Taguchi-Based Process Design for Enhanced Flexural Performance of 3D-Printed Polycarbonate/Graphene Composites

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**Abstract:** The study investigates the Optimization of Flexural strength and Flexural modulus for using 95% polycarbonate and 5% graphene merged composite printed samples using the Taguchi method. In this Taguchi method 3 level of Experimental design for Nozzle temperature, printing speed and bed temperature. In this Orthogonal array analysis for signal to noise ratio (s/n), ANOVA, Regression model, and contour plot are discussed in detail. In this experimental study nozzle temperature (210 -220) degree Celsius is the most important temperature factor for flexural strength and modulus, second one is Bed temperature (70-80) degree Celsius, both factors are vital in the Taguchi 3 level of parameter design. In this work, the participation of flexural strength and flexural modulus is confirmed by analysis of variances (ANOVA), and regression models are being developed to predict mechanical behavior. The contour plot displays the color red, indicating that orange has the highest flexural strength, while the color red indicates that orange has the highest flexural modulus. In terms of mechanical behavior, bed temperature, and nozzle temperature, both Flexural strength and Flexural modulus are operating at very high levels.

**Keywords:** Polycarbonate, graphene, nozzle temperature, Bed temperature, signal to noise ratio, ANOVA regression model, contour plot.

# Introduction

Additive manufacturing is often used to produce complicated plastic components; it can print three degrees of freedom and create unfathomable designs [1]. Polycarbonate is a thermoplastic material that can withstand loads, has high toughness, and is resistant to heat. Graphene is resistant to all forms of hazards, which means it may perform very well in thermal, mechanical, and electrical characteristics [2]. Fused Deposition modeling focuses on materials as well as characteristics such as nozzle temperature, bed temperature, and printing speed. This Fused Deposition Modeling Machine is critical for enhancing layer thickness and material forms while maintaining high precision, quality, and lightweight materials [3]. Basically, these three factors are critical for printing filaments or samples. In the majority of printing scenarios, precision is critical; only correct filament design allows every item to be sold in the market; without accuracy, materials cannot survive in the market [4]. As a result, each printing portion requires precise design. The precise designing nozzle temperature, printing speed, and bed temperature are critical for manufacturing the accurate design. Nowadays, polycarbonate and graphene materials are very advanced. Polycarbonate is a relatively affordable material, but graphene is pricey [5]. Using various optimization techniques on these two materials is a novel strategy to improve research and simplify machine manufacturing. This is an enormous approach to process the greatest materials in the market [6]. Additive manufacturing printing is generally used to improve material structure design and quality. In the realm of 3D printing, the Taguchi technique is an important optimization tool [7].

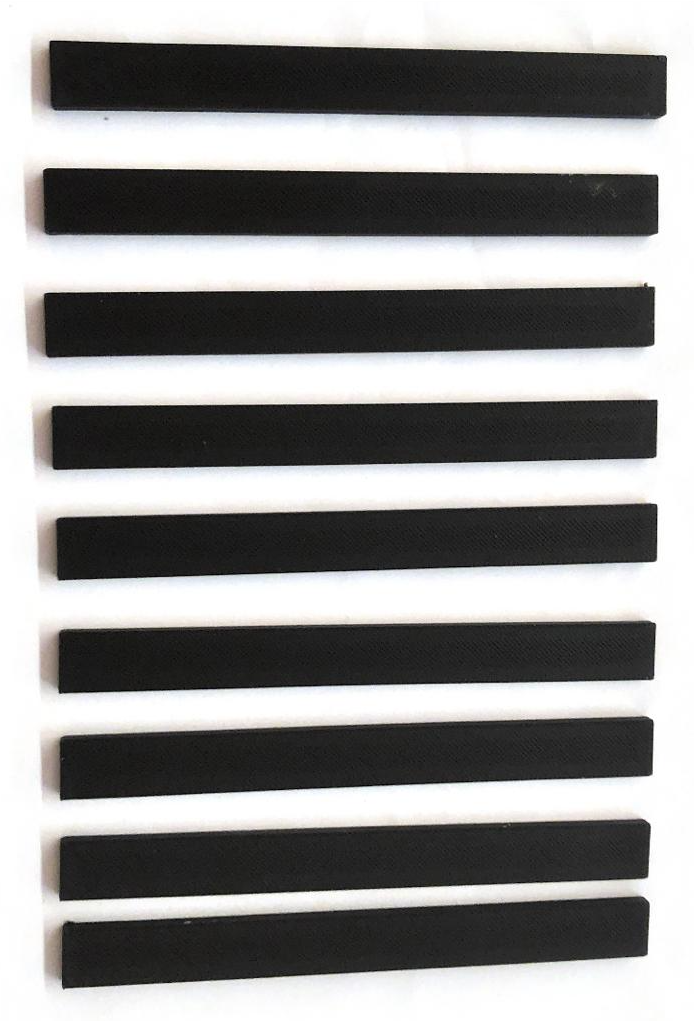
In addition to reducing the number of physical trials, the Taguchi method may save labor costs and time consumption by boosting material strength. For short periods of time, the Taguchi method can yield consistent results. Polycarbonate is primarily a material with strong characteristics [8]. It is very heat resistant and can withstand any large load [9]. This chemical is created using several industries. Graphene is one of the most durable materials available. One of the best alternatives in this scenario is a mixture of polycarbonate and graphene, both of which have distinct mechanical properties that provide the material combination a high degree of strength and quality. There are various advantages to this combination [10]. In essence. Fused deposition modeling is one of the most advanced processes for producing high-quality filament. Many firms use FDM to make their filaments. The literature gap in this study is the lack of additional in-depth research studies on previously published work on polycarbonate and graphene merged composites. This study's graphene and polycarbonate work is restricted, and it does not go into depth regarding the current circumstances. In this polycarbonate and graphene merged composite printed samples, the Taguchi technique is used for signal to noise ratio, analysis of variance, regression model, and contour plot. Previous published studies are not discussed in depth. These previously published articles just discuss the characteristics of polycarbonate and graphene powder materials; no work was done on the polycarbonate and graphene merged composite printed samples. This previously published study did not use the number of parameters optimization utilizing a rigorous statistical tool technique. Previously, no study was done on flexural strength and flexural modulus in printed polycarbonate and graphene samples using the Taguchi technique to identify several factors such as nozzle temperature, printing speed, and bed temperature. Previous research has mostly focused on stiffness and strength, but the bulk of publications have not provided in-depth analysis of mechanical characteristics for merged composite materials. The prior study did not go into depth concerning adequate bed temperature, high printing speed, and high nozzle temperature to determine the optimal values [11-15].

Flexural strength and modulus are essential considerations in the materials business. The majority of the industry follows these properties. However, earlier study did not focus on these aspects. Essentially, contour plot color focuses on color strength for high, mid, and low levels. However, earlier work on contour plots did not provide in-depth analysis regarding this approach [16-22]. The Previous studies are limited. Although regression models are commonly used to study mechanical behavior, earlier research has not been conducted on polycarbonate and graphene merged printed composite samples. The objective of this project is to print samples of a polycarbonate 95% and 5% graphene merged composite. In this combination, printed samples use flexural strength and flexural modulus results obtained using Taguchi method optimization for three levels of parameters: nozzle temperature, bed temperature, and printing speed. In this three-level parameter set, one parameter is the best for flexural strength and modulus. The signal-to-noise ratio is the initial stage in designing tests for nine values. The 9-value Taguchi approach is used to determine the rank of three categories [23-26]. Print speed, bed temperature, and nozzle temperature. Flexural strength and Flexural modulus are two qualities that must be checked to determine the optimal nozzle, maximum temperature, printing speed, and bed temperature. Taguchi analysis is the capacity to determine the rank of three parameters based on nine experiments. Regression models are typically used to determine mechanical strength and quality; in this case, printed samples must determine mechanical behavior and stability. For this task objective, the analysis of variance must show a contribution percentage level of at least 1% and a correlation coefficient of more than 95%. This Contribution value must be used to check the Flexural strength and Flexural modulus, and the experiment is on the correct track after that. The contour plot is the final stage for determining the color shape of Flexural strength and flexibility. Red orange is the strongest color shape for flexural strength and modulus. This is a general term for Contour plot using Taguchi method, contour plot can show the Color for the strength of each operation for flexural strength and flexural modulus. This is a Taguchi experimental design approach and the outcome for all printed samples. The Taguchi technique is one of the most effective operations for reducing manufacturing waste. This is one of the greatest techniques in the present world 2025, and the future comes under the optimization approach [27-30].

# Materials and Methods

## Materials

The experiment uses **Ulti maker S5 Pro Bundle 3D printer to print the flexural sample, Figure 1 shows the Polycarbonate composite printed flexural sample In this flexural sample is the combination of 95% Polycarbonate and 5% graphene. The ASTM Standard for Flexural strength is D790. Figure 1 shows the Polycarbonate composite Flexural Printed samples.**



**Figure 1: Flexural Polycarbonate ted samples**

**Table 1: Parameters and Levels**

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

**In this Experiment table 1 shows the level of parameters, In this work nozzle temperature for level 1 is 200, level 2 is 210 and level 3 is 220 degree Celsius. In this work printing speed for Level 1 is 15, level 2 is 20 and level 3 is 25 mm/s and Bed Temperature of level 1 is 60,Level 2 is 70 and level 3 is 80 degree Celsius. These are the levels of parameters for Taguchi L9 Experimental works [31-35].**

## ****Experimental Design****

**Table 2 shows the Taguchi 9 experiments design. In that Nozzle temperature for experimental one is 200 degree Celsius, Printing speed 15mm/s and Bed Temperature is 60 degree Celsius. Experimental 2 design for nozzle temperature is 200 degree Celsius,Printing speed 20mm/s and Bed Temperature is 70 degree Celsius. Experimental 3 design for nozzle temperature is 200 degree Celsius,Printing speed 25mm/s and Bed Temperature is 80 degree Celsius. Experimental 4 design for nozzle temperature is 210 degree Celsius,Printing speed 15mm/s and Bed Temperature is 70 degree Celsius. Experimental 5 design for nozzle temperature is 210 degree Celsius,Printing speed 20mm/s and Bed Temperature is 80 degree Celsius [36-40]. Experimental 6 design for nozzle temperature is 210 degree Celsius,Printing speed 25mm/s and Bed Temperature is 60 degree Celsius. Experimental 7 design for nozzle temperature is 220 degree Celsius,Printing speed 15mm/s and Bed Temperature is 80 degree Celsius. Experimental 8 design for nozzle temperature is 220 degree Celsius,Printing speed is 20mm/s and Bed Temperature is 60 degree Celsius. Experimental 9 design for nozzle temperature is 220 degree Celsius,Printing speed is 25mm/s and Bed Temperature is 70 degree Celsius.**

**Table 2: Experimental design for 9 Experiments parameters**

|  |  |  |  |
| --- | --- | --- | --- |
| **Experiment no** | **Nozzle Temperature** | **Printing speed** | **Bed Temperature** |
| 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 Flexural strength and modulus are texting in signal to noise ratio, the better strength value is finding. In this Flexural strength and modulus ASTM standard is D790. This standard provides excellent shaping and accurate design for the printed flexural samples [37-40].

# Result and Discussion

In this experiment table 3 shows the orthogonal array for signal to noise ratio and FITS for flexural strength and flexural modulus. In this Taguchi analysis Experiment level 1 shows the nozzle temperature is 200 degree Celsius, Printing speed is 15mm/s, Bed temperature is 60 degree Celsius, Flexural strength is 96 MPa, Flexural modulus is 2300 MPa, Signal to noise ratio 1 is 39.645425, signal to noise ratio 2 is 67.234557, FITS is 97 and FITS 1 is 2306.6667 [41-45].

Experiment level 2 shows the nozzle temperature is 200 degree Celsius, Printing speed is 20mm/s, Bed temperature is 70 degree Celsius, Flexural strength is 97 MPa, Flexural modulus is 2320 MPa, Signal to noise ratio 1 is 39.735, signal to noise ratio 2 is 67.309, FITS is 96.33 and FITS 1 is 2313.33.Experiment level 3 shows the nozzle temperature is 200 degree Celsius, Printing speed is 25mm/s, Bed temperature is 80 degree Celsius, Flexural strength is 100 MPa, Flexural modulus is 2340 MPa, Signal to noise ratio 1 is 40, signal to noise ratio 2 is 67.38, FITS is 99.67 and FITS 1 is 2340.Experiment level 4 shows the nozzle temperature is 210 degree Celsius, Printing speed is 15 mm/s, Bed temperature is 70 degree Celsius, Flexural strength is 102 MPa, Flexural modulus is 2350 MPa, Signal to noise ratio 1 is 40.17, signal to noise ratio 2 is 67.42, FITS is 101.67 and FITS 1 is 2350.Experiment level 5 shows the nozzle temperature is 210 degree Celsius, Printing speed is 20mm/s, Bed temperature is 80 degree Celsius, Flexural strength is 106 MPa, Flexural modulus is 2400 MPa, Signal to noise ratio 1 is 40.506, signal to noise ratio 2 is 67.604, FITS is 107 and FITS 1 is 2406.67.Experiment level 6 shows the nozzle temperature is 210 degree Celsius, Printing speed is 25mm/s, Bed temperature is 60 degree Celsius, Flexural strength is 105 MPa, Flexural modulus is 2380 MPa, Signal to noise ratio 1 is 40.423, signal to noise ratio 2 is 67.531, FITS is 104.33 and FITS 1 is 2373.33.Experiment level 7 shows the nozzle temperature is 220 degree Celsius, Printing speed is 15mm/s, Bed temperature is 80 degree Celsius, Flexural strength is 104 MPa, Flexural modulus is 2370 MPa, Signal to noise ratio 1 is 40.340, signal to noise ratio 2 is 67.494, FITS is 103.33 and FITS 1 is 2363.33.Experiment level 8 shows the nozzle temperature is 220 degree Celsius, Printing speed is 20mm/s, Bed temperature is 60 degree Celsius, Flexural strength is 103 MPa, Flexural modulus is 2360 MPa, Signal to noise ratio 1 is 40.256, signal to noise ratio 2 is 67.458, FITS is 102.67 and FITS 1 is 2360.Experiment level 9 shows the nozzle temperature is 220 degree Celsius, Printing speed is 25mm/s, Bed temperature is 70 degree Celsius, Flexural strength is 99 MPa, Flexural modulus is 2330 MPa, Signal to noise ratio 1 is 39.912, signal to noise ratio 2 is 67.347, FITS is 100 and FITS 1 is 2336.67. These are the data’s for 9 experiments Taguchi analysis.

## Response for Signal to noise ratio

Table 3: Experimental Results using orthogonal array and s/n ratio for Flexural strength and modulus

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Experiment | Nozzle temperature degree C | Printing speed mm/s | Bed temp  Degree C | Flexural strength MPa | Flexural modulus MPa | S/N Ratio for Flexural strength | S/N Ratio for Flexural modulus |
| 1. | 200 | 15 | 60 | 96 | 2300 | 39.645425 | 67.234557 |
| 2. | 200 | 20 | 70 | 97 | 2320 | 39.735435 | 67.30976 |
| 3. | 200 | 25 | 80 | 100 | 2340 | 40 | 67.384317 |
| 4. | 210 | 15 | 70 | 102 | 2350 | 40.172003 | 67.421357 |
| 5. | 210 | 20 | 80 | 106 | 2400 | 40.506117 | 67.604225 |
| 6. | 210 | 25 | 60 | 105 | 2380 | 40.423786 | 67.531539 |
| 7. | 220 | 15 | 80 | 104 | 2370 | 40.340667 | 67.494967 |
| 8. | 220 | 20 | 60 | 103 | 2360 | 40.256744 | 67.45824 |
| 9. | 220 | 25 | 70 | 99 | 2330 | 39.912704 | 67.347118 |

In this experiment, Table 4 and Figure 2 show the response to signal ratio for flexural strength. In this flexural strength for signal to noise ratio of Level 1 Nozzle temperature is showing 39.79 Degree Celsius, Printing speed is 40.05mm/s and Bed temperature is 40.11 degree Celsius. Level 2 for flexural strength of nozzle temperature is 40.37 degree Celsius, Printing speed is 40.17 mm/s and Bed temperature is 39.94 degree Celsius. Level 3 for Nozzle temperature is 40.17 degrees Celsius, Printing speed is 40.11 mm/s, and Bed temperature is 40.28 degrees Celsius [46-50].

Table 4: Flexural strength for signal to noise ratio

|  |  |  |  |
| --- | --- | --- | --- |
| Level | Nozzle temperature | Printing speed mm/s | Bed temp |
| 1 | 39.79 | 40.05 | 40.11 |
| 2 | 40.37 | 40.17 | 39.94 |
| 3 | 40.17 | 40.11 | 40.28 |
| Delta | 0.57 | 0.11 | 0.34 |
| Rank | 1 | 3 | 2 |

In this 3 level of parameters figure 2 graph shows the nozzle temperature is giving first highest rank of 0.57 delta. second highest rank is Bed temperature, delta value is 0.34 degree Celsius and the last one is printing speed the value is 0.11 mm/s



Figure 2: Graph for Signal to noise ratio of Flexural strength

In this experiment, Table 5 and Figure 3 show the response to signal ratio for flexural modulus. In this flexural modulus for signal to noise ratio of Level 1 Nozzle temperature is showing 67.31 degree Celsius, Printing speed is 67.38mm/s and Bed temperature is 67.41 degree Celsius. Level 2 for flexural strength of nozzle temperature is 67.52 degree Celsius, Printing speed is 67.46 mm/s and Bed temperature is 67.36 degree Celsius. Level 3 for Nozzle temperature is 67.43 degree Celsius, Printing speed is 67.42 mm/s and Bed temperature is 67.49 degree Celsius

Table 5: Flexural modulus for signal to noise ratio

|  |  |  |  |
| --- | --- | --- | --- |
| Level | Nozzle temperature | Printing speed | Bed temp |
| 1 | 67.31 | 67.38 | 67.41 |
| 2 | 67.52 | 67.46 | 67.36 |
| 3 | 67.43 | 67.42 | 67.49 |
| Delta | 0.21 | 0.07 | 0.14 |
| Rank | 1 | 3 | 2 |

In this 3 level of parameters figure 3 graph shows the nozzle temperature is giving first highest rank of 0.21 delta. second highest rank is Bed temperature, delta value is 0.14 degree Celsius and the last one is printing speed the value is 0.07 mm/s



Figure 3: Flexural modulus of signal to noise ratio

## Analysis of Variance (ANOVA)

In this experiment table 6 shows the flexural strength of ANOVA, there having nozzle temperature, printing speed, Bed temperature, Error. these are comes under source list after that Deformation, Seq SS, Contribution, Adj SS, Adj MS, F-vale and P-value. In this experiment total DF value is 8 for Nozzle temperature, Bed Temperature, Printing speed. after that total value of contribution is 100.00% for Nozzle temp, Bed temp and Printing speed. Seq.SS total value is 100 for Nozzle temp, Bed temp and Printing speed and the S value is 1.52753 and coefficient of correlation is 95.33%, R -sq. (adj)is 81.33%, Press value is 94.5 and R-Sq.(pred) 5.50 %.

Table 6: Flexural Strength - Analysis of variance ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle temperature | 2 | 68.667 | 68.67% | 68.667 | 34.333 | 14.71 | 0.064 |
| Printing speed | 2 | 2.667 | 2.67% | 2.667 | 1.333 | 0.57 | 0.636 |
| Bed temp | 2 | 24 | 24.00% | 24 | 12 | 5.14 | 0.163 |
| Error | 2 | 4.667 | 4.67% | 4.667 | 2.333 |  |  |
| Total | 8 | 100 | 100.00% |  |  |  |  |

In this experiment figure 4 shows the normal probability plot is showing smooth standardized residual,versus fits shows the good fitted value,Histogram shows the standardized residual in flexural strength. Versus order for flexural strength is showing observation order.



Figure 4 graph for Residual Plots for Flexural strength

In this experiment table 7 shows the flexural modulus of ANOVA, there having nozzle temperature, printing speed, Bed temperature, Error. these are comes under source list after that Deformation, Seq SS, Contribution, Adj SS, Adj MS, F-vale and P-value. In this experiment total DF value is 8 for Nozzle temperature, Bed Temperature, Printing speed. after that total value of contribution is 100.00% for Nozzle temp, Bed temp and Printing speed. Seq.SS total value is 7800 for Nozzle temp, Bed temp and Printing speed and the S value is 11.547 and coefficient of correlation is 96.58%, R -sq (adj)is 86.32%, Press value is 5400 and R-Sq.(pred) 30.77 %..

In this experiment figure 5 shows the normal probability plot is showing standardized residual, versus fits shows the fitted value,Histogram shows the standardized residual in flexural modulus. Versus order for flexural modulus is showing observation order.This graph generally shows the flexural modulus of four operating structures.

Table 7: Flexural modulus -Analysis of variance ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
| Nozzle temperature | 2 | 4866.7 | 62.39% | 4866.7 | 2433.3 | 18.25 | 0.052 |
| Printing speed | 2 | 600 | 7.69% | 600 | 300 | 2.25 | 0.308 |
| Bed temp | 2 | 2066.7 | 26.50% | 2066.7 | 1033.3 | 7.75 | 0.114 |
| Error | 2 | 266.7 | 3.42% | 266.7 | 133.3 |  |  |
| Total | 8 | 7800 | 100.00% |  |  |  |  |



Figure 5: Residual Plots for Flexural modulus

## Regression model

In this experiment, flexural strength shows Intercept (101.333): This is the baseline flexural strength when all category variables are at their reference values. Categorical Variables (One-hot Encoded):Nozzle temperature levels: 200, 210, and 220 °C. Printing speeds: 15, 20, and 25 mm/s. Bed temperatures: 60, 70, 80 °C. Interpretation of Coefficients: Nozzle temp\_200 reduces strength by 3.667 MPa; Nozzle temp\_210 raises strength by 3.000 MPa; Printing speed\_15 reduces strength by 0.667 MPa; Bed temp\_70 reduces strength by 2.000 MPa. Bed temperature\_80: improves strength by 2.000 MPa. So, greater nozzle temperatures (up to 210°C) and higher bed temperatures (80°C) tend to increase strength, but printing too slowly (15 mm/s) or at a nozzle temperature of 200°C diminishes it.

Regression Equation

|  |  |  |
| --- | --- | --- |
| Flexural strength MPa | = | 101.333 - 3.667 Nozzle temperature\_200 + 3.000 Nozzle temperature\_210 + 0.667 Nozzle temperature\_220 - 0.667 Printing speed\_15 + 0.667 Printing speed\_20 + 0.000 Printing speed\_25 + 0.000 Bed temp\_60 - 2.000 Bed temp\_70 + 2.000 Bed temp\_80 |

In this experiment, Intercept (2350.00) represents the baseline modulus value when reference categories are employed. Interpretation of Coefficients: Nozzle temperature\_200: greatly reduces modulus (-30 MPa). Nozzle temperature\_210: raises modulus significantly (+26.67 MPa) Printing speed\_15 decreases modulus by -10 MPa. Bed temperature\_80: increases modulus (+20 MPa).Bed temperature\_70: reduces modulus (-16.67 MPa).This suggests that higher bed temperatures (particularly 80°C) and nozzle temperatures of 210°C are beneficial to modulus, but low printing speeds and bed temperatures have a detrimental impact.

|  |  |  |
| --- | --- | --- |
| Flexural modulus | = | 2350.00 - 30.00 Nozzle temperature\_200 + 26.67 Nozzle temperature\_210 + 3.33 Nozzle temperature\_220 - 10.00 Printing speed\_15 + 10.00 Printing speed\_20 + 0.00 Printing speed\_25 - 3.33 Bed temp\_60 - 16.67 Bed temp\_70 + 20.00 Bed temp\_80 |

## Contour plot for Flexural strength and Flexural modulus

In this experiment figure 6 shows the flexural strength of contour graphic shows how flexural strength fluctuates with nozzle and bed temperatures. The deepest green zone, indicating the maximum flexural strength (>105 MPa), occurs around a nozzle temperature of 210-215°C and a bed temperature of 70-75°C. Lower strength is seen at 200°C nozzle temperature and bed temperatures of 60°C or 70°C. The regression model indicates that higher nozzle and bed temperatures (excluding 70 °C) increase flexural strength.



Figure 6: Contour plot for Flexural strength

In this experiment figure 7 shows the contour plot depicts the influence of nozzle and bed temperatures on the printed material's flexural modulus. The color gradient goes from dark blue (the lowest modulus) to dark green (the greatest modulus). The nozzle temperature of 210-215 °C and the bed temperature of 75-80 °C result in the greatest flexural modulus values (over 2400 MPa), as seen by the darkest green region. The lowest values (below 2310 MPa) occur at low nozzle temperatures (200 °C) and bed temperatures (60-65 °C), as illustrated in dark blue. This pattern is consistent with the regression model, which showed that increasing nozzle and bed temperatures often increase flexural modulus.



Figure 7 Contour plot for flexural modulus

# Conclusion

The study has successfully shown how to optimize the flexural strength and flexural modulus of 3D-printed polycarbonate–graphene composite samples using the Taguchi technique. The experiment found that nozzle temperature (specifically 210–220 °C) had the greatest impact on both mechanical characteristics, followed by bed temperature (70–80 °C), after examining the impacts of nozzle temperature, bed temperature, and printing speed across three levels. While contour plots visually verified that the mid-to-high ranges of nozzle and bed temperatures are where best mechanical performance occurs, the regression models that were created offered predictive insight into material behavior, displaying good correlation values (R2 > 95%). The substantial role that these parameters—particularly nozzle temperature—play in influencing the ultimate flexural performance was further confirmed by ANOVA. By concentrating on printed PC–graphene composites, the study not only closes a gap in the literature but also validates the Taguchi technique as a very successful strategy for additive manufacturing process optimization. These results offer a useful guide for enhancing the mechanical integrity of polymer nanocomposites in engineering applications.

# References

1. Anand et al., (2024). A comprehensive analysis of small-scale building integrated photovoltaic system for residential buildings: Techno-economic benefits and greenhouse gas mitigation potential. Journal of Building Engineering, 82, 108232.
2. Grosious et al., (2024, June). Utilizing 3D printing in marine industries: innovations for enhanced ship and boat production. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 132-143). SPIE.
3. Nourmohammadi, M., Jahanmardi, R., Moeenfard, H., Zohuri, G., & Bazgir, S. (2023). Optimization of acoustic performance of EPDM-based foams using Taguchi design of experiments: Appropriate content of additives. *Polyolefins Journal*, *10*(4), 211-224.
4. Grosious et al., (2024, June). Advancements in automotive production: exploring the role of 3D printing and selective laser sintering. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 403-415). SPIE.
5. Manu, M., Aravind, J., Sanal Mohammed, B., KE, R. R., & Mubarak Ali, M. (2024). Optimization of tribological characteristics in cryo-treated plastic/graphene oxide modified CFRP via ANN-based predictive modeling for aerospace applications. *Composites Science and Technology*, *250*, 110520.
6. Grosious et al., (2024, June). Impact of additive manufacturing on sports safety prevention and performance enhancement: a review. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 46-56). SPIE.
7. Kavimani, V., Prakash, K. S., Thankachan, T., & Udayakumar, R. (2020). Synergistic improvement of epoxy derived polymer composites reinforced with Graphene Oxide (GO) plus Titanium di oxide (TiO2). *Composites Part B: Engineering*, *191*, 107911.
8. Mariya Louis et al., Multiresponse optimization and network-based prediction modelling for the WEDM of AM60B biomedical material. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 238(20), 10045-10066.
9. Niyobuhungiro, D., & Hong, L. (2021). Graphene polymer composites: Art of review on fabrication method, properties, and future perspectives. *Advances in Science and Technology. Research Journal*, *15*(1), 37-49.
10. Kaushal et al., (2024). Fault prediction and awareness for power distribution in grid connected res using hybrid machine learning. Electric Power Components and Systems, 1-22.
11. Selvi, S., et al. Optimization of solar panel orientation for maximum energy efficiency. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
12. Sai, Samavedam Aditya, et al. Transfer learning based fault detection for suspension system using vibrational analysis and radar plots. Machines 11.8 (2023): 778.
13. P. Sakthivel et al. Mechanical and thermal properties of a waste fly ash-bonded Al-10 Mg alloy composite improved by bioceramic silicon nanoparticles. Biomass Conversion and Biorefinery, pp.1-12.
14. A. Baraniraj et al. 2023. Silicon Carbide Particle Enriched Magnesium Alloy (AZ91) Composite: Physical, Microstructural and Mechanical Studies. Silicon, 15(15), pp.6367-6374.
15. Paranthaman et al., Influence of SiC particles on mechanical and microstructural properties of modified interlock friction stir weld lap joint for automotive grade aluminium alloy. Silicon 14.4 (2022): 1617-1627.
16. Sureshkumar, P., et al., Electrochemical corrosion and tribological behaviour of AA6063/Si3N4/Cu (NO3) 2 composite processed using single-pass ECAPA route with 120 die angle. Journal of Materials Research and Technology 16 (2022): 715-733.
17. M. Senthil Kumar. Influence of silicon carbide on tribological behaviour of AA2024/Al2O3/SiC/Gr hybrid metal matrix squeeze cast composite using Taguchi technique. Materials Research Express 6.12 (2020): 1265f9.
18. C. Devanathan et al. 2024. Significance of Hemp Fiber on Mechanical and Thermal Performance of Polypropylene Nanocomposite Developed by Compression Mould Technique. Journal of The Institution of Engineers (India): Series D, pp.1-5.
19. M. V. Kumar et al. 2024. Development of Low-Density Polyethylene Nanocomposite with CNT Fibre Via Injection Moulding: Performance Study. Journal of The Institution of Engineers (India): Series D, pp.1-5.
20. P. Chandramohan et al. Processing and Characteristics Evaluation of Polyester Resin Nanocomposite Synthesized with Natural Fiber. Journal of The Institution of Engineers (India): Series D, pp.1-5.
21. Chennai Viswanathan, Prasshanth, et al., Deep learning for enhanced fault diagnosis of monoblock centrifugal pumps: Spectrogram-based analysis. Machines 11.9 (2023): 874.
22. R. Anand, and S. Santhosh Kumar. Optimization of process parameters in TIG welding of AISI 4140 stainless steel using Taguchi technique. Materials today: proceedings 37 (2021): 1550-1553.
23. Balaji, S., Bharathiraja, G., Kaliappan, S., Veeman, D., & Mammo, W. D. (2021). Experimental investigation on mechanical properties of TiAlN thin films deposited by RF magnetron sputtering. Journal of Nanomaterials, 2021(1), 5943486.
24. Seeniappan and Neha Garg. Checking and supervisory system for calculation of industrial constraints using embedded system. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
25. V. Vijayan et al. 2016. Performance Evaluation of Multipurpose Solar Heating System. Mechanics & Mechanical Engineering, 20(4).
26. I. J. Isaac Premkumar et al. Combustion analysis of biodiesel blends with different piston geometries. Journal of Thermal Analysis and Calorimetry, 142(4), pp.1457-1467.
27. M. Vivekanandan et al. 2021. Experimental and CFD investigation of helical coil heat exchanger with flower baffle. Materials Today: Proceedings, 37, pp.2174-2182.
28. C. B. Priya et al. "Bio-degradable waste banana and neem fiber reinforced epoxy hybrid composites: characteristics study." Journal of Mechanical Science and Technology 38, no. 4 (2024): 1891-1896. <https://doi.org/10.1007/s12206-024-0322-7>
29. M. Aruna et al. "Alkali-Processed Flax Natural Made High-Density Polyethylene Waste Recycled Composites: Performance Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00739-z>
30. Vaishali, Kokila R., et al., Guided container selection for data streaming through neural learning in cloud. International Journal of System Assurance Engineering and Management (2021): 1-7.
31. Yogeshwaran, S., et al., Experimental investigation on mechanical properties of epoxy/graphene/fish scale and fermented spinach hybrid bio composite by hand lay-up technique. Materials Today: Proceedings 37 (2021): 1578-1583.
32. Kaliappan, S., and Akshay Rajput. Sentiment Analysis of News Headlines Based on Sentiment Lexicon and Deep Learning. 2023 4th International Conference on Smart Electronics and Communication (ICOSEC). IEEE, 2023.
33. Josphineleela, R., and Upendra Mohan Bhatt. Intelligent Virtual Laboratory Development and Implementation using the RASA Framework. 2023 7th International Conference on Computing Methodologies and Communication (ICCMC). IEEE, 2023.
34. Suman, Turpati, et al., IoT based Social Device Network with Cloud Computing Architecture. 2023 Second International Conference on Electronics and Renewable Systems (ICEARS). IEEE, 2023.
35. S. Kaliappan. Mechanical Assessment of Carbon–Luffa Hybrid Composites for Automotive Applications. No. 2023-01-5070. SAE Technical Paper, 2023.
36. Muralidaran, V. Manivel, et al., Grape stalk cellulose toughened plain weaved bamboo fiber-reinforced epoxy composite: load bearing and time-dependent behavior. Biomass Conversion and Biorefinery 14.13 (2024): 14317-14.
37. Pethuraj Manickaraj, and V. Sakthi Murugan. "Featuring with Nano Alumina Made Hybrid Epoxy/Carbon Fiber Nanocomposite: Performance Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00754-0>
38. De Poures, Melvin Victor et al. "Sodium Hydroxide Processed Natural Sisal Fiber Made Polypropylene Composite: Characteristics Evaluation." Journal of The Institution of Engineers (India): Series D (2024): 1-5. <https://doi.org/10.1007/s40033-024-00761-1>
39. Khimsuriya, Yogeshkumar D., et al., Artificially roughened solar air heating technology–A comprehensive review. Applied Thermal Engineering 214 (2022): 118817.
40. Kumar, M. Senthil, et al., Experimental investigations on mechanical and microstructural properties of Al2O3/SiC reinforced hybrid metal matrix composite. IOP Conference Series: Materials Science and Engineering. Vol. 402. No. 1. IOP Publishing, 2018.
41. C. Angalaparameswari et al. Effective Utilization of Bast Fiber in High Density Polyethylene Nanocomposite Enriched by Alumina Nanoparticle: Mechanical Performance Evaluation. Journal of The Institution of Engineers (India): Series D, pp.1-5.
42. D. Dillikannan et al. 2024. An Approach of Nano-SiC-Filled Epoxy Nanocomposite Tensile and Flexural Strength Enriched by the Addition of Sisal Fiber. Journal of The Institution of Engineers (India): Series D, pp.1-5.
43. L. Kamaraj et al. 2024. Fabrication and Behavior Study of Natural Fiber Utilized Low-Density Polyethylene Nanocomposite via Injection Mold. Journal of The Institution of Engineers (India): Series D, pp.1-5.
44. V. Vijayan et al. CFD modeling and analysis of a two-phase vapor separator. Journal of Thermal Analysis and Calorimetry, 145(5), pp.2719-2726.
45. S. Baskar 2022, July. Thermal management of solar thermoelectric power generation. In AIP conference proceedings (Vol. 2473, No. 1). AIP Publishing.
46. P. Sakthivel et al. Synthesis and Thermal Adsorption Characteristics of Silver-Based Hybrid Nanocomposites for Automotive Friction Material Application. Adsorption Science & Technology, 2023.
47. Yogeshwaran, S., et al. Mechanical properties of leaf ashes reinforced aluminum alloy metal matrix composites. International Journal of Applied Engineering Research 10.13 (2015): 11048-11052.
48. M. Senthil Kumar, and Mukesh Chaudhari. Optimization of squeeze casting process parameters to investigate the mechanical properties of AA6061/Al2O3/SiC hybrid metal matrix composites by taguchi and anova approach. Advanced Engineering Optimization Through Intelligent Techniques: Select Proceedings of AEOTIT 2018. Singapore: Springer Singapore, 2019. 393-406
49. K. Logesh et al. "Performance investigation of silicon nitride (SiNx) layer doped with twin thin films of gallium and zinc oxide for solar cell." Optical and Quantum Electronics 56, no. 7 (2024): 1-13.<https://doi.org/10.1007/s11082-024-07100-4>
50. R. Karthik et al. "Characteristics performance evaluation of AZ91-fly ash composite developed by vacuum associated stir processing." International Journal of Cast Metals Research (2024): 1-8.<https://doi.org/10.1080/13640461.2024.2364129>