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The Effect of Fill Rate on Mechanical Properties of PLA Printed Samples

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ABSTRACT: Three-dimensional (3D) printers are a rapidly developing technology used in many fields today. Polylactic acid (PLA) is one of the most researched and used biodegradable polymers to date. PLA stands out as a biomaterial in other industries due to its many benefits, as it replaces conventional petrochemical-based polymers. The main purpose of this study is; to investigate the effect of different fill rates (5%, 50% and 100%) on the mechanical properties of samples produced from PLA in 3D printers. For each filling ratio, 5 samples were produced for bending test defined by ASTM D-790 standard and tensile tests defined by ASTM D-638 standard. In this study, it is aimed to model a printer producing with stacking technology and to compare the effects of occupancy rate on mechanical properties in the modeled 3D printer.

Keywords: 3D printer, polylactic acid (PLA), fused deposition modeling

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INTRODUCTION

3D printer is a machine that transforms 3D computer data into real objects (Bellini and Güçeri, 2003; Puebla, 2012; Schöppner and KTP, 2011). This technology can produce geometries that traditional manufacturing methods cannot be realized (Fodran et al., 1996; Schöppner and KTP, 2011; Puebla et al., 2012). 3D printer technology is not a new technology, but its first application dates back to 1984, but in the past 20 years, this method has not received much attention outside the field of rapid prototyping. With the RepRap project that started in 2006, it reached much larger masses. Thanks to this project, many ordinary users, hobbyists, people with a do-it-yourself culture have a 3D printer. Even three years after the start of the project, many companies have managed to spread the technology to a much wider audience by making use of the RepRap project to produce and sell open source 3D printers (Bellini and Güçeri, 2003; Schöppner and KTP, 2011; Puebla, 2012). 3D printers work with a production method called additive manufacturing. Although many raw materials are used for printing, thermoplastic materials, which are generally referred to as filaments, are used. One of the most commonly used thermoplastics in 3D printers is PLA (Fodran et al., 1996; Schöppner and KTP, 2011; Ziemian et al., 2012). It stands out with its biocompatible and biodegradable properties and low cost. It is one of the most preferred thermoplastics in personal care products, kitchenware and biomedical industry in the food packaging industry. The mechanical properties of the parts produced in the 3D printer vary depending on parameters such as layer thickness, table temperature, nozzle temperature, nozzle diameter, filling density, direction of printing. Parameters need to be optimized to obtain mechanical performance from parts produced in 3D printers (Fodran et al., 1996; Montero et al., 2001; Bellini and Güçeri, 2003; Schöppner and KTP, 2011; Puebla 2012; Ziemian et al., 2012). Çelebi et al. (2017) compared the strength values by making tensile and bending tests in 3D printer according to different occupancy rates. They determined that the tensile strength of the samples with the same fill rate up to 50%. As a result, they concluded that there were micro cracks that occurred during the printing process. They suggested that the ambient temperature be kept constant during production, the temperature difference between the table and the nozzle is low, the cooling fan speed is not high, and that the product is treated precisely when removing it from the tray. Günay et al. (2020) melt agglomeration from PLA + material produced using 3D printer by modeling in samples, the print speed, fill rate, and scan angle They examined the effects of tensile strength on variance analysis. In addition, using the Taguchi methodology, the optimum have determined the process parameters. Evlen et al. (2018) printed 54 test samples in total using three different occupancy rates (10%, 30% and 50%) and two different working environments (open and closed system). They subjected their samples to tensile test and shore hardness test. As a result of the study, they determined that the samples written in the closed system had a lower hardness value than the samples written in the open system, and their tensile strengths and % elongation were higher. Öz et al. (2018) investigated the effect of the print fill rate on the pull damage load of the parts printed in the 3D printer. They chose occupancy rates as 15%, 50% and 100% for the parts they printed. From the experimental results they obtained, they revealed that there was a significant increase in damage loads due to the increase in occupancy rates. Evlen et al. (2019) modeled a printer producing with deposition modelling technology and examined the effects of occupancy rate on the mechanical properties of the modeled 3D printer. As a result of their measurements, they have seen that the hardness value in PET and PLA materials is directly proportional to the material's fullness rate, and the hardness of the materials increases as the fullness rate increases. They determined that the roughness and tensile values of the samples produced from PLA and PET materials were inversely proportional to each other, and that the roughness and tensile strength values were in the opposite direction from 10% to 20% filling rate.

3D printers are useful to underline that printing parameters play a very important role in the emergence of these areas of use. For example, if you are going to produce a prototype that will be used in the automotive supplier industry, it will be desired to be durable since the part will load on it. Or vice versa, visuality rather than strength will come to the fore in 3D parts to be produced in a company in the model sector. In this case, you have to master how you should apply your parameters according to your usage area.

We can collect the printing parameters under five main headings. These:

- Fill Rate
- Number of Shells
- Layer Thickness
- Exturuder Temperature
- Print Speed

It is developing and renewing day by day, so different parameters appear in 3D printing processes. This may vary depending on the brand and software of the 3D printer, but the main parameters mentioned above will often remain the same. On the other hand, it would be better not to change the parameters other than those without knowing how to affect the 3D printer and printing.

MATERIALS AND METHODS

Materials

PLA is the most used 3D printer material according to current statistics (Fodran et al., 1996; Montero et al., 2001; Bellini and Güçeri, 2003; Schöppner and KTP, 2011; Puebla, 2012; Ziemian et al., 2012). The main reason for preferring this material is that it is easy to work as it can melt at low temperatures as seen in Table 1. It is also another advantage that PLA material is much less likely to be bent when printing. Therefore, it does not require the use of a heater table. Unlike Akrilonitril Butadin Stiren (ABS) material, PLA is produced from products containing starch, not oil origin. PLA material is also frequently used in the medical industry in implants and prostheses (Fodran et al., 1996; Montero et al., 2001; Bellini and Güçeri, 2003; Schöppner and KTP, 2011; Puebla, 2012; Ziemian et al., 2012; Evlen et al., 2020).

Table 1. Technical characteristics of PLA (Ziemian et al., 2012)

Features	Polylactic Acid (PLA)	Unit
Density	1.24	$g\ cm^{-3}$
Tensile Strength	50-70	MPa
Elasticity Module	3-4	GPa
Breaking Elongation	2-10	%
Bending Strength	100	MPa
Bending Modulus	4-5	GPa
Impact Strength (Izod, notched)	3-7	
Hardness (Rockwell-H)	70-90	$kg\ m^{-2}$
Melting temperature	180	°C
Glass Transition Temperature	60-70	°C

Preparation of Test Samples

Dream maker 3D printer and ESUN PLA plus filament shown in Figure 1 were used for the production of the test samples. Solid models of tensile and bending samples in accordance with ASTM D-638 (Figure 2.a) and ASTM D-790 (Figure 3.a) standards were created at Solidworks 2015 program, and transferred to the 3D printing program shown in Figure 2.b and Figure 3.b. The created solid model was transferred in Slic3r 3D printer slicing program, and after the position of the sample on the printer tray and other production parameters were entered, printing of the samples was started. The tray was heated up to 50 °C to prevent the produced samples from sticking to the printer tray. The samples with the same occupancy rate were produced in one go by writing in groups of 5.

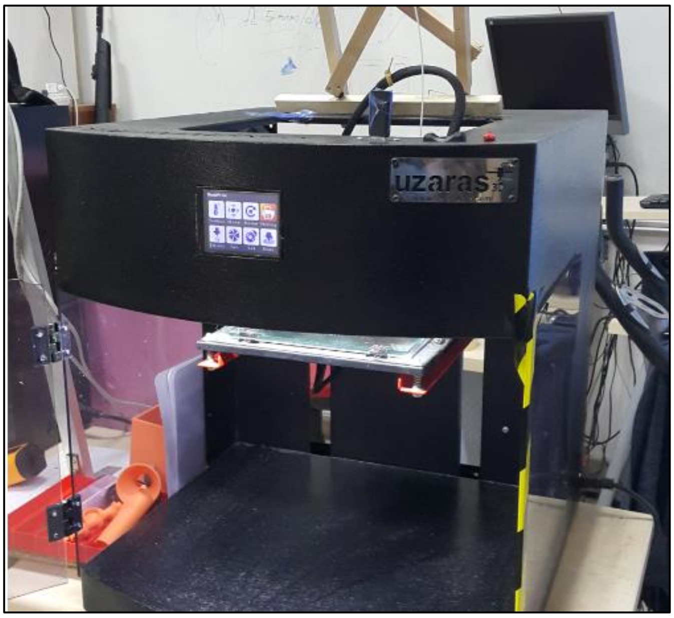

Figure 1. Dream maker 3D printer where tensile and bending samples are produced

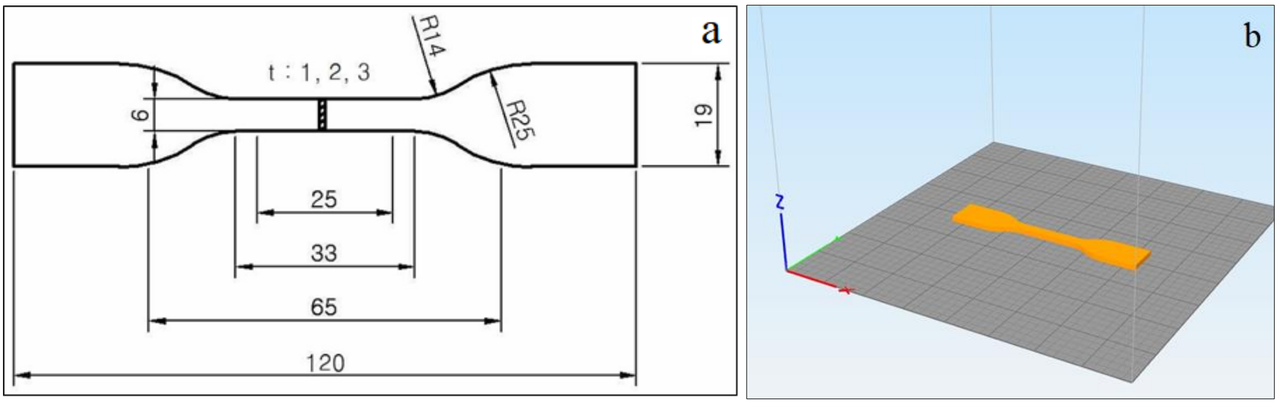

Figure 2. Tensile test sample (a) drawing in accordance with ASTM D-638 (b) 3D printing (ASTM, 1989)

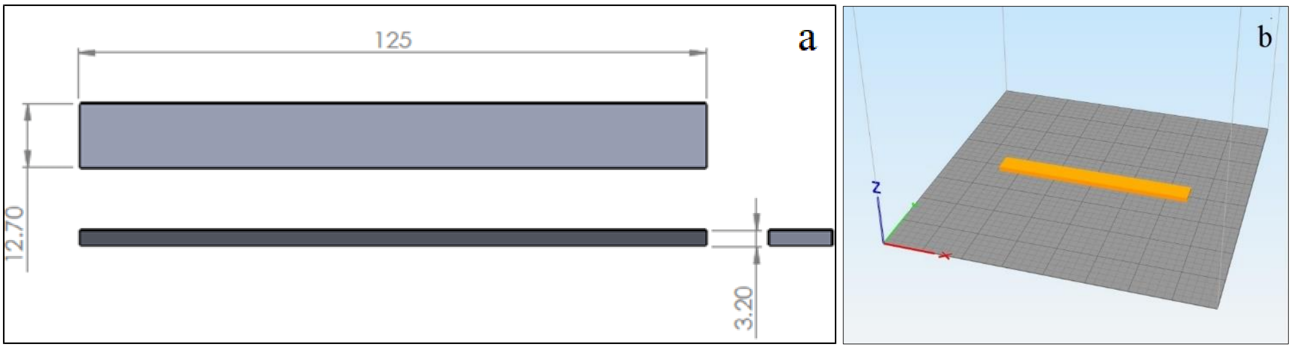

Figure 3. Bending test sample (a) drawing in accordance with ASTM D-790 (b) 3D printing (ASTM, 2003)

5 tensile specimens produced from PLA at 5%, 50% and 100% occupancy rates, respectively, in ASTM D-638 standard, and at 5%, 50% and 100% occupancy rates, respectively, in ASTM D-790

standard a total of 30 test samples, including the bending sample, were prepared in the 3D printer. Findings obtained by applying tensile and bending tests to the prepared samples were examined.

Tensile Test

With the ASTM D-638 standard, the samples clamped to the upper and lower jaws in the Shimadzu Autograph AGS-X 100KN model tensile tester, as shown in Figure 4.a, were subjected to shrinkage at a rate of 5 mm/min as shown in Figure 4.b. The tensile strength, flexibility modulus and percent elongation values of the samples were determined using the same stress rate for the samples at all occupancy rates.

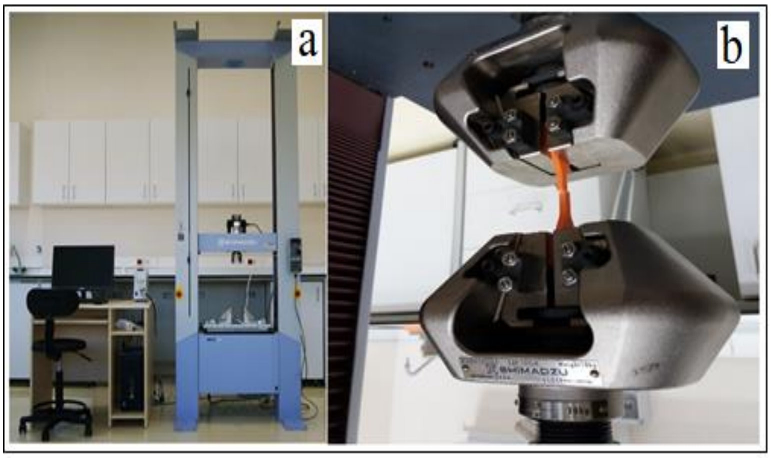

Figure 4. Tensile testing (a) tensile testing setup (b) tensile tested sample

Bending Test

In the Shimadzu Autograph AGS-X 100KN model pulling device, the ASTM D-790 standard bending process was performed at 5 mm/min by determining the distance between the supports to be 16 times the sample thickness as required by the standard (Figure 5.a). Figure 5.b shows the 3D printed part with bending test completed. The bending strength, bending modulus and elongation amounts of the samples were determined using the same bending speed in the samples at all occupancy rates.

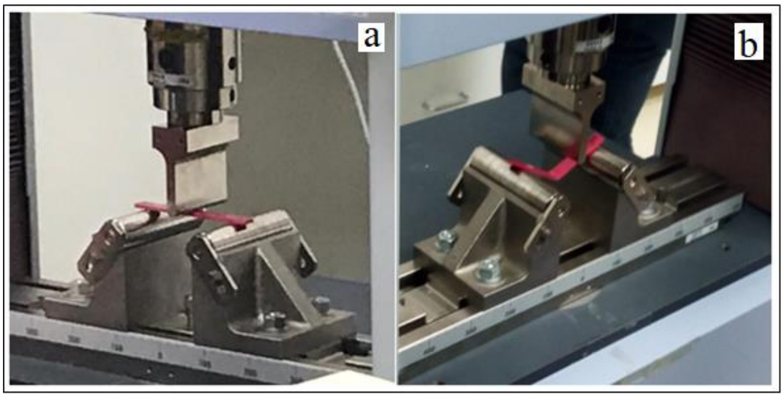

Figure 5. Bending testing (a) placing the sample on the instrument (b) test result

RESULTS AND DISCUSSION

In this study, the effects of raw materials and production parameters used in 3D printers, which are widely used today and will be used in many fields in the coming years, were investigated. The behavior of the PLA used in these printers, which have gradually entered our homes and are quite easy to reach, has been examined in different parameters and at different occupancy rates. Considering that it is also possible to produce PLA with different physical properties and obtain the desired performance value, the mechanical properties of the samples that we prepared from the PLA filament used in the printer have been examined by making pulling and bending tests. Tensile curves of samples with 5%, 50% and 100% fill rates are given in Figure 6.

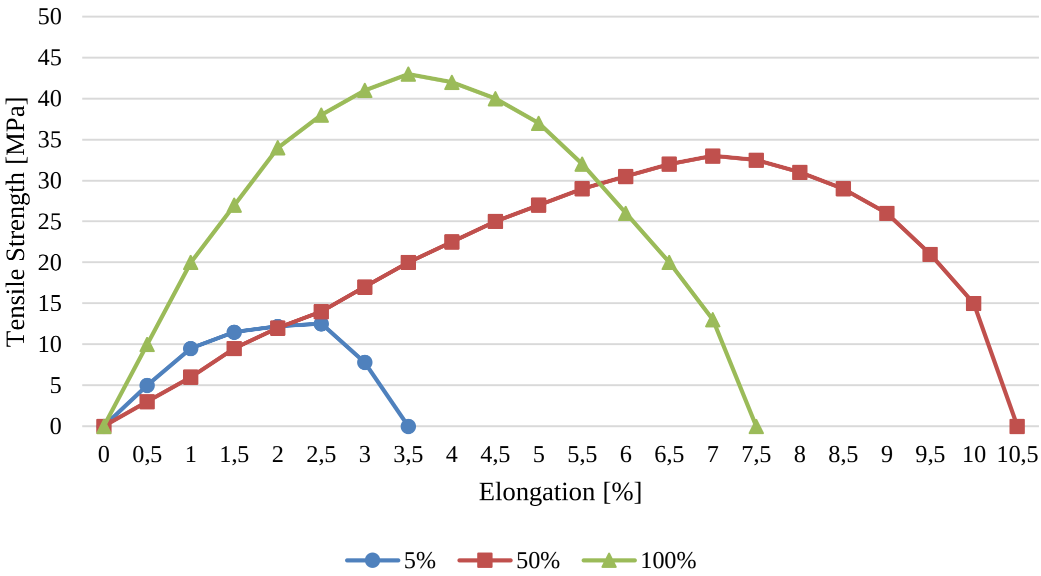

Figure 6. Tensile curve of samples with 5%, 50% and 100%

The results obtained are summarized in Table 2. In line with these results, differences in tensile strengths of samples with the same occupancy rate up to 50% were determined. The reason for the difference is that micro cracks occur during 3D printing. It has been suggested that the ambient temperature is kept constant during production, the temperature difference between the table and the nozzle is low, the cooling fan speed is not high and that the product is treated precisely during separation from the tray. When the bending test results were examined, it was observed that the effect of occupancy rate on the maximum force during cracking started was quite small. It is thought that the occupancy rate can be decreased in a reasonable amount in order to reduce the cost without compromising the mechanical properties in the products that will be subjected to compression force.

Table 2. Bending and tensile test results

	Tensile Strength [MPa]			**Bending Strength [MPa]**		
Solidity ratio	**5%**	**50%**	**100%**	**5%**	**50%**	**100%**
Sample 1	5	32	42	63	82	97
Sample 2	8	24	36	61	79	98
Sample 3	9	28	21	70	83	96
Sample 4	7	27	25	69	81	103
Sample 5	9	25	33	68	79	101
Average	7.6	27.2	31.4	66.2	80.8	99

When the effects of bending strength are analyzed, it is seen in Figure 7 that at least 61 MPa strength was obtained at 5% fullness, while at least 79 MPa at 50% fullness and at least 96 MPa at 100% fullness.

Build time, filament length amount and plastic weight spent in tensile and bending test samples produced in different filling ratios are given in Table 3. The output variables here may show a nonlinear change depending on the geometric structure of the part produced. The filling rate selection should be determined by the user according to the material to be used and the physical conditions.

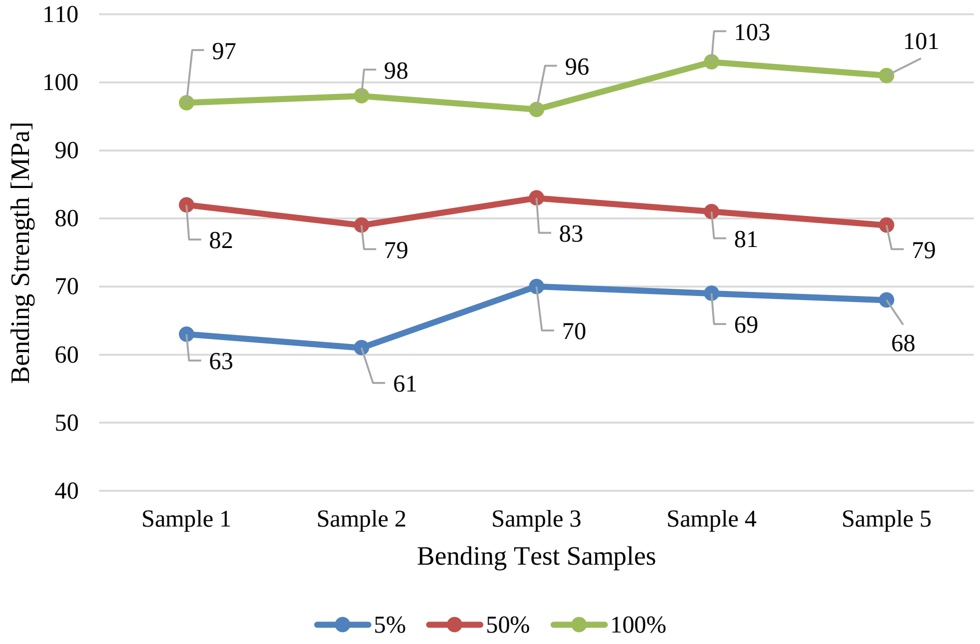

Figure 7. Effect of filling rates of samples on bending strength

Table 3. Manufacturing outputs.

Manufacturing Outputs	Tensile Test Samples			Bending Test Samples		
	5%	50%	100%	5%	50%	100%
Build time	15 min.	19 min.	24 min.	14 min.	18 min.	23 min.
Filament length	1057.1 mm	1462.4 mm	1969.1 mm	993.4 mm	1368.7 mm	1836.8 mm
Plastic weight	3.18 g	4.40	5.92 g	2.99 g	4.12 g	5.52 g

The most important criterion that determines the strength of the model is the filling ratio. The more full your model will be, the more resistant it will be. Of course, the type of filament used will also affect durability. Even if the model is designed as 100% full, it can be adjusted with the 3D printer interface at the desired occupancy rate. The cell sizes of the spaces between 30-40% occupancy rate and 100% occupancy rate in 3D printing do not change much. For this reason, 10-50% occupancy rate will be sufficient to produce high strength models with less material. If only model or figure will be produced, the model may not need to have high strength since it will not be subjected to heavy processes or stress. Therefore, it may be thought that it would be sufficient to select the internal filling rate at 10% levels.

CONCLUSION

The results and suggestions obtained from the study can be listed as follows:

• The main result of this experimental research study is that it is demonstrated that high strength values can be achieved with 50% occupancy rate. Compared to the results obtained from 100% occupancy rate; It has been determined that it has an average of 3/4 strength in tensile strength. Thus, it has been determined that acceptable tensile strengths can be achieved by using half the raw material in product manufacturing.

• In the results of bending strength, it has been shown that it has resistance values at 3/5 times the 100% occupancy rate even at 5% occupancy rate. Based on this result, it is an important amount of raw material savings to obtain approximate results for the bending strengths of 100% filling ratio without more raw material with 5% filling rate of parts produced from the 3D printer that will be exposed to bending.

• The lightness of the produced parts is another positive side. An assembly system consisting of many parts, parts manufactured in all parts at low occupancy rates will mean that the assembled system will be developed more lightly and compactly.

• One of the important results obtained from the study is the cost of the raw material used in the 3D printer, and the plastic wastes it produces after its use. Using less raw material also means creating less plastic waste in order to demonstrate that the products can reach the desired resistance values with a lower filling rate. Thus, it has been demonstrated that the low filling rate is both a good strength and a more environmentalist approach.

• Another dimension of product printing with 3D printers is the amount of energy consumed during the manufacture of the product. The amount of plastic consumed per product will also decrease as the amount of plastic that needs to be melted will be less with lower filling rates. In the production process, work can be done to determine the amount of electricity consumed according to occupancy rates.

• On the other hand, how long the layered production technique in 3D printers is required per product. Increasing occupancy rates in terms of time planning is a factor that will increase the product manufacturing time. Therefore, the effect of occupancy rates on unit product manufacturing time can also be investigated.

• The 3D printer's uptime will also increase depreciation costs and directly affect the overall life of the printer. Prints at a low fill rate will shorten the printer's uptime and wear, etc. It will also contribute to the reduction of such problems. Prints at different fill rates can be determined to determine the life of the printer.

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