Production of compression and flexural test samples in 3D printer with PLA polymeric biomaterial and bone compression with appropriate properties

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ABSTRACT

In this study, it is planned to design and develop a structure close to the real bone strength properties by using PLA (polylactic acid) material. 3D printers have started to take place in our daily lives with today's developing technology and are preferred because of their ease of production and low cost. It has been determined that the PLA biomaterial can be used as a bone substitute in the body. The samples produced have different filling ratios and different internal structures. In the study, the effects of changes in the internal structure on the mechanical properties were investigated. Bone geometry is considered as an important factor among the parameters affecting biomechanical properties. In order to determine the mechanical properties of PLA filament material, bending and compression samples were prepared as 3 pieces for each test. The aim of this study is to determine whether it can be used as bone in the body by measuring the mechanical properties of biocompatible PLA polymer material. In the current work, the quality of the 3d printer and the material used in production directly affects the mechanical properties. In bones in the human body, trabecular bone has 80% porosity and cortical bone 10% infill. In this study, it was tried to obtain structures with properties close to real bone strength by using test specimens with different infill rates. It has been determined from the obtained data that PLA polymer material can be developed and meet the mechanical values in bone.

Keywords:	3D printer, PLA, Biomaterials, Bone, Compression

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1. Introduction

Biomaterials are natural and synthetic materials used to replace organs or tissues that cannot function in the human body. After being placed in the body, biomaterials are in constant contact with the body's fluids and tissues. Therefore, it is of great importance that they are biocompatible. Other properties expected from biomaterials are strength, corrosion resistance, hardness, toughness, density and bioactivity. Biopolymers, which have a wide range of uses in medical applications, also behave biocompatible in the body and can be biodegraded. Surgical sutures, especially used in surgical applications, are produced from polymeric biomaterials [1-2].

The aim of this study is to design PLA material to give mechanical properties close to real bone properties and to investigate its applicability. For this purpose, compression and bending tests were applied [3-5]. By using the developed internal structures, it is aimed to calculate the strength of the samples designed and produced with different patterns and features and to produce finger bones. With the results to be obtained from the research, it is planned to contribute to the literature on biomaterials and 3D printers and personalized bone production.

In this study, samples with 10% porosity and 100% infill parameters were produced by using 4 different patterns as honeycomb, gyro, rectangular and full. The strength values of the samples produced at 10% infill rate and in different patterns were determined and compared with the sample at 100% infill, it was tried to determine the change in strength depending on the pattern and porosity. The results obtained were compared with the data in the literature and interpreted.

2. Experimental study

2.1. Materials and properties

The samples used in the experimental study were designed and produced in a 3D printer using the PLA material, using the fused deposition modeling (FDM) method. The PLA filament used for the 3D printer is 1.75 mm in diameter, 1.0 kg in weight and gray in color [6]. Sample printing temperature is between 190 ^{0}C- 220 ^{0}C. PLA is a biodegradable thermoplastic polymer produced from renewable resources (corn starch or sugar cane), with less toxic content and lower temperature requirements in 3D printing, thus consuming less energy. Mechanical and thermal properties of PLA filament are given in Table 1 [6,7].

Table 1. Mechanical and thermal properties of PLA filament [6,7]

Mechanical Properties	PLA
Tensile Strength	45 MPa
Flexure Strength	97 MPa
Elongation	7.5 %
Density	1.24
Thermal Properties	
Melting Temperature	160-190 C
Printing Temperature	190-220 C

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Production and tests with a 3D printer were carried out on a ZAXE printer at Sakarya University, Department of Mechanical Engineering. The compression and bending samples to be produced were first modeled in the solidworks program in standard test sample sizes and G-codes were obtained using the ZAXE software and the samples were produced in a 3D printer.

2.2. Experiment design and method

The test specimens are at 10% and 100% infill rates, and a total of 12 were produced to perform compression and 3-point bending tests. Samples produced in 3 different patterns and 2 different filling ratios were used in the experiments and their mechanical properties were determined.

2.2.1. Compression test sample

In order to determine the mechanical properties, the diameter of the compression test specimen is 38.4 mm (1.5 inches) and its height is 25.4 mm (1 inch). For the compression test, a total of 12 samples of these dimensions were produced. Internal structure patterns, rectangle, honeycomb, gyro, 3 pieces of each at 10% infill rate and 3 pieces of 100% filled samples were produced (Table 2). In the sample production, the number of walls was determined as 3 and the layer thickness were determined as 0.3 mm.

Table 2. Design images of the internal structures of the designed samples

Internal Structure Pattern	Appearance of the Pattern
Rectangular (10% infill)	
Honeycomb (10% infill)	
Gyro (10% infill)	
Full model (100% infill)	
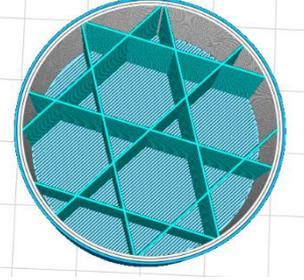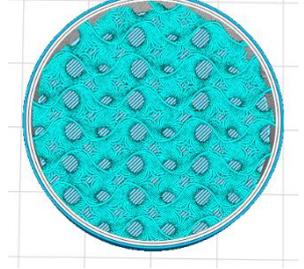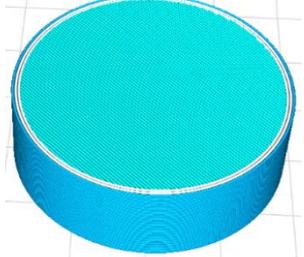
2.2.2. Three-point bending test specimen

Since the three-point bending test specimen is a method frequently used in medical applications, since the bending test specimen is produced. Its length, thickness and height are selected as 140 mm, 5 mm, and 15 mm, respectively. In total, 4 pieces were produced and printed as rectangular, honeycomb, three-dimensional (gyro) and fully filled. The layer thickness is the same as the compression sample.

2.2.3. Printing of bending samples in 3D-printer

The designed bending samples were converted into STL files, and the G code software was matched with the ZAXE 3-D printer, and the printing process was started. The bending specimen was produced 140 mm long, 15 mm wide and 5 mm thick. The rectangular internal structure bending specimen was printed in 26 minutes. The filament used was 2.22 m, and the weight of the sample was 6.654 g. The honeycomb pattern bending sample was printed in 25 minutes. The filament used is 2.22 meters. Its weight was measured as 6.622 gr. The bending specimen has a three-dimensional (gyro) internal structure pattern. The filament used is 2.20 meters and was printed in 26 minutes. Its weight was measured as 6,670 gr.

The bend test specimen is fully loaded. The filament used in production is 4.04 meters long. The weight of the sample displayed on the computer is 11.76 grams. Its actual weight was measured as 12.06 grams. Printed in 40 minutes. After these procedures, the mechanical laboratory was visited for the tests and the tests were carried out.

2.3. Compression and three-point bending tests

The mechanical properties of the products produced by the FDM method are related to the selection of the printer parameters. In this context, test samples with two different fill rates (10%-100%) and four different internal structure geometry patterns [rectangular, honeycomb, three-dimensional (gyro), and fully filled] were printed. Compression samples have a diameter of 38.1 and a height of 25.4. 4 pieces were printed, one of them is 100% filled and the others are 10% full and have different internal structure patterns. Compression samples consisted of a total of 84 layers. There are three solid layers in the lower base and the upper base. In addition, three outer layers with a thickness of 0.3 mm were added to all samples. The nozzle tip is 0.4mm thick. PLA filament was used for the production of the samples. The same filament was used in the manufacturing process. Compressive strength is the performance value of a material under load. The application of the load and the examination of its effect on the sample occurs reversibly as in the tensile test. As a result of the compressive load, the cross-sectional area increases continuously while the sample length decreases. Compressive strength is measured in polymers in the same way as metals. Compression and bending tests were carried out using the 30 KN capacity INSTRON brand test device in the Metallurgical and Materials Engineering Department of Sakarya University. Compression and Bending tests were carried out at a compression speed of 5 mm/s. A total of 8 test specimens were printed, including 4 specimens for the compression test and 4 specimens for the bending test. The compression specimen has a diameter of 38.1 mm and a height of 25.4 mm. The bending test specimen is 140 mm long, 15 cm wide and 5 mm thick.

Bending tests are a method used especially in the medical field, where both the tensile and compression load of the material can be determined and its strength can be measured. The bending stress is the maximum load applied to the sample by the applied load, and after that, the fracture occurs. Deflection is a measure of how much the specimen bends under load. As a result of all these, the mechanical values of the tested sample are revealed and interpretation is made [8-11].

3. Experimental results

In this section, compression and bending tests of our compression and three-point bending test specimens produced on a 3-D printer were performed on the INSTRON 3367 test device at a speed of 5 mm/min, and the test result data were analyzed. The microstructure of some sections of the latest samples has been examined and presented.

3.1 Three-point bending test results

It is applied to determine the strength of materials against flexure strength. A force is applied to the middle of the rectangular sample placed on two supports and the resulting deformation is called flexure. Compressive stress occurs on the inner surface of the test specimen and tensile stress occurs on the outer surface. Bending

tests are generally applied to implants and other materials to be used in the body in medical applications. It is mainly applied to hard and elastic materials.
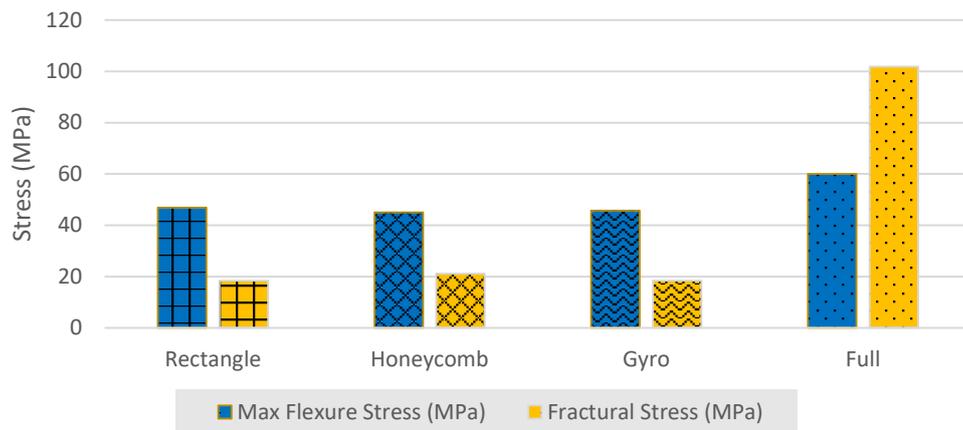
Figure 1. Flexural and fracture stress values of the bending test specimens for different patterns

In the graph given in Figure 1, the values of four flexural samples in different internal structures measured in a 3-ton compression device are given. Accordingly, the flexural stress values of the rectangular, honeycomb, three-dimensional (gyro) microstructure samples are quite close to each other, while the flexural stress of the rectangular microstructure was slightly higher than the others. The flexural stress at break in rectangular, honeycomb, three-dimensional (gyro) microstructure pattern was higher in honeycomb patterned sample. The mechanical values of the filled sample are naturally higher. But what is important here is the mechanical properties of hollow structures. The filled sample showed a very high resistance to tensile.

The graph of the modulus of elasticity of the three-point bending test specimens is given above. According to the graph, it is the honeycomb sample with the highest modulus of elasticity. Then comes the rectangular and three-dimensional (gyro) internal structure. The modulus of elasticity is determined as the ratio of stress to strain within elastic limits. A tangent to the curve is drawn from the initial straight line portion of the load deflection curve [12].

The greater the modulus of elasticity of a material, the greater its stiffness. A non-rigid material has a low modulus of elasticity. A hard material has high elasticity. As can be seen from Figure 2, the elastic modulus of the honeycomb interior pattern sample is high, that is, its hardness is better. As the elasticity value of the material increases, the material becomes harder and changes shape less. Likewise, when the E value decreases, the flexibility and deformation rate of the material increase.
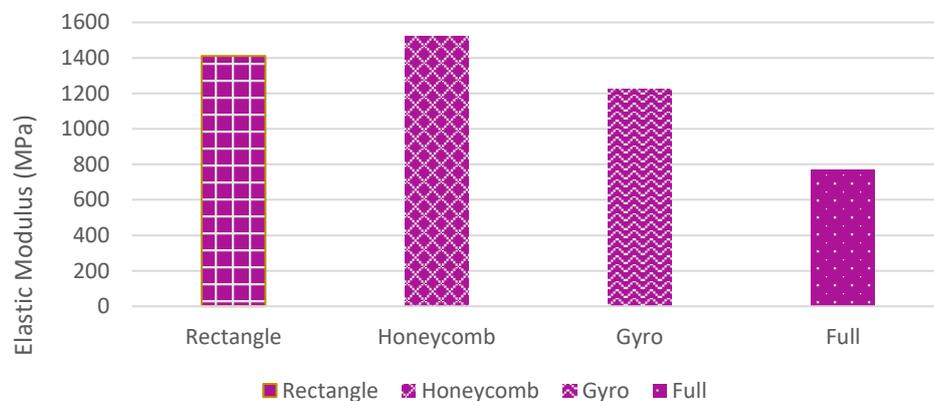
Figure 2. Elastic modulus variation in bending samples for different patterns
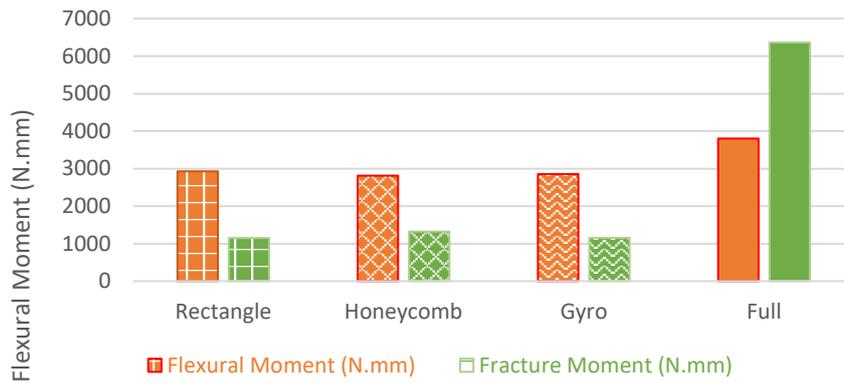
Figure 3. The relationship between flexural and fractural moments values

The flexural moment is found by dividing the product of the distance between the applied force support centers by four, since the force acts in the middle of the test specimen that is freely seated on the two supports (Figure 3). The flexural moment of the full flexural test specimen in the graph is at the highest value. It is followed by a rectangular core sample, a honeycomb sample, and a three-dimensional (gyro) core sample. For ductile materials (metals, polymers), the plastic deformation begins and for brittle materials (ceramics) the force at which the material breaks give the flexural strength of the material. When the flexural test is applied to the material, it is determined as the ratio of the pressure on the material to the deformation of the material during the elastic deformation of the material.
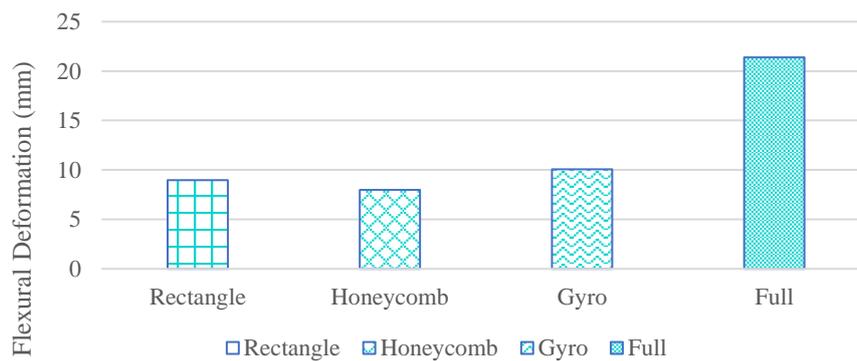
Figure 4. Comparison of flexural deformations for different patterns

Deflection is the amount of flexural in the sample after reaching the maximum flexural point during bending. Here, since the amount of load force acting on the filled sample is greater, the flexure occurred more (Figure 4). This means that the samples with 10% fill rate break after reaching a certain flexural elongation and the process is finished, but since the filled sample does not break quickly, the flexure rate, that is, the amount of deflection, is high.
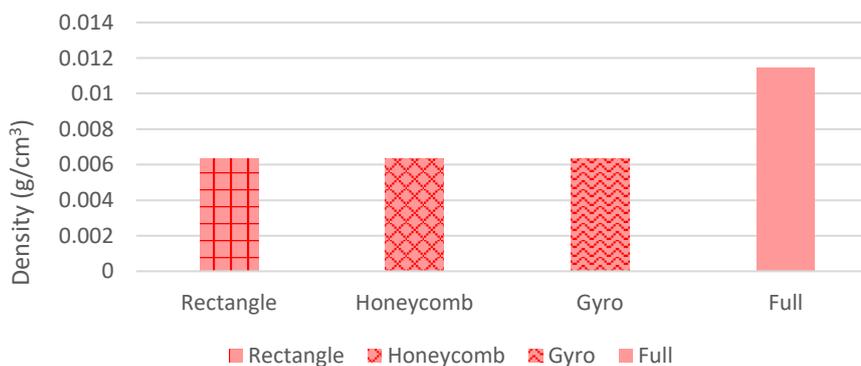
Figure 5. Density variation in bending samples for different patterns

Density calculation is made from D=m/v and here D is the density, m is mass and v is volume, and a graph is obtained according to the result (Figure 5). It is the full sample with the highest density. Afterwards, the three-dimensional (gyro) 10% filled sample with honeycomb core structure and rectangular core sample come. When the three-dimensional (gyro) sample has a wavy structure in shape, it is not in a structure with much space compared to other internal structures, which affects the density. The material to be used in the body should not be too heavy, it is necessary for a person to continue his life more comfortably. For this reason, a conclusion will be reached by considering the parameters of other mechanical properties.

3.2. Compression test results

The compression test is performed by compressing a material and applying the force that causes it to crush. The test sample is placed between two plates. Then the sample is subjected to compression test at the force and speed determined between the two plates. Data and tables related to the test result are obtained from the computer connected to the test device and interpretation can be made about the sample. The main purpose of compression tests is to determine the response of the material under compression load by measuring variables such as stress and deformation. Thanks to the compression test force applied to the material, the compressive strength, yield strength and elastic modulus of the material are determined. As a result, we learn whether the material is suitable for certain applications.
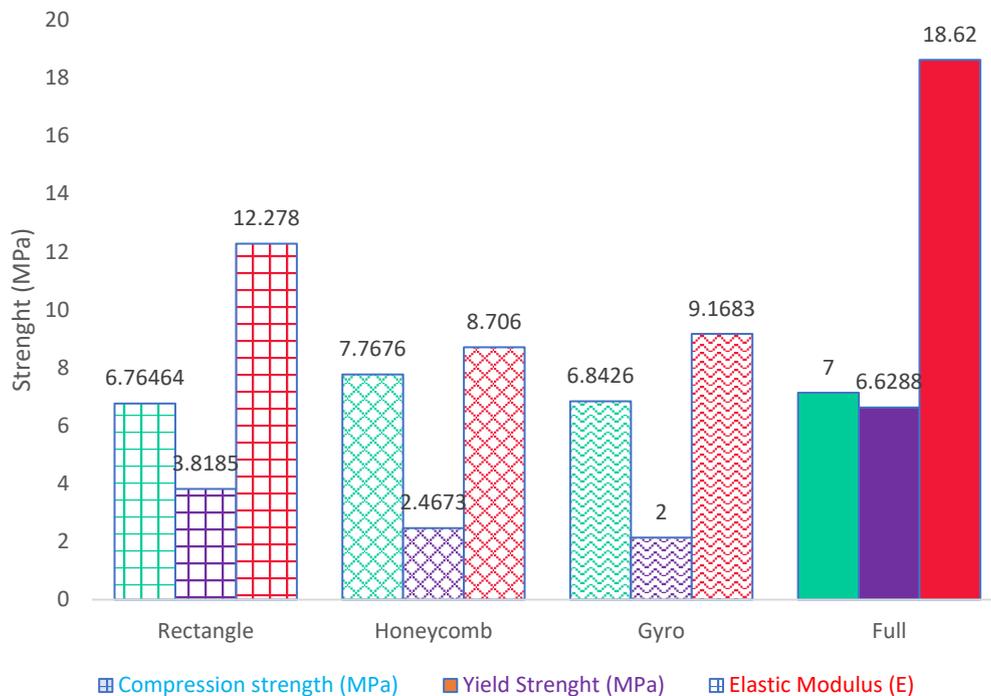
Figure 6. Strength variation in compression test samples for different patterns

In Figure 6, the strength values as a result of the compression test applied to the compression test specimens are given. It is the 10% full sample in the honeycomb inner structure with the highest compressive strength. Compressive strength is determined as the maximum amount of maximum stress that the material can withstand without breaking. For materials with ductile and brittle fracture behavior, the compressive strength has a greater value than the tensile strength.

The sample with the highest yield strength is the fully loaded sample. The return of the material to its original shape after a load is applied to the sample is called elastic deformation. Yield strength is the maximum amount of load that the material can withstand without permanently deforming. The specimen has undergone permanent deformation since the load is applied more than the yield strength. After the full sample, the one with the highest yield strength has a rectangular internal structure, and it could reach a strength of 3.81 MPa.
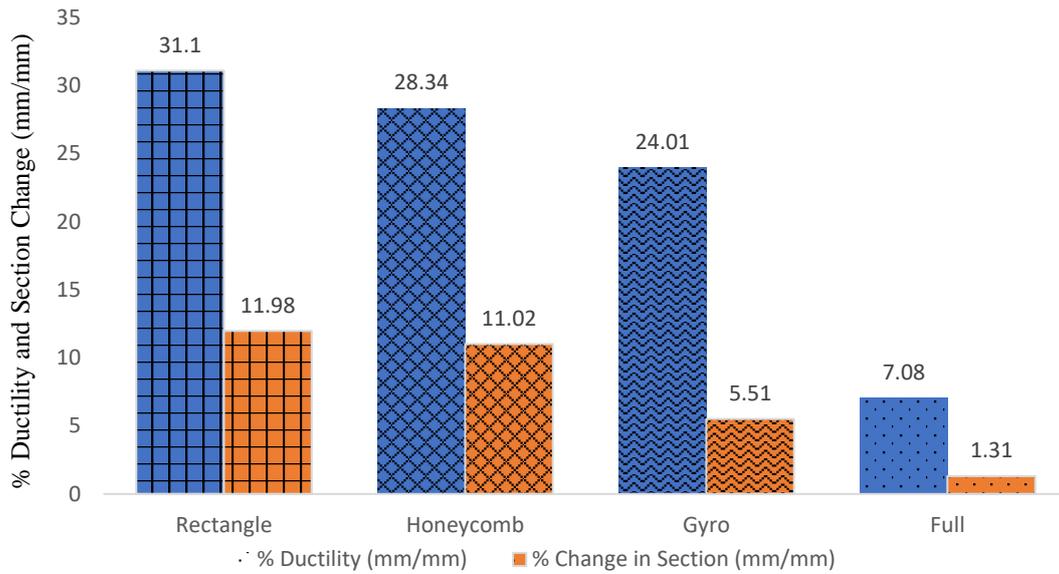
Figure 7. Percentage of slumping and section change in compression test

In order to calculate the changes in the surface and shape of the sample as a result of the test, the % reduction in cross section (ductility) and % section changes are calculated (Figure 7). It is the sample with rectangular microstructure with the highest % reduction in cross section. It is the honeycomb sample with the highest % section change. It occurs as a result of shortening and stacking of the sample, which is exposed to the most compressive strength and compressed the most in the % slumping compression test. The % cross-section change is the rate that occurs as a result of shortening the length and increasing the cross-sectional area during compression.
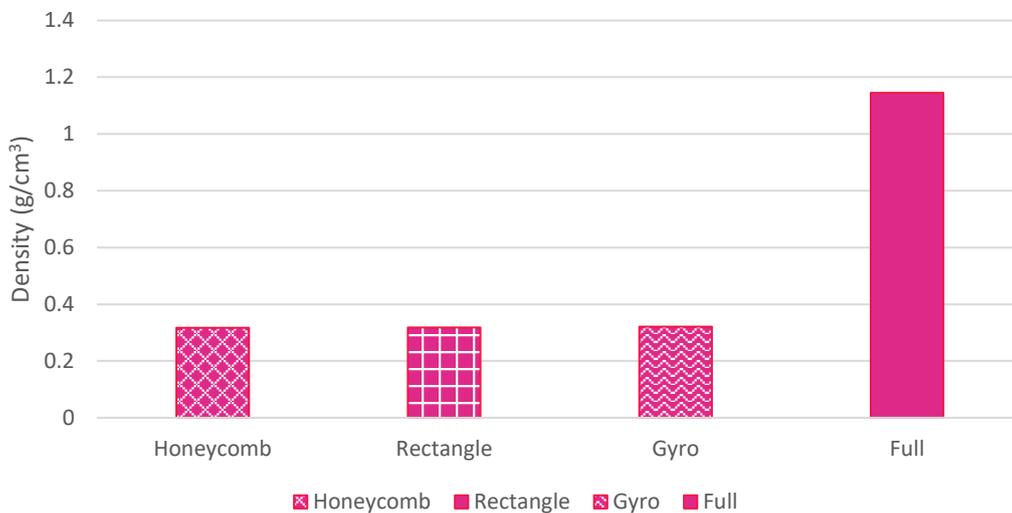
Figure 8. Density variation in compression test samples for different patterns

Density values for hail and 3 different structures are given in Figure 8. As seen in Figure 8, the filled sample is the densest. The densities of the other three structures are very close to each other. From this point of view, it can be concluded that almost the same density of materials is used in 3-D printers, in pallet, rectangular and three-dimensional (gyro) systems.

The mechanical and physical properties obtained after applying compression tests for a total of 4 different patterns, one of which is the full pattern, are shown in Table 3. The full model is given to compare the strength values of other patterns. While the full model has the best values, it also has high values in terms of weight,

production time and amount of material used. Comparison was made to determine the pattern with the best weight-to-weight ratio (specific strength). As can be seen from the table, the highest yield strength and elastic modulus were obtained in the rectangular pattern, and the compressive strength was obtained in the honeycomb pattern among the fabrication patterns examined. Density values were close to each other. In general, it has been determined that the rectangular pattern has higher values.

Table 3. Experimental compression test results of mechanical and physical properties for different patterned samples

Properties / Patterns	Yield Strength (MPa)	Compression Strength (MPa)	Reduction in cross-section (%)	Section Change (%)	Elastic Modulus (MPa)	Density (g/cm^3)
Rectangle	3,82	6,76	31,10	4,98	12,28	0,318
Honeycomb	2,47	7,77	28,34	11,20	8,71	0,317
Gyro	2,20	6,84	24,01	5,50	9,17	0,321
Full	66,80	70,37	24,00	1,31	276,20	1,145

The mechanical and physical properties obtained after applying the bending tests for a total of 4 different patterns, one of which is the full pattern, are shown in Table 4. The full model is given to compare the strength values of other patterns. While the full model has the best values, it also has high values in terms of weight, production time and amount of material used. Comparison was made to determine the pattern with the best weight-to-weight ratio (specific strength). As can be seen from the table, the highest yield strength and elastic modulus were obtained in the rectangular pattern, and the compressive strength was obtained in the honeycomb pattern among the fabrication patterns examined. Density values were close to each other. In general, it has been determined that the rectangular pattern has higher values.

Table 4. Experimental flexural test results of mechanical and physical properties for different patterned samples

Properties / Patterns	Flexural Moment (N.mm)	Flexural Stress (MPa)	Elastic Modulus (MPa)	Deflection (elongation-mm)	Density (g/cm^3)
Rectangle	2928,9	46,86	1410,76	8,969	0,00634
Honeycomb	2813,6	45,08	1522,77	7,982	0,00630
Gyro	2854,8	45,68	1225,31	10,065	0,00635
Full	3803,8	60,08	768,40	21,385	0,011

In Table 5, the mechanical and physical properties for 3 different bone internal structures are compared. It is seen that the strength values of the cortical bone and femur bone are higher. Although the strength of cancellous bone is low, it is light, has high porosity and allows oxygen exchange and bone formation. On the other hand, it is known that cortical bones are used in places where high strength is expected.

Table 5. Mechanical and physical properties for different bone internal structures [13,14]

Properties / Bone Type	Compression Strength (MPa)	Elastic Modulus (MPa)	Deflection (mm)	Flexural Stress (MPa)	Density (g/cm^3)
Cortical Bone	133	70000	-	-	2.0
Spongy Bone	1.9	90	-	-	1.0
Thigh Bone (Femur)	167	17000	0.075	173,5	2.0

The average trabecular bone occupancy (porosity) in a healthy animal is in the range of 70–80%. In cortical bone, this rate drops to 2–4% because its internal structure is spongier. In bone diseases such as osteoporosis, the porosity rate of the cortical bone can reach 10-12%. Porosity is closely related to the strength and flexibility of bone. A small change observed in porosity causes a decrease in mechanical properties and hardness. Cortical

bones have more strength than other regions. The fragility of the bone depends on its shape, density, internal structure and geometry [13,14]. When a compression, tensile or torsion test is applied to the bone, it differs according to the geometric structure and internal structure of the bone, and the test results show different values in the values. It is the honeycomb sample with the highest strength in the compression sample, with a force of 7,767 MPa, and it has a higher value than the compressive strength of cancellous bone, so it can be used instead of cancellous bone. However, the modulus of elasticity is slightly lower, and we can improve this feature by reinforcing the polymer material used. The flexural stress of the femur was measured at 170 MPa. The value of our full flexure sample is 60 MPa, and it may not be suitable because the flexure values are low, about half of it. The flexural elongation deflection values were quite high as 8.96 MPa in the flexural sample, but the deflection of a bone was measured as approximately 0.075 MPa. For this reason, it must be difficult to use instead of bone due to its low fracture strength, or the printed sample should be more comprehensive and in the form of a real bone sample so that the most realistic results can be obtained and development can be made accordingly. As a result, the mechanical properties of compression and flexural specimens in rectangular or honeycomb internal structure are closer to cortical and trabecular bone. In this internal structure, the bone sample below was designed and printed on a 3-D printer (Figure 9).

a)   İnternal pattern

b)   Support material
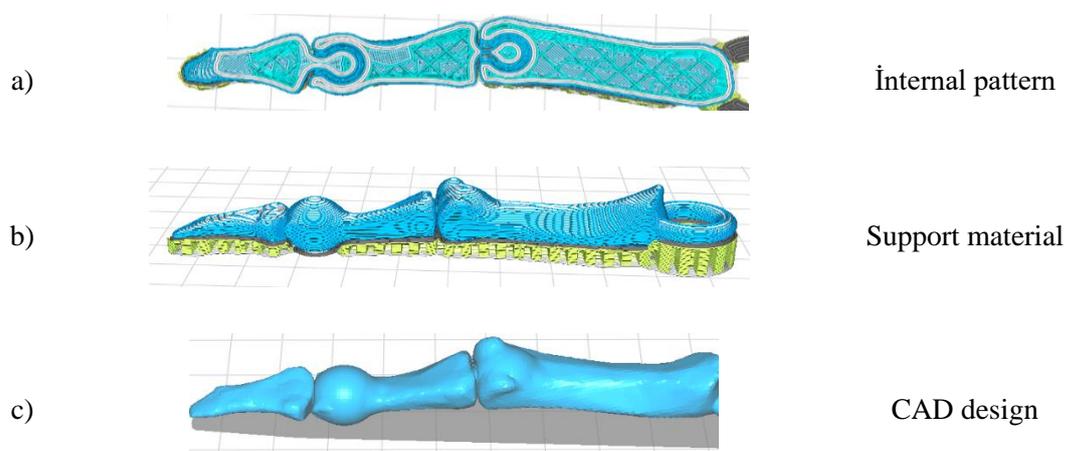
c)   CAD design

Figure 9. Thumb bone design in Zaxe software with appropriate parameters; a) Internal pattern, b) Support material, c) CAD design) [15]

It was designed in a bone interior structure with a rectangular interior geometry, which has a mechanical value suitable for the investigated samples (Tables 3-5). It was printed with the same parameters as the top and bottom three layers at 10% coverage, on the fully filled edge layer, as three layers.

Figure 10. Bone structure produced in accordance with the specified parameter

Thumb bone produced according to the most suitable parameter determined is given in the image of Figure 10. Based on the results we compared with the bone tissue according to the compression and flexural test samples we determined, it was determined that the samples with 10% filling ratio with rectangular or honeycomb inner pattern geometry showed closer mechanical properties to the real bone tissue. The finger bone sample, which has a finger bone, was produced by printing in a 3-D printer. Since it is lighter than metallic implants and does not cause corrosion in the body, PLA polymeric material was chosen and samples were produced and mechanical values were compared.

4. Conclusion

In this study, the mechanical properties of the samples produced from PLA polymeric material, which is used as a biomaterial, were determined and evaluated. Even the smallest negative events that happen to us in our daily life can affect our lives in a bad way, for example, when we walk with an object and fall, and the resulting bone fracture problems can cause a very painful and difficult period [16].

In such cases, implant materials used instead of bone tissue are attached to the body. In general, the most used implant is metallic implants, but there are also many negative aspects. It can corrode the body and release harmful substances into the body, and in some cases, it has adverse effects because it cannot adapt to the body. In this study, samples printed from PLA (polylactic acid) polymer material, which can be produced with a 3-D printer, were produced and compression and three-point bending tests of these samples were carried out. First of all, different internal structure porosities and patterns were determined at 10% and 100% occupancy rate of the samples, which were designed on the computer according to the determined parameters, and then they were produced, and then mechanical tests were carried out. As a result of the mechanical tests, the thumb bone was printed with a 3-D printer in accordance with the internal structure shape and ratio of the samples that gave the closest value to the bone.

The samples that give the closest result to the bone are the 10% filled rectangular and 10% full honeycomb samples. The full sample was not preferred due to its full structure. It was used only for the determination and comparison of mechanical values. If the produced samples are produced and tested in different sizes and thicknesses closer to the bone, better results will be obtained and they can be used as implant material. PLA material is preferred both for its ease of production and because it is easy to procure. Likewise, 3-D printers have become a preferable program because they provide ease of production and are more convenient than production in the factory.

In addition, it is preferred because many parameters can be adjusted from the thickness of the implant materials to be produced, the number of layers and the internal structure to the fullness ratio. At the same time, it provides great convenience and advantage in the production of complex shaped parts that are difficult to produce in the industry.

In this study, the answer to the question of whether the implant produced in a 3-D printer is suitable as a faster solution and to avoid large costs was investigated. In addition, since the use of a renewable material such as PLA in the body will be healthier than metals, it has been observed that better results will be obtained if its mechanical properties can be determined and improved a little more.

In addition, a re-operation is required to remove metallic implants after a certain period of time after they are attached to the body. This is a very important element for the comfort of the patient, but when the PLA biopolymer material enters the body, it melts over time and leaves its place to the bone tissue, which is a great advantage. As in the bone tissue, when the muscles are in contact with the porous structure, bonding occurs, but in most metallic implants, this is a bit difficult.

As a result, the polylactic acid (PLA) polymer material is biocompatible with the body and can bond with tissue. It even disintegrates over time and leaves the tissue formed in its place. Being a renewable resource and being obtained from natural resources is the advantage of using this material. It was seen that the PLA material examined in this study is a biocompatible material chemically and almost approaches the bone tissue in terms of mechanical properties.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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