Statistical Modelling and Optimization of Tensile Behaviour in 3D-Printed Polycarbonate/Basalt Fibre Reinforced Composites

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**Abstract:** This study focuses in using the Taguchi technique to optimize 3D printing settings for 95% polycarbonate reinforced with 5% basalt fiber (PC+BF) in order to enhance mechanical performance. With an emphasis on their impacts on tensile strength and tensile elongation, the three main process variables—nozzle temperature, bed temperature, and printing speed—were examined at three different levels each. Higher tensile strength is better, but lower elongation is desired. Signal-to-noise (S/N) ratios were utilized to determine the ideal parameters for the tests, which were designed using a L9 orthogonal array. As demonstrated by ANOVA with statistically significant p-values (<0.05), nozzle temperature was the most important component, contributing to 87.14% of tensile strength and 87.09% of tensile elongation. The lowest tensile elongation (8.98%) is measuring at 200°C nozzle temperature, 60°C bed temperature, and 15 mm/s printing speed, while the maximum tensile strength (108 MPa) was attained at these same conditions. R2 values for Coefficient of Correlation regression models were 98.57% for strength and 98.60% for elongation, indicating high predictive accuracy. Visual confirmation from contour plots showed that raising the bed and nozzle temperatures enhances elongation while simultaneously improving strength.

**Keywords:** Tensile strength, Tensile Elongation, Polycarbonate, Basalt fiber, Regression model, ANOVA, Contour plot and signal to noise ratio

# Introduction

Additive Manufacturing 3D printing is most commonly used in the sports industry to create balls, hockey sticks, bats, volleyball balls, food balls, helmets, protective pads, and other safety components [1]. Nowadays, polycarbonate materials are used in the sports industry for manufacture. Polycarbonate material is also used in the fabrication of face helmets, eye shields, and other safety protection elements [2]. Polycarbonate is a lightweight material with the capacity to withstand high levels of stress. This material has a high strength and quality; it is also quite robust [3]. Another type of sports item is sports eye lenses, which are likewise made of polycarbonate material. Sports googles are also made of polycarbonate material and come in a variety of designs. Sunglasses also use this material to make its pieces [4]. Because polycarbonate materials provide good shine and comfort for safety purposes in the sports business [5]. This polycarbonate substance is used for bicycles, and the bulk of the components are built using this material in 3D printing [6]. Polycarbonate material is used to manufacture blades in the sports sector, and water bottles use polycarbonate materials to construct components for various models and exact unimaginable design structures for printing using additive manufacturing technology. Polycarbonate is a very essential material in the sports business [7]. Because of its great quality, strength, and resilience to heat, basalt fiber is also used in the sports industry. Bicycle frames are mostly used to produce the portions of these basalt fibers. This basalt fiber is made using components that essentially have better performance frames [8]. This basalt fiber is pollution-free and environmentally beneficial. Additionally, fishing rods are manufactured utilizing this basalt fiber material. Paddles are also made from this basalt fiber, which has significant benefits for the material [9]. This basalt fiber is also used in numerous skis and snowboards to increase its strength, stiffness, accuracy, and light weight. This basalt fiber material is also used to make hockey sticks, rackets, sticks, and bats. This basalt fiber is very strong and resistant [10]. Basalt fiber and polycarbonate are two distinct materials with a wide range of qualities, including high mechanical strength. Combining these two resources is a great way to identify the study project's next level of uniqueness [11]. In general, basalt fiber has strong thermal conductivity and a high fire-resistant capability. In essence, polycarbonate provides great strength, superior quality, and a lightweight construction [12]. These two materials have a high market worth due to their exceptional strength and well-functioning processes. Basically, the cost of using basalt fiber and polycarbonate materials is high. This combination material is particularly helpful to the sports business [13-19]. The research's primary gap in the literature is the mix of polycarbonate and basalt fibers used to print the sample for tensile strength and tensile elongation. The mechanical characteristics of polycarbonate composite filaments have not been covered in earlier studies. The prior research did not address the tensile strength and elongation of these printed samples according to ASTM standard D638. The previous publications provided a basic explanation of the minor features without going into depth. The preceding study did not address the three various levels of conditions for this printed sample's tensile strength and elongation.

Tensile strength and elongation are created utilizing the optimization approach. There is no discussion of experiment design or response measurement for tensile strength and elongation in the previous study. creation of tests for the combination of polycarbonate and basalt fibers utilizing the optimization approach for tensile strength and elongation. Previous research has not addressed the signal to noise ratio response for tensile strength and elongation [20-25]. The previous work did not address regression modeling or analysis of variance for tensile strength and elongation for this combination of polycarbonate and basal fiber. The first study did not address contour plots either. The study's goal is to determine the tensile strength and tensile elongation of a 95% Polycarbonate and 5% Basalt fibre merged mixture. In order to determine the optimal value of results, this experiment was created for three various levels of circumstances utilizing the optimization approach for tensile strength and tensile elongation, which is based on the ASTM standard D638 [26-30].Tensile strength and tensile elongation in these printed samples are measured utilizing response. In order to determine the most accurate result for the designing purpose of these optimization methodologies, this printing sample is designed for nine condition of experiments utilizing tests for three conditions: tensile strength, elongation, S/N ratio, and FITS. The optimal three parameters for these two qualities are determined by this response for the signal to noise ratio for tensile strength and tensile elongation. To improve the mechanical strength and contribution for both tensile strength and elongation, the optimal coefficient of correlation and contribution value should be found using analysis of variance [31-36].

To determine the optimal nozzle temperature, bed temperature, and printing speed for tensile strength and tensile elongation, a regression model is used to get the optimum strength value for these two attributes. With color and circumstances for this tensile and tensile elongation, a contour plot can graphically represent high strength, high rigidity, and high flexibility. Ultimately, the power of these two features is at its peak for the assistance of optimization techniques for low operating costs. Both the number of times and the waste may be decreased with this optimization strategy. The tensile strength and elongation of the combination polycarbonate and basalt fiber merging materials may be analyzed in depth using this optimization approach. The maximum strength of two categories can be increased by this optimization [37-39].

# Materials and method

## Material

The tensile strength sample from this experiment is displayed in figure 1. The mechanical parameters of this mixture of 95% polycarbonate and 5% basalt fiber include tensile strength and tensile elongation. The ASTM standard for tensile strength is D638 [40-45]. This combination printed samples for tensile strength and tensile elongation comply with the ASTM standard. In this printing samples are using ultima Ker 3d printing machine to print this samples.



Figure 1: Tensile sample for polycarbonate composite material

In this work, table 1 shows the Conditions and levels. In this condition level 3 is showing 80-degree Celsius Bed temperature, Level 1 is showing 60-degree Celsius bed temperature and Level 2 is showing 70-degree Celsius Bed temperature. Level 1 for Nozzle temperature is 200 degrees Celsius; Level 3 for Nozzle temperature is 220 degree Celsius and Level 2 for Nozzle temperature is 210 degrees Celsius. Level 3 for printing speed is 25 mm/s, Level 1 for Printing speed is 15 mm/s and level 2 for printing speed is 20 mm/s [46-48].

Table 1 Conditions and levels

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

## Experimental process

In this work, table 2 shows the creation of experiments for these three conditions. Level 1 for Nozzle temperature is 200 degrees Celsius; Bed temperature is 60 degree Celsius and Printing speed is 15 mm/s. Level 3 for Nozzle temperature is 200 degrees Celsius; Printing speed is 25mm/s and Bed temperature is 80 degrees Celsius. Level 2 for Bed temperature is 70 degrees Celsius; Nozzle temperature is 200 degree Celsius and Printing speed is 20 mm/s. Level 9 for Nozzle temperature is 220 degrees Celsius, Printing speed is 25mm/s and Bed temperature is 70 degrees Celsius. Level 7 for Nozzle temperature is 220 degrees Celsius; Bed temperature is 80 degree Celsius and Printing speed is 15mm/s. Level 8 for Nozzle temperature is 220 degrees Celsius; Printing speed is 20 mm/s and Bed temperature is 60 degrees Celsius. Level 4 for Nozzle temperature is 210 degrees Celsius; Printing speed is 15mm/s and Bed temperature is 70 degrees Celsius. Level 5 for Bed temperature is 80 degrees Celsius; Nozzle temperature is 210 degree Celsius and Printing speed is 20 mm/s. Level 6 for Printing speed is 25 mm/s, Bed temperature is 60 degree Celsius and Nozzle temperature is 210 degrees Celsius.

Table 2: Creation of Experiments

|  |  |  |  |
| --- | --- | --- | --- |
| Levels | Nozzle Temp | Printing speed | Bed Temp |
| 1. | 200 | 15 | 60 |
| 2. | 200 | 20 | 70 |
| 3. | 200 | 25 | 80 |
| 4. | 210 | 15 | 70 |
| 5. | 210 | 20 | 80 |
| 6. | 210 | 25 | 60 |
| 7. | 220 | 15 | 80 |
| 8. | 220 | 20 | 60 |
| 9. | 220 | 25 | 70 |

## Response Measurement

In this experiment work for the combination of Polycarbonate and basalt fiber merged Tensile strength and Tensile Elongation as per ASTM standard. In these two properties, Response for signal to noise ratio for Tensile strength highest value is the best value. Tensile Elongation for signal to noise ratio lowest value is the best value in this Taguchi response measurement for these two properties.

# Result and Discussion

## Taguchi evaluation

In this experiment, Table 3 presents the evaluation of nine Taguchi levels for tensile strength and tensile elongation. At a nozzle temperature of 200 °C, the first three levels showed a gradual increase in both properties. Level 1 (200 °C, 15 mm/s, 60 °C bed) recorded a tensile strength of 97 MPa with elongation of 8.98%, supported by S/N ratios of 39.73 and 20.93. Level 2 (200 °C, 20 mm/s, 70 °C bed) slightly improved strength to 98 MPa with elongation of 9.07%, while Level 3 (200 °C, 25 mm/s, 80 °C bed) further increased strength to 99 MPa with elongation of 9.17%. These results indicate that at lower nozzle temperatures, increasing speed and bed temperature provided marginal improvements in tensile performance while maintaining moderate elongation.

At a nozzle temperature of 210 °C, both strength and elongation improved more significantly. Level 4 (15 mm/s, 70 °C bed) yielded 100 MPa strength and 9.26% elongation, while Level 5 (20 mm/s, 80 °C bed) increased strength to 104 MPa and elongation to 9.63%. Level 6 (25 mm/s, 60 °C bed) reached the peak strength of 105 MPa with elongation of 9.72%, showing the combined benefit of higher nozzle temperature and increased printing speed. At 220 °C, the trend continued, with Level 7 (15 mm/s, 80 °C bed) producing 107 MPa strength and 9.91% elongation, while Level 8 (20 mm/s, 60 °C bed) achieved the maximum values of 108 MPa and 10.00% elongation. Finally, Level 9 (25 mm/s, 70 °C bed) maintained high performance with 106 MPa strength and 9.81% elongation. These results confirm that higher nozzle temperatures and optimized parameter settings consistently enhance both tensile strength and ductility, with 220 °C producing the best overall results.

Table 3: Experimental results

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Levels | Nozzle Temp | Printing speed | Bed Temp | Tensile strength | Tensile Elongation | S/N ratio for Tensile strength | S/N ratio for Tensile Elongation |
| 1 | 200 | 15 | 60 | 97 | 8.98% | 39.73543469 | 20.93447 |
| 2 | 200 | 20 | 70 | 98 | 9.07% | 39.82452151 | 20.84785 |
| 3 | 200 | 25 | 80 | 99 | 9.17% | 39.91270389 | 20.75261 |
| 4 | 210 | 15 | 70 | 100 | 9.26% | 40 | 20.66778 |
| 5 | 210 | 20 | 80 | 104 | 9.63% | 40.34066679 | 20.32747 |
| 6 | 210 | 25 | 60 | 105 | 9.72% | 40.42378598 | 20.24667 |
| 7 | 220 | 15 | 80 | 107 | 9.91% | 40.58767555 | 20.07853 |
| 8 | 220 | 20 | 60 | 108 | 10.00% | 40.66847511 | 20 |
| 9 | 220 | 25 | 70 | 106 | 9.81% | 40.50611731 | 20.16662 |

## Response ratio for signal to noise ratio

### Tensile strength for signal to noise ratio

In this work, table 4 shows the tensile strength response for signal ratio for Level 1 for Nozzle temperature is 39.82 degree Celsius, Printing speed is 40.11 mm/s and Bed temperature is 40.28 degree Celsius. Level 2 for Nozzle temperature is 40.25 degree Celsius; Printing speed is 40.28 mm/s and Bed temperature is 40.11 degree Celsius. Level 3 for Nozzle temperature is 40.59 degree Celsius; Printing speed is 40.28 mm/s and Bed temperature is 40.28 degree Celsius.

Table 4: Tensile strength response for signal to noise ratio

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 39.82 | 40.11 | 40.28 |
| 2 | 40.25 | 40.28 | 40.11 |
| 3 | 40.59 | 40.28 | 40.28 |
| Delta | 0.76 | 0.17 | 0.17 |
| Rank | 1 | 2 | 3 |

The nozzle temperature curve in this plot, figure 2, has the largest delta value at 0.76, while the printing speed curve has the second-highest delta value at 0.17. The delta value displayed by the bed temperature direction is 0.17. The third ranking category is displayed.



Figure 2: Signal to noise ratio for for tensile strength

### Tensile Elongation for Signal to noise ratio

In this work, table 5 shows the tensile Elongation response for signal ratio for Level 1 for Nozzle temperature is 20.84 degree Celsius, Printing speed is 20.56 mm/s and Bed temperature is 20.39 degree Celsius. Level 2 for Nozzle temperature is 20.41 degree Celsius; Printing speed is 20.39 mm/s and Bed temperature is 20.56 degree Celsius. Level 3 for Nozzle temperature is 20.08 degree Celsius; Printing speed is 20.39 mm/s and Bed temperature is 20.39 degree Celsius.

Table 5: Tensile Elongation response for signal to noise ratio

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 20.84 | 20.56 | 20.39 |
| 2 | 20.41 | 20.39 | 20.56 |
| 3 | 20.08 | 20.39 | 20.39 |
| Delta | 0.76 | 0.17 | 0.17 |
| Rank | 1 | 3 | 2 |

In this plot (figure 3), the nozzle temperature curve has the highest delta value (0.76), followed by the bed temperature curve (0.17). The printing speed direction shows a delta value of 0.17. It shows the third ranking category.



Figure 3: Plot for tensile Elongation signal to noise ratio

## Analysis of Variance (ANOVA)

### Tensile strength

The tensile strength table 6 shows the printed polycarbonate Composite specimens was found to be most significantly influenced by nozzle temperature, accounting for 87.14% of the total variation with an F-value of 61 and a statistically significant p-value of 0.016 (p < 0.05), according to the analysis of variance (ANOVA) table 6. Comparatively, bed temperature and printing speed each made an identical contribution of 5.71%, with p-values of 0.2 and F-values of 4, suggesting that their impacts were not statistically significant at the 95% confidence level. There was good model dependability as the model error only explained 1.43% of the variance. With a high coefficient of correlation (R2) of 98.57%, the model performed exceptionally well overall, explaining almost all of the variation in tensile strength. Although the expected R2 of 71.07% indicates strong predictive power, the corrected R2 of 94.29% confirmed negligible overfitting. Based on the selected parameters, the model's robustness in forecasting tensile strength results is supported by the PRESS value of 40.5.

Table 6: Tensile strength ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle Temp | 2 | 122 | 87.14% | 122 | 61 | 61 | 0.016 |
| Printing speed | 2 | 8 | 5.71% | 8 | 4 | 4 | 0.2 |
| Bed Temp | 2 | 8 | 5.71% | 8 | 4 | 4 | 0.2 |
| Error | 2 | 2 | 1.43% | 2 | 1 |  |  |
| Total | 8 | 140 | 100.00% |  |  |  |  |

The residual plots for tensile strength, which support the assumptions of the ANOVA model, are displayed in Figure 4. The residuals appear to be about normally distributed based on the normal probability plot and histogram. There is no discernible pattern in the "Versus Fits" plot, which suggests continuous variance, and no trend in the "Versus Order" plot, which suggests residuals are independent. The model's statistical reliability is confirmed by the residuals' generally acceptable behavior.



Figure 4: Residual plot for Tensile strength ANOVA

### Tensile Elongation

This ANOVA table (Table 7) examines how several factors affect tensile elongation throughout the 3D printing process. With two degrees of freedom (DF), nozzle temperature, printing speed, and bed temperature are the main causes of variance. Due to its high F-value of 62.18, adjusted mean square (Adj MS) of 0.000052, sum of squares (Seq SS) of 0.000105, and statistically significant P-value of 0.016 (usually regarded as significant if <0.05), the nozzle temperature contributes the most (87.09%) to the variability in tensile elongation. Less impact on tensile elongation is shown by the lower F-values (4 and 4.22) and non-significant P-values (0.2 and 0.192) of printing speed and bed temperature, which only contribute 5.60 and 5.91 percent, respectively. The sum of squares is 0.00012 in total. Although the expected R-sq is somewhat lower at 71.64%, indicating significant overfitting or restricted predictive strength, the model summary displays a very low standard error (S = 0.0009171), high R-sq Coefficient of Correlation is (98.60%), and adjusted R-sq (94.40%), indicating good model fit. The model validation using prediction residuals is supported by the PRESS value of 0.0000341 [49-51].

Table 7: Tensile Elongation ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle Temp | 2 | 0.000105 | 87.09% | 0.000105 | 0.000052 | 62.18 | 0.016 |
| Printing speed | 2 | 0.000007 | 5.60% | 0.000007 | 0.000003 | 4 | 0.2 |
| Bed Temp | 2 | 0.000007 | 5.91% | 0.000007 | 0.000004 | 4.22 | 0.192 |
| Error | 2 | 0.000002 | 1.40% | 0.000002 | 0.000001 |  |  |
| Total | 8 | 0.00012 | 100.00% |  |  |  |  |

The residual graphs for tensile elongation are displayed in Figure 5. The histogram and normal probability plot indicate that the residuals are somewhat skewed but otherwise about normally distributed. Because the residuals are dispersed randomly around zero, the "Versus Fits" figure shows continuous variance. The "Versus Order" figure confirms the residuals' independence by displaying no discernible pattern. The validity of the ANOVA for tensile elongation is supported by the model assumptions being generally satisfied.



Figure 5: Residual plots for Tensile Elongation ANOVA

## Regression Model

### Tensile Strength

Tensile strength is modeled by the provided regression equation using categorical levels of bed temperature, printing speed, and nozzle temperature. The average tensile strength when all factor levels are in their reference states is represented by the base value, which is 102.667. In comparison to the reference level, adjusting the nozzle temperature to 200°C results in a 4.667 decrease in tensile strength, a 0.333 rise at 210°C, and a 4.333 increase at 220°C. In terms of printing speed, tensile strength decreases by 1.333 at 15 mm/s and increases by 0.667 at 20 and 25 mm/s, respectively, in comparison to the baseline. Tensile strength increases by 0.667 at 60°C and 80°C and falls by 1.333 at 70°C for bed temperature. These coefficients aid in determining the best configuration of parameters to maximize tensile strength.

Regression Equation

|  |  |  |
| --- | --- | --- |
| Tensile strength | = | 102.667 - 4.667 Nozzle Temp\_200 + 0.333 Nozzle Temp\_210 + 4.333 Nozzle Temp\_220 - 1.333 Printing speed\_15 + 0.667 Printing speed\_20 + 0.667 Printing speed\_25 + 0.667 Bed Temp\_60 - 1.333 Bed Temp\_70 + 0.667 Bed Temp\_80 |

### Tensile Elongation

This regression equation models tensile elongation as a function of different levels of nozzle temperature, printing speed, and bed temperature. The base value is 0.095056, which represents the predicted tensile elongation when all parameters are at their reference levels. Changing the nozzle temperature to 200°C decreases elongation by 0.004322, while 210°C slightly increases it by 0.000311, and 220°C increases it further by 0.004011. For printing speed, a speed of 15 mm/s reduces elongation by 0.001222, whereas 20 mm/s and 25 mm/s both contribute positively by 0.000611. Regarding bed temperature, 60°C adds 0.000611, 70°C decreases elongation by 0.001256, and 80°C increases it by 0.000644. These equations show that tensile elongation is positively impacted by higher nozzle and bed temperatures, especially 220°C and 80°C, and adversely impacted by lower printing rates and bed temperatures of about 70°C.

Regression Equation

|  |  |  |
| --- | --- | --- |
| Tensile Elongation | = | 0.095056 - 0.004322 Nozzle Temp\_200 + 0.000311 Nozzle Temp\_210 + 0.004011 Nozzle Temp\_220 - 0.001222 Printing speed\_15 + 0.000611 Printing speed\_20 + 0.000611 Printing speed\_25 + 0.000611 Bed Temp\_60 - 0.001256 Bed Temp\_70 + 0.000644 Bed Temp\_80 |

## Contour plot

The contour plot figure 6 depicts how bed temperature and nozzle temperature interact to affect tensile strength. The color gradient, which goes from dark blue (less than 98) to dark green (more than 108), illustrates the values of tensile strength. As demonstrated, tensile strength rises with increasing bed and nozzle temperatures. Low tensile strength (<102) is indicated by the dark blue and blue zones on the left side at lower nozzle temperatures (200–205°C), particularly when the bed temperature is also low (60–70°C). As we move into the green zones (right), we can observe that higher nozzle temperatures (215–220°C) and moderate to high bed temperatures (70–80°C) are associated with increased tensile strength (over 106). The dark green area of the figure indicates that maximum tensile strength is achieved by maximizing both temperatures, especially by putting the bed at or above 75°C and the nozzle at or near 220°C.The relationship between nozzle and bed temperatures and tensile elongation is seen in contour plot figure 6, where lower values are preferred. Tensile elongation values (< 0.090) are the most ideal in this situation, and the dark blue area on the left side of the figure (nozzle temperature around 200–205°C and bed temperature approximately 60–70°C) indicates these values. Higher nozzle and bed temperatures cause the colors to change from light blue to green, which is a sign of less desirable elongation values. The most undesirable elongation values (> 0.100) are seen in the dark green area in the upper-right corner (nozzle temperature >215°C, bed temperature >75°C). Consequently, the blue areas provide the optimal combination for reducing tensile elongation, particularly when the bed temperature is between 60 and 70°C and the nozzle temperature is between 200 and 205°C.



1. (b)

Figure 6: (a) (b) shows the Contour plot for Tensile strength and Tensile Elongation

# Conclusion

This study successfully applied the Using the Taguchi approach, 95% polycarbonate and 5% basalt fibre (PC+BF) composites' FDM 3D printing settings are optimized to enhance tensile strength and minimize tensile elongation. According to the ANOVA findings, nozzle temperature was the most significant of the three parameters examined—bed temperature, printing speed, and nozzle temperature. It contributed 87.14% to tensile strength (F = 61, p = 0.016) and 87.09% to tensile elongation (F = 62.18, p = 0.016). At 220°C nozzle temperature, 60°C bed temperature, and 20 mm/s printing speed, the maximum tensile strength of 108 MPa was attained, along with a matching signal-to-noise ratio of 40.66. On the opposite together, 200°C nozzle temperature, 60°C bed temperature, and 15 mm/s printing speed produced the lowest tensile elongation of 8.98%, which is the ideal condition, with a S/N ratio of 20.93. Excellent fit was demonstrated by the regression models for both outputs, which had low error values (S = 1 and 0.0009171, respectively) and R2 values of 98.57% for tensile strength and 98.60% for tensile elongation. Contour plots provided additional confirmation that although lower settings decrease elongation at the expense of strength, higher nozzle and bed temperatures increase tensile strength but increase elongation. These findings show how well the Taguchi technique works to optimize 3D printing settings for improved mechanical performance of PC+BF composites, providing a dependable process window depending on the demands of a given application.

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