDA 2022), held in Porto, Portugal, during July 7–8, 2022. The goal of the conference was to provide a unique opportunity to exchange information, present the latest results as well as to discuss issues relevant to materials design and applications. The focus is on fundamental research and application areas in the field of the design and application of engineering materials, predominantly within the context of mechanical engineering applications. This includes a wide range of materials engineering and technology, including metals, e.g., lightweight metallic materials, polymers, composites, and ceramics. Advanced applications include manufacturing of new materials, testing methods, multi-scale experimental and computational aspects. Approximately, 110 papers were presented by researchers from nearly 25 countries.

In order to disseminate the work presented in MDA 2022, selected papers were prepared which resulted in the present volume dedicated to *Materials Design and Applications IV*. A wide range of topics are covered resulting in 11 papers dealing with metals, composites, additive manufacturing, design, forming, and joining. The book is a state of the art of materials design and applications and also serves as a reference volume for researchers and graduate students working with advanced materials.

The organizer and editor wish to thank all the authors for their participation and cooperation, which made this volume possible. Finally, I would like to thank the team of Springer-Verlag, especially Dr. Christoph Baumann, for the excellent cooperation during the preparation of this volume.

August 2022 Lucas F. M. da Silva

Contents

Mechanical and physical characterization of parts manufactured by 3D printing

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Abstract. Fused deposition modelling is an additive manufacturing technique, classified as one of the most popular 3D manufacturing processes, because of its low cost and easy usability, resulting in good quality products. However, the mechanical properties of manufactured pieces depend on the base material properties, manufacturing parameters and room conditions (temperature and moisture). For those reasons, to obtain the optimal conditions, three different types of experimental tests were performed: tensile, flexural and water absorption. These tests were carried out to determine ABS and PLA's mechanical and physical properties, which are the main materials used in FDM technique. Results showed that PLA has higher values of tensile and flexural strength comparatively to ABS and in the other hand, ABS had greater weight of water absorption.

Keywords: ABS, PLA, 3D printing, FDM, tensile test, flexural test, water absorption

1 Introduction

Additive Manufacturing (AM), also known as 3D printing, has been attracting interest from industry and the research community [1] nowadays, not cheaper and faster AM techniques have been established, which can manufacture high print qualities. In addition, polymer materials for 3D printing are currently being produced with a wider range of properties [2]. Today, AM is being used to produce materials for different applications, namely, automotive [3] electronics [4] robots [3], construction [5], apparel [6], medicine [7], dentistry [8] aerospace [9], military [10], and others. However, in these practical applications, the parts manufactured by 3D-printing processes must withstand different quantities of mechanical stress imposed by the environment. Therefore, it's crucial to know the imposed strengths in each application, considering various loading conditions. Furthermore, the mechanical properties of the 3D-printed parts must be equal to those manufactured by traditional methods, such as injection molding [11,12].

Additive manufacturing processes are classified in seven categories: powder bed fusion, binder jetting, material jetting, directed energy deposition, vat photo polymerization, sheet lamination and material extrusion [12 Among these, one of the most popular is the defused deposition modelling (FDM) technique [13] and it is based on extrusion additive manufacturing systems. FDM is a material-melting method which utilizes a coil of thermoplastic filament such as PC, ABS and PLA with different diameters, that are melted and extruded through a heated nozzle [14]. Even though, the referred materials are the most used in recent years, thermoplastic materials, like PEEK, with higher melting points have appeared [15]. Because of this singular mechanism of FDM, the use of thermoplastics and its process of material-melting are its major limitations. So, it is essential to determine the mechanical properties [16] of the materials used in FDM process, mainly the ABS and PLA because they are the most employed. In addition, the resolution and the accuracy of the FDM process are also considered limitations, which must be evaluated and optimized [17].

The aim of this work is to define reference values for each pair of material printed, to enable the designer to make a pre-selection when starting the production of the parts. To achieve this, tests will be performed to obtain the mechanical and physical properties, such as tensile strength, bending strength and water absorption of specimens manufactured by FDM printers using ABS and PLA. The experimental values obtained will be compared with values from literature.

2 Experimental Procedure

The polymeric materials chosen to work on this project were ABS and PLA. Before the tensile test, the specimens were conditioned according to ASTM D618 – 13, in order to standardize the humidity and temperature conditions in which the models were subjected before the tensile test. Tensile tests were performed in accordance with ASTM D638 – 14 named "Standard Test Method for Tensile Properties of Plastic". The standard used for Flexion Test met the ASTM D790 – 17, "Standard Test Methods for Flexural Properties of Unreinforced and Rein-forced Plastics and Electrical Insulating Materials". To determine the water absorption, the procedure described in ASTM D570 - 98 (2018) was followed.

The printers used were the Big Builder Dual Feed printer, the Cube printer, and the Robox® Dual printer.

From the results of the tensile, bending and water absorption tests, values were obtained for the strength of the materials used. The percentage of water absorbed by them was also obtained. Furthermore, from the results, a brief characterization of these materials was obtained, in which they could be used to assist a designer in the adequate choice of materials for different applications.

Based on the results, it was concluded that the parts made by the FDM process using ABS and PLA are highly anisotropic, a consequence from the variation of the layers' orientation, of the extrusion temperature and the percentage of infilling, which affects mechanical strength, dimensions and geometry.

2.1 Tensile test

In agreement with the ASTM D883 [18] standard, was chosen to manufacture the V type specimens [19,20] making rigid or semi-rigid plastic with thicknesses up to 4 mm.

Five models were produced, with geometry dimensions in accordance to the standard for ABS and another five for PLA+.

In order to manufacture ABS models, the stl file was sent to the Robox® Dual printer AutoMaker® software. Parameters used to 3D print ABS [21] and PLA+ [22] specimens are shown in Table 1.

Table 1. Mean masses, standard deviation, and variation coefficient.

Parameters	ABS	PLA+
Infill	100 %	100 %
Color	Orange	Black
Layer thickness	0.3 mm	0.2 mm
Extruder temperature	235 °C	215 °C
Room temperature	55 °C	~20 °C
Build base temperature	115 °C	~20 °C
Raster angle	+45°/-45°	+45°/-45°
Number of layers	11	15

The Robox® Dual contains heated printing base, which ensures better material adhesion, and has a controlled printing environment. These two features help to avoid printing defects, as they keep the entire object warm until the end of the printing, causing it to cool down. Figure 1 a and b show the ABS and PLA+ specimens for the Tensile Test.

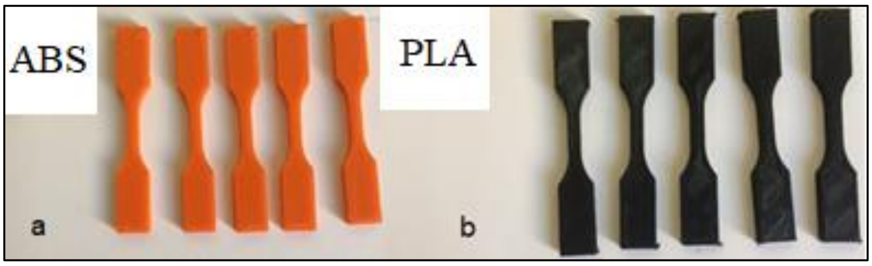

Fig. 1. Specimens of ABS (a) and PLA+ (b) for tensile test.

The specimens were tested in a universal test machine, Shimadzu Autograph AGS-X 10kN, with a constant de-formation velocity of 1mm/min. The tensile test was performed until the specimen rupture.

2.2 Flexural test

The specimens were manufactured with dimensions of 71.2 mm x 12.7 mm x 3.2 mm, taken from ASTM D790 – 17 standard [20]. T Table 2 display the data provided by the printer's software, except for fill percentage and filament colour parameters.

Table 2. Manufacturing parameters of ABS and PLA+ models.

Parameters	ABS	PLA+
Infill	100 %	100 %
Color	Orange	Black
Layer thickness	0.3 mm	0.2 mm
Extruder temperature	235 °C	215 °C
Room temperature	60 °C	~20 °C
Build base temperature	125 °C	~20 °C
Raster angle	+45°/-45°	+45°/-45°
Number of layers	11	15

Figure 2 (b) shows an ABS specimen in the machine at the beginning of the test and Figure 2 (a) shows the ABS and PLA+ specimens after the test.

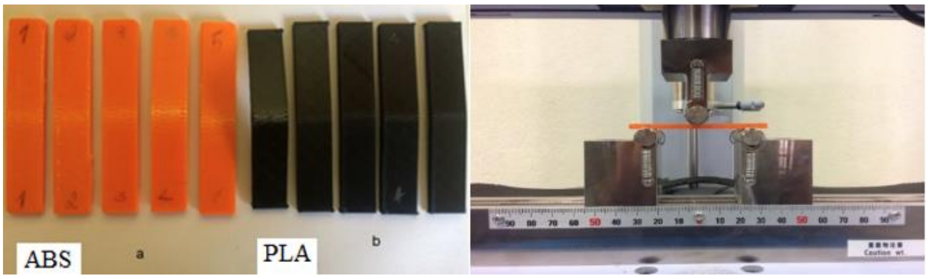

Fig. 2. a) Flexural specimens and three points flexural test.

For the flexural tests, the specimens were positioned on the supports of the Shimadzu Universal Testing machine, Autograph AGS – X series (500 N to 10 kN) with its longest axis perpendicular to the load applicator. The test ended when a maximum strain of 0.05 mm/mm was reached, before breaking.

2.3 Water Absorption Test

According to D570 – 98[23], the profile of the specimens follows the ISO standard, and their dimensions are 60x60x1 mm with tolerances of ±2 and 0.05 mm, respectively.

Table 3 shows the printing parameters for PLA and ABS models manufactured by the Robox® Dual printer, together with parameters for PLA+ manufactured by the Big Builder® Dual Feed.

Table 3. Printing parameters of PLA and PLA+ specimens for Water Absorption test.

Parameters	PLA	PLA+	ABS
Infill	100 %	100 %	100 %
Color	Blue	Black	Orange
Layer thickness	0.3 mm	0.2 mm	0.3 mm
Extruder temperature	195 °C	210 °C	235 °C
Room temperature	70 °C	~20 °C	125 °C
Build base temperature	35 °C	~20 °C	60 °C
Raster angle	+45°/-45°	+45°/-45°	+45°/-45°
Number of layers	3	5	3

Figure 3 a and b show the specimens used in the water absorption test: ABS, PLA+ (black) and PLA, respectively.

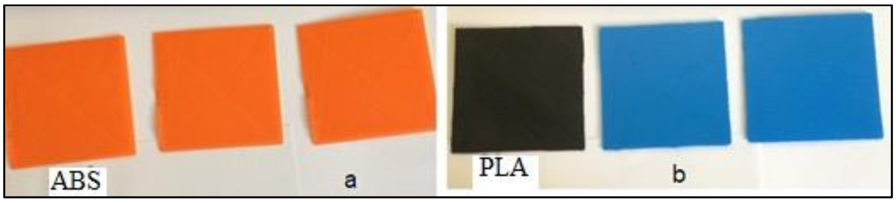

Fig. 3. Specimens in ABS (a), PLA+ and PLA for water absorption test (b).

Fig. 3 Specimens in ABS (a), PLA+ and PLA for water absorption test (b).

It was chosen a 24h immersion, with all specimens fully immersed in a container with distilled water in a vertical position, in order to have the largest possible surface in contact with water. After 24h, the specimens were removed from water, one at a time, then their surface was dried with absorbent paper and immediately measured with a calliper and weighed on a scale.

3 Results And Discussion

3.1 Tensile test

The stress-strain curves obtained from the tensile tests for the ABS material and PLA+ are represented in Figure 4 and Figure 5, respectively. It is possible to observe that the five specimens of each material present a very similar behaviour until the yield stress. The maximum plastic strain, in the case of ABS samples, varies a lot until failure, with failure observed for a minimum around 4.0% and a maximum of more than 6.6%. In the case of PLA+ samples, there was also a large variation, between 5.7% and 7.6%, although the stress has dropped more progressively than ABS.

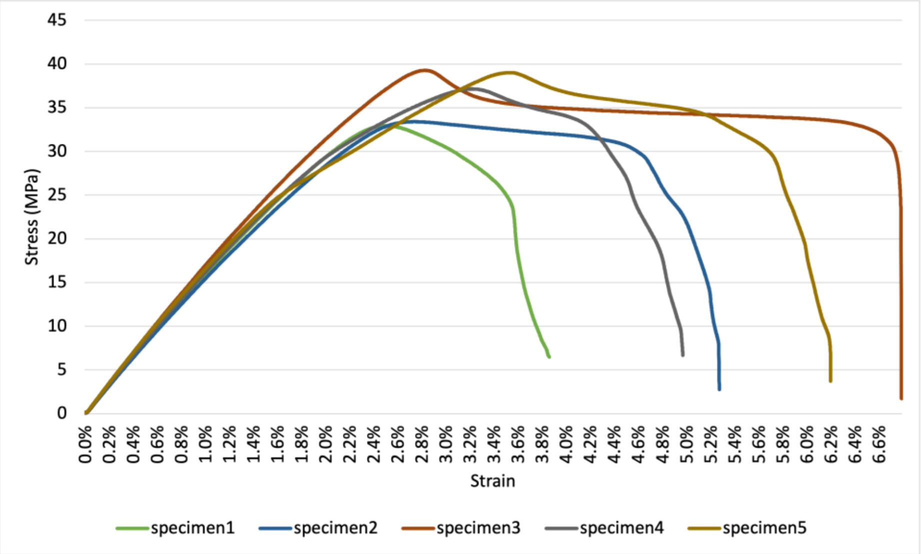

Fig. 4. Stress x Strain curves of the tensile test of ABS samples.

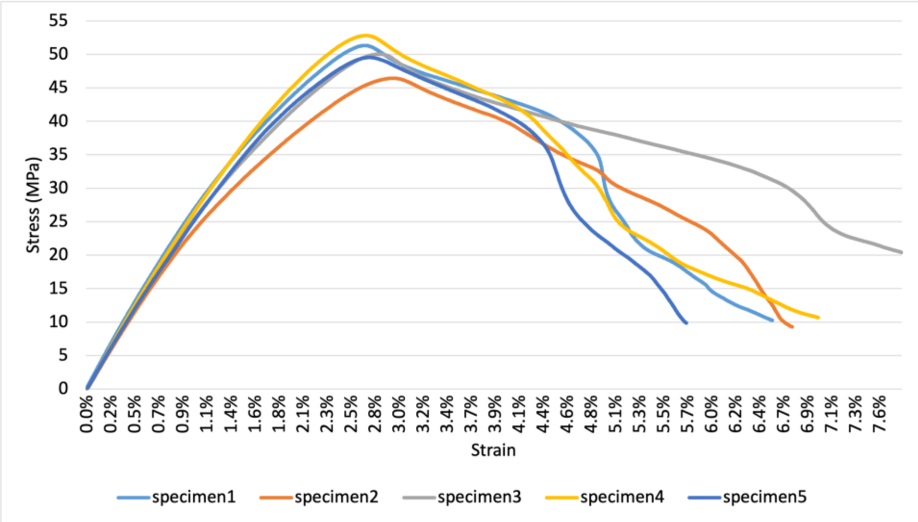

Fig. 5. Stress x Strain curves of the tensile test of PLA+ samples.

Figure 6 presents average values of stress obtained from the experimental tests together with values obtained from literature, for comparison. ABS values were taken from [24–31] and PLA+ from [25,28,29,32].

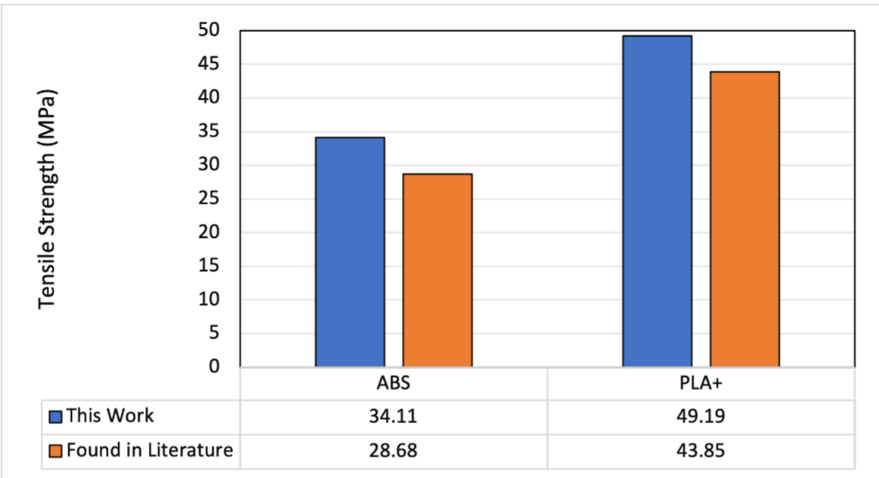

Fig. 6. Tensile strength values of Samples in ABS and PLA+.

The values obtained for ABS and PLA+ were a little higher than averages taken from literature, this is due to several parameters that influence the results, such as different print settings, controlled environment inside the printer, layer and pigment orientations.

3.2 Flexural test

The tests were carried out and the stress x strain curves of the samples were obtained, shown in Figure 7 and Figure 8. These figures present the graph with the stress values of the test specimens. The tests were interrupted until a strain value of, approximately, 5%. It can be observed that the samples had a very similar behaviour. For ABS a maximum of 55 MPa was observed and for PLA + a maximum of 85 MPa. Figure 8 shows a discontinuity in the graph which can be explained due to existing defects in the plastic filament.

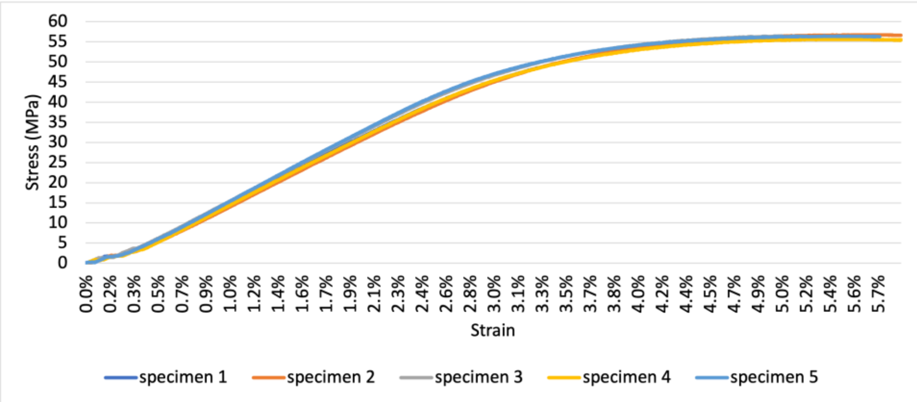

Fig. 7. Stress x Strain curves of the bending test of the ABS samples.

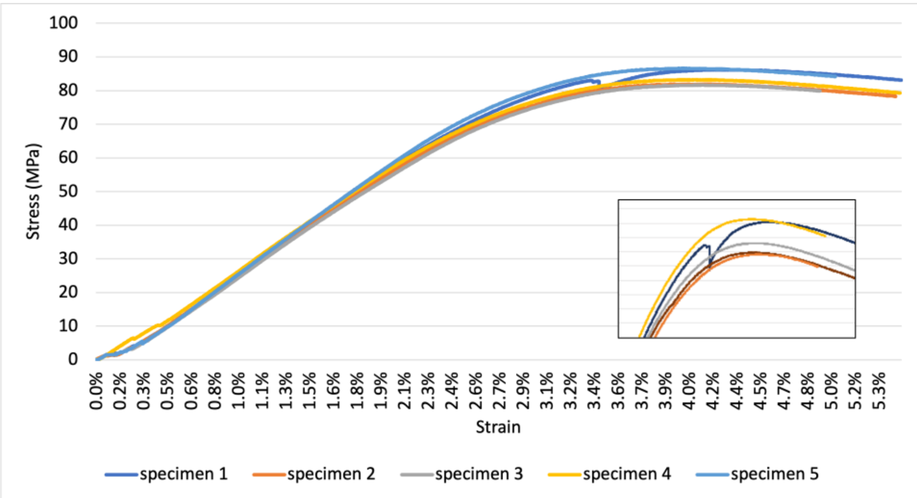

Fig. 8. Stress x Strain curves of the bending test of the PLA+ samples.

Figure 9 shows the mean values of the bending stresses obtained from experimental tests in comparison to the literature, for ABS specimens [30,33–35] and PLA+ specimens [36–39].

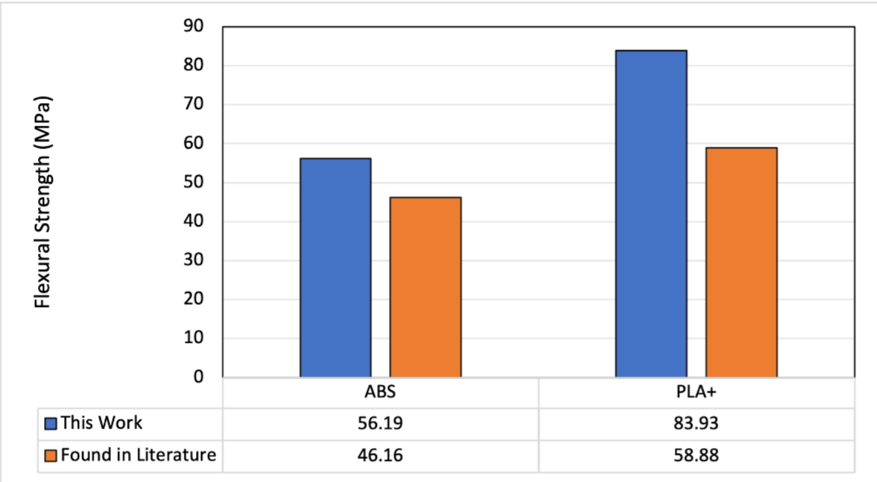

Fig. 9. Flexural strength values of samples in ABS and PLA+.

The higher values obtained may be caused by the good adhesion between layers. They have small thicknesses [37] and raster angles (45°/-45°) [22] that facilitate an increase in strength.

3.3 Water absorption test

The absorption of water in objects built using FDM printing is essentially due to gaps between layers and printing flaws. In addition, the more porous they are, the more water absorption is expected. ABS was the material with higher amount of water absorbed.

In this work, it was found that the smallest thickness presented the smallest water absorption (PLA+ thickness 0.2 mm), followed by PLA (0.3 mm thickness) and ABS (0.3 mm thickness).

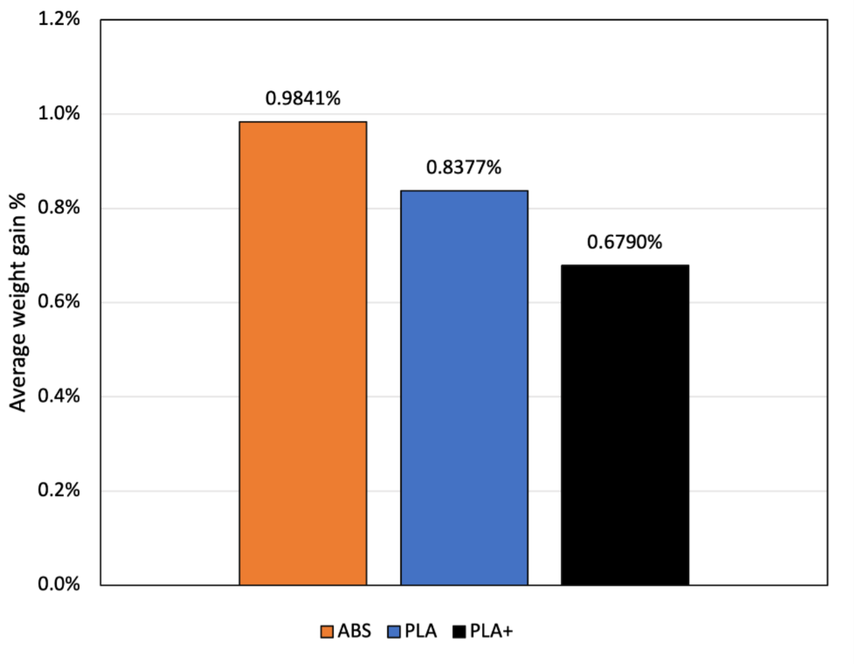

Fig. 10. Average percentage increase in sample weight.

Analysing Figure 10, it can be concluded that ABS has the highest porosity values and was also the material that presented the highest weight percentage increase. A higher number of voids between the layers (porosities) end up influencing the mechanical strength of the material, decreasing it.

4 Conclusions

In this work, three different types of experimental tests were performed in order to determine the mechanical and physical properties of the most common thermo-plastic filament used in FDM, namely, ABS and PLA. Furthermore, it was analyzed a special kind of PLA designated by PLA+., the tensile strength of PLA+ (49 MPa) is higher than ABS (39 MPa). The values obtained with experimental tensile tests were higher than the observed from specialized literature. From the flexural tests, it was determined the flexural strength, results showed higher value for PLA+ (85 MPa) and lower for ABS (57 MPa) and these values are higher when compared with the ones showed in literature. In the water absorption test, it was observed that ABS (0.984%) had more water than the PLA (0.838%) and PLA+(0.679%).

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References

1. Dizon JRC, Espera AH, Chen Q, Advincula RC. Mechanical characterization of 3D-printed polymers. Vol. 20, Additive Manufacturing. 2018.
2. Chapiro M. Current achievements and future outlook for composites in 3D printing. Reinforced Plastics. 2016;60(6).
3. Lee JY, An J, Chua CK. Fundamentals and applications of 3D printing for novel materials. Vol. 7, Applied Materials Today. 2017.
4. MacDonald E, Salas R, Espalin D, Perez M, Aguilera E, Muse D, et al. 3D printing for the rapid prototyping of structural electronics. IEEE Access. 2014;2.
5. Paolini A, Kollmannsberger S, Rank E. Additive manufacturing in construction: A review on processes, applications, and digital planning methods. Additive Manufacturing [Internet]. 2019;30:100894. Available from: https://www.sciencedirect.com/science/article/pii/S2214860419309029.
6. Hashemi Sanatgar R, Campagne C, Nierstrasz V. Investigation of the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles: Effect of FDM printing process parameters. Applied Surface Science [Internet]. 2017;403:551–63. Available from: https://www.sciencedirect.com/science/article/pii/S0169433217301137
7. Souza A, Souza MS, Pinho D, Agujetas R, Ferrera C, Lima R, et al. 3D manufacturing of intracranial aneurysm biomodels for flow visualizations: Low cost fabrication processes. Mechanics Research Communications [Internet]. 2020;107:103535. Available from: https://www.sciencedirect.com/science/article/pii/S0093641320300641
8. Bhargav A, Sanjairaj V, Rosa V, Feng LW, Fuh YH J. Applications of additive manufacturing in dentistry: A review. Vol. 106, Journal of Biomedical Materials Research - Part B Applied Biomaterials. 2018.
9. Blakey-Milner B, Gradl P, Snedden G, Brooks M, Pitot J, Lopez E, et al. Metal additive manufacturing in aerospace: A review. Materials & De-sign [Internet]. 2021;209:110008. Available from: https://www.sciencedirect.com/science/article/pii/S0264127521005633
10. Bird DT, Ravindra NM. Additive manufacturing of sensors for military monitoring applications. Polymers (Basel). 2021;13(9).
11. Goh GD, Agarwala S, Goh GL, Dikshit V, Sing SL, Yeong WY. Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential. Vol. 63, Aerospace Science and Technology. 2017.
12. Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, et al. The status, challenges, and future of additive manufacturing in engineering. CAD Computer Aided Design. 2015;69.
13. Crump SS. Fast, precise, safe prototypes with FDM. In: American Society of Mechanical Engineers, Production Engineering Division (Publication) PED. 1991.
14. Erratum: A review on 3D micro-additive manufacturing technologies (International Journal of Advanced Manufacturing Technology, (2013), 67,(5-8), (1721-1754), 10.1007/s00170-012-4605-2). Vol. 67, International Journal of Advanced Manufacturing Technology. 2013.

15. Hoskins TJ, Dearn KD, Kukureka SN. Mechanical performance of PEEK produced by additive manufacturing. Polymer Testing. 2018;70.
16. Algarni M, Ghazali S. Comparative study of the sensitivity of pla, abs, peek, and petg's mechanical properties to fdm printing process parameters. Crystals (Basel). 2021;11(8).
17. Charalampous P, Kostavelis I, Kontodina T, Tzovaras D. Learning-based error modeling in FDM 3D printing process. Rapid Prototyping Journal. 2021;27(3).
18. ASTM. ASTM D883: Standard Terminology Relating to Plastics. ASTM Standards. 2020.
19. ASTM INTERNATIONAL. Astm D638-14. Annual Book of ASTM Standards. 2014.
20. American Society for Testing and Materials. ASTM D790-17 - Standard Test Methods for Flexural Proper-ties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. Annual Book of ASTM Standards. 2017.
21. CEL-Robox. Product datasheet ABS CEL-Robox 1.75mm Orange ABS 3D Printer Filament, 600g [Internet]. RS. 2022 [cited 2022 Jun 22]. Available from: https://export.rsdelivers.com/product/cel/rbx-abs-or023/cel-robox-175mm-orange-abs-3d-printer-filament/9031359
22. Ultimaker. Technical data sheet Tough PLA [Internet]. 2022 [cited 2022 Jun 22]. Available from: https://docs.rs-online.com/d6e4/0900766b81697f3b.pdf
23. ASTM D570-98. D 570 – 98 Standard Test Method for Water Absorption of Plastics ASTM D570-98. ASTM Standards. 2010;98(Reapproved 2010).
24. Kanu RC, Hale C, Piper PON. The use of 3D printing to introduce stu-dents to ASTM standards for testing tensile properties of acrylonitrile-butadiene-styrene (ABS) plastic material. In: ASEE Annual Conference and Exposition, Conference Proceedings. 2016.
25. Banjanin B, Vladić G, Pál M, Baloš S, Dramićanin M, Rackov M, et al. Consistency analysis of mechanical properties of elements produced by FDM additive manufacturing technology. Revista Materia. 2018;23(4).
26. Novakova-Marcincinova L, Novak-Marcincin J. Testing of ABS material tensile strength for fused deposition modeling rapid prototyping meth-od. In: Advanced Materials Research. 2014.
27. Letcher T, Rankouhi B, Javadpour S. Experimental study of mechanical properties of additively manufactured abs plastic as a function of layer parameters. In: ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE). 2015.
28. Lovo JFP, Fortulan CA. Estudo de propriedades mecânicas e anisotropia em peças fabricadas por manufatura aditiva tipo FDM. I Simpósio do Programa de Pós-Graduação em Engenharia Mecânica da EESC-USP (SiPGEM/EESC-USP). 2016;(1).
29. Tymrak BM, Kreiger M, Pearce JM. Mechanical properties of components fabricated with open-source 3-D printers under realistic environ-mental conditions. Materials and Design. 2014;58.
30. Wu W, Geng P, Li G, Zhao D, Zhang H, Zhao ji. Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-Printed PEEK and a Comparative Mechanical Study between PEEK and ABS. Materials. 2015 Sep 1;8:5834–46.
31. Hibbert K, Warner G, Brown C, Ajide O, Owolabi G, Azimi A. The Effects of Build Parameters and Strain Rate on the Mechanical Properties of FDM 3D-Printed Acrylonitrile Butadiene Styrene. Open Journal of Organic Polymer Materials. 2019;09(01).
32. Santana L, Alves J, Netto A, Merlini C. Estudo comparativo entre PETG e PLA para Impressão 3D através de caracterização térmica, química e mecânica. Matéria (Rio de Janeiro). 2018 Dec 6;23.
33. Es-Said OS, Foyos J, Noorani R, Mendelson M, Marloth R, Pregger BA. Effect of layer orientation on mechanical properties of rapid prototyped samples. Materials and Manufacturing Processes. 2000;15(1).

34. Durgun I, Ertan R. Experimental investigation of FDM process for improvement of mechanical properties and production cost. Rapid Prototyping Journal. 2014;20(3).
35. Dawoud M, Taha I, Ebeid SJ. Mechanical behaviour of ABS: An experimental study using FDM and injection moulding techniques. Journal of Manufacturing Processes. 2016;21.
36. Rajpurohit SR, Dave HK. Flexural strength of fused filament fabricated (FFF) PLA parts on an open-source 3D printer. Advances in Manufacturing. 2018;6(4).
37. Jaya Christiyan KG, Chandrasekhar U, Venkateswarlu K. Flexural Properties of PLA Components Under Various Test Condition Manufactured by 3D Printer. Journal of The Institution of Engineers (India): Series C. 2018;99(3).
38. Nugroho A, Ardiansyah R, Rusita L, Larasati IL. Effect of layer thick-ness on flexural properties of PLA (PolyLactid Acid) by 3D printing. In: Journal of Physics: Conference Series. 2018.
39. Chacón JM, Caminero MA, García-Plaza E, Núñez PJ. Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection. Materials and Design. 2017;124.