



Comparison of Mechanical Properties of PLA and ABS Based Structures Produced by Fused Deposition Modelling Additive Manufacturing

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Abstract

Fused deposition modelling (FDM) additive manufacturing is a technology that works horizontally and vertically in which an extrusion nozzle moves on a building platform. Knowing the mechanical properties of the parts manufactured by the FDM method is very important for the parts to work efficiently in places of usage. Additive manufacturing with the FDM method is widespread due to its advantages such as easy-to-use features, low cost, flexibility in material options, and less processing after printing. Two different polymer materials (PLA and ABS), tensile, compression test and 3 point bending tests, a total of 36 test specimens were printed on the FDM type printer. The samples obtained were subjected to mechanical tests to determine their mechanical properties. As a result of the study, the effect of the samples' mechanical properties produced by the PLA and ABS-based FDM method was examined and compared with the literature. The results showed that the mechanical properties of PLA and ABS material are highly dependent on the filling density. While the mechanical properties were improved by the increase in filling density rate, the print speed has been decreased. The research findings obtained are of a nature that will guide the optimization of the FDM method's parts in terms of mechanical properties.

Keywords: Additive Manufacturing, Fused Deposition Modelling, PLA, ABS, Tensile Strength, 3-Point Bending.

Eriyik Yığma Modellemesi Eklemeli İmalat ile Üretilen PLA ve ABS Esaslı Yapıların Mekanik Özelliklerinin Karşılaştırılması

Öz

Eriyik yığma Modellemesi (FDM), bir ekstrüzyon nozulunun bir inşa platformu üzerinde hareket ettiği yatay ve dikey olarak çalışan bir teknolojidir. FDM yöntemiyle üretilen parçaların mekanik özelliklerinin bilinmesi, parçaların kullanım yerlerinde verimli çalışabilmesi için çok önemlidir. FDM yöntemi ile eklemeli imalat, kolay kullanım özellikleri, düşük maliyeti, malzeme seçeneklerinde esneklik ve baskı sonrası daha az işlem yapılması gibi avantajları nedeniyle yaygın olarak kullanılmaktadır. FDM tipi yazıcıda iki farklı polimer malzeme (PLA ve ABS), çekme, basma testi ve 3 nokta eğilme testleri olmak üzere toplam 36 adet test numunesi basılmıştır. Elde edilen numuneler mekanik özelliklerini belirlemek için mekanik testlere tabi tutulmuştur. Çalışma sonucunda PLA ve ABS esaslı FDM yöntemi ile üretilen numunelerin mekanik özelliklerine etkisi incelenmiş ve literatür ile karşılaştırılmıştır. Elde edilen araştırma bulguları, FDM yönteminin parçalarının mekanik özellikler açısından optimizasyonuna rehberlik edecek niteliktedir.

Anahtar Kelimeler: Eklemeli İmalat, Eriyik Yığma Modellemesi, PLA, ABS, Çekme Dayanımı, 3-Nokta Eğme.

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1. Introduction

Additive manufacturing (AM) is a manufacturing method that has entered our lives as a result of the inadequacy of traditional methods and allows the three-dimensional model drawn with computer-aided design to be presented as a product (Nagesha et al., 2020; Çevik et al., 2021). In the AM process, using the model data, a three-dimensional model is produced as a result of adding the material layer by layer (Jiang et al., 2019). The rapid production of parts with complex geometries provides freedom and development in design due to the AM method (Allevi et al., 2019). AM processes are divided into seven categories according to the American Society for Testing and Materials (ASTM) standard. These are classified as binder jetting (BJ), directed energy deposition (DED), material extrusion (ME), material jetting, powder bed fusion (PBF), sheet lamination (SL) and photopolymerization (Tofail et al., 2018; Jiang et al., 2018). AM methods include different processes according to the material, technique and technology used. Commonly used AM methods include stereolithography (SLA), (Gür, 2021) selective laser sintering (SLS), selective laser melting (SLM), fused deposition modeling (FDM), direct metal laser sintering/melting (DMLS/M) technologies (Gardan, 2016; Celebi et al., 2020). Besides, microelectromechanical (MEMS) and actuator systems are also being fabricated with AM techniques (Ertugrul et al., 2020).

Stratasys founder Scott Crump has developed a 3D manufacturing system inspired by his young child playing with colorful play dough. The main name of this technique, which emerged in 1988, is "Fused Deposition Modeling (FDM)". Stratasys company produced its first commercial device in 1991 (Stratasys 1998). FDM is one of the 3D printing technology methods and constitutes 40% of the systems used in the industry in the world (Damodaran et al., 2021). It is a system based on the principle that the layer formed by melting fibrous thermoplastic materials is suddenly cooled and adhered to the previous layer (Burns, 1991). The plastic fiber material, wound on a roll, is fed into the heated FDM head.

In the FDM method, polymer-based material is widely used because of its easy accessibility and low cost. The most common raw materials are Acrylonitrile Butadiene Styrene (ABS) (Çelik et al., 2021), PolyLactic Acid (PLA) (Boğa et al., 2021),

PolyCarbonate (PC), PC/ABS mixture, epoxy, epoxy resins, polyamide (nylon), thermoset and thermoplastic polyurethane. Thermoplastic polymers are used in material extrusion and powder bed melting methods. In the material extrusion method, complex thermoplastics and semi-crystalline polymers are ideally specified in the powder bed melting method. Complex thermoplastics (ABS, PLA, etc.) are high temperature resins and have a randomly arranged molecular structure that does not have a sharp melting point. Therefore, there is a wide viscosity range and temperature control can be done easily in methods such as FDM (Demiray et al., 2018).

Studies on the effect of parameters and fill rates on mechanical properties are continuing in the production of 3D printed components (Yeşil, et al., 2018; Kaptan et al., 2020; Küçüköğlü et al., 2021). However, more detailed studies are still needed. In addition, there is a lack in the literature on comparative analysis of the mechanical properties of popularly used materials such as ABS and PLA.

This study is about examining the processing parameters and material properties of the FDM 3D printing method, which is one of the additive manufacturing methods. Test samples were drawn according to ISO standards for plastics. With the FDM 3D printing method, tensile, compression and bending test specimens containing PLA and ABS materials were produced according to the test standards. Production parameters were chosen as 0.15-0.2 mm layer thickness, 50% and 70% fill rate, 0.8 and 1.2 mm wall thicknesses, 50 mm/sec printing speed, 220 °C nozzle temperature, 60 °C table temperature. Twelve tensile, compression and bending tests were performed with three repetitions for each processing parameter of PLA and ABS material. The obtained results were compared with the literature.

2. Material and Method

2.1. Material

In the study, PLA and ABS filaments were used as workpiece materials and the general properties are given in Table 1. The experimental specimens containing PLA and ABS materials were produced using the Teira 3D brand FDM type printer device as shown in Figure 1.

Table 1. Properties of PLA+ and ABS filament

Printing temperature (°C)	Density (g/cm ³)	Distortion temperature (°C,0.45 MPa)	Tensile Strength (MPa)	Elongation at break (%)	Bending Strength (MPa)	Impact resistance (kJ/m ²)
205-225	1.24	52	60	29	87	7.0
210-250	1.04	98	40	40	73	7.7

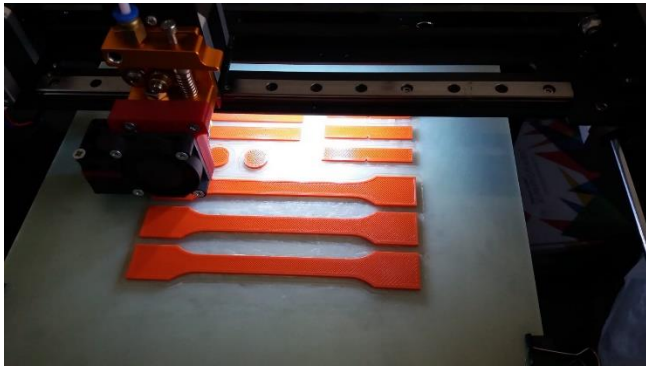


Figure 1. Manufacturing image of FDM 3D printing

2.2. Method

Figure 2 shows technical drawing and dimensions of the test specimens in ISO 527: 1993 standard for tensile strength test, in ISO 604:2002 standard for compressive test, in ISO 178:2001 standard for 3 point bending test of the samples fabricated FDM 3D printer, respectively (Pilipovic et al. 2009). Manufacturing parameters in FDM additive manufacturing using both PLA and ABS materials are given in Table 2.

Tensile test was conducted in a test machine (AGS-X, Shimadzu Co., Kyoto, Japan) with a 10 kN force transducer capacity as shown in Figure 2. Tensile test employed two grips (one fixed grip and one movable grip) to hold the specimens, the specific testing parameters for the tensile test were carried out at a pull rate of 1 mm/s. To minimize the experimental errors, three test specimens were used for each parameter and the average value was accepted as the real value of applied parameter.

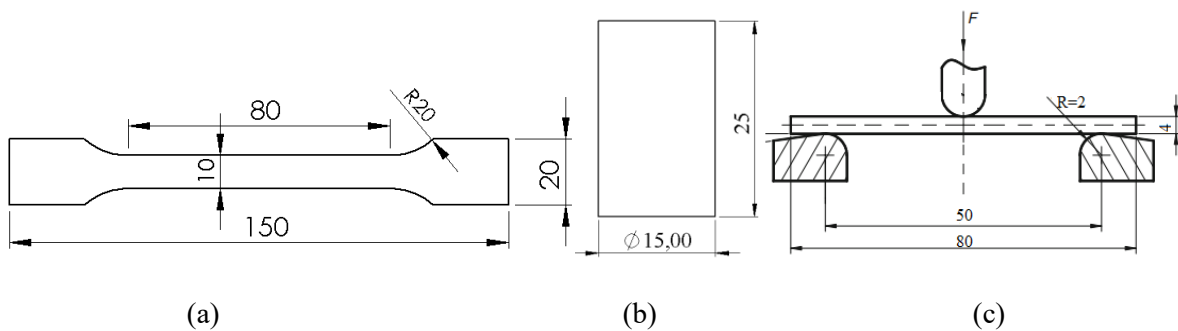


Figure 2. The specimen dimensions (mm) for a) tensile test, b) compressive test, c) 3 point bending test

Table 2. Manufacturing parameters in FDM additive manufacturing method using both PLA and ABS materials

PLA/ABS	Fill Density (%)	Layer Thickness (mm)	Wall Thickness (mm)	Print Speed (mm/s)	Nozzle Temperature (°C)	Table Temperature (°C)
1	70	0,2	1,2	50	220	60
2	50	0,15	0,8	50	220	60

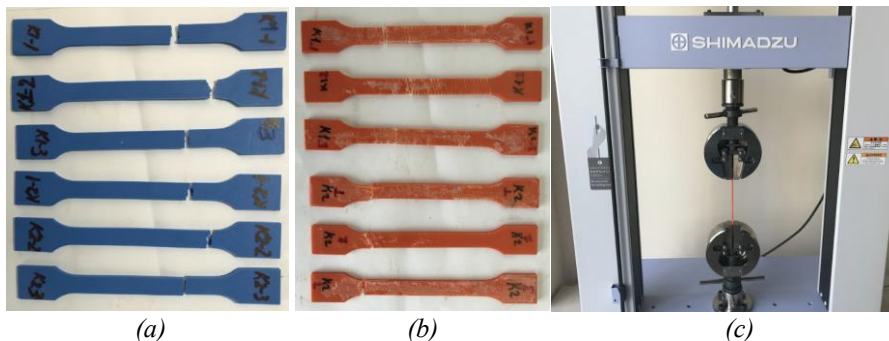


Figure 2. Images of all components of tensile strength test; a) PLA specimens b) ABS specimens c) experimental setup

A compressive test was conducted in a test machine (AGS-X, Shimadzu Co., Kyoto, Japan) with a 10 kN force transducer capacity as shown in Figure 3. The compression test is essentially the opposite of the tension test in terms of the effects of applying a load on the sample. A constant increasing compression load was

applied to both PLA and ABS material specimens placed between two grips in the study.

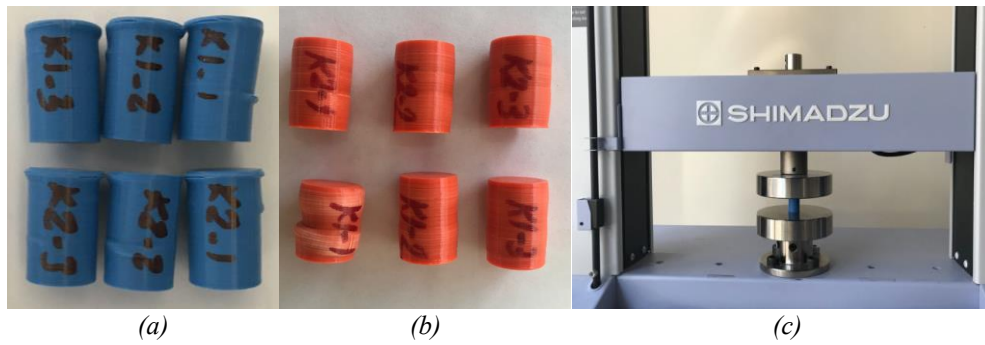


Figure 3. Images of all components of compressive test; a) PLA specimens b) ABS specimens c) experimental setup

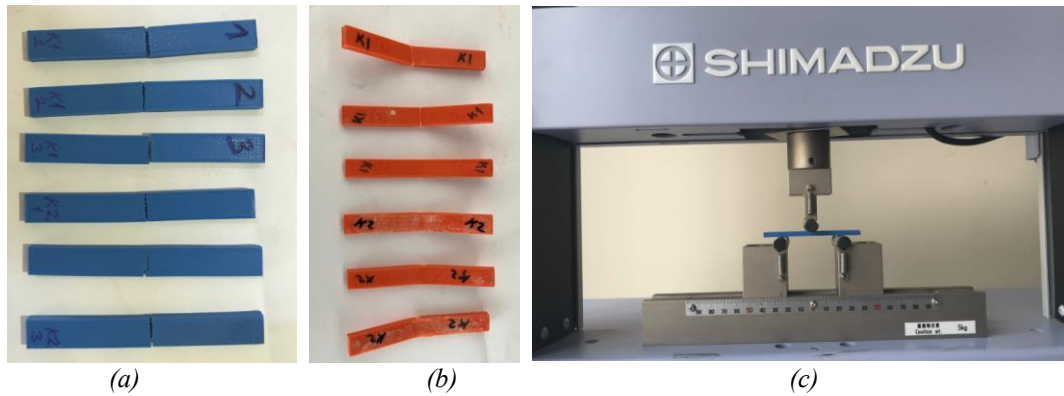


Figure 4. Images of all components of 3 point bending test; a) PLA specimens b) ABS specimens c) experimental setup

The 3-point bending test is usually performed on brittle materials as a substitute for the tensile test. Therefore, 3-point bending test gives more meaningful results in brittle materials. 3 point bending tests were carried out on the machine (AGS-X, Shimadzu Co., Kyoto, Japan) with a 10 kN force transducer capacity as shown in Figure 4. In the tests, the diameter of the mandrel and the diameter of the supports were fixed in accordance with the standard. After the assemblies were fixed, both PLA and ABS material for 3 point bending test specimens were placed on the supports and the specimens were bent with the help of a mandrel with the application of the load.

3. Results and Discussions

Mechanical testing sample groups manufactured by the FDM additive manufacturing method were named according to the mechanical tests to be applied. According to this; the specimen group is named with tensile test specimen group “T”, the compression test sample group “C”, 3-point bending test

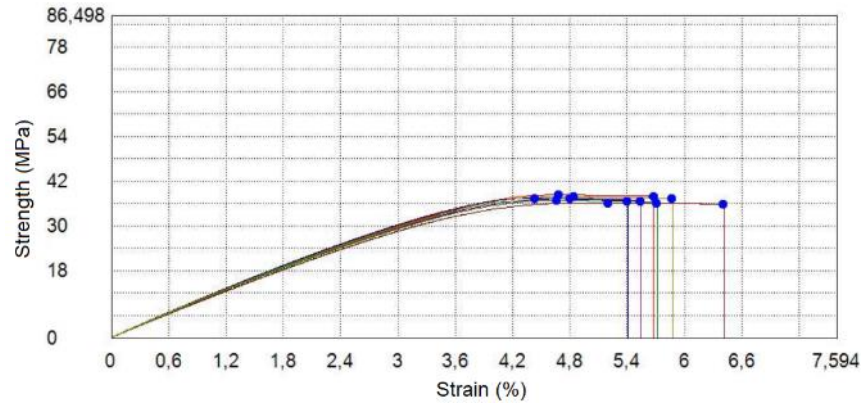
specimen group with the letter “B”. The test results of tensile, compression, and bending specimens manufactured with different process parameters were determined by taking the average of three samples using two different parameters. The research findings were analyzed separately for each mechanical experiment and given in tables.

3.1. Results of Tensile Strength Tests

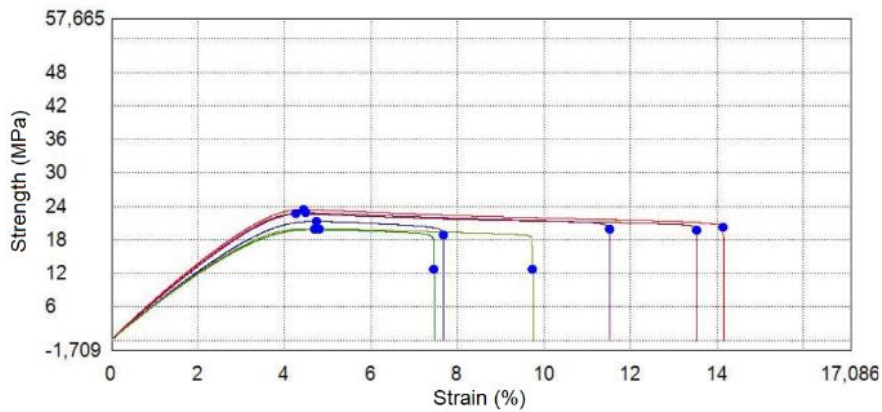
The tensile strength test results obtained from the study are given in Table 3. In Table 3, it is seen that PLA material samples have higher strength values than ABS samples. This is due to the fact that the bond provided between the layers in the sample manufacturing process is better for PLA material samples than ABS samples. In Figure 5, it is seen that the tensile strength of both PLA and ABS material samples increased partially as the fill rate of the samples increased.

Table 3. Results of tensile tests of PLA and ABS material

PLA	Elasticity Module (GPa)	Yield Strength (MPa)	Strain (%)	ABS	Elasticity Module (GPa)	Yield Strength (MPa)	Strain (%)
T1	1.094	38.32	5.67	T1	0.704	23.45	14.14
T2	1.039	36.21	6.40	T2	0.681	22.68	13.52
T3	1.082	37.32	5.53	T3	0.676	22.82	11.51
T4	1.072	36.87	5.71	T4	0.603	19.86	7.45
T5	1.104	37.41	5.40	T5	0.624	21.29	7.66
T6	1.089	37.81	5.86	T6	0.612	20.00	9.74
Average	1.080	37.33	5.76	Average	0.65	21.68	10.67
Standard Deviation	23.01	0.73	0.351	Standard Deviation	42.10	1.53	2.86



(a)



(b)

Figure 5. Stress-strain diagrams of tensile tests for samples manufactured from different parameters a) PLA material, b) ABS material

With the examining of present study and literature studies, in the Svensson study (Svensson, 2017), tensile samples were produced from PLA, ABS, Nylon and TPU materials with the FDM additive manufacturing method and subjected to a tensile test. According to the results obtained, the tensile strengths are 62 MPa, 35 MPa, 29 MPa and 55 MPa, respectively (Svensson, 2017). Grabowik et al. (2017) analyzed wood, PLA, ABS, PET, PMMA and ASA filament material group and material properties with tensile tests using FDM additive manufacturing method. In the results of tensile strength for PLA materials, the value of the peak stress is between 38 and 38.4 MPa. The value of the strain at peak stress is between 5 and 5.3%. The value of the Young's modulus is between 1074 and 1100 MPa. In the results of tensile strength for PLA materials, the value of the peak stress is between 34.6 and 35 MPa. The value of the strain at peak stress is between 5.5 and 5.6%. The value of the Young's modulus is between 856 and 864 MPa (Grabowik et al., 2017). While the tensile test results (66.5 MPa) for horizontal, (49.5 MPa) for flat, (26.1 MPa) for vertical values are obtained, the bending test results are (98.6 MPa) for horizontal, (93.5 MPa) for straight and (42.3 MPa) vertical values were obtained (Caminero et al., 2019). The results obtained in the present study are similar to the literature.

3.2. Results of Compression Tests

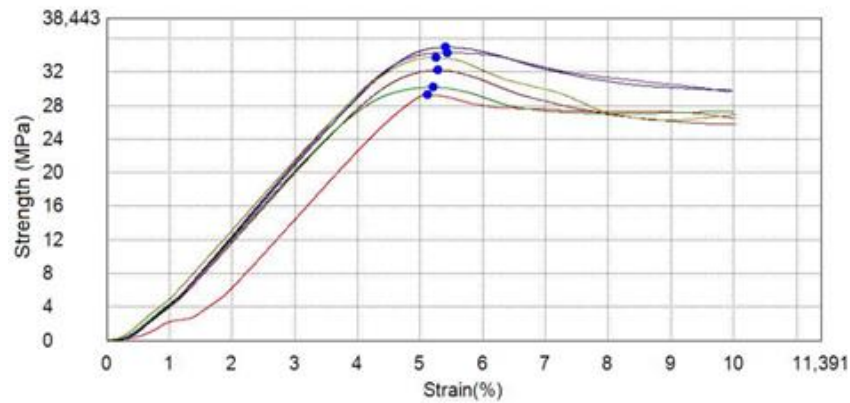
Compression test results obtained from the study are given in Table 4. With the examining the of Table 4, it is seen that PLA

material samples have higher compressive strength values than ABS samples. This is due to the differences in the molecular structure of these materials and differences in the number of branches and functional groups of polymers. PLA has a CH₃ and O₂ group substitutes in materials. This affects the chain entanglement in PLA and increases the glass transition temperature. In addition, as the fill rate increased in PLA and ABS samples, it was observed that the samples were stacked and shortened in the longitudinal section without spreading in the cross section as a result of the compression test. In Figure 6, as the fill rate of the samples decreased, the compressive strength of both PLA and ABS material increased partially. However, the ductility of ABS material shows the rigidity of ABS material and can also be expressed as its resistance to elastic stretching.

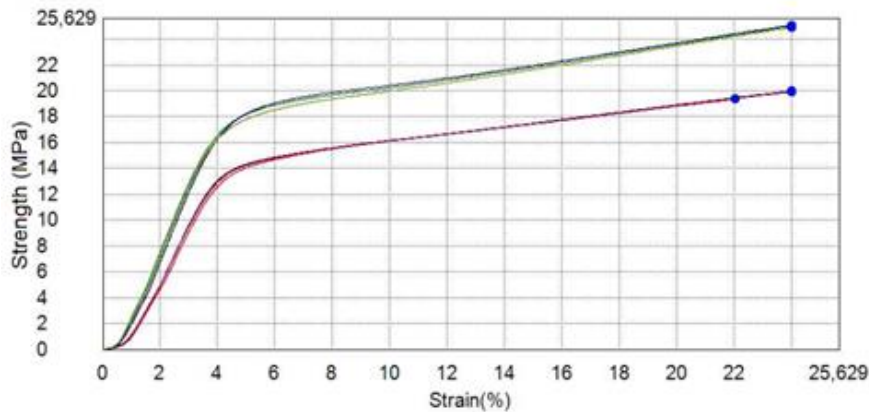
Abeykon et al. (2020) have reported that compressive strength values are 32 MPa and 25 MPa for PLA and ABS materials, respectively. The % strain values are also obtained from 6% for PLA and 17% for ABS (Abeykon et al., 2020). Sood et al. (2012) have investigated that ABS P400 material has five important processing parameters such as layer thickness, part orientation, air gap, raster angle and width, and their effects on compressive strength. The maximum compressive strength was obtained as 17.45 MPa by Sood et al., (2012). The obtained compressive strength results do not contradict other studies in the literature.

Table 4. Results of compression tests of PLA and ABS material

PLA	Elasticity Module (GPa)	Yield Strength (MPa)	Strain (%)	ABS	Elasticity Module (GPa)	Yield Strength (MPa)	Strain (%)
C1	0.814	29.32	5.11	C1	0.412	19.35	22.03
C2	0.818	32.21	5.27	C2	0.430	19.98	24.00
C3	0.865	34.31	5.42	C3	0.420	19.91	23.99
C4	0.822	30.18	5.21	C4	0.547	25.02	24.00
C5	0.857	34.95	5.40	C5	0.547	25.08	24.00
C6	0.829	33.75	5.24	C6	0.547	24.92	24.00
Average	0.834	32.45	5.27	Average	0.484	22.38	23.67
Standard Deviation	21.59	2.29	0.12	Standard Deviation	69.26	2.88	0.80



(a)



(b)

Figure 6. Stress-strain diagrams of compression tests for samples manufactured from different parameters a) PLA material, b) ABS material

3.3. Results of 3-Point Bending Tests

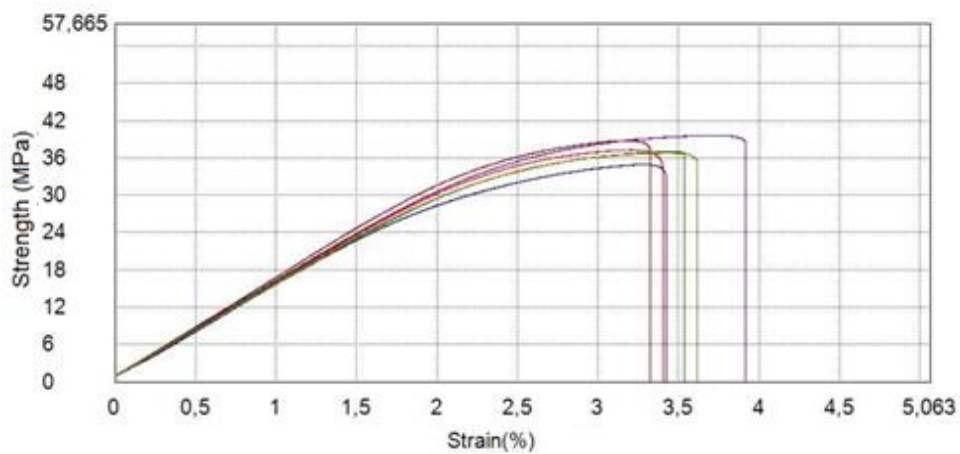
The 3-point bending test results obtained from the study are given in Table 5. Figure 7 shows stress-strain diagrams of samples manufactured from different parameters. It is seen that PLA-containing samples have higher bending strength values than ABS samples. This is due to differences in the molecular structure of these materials and differences in the number of branches and functional groups of polymers. PLA has a CH₃ and O₂ group substitutes in materials.

Palic et al. [17] have produced the samples with a layer thickness of 0.1 mm and 100% fill rate by FDM method with PLA material. Subsequently, these specimens were subjected to the three-point bending test and the obtained bending strength was 214 MPa (Palic et al., 2019). Caminero et al. (2019) subjected PLA-containing samples to tensile and three-point bending tests.

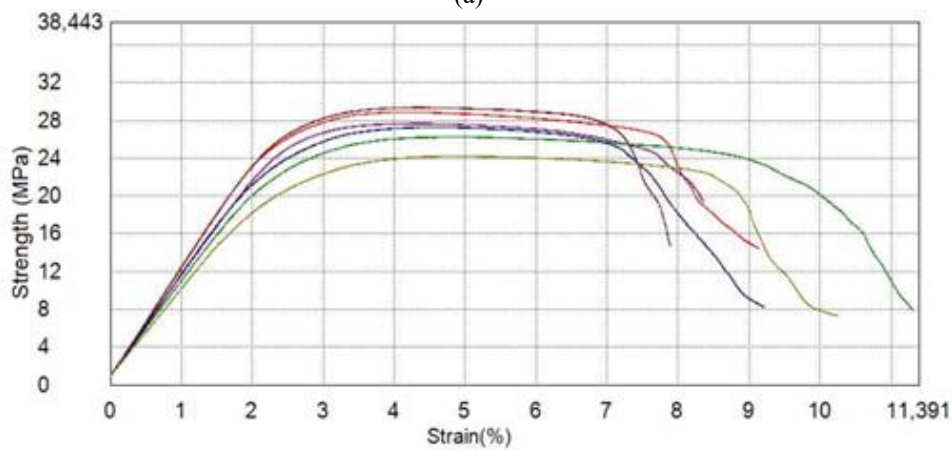
With the FDM 3D printing method, the production direction has achieved 99 MPa for flat, 94 MPa for the front edge and 43 MPa for upright (Caminero et al., 2019). In a study of Kuznetsov (2018), flexural strengths ranging from a minimum of 17.5 MPa to 70.7 MPa were obtained by changing the layer thickness with PLA material with a nozzle diameter of 0.4, 0.6 and 0.8 mm (Kuznetsov, 2018). Khuong et al. (2014) studied the bending strength properties of ABS material samples. The average stress values of the bending samples were 21MPa, and the elongation values were in the range of 12-14% (Khuong et al., 2014). Findings show that the yield strength 3 point bending tests of PLA and ABS materials variable is also related to the filling density, the results obtained are also lower than the literature value in this respect.

Tablo 5. Results of 3 point bending tests of PLA and ABS materials

PLA	Elasticity Module (GPa)	Yield Strength (MPa)	Strain (%)	ABS	Elasticity Module (GPa)	Yield Strength (MPa)	Strain (%)
B1	1.565	37.26	3.40	B1	1.161	28.90	9.14
B2	1.596	38.76	3.32	B2	1.156	29.39	7.88
B3	1.568	39.61	3.91	B3	1.052	27.69	8.36
B4	1.522	36.99	3.53	B4	0.996	26.27	11.30
B5	1.535	34.95	3.42	B5	1.089	27.30	9.21
B6	1.496	36.79	3.61	B6	0.923	24.23	10.25
Average	1.547	1.63	3.53	Average	1.063	27.30	9.36
Standard Deviation	36.18	4.66	0.21	Standard Deviation	92.60	1.87	1.25



(a)



(b)

Figure 7. Stress-strain diagrams of 3-point bending tests for samples manufactured from different parameters a) PLA material, b) ABS material

4. Conclusions

In the study, tensile, compression and three-point bending test specimens were produced through FDM additive manufacturing method with PLA and ABS type filament in accordance with the standards. The direct effects of parameters such as layer thickness, filling ratio and nozzle temperature on mechanical properties were investigated. The mechanical properties of PLA and ABS materials are also compared. According to the findings obtained from the experimental results, it has been observed that the

increase in the filling rate improves the mechanical properties. The best mechanical properties belong to test specimens made of PLA material. ABS materials have the highest strain, and still the analysis results show that it is the lowest strength as compare PLA material. However, their properties depend on the reinforcing agent which is added to binding. In future studies, estimation or regression analysis regarding the surface quality can be examined via big data and artificial intelligence algorithms by expanding the number of materials used in the study and changing the process parameters.

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