Influence of Printing Speed, Layer Thickness, and Infill Percentage on the Mechanical Properties of 3D-Printed PLA Filament for Prototyping

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ABSTRACT: Proper selection of infill density, printing speed, and layer thickness could conserve material use, reduce printing time, and give acceptable mechanical properties for prototyping. Previous research has emphasized infill density as the major influencer on mechanical properties in additive manufacturing because a wider range of values is usually considered. However, for this study, 15 %, 17.5%, and 20 % infill densities used in prototyping; 60 mm/s, 70 mm/s, and 80 mm/s printing speeds; and 0.1 mm, 0.2 mm, and 0.3 mm layer thicknesses were selected. Twenty-seven samples were derived based on the Taguchi orthogonal array with three factors and nine runs, and a tensile test according to ASTM D638 was performed on each. Statistical and regression analysis was done to investigate the influence of each of the parameters on maximum tensile stress, load at maximum tensile stress, and modulus respectively for each sample and present a model for further parameter investigation. Printing speeds of 60 mm/s and 80 mm/s gave the highest mechanical properties with layer thicknesses of 0.1 mm and 0.2 mm. The sample with 70 mm/s printing speed at a layer thickness of 0.1 mm has the lowest modulus of elasticity. Lower and medium printing speeds and layer thickness showed higher tensile stress and modulus of elasticity.

KEYWORDS: Printing Speed, Layer thickness, Mechanical Properties, Regression

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I. INTRODUCTION

Additive manufacturing (AM) is fast becoming the choice of manufacturing technique due to its flexibility and adaptability (Suteja & Soesanti, 2020; Travieso-Rodriguez et al., 2019) in prototyping. Several technological innovations which are physical models are first tested with additively manufactured models as proof of concepts before actual fabrication employing the Fusion Deposition Modelling (FDM) method. It is therefore important to painstakingly select the suitable method and parameters that suit the desired performance of the prototype (Song et al., 2022) while reducing the printing time and quantity of materials used. The mechanical properties of additively manufactured parts with varying parameters must be evaluated to ascertain the printing conditions to produce suitable parts for required applications (Ćwikła et al., 2017; Liu et al., 2021; Tetsuka & Shin, 2020). Printing speed, layer thickness, and infill density are considered factors in printing time and quantity of materials (Suteja & Soesanti, 2020). However, most literature investigating these parameters often adopts a wider range of values for the infill density as seen in Table 1, which seems to overshadow the insight on the influence of other parameters. The infill density, layer thickness, and printing speed have been examined individually or combined with different parameters such as infill pattern, build orientation, and rafter angle to investigate their influence on the mechanical properties of selected additive manufacturing materials (Doshi et al., 2021; Jackson et al., 2022), but the range of values usually selected, and the experimental procedures do not represent the real influence (Chicos et al., 2022). In industrial practice, infill density is compromised by other parameters to reduce printing time and material usage (Tanveer et al., 2019) hence the need to investigate the implications of this on the tensile properties of 3D-printed PLA.

Layer thickness is a parameter that affects the print quality, printing time, quantity of materials, and properties of 3D-printed material. Studies have reported the contribution of layer thickness when investigated with other parameters on the mechanical properties of 3D printed materials (Chockalingam et al., 2006). The effect of layer thickness has been studied on the water absorption characteristics of 3D printed PLA based on four layers of 0.05 mm, 0.1 mm, 0.2 mm, and 0.3 mm. It was found that it increased the water absorption property (Ayrilmis et al., 2019). This parameter has also been considered with other parameters for its influence on flexural strength (Nugroho et al., 2018), bond and tensile strength (Liu et al., 2021) hardness (Alshamrani et al., 2022), and the accuracy of a printed specimen (Zhang et al., 2019). The findings showed that higher values of layer thickness may reduce the tensile stress of printed materials but may increase other properties such as the flexural, impact and fatigue strength (Vaezi & Chua, 2011).

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Table 1: Related Works on ANOVA and Printing Parameters

Author	Analysis	Properties	Materials	Sample size	Parameters considered and range
Ahmad et al., 2022	Numerical	Warpage deformation	PEI ABS PA 6	81	Print Temperature, Printing speed, Bed Temperature, Infill Density, Layer Thickness, Infill Pattern
Kechagias, 2024	Experimental	Flexural strength	ABS	25	Infill Density (15-100) Rafter Angle (0-90) Nozzle Temperature (20-60) Layer Thickness (0.1-0.3) Bed Temperature (90-110)
Sultana et al., 2024	Experimental	Tensile strength Maximum load Elongation Elastic modulus	Wood-PLA	9	Layer Thickness (0.1-0.3) Infill Density (50-100) Printing speed (10-20) Nozzle Temperature (180-190)
Alzyod et al., 2023	Numerical	Residual stress	ABS	27	Print Orientation (Horizontal, Slant, Vertical) Rafter Angle (0 -90) Infill Pattern (0, Z, 90)
Dixit & Jain, 2022	Experimental	Compressive strength Tensile strength	TPU PLA	9	Printing speed (40-60) Layer Thickness (0.1-0.3) Infill Density (50 - 100)
	Experimental	Max. Tensile Stress Elastic Modulus Load @ Max Tensile Stress	PLA	27	Printing speed (60-80) Layer Thickness (0.1-0.3) Infill Density (15, 17.5, 20)

PEI- Polyetherimide, ABS-Acrylonitrile butadiene styrene, PA 6- Polyamide 6, TPU -Thermoplastic polyurethane, PLA- Polylactic acid

Printing speed plays an important role in the outcome of printed materials as a measure of the rate of building up the materials in layers. The deposition rate of the layers affects grain cohesion, which determines and controls how the material deflects to force or applied load. It is influential, especially for continuous fiber composite printing based on its role in the morphology output (Akhoundi et al., 2023). The influence of printing speed on wood polylactic acid composite morphology and mechanical properties was studied and found to influence tensile properties negatively at higher values (Yang & Yeh, 2020). When the effect of printing speed was investigated with extrusion temperature on the tensile strength and dimensional quality, it was observed that the printing speed increases the tensile strength (Ansari & Kamil, 2021). The type of material being printed also influence the printing speed. For instance, despite the initial assertion, high printing speed produces high-quality and high-performance thermosetting polymers (Kuang et al., 2018). However, Geng et al (2019) opined that the printing speed contribution can be improved by optimizing the extrusion diameter thereby eliminating the inconsistencies in the extrusion process (Geng et al., 2019).

The infill density is a major determinant of weight in printed materials. Hence the justification for its high tensile and yield strength, and its contribution to higher printing time and more material usage (Sriya Ambati & Ambatipudi, 2022; Suteja, 2021; Suteja & Soesanti, 2020). The effect of infill density is peculiar to different mechanical properties and varies with the choice of parameter selection and combination.

Similar works as summarized in Table 1, examining the effect of printing speed, layer thickness, and infill density on the mechanical properties of 3D printed parts, chose a wide range of values 0 – 100 % at an interval of 20 % for the infill density (Ahmad et al., 2022; Alzyod et al., 2023; Alzyod & Ficzere, 2023; Dixit & Jain, 2022; Kechagias, 2024; Sultana et al., 2024). They are closely related to the presented work which employed Taguchi design of experiment (DOE) to select several experimental samples among several printing parameters. It was obvious from these works that a wider range of values for the infill density places it above other parameters, which is the major influence for higher mechanical properties. None of the articles considered infill density, printing speed, and layer thickness within the range of values selected for this study. However, these higher or wider ranges of infill density are not necessary for printing experimental prototypes which are for laboratory testing rather than real-life test scenarios (Kotlinski, 2014).

A similar work by Khan et al., 2023 considered infill densities of 15 %, 30 %, and 45 % for a tri-material. The result showed tensile strength between 27 and 39 MPa. dos Reis et al., 2024 investigated the geometrical behaviour of PLA and Polycarbonate (PC) materials with different infill densities. The mechanical properties increased with increased infill densities. Similarly, Hamoud et al., 2024 reported that maximum strain was exhibited at 50% infill density for a PLA/Cu composite when infill densities and infill patterns were varied. PLA reinforced with chopped carbon fibre (cCF PLA was tested with 60 %, 80 %, and 100 % infill densities under tensile loading. The mechanical properties measured showed that the sample with 100 % infill density had the highest value (Mayandi et al., 2024). Meanwhile in another work to investigate the impact of infill density on rotating bending fatigue behaviour for PLA materials, the experimental data was modelled and the mechanical properties values compared well (Ftoutou et al., 2024).

In practice, an infill density of 20 % is enough for prototyping and experimental purposes according to Chicos et al., 2022 who concluded that an infill density of 25 % can be used in place of 50 % infill density because the difference between the investigated properties of samples with these values was minimal (Chicos et al., 2022). In addition, Chicos et al., 2022 established that selecting uniform close values of infill density as factors of consideration gives the actual behaviour other than a wide range of values. Taking a cue from this, this work investigated the influence of printing speed and layer thickness within a short range of values of infill density on the tensile properties of 3D printed samples through experimental and statistical approaches. In addition, efforts were made to verify if low infill density values are sufficient to describe its influence by deriving a regression equation for this purpose. The material use and printing time in this range of values are minimal.

II. MATERIALS AND METHODS

A. *Material Preparation*

As discussed earlier, three printing parameters were varied: layer thickness, infill density, and printing speed. These three parameters directly influence the print quality, because an alteration in any of the parameters results in a change in the printing time and quantity of materials consumed. Flash Forge Creator Pro 2 FDM printer was used because it has two nozzles to achieve faster printing since multiple prints are made at a time. The printer specifications are a nozzle diameter of 0.4 mm, filament diameter of 1.75 mm, XY accuracy of 0.011 mm, and Z resolution of 0.0205 mm. Ultimaker CURA slicer was used for its general adaptability for most printers as the PC connects to several printer types. The samples were placed on the slicer bed with different orientations to investigate the orientation with the lowest printing time. The short printing time was recorded when the samples were laid flat on the bed, hence the flat position was used in this study. The horizontal position was used because the print bed of the printer allows easy removal of printed parts, however small, hence no brim was added. The commercial Wanhao PLA used in this study was made in China. It has a tolerance of + - 50 Micron, 100 % with no bubbles, and a bed temperature range of 0 – 60 ^{0}C. Samples with 0.3 mm layer thickness consumed more materials than those of 0.1 mm and 0.2 mm.

Printing time and material consumption are major interests in the prototyping laboratory since the models are not for real applications. Within the research period, multiple models will be made, hence cheaper and faster prototyping is desirable. The printing speed and layer thickness range are closer than the infill density values. It was reported that the middle range of values of infill density is sufficient to achieve the desired print quality required for these prototypes and that 25 % infill density can replace 50 % infill density with similar results (Chicos et al., 2022; Mishra et al., 2021). A print temperature of 2200C and bed temperature of 600C was used. The filament storage and the printing were in the 3D printing laboratory with monitored ventilation and dust-free enclosure. These are necessary for the integrity and accuracy of the results.

The layer thickness range depends on the manufacturing specifications for each FDM printer. However, the Creator Pro 2 used for this experiment has a layer thickness range between 0.1 mm and 0.33 mm. Three levels of thickness were used: 0.1 mm, 0.2 mm, and 0.3 mm. These values and their variants have been used extensively in literature (Chockalingam et al., 2006; Shubham et al., 2016)

Printing speed is the rate at which the nozzle moves along the X and Y axes while depositing molten filament onto the platform, which also dictates the movement of the z-axis. The printing speed can affect surface finish, accuracy, and strength. Like the layer thickness, the range of values for the printing speed depends on the manufacturer's specifications. The default printing speed for the Creator Pro used is 70 mm/s, but the three levels of printing speed used for this experiment are 60 mm/s, 70 mm/s, and 80 mm/s.

Infill density relates to the amount of material between the surface layers of the printed part. It is very critical to the strength of the part, and it determines the weight, the strength, and the durability of the part. Like the other two parameters, its range of values depends on the printer type. The three levels used for the experiment are 15 %, 17.5 %, and 20 %. The choice of this range was based on previous prints which showed there was little variation in printing time and material usage when this range was used. However, in most literature, a wide range of these parameters is used as seen in Table 1, it does not reflect the exact influence of this parameter because the wide range values are too wide to intimately track the effect of the infill density. The grid infill pattern was selected for this experiment.

Taguchi's design of the experiment is considered to reduce the number of variable mixes in experimental investigations. Sabarish and Paul (2019) berated this method for its inadequacy to sufficiently test all variable combinations indicating that most experimental designs only account for a few parameter considerations and are usually not sufficient to describe the behaviour of these parameters (Sabarish & Paul, 2020). However, it was discovered that to improve the output, more runs can be chosen in the orthogonal array. This yields more experimental samples, ensuring all possible variable mixes are combined and evaluated. The Taguchi L9 orthogonal array with three factors was selected for this study. To ensure all possible mixes, nine runs were chosen, and 27 experimental samples were derived as shown in Table 2. This experimental design ensures that all possible mixes of variables are drawn for the experimentation by varying the parameters on three levels: infill density (15 %, 17.5 %, and 20 %), printing speed (60 mm/s, 70 mm/s, and 80 mm/s), and layer thickness (0.1 mm, 0.2 mm, and 0.3 mm). Initially, the L9 array (3 by 4), which results in 9 experiments, was investigated, but it was observed that the parameter mix was insufficient to give a wide range of results (Table 3).

B. Experimental setup

Plastic tensile tests were conducted using the Instron Series 3369 – 50kN capacity Tensile testing machine (Figure 1) according to the ASTM D638 type I (Figure 2) because it is known for its precision and reliability in conducting tension tests according to various international standards. The experiment was repeated once to ensure consistency and credibility of the experimental results, ensuring consistent and repeatable results. The tensile testing was conducted at a rate of 1 mm/min at room temperature in the mechanics laboratory while the values of the force and extension were recorded in real time by the data acquisition system. These results were extracted from the data unit and analyzed for the various properties desired. From the experimental data recorded, the maximum tensile stress and modulus of elasticity were determined according to equations 1 & 2. Similarly, the load at the maximum tensile stress was also determined.

$$\sigma_{max} = {P_{max}}/{A_0} \quad (1)$$

$$E = {Stress}/{Strain} = (\sigma_2 - \sigma_1)/(\varepsilon_2 - \varepsilon_1) \quad (2)$$

where P_{max} is the force required to break the sample, A_0 is the original cross-sectional area, σ_{max} is the ultimate tensile strength and E is the modulus of elasticity.

C. *Determination of Significance of Printing Speed and Layer Thickness in ANOVA*

The experimental data was further analyzed using Taguchi and ANOVA to determine the significance of each parameter on the maximum tensile stress equation, modulus of elasticity of the material equation, and load at maximum tensile stress at 95% confidence level.

D. *Regression Analysis*

The regression of the evaluated mechanical properties was carried out to derive equations to derive or predict mechanical properties of selected infill density, layer thickness, and printing speed printing parameters. The K value for the validation was set at 10. Higher values of infill density were inserted using data from the work of Lundberg et al., 2022 to validate the suitability of the equations derived. These values were plotted and compared with experimental data.

Figure 1: Instron Series 3369 Tensile Testing Machine

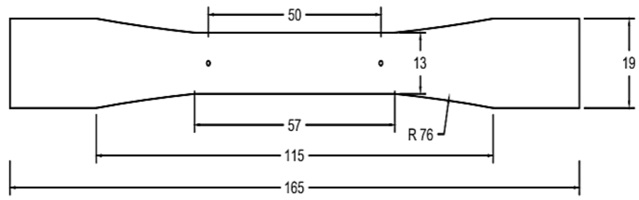


Figure 2: PLA Test Sample

III. RESULTS AND DISCUSSIONS

In this section, Figures 3 – 9 present the mechanical properties evaluated, the effect of the infill density and layer thickness on the mechanical properties, the experimental analysis, and the evaluations reported and discussed.

A. Experimental results of the mechanical properties

The experimental results of the testing were acquired by the data acquisition unit as force and extension. From these results, the maximum tensile stress, load at maximum tensile stress, and the modulus of elasticity were calculated as presented in Table 2. The results of the 9 experimental samples are presented in Table 3. From these two tables, the factor mixes with the highest and lowest modulus of elasticity 930 MPa and 400 MPa were not considered. Similarly, the values of tensile stress corresponding to these values were missing. This validates the assertion that Taguchi DOE limits the quality of outputs in an experiment unless more experimental runs are selected to cater to all parameter mixes (Sabarish & Paul, 2020).

In Figure 4, when the printing speed was 60 mm/s and 15% infill density, the modulus reduced with an increase in layer thickness. However, a different scenario is recorded for the 70 mm/s and 80 mm/s, with fluctuations in the values. A similar scenario was noticed for the 17.5 % and 20 % infill densities, where the lowest speed and layer thickness gave higher values for the modulus of elasticity than when the factor values were high, like the findings of Shergill et al, 2023 on the effect of layer thickness on the modulus of printed PLA (Shergill et al., 2023). Furthermore, in most cases within this region, the values of the properties at lower printing speeds are higher than the range for higher speeds for each of the group's infill density looking at A, B, C, J, K, L, S, T, and U. This goes to prove that lower printing speeds can improve toughness, which can be explained by improved cohesion as the deposition of material is gradual allowing for slow cooling (Loskot et al., 2023).

During the printing, samples with lower layer thickness took more time to print compared to those with higher layer thickness. Summarily, the printing time is inversely proportional to the layer thickness (S. Song et al., 2023).

B. Influence of layer thickness and printing speed on the properties of the printed samples

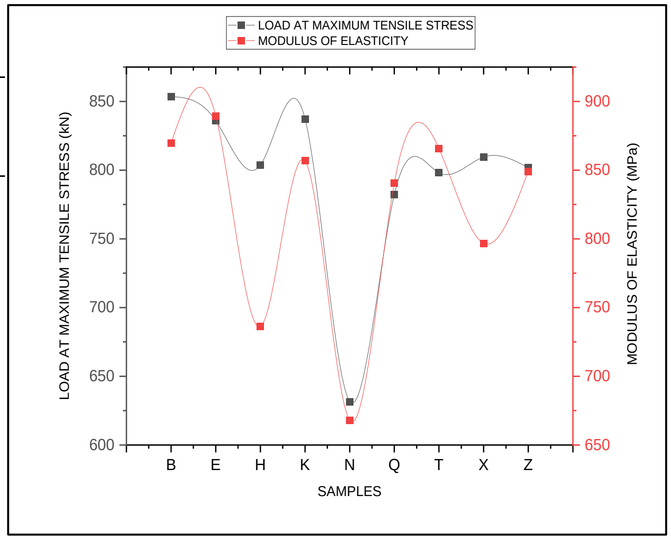
The experimental results were grouped according to the layer thickness as 0.1 mm, 0.2 mm, and 0.3 mm respectively for the modulus of elasticity and load at maximum tensile stress are presented in Figure 3. In the plots, samples with 0.1 mm layer thickness had more variations than 0.2 mm and 0.3 mm.

Table 2. Experimental results of σ_{max}, P_{max} , and E

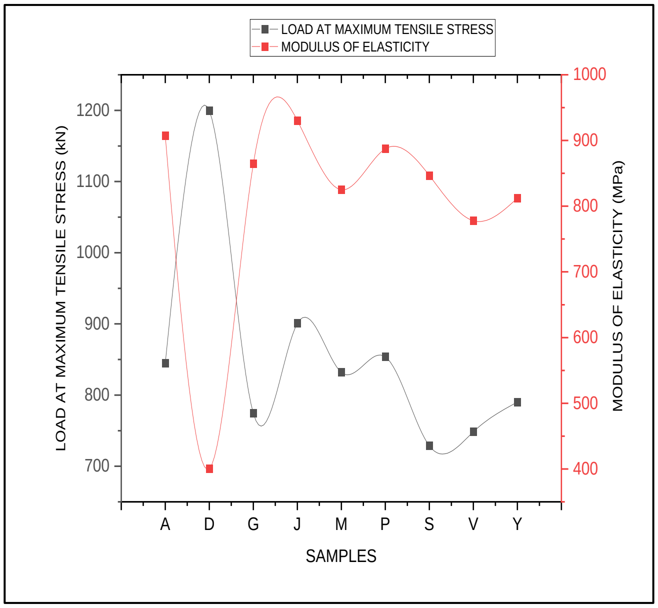
	Infill Density (%)	Printing speed (mm/s)	Layer Thickness (mm)	Maximum Tensile Stress (MPa)	Load at Maximum Tensile Stress (kN)	Modulus of Elasticity (MPa)
A	15	60	0.1	24.143	844.99	907.05
B	15	60	0.2	24.39	853.64	869.85
C	15	60	0.3	24.271	849.5	755.16
D	15	70	0.1	34.276	1199.6	400.28
E	15	70	0.2	23.886	836	889.46
F	15	70	0.3	23.799	832.95	840.2
G	15	80	0.1	22.126	774.4	864.57
H	15	80	0.2	22.964	803.73	736.16
I	15	80	0.3	23.371	818	783.03
J	17.5	60	0.1	25.737	900.78	930.27
K	17.5	60	0.2	23.924	837.33	856.84
L	17.5	60	0.3	22.888	801.08	912.13
M	17.5	70	0.1	23.765	831.78	824.83
N	17.5	70	0.2	18.044	631.53	667.78
O	17.5	70	0.3	21.465	751.28	824.81
P	17.5	80	0.1	24.391	853.7	887.36
Q	17.5	80	0.2	22.344	782.06	840.45
R	17.5	80	0.3	22.244	778.55	884.38
S	20	60	0.1	20.822	728.78	846.7
T	20	60	0.2	22.803	798.1	865.79
U	20	60	0.3	23.181	811.33	774.8
V	20	70	0.1	21.382	748.36	777.83
W	20	70	0.2	23.13	809.54	796.75
X	20	70	0.3	22.951	803.3	852.02
Y	20	80	0.1	22.573	790.04	812.27
Z	20	80	0.2	22.908	801.79	849.08
A1	20	80	0.3	21.089	800.29	830.12

Table 3: Experimental result for 9 experiments

Infill Density (%)	Printing Speed (mm/s)	Layer Thickness (mm)	Maximum Tensile Stress (MPa)	Load at Maximum Tensile Stress (kN)	Modulus of Elasticity (MPa)
15.0	60	0.1	24.1425	844.989	907.047
15.0	70	0.2	23.8858	836.004	889.464
15.0	80	0.3	23.3714	818.000	783.026
17.5	60	0.2	23.9237	837.328	856.838
17.5	70	0.3	21.4653	751.285	824.812
17.5	80	0.1	24.3914	853.698	887.363
20.0	60	0.3	23.1809	811.331	774.798
20.0	70	0.1	21.3818	748.363	777.826
20.0	80	0.2	22.9082	801.790	849.078



(a)



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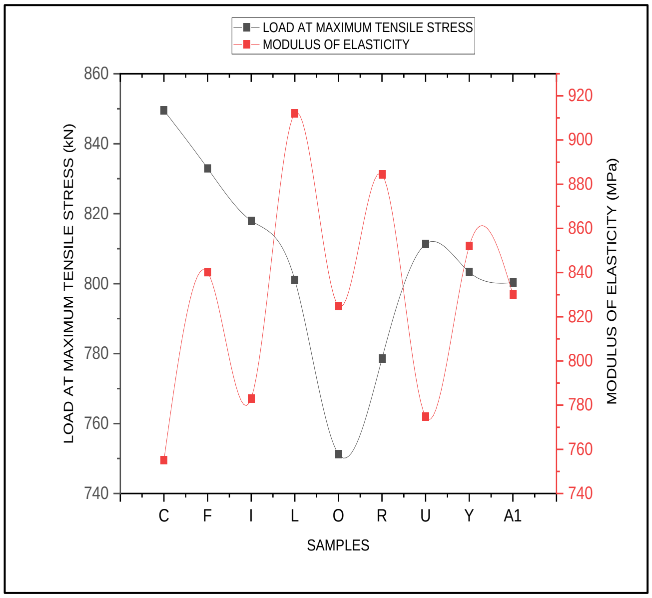
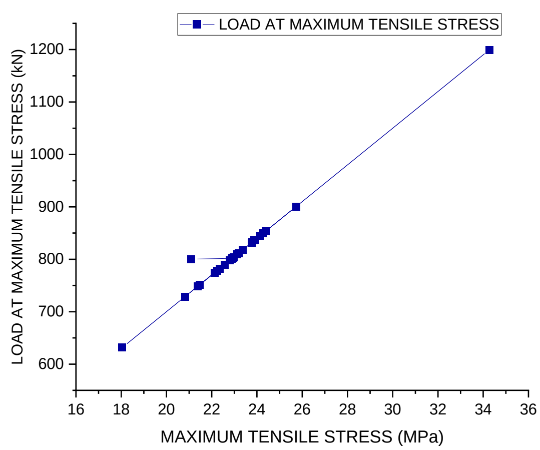


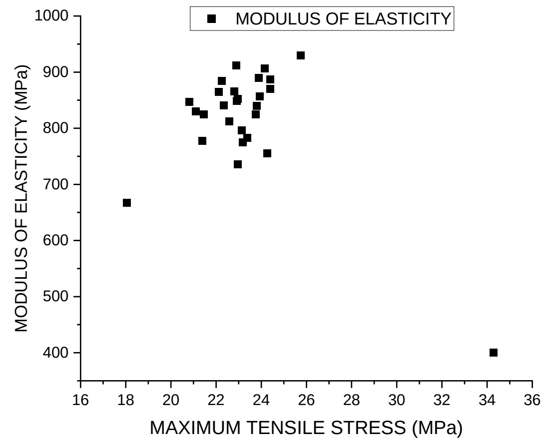
(c)

Figure 3. Plots of the influence of layer thickness: (a) 0.1 mm (b) 0.2 mm (c) 0.3 mm

From Figure 3a, it was observed that at 70 mm/s printing speed, sample 4 has the lowest modulus of elasticity at 17.5 % infill density when the layer thickness was 0.1 mm. The modulus of elasticity had the best performance at the 0.2 mm layer thickness as seen in Figure 3b. However, there is a peculiarity with the 0.3 mm layer thickness plot (Figure 3c), where the modulus of elasticity has very close figures for all printing speeds, which means they exhibit similar behaviour. This further confirms that the layer thickness becomes less significant at higher values irrespective of the other parameters (Song et al., 2023).

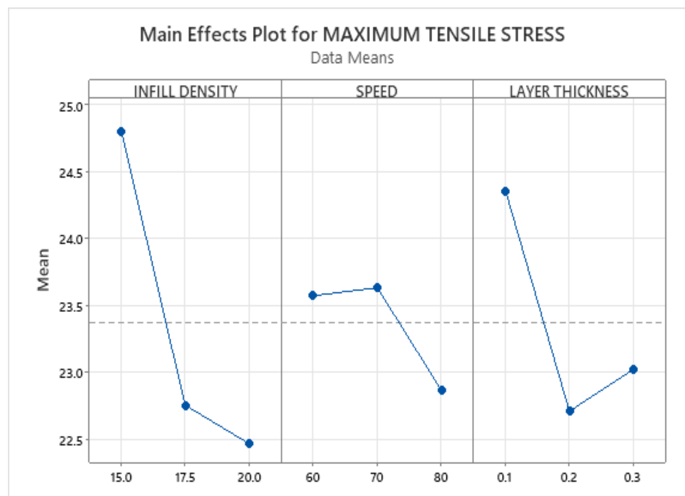


(a)

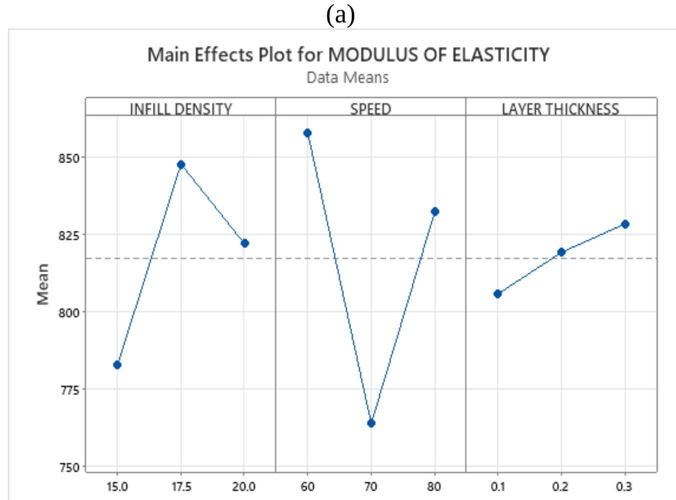


(b)

Figure 4. Plots of (a) load at maximum tensile (b) modulus of elasticity and maximum tensile stress



(a)



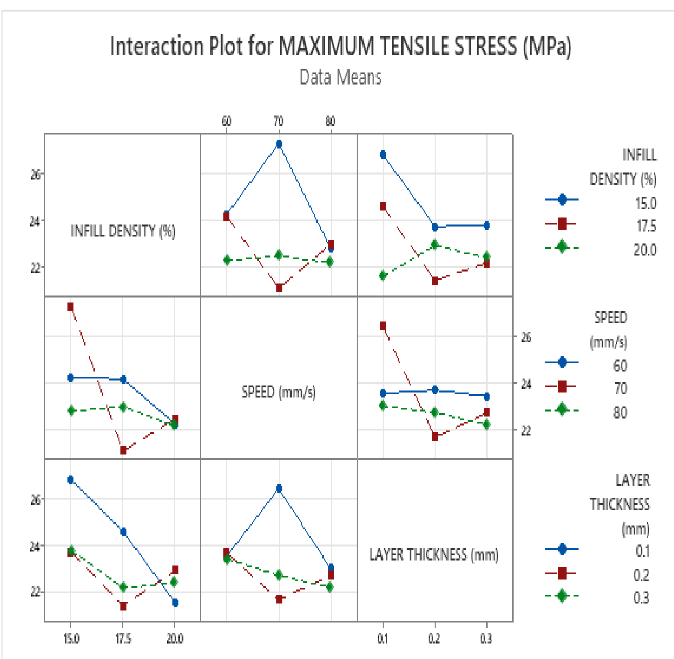
(b)

Figure 5. Taguchi Analysis showing Main Effects Plots for: (a) Maximum Tensile stress and (b) Modulus of Elasticity.

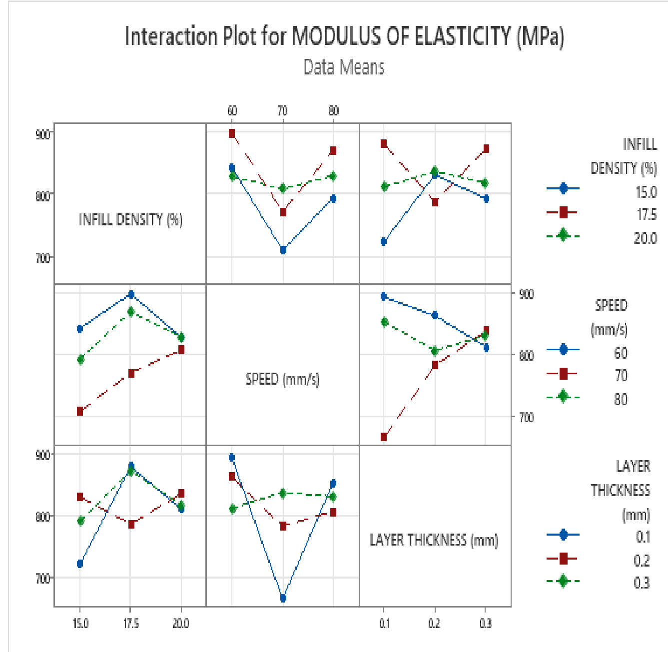
From Figures 4 (a and b), the load at the highest tensile stress increases with the maximum tensile stress with minimal variations regardless of the change in input values. The modulus of elasticity varies between 650 MPa to 900 MPa for most of the specimen. The maximum tensile stress varies directly with the load at maximum tensile stress while the modulus of elasticity plot is a scattered plot.

From Figure 5, the highest tensile stress was observed when the infill density and layer thickness were lowest corresponding to 15 % and 0.1 mm. It can also be observed that the combination of infill density of 20% and 0.2 mm layer thickness yields a low value for the mechanical properties. The lower printing speed similarly influences the tensile stress, while the influence of infill density and layer thickness were low at higher values. On the contrary, the infill density of 17. 5 %, printing speed of 60 mm/s, and layer thickness of 0.3 mm gave the highest modulus of elasticity. Unlike the maximum tensile stress, the higher values of infill density and layer thickness are significant on the modulus of elasticity. It can be deduced that higher values of infill density and layer thickness have less influence on the tensile strength of PLA but greater influence on the modulus of elasticity.

From Figure 6a, the printing parameters all influence the maximum tensile strength and modulus of elasticity. For the tensile property, the speed is most significant with higher values at 60 mm/s, which also corresponds to the lower values of infill density and layer thickness. The layer thickness showed the highest influence at its lowest value of 0.1 mm when the infill density is lowest, and the speed is 70 mm/s. The infill density shows a higher value when the speed is 70 mm/s and the layer thickness is 0.1 mm. It can be deduced that lower printing speed, layer thickness, and infill density have the highest significance on the tensile strength.



(a)



(b)

Figure 6. (a) Interaction plot for Maximum Tensile Stress. (b) Interaction plot for Modulus of elasticity.

In Figure 6b for the modulus of elasticity, the speed is highly significant at 60 mm/s for the three values of infill density and layer thickness. The infill density at 17.5 % showed the highest impact at the highest and lowest printing speed and layer thickness. However, the layer thickness showed significance at all values of infill density and most of the printing speed with the highest values corresponding to the lowest values of printing speed and 17.5 % infill density.

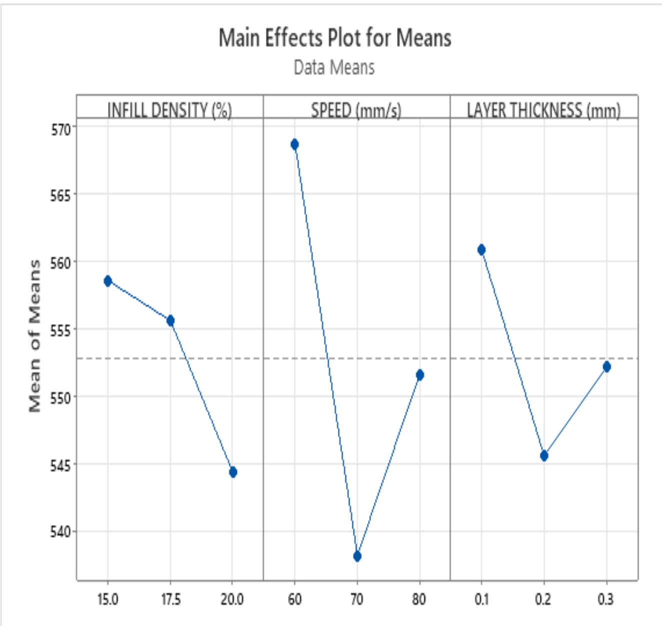
Generally, lower layer thickness and printing speed values have had more influence on the tensile strength and modulus of elasticity. However, the case of the layer thickness is that higher layer thickness reduces the modulus, because of the increase in the porosity of the material (Chockalingam et al., 2006; Shubham et al., 2016).

C. ANOVA Results and Discussions

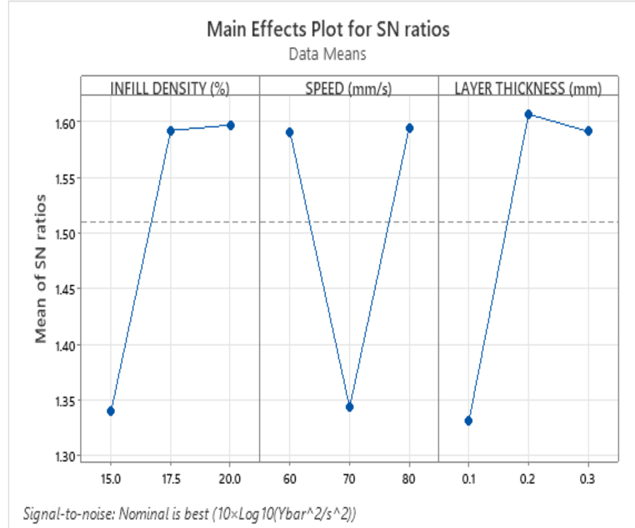
The results obtained from the testing were first analysed using the Taguchi approach since the experiment was designed based on the Taguchi DOE (Design of Experiment). The intention is to present the hierarchy of dominance among the parameters from the main effects plot for each factor. The results of the Taguchi analysis are seen in Figure 7.

In Figure 7a, speed at 60 mm/s is the most significant on the means followed by 0.1 mm layer thickness. Similarly, the speed of 60 mm/s has a significant impact on the means. The highest value of output was recorded when the infill density and printing speed were lowest corresponding to 15 % and 60 mm/s respectively. When the infill density was 20 % and the layer thickness 0.3 mm, the material properties were low (Lundberg et al., 2022). Meanwhile, in Figure 7b, all three parameters showed high value for the signal-to-noise ratio. When infill density was 20 % and the layer thickness was 0.2 mm, the printing speed had little effect on the mechanical property. This supports the assertion that the medium parameters of infill density and layer thickness can produce a material with better mechanical properties irrespective of the printing speed (Agrawal et al., 2023; Brackett et al., 2022).

The printing speed always influences the output; hence, it is a major factor regarding the modulus. Specifically, the factor mixes lower values of infill density of 15 %, printing speed of 60 mm/s, and layer thickness of 0.1 mm had the greatest effect on the modulus in the main effects plot for the modulus (Kamer et al., 2022).



(a)



(b)

Figure 7. Main Effects plot for (a) Means (b) Signal-Noise ratio

D. Regression result and analysis

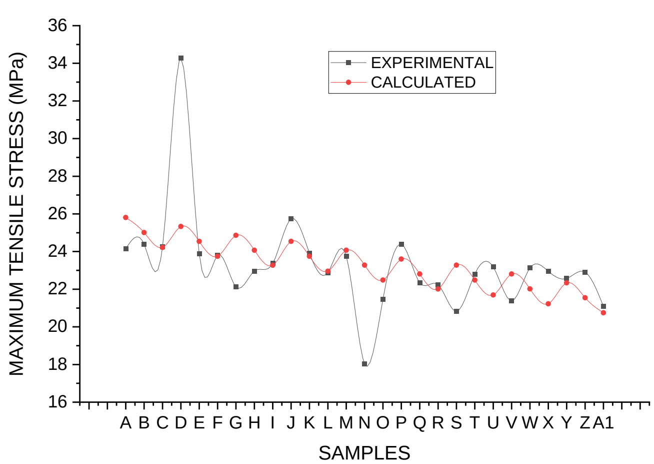
Regression analysis was carried out using experimental data in Minitab. The regression generated the equations to develop the values within the range of the commonly used printing parameters. Equations 4–6 represent the regression equations derived for the maximum tensile stress, load at maximum tensile stress, and the modulus of elasticity respectively and the plot of the calculated parameters presented in Figure 8. The analysis of the regression equations is presented in Table 4. These equations can be used to optimize the parameters for customized slicer and printing software.

$$36.72 - 0.497 \text{ Infill Density} - 0.0453 \text{ Speed} - 7.75 \text{ Layer Thickness} \quad (4)$$

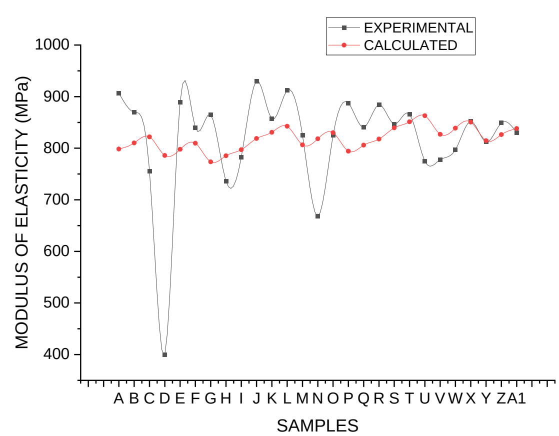
$$1295 - 17.67 \text{ Infill Density} - 1.65 \text{ Speed} - 278 \text{ Layer Thickness} \quad (5)$$

$$738 + 8.2 \text{ Infill Density} - 1.24 \text{ Speed} + 118 \text{ Layer Thickness} \quad (6)$$

Table 5 shows the higher values of infill density tested in the regression equations and compared with experimental values from (Lundberg et al., 2022).



(a)



(b)

Figure 8: Plots for calculated (a) Max. Tensile Stress (b) Modulus of Elasticity

Table 4: Regression data analysis for Maximum tensile stress and Modulus of elasticity

	P-value		F-value		DF	R-Square (%)	
	σ_{max}	E	σ_{max}	E		σ_{max}	E
						0.19	0.04
Infill density (%)	0.064	0.431	3.79	0.64	1		
Speed (mm/s)	0.553	0.611	0.36	0.27	1		
Layer thickness (mm)	0.262	0.651	1.32	0.21	1		
Regression	0.171	0.773	1.82	0.37	3		

Table 5: Comparison of calculated regression results with values from literature

Infill density (%)	Layer thickness (mm)	Printing speed (mm/s)	Modulus of elasticity (MPa)			Maximum tensile stress (MPa)		
			Calculated	Lundberg et al., 2022	Error (%)	Calculated	Lundberg et al., 2022	Error (%)
60	0.2	50	1192.2	997	16.4	34.76	34	2.2
80	0.2	50	1356.4	1086	20.0	44.87	35	21.4
100	0.2	50	1520.6	1481	2.6	54.96	58	-5.5

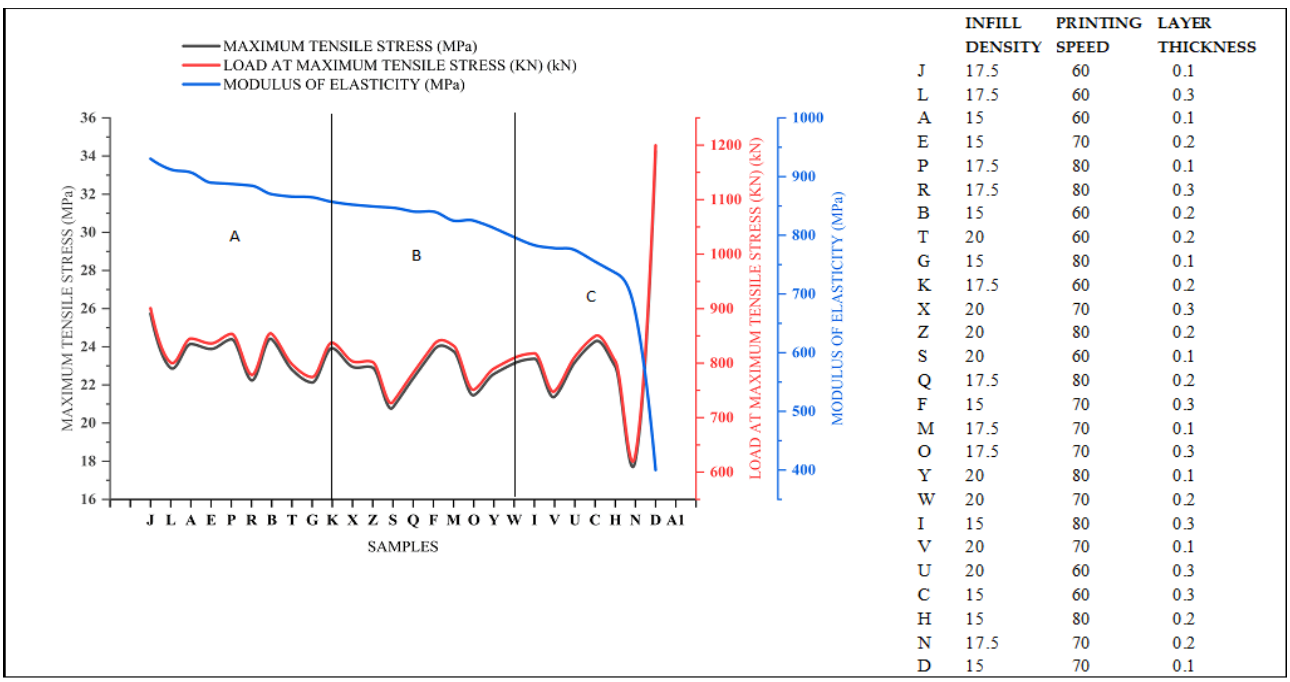


Figure 9. Plot of mechanical properties and printing parameters

From Tables 4 and 5, the significance of each factor in the regression model is expressed. The P values are all greater than 0.05, hence the parameters are not statistically significant on the outputs. However, looking at previous analyses, especially the interaction plots, the parameters have interaction and influence the output by Newman & Newman, 2000. The R-squared values are greater than 0, which shows that the fitted values correlate to the experimental data. Further analysis when values from the literature were inserted showed an error between 2 % and 20 %, suggesting that the linear fit is sufficient to describe the relationship between the factors and the output. There is a correlation between these values, hence the equations can be used to predict values of mechanical properties based on printing speed and layer thickness combination. Furthermore, it validates the method adopted in this research as appropriate. An increase in the printing speed increases the maximum tensile stress while reducing the modulus of elasticity.

In Figure 8, the experimental and the calculated plots have similar trends, and thus can be said that the relationship between the printing parameters and the mechanical properties in the experimental data are well represented by the regression equations. Hence, a wider range of these values is possible by inserting required input data into the variable as printing parameters. However, the output may be different from applications that use another type of printer and filament, but this procedure can be adopted for each printer and set of materials acquired for use in FDM additive manufacturing explorations.

The plot of the mechanical properties and printing parameters sorted in ascending order of modulus of elasticity is presented in Figure 9. This plot serves as a lookup chart where the properties desired are matched with the corresponding printing materials. For example, if 680 MPa modulus is required, the point is drawn from the left-hand side to touch the curves and the point on the curve is traced to the x-axis to choose the closest sample. To get the other properties, the trace is extended to the chart of the required property. After that, this sample is checked on the right-hand side for the corresponding configuration. This method can be replicated for any other known property and the printing parameters can be determined. The look-up chart is vital as it assists the designer in estimating the cost and time for the desired printing, corresponding to the mechanical properties suitable for the parts. The specimen with infill density of 15 %, and 17.5 % with 60 mm/s and 80 mm/s printing speed dominated region A which is the upper 1/3 of the chart with the highest values of tensile stress. The layer thicknesses were majorly 01 mm and 0.2 mm thickness. These values conform with previous observations when the contribution of the infill density and layer thickness were discussed. It was established that lower values of infill density combined with medium printing speed result in printed materials with the highest modulus.

Region B with the medium values of modulus presents samples with a printing speed of 70 mm/s and infill density of 20 %. However, the layer thickness is evenly distributed here. Infill density of 17.5 % and printing speed of 60 mm/s topped the range of modulus in this region. The third region (region C) had the rest of the specimen combinations, with just one 17.5 % infill density. Printing speed of 70 mm/s combined with 0.1 mm dominated the region. Considering regions, A and B, a high modulus exists between the interchange of infill density and printing speed. Low infill densities require either low or high printing speed, and when the infill density is high, lower printing speed will impact the relatively moderate modulus of the material.

The load-bearing capacity compares to the modulus as the slope of the range of values in each region decreases with decrease with decreasing modulus. Though the range of values considered for the infill density is not wide, the results here show that a good relationship exists between infill density and the printing speed more than it compares with the layer thickness. Also, there is no need to select high infill densities when one can vary the value with the printing speed and layer thickness which gives good quality printed material. In addition, this work addressed tensile properties, the same interactions may not be the same for other properties such as flexural strength, surface finish, impact strength, and fatigue strength. Although these other properties apply to applications with greater force experience than tensile applications.

IV. CONCLUSION AND FUTURE WORK

The experimental design presented twenty-seven samples with three variables for each printing parameter considered. The tensile stress, load at maximum tensile stress, and Modulus of elasticity were determined through the relationship between force, stress, and strain. The effects of printing speed and layer thickness were assessed to see how they influenced the mechanical properties. An analysis of the distinction of each parameter was carried out to investigate how each parameter influences the mechanical properties of each sample. Regression analysis as models for customized printing was also presented. Lastly, charts of the tensile properties were plotted, and the lookup chart for these properties where the printing parameters suitable for a desired mechanical property was presented.

The following conclusions were drawn.

1. The quantity of material used increased with increased layer thickness, while printing time decreased with increased layer thickness.
2. Infill densities of 15 %, 17.5 %, and 20 % were sufficient to describe the influence of printing speed and layer thickness on the tensile properties of printed PLA. A whole range of infill density values is not necessary to investigate its influence on tensile properties.
3. For the printing speed, the highest tensile stress was observed when the infill density and printing speed were lowest corresponding to 15 % and 60 mm/s. A low printing speed below 60 mm/s is desirable for better mechanical properties.
4. Printing speeds of 60 mm/s and 80 mm/s gave the highest mechanical properties when combined with layer thicknesses of 0.1 mm and 0.2 mm. The sample with 70 mm/s printing speed at a layer thickness of 0.1 mm has the lowest modulus of elasticity. This shows that lower printing speed and layer thickness give better mechanical properties.
5. At 0.3 mm layer thickness, the modulus of elasticity has close values. This shows that layer thickness seems to be insignificant at higher values.
6. The highest and lowest modulus of elasticity was recorded at 930 MPa and 736 MPa, while that of maximum tensile stress was 25.4 MPa and 18.04 MPa.
7. The regression equations show percentage errors between 2 % and 22 %, hence the parameter range adopted is suitable especially for higher values of infill density.
8. The prototypes in the laboratory can be printed with this range of values since they are not for functional purposes but for prototyping, proofs of concepts, and parts not experiencing prolonged or repeated loading.

The parameters considered here are not sufficient to investigate other mechanical properties such as flexural strength, surface finish, and impact strength. However, it is necessary to investigate if the range of values of infill density adopted will be sufficient to describe these mechanical properties of 3D printed PLA for prototyping. The choice of values of other parameters should bear in mind minimal material use and low printing time.

AUTHOR CONTRIBUTIONS

O. K. Ajayi: Conceptualization, Supervision, Manuscript preparation, Validation. **S. Du**: Conceptualization, Supervision. **O. K. Ajayi, T. A. Odekomaiya, and O. Bayonle:** Literature, Data, Experimentation, Analysis, Writing - original draft. **O. K. Ajayi and S. Du:** Writing – review and editing

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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