Chapter 6
Mechanical and Physical Characterization of Parts Manufactured by 3D Printing

C. Oliveira, J. Rocha, and J. E. Ribeiro

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

6.1 Introduction

Additive manufacturing (AM), also known as 3D printing, has been attracting interest from industry and the research community (Dizon et al. 2018); 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 (Chapiro 2016). Today, AM is being used to produce

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materials for different applications, namely automotive (Lee et al. 2017), electronics (MacDonald et al. 2014), robots (Lee et al. 2017), construction (Paolini et al. 2019), apparel (Hashemi Sanatgar et al. 2017), medicine (Souza et al. 2020), dentistry (Bhargav et al. 2018) aerospace (Blakey-Milner et al. 2021), military (Bird and Ravindra 2021) 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 is 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 moulding (Goh et al. 2017; Gao et al. 2015).

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 (Gao et al. 2015). Among these, one of the most popular is the defused deposition modelling (FDM) technique (Crump 1991) 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 (Vaezi et al. 2013). Even though, the referred materials are the most used in recent years, thermoplastic materials, like PEEK, with higher melting points have appeared (Hoskins et al. 2018). 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 (Algarni and Ghazali 2021) 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 (Charalampous et al. 2021).

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.

6.2 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 Reinforced Plastics and Electrical Insulating

Materials”. To determine the water absorption, the procedure described in ASTM D570-98 (2010) 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.

6.2.1 Tensile Test

Following the recommendations defined by ASTM D883 (ASTM 2020) standard, was chosen to manufacture the V type specimens (ASTM International 2014; American Society for Testing and Materials 2017) making rigid or semi-rigid plastic with thicknesses up to 4 mm. Five models were produced, with geometry dimensions in accordance with 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 (CEL-Robox 2022) and PLA+ (Ultimaker 2022) specimens are shown in Table 6.1.

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 6.1a, b shows the ABS and PLA+ specimens for the Tensile Test.

Table 6.1 Mean masses, standard deviation and variation coefficient

Parameters	ABS	PLA+
Infill	100%	100%
Colour	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

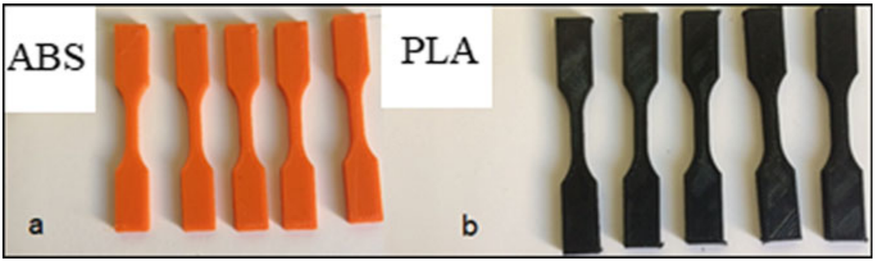


Fig. 6.1 Specimens of ABS **a** and PLA+ **b** for tensile test

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

6.2.2 Flexural Test

The specimens were manufactured with dimensions of 71.2 mm × 12.7 mm × 3.2 mm, taken from ASTM D790-17 standard (American Society for Testing and Materials 2017). Table 6.2 displays the data provided by the printer's software, except for fill percentage and filament colour parameters.

Figure 6.2b shows an ABS specimen in the machine at the beginning of the test, and Fig. 6.2a shows the ABS and PLA+ specimens after the 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.

Table 6.2 Manufacturing parameters of ABS and PLA+ models

Parameters	ABS	PLA+
Infill	100%	100%
Colour	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

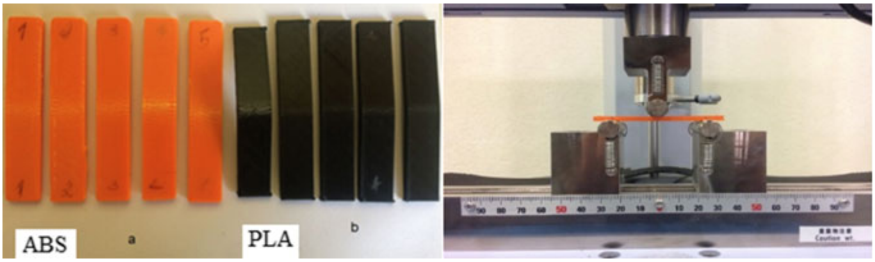


Fig. 6.2 Flexural specimens and three points flexural test

6.2.3 Water Absorption Test

According to D570-98 (ASTM D570-98 2010), the profile of the specimens follows the ISO standard, and their dimensions are 60 × 60 × 1 mm with tolerances of ± 2 and 0.05 mm, respectively.

Table 6.3 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.

Figure 6.3a, b shows the specimens used in the water absorption test: ABS, PLA+ (black) and PLA, respectively.

Table 6.3 Printing parameters of PLA and PLA+ specimens for Water Absorption test

Parameters	PLA	PLA+	ABS
Infill	100%	100%	100%
Colour	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

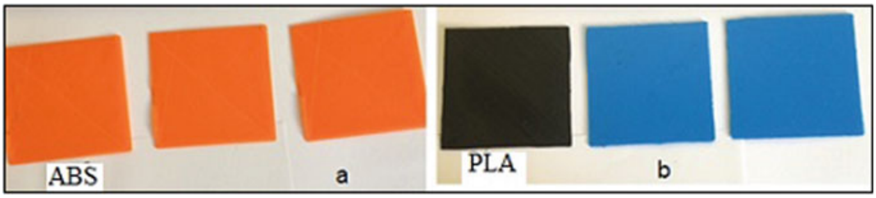


Fig. 6.3 Specimens in ABS (**a**), PLA+ and PLA for water absorption test (**b**)

It was chosen a 24-h 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 24 h, the specimens were removed from water, one at a time, and then, their surface was dried with absorbent paper and immediately measured with a calliper and weighed on a scale.

6.3 Results and Discussion

6.3.1 Tensile Test

The stress–strain curves obtained from the tensile tests for the ABS material and PLA+ are represented in Figs. 6.4 and 6.5, 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.

Figure 6.6 presents average values of stress obtained from the experimental tests together with values obtained from literature, for comparison. ABS values were taken from (Kanu et al. 2016; Banjanin et al. 2018; Novakova-Marcincinova and Novak-Marcincin 2014; Letcher et al. 2015; Lovo and Fortulan 2016; Tymrak et al. 2014; Wu et al. 2015; Hibbert et al. 2019) and PLA+ from Banjanin et al. 2018; Lovo and Fortulan 2016; Tymrak et al. 2014; Santana et al. 2018).

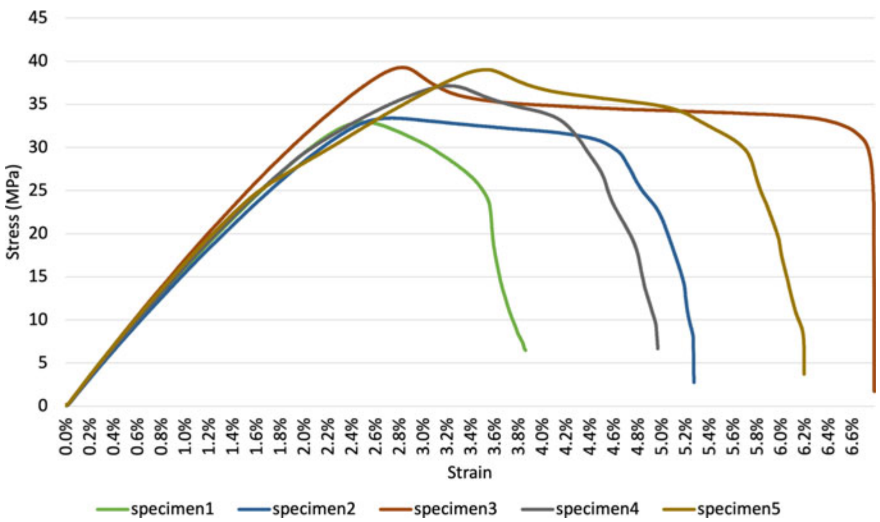


Fig. 6.4 Stress × Strain curves of the tensile test of ABS samples

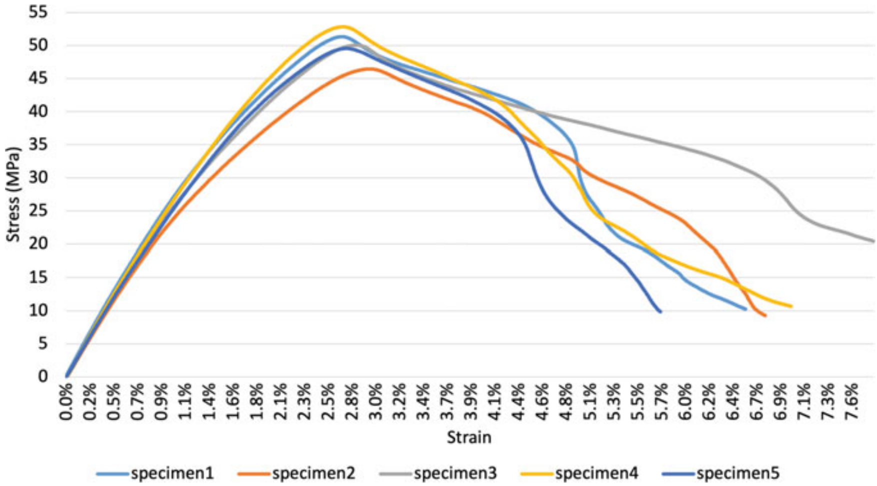
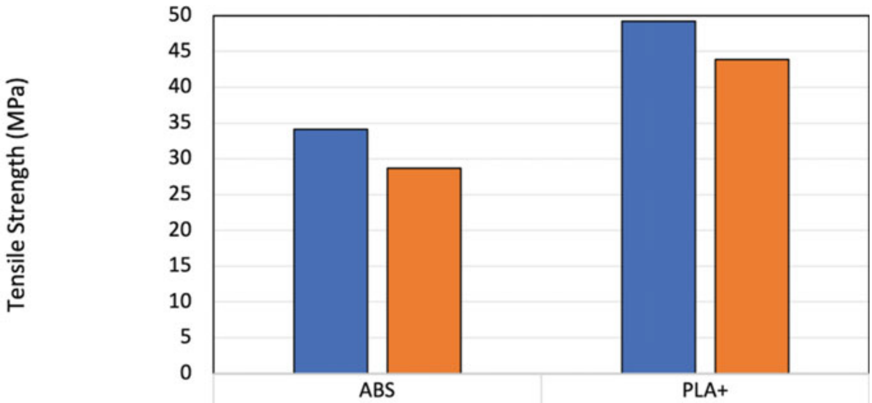


Fig. 6.5 Stress × Strain curves of the tensile test of PLA+ samples



	ABS	PLA+
This Work	34.11	49.19
Found in Literature	28.68	43.85

Fig. 6.6 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, and this is due to several parameters that influence the results, such as different print settings, controlled environment inside the printer, layer and pigment orientations.

6.3.2 Flexural Test

The tests were carried out and the stress x strain curves of the samples were obtained, shown in Figs. 6.7 and 6.8. 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 6.8 shows a discontinuity in the graph which can be explained due to existing defects in the plastic filament.

Figure 6.9 shows the mean values of the bending stresses obtained from experimental tests in comparison to the literature, for ABS specimens (Wu et al. 2015;

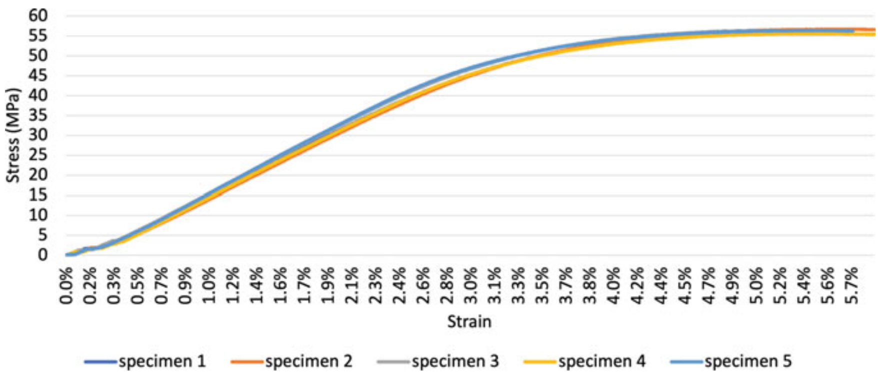


Fig. 6.7 Stress x Strain curves of the bending test of the ABS samples

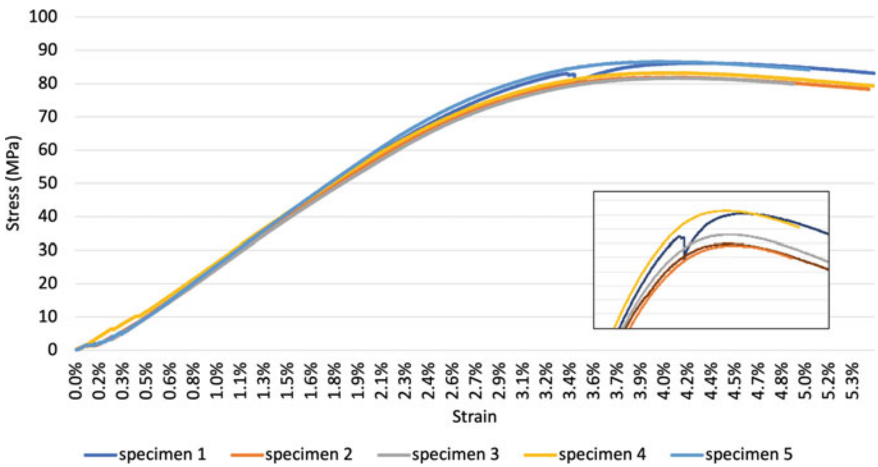


Fig. 6.8 Stress x Strain curves of the bending test of the PLA+ samples

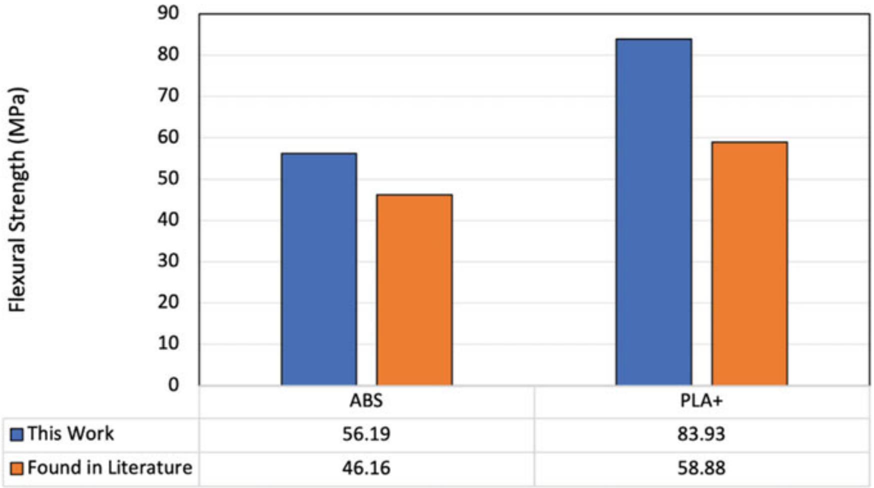


Fig. 6.9 Flexural strength values of samples in ABS and PLA+

Es-Said et al. 2000; Durgun and Ertan 2014; Dawoud et al. 2016) and PLA+ specimens (Rajpurohit and Dave 2018; Jaya Christiyan et al. 2018; Nugroho et al. 2018; Chacón et al. 2017).

The higher values obtained may be caused by the good adhesion between layers. They have small thicknesses (Jaya Christiyan et al. 2018) and raster angles (45°/−45°) (Ultimaker. 2022) that facilitate an increase in strength.

6.3.3 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).

Analysing Fig. 6.10, 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.

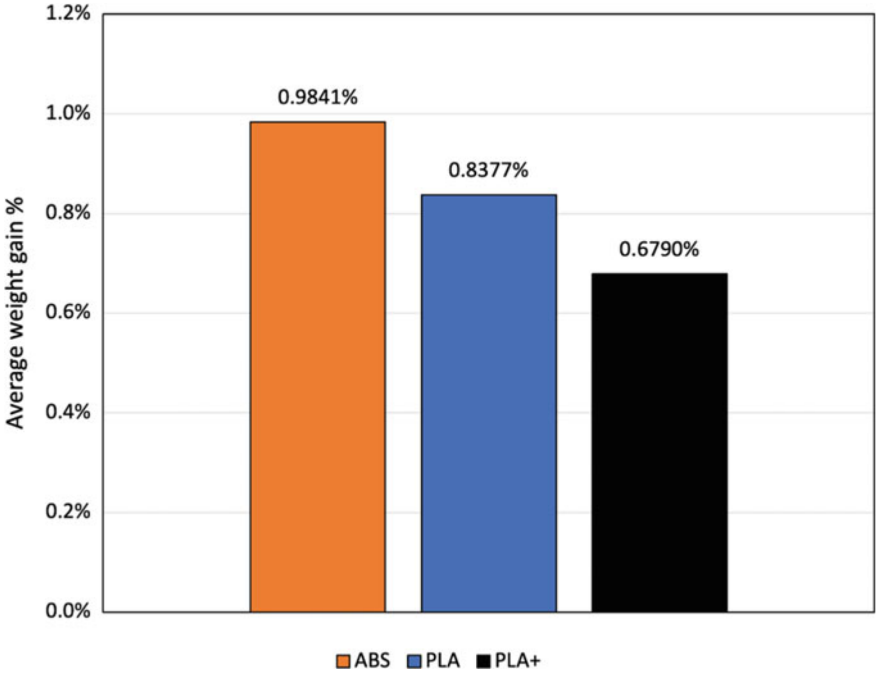


Fig. 6.10 Average percentage increase in sample weight

6.4 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 thermoplastic filament used in FDM, namely ABS and PLA. Furthermore, it was analysed a special kind of PLA designated by PLA+, and 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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