Heat-Driven Parameter Optimization of Youngs Modulus and Flexural Strength in 3D-Printed Polycarbonate–Basalt Fibre Composites Using Taguchi–ANOVA Approach

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**Abstract:** This study investigates, work uses the Taguchi design of experiments to examine how the mechanical characteristics of polycarbonate (95%) reinforced with 5% basalt fibre are affected by the 3D printing process parameters of nozzle temperature, bed temperature, and printing speed. An Ultima Ker 3D printer was used to create the samples in accordance with ASTM guidelines for measuring flexural and tensile strength (Young's modulus). Nine experimental trials with different parameter values were carried out in all. The most important element, according to analysis of variance (ANOVA), was nozzle temperature, which contributed 88.61% to tensile modulus and 88.37% to flexural strength. According to regression modelling, flexural strength increased with higher nozzle temperatures (220°C) and comparable bed settings, whereas tensile stiffness was maximized at lower nozzle temperatures (200–210°C) and higher bed temperatures (80°C). Flexural strength peaked at 108 MPa, whereas the tensile Young's modulus peaked at 6000 MPa. With R2 values of 97.23% for tensile modulus and 98.57% for flexural strength, the models demonstrated good statistical validity. The ideal parameter zones for enhanced mechanical performance were further validated using contour plots. This study shows that the mechanical performance of fibre-reinforced thermoplastic composites is greatly improved by careful heat management during fused filament production.

**Keywords:** Polycarbonate Basalt fibre, Tensile Youngs modulus, Flexural strength, Signal to noise ratio,R2 (Coefficient of Corelation ), ANOVA, Regression model and contour plot.

# Introduction

Additive manufacturing is a technology for quick prototyping. This is a high-speed, productive technology [1]. This technique is sweeping the world in various manufacturing areas. The combination of polycarbonate and basalt fiber materials is an excellent bonding medium between primary and secondary components [2]. Polycarbonate materials are known to be highly resistant. This material can withstand pressure and stress. Basalt fiber is derived primarily from volcanic material [3]. This material is very fire and chemical resistant. It has the capacity to give strong strength and resistance. This is a very good advanced material, and many businesses are actively focused on merged combination materials [4]. Prior research on the combination of polycarbonate and basalt fibers has been restricted. Previous research has not focused on this polycarbonate 95% and 5% basalt fiber merged combination printed samples as per ASTM standards [5]. Previous study has not focused on tensile young’s modulus and flexural strength samples for these mechanical parameters [6]. They often focus on mechanical qualities rather than delving further into them. Previous research on the combined use of polycarbonate and basalt fibers was limited [7]. This merging combination printing example has a large task to enhance the correct structure and forms as per the ASTM standard. As a result, many industries are not focusing on these combination materials [8].

Combination of polycarbonate and basalt printing samples for tensile Young's modulus and flexural strength was not done in the earlier studies for mechanical properties [9]. This combination does not do the optimization work for printing samples [10]. The signal to noise ratio, Taguchi design, correlation coefficient finding, regression model for both characteristics, and contour plot for both properties are not being discussed in depth in the earlier studies [11]. This entire process for flexural strength and tensile young’s modulus is not covered in previous work. The literature gap of this research is lack of prior study on the combined properties of polycarbonate and basalt fiber for tensile Young's modulus and flexural strength represents the research's literature gap. These two samples were not included in the prior study; the optimization work for tensile young’s modulus and flexural strength was not covered in the earlier research for a step-by-step explanation; and the signal to noise ratio for tensile young’s modulus and flexural strength was not previously covered. In the prior study, the three levels of parameters for nozzle temperature, bed temperature, and printing speed for tensile young’s modulus and flexural strength were not thoroughly covered [12-26]. The prior study did not do analysis of variance for the flexural strength and tensile young’s modulus samples. Both tensile and flexural samples are not thoroughly discussed in previous studies' analysis of variance over 95%. The combined contribution value for nozzle temperature, bed temperature, and printing speed is not well covered in the prior work, despite the fact that both samples are highly significant in the field of study. In the earlier paper, the regression model for flexural strength and tensile Young's modulus was not thoroughly discussed. In the prior study, the contour plot for tensile Youngs modulus and flexural strength was not thoroughly discussed with color for high strength, low strength, and medium for color basic strength [27-33]. These are the primary steps in the optimization process.

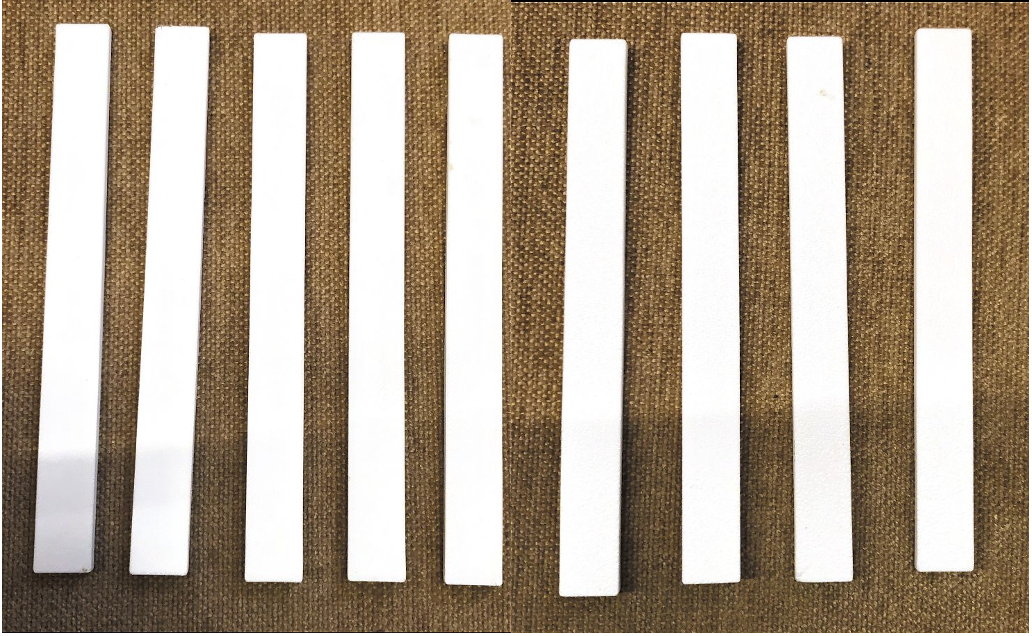
These are the steps that were not taken in earlier research while printing samples. These two combinations of printing samples were also used in earlier research. The paper goes into great length about the literature gap. The objective of this study is to print samples for tensile Youngs modulus and flexural strength using a mix of basalt fiber and polycarbonate [34-36]. Both of these samples use the ASM standard. additional tensile Youngs modulus and flexural modulus employing three levels of parameters for printing speed, bed temperature, and nozzle temperature in order to determine the optimal values for these three parameters. Nine distinct levels of experiments are used to determine these three factors. in order to calculate the signal to noise ratio, signal to noise ratio 1, FITS, and FITS 1 value, as well as to construct more trials with varying levels of flexural strength and tensile Youngs modulus value updating [37-42]. This approach is used to determine the precise experiment value for all of these values. Next, Taguchi analysis is used to determine the optimal output value and signal to noise ratio for tensile Youngs modulus and flexural strength. Three different levels of nozzle temperature are determined, and the highest data value for nozzle temperature is found along with the second-highest value for bed temperature. As a source list for Nozzle temperature, Bed temperature, printing speed, and error, tensile Youngs modulus and flexural strength are frequently employed. This list of sources is shared by both properties. In general, the contribution value, sequence SS value, and total deformation value must all remain above 1% for any source list. A correlation coefficient greater than 95% is required to preserve both flexural strength and tensile young’s modulus. Regression modeling is the primary method for enhancing mechanical performance, and it is used to determine the optimal value for flexural strength and tensile Youngs modulus [43-47].

For this optimization work, regression is one of the key tools. It is possible to determine the tensile Young's modulus and flexural strength using contour plotting. The color of a contour plot may be predicted for both flexural strength and tensile Youngs modulus. With precise nozzle, bed, and printing temperature settings, this optimization method can improve mechanical behavior strength. Both the flexural and tensile Young's modulus can be strengthened by this nine-step testing process [48-51].

# Materials and Methods

## Materials

According to ASTM standards, figure 1-a )shows the flexural strength and Figure 1-b shows the Tensile Youngs modulus of a 95% polycarbonate and 5% basalt fibre merged combination. The Ultima Ker 3D printer is being used to manufacture the tensile Youngs modulus and flexural strength standards. The ASTM standard for flexural Strength sample, it is D790.

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(a)

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**(b)**

Figure 1: (a) Polycarbonate composite flexural strength (b) **Polycarbonate composite Tensile Youngs modulus**

**In this experiment work, Table 1 shows the Bed temperature for Level 1 to level 3 is 60,70 and 80 degree Celsius, Nozzle Temperature for Level 1 to 3 is 200, 210 and 220 degree Celsius. Printing speed for Level 1 to level 3 is 15,20 and 25 mm/s. In this three different parameters is important for this Taguchi method.**

Table 1: Parameters and level

|  |  |  |  |
| --- | --- | --- | --- |
| **Factor** | **Level 1** | **Level 2** | **Level 3** |
| Bed temperature | 60 | 70 | 80 |
| Nozzle Temperature | 200 | 210 | 220 |
| Printing speed | 15 | 20 | 25 |

## Experimental design

In this experimental design work, table 2 shows the design for three parameters at nine level of experiments [22]. Level 1 design for Bed temperature is 60 degree Celsius, Nozzle Temperature is 200 degree Celsius and Printing speed is 15 mm/s. Level 2 design for Bed temperature is 70 degree Celsius, Nozzle Temperature is 200 degree Celsius and Printing speed is 20 mm/s. Level 3 design for Bed temperature is 80 degree Celsius, Nozzle Temperature is 200 degree Celsius and Printing speed is 25 mm/s. Level 4 design for Bed temperature is 70 degree Celsius, Nozzle Temperature is 210 degree Celsius and Printing speed is 15 mm/s. Level 5 design for Bed temperature is 80 degree Celsius, Nozzle Temperature is 210 degree Celsius and Printing speed is 20 mm/s. Level 6 design for Bed temperature is 60 degree Celsius, Nozzle Temperature is 210 degree Celsius and Printing speed is 25 mm/s. Level 7 design for Bed temperature is 80 degree Celsius, Nozzle Temperature is 220 degree Celsius and Printing speed is 15 mm/s. Level 8 design for Bed temperature is 60 degree Celsius, Nozzle Temperature is 220 degree Celsius and Printing speed is 20 mm/s. Level 9 design for Bed temperature is 70 degree Celsius, Nozzle Temperature is 220 degree Celsius and Printing speed is 25 mm/s.

Table 2 : Experimental design for three parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Experimental no** | **Bed Temperature** | **Nozzle Temperature** | **Printing speed** |
| 1 | 60 | 200 | 15 |
| 2 | 70 | 200 | 20 |
| 3 | 80 | 200 | 25 |
| 4 | 70 | 210 | 15 |
| 5 | 80 | 210 | 20 |
| 6 | 60 | 210 | 25 |
| 7 | 80 | 220 | 15 |
| 8 | 60 | 220 | 20 |
| 9 | 70 | 220 | 25 |

## Response Measurement

The Taguchi method's optimal signal to noise ratio in this experiment is the larger number for the response measurement for tensile Youngs modulus and flexural strength [23]. Tensile Youngs modulus and flexural strengths in this case adhere to ASTM standards. The flexural sample is D790.

# ****Result and Discussion****

## ****Taguchi analysis****

**In this experiment, Table 3 presents the Taguchi analysis of flexural strength and tensile Young’s modulus. At a nozzle temperature of 200 °C, performance was fairly stable across the first three experiments. Experiment 1 (200 °C, 15 mm/s, 60 °C bed) produced a flexural strength of 98 MPa and a Young’s modulus of 5985 MPa, supported by S/N ratios of 39.82 and 75.54. At Experiment 2 (200 °C, 20 mm/s, 70 °C bed), the strength slightly improved to 99 MPa, while modulus decreased marginally to 5970 MPa. In Experiment 3 (200 °C, 25 mm/s, 80 °C bed), the strength rose further to 100 MPa with modulus of 6000 MPa, suggesting that increased speed and bed temperature improved stiffness but only marginally influenced flexural strength. Overall, results at 200 °C showed balanced performance with modulus values close to 6000 MPa and strengths under 100 MPa.**

**When the nozzle temperature was increased to 210 °C, more pronounced variations appeared. Experiment 4 (15 mm/s, 70 °C bed) yielded 104 MPa strength but with a reduced modulus of 5800 MPa. At Experiment 5 (20 mm/s, 80 °C bed), strength reached 105 MPa, while modulus recovered to 5950 MPa, showing improved load-bearing capability. However, Experiment 6 (25 mm/s, 60 °C bed) showed a drop in modulus to 5700 MPa, with strength also reducing to 101 MPa, highlighting sensitivity to speed–bed combinations. At the highest nozzle setting of 220 °C, flexural strength improved further while modulus declined. Experiment 7 (15 mm/s, 80 °C bed) recorded the maximum strength of 108 MPa but the lowest modulus of 5600 MPa, while Experiment 8 and Experiment 9 (20–25 mm/s) maintained high strength values (106–107 MPa) but showed tensile moduli between 5500–5550 MPa. These results confirm that increasing nozzle temperature enhances flexural strength but simultaneously reduces stiffness, indicating a trade-off between load-bearing capacity and elasticity in the composites.**

**Table 3: Taguchi analysis for Flexural strength and Tensile Youngs modulus**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Experiment no** | **Nozzle Temp** | **Printing speed** | **Bed Temp** | **Flexural strength** | **TS-Youngs modulus** | **S/ N ratio for Flexural strength** | **S/ N ratio for TS-Youngs modulus** |
| 1 | 200 | 15 | 60 | 98 | 5985 | 39.82452151 | 75.54128309 |
| 2 | 200 | 20 | 70 | 99 | 5970 | 39.91270389 | 75.51948662 |
| 3 | 200 | 25 | 80 | 100 | 6000 | 40 | 75.56302501 |
| 4 | 210 | 15 | 70 | 104 | 5800 | 40.34066679 | 75.26855987 |
| 5 | 210 | 20 | 80 | 105 | 5950 | 40.42378598 | 75.49033931 |
| 6 | 210 | 25 | 60 | 101 | 5700 | 40.08642748 | 75.11749711 |
| 7 | 220 | 15 | 80 | 108 | 5600 | 40.66847511 | 74.96376054 |
| 8 | 220 | 20 | 60 | 107 | 5500 | 40.58767555 | 74.80725379 |
| 9 | 220 | 25 | 70 | 106 | 5550 | 40.50611731 | 74.88585966 |

## Response ratio for signal to noise ratio

## Tensile Youngs modulus

In this work, table 4 shows the signal to noise ratio for tensile Youngs modulus [25]. Level 1 for Nozzle temperature is 75.54, Printing speed 75.26 and Bed Temperature is 75.16. Level 2 for Nozzle temperature is 75.29, Printing speed is 75.27 and Bed temperature is 75.22. Level 3 for nozzle temperature is 74.89, Printing speed is 75.19 and Bed temperature is 75.34.

Table 4: Signal to noise ratio for Tensile Youngs modulus

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 75.54 | 75.26 | 75.16 |
| 2 | 75.29 | 75.27 | 75.22 |
| 3 | 74.89 | 75.19 | 75.34 |
| Delta | 0.66 | 0.08 | 0.18 |
| Rank | 1 | 3 | 2 |

The signal to noise ratio graph for Young's modulus is shown in Figure 2 of this study. The highest delta wave in this graph is displayed by the nozzle temperature, which has a value of 0.66. Printing speed has the lowest graph wave, with a delta value of 0.08 mm/s, while bed temperature has the second-highest, with a delta value of 0.18.



Figure 2: Signal to noise ratio of Tensile Youngs modulus

### Flexural strength

In this work, table 5 shows the signal to noise ratio for Flexural strength, Level 1 for Nozzle temperature is 39.91, Printing speed 40.28 and Bed Temperature is 40.17. Level 2 for Nozzle temperature is 40.28, Printing speed is 40.31 and Bed temperature is 40.25. Level 3 for nozzle temperature is 40.59, Printing speed is 40.20 and Bed temperature is 40.36.

Table 5: Signal to noise ratio for flexural strength

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 39.91 | 40.28 | 40.17 |
| 2 | 40.28 | 40.31 | 40.25 |
| 3 | 40.59 | 40.20 | 40.36 |
| Delta | 0.68 | 0.11 | 0.20 |
| Rank | 1 | 3 | 2 |

The signal to noise ratio graph for Flexural strength is shown in Figure 3 of this study. The highest delta wave in this graph is displayed by the nozzle temperature, which has a value of 0.68. Printing speed has the lowest graph wave, with a delta value of 0.11 mm/s, while bed temperature has the second-highest, with a delta value of 0.20.



Figure 3: Signal to noise ratio for Flexural strength

## Analysis of variance

### Tensile Youngs modulus

In this work, Table 6 shows the Analysis of Variance of Tensile Youngs modulus, source list for Nozzle temperature, Printing speed, Bed temperature and Error. This all source list total DF value is 8, Total Sequence SS is 325789 and Contribution for Nozzle temperature is 88.61%, Printing speed is 1.65% and Bed Temperature is 6.97% and Error is 2.77%. Total contribution is 100.00%.

Table 6: Tensile Youngs modulus for ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle Temp | 2 | 288672 | 88.61% | 288672 | 144336 | 31.94 | 0.03 |
| Printing speed | 2 | 5372 | 1.65% | 5372 | 2686 | 0.59 | 0.627 |
| Bed Temp | 2 | 22706 | 6.97% | 22706 | 11353 | 2.51 | 0.285 |
| Error | 2 | 9039 | 2.77% | 9039 | 4519 |  |  |
| Total | 8 | 325789 | 100.00% |  |  |  |  |

The Tensile Youngs modulus ANOVA is displayed in the experiment's figure 4 graph. The normal probability plot in this graph provides a standard % level, the histogram provides a constant frequency, the versus order provides a constant order, and the versus fits provide a standard fitted value. R-sq -coefficient of correlation is 97.23%, R-sq.(adj) is 88.90%, PRESS is 183037, R-sq(pred) is 43.82%, and the tensile Youngs modulus of S is 67.2268.



Figure 4: Tensile Youngs modulus ANOVA

### Flexural strength

In this work, Table 7 shows the Analysis of Variance of Flexural strength, source list for Nozzle temperature, Printing speed, Bed temperature and Error [26]. This all source list total DF value is 8, Total Sequence SS is 108.889 and Contribution for Nozzle temperature is 88.37%, Printing speed is 2.65% and Bed Temperature is 7.55% and Error is 1.43 %. Total contribution is 100.00%.

Table 7: Flexural strength for ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle Temp | 2 | 96.222 | 88.37% | 96.222 | 48.1111 | 61.86 | 0.016 |
| Printing speed | 2 | 2.889 | 2.65% | 2.889 | 1.4444 | 1.86 | 0.35 |
| Bed Temp | 2 | 8.222 | 7.55% | 8.222 | 4.1111 | 5.29 | 0.159 |
| Error | 2 | 1.556 | 1.43% | 1.556 | 0.7778 |  |  |
| Total | 8 | 108.889 | 100.00% |  |  |  |  |

The experiment's figure 5 graph shows the Flexural strength ANOVA. In this graph, the histogram gives a good frequency, the versus order gives a constant order, the versus fits give a standard fitted value, and the normal probability plot gives a standard percentage level. S has a flexural strength of 0.881917, R-sq- Coefficient of Correlation is 98.57%, R-sq.(adj) is 94.29%, PRESS is 31.5, and R-sq(pred) is 71.07%.



Figure 5 graph shows the Flexural strength of ANOVA

## Regression model

### Tensile Youngs modulus

The regression model for tensile Young’s modulus reveals how 3D printing parameters influence the stiffness of printed parts [27]. The base value of the modulus is 5783.9, and it increases with nozzle temperatures of 200°C and 210°C by 201.1 and 32.8 units respectively, while a higher nozzle temperature of 220°C reduces it by 233.9 units. Printing speeds of 15 mm/s and 20 mm/s slightly improve the modulus, increasing it by 11.1 and 22.8 units, whereas a speed of 25 mm/s decreases it by 33.9 units. Bed temperature shows a strong effect: 80°C significantly increases the modulus by 66.1 units, while lower bed temperatures of 60°C and 70°C reduce it by 55.6 and 10.6 units respectively. The model indicates that higher bed temperatures (80°C), lower printing speeds (15–20 mm/s), and moderate nozzle temperatures (200–210°C) all help to increase the tensile stiffness of 3D printed parts.

|  |  |  |
| --- | --- | --- |
| TS-Youngs modulus | = | 5783.9 + 201.1 Nozzle Temp\_200 + 32.8 Nozzle Temp\_210 - 233.9 Nozzle Temp\_220 + 11.1 Printing speed\_15 + 22.8 Printing speed\_20 - 33.9 Printing speed\_25 - 55.6 Bed Temp\_60 - 10.6 Bed Temp\_70 + 66.1 Bed Temp\_80 |

### Flexural strength

The regression model for flexural strength identifies how various 3D printing parameters affect the bending strength of printed parts. The base value of flexural strength is 103.111. A nozzle temperature of 200°C reduces the strength by 4.111 units, while temperatures of 210°C and 220°C increase it slightly by 0.222 and 3.889 units, respectively. Printing speeds also show a minor influence: speeds of 15 mm/s and 20 mm/s increase the flexural strength by 0.222 and 0.556 units, while a speed of 25 mm/s decreases it by 0.778 units. The strength decreases by 1.111 and 0.111 units at 60°C and 70°C, respectively, whereas it increases by 1.222 units at 80°C. This is the primary adverse effect of bed temperature. According to the model, flexural strength in 3D printed objects is positively impacted by a nozzle temperature of 220°C, moderate printing rates (15–20 mm/s), and a higher bed temperature of 80°C.

|  |  |  |
| --- | --- | --- |
| Flexural strength | = | 103.111 - 4.111 Nozzle Temp\_200 + 0.222 Nozzle Temp\_210 + 3.889 Nozzle Temp\_220 + 0.222 Printing speed\_15 + 0.556 Printing speed\_20 - 0.778 Printing speed\_25 - 1.111 Bed Temp\_60 - 0.111 Bed Temp\_70 + 1.222 Bed Temp\_80 |

## Contour plot

### Tensile Youngs modulus

In this contour plot, Figure 6 shows a contour map that uses colour gradients to clearly illustrate how tensile Young's modulus changes with nozzle and bed temperatures. The greatest modulus values (over 6000) are observed at low nozzle temperatures (200–205°C) and high bed temperatures (75–80°C), as indicated by the dark green zone. When the colour changes from green to light green, the modulus drops to between 5900 and 6000 and between 5800 and 5900, which indicates a little less rigidity. Further exploration of the light blue and blue zones (5600–5700 and below 5500), which predominate on the plot's right side, reveals that a much lower tensile modulus is the consequence of combining higher nozzle temperatures (215–220°C) with lower bed temperatures (60–70°C). This colour trend shows that the green areas, where the bed temperature is greater and the nozzle temperature is lower, have the best rigidity.



Figure 6: Contour plot for Tensile Youngs modulus

### Flexural strength

Contour plot figure 7 illustrates the variation of flexural strength in relation to nozzle temperature and bed temperature, using a colour gradient [28]. The dark green region, representing the highest flexural strength values (above 108), is located at higher nozzle temperatures (215–220°C) and moderate to high bed temperatures (70–80°C). As the colour transitions to lighter green and cyan (values between 102 and 106), the strength slightly decreases. The blue zones, especially dark blue (< 98), dominate the lower left corner of the plot where nozzle temperatures are low (200–205°C) and bed temperatures are also low (60–65°C). This indicates that higher nozzle temperatures and slightly elevated bed temperatures result in improved flexural strength, while lower temperatures reduce it significantly.



Figure 7: Contour plot for Flexural strength

# Conclusion

This research investigated the influence of 3D printing parameters—nozzle temperature, bed temperature, and printing speed—on the tensile Young’s modulus and flexural strength of polycarbonate (95%) reinforced with basalt fibre (5%) using the Taguchi method. The experimental results identified optimal mechanical performance under specific parameter combinations. The highest tensile Young’s modulus (6000 MPa) was obtained at a nozzle temperature of 200°C, printing speed of 25 mm/s, and bed temperature of 80°C. The maximum flexural strength (108 MPa) was recorded at 220°C nozzle temperature, 15 mm/s speed, and 80°C bed temperature. ANOVA revealed that nozzle temperature had the most significant influence on both responses, contributing 88.61% to tensile modulus and 88.37% to flexural strength. Regression models verified that while tensile stiffness declined at increasing nozzle temperatures, mechanical characteristics increased at higher bed temperatures and moderate printing rates. Strong statistical indications confirmed the model fit: R² = 97.23%, R²(adj) = 88.90%, R²(pred) = 43.82%, S = 67.23 for tensile modulus, and R² = 98.57%, R²(adj) = 94.29%, R²(pred) = 71.07%, S = 0.88 for flexural strength. These results were visually supported by contour plots, which showed that areas with higher bed temperatures and regulated nozzle settings had the best strength and stiffness. The importance of heat management in improving 3D printed fibre-reinforced composites is highlighted by this work.

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