OPTIMIZATION OF PROCESS PARAMETERS FOR WOVEN FLAX EPOXY LAMINATES AFTER POST TREATMENT WITH ALKALI SOLUTION

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Abstract: Alkali treatment is important because it enhances the interfacial bonding between the flax fabrics and the epoxy matrix. This process removes impurities and increases the surface roughness of the fibers, leading to improved mechanical properties of the laminate. As a result, the treated woven flax epoxy laminates exhibit better strength and durability compared to untreated ones. The optimization process involves systematically adjusting various parameters such as alkali concentration, ply orientation to enhance the mechanical properties of the laminates with 3mm thickness. By conducting experiments and analyzing the results, this work can identify the optimal conditions that improve tensile strength, flexural strength. This method ensures that the low percentage up to 5% treated laminates perform better in practical applications while maintaining their environmental friendliness.

Key words: Woven flax fabric, Hand Lay-up, Optimization, Ply-orientation, Tensile, Flexural Strength.

1. **Introduction:**

Woven flax fabric is known for its excellent tensile strength and biodegradability, making it an eco-friendly alternative to synthetic fibers. Its natural fibers provide good thermal insulation and moisture absorption, which enhances the comfort and functionality of composite materials. Additionally, flax fabric exhibits a distinctive texture and appearance, contributing to the aesthetic appeal of the final product. Optimizing process parameters is crucial for enhancing the mechanical properties and overall performance of woven flax fabric epoxy laminates. By fine-tuning these parameters, manufacturers can achieve superior strength, durability, and resistance to environmental factors. This optimization not only improves the quality of the final product but also enhances its applicability in various industrial sectors. The post-treatment of woven flax fabric epoxy laminates with an alkali solution can significantly enhance their mechanical properties. This process improves the interfacial bonding between the flax fibers and the epoxy matrix, resulting in increased tensile strength and rigidity. Additionally, alkali treatment can remove impurities and enhance the surface roughness of the fibers, further contributing to the overall performance of the laminate. The methodology for optimization involves systematically varying key process parameters such as alkali concentration, treatment time, and temperature. By employing a design of experiments (DOE) approach, we can analyze the effects of these variables on the mechanical properties of the laminated composites. This approach allows us to identify the optimal conditions that enhance the performance of the woven flax fabric epoxy laminates.

2. Literature Review

The Taguchi method, a statistical design of experiments (DOE) approach, is employed to optimize the parameters affecting the performance of natural fiber epoxy composites. By systematically varying factors like fiber content, resin type, curing conditions, and fiber treatment, the Taguchi method helps identify optimal combinations that enhance mechanical properties such as tensile strength, flexural strength, and impact resistance. **Kumar et al. [1]** used the Taguchi approach to optimize the processing parameters for flax fiber epoxy composites. They investigated the effects of parameters such as fiber orientation, fiber volume fraction, and curing time on the tensile strength and flexural modulus of the composites. They found that the fiber orientation had a significant effect on tensile strength, with unidirectional fibers providing the highest strength compared to woven or bi-directional fiber orientations. **Jayaraman et al. [2]** applied the Taguchi method to hemp fiber/epoxy composites. They optimized parameters such as fiber length, fiber content, and molding pressure to enhance the flexural strength and impact resistance of the composite material. The results demonstrated that higher fiber content and longer fiber length improved the mechanical properties, while molding pressure played a critical role in the fiber-matrix bonding. **Patel et al. [3]** used the Taguchi optimization technique to improve the impact resistance of jute fiber epoxy composites. They optimized factors such as alkali treatment, curing time, and fiber volume fraction. Their findings showed that alkali treatment enhanced the fiber-matrix adhesion, leading to improved impact resistance and toughness. **Das et al. [4]** used the Taguchi approach to optimize the moisture absorption of kenaf fiber/epoxy composites. They examined the effects of fiber surface treatments, fiber volume fraction, and curing conditions on moisture uptake. Their study concluded that fiber surface treatment (such as alkali treatment) significantly reduced moisture absorption, which improved the dimensional stability and durability of the composite **Babu et al. [5]** used the Taguchi method to optimize flax fiber/epoxy composites for automotive applications. The study focused on optimizing fiber orientation, curing temperature, and resin content to improve mechanical strength and dimensional stability. **Rout et al. [6]** applied the Taguchi optimization technique to jute fiber reinforced composites to determine the influence of fiber length, fiber volume fraction, and molding pressure on tensile strength and impact resistance. Their study showed significant improvements in mechanical properties with optimal processing conditions. **Reddy et al. [7]** utilized the Taguchi method to improve the flexural strength and moisture resistance of kenaf fiber/epoxy composites by optimizing fiber content, curing time, and fiber surface treatments.

A study by **Yusuf et al. [8]** utilized the Taguchi method to optimize the tensile and flexural strength of composites made from sponge gourd, coir, and jute fibers reinforced in epoxy resin. The optimal combination of parameters was identified, leading to improved mechanical properties. **Ahmed et al. [9]** focused on optimizing the impact strength of natural fiber composites using the Taguchi method. The study highlighted the influence of fiber type and content on the impact resistance of the composites. **Nayak et al. [10]** applied the Taguchi method to analyze the wear characteristics of basalt fiber-reinforced epoxy composites. The research identified key factors influencing wear resistance, providing insights for optimizing composite durability. **Kumar et al. [11]** applied the Taguchi method to optimize the tensile, flexural, and impact properties of jute fiber-reinforced epoxy composites. The study identified the key factors affecting the mechanical properties, such as fiber content and curing time, and determined the optimal levels for maximizing these properties. Their results demonstrated a significant improvement in the composites' mechanical performance compared to the control specimens **Banerjee et al. [12]** used the Taguchi method to optimize the flexural strength of banana fiber-reinforced epoxy composites. Their study revealed that fiber loading and resin matrix type had the most significant influence on the flexural strength. The optimal processing conditions resulted in a composite that exhibited superior mechanical properties compared to composites without optimization. **Singh et al. [13]** explored the impact resistance of jute and coir fiber-reinforced epoxy composites using the Taguchi method. By optimizing factors such as fiber content and resin type, the study showed a marked improvement in the impact resistance of these composites, which is crucial for automotive and construction applications. **Patel et al. [14]** focused on the wear behavior of hemp fiber-reinforced epoxy composites. By applying the Taguchi optimization technique, the researchers determined the optimal parameters, including fiber volume fraction and resin matrix, which significantly reduced the wear rate and enhanced the durability of the composites. **Sharma et al. [15]** investigated the mechanical properties of flax fiber-reinforced epoxy composites using the Taguchi method. The study demonstrated that factors such as curing time and temperature had a profound effect on the tensile and flexural properties of the composites.

3. Methodology

In this study the Composite laminates were fabricated using woven flax fabric and epoxy resin via the hand layup technique. A clean mold surface was coated with a release agent, and pre-cut flax layers were stacked in angle-ply and cross-ply orientations. An epoxy-hardener mixture (10:1 ratio) was applied to maintain a 40:60 fiber-to-resin weight ratio for optimal impregnation. Resin was brushed between layers, and manual rolling ensured air removal and laminate compaction. The layup was cured at room temperature under pressure, followed by ambient post-curing before demolding. After fabrication, cured laminates were post-treated by immersion in 5% and 10% NaOH solutions to evaluate the effect of alkaline exposure on fiber–matrix interaction and surface properties. The influence of ply orientation was also examined by comparing the mechanical performance of treated and untreated laminates across various layup configurations.

Figure 1: Hand layup process and final specimen

3.1 Materials

Woven flax fabrics: The material were sourced from a reliable supplier and used in their raw form without any pretreatment for the control group. The flax fabric was carefully cleaned to remove any debris or loose fibers before use.

Epoxy Resin: A commercial-grade epoxy resin system was used as the matrix material. The resin was mixed according to the manufacturer's instructions, ensuring proper curing and optimal bonding.

Sodium Hydroxide (NaOH): Two concentrations of NaOH (5% and 10%) were prepared by dissolving the appropriate amount of NaOH pellets in distilled water. These solutions were used for the alkali treatment of the flax fibers.

Selection of Material

Flax comes from the stem of the flax plant of the species Linum usitatissimum. Flax fibre is classified as a natural cellulose, bast and multicellular fibre. When the fibre is processed into fabric, then it is called as Lenin. It is one of the strongest fibres, and it is considered for their strength, durability, and absorbency, as well as their unique texture. In addition to its traditional uses, flax fibre is becoming increasingly popular in modern times as a sustainable alternative to synthetic fibres. and the chemical composition is as shown below Table.1

Table 1: Structural composition of Flax fibre

Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Pectins (wt%)	Micro fibril angle (degree)	Moisture content (wt%)
71	18.6–20.6	2.2	2.3	6-7	10

Table2: L18 Orthogonal Array

S.No	Parameters	Level -1	Level-2	Level-3	Level-4	Level-5	Level-6
1	Ply angle	[0°/90°]$_{16}$	[±45°]$_{16}$	[[0°/90°], [±45°]]$_{8}$	[0°/90°, ±45°, ±45°, 0°/90°]$_{4s}$	[0°/90°]$_{8}$/[±45°]$_{8}$	[[±30°], [±60°]]$_{8}$
2	Type of treatment	UT	T(5%)	T(10%)	-	-	-

Table 3: Design of experiments (DOE) L18 Orthogonal Array

Ply Orientation	Treatment	Ply orientations	Type of Treatment
1	1	[0°/90°]$_{16}$	Untreated
1	2	[0°/90°]$_{16}$	Treated with 5% NaOH
1	3	[0°/90°]$_{16}$	Treated with 10% NaOH
2	1	[±45°]$_{16}$	Untreated
2	2	[±45°]$_{16}$	Treated with 5% NaOH
2	3	[±45°]$_{16}$	Treated with 10% NaOH
3	1	[[0°/90°], [±45°]]$_{8}$	Untreated
3	2	[[0°/90°], [±45°]]$_{8}$	Treated with 5% NaOH
3	3	[[0°/90°], [±45°]]$_{8}$	Treated with 10% NaOH
4	1	[0°/90°, ±45°, ±45°, 0°/90°]$_{4S}$	Untreated
4	2	[0°/90°, ±45°, ±45°, 0°/90°]$_{4S}$	Treated with 5% NaOH
4	3	[0°/90°, ±45°, ±45°, 0°/90°]$_{4S}$	Treated with 10% NaOH
5	1	[0°/90°]$_{8}$/[±45°]$_{8}$	Untreated
5	2	[0°/90°]$_{8}$/[±45°]$_{8}$	Treated with 5% NaOH
5	3	[0°/90°]$_{8}$/[±45°]$_{8}$	Treated with 10% NaOH
6	1	[[±30°], [±60°]]$_{8}$	Untreated
6	2	[[±30°], [±60°]]$_{8}$	Treated with 5% NaOH
6	3	[[±30°], [±60°]]$_{8}$	Treated with 10% NaOH

4. Results and discussions

The study revealed that post-treatment with an alkali solution significantly improved the mechanical properties of woven flax fabric epoxy laminates. Optimal process parameters were identified, leading to enhanced tensile strength and durability. The findings suggest that alkali treatment can be an effective method for enhancing the performance of flax-based composites.The following are the results obtained from the experiments after post treatment.

Table:4 Results for Tensile and Flexural tests

Ply Orientation	Treatment	TS(Tensile strength (MPa)	FS (Flxural strength MPa)
1	1	134.133	168.770
1	2	125.110	115.120
1	3	120.910	110.220
2	1	120.110	160.899
2	2	109.180	92.800
2	3	112.210	92.430
3	1	117.600	162.220
3	2	112.210	100.110
3	3	100.150	96.340

4	1	121.330	163.550
4	2	100.840	110.220
4	3	90.780	106.670
5	1	190.733	161.330
5	2	91.240	105.830
5	3	80.790	100.150
6	1	118.660	159.890
6	2	85.340	90.230
6	3	75.780	87.210

4.1 Steps for Using Taguchi Method in Minitab

To use the Taguchi Method in Minitab, start by defining the problem and identifying the factors and levels you want to optimize. Then, create an experimental design by selecting the appropriate orthogonal array under the DOE (Design of Experiments) menu. Input the factors and their respective levels, and Minitab will generate the experimental runs. Conduct the experiment and input your results into Minitab. Afterward, analyze the data using the Analysis of Means and Signal-to-Noise Ratios tools to identify significant factors. Finally, use the results to optimize the process, adjusting factor levels to improve performance.

Table:5 Taguchi Design Summary

Taguchi Array	L18(6^1 3^1)
Factors:	2
Runs:	18

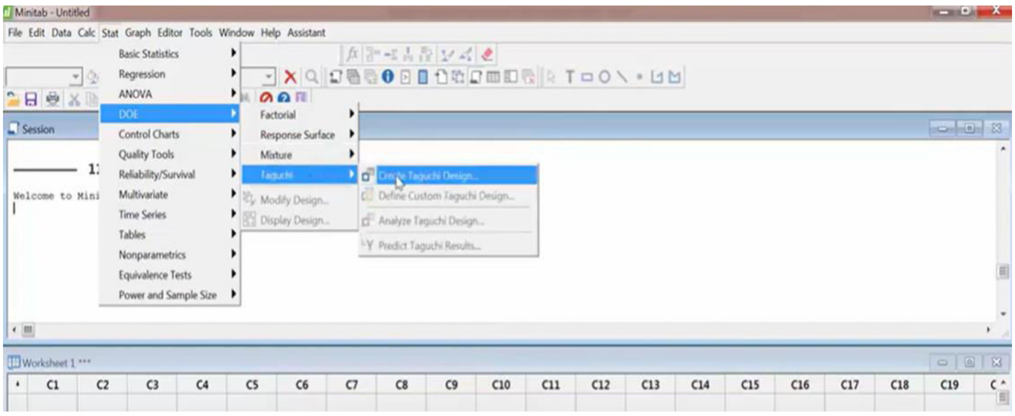

Figure 2: Mini tab layout Taguchi optimization

Table6: Taguchi Analysis: TS, FS versus Ply Orientation, Treatment

Term	Coef	SE Coef	T	P
Constant	41.0073	0.1797	228.255	0.000
Ply Orie 1	1.0703	0.4017	2.664	0.024
Ply Orie 2	-0.0888	0.4017	-0.221	0.829
Ply Orie 3	-0.0398	0.4017	-0.099	0.923
Ply Orie 4	0.0031	0.4017	0.008	0.994
Ply Orie 5	0.1933	0.4017	0.481	0.641
Treatment 1	2.1418	0.2541	8.430	0.000
Treatment 2	-0.8162	0.2541	-3.213	0.009

This table6 presents the results of a Taguchi analysis examining the effects of ply orientation and treatment on TS (tensile strength) and FS (flexural strength). The coefficients (Coef) indicate the influence of each term, while the standard error (SE Coef) provides an estimate of the variability. Significant terms are identified with p-values (P) below 0.05, such as Ply Orie 1 (p = 0.024) and Treatment 1 (p = 0.009), suggesting they have a meaningful impact on the response variables. Other terms, like Ply Orientation 2, 3, 4, and 5, show higher p-values, indicating they are not statistically significant.

Table7: Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Model summary		
Ply Orientation	5	7.463	7.463	1.4925	2.57	0.096	S	R-Sq	R-Sq(adj)
Treatment	2	42.063	42.063	21.0314	36.20	0.000	0.7622	89.50%	82.15%
Residual Error	10	5.810	5.810	0.5810					
Total	17	55.335							

This table shows the Analysis of Variance (ANOVA) for Signal-to-Noise (SN) ratios, evaluating the impact of ply orientation and treatment on the performance metrics. The analysis reveals that the treatment factor has a highly significant effect, with a p-value of 0.000 and a large F-value of 36.20. In contrast, ply orientation has a p-value of 0.096, suggesting it does not have a statistically significant influence at the 0.05 level. The model summary indicates that the model explains 89.50% of the variability in the data (R-Sq), with the adjusted R-Sq value of 82.15%, highlighting the adequacy of the model in explaining the SN ratios.

Table8 : Linear Model Analysis: Means versus Ply Orientation, Treatment Estimated Model Coefficients for Means

Term	Coef	SE Coef	T	P
Constant	116.419	2.487	46.806	0.000
Ply Orie 1	12.625	5.562	2.270	0.047

Ply Orie 2	-1.814	5.562	-0.326	0.751
Ply Orie 3	-1.648	5.562	-0.296	0.773
Ply Orie 4	-0.854	5.562	-0.154	0.881
Ply Orie 5	5.260	5.562	0.946	0.367
Treatment1	31.849	3.518	9.054	0.000
Treatment 2	-13.233	3.518	-3.762	0.004

This table presents the results of a linear model analysis examining the effects of ply orientation and treatment on the mean response. The coefficient (Coef) values represent the estimated effect of each term, with the corresponding standard errors (SE Coef) showing the variability. Significant terms include Ply Orie 1 (p = 0.047) and both Treatment 1 (p = 0.000) and Treatment 2 (p = 0.004), indicating their meaningful impact on the response. In contrast, terms like Ply Orie 2, Ply Orie 3, and Ply Orie 4 have higher p-values, suggesting they do not significantly affect the mean response.

Table 9: Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Model summary		
Ply Orientation	5	1134	1134	226.7	2.04	0.158	S	R-Sq	R-Sq(adj)
Treatment	2	9216	9216	4608.2	41.38	0.000	10.5526	90.29%	83.49%
Residual Error	10	1114	1114	111.4					
Total	17	11464							

This table presents the Analysis of Variance (ANOVA) for the mean response, focusing on the effects of ply orientation and treatment. The analysis reveals that treatment has a highly significant impact (p = 0.000) with a large F-value of 41.38, indicating that treatment factors play a crucial role in influencing the response. In contrast, ply orientation has a p-value of 0.158, which suggests it does not significantly affect the mean response at the 0.05 significance level. The model summary indicates that the model explains 90.29% of the variation in the data (R-Sq), with an adjusted R-Sq value of 83.49%, indicating a good fit.

Table:10 Response Table for Signal to Noise Ratios (Larger is better)

Level	Ply Orientation	Treatment
1	42.08	43.15
2	40.92	40.19
3	40.97	39.68
4	41.01	
5	41.20	
6	39.87	

Delta	2.21	3.47
Rank	2	1

This table shows the Response Table for Signal-to-Noise (S/N) Ratios, where a higher value indicates better performance. The table compares two factors—ply orientation and treatment—at six different levels. For ply orientation, the highest S/N ratio occurs at level 1 (42.08), with a delta of 2.21, ranking it second in importance. In contrast, treatment exhibits the highest S/N ratio at level 1 (43.15), with a delta of 3.47, making it the most influential factor. This suggests that treatment has a stronger impact on improving the response, as it ranks higher than ply orientation.

Table 11: Response for Means

Level	Ply Orientation	Treatment
1	129.04	148.27
2	114.60	103.19
3	114.77	97.80
4	115.57	
5	121.68	
6	102.85	
Delta	26.19	50.47
Rank	2	1

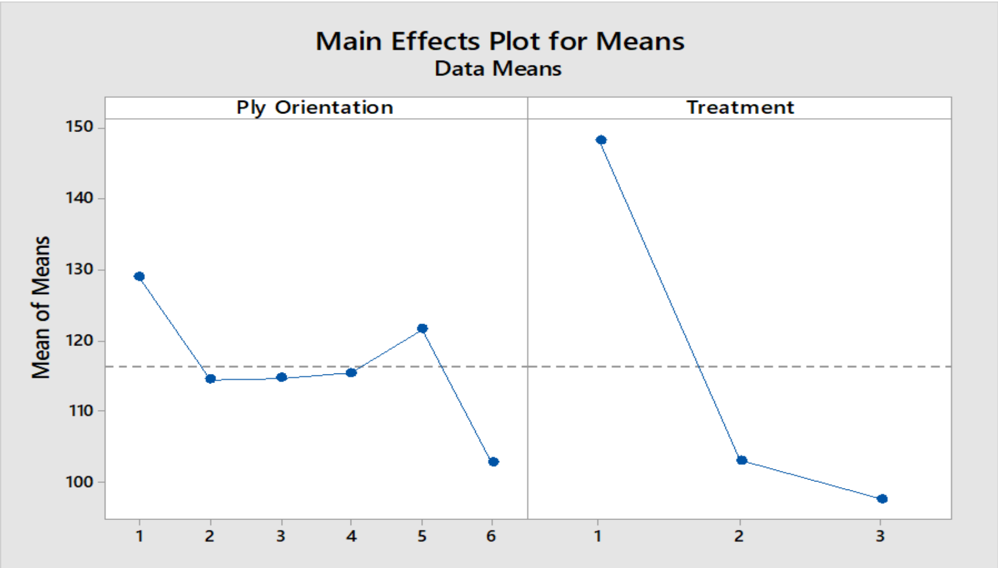

Figure 3: Main effects plot for Means

This Main Effects Plot for Means visualizes the average response for ply orientation and treatment. For ply orientation, the plot shows a declining trend in the mean of means as the levels increase, with level 1 having the highest mean and level 6 the lowest. For treatment, the plot highlights a significant drop in the mean at level 1, followed by a slight increase at levels 2 and 3. This suggests that treatment has a more pronounced impact on the response, while ply orientation shows a relatively stable trend

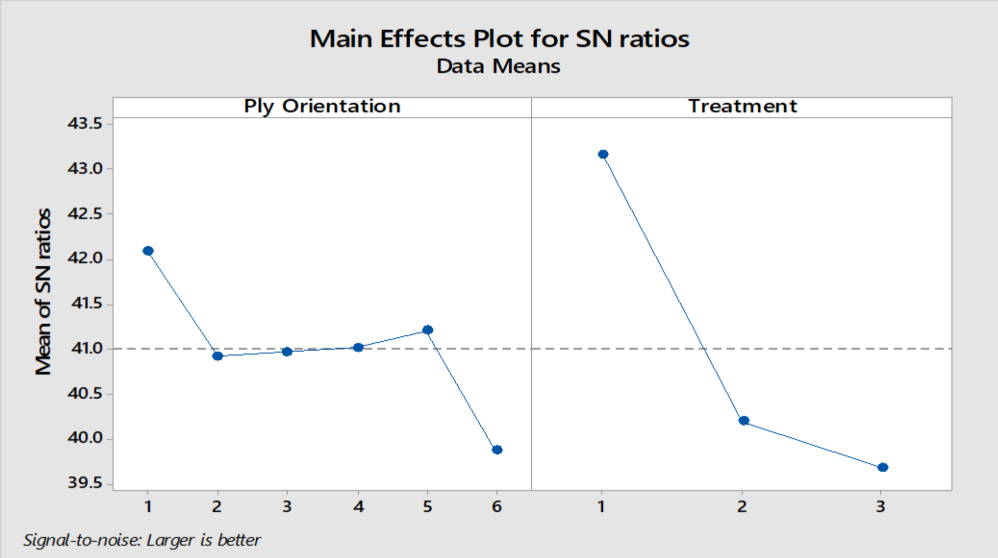

Figure 4: Main effects plot for SN ratios

This Main Effects Plot for Signal-to-Noise (SN) Ratios illustrates the average SN ratios for ply orientation and treatment, with larger values indicating better performance. For ply orientation, the plot shows a notable increase in the mean SN ratio at level 1, followed by a gradual decrease across the other levels, indicating that level 1 yields the best performance. For treatment, the SN ratio sharply declines at level 1 and remains stable at levels 2 and 3, suggesting treatment level 1 has the most significant impact on performance, with subsequent levels showing little improvement.

Table:12 Taguchi Analysis: TS, FS versus Ply Orientation, Treatment

Term	Coef	SE Coef	T	P
Constant	14.9745	0.9541	15.695	0.000
Ply Orie 1	-1.9362	2.1334	-0.908	0.385
Ply Orie 2	3.1625	2.1334	1.482	0.169
Ply Orie 3	-0.7075	2.1334	-0.332	0.747
Ply Orie 4	0.9330	2.1334	0.437	0.671
Ply Orie 5	-0.0421	2.1334	-0.020	0.985
Treatment 1	12.4729	1.3493	9.244	0.000
Treatment 2	-7.0396	1.3493	-5.217	0.000

This table presents the results of a Taguchi analysis for tensile strength (TS) and flexural strength (FS), examining the effects of ply orientation and treatment. The p-values reveal that treatment 1 ($p = 0.000$) and treatment 2 ($p = 0.000$) are highly significant, indicating they strongly affect the response.

In contrast, the ply orientation terms (ply orie 1 through 5) show higher p-values, suggesting they have little to no significant effect on the response. The coefficients (Coef) represent the estimated effect of each term, with treatment 1 showing the highest positive impact on the response.

Table: 13 Analysis of Variance for St.Devs

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Model Summary		
Ply Orientation	5	51.33	51.33	10.27	0.63	0.684	S	R-Sq	R-Sq(adj)
Treatment	2	1407.90	1407.90	703.95	42.96	0.000	4.0478	89.91%	82.84%
Residual Error	10	163.84	163.84	16.38					
Total	17	1623.07							

This Analysis of Variance (ANOVA) table examines the standard deviations (StDevs) for the factors of ply orientation and treatment. The p-value for ply orientation is 0.684, indicating that it does not significantly affect the standard deviations at the 0.05 level. However, treatment has a p-value of 0.000, suggesting it significantly influences the response. The model summary shows that the model explains 89.91% of the variability in the data (R-Sq), with the adjusted R-Sq value of 82.84%, highlighting the model's good fit for the data.

Table:14 Response for Standard Deviations

Level	Ply Orientation	Treatment
1	13.038	27.447
2	18.137	7.935
3	14.267	9.541
4	15.908	
5	14.932	
6	13.565	
Delta	5.099	19.512
Rank	2	1

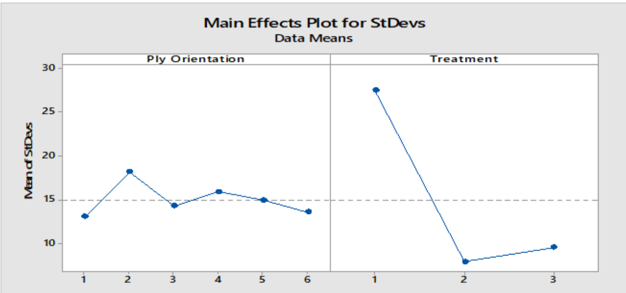

Figure 5: Main effects plot for StDevs

This Main Effects Plot for Standard Deviations (StDevs) shows the average variability for ply orientation and treatment. For ply orientation, the plot indicates a fluctuating trend, with the mean of standard deviations higher at levels 1 and 6 and lower at other levels, suggesting some influence of ply orientation on variability. On the other hand, for treatment, there is a sharp decline in variability from level 1 to levels 2 and 3, suggesting that treatment significantly reduces standard deviation and thus enhances consistency in the response.

Table: Taguchi results for Tensile and flexural

Ply Orientation	Treatment	TS	FS	S/N Ratio	Mean	StDev	Ln(StDev)
1	1	134.133	168.770	44.2194	160.893	25.5112	3.21623
1	2	125.110	115.120	41.2614	115.810	5.99874	1.91661
1	3	120.910	110.220	40.7520	110.428	7.60505	2.04325
2	1	120.110	160.899	43.0602	146.454	30.6099	3.64068
2	2	109.180	92.800	40.1022	101.371	11.0975	2.34106
2	3	112.210	92.430	39.5929	95.9889	12.7038	2.46769
3	1	117.600	162.220	43.1092	146.621	26.7400	3.02063
3	2	112.210	100.110	40.1513	101.538	7.22746	1.72102
3	3	100.150	96.340	39.6419	96.1557	8.83377	1.84765
4	1	121.330	163.550	43.1522	147.414	28.3804	3.39335
4	2	100.840	110.220	40.1942	102.332	8.86794	2.09373
4	3	90.780	106.670	39.6849	96.9490	10.4743	2.22036
5	1	190.733	161.330	43.3424	153.528	27.4053	3.48584
5	2	91.240	105.830	40.3844	108.445	7.89284	2.18622
5	3	80.790	100.150	39.8750	103.063	9.49915	2.31286
6	1	118.660	159.890	42.0110	134.701	26.0376	3.05850
6	2	85.340	90.230	39.0530	89.6182	6.52506	1.75888
6	3	75.780	87.210	38.5437	84.2357	8.13137	1.88551

5. Conclusions:

The study found that post-treatment with alkali solution significantly improved the mechanical properties of woven flax fabric epoxy laminates. Optimal process parameters led to enhanced tensile strength and better interfacial bonding between the fabric and matrix. Additionally, the treatment improved the overall durability and performance of the laminates under various testing conditions. From the parameters taken for the optimization ply orientation of 30^0 and treated composite laminate of 5% given better result than higher alkali percentage of 10%. this ensures low concentration alkali treatment given better result.

6. References

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