Towards High-Performance 3D-Printed Polycarbonate Composites: Statistical Modelling of Impact and Flexural Properties

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**Abstract:** This study focuses on mechanical characteristics of 3D-printed 90% polycarbonate (PC) composites supplemented with 5% graphene and 5% carbon powder were optimized using the Fused Deposition Modelling (FDM) technique. The Taguchi approach was used to assess the impacts of three critical process parameters—nozzle temperature, bed temperature, and printing speed on Izod impact strength and flexural modulus. The tests were designed using a L9 orthogonal array. The results showed that nozzle temperature strongly impacted both parameters, contributing to 90% of the variance in Impact strength and 75.07% in flexural modulus, as validated by ANOVA. The best mechanical performance was attained at a nozzle temperature of 220 °C, bed temperature of 60-80 °C, and printing speed of 20-25 mm/s, resulting in an Impact strength of 858 J/m and a flexural modulus of 2580 MPa. Regression models accurately predicted Impact strength and flexural modulus, with R² values of 96.67% and 95.36, respectively. These discoveries have important implications for enhancing the performance of polymer composites in additive manufacturing applications. Contour plots show that increasing nozzle and bed temperatures increased Impact strength and flexural modulus, indicating the ideal mechanical performance zones.

**Keywords:** Polycarbonate, Carbon powder, Graphene, Impact strength, Flexural modulus, ANOVA, Regression model, Orthogonal array, Contour plot.

# Introduction

Additive manufacturing technology is commonly utilizing in the maritime sector, and polycarbonate materials are used to manufacture numerous marine interior components. Polycarbonate materials are commonly used in ship interior parts to create a wide range of 3D printing designs [1]. Polycarbonate materials provide great toughness, high strength, and precise stability in standard design. This polycarbonate material has the potential to make durable interior covers and protective covers for the ship marine sector [2]. According to client expectations, the design may be simply printed using 3D printing technology. Enclosures are also commonly made from polycarbonate [3]. This polycarbonate-based ship interior parts are visually appealing and highly resistant to any sea-level exterior threat. This polycarbonate material has the potential to protect internal elements [4]. Graphene materials are among the greatest mechanical properties, high resistance, and UV resistance materials in the materials market. Graphene materials are being used in the marine industry to coat the ship's body and improve mechanical properties such as strength, durability, and accurate part defining [5]. This graphene substance is often used as a reinforcing material in the construction of sensors inside ships. Graphene materials are frequently used in structural reinforcement to enhance the strength of structural components [6]. This graphene substance has the capacity to withstand extreme temperatures and flames. As a result, maritime sectors are increasingly relying on graphene materials to improve ship strength and quality. This graphene substance has several advantages [7]. Carbon powder has one of the greatest stiffness levels among additive manufacturing process materials. Basically, carbon powder has a high electrical conductivity. This carbon powder is mostly used in ship construction and maritime sectors [8]. This carbon powder is used as an electromagnetic barrier for naval vessels. This shield is incredibly sturdy and powerful, with precise design in marine ships [9]. Antistatic parts are primarily designed for use with carbon powder in maritime ships. Functional enhancement mostly uses this carbon powder to create materials with excellent conductivity [10]. As a result, maritime industries are primarily focused on this carbon powder material to improve the strength and quality of work in the future. Marine materials must be extremely strong, durable, and resistant to a wide range of hazards [11]. The literature gap in this study is Prior study has not addressed the strength and flexural modulus of printed Izod made of polycarbonate, graphene, and carbon powder [12].

The prior research did not follow the ASTM standard for printed Impact strength and flexural modulus. This Impact strength sample and flexural modulus are unique to this multiple filler composite sample. This multiple filler polycarbonate printed samples were not covered in previous study [13-19]. In this Impact strength and flexural modulus investigation, no three-level parameter design was used, as was the Taguchi technique in previous studies. The previous paper did not cover the orthogonal array L9 experiment design for Impact strength and flexural modulus. Impact strength and flexural modulus for different fillers using Taguchi analysis for three metrics, polycarbonate composite printed samples are not covered in previous research on this multiple composite material: Izod strength, flexural modulus, signal to noise ratio, and FITS. Previous studies for these two attributes of work have not addressed the signal to noise ratio for Impact strength and flexural modulus for nozzle temperature, printing speed, and bed temperature. For this Izod and flexural modulus in this multiple filler combination merged samples, the previous study did not address analysis of variance for coefficient of correlation over 95% and contribution above 1% [20-27]. Impact strength and flexural modulus regression model for determining mechanical behavior for three parameter conditions excellent results for applying regression model to assess both Impact strength and flexural modulus without the use of previous research in this approach. Using a contour map, one may visually determine the ideal nozzle and bed temperatures by calculating the maximum Impact strength and flexural modulus [28-34]. This work has not been covered in previous papers. The current research aims to achieve 5% graphene and 5% carbon powder. These two are secondary materials; the main material used in this study is 90% polycarbonate; the combination of these three materials is polycarbonate multi-filler composite filament. this multi filler composite filament utilizing ultimate machine to printing the sample for Impact strength and flexural modulus. The ASTM standard is being followed by these printed examples. following that Taguchi optimization approach to produce the parameters and 3 level of level for 3 vital parameters. For the L9 Taguchi technique, an orthogonal array is used to create a nine-level experiment design for all parameters, including Izod strength, flexural modulus, signal to noise ratio, and FITS and FITS 1 [35-40].

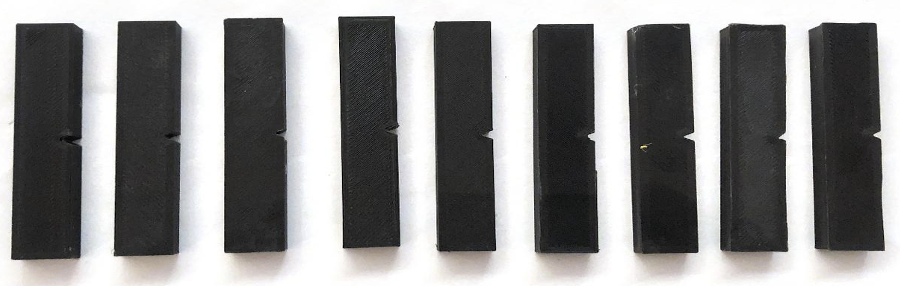
Impact strength sample and flexural modulus for signal-to-noise ratio response are included in this. For these two qualities, the optimal nozzle temperature, printing speed, and bed temperature may be determined using this signal to noise ratio. The results of the analysis of variance indicate that the flexural modulus and Impact strength have good coefficients of correlation and contribution [41-45]. This ANOVA may provide the best mechanical behavior together with excellent quality and strength. The regression model for Impact strength and flexural modulus, which uses the best three parameters—degree Celsius and speed condition—shows the maximum value for both. The Taguchi technique heavily relies on this regression model. A contour plot shows strong Izod strength, high flexural modulus, precise bed temperature, nozzle temperature, printing speed, and correct color. Ultimately, this Taguchi approach can determine the Impact strength and flexural modulus with the maximum strength, quality, mechanical behavior, and excellent stiffness [46-52]. This is the most significant and distinctive method of achieving a high degree of strength in this research.

# Materials and Methods

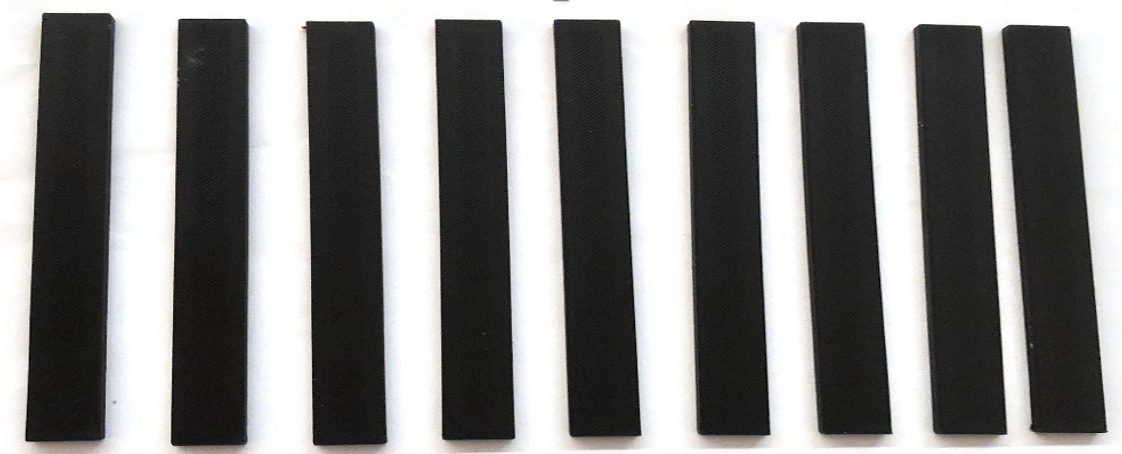
## Materials

In this experiment, Figure 1 (a and b) shows the printed samples for Impact strength and Flexural modulus. This printed materials combination includes 90% polycarbonate, 5% graphene, and 5% carbon powder. This is a material combination for using ultima Ker 3d printing machine to print the Impact strength and flexural modulus samples. Impact strength and flexural modulus are determined according to ASTM standards. The Impact strength ASTM standard is D256.

In this work table 1 shows the parameters and level. In this experiments level 3 for Nozzle temperature is 220 degree Celsius, Level 2 for Nozzle temperature is 210 degree Celsius and Level 1 for Nozzle temperature is 200 degree Celsius. Bed temperature for level 3 is 80 degree Celsius, Level 2 is 70 degree Celsius and Level 1 is 60 degree Celsius. Printing speed for Level 3 is 25 mm/s, Level 2 is 20 mm/s and level 1 is 15 mm/s.



(a)



**(b)**

Figure 1: (a) Polycarbonate Composite Impact strength **(b) Polycarbonate composite Flexural modulus**

**Table 1: Parameters and levels**

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

**Table 2: L9 Experimental design**

|  |  |  |  |
| --- | --- | --- | --- |
| Exp No. | Nozzle Temp | Bed Temp | Printing speed |
| 1 | 200 | 60 | 15 |
| 2 | 200 | 70 | 20 |
| 3 | 200 | 80 | 25 |
| 4 | 210 | 70 | 15 |
| 5 | 210 | 80 | 20 |
| 6 | 210 | 60 | 25 |
| 7 | 220 | 80 | 15 |
| 8 | 220 | 60 | 20 |
| 9 | 220 | 70 | 25 |

**This experiment printed samples for Impact strength and flexural modulus using a mix of polycarbonate, graphene, and carbon powder. These merged combination printed samples comply with ASTM standards. The ASTM standard for Impact strength is D256. This flexural modulus and Impact strength for reaction to the signal to noise ratio. In this Taguchi approach, the higher the value, the better the mechanical qualities.**

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

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

**In this work, Table 3 presents the analysis of impact strength and flexural modulus using the Taguchi method. At Level 1 (200 °C nozzle, 15 mm/s speed, 60 °C bed), the impact strength was 851 J/m with a flexural modulus of 2400 MPa, supported by a signal-to-noise (S/N) ratio of 58.59 and a secondary ratio of 67.60. The FITS values were 850.67 and 2413.33, respectively. At Level 2 (200 °C, 20 mm/s, 70 °C), impact strength slightly decreased to 850 J/m while flexural modulus increased to 2470 MPa. Increasing the printing speed to 25 mm/s and bed temperature to 80 °C at Level 3 resulted in 852 J/m impact strength and 2490 MPa flexural modulus, showing that higher speed and bed temperature slightly improved flexural stiffness while maintaining impact strength.**

**At higher nozzle temperatures, the material showed consistent improvements. At Level 4 (210 °C, 15 mm/s, 70 °C), impact strength increased to 853 J/m and modulus to 2500 MPa, while Level 5 (210 °C, 20 mm/s, 80 °C) gave further improvements with 855 J/m and 2530 MPa. Similarly, Level 6 (210 °C, 25 mm/s, 60 °C) maintained high performance with 854 J/m and 2520 MPa. The best results were achieved at 220 °C nozzle temperature: Level 7 (220 °C, 15 mm/s, 80 °C) yielded 856 J/m and 2540 MPa, while Level 8 (220 °C, 20 mm/s, 60 °C) produced the maximum values of 858 J/m impact strength and 2580 MPa flexural modulus. At Level 9 (220 °C, 25 mm/s, 70 °C), the performance remained strong with 857 J/m and 2560 MPa. These results confirm that higher nozzle temperatures, combined with moderate bed and printing speeds, consistently improve both impact resistance and stiffness in the polycarbonate hybrid composites.**

**Table 3: Analysis for Impact strength and Flexural modulus using Taguchi method**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** | **Impact strength** | **Flexural modulus** | **S/N ratio for Impact strength** | **S/N ratio for Flexural modulus** |
| 1 | 200 | 15 | 60 | 851 | 2400 | 58.5985912 | 67.604225 |
| 2 | 200 | 20 | 70 | 850 | 2470 | 58.58837851 | 67.853939 |
| 3 | 200 | 25 | 80 | 852 | 2490 | 58.6087919 | 67.923987 |
| 4 | 210 | 15 | 70 | 853 | 2500 | 58.61898062 | 67.9588 |
| 5 | 210 | 20 | 80 | 855 | 2530 | 58.63932229 | 68.06241 |
| 6 | 210 | 25 | 60 | 854 | 2520 | 58.62915741 | 68.028011 |
| 7 | 220 | 15 | 80 | 856 | 2540 | 58.64947529 | 68.096674 |
| 8 | 220 | 20 | 60 | 858 | 2580 | 58.66974576 | 68.232394 |
| 9 | 220 | 25 | 70 | 857 | 2560 | 58.65961644 | 68.164799 |

## ****Response Ratio For Signal To Noise Ratio****

**In this experiment response ratio for signal to noise ratio are divided in two types. Impact strength and flexural modulus**

### **Impact strength**

**In this work, Table 4 shows the Impact strength response for signal to noise ratio. In his level 1 Nozzle temperature is 58.60 degree Celsius, Printing speed is 58.62 mm/s and Bed temperature is 58.63. Level 2 Nozzle temperature is 58.63 degree Celsius,Printing speed is 58.63 mm/s and Bed temperature is 58.62 degree Celsius. Level 3 Nozzle temperature is 58.66 degree Celsius, Printing speed is 58.63 mm/s and Bed temperature is 58.63.**

**Table 4: Impact strength for signal to noise ratio**

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 58.60 | 58.62 | 58.63 |
| 2 | 58.63 | 58.63 | 58.62 |
| 3 | 58.66 | 58.63 | 58.63 |
| Delta | 0.06 | 0.01 | 0.01 |
| Rank | 1 | 3 | 2 |

**In this work,** **Figure 2 depicts the Impact strength plot for nozzle temperature, which has the greatest wave and the highest delta value of 0.06, whereas printing speed and bed temperature have the same wave and delta value of 0.01. According to the table 4, bed temperature is the second-ranking delta value, while printing speed is the lowest.**



**Figure 2: Impact strength graph for signal to noise ratio**

### **Flexural modulus**

**In this work, Table 5 shows the Flexural modulus response for signal to noise ratio. In this level 1 Nozzle temperature is 67.79 degree Celsius, Printing speed is 67.89 mm/s and Bed temperature is 67.95 degree Celsius. Level 2 Nozzle temperature is 68.02 degree Celsius,Printing speed is 68.05 mm/s and Bed temperature is 67.99 degree Celsius. Level 3 Nozzle temperature is 68.16 degree Celsius, Printing speed is 68.04 mm/s and Bed temperature is 68.03.**

**Table 5: Flexural modulus for signal to noise ratio**

|  |  |  |  |
| --- | --- | --- | --- |
| **Level** | **Nozzle Temp** | **Printing speed** | **Bed Temp** |
| 1 | 67.79 | 67.89 | 67.95 |
| 2 | 68.02 | 68.05 | 67.99 |
| 3 | 68.16 | 68.04 | 68.03 |
| Delta | 0.37 | 0.16 | 0.07 |
| Rank | 1 | 2 | 3 |

**In this work,** **figure 3 shows the flexural modulus plot for nozzle temperature, which has the largest wave and the highest delta value of 0.37; printing speed has the second-best wave ranking delta value of 0.16.The bed temperature has the smallest wave delta value, 0.07.**



**Figure 3: Flexural modulus for signal to noise ratio**

## Analysis of variance (ANOVA)

### Izod strength

The ANOVA analysis for Impact strength (Table 6), nozzle temperature contributed 90% of the total variation (Sum of Squares = 54, Adj SS = 54, Adj MS = 27). At the 95% confidence level, this influence was statistically significant, as indicated by an F-value of 27 and a P-value of 0.036. Both bed temperature and printing speed contributed just 3.33% (Sum of Squares = 2 for each factor, Adj SS = 2, Adj MS = 1), with F-values of 1 and higher P-values of 0.5, indicating that their impacts were not statistically significant. The remaining 3.33% of variance was explained by the error term (SS = 2). With an adjusted R2 of 86.67% that validates the model's dependability after controlling for the number of variables and an R2 Coefficient of correlation value of 96.67% that shows the model explains almost all of the variability in Izod strength, the overall model fit is extremely strong. The model's predictive power may be limited, though, as the expected R2 is lower at 32.50%. The difference between expected and actual outcomes for fresh observations is further highlighted by the PRESS (Prediction Error Sum of Squares) value of 40.5 and the residuals' standard deviation (S), which is 1. Overall, printing speed and bed temperature have little bearing on Izod strength, however nozzle temperature is found to be the primary determinant.

Table 6: Impact strength ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| Nozzle Temp | 2 | 54 | 90.00% | 54 | 27 | 27 | 0.036 |
| Printing speed | 2 | 2 | 3.33% | 2 | 1 | 1 | 0.5 |
| Bed Temp | 2 | 2 | 3.33% | 2 | 1 | 1 | 0.5 |
| Error | 2 | 2 | 3.33% | 2 | 1 |  |  |
| Total | 8 | 60 | 100.00% |  |  |  |  |

The residuals plot for Impact strength in this study are randomly distributed, normally distributed, and devoid of patterns or trends, as seen in figure 4. While the vs fits and versus order plots show no bias, uneven variance, or sequence effects, the normal probability plot and histogram validate near-normality, confirming the ANOVA model's dependability.



Figure 4: Impact strength Plots

### Flexural modulus

The flexural modulus ANOVA results (Table 7) show that the most significant factor is nozzle temperature, which accounts for 75.07% of the total variation (Sum of Squares = 17,266.7, Adj SS = 17,266.7, Adj MS = 8,633.3). The F-value is 16.19, and the P-value is 0.058, indicating a significant but marginally above-threshold significance. At 17.68% of the variation (Sum of Squares = 4,066.7, Adj MS = 2,033.3), printing speed is the second most significant component. Its F-value is 3.81, and its P-value is 0.208, suggesting a lesser statistical effect. The contribution of bed temperature is a very low F-value of 0.56 and a high P-value of 0.64, indicating negligible effect (Sum of Squares = 600, Adj MS = 300). The error term (SS = 1,066.7) indicates 4.64% of variance, which is within allowable bounds for experimental activity. A high R2 Coefficient of Correlation of 95.36% in the model summary indicates that the model accounts for the majority of the variation in flexural modulus, and an adjusted R2 of 81.45% demonstrates that the model is dependable after predictors are taken into consideration. At 6.09%, the projected R2 is significantly lower, indicating that the model might not be very good at predicting new data. Both the residuals' standard deviation (S) and PRESS (Prediction Error Sum of Squares) values are 23.094 and 21,600, respectively. Overall, the most important component influencing flexural modulus is nozzle temperature, followed by printing speed, which has a small effect, and bed temperature.

Table 7: Flexural modulus ANOVA

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| Nozzle Temp | 2 | 17266.7 | 75.07% | 17266.7 | 8633.3 | 16.19 | 0.058 |
| Printing speed | 2 | 4066.7 | 17.68% | 4066.7 | 2033.3 | 3.81 | 0.208 |
| Bed Temp | 2 | 600 | 2.61% | 600 | 300 | 0.56 | 0.64 |
| Error | 2 | 1066.7 | 4.64% | 1066.7 | 533.3 |  |  |
| Total | 8 | 23000 | 100.00% |  |  |  |  |

The flexural modulus residual plots in this experiment, which are displayed in figure 5, validate the correctness of the model. The residuals are about normal, as indicated by the spots near the straight line in the normal probability plot. The residuals versus fits plot displays random scatter devoid of patterns, demonstrating continuous variance, while the histogram is balanced around zero. There is no trend in the vs order plot, indicating that there are no sequence effects. When combined, these figures support the flexural modulus ANOVA assumptions.



Figure 5: Flexural modulus Plots

## Regression model

### Izod strength

The relationship between nozzle temperature, printing speed, and bed temperature and test results is expressed by the regression equation for Impact strength (j/m). When every factor is at its reference level, the baseline Impact strength is represented by the constant value of 854.000. At 200°C, the nozzle temperature has the most influence, decreasing strength by 3.000 j/m, remaining unchanged at 210°C (coefficient -0.000), and increasing strength by 3.000 j/m at 220°C. The impact of printing speed is less pronounced; 15 mm/s somewhat reduces strength by 0.667 j/m, whilst 20 mm/s and 25 mm/s each raise it by 0.333 j/m. Similar to this, bed temperature has a little impact: Impact strength increases by 0.333 j/m at 60°C, falls by 0.667 j/m at 70°C, and increases by 0.333 j/m at 80°C. Overall, the equation shows that the main factor influencing Impact strength is nozzle temperature, with printing speed and bed temperature having negligible effects.

|  |  |  |
| --- | --- | --- |
| Izod strength j/m | = | 854.000 - 3.000 Nozzle Temp\_200 - 0.000 Nozzle Temp\_210 + 3.000 Nozzle Temp\_220 - 0.667 Printing speed\_15 + 0.333 Printing speed\_20 + 0.333 Printing speed\_25 + 0.333 Bed Temp\_60 - 0.667 Bed Temp\_70 + 0.333 Bed Temp\_80 |

### Flexural modulus

The flexural modulus is predicted by the regression equation based on the nozzle temperature, printing speed, and bed temperature, among other 3D printing characteristics. Depending on the parameters, certain numbers are added or subtracted from the starting value of 2510.00. The modulus decreases by 56.7 at nozzle temperature of 200°C, increases by 6.7 at nozzle temperature of 210°C, and increases by 50.0 at nozzle temperature of 220°C. In terms of printing speed, the modulus is reduced by 30.0 at 15 mm/s, increased by 16.7 at 20 mm/s, and increased by 13.3 at 25 mm/s. In terms of bed temperature, the modulus decreases by 10.0 at 60°C, increases by 10.0 at 80°C, and remains unchanged at 70°C. This formula makes it easier to comprehend how various parameter combinations affect the printed part's flexural modulus.

|  |  |  |
| --- | --- | --- |
| Flexural modulus | = | 2510.00 - 56.7 Nozzle Temp\_200 + 6.7 Nozzle Temp\_210 + 50.0 Nozzle Temp\_220 - 30.0 Printing speed\_15 + 16.7 Printing speed\_20 + 13.3 Printing speed\_25 - 10.0 Bed Temp\_60 - 0.0 Bed Temp\_70 + 10.0 Bed Temp\_80 |

## Contour plot

The relationship between Impact strength (J/m) and bed and nozzle temperatures is seen in the contour plot on the left side of Figure 6. Different Impact strength levels are shown in the plot by a gradient of green hues. With values below 850 J/m, the lightest green denotes the lowest strength. Darker green regions are represented by the following shade, which is 850–852 J/m, followed by 852–854 J/m, 854–856 J/m, and 856–858 J/m. The areas of maximal impact strength are indicated by the deepest green zones, which match Izod strengths higher than 858 J/m. The deeper green areas in the upper-right quadrant of the plot indicate that higher bed temperatures (around 80°C) and nozzle temperatures (nearer 220°C) lead to greater Izod strength. This implies that higher temperature settings enhance the material's ability to withstand impacts. The contour plot on the right side of Figure 6 shows how the flexural modulus fluctuates with bed temperature and nozzle temperature, with a gradient of green shades representing distinct modulus ranges. The lightest green section represents values less than 2400, indicating the lowest flexural stiffness. As the green hues deepen, the modulus rises: 2400-2440, 2440-2480, 2480-2520, and 2520-2560. The deepest green patches have values more than 2560, indicating the maximum flexural modulus. The contour distribution shows that higher nozzle temperatures (approaching 220°C) and moderate to high bed temperatures (about 70-80°C) help to increase flexural performance. These particular temperature settings appear to provide the stiffest printed samples, as indicated by the darkest areas near the upper right of the figure.

1. (b)

Figure 6: (a) (b) Contour plot for Impact strength and Flexural modulus

# Conclusion

This research investigated the mechanical characteristics of 95% polycarbonate composites that were 3D printed and reinforced with 5% graphene and 5% carbon powder utilizing the Taguchi optimization technique. The study concentrated on the effects of process variables on Izod impact strength and flexural modulus, including nozzle temperature, bed temperature, and printing speed. Nozzle temperature was the most significant factor, contributing to 90% of the variance in Impact strength and 75.07% of the variation in flexural modulus, according to the results of Taguchi analysis and ANOVA. A maximum Impact strength of 858 J/m and a flexural modulus of 2580 MPa were obtained using the best possible combination of nozzle temperature (220°C), printing speed (20–25 mm/s), and bed temperature (60–80°C). The Impact strength regression model showed a 96.67% coefficient of correlation (R2), which means that the predicted and experimental values agreed very well. An R2 value of 95.36% was also obtained using the flexural modulus model, indicating a high predictive association. The models' predictive capacity for unknown data, however, may be limited by lower anticipated R2 values (32.50% for Impact strength and 6.09% for flexural modulus). Both impact strength and stiffness are improved by moderate to high bed temperatures and higher nozzle temperatures, as the contour plots clearly confirmed. In conclusion, nozzle temperature is the most important component in optimizing mechanical performance, and the regression models verify that input parameters and output responses are highly correlated. These results aid in the optimization of 3D printing parameters for structural applications using high-performance polymer composites.

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