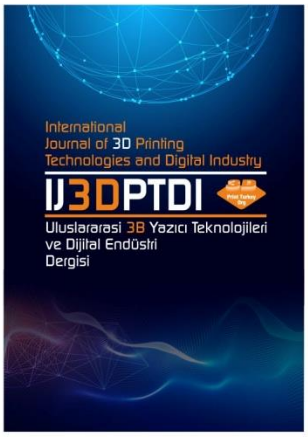

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OPTIMIZATION OF 3D PRINTING PARAMETERS TO MECHANICAL STRENGTH IMPROVEMENT OF SUSTAINABLE PRINTING MATERIAL USING RSM

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ABSTRACT

Fused Deposition Modelling (FDM), one of the most widely used methods of Additive Manufacturing Technique known as 3D Printing, is a popular technique used to produce different engineering components using common engineering polymers. PLA filament, a synthetic polymer derived from corn starch, is generally used in production with the FDM. Although PLA material is recyclable and biodegradable, its carbon emission is not zero. One of the filament types developed to produce more sustainable products is Wood PLA filament materials. This study presents an experimental study examining the effect of printing parameters on the mechanical properties of components produced with Wood PLA filaments. The effects of the printing parameters determined as infill pattern, infill density and nozzle temperature on the mechanical strength parameter determined as tensile strength and flexural strength of PLA Wood samples produced in standard sizes were investigated experimentally. The experimental design was carried out in accordance with the Taguchi L9 orthogonal array, and the relationship between the printing parameters and the mechanical strength parameters was modelled mathematically. The predicted strength values calculated using mathematical models were compared with the experimental test results. The results showed that the tensile strength and flexural strength values were directly proportional to the infill density. Experiments have shown that the most effective 3D printing parameter on the mechanical strength parameters is the infill density parameter with a contribution ratio of 63.09% for tensile strength and 73.83% for flexural strength. As a result of the RSM optimization, it was determined that the infill density 60%, the nozzle temperature value 202.62 C° and the infill pattern type lines to maximize the flexural strength and tensile strength values.

Keywords: Sustainable material, 3D printing parameters, Mechanical strength optimization, Response Surface Methodology.

1. INTRODUCTION

Three-dimensional production technique has become increasingly popular due to its advantages such as ease of use, economic accessibility and fast production process. One of the most important factors in the spread of this technique is the easy accessibility of this technology. In addition, researchers can produce prototypes of the designs they have developed with this technique without the need for complex and experience-requiring production techniques and they can make design changes when necessary. The production of products with complex geometry has also become possible with this method [1]. The interest in 3D production techniques has led to the development of 3D printers, and it has become possible to use different materials in production from polymers to metals, from glass to concrete.

The Fused Deposition Technique (FDM) is the most common production technique known in additive manufacturing technology. A printer working with the FDM technique heats the filament material until it becomes semi-molten using a heater extruder and follows the tool path created by the software, stacking the layers on top of each other from the bottom up to form a three-dimensional object. In the FDM technique, printing parameters can be easily changed and optimized [2, 3].

Different filament materials have been developed by considering factors such as the melting point and extrudability of the material to be used in the FDM technique [4]. The most commonly used ones are acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (Pet-G) and polylactic acid (PLA) thermoplastic filaments with low melting temperatures. PLA filaments are the most commonly used filament material due to their low melting temperature, low cost and positive environmental effects [5, 6]. PLA is one of the biodegradable polymers produced from corn starch. PLA is environmentally friendly, unlike materials such as polypropylene, polyethylene and acrylonitrile butadiene styrene [7]. In addition, it does not pose any health risk to humans in areas where ventilation is provided under appropriate conditions, and it is biodegradable [8].

Although PLA material is an environmentally friendly material, it emits ~1.3 kg of CO^2 equivalent/kg of synthesized plastic [9]. Considering the advantages of PLA filament material, the idea of producing more sustainable materials by mixing these thermoplastic filaments with different biological materials has come to the fore to reduce the effects of intensive material use.

Wood-filled polylactic acid filaments are one of the highly sustainable renewable materials used in production with the FDM technique. Wood is a lignocellulosic material and is carbon negative [10]. By using biological materials, the carbon emissions from printing materials can be reduced. The wood raw material is turned into flour and combined with PLA material by foaming technique, and wood-based PLA filaments can be produced [11]. Wood flour imparts good workability, low density, thermal resistance and corrosion resistance to PLA filament, while also facilitating interlayer adhesion [12].

Academic studies carried out in recent years have focused on examining the effect of printing parameters on different mechanical properties. Optimization of printing parameters for ideal properties determined by different application areas is an important issue for the final use of the product. There is still a deficiency in the literature examining the mechanical properties of filaments developed with different filling materials. Optimization of the mechanical properties of biomaterials is important in terms of increasing the use of sustainable materials.

In this study, the effect of 3D printing parameters on the mechanical properties of samples produced using Wood PLA filament was investigated. The effects of the production parameters determined as infill type, infill density and nozzle temperature on the tensile strength and flexural strength of the samples produced according to the Taguchi L9 experimental design were investigated. Response Surface Methodology was used to determine the effect of each printing parameter on the output values and to determine the optimum printing parameters.

2. MATERIAL AND METHODS

2.1. Printing Material and Parameters

In this study, the effect of the 3D printing parameters of the samples produced with biomaterial (Wood) based filament material on the mechanical properties of the samples was investigated experimentally, and the results were evaluated using statistical methods. ESUN brand Wood PLA filament with wood additive was used in the production of the samples. The filament diameter is 1.75 mm and the same filament was used from a single package throughout the production. The vendor supplied material properties of the filament used are given in Table 1.

Table. 1. Wood PLA filament properties.

Parameters	Value
Density	1.1 g/cm3
Melt index	190 C°/2.16 Kg
Tensile strength	40.74 MPa
Izod notched impact strength	10.55 kJ/m^2
Elongation at break	76.85 %
Flexural strength	61.62 MPa
Flexural modulus	2570.75 MPa
Heat distortion temperature	50.4 C°

For experimental tests, tensile test specimens were designed in accordance with ASTM D638-IV and three-point bending test specimens ASTM D790 test standards. Three-dimensional models of the samples were created with Solidworks solid modeling software and then converted to STL format with Ultimaker Cura software.

2.2. Experimental Design

The printing parameters are an effective factor on the mechanical strength criteria of the samples produced with the FDM technique [13]. Three different printing parameters were used in the production of the samples produced with Wood PLA filaments: infill pattern, infill density and nozzle temperature. Taguchi optimization technique is a frequently used method in the literature to determine optimum mechanical parameters by reducing product development costs [14]. Experimental design was carried out in accordance with the Taguchi L9 orthogonal array with the printing parameters and levels given in Table 2. The cross-sectional views of the tensile specimens converted to STL format for different printing parameters are given in Figure 1.

Table 2. Taguchi design factors and levels.

Factors	Units	Level 1	Level 2	Level 3
Infill Pattern	-	Lines	Triangles	Cubic
Infill Density	%	20	40	60
Nozzle Temp	C°	190	205	215

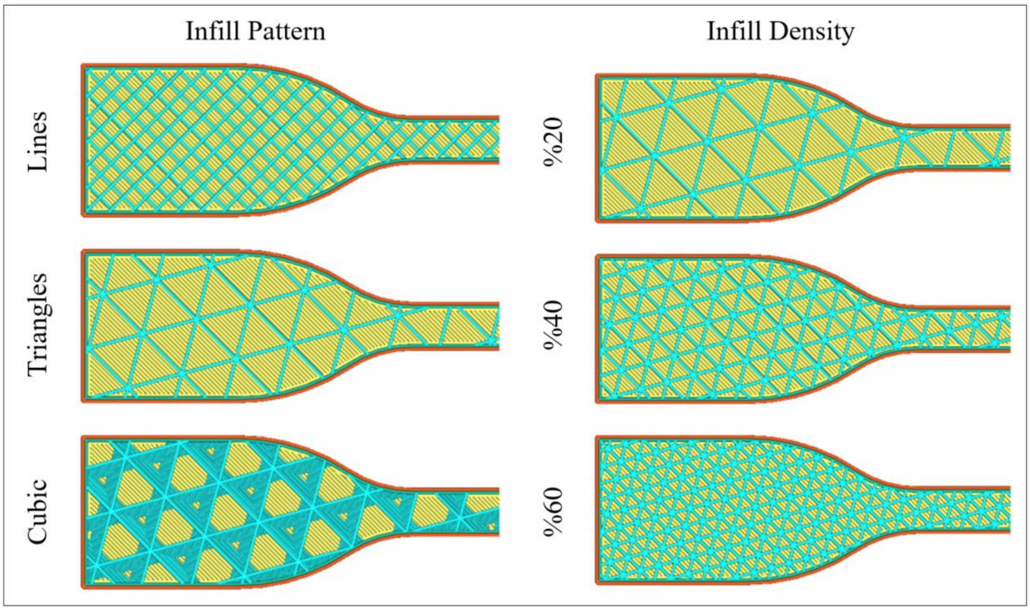


Figure 1. Infill pattern and infill density cross section views.

2.3. Production of Experimental specimens

Experimental test samples based on Wood PLA were produced at room temperature in a commercially available Creality Ender 3 S1 printer, which produces with FDM technique. In the mechanical tests, the number of upper and lower layers was limited to three layers in order to make the effect of the printing parameters on the mechanical properties more evident. Thus, it is aimed to increase the effect of infill pattern and infill density parameters on mechanical properties. In order not to deteriorate the dimensional stability of PLA Wood filaments by being affected by thermal changes, support was created for the samples in the production of the first layer. The printing parameters used in the production of experimental test samples are given in Table 3. In order to ensure the experimental measurement accuracy, a total of 27 samples, three from each sample, were produced.

Table 3. FDM printing parameters.

Parameters	Values
Filament colour	Grey
Filament diameter	1.75 mm
Nozzle size	0.4 mm
Build plate temperature	65 C°
Printing speed	50 mm/s
Density	1.1 g/cm^3
Layer height	0.2 mm
Wall thickness	0.8 mm
Wall line count	2
Top/bottom thickness	0.8 mm
Layer number	3
Build plate adhesion type	Brim
Brim width	4 mm

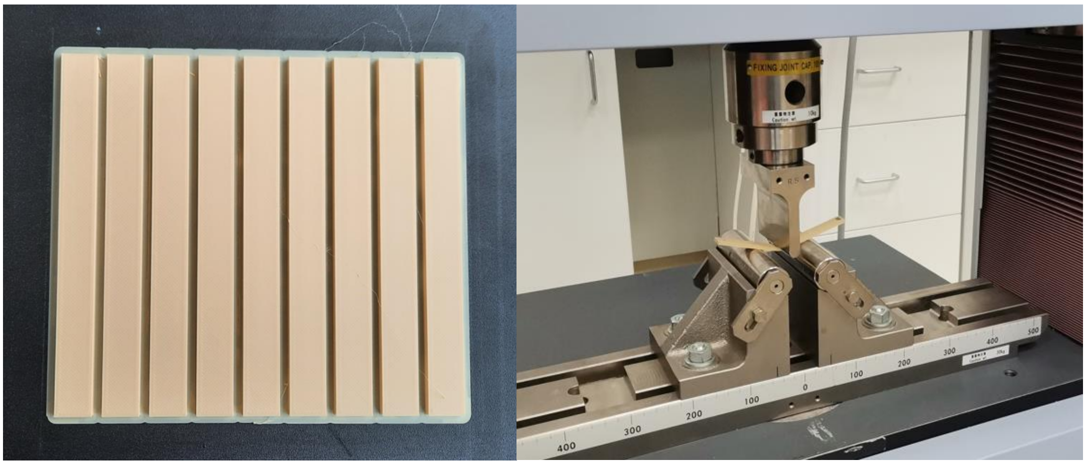
3. EXPERIMENTAL STUDY

3.1. Tensile Test Setup

Tensile test specimens were produced in accordance with ASTM D638-IV test standard. The tests were carried out in the 100 kN capacity Schimadzu Autograph AGS-X tensile testing device in Kastamonu University Central Research Laboratory. Tensile tests were carried out with reference to the literature at a speed of 5 mm/min and the tests were continued until the specimens fractured. Tests for each sample were performed at room temperature in triplicate. As a result of the experiments, the tensile strength values of the samples were determined.

3.2. Flexural Test Setup

The flexural test specimens were produced in accordance with the ASTM D790 test standard (Figure 2a) and the specimens were tested using a three-point bending test apparatus in the device used for the tensile test (Figure 2b). Tests for each sample were carried out at a speed of 1.365 mm/min with reference to the literature, and the test was terminated after 5% deflection occurred in the samples. Three point bending test apparatus loading span diameter of 10 mm and a support roller with a diameter of 30 mm with supporting span length of 51.2 mm were used for the flexural tests. Bending load-displacement curves were recorded from the experimental tests. Experimental specimens and test setup is shown in Figure 2.



(a) (b)

Figure 2. a) Flexural test specimens and b) test setup.

4. RESULTS AND OPTIMIZATION

4.1. Experimental Results

In this study, the effect of 3D printing parameters on the mechanical properties of Wood PLA material samples was investigated. As a result of the experiments carried out with 27 samples, the tensile strength and flexural strength values of the samples were obtained. The arithmetic means of the test results performed three times for each sample was calculated. Experimental test results are given in Table 4. The post-test images of the tensile test specimens are shown in Figure 3.

Table 4. L_9 Taguchi orthogonal array and experimental results.

	Infill Pattern	Infill Density (%)	Nozzle Temp (*C*°)	Tensile Strength (MPa)	Flexural Strength (MPa)
1	Lines	20	190	13.53	36.67
2	Lines	40	205	14.30	43.94
3	Lines	60	215	16.76	49.30
4	Triangles	20	205	12.35	34.98
5	Triangles	40	215	12.78	39.34
6	Triangles	60	190	14.56	40.68
7	Cubic	20	215	13.24	33.98
8	Cubic	40	190	14.64	39.14
9	Cubic	60	205	17.98	47.56

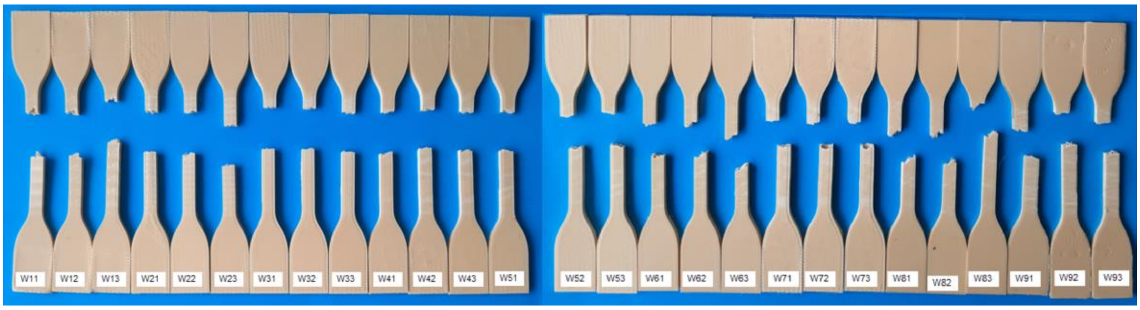


Figure 3. Image of tensile test specimens after testing.

4.2. Response Surface Methodology

In order to produce Wood PLA samples with the best mechanical strength properties, optimization of 3D printer printing parameters is required. Response Surface Methodology (RSM) is a method that optimizes output parameters according to the determined objective function by calculating the statistical relationship between input parameters and output parameters [15]. In this study, RSM was used to determine the relationship between 3D printing parameters and tensile strength and flexural strength output parameters. Optimization calculations were performed using Minitab 21.2 software. The "maximize" objective function was determined for both output variables as the optimization criterion (Figure 4).

Response	Goal	Lower	Target	Upper
Flexural Strength	Maximize	33.98	49.3	49.3
Tensile Strength	Maximize	12.35	17.98	17.98

Figure 4. RSM optimization parameters.

Analysis of variance (ANOVA) at the 95% confidence interval was applied on experimental test results to determine the contribution of 3D printing parameters on output parameters. When the results of the ANOVA analysis were examined, it was determined that the most effective 3D printing parameter on tensile strength was infill density with an additive ratio of 63.09%. The infill pattern parameter, on the other hand, was calculated as the second most effective parameter on tensile strength with a contribution rate of 25.85% (Table 5). The R^2 value of the ANOVA analysis for the tensile strength parameter was calculated as 0.89. This value shows that the regression equations are highly successful in explaining the predicted tensile strength [16].

When the results of the ANOVA analysis performed for the flexural strength parameter are examined; it was determined that the most effective 3D printing parameter on flexural strength was the infill density parameter with an additive rate of 73.83%. The infill pattern parameter, on the other hand, was calculated as the second most effective parameter on flexural strength with a 16.42% contribution rate (Table 6). The R^2 value of the ANOVA analysis for flexural strength was calculated as 93.81. This value shows that the regression equations are highly successful in explaining the predicted flexural strength value.

Regression equations to be used to optimize the output variables were created in accordance with the objective function determined by RSM. The regression equations for the factors are presented in Equations 1-6, respectively, to predict the responses of tensile strength and flexural strength. Since the infill pattern is a categorical variable, the constant coefficients of the regression equations change for different infill patterns. For this reason, the regression equations for the infill pattern were given separately. Using these regression equations, the predicted output parameters for the experimental design parameters were calculated (Table 7). In addition, a graph showing the relationship between the predicted output values and the experimental test results is given in Figure 5.

Table 5. Results of ANOVA for tensile strength.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	24.3637	89.00%	24.3637	6.0909	8.09	0.034
Infill Density	1	17.2721	**63.09%**	17.2721	17.2721	22.93	0.009
Nozzle Temp	1	0.0148	0.05%	0.0148	0.0148	0.02	0.895
Infill Pattern	2	7.0769	25.85%	7.0769	3.5384	4.70	0.089
Error	4	3.0125	11.00%	3.0125	0.7531		
Total	8	27.3762	100.00%				
R^2			89.00%				

Table 6. Results of ANOVA for flexural strength.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	215.642	93.81%	215.642	53.910	15.16	0.011
Infill Density	1	169.708	**73.83%**	169.708	169.708	47.74	0.002
Nozzle Temp	1	8.182	3.56%	8.182	8.182	2.30	0.204
Infill Pattern	2	37.751	16.42%	37.751	18.876	5.31	0.075
Error	4	14.220	6.19%	14.220	3.555		
Total	8	229.862	100.00%				
R^2			93.81				

Infill Pattern	Regression Equations			
Cubic		*11.09*	*+ 0.0848 Infill Density + 0.0039 Nozzle Temp*	(1)
Lines	*Tensile Strength (MPa) =*	*10.67*	*+ 0.0848 Infill Density + 0.0039 Nozzle Temp*	(2)
Triangles		*9.03*	*+ 0.0848 Infill Density + 0.0039 Nozzle Temp*	(3)
Cubic		*10.7*	*+ 0.2659 Infill Density + 0.0928 Nozzle Temp*	(4)
Lines	*Flexural Strength (MPa) =*	*13.8*	*+ 0.2659 Infill Density + 0.0928 Nozzle Temp*	(5)
Triangles		*8.8*	*+ 0.2659 Infill Density + 0.0928 Nozzle Temp*	(6)

Table 7. Experimental test results and predicted output values in accordance with the experimental design parameters.

	Infill Pattern	Infill Density	Nozzle Temp	Tensile Strength (MPa)	Predicted Tensile Strength (MPa)	Difference ratio (%)	Flexural Strength (MPa)	Predicted Flexural Strength (MPa)	Difference ratio (%)
1	Lines	20	190	13.53	13.22	-2.29	36.67	36.10	-1.55
2	Lines	40	205	14.30	14.72	2.94	43.94	45.02	2.46
3	Lines	60	215	16.76	16.63	-0.78	49.30	48.78	-1.05
4	Triangles	20	205	12.35	12.22	-1.05	34.98	34.46	-1.49
5	Triangles	40	215	12.78	12.47	-2.43	39.34	38.77	-1.45
6	Triangles	60	190	14.56	14.98	2.88	40.68	41.76	2.65
7	Cubic	20	215	13.24	13.66	3.17	33.98	35.06	3.18
8	Cubic	40	190	14.64	14.51	-0.89	39.14	38.62	-1.33
9	Cubic	60	205	17.98	17.67	-1.72	47.56	46.99	-1.20

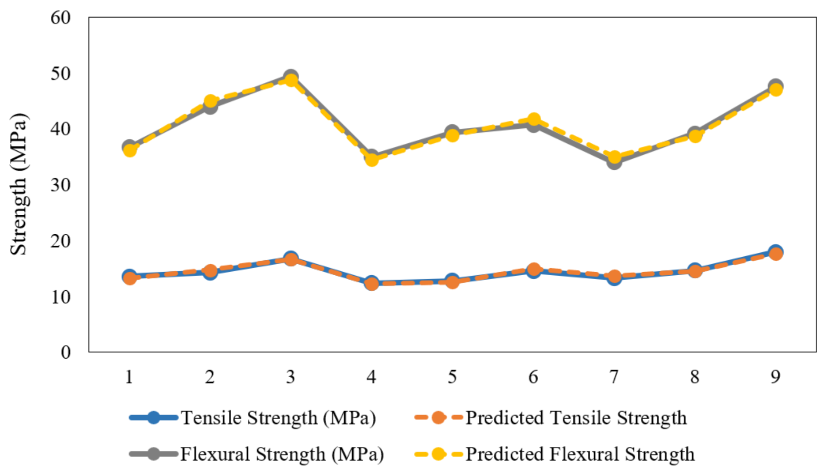


Figure 5. Comparison of experimental and predicted mechanical strength results.

Contour plots graphs are very useful for examining the relationship between a response variable and two factors. In a contour plot graph, the factor values that affect the response variable are shown on the x and y axes, and the values of the response variable are represented by shaded regions called contours [17]. A contour plots graphs is similar to a topographic map, using coordinates instead of longitude, latitude, and elevation. Contour plot graphs obtained as a result of the optimization performed with the RSM method show the relationship between 3D printing parameters and output parameters. In the contour plot graphs were given in Figure 6, the relationship between two different 3D printing parameters and output variables is shown for the factor levels of the categorical 3D printing parameter infill pattern.

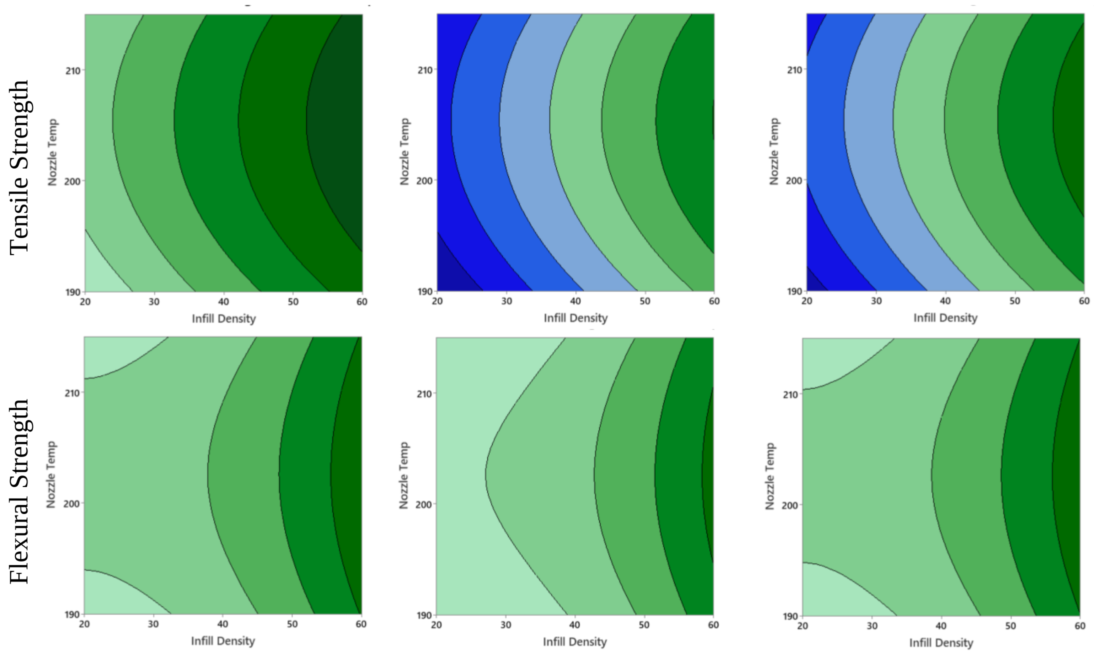


Figure 6. Contour Plot graphs of the relationship between printing parameters and mechanical strength criteria.

As a result of RSM optimization, necessary factor levels were calculated to maximize flexural strength and tensile strength values. The response optimizer graph shown in Figure 7 gives 3D printing parameters that can optimize flexural strength and tensile strength values together. When the results were interpreted, it was determined that in order to maximize flexural strength and tensile strength values, infill density value should be 60%, nozzle temperature value should be 202.62 C° and infill pattern type should be lines categorical parameters. The predicted flexural strength value to be obtained as a result of the selection of these parameters was calculated as 49.96 MPa and the predicted tensile strength value was calculated as 17.27 MPa.

The response optimizer graph also calculates the composite desirability. This value represents the value of countervailing the objective function of the optimization and varies between 0 and 1 [18]. The composite desirability value calculated for this optimization is 0.93. This shows that the determined factor values are 93% successful in countervailing the objective function.

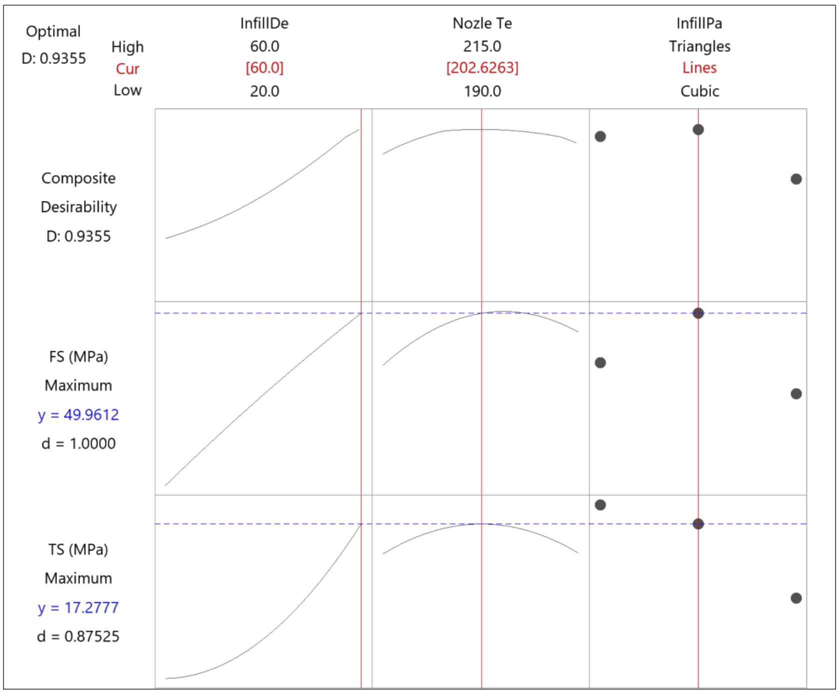


Figure 7. Response optimizer graph.

5. CONCLUSIONS

In this study, statistical analysis and optimization of 3D printing parameters affecting the mechanical properties of samples produced from Wood PLA material were performed using Response Surface Methodology. Regarding experimental tests and statistical analysis, the following conclusions can be drawn:

• Changes in 3D printing parameters are effective on the mechanical properties of the samples, and the mechanical properties can be improved by parameter optimization.

• ANOVA analysis results show that the most effective parameter among the tested parameter values in improving the mechanical properties of the samples produced from Wood PLA material is the infill density parameter. The second most effective parameter is the infill pattern, and the effect of nozzle temperature on mechanical properties is too low to be considered.

• The low difference (less than 4%) between the experimental test results and the predicted test results confirms the accuracy and precision of the optimization procedure to determine the optimized combination of input variables.

• The optimal values of the input variables were determined so that the samples produced from Wood PLA material could provide maximum tensile strength and flexural strength.

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