A STUDY OF THE EFFECT OF FIBER CONTENT AND FIBER ORIENTATION ON THE TENSILE STRENGTH OF GLASS FIBER REINFORCED EPOXY COMPOSITE FOR PIPE PRODUCTION: A STATISTICAL APPROACH

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Abstract

This study was aimed at optimizing the development parameters of a glass fiber reinforced epoxy composite for pipeline application. In this study, the Taguchi experimental design technique was applied to determine the best combination of process parameters (fiber content and orientation) for optimum tensile strength. The optimum tensile strength of 209.65MPa was reported at the fiber content of 50% and Fiber orientation of 45º. Analysis of variance also showed that in optimizing for high tensile strength, the glass fiber content and the fiber orientation are significant factors. The material at optimum tensile properties was applied in the simulation of the behavior of a high-pressured gas pipeline and results proved the reliability of the material in such application.

Keywords: Composites, Natural Fibers, Optimization, Taguchi

1.0 INTRODUCTION

Pipeline increasingly found application in diverse industries worldwide due to their low-cost transportation of strategic fluids. In the development of pipelines for the transportation of various industrial fluids like water, acids, gases, oil, etc., fiber-reinforced polymer composites have been used due to their excellent properties like high strength, low density, corrosion resistance, etc. Also, the installation cost of these forms of composite pipes has been reduced due to technological development. With good mechanical strength, durability, pressure capacity, low cost, these fiber reinforced polymer composites (FRP) can be combined with other materials to achieve a good environmental footprint. Metallic and composite pipes have been the most economic means of transportation of oil and gas and since metallic pipes are susceptible to corrosion, the FRPs have an advantage. With good mechanical, insulating, and deterioration resistance, glass fibers are economical and the most popularly used reinforcements in the development of polymer-based pipes. The most popular among these glass fiber reinforced polymer composites are the thermoset resin-based composites while the thermoplastic-based reinforced polymer composites are rarely applied in the development of pipes. Even for pipeline repairs, these thermosets can easily form on walls and harden quickly and they are also deterioration resistant. This gives them an advantage over thermoplastics in piping development. Some of these thermosets that are used in piping applications are polyesters, vinyl esters, phenolic, polyurethane, epoxy, polyamide, etc. Epoxy stands as the most popular in the development of glass fiber reinforced polymer composites for piping application due to its good mechanical properties, adhesion, chemical corrosion resistance, shrinkage, cure properties

Many studies on the behavior of glass fiber reinforced composites in various applications have been carried out. According to Joseph et al. (2002), composite development factors and parameters affects the mechanical strength, failure mode, fracture toughness, and modulus of fiber-reinforced composites. Some of these parameters include the volume fraction and angular orientation of the fiber. But, the interfacial parameters are of significance.

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Mostafa et al. (2019) developed a jute/glass fiber hybrid reinforced epoxy composite and studied the effect of hybridization using tensile experiments. The hybridization resulted in a reduction in the tensile strength of the materials even though it increased the possibility of applying these agro-residues for composite material development. This implies that hybridization of the glass fiber reinforced particles with natural fibers is not advantageous to the mechanical property of the material as results prove lower performance when compared to composites reinforced with purely glass fibers. To improve the mechanical properties of these glass fiber reinforced polymer composites, other factors like the fiber orientation are more likely to be of significant and positive effect on the mechanical properties of these materials other than hybridization with natural fibers.

Elkazaz et al. (2020) investigated the effect of development parameters such as fiber length and volume fraction on the mechanical properties of short fiber reinforced polymer composites. An increase in fiber loading at a constant fiber length of 10mm was more effective in increasing the strength and modulus of the material than increasing the fiber loading at a constant length of 5mm. Increasing tensile strength and modulus was also reported by Aramide et al. (2012) in a study that investigated the mechanical properties of woven mat fiberglass as reinforcement in polyester resin at a fiber loading of 5-30%.

Many studies have detailed the excellent properties of glass fiber reinforced composites, but none have studied the combined effect of varied fiber content and orientation on the performance of such composites in high pressured pipeline production. This study will take advantage of the robust nature of the Taguchi design technique to optimize the tensile behavior of a glass fiber reinforced epoxy composite with varied fiber orientation. This will be achieved by considering the tensile strength based on the higher the better signal to noise ration criteria which is expressed in Equation 1.

$$\left(\frac{S}{N}\right)_{HTB} = -10 * log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

Where S/N is the signal to noise ratio, HTB represents “higher the better”, n is the number of runs (combination) and y_i are tensile observations for each run.

2.0 EXPERIMENTATION

Design of Experiment

In this study, two factors (glass fiber content and orientation) will be optimized through five levels. Table 1 shows the different factors and their levels considered.

Table 1: Development factors and the levels of observation

Factors (Parameters)	Levels				
	1	2	3	4	5
Fiber Composition wt. (%) (A)	10	20	30	40	50
Fiber Orientation (º) (B)	0	15	30	45	60

Using the Minitab 2018 software, an orthogonal array that detailed the combination of the factors at their various levels was developed. Since the number of factors considered was only two, a full factorial combination was observed. This is shown in Table 2.

Table 2: Orthogonal array for factors and level combination

S/N	Glass fiber content (%)	Glass fiber Orientation (º)
1	10	0
2	10	15
3	10	30

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4	10	45
5	10	60
6	20	0
7	20	15
8	20	30
9	20	45
10	20	60
11	30	0
12	30	15
13	30	30
14	30	45
15	30	60
16	40	0
17	40	15
18	40	30
19	40	45
20	40	60
21	50	0
22	50	15
23	50	30
24	50	45
25	50	60

Composite development

The hand-lay-up technique was used to produce the composites in line with the procedures of Batu et al., (2020) and Negawo et al., (2021) wherewith the concept of fiber orientation was also adopted. The epoxy resin and hardener were mixed in the ratio of 5:2 according to the manufacturer's specifications. The composite production was carried out at room temperature. The glass fiber strands were laid in the 3mm thick mold according to their various specified orientation and the mixed resin and hardeners were poured into the mold and allowed to cure at room temperature. This method was used to produce the nine different combinations as specified in the orthogonal array presented in Table 2.

Tensile Test

Tensile tests on the specimens produced were carried out according to ASTM D638 using a Universal Testing Machine (INSTRON-3369). The specimen for the tensile test were cut from the prepared specimen and 3 tests each were carried out on the combinations.

3.0 RESULTS AND DISCUSSION

Table 3 presents the mean and S/N ratio of the tensile test carried out. The general mean of means of the different combinations or runs was 79.26MPa and the average S/N ratio was 35.713. Also, Table 4 presents the response table for means and S/N ratio. The response table was obtained by averaging the levels of each factor through the runs.

Table 3: Means and S/N ratio

SN	Glass Fiber Content (%)	Fiber Orientation (º)	Tensile Strength	
			Mean (MPa)	S/N Ratio (dB)
1	10	0	17.49	24.8558
2	10	15	16.91	24.5629
3	10	30	15.19	23.6312

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4	10	45	14.54	23.2513
5	10	60	14.39	23.1612
6	20	0	49.70	33.9271
7	20	15	59.65	35.5122
8	20	30	70.96	37.0203
9	20	45	78.04	37.8463
10	20	60	72.81	37.2438
11	30	0	51.09	34.1667
12	30	15	56.87	35.0977
13	30	30	61.03	35.7109
14	30	45	64.70	36.2181
15	30	60	62.91	35.9744
16	40	0	59.28	35.4582
17	40	15	80.25	38.0889
18	40	30	106.30	40.5307
19	40	45	125.74	41.9895
20	40	60	116.96	41.3607
21	50	0	78.49	37.8963
22	50	15	129.61	42.2528
23	50	30	183.25	45.2609
24	50	45	209.65	46.4299
25	50	60	185.70	45.3762
		Mean	79.26	35.712954

Table 4: Response table for means and S/N ratio

SN	Glass Fiber Content		Fiber Orientation	
	Mean (MPa)	**S/N Ratio (dB)**	**Mean (MPa)**	**S/N Ratio (dB)**
1	15.7	23.89	51.21	33.26
2	66.23	36.31	68.66	35.1
3	59.32	35.43	87.35	36.43
4	97.71	39.49	98.53	37.15
5	157.34	43.44	90.55	36.62
Delta	141.64	19.55	47.32	3.89
Rank	1	1	2	2

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In Table 4, it is observed that the glass fiber content has the highest ranking, implying its ability to influence the tensile strength of the glass fiber reinforced epoxy composites more than the fiber orientation. Figure 1 and Figure 2 show the variation of tensile strength with change in glass fiber content and fiber orientation respectively. The rise in tensile strength of the composite from glass fiber composition of 10% is due to the ease and efficient transfer of stress from the matrix to the fiber due to the increase in fiber strength. The increase in tensile strength with the increase in fiber content is a logical trend that has been observed by other studies (Pothan et al., 1997; Khan et al., 2021; Sapuan et al., 2020).

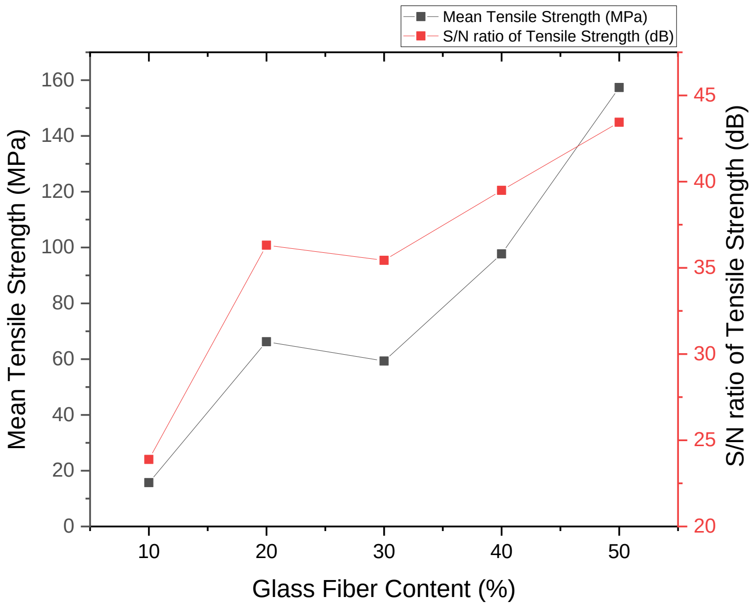

Figure 1: Variation tensile strength with glass fiber content

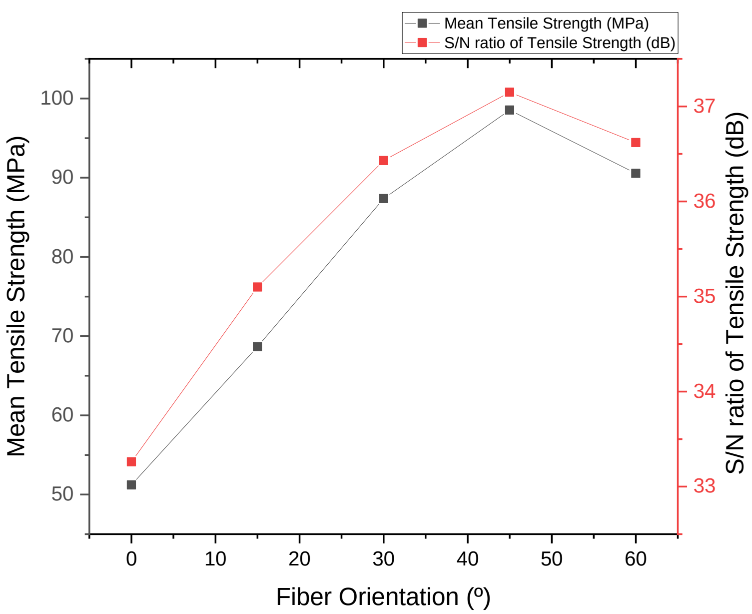

Figure 2: Variation tensile strength on fiber orientation

Figure 2 shows a corresponding increase in tensile strength of the glass fiber reinforced epoxy composite with an increase in fiber orientation (angle). The increase in fiber orientation is due to the best possible alignment of the fiber

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with the direction of stress. The best tensile strength was observed at a fiber orientation of 45º. This agrees with the work of Kumar et al., (2020) in which the best fiber orientation was observed to be at ±45º. Pressure build-up within pipelines acts at direction transverse to the pipe's main axis. The drop in tensile strength of the material beyond the 45º is indicative of the reverse in alignment between the fiber and the tensile force.

Analysis of Variance

An analysis of variance at a confidence level of 0.05 (95%) was used to determine the significance of each of the development factors (glass fiber content and fiber orientation) on the tensile strength of the composite. The analysis of variance for mean and S/N ratio is presented in Table 5 and Table 6.

Table 5: Analysis of variance for means

Factor (Variable Parameter)	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage Contribution (%)
Glass fiber content (%) (A)	4	55217	55217	13804.3	29.29	0.000	78.8
Fiber orientation (º) (B)	4	7318	7318	1829.5	3.88	0.022	10.44
Residual Error	16	7540	7540	471.2			10.76
Total	24	70075					100

Table 6: Analysis of variance for S/N ratio

Factor (Variable Parameter)	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage Contribution (%)
Glass fiber content (%) (A)	4	1070.74	1070.74	267.685	98.66	0.000	92.06
Fiber orientation (º) (B)	4	48.93	48.93	12.232	4.51	0.013	4.21
Residual Error	16	43.41	43.41	2.713			3.73
Total	24	1163.08					100

Table 5 and Table 6 show that the glass fiber content had a significant effect on the tensile strength of the angularly oriented glass fiber reinforced epoxy composite with a P-value of 0.00 at means and S/N ratio which is less than 0.05. Also, the glass fiber content in the polymer composite was observed to have a percentage contribution of 78.8% at means and 92.06% at the S/N ratio. This implies that the glass fiber content has a 92.06% efficiency in affecting (increasing or decreasing) the tensile strength of the material.

Also, it was observed that the fiber orientation was significant with a P-value at a confidence level of 95% was of 0.022 at means and 0.013 at S/N ratio. This significance was also observed at a fiber orientation percentage contribution of 10.44% at means and 4.21% at the S/N ratio. This implies that the fiber orientation has significant potential in affecting the tensile strength of a glass fiber reinforced epoxy composite.

Optimal Combination

From Figure 1 and Figure 2, the best tensile strength is observed at a fiber content of 50% (A5), and fiber orientation of 45º (B4). This implies that in other to obtain the best tensile strength, the material must be developed with a glass fiber content of 50% oriented at 45º to the stress direction. The predicted optimum tensile strength is calculated from Equation 2:

$$T_{opt} = T_m + \sum_{i=1}^{x}(T_i - T_m) \tag{2}$$

Where T_{opt} is the optimal tensile strength, T_m is the mean of means obtained from Table 3, and T_i is the maximum tensile strength at each factor (obtained from Table 4). Therefore, the optimum tensile strength is 176.61MPa. In other to confirm the suitability of Equation 1 for predicting the optimal tensile strength, a confirmation test is carried out

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with the optimum combination. The tensile strength at an optimum combination (fiberglass at 50% and 45º) was observed to be 209.65MPa. Comparison is made between the predicted tensile strength of 176.61MPa with an experimental tensile strength of 209.65MPa. The percentage error is calculated using equation (3).

$$Percentage\ error = \frac{Confirmation\ Tensile\ Strength - Predicted\ Tensile\ Strength}{Predicted\ Tensile\ Strength} \quad (3)$$

Therefore, the percentage error between the predicted and observed optimal strength is 18.7%. This implies that the Taguchi design of experiment is 82% efficient in the determination of the optimal tensile strength of the angularly oriented glass fiber reinforced epoxy composite.

Regression Analysis

The tensile strength of the glass fiber reinforced epoxy composite was modeled with respect to the glass fiber content and fiber orientation using the regression analysis. The model is presented in equation 4.

$$Tensile\ strength = -36.88 + A3.15 + B0.724 \quad (4)$$

The model R-Square value was 0.791 which shows a high degree of accuracy. This implies that the model has a 79.1% chance of predicting the tensile strength of the developed composite at various combinations of fiber content and fiber orientation. Figure 3 shows a comparison between the predicted (modeled) tensile strength and the experimented value.

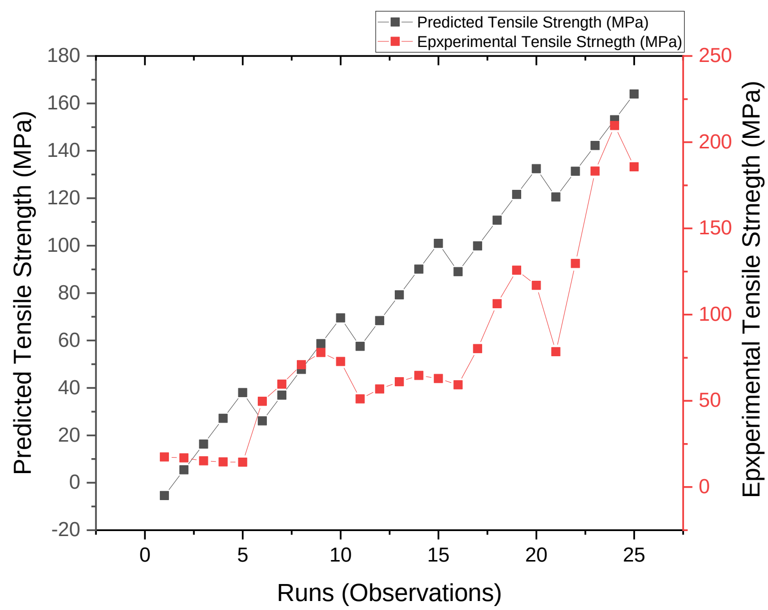

Figure 3: Comparison between the modeled and experimented tensile strength of the composite

4.0 CONCLUSION

In this study, parameters for the development of glass fiber reinforced epoxy composite was optimized using the robust Taguchi experimental design, and the effect of fiber orientation and fiber content on the tensile strength of the developed composite was studied using statistical analysis, and the following conclusions were made:

- Glass fiber at 50% fiber content and 45º fiber orientation produced the optimum tensile strength of 209.65MPa.
- The fiber content and fiber orientation were observed to have a significant effect on the tensile strength of the materials.

This study paves the way for the study on multi-angular orientation stacked fiberglass reinforced epoxy composites.

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