

Analysis of Flexural Strength of Kenaf/PLA Composite Material Structures using Ansys Static Structural Simulation

Izdihar Tharazi^a, Muhammad Syakir Mohamad Saidi^a, Nurul Hayati Abdul Halim^{a*}, Freddawati Rashidyy Wong^a, Farrahshaida Mohd Salleh^a, Mohamad Firhan Morni^a, Zalina binti Ya^{b,c} & Muhammad Ilham Khalit^d

^a*School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*

^b*Advanced Manufacturing Research Group (AMReG), Department of Mechanical Engineering and Manufacturing,*

Faculty of Built Environment and Engineering, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Malaysia

^c*Department of Mechanical Engineering, German-Malaysian Institute, Jalan Ilmiah, Taman Universiti,*

43000, Kajang, Selangor, Malaysia

^d*Department of Mechanical Engineering, School of Engineering, Bahrain Polytechnic, Isa Town 33349, Kingdom of Bahrain*

*Corresponding author: hayatihilim@uitm.edu.my

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ABSTRACT

As the automotive sector moved with natural composite materials to enhance performance and reduce the environmental impact, automotive companies are continuously investing in finding the optimum ways to apply kenaf fiber. This study aims to analyze the influence of different controlled factors on the flexural strength of polylactic-acid reinforced kenaf fiber (PLA/kenaf) composites. Design of Experiment approach under Response Surface Methodology-Central Composite Design (RSM-CCD) on 3 levels of controlled factors of fiber orientation (0°, 45°, 90°) and temperature (30 °C, 60 °C, 90 °C) which entailed 10 sets of parameters. To identify the flexural strength under different loading conditions, simulation works using Ansys Static Structural software version 2024 R1 were performed. The findings were then analyzed statistically through Analysis of Variance (ANOVA) where how the controlled factors and interaction between them influences the response was illustrated and discussed. From the simulation works, the response varies from 11.431 MPa to 250.35 MPa. The ANOVA revealed that the flexural strength of PLA/kenaf composites was significantly influenced by the controlled factors where the highest value was generated at 0° fiber orientation and 30 °C temperature. While the lowest value was observed at the maximum values of each factor. Based on the F-value, the response was dominantly affected by the fiber orientation, followed by temperature and interaction between them. Through optimization, RSM-CCD predicted the maximum flexural strength at 246.65 MPa to be generated at the optimal parameters of 0.674° fiber orientation and 30 °C temperature. Validation of these optimal parameters further confirmed the accuracy of the predictive model developed by RSM-CCD in enhancing the mechanical properties of the composite material. In conclusion, this study shows the importance of considering fiber orientation and temperature in optimizing the flexural strengths of PLA/kenaf composite materials. Exploring the effects of other process parameters and conducting experimental validation to further refine the optimization process and enhance the performance of these composite materials in automotive applications are fully recommended.

Keywords: Natural fiber; RSM; kenaf composites; Kenaf/PLA; ANOVA; ansys static structure

INTRODUCTION

Kenaf fibers are derived from the bast or core of *Hibiscus cannabinus* which belongs to the Malvaceae family. These fibers are widely used in various applications due to their high commercial significance and ecological advantages. Polylactic-acid reinforced kenaf fiber (PLA/kenaf) composites are said to have higher mechanical strength and thermal properties compared to other bast fiber-reinforced polymers (Fauzi et al. 2016). The collective publication of natural fibers composite and finite element analysis (FEA) documents from 2004 to 2020 demonstrate a growing interest in these areas (Alhijazi et al. 2020). To progress toward a sustainable future, the recent increase in the development of full biocomposites, often called “green composites” appears to offer a solution. However, the widespread use of green composites in automobiles has introduced a variety of design issues and challenges. Mainly, the components for plant fiber-based automobile products require high mechanical performance, easy fabrication, and recyclability (Tharazi et al. 2023).

Kenaf is available abundantly from several countries including India, Malaysia, the United States, Indonesia, Thailand, and Vietnam. This fiber has excellent sustainability properties as it is produced from renewable sources and grows rapidly in approximately 150 days. It also has a high strength-to-weight ratio, and good tensile strength, along with other inherent characteristics such as high specific strength and modulus, non-abrasiveness, and lower density, and is less costly (Yusuff et al. 2021). In automotive body applications, PLA/kenaf composites are usually used to produce components such as interior panels, and rear and front bumpers where great strength is needed to keep them from being pulverized by heavy impact (Tharazi et al. 2023). Conventionally, car manufacturers used traditional materials such as glass fibers and manufactured foams in automotive manufacturing. However, both of these materials pose a disposal issue due to their non-biodegradable nature. In addition, lightweight and environmentally friendly car interiors can take advantage of kenaf fibers which have lower density compared to traditional materials (Yong et al. 2015).

Literature shows that the attempt to investigate the mechanical performance of PLA/kenaf composites has been continuously conducted, particularly in terms of how various parameters, including fiber orientation and temperature, affect their properties such as tensile and flexural strengths. Research by Atiqah et al. (2024) demonstrated that PLA/kenaf composites have been shown to have superior mechanical qualities, such as better tensile and flexural strength when compared to pure PLA. The

study found that adding kenaf fibers, which operate as a reinforcing agent, enhanced the tensile strength of the composites, increasing the material's overall structural integrity. Another significant study by Yan et al. (2014) examined the mechanical performance of kenaf/PLA composites in terms of fiber orientation and content. The results showed that aligning fibers along the load direction greatly improved tensile strength, with the best performance found at 0° fiber orientation. A comprehensive study by Mohanty et al. (2000) evaluated the practicality of employing PLA/kenaf composites in automobile parts, emphasizing their ability to reduce vehicle weight and environmental effects. The study stressed the importance of tailoring processing parameters and fiber content to achieve the requisite mechanical qualities for various applications.

Thus, this study attempts to fill a knowledge gap by examining the flexural strength of PLA/kenaf composites using Ansys Static Structural models and finite element modeling. This study aims to provide significant insights into the design and optimization of this sustainable material for automotive applications by systematically investigating the effect of fiber orientation (0°, 45°, and 90°) and temperature (30 °C, 60 °C, and 90 °C) on the flexural strength of these composites with the help of Design of Experiment (DOE) approach. Flexural strength is one of the key indicators in analyzing the ability of kenaf fiber to withstand bending forces without failure (Najwa et al. 2022). The goal is to aid in material selection for the currently used synthetic fiber composite in the automotive industry, particularly for lightweight components where bending and flexural common are common. Thus, the simulation results need to be convincing. Compared to physical testing, this approach allows for a comprehensive exploration of composite materials cost-effectively and time-efficiently. Additionally, a comparison against past research was performed to validate the consistency and credibility of results, providing insight into any potential modifications or improvements over time.

METHODOLOGY

DESIGN OF EXPERIMENT (DOE)

In this study, the simulation works were conducted based on the controlled factors and controlled levels as listed in Table 1. The controlled factors and ranges were chosen based on intensive literature conducted by (Tharazi, 2021) with the main application is in automotive components application.

TABLE 1. Design of experiment with controlled factors and response

Controlled factors	Controlled Level			Response	Objective
	-1	0	1		
Fiber orientation (°)	0	45	90	Flexural strength (MPa)	Maximum
Temperature (°C)	30	60	90		

This study focuses on the parametric study to analyze and optimize the flexural strength of the PLA/kenaf composite at different levels and combinations of fiber orientation and temperature. The goal is to statistically analyze how the controlled factors and interaction between them influence the response through the simulation method. At the same time, to optimize the response which contributes to the development of sustainable automotive structural components (Sharba et al. 2016). The Central Composite Design (CCD) approach in Design Expert Version 13 was applied to design the simulation parameter which entailed a total of 10 sets of process parameters. This RSM-CCD method develops a structured simulation plan, enabling data collection at multiple levels of the effectors (Harun et al. 2017). The data provides the basis for a comprehensive design of experiment analysis, ensuring robustness and statistical relevance due to the capabilities of this software.

ANALYSIS SETUP FOR SIMULATION USING ANSYS

The geometry model of the specimen was created using Ansys Discovery software. This specimen was standardized to provide a repeatable and consistent platform for conducting flexural tests. This was achieved by ensuring that all samples have consistent dimensions of 115 x 20 x 2 mm as shown in Figure 1(a) (Tharazi, 2021). Simulations are utilized to reduce potential size-related variations that could impact the outcomes.

The material properties of the PLA/kenaf composite material are listed in Table 2. After adding the information into the Ansys material library, the next step was to perform meshing as outlined in Figure 1(b). Meshing involves dividing the data around the model geometry into smaller discrete elements to accurately model the structure of the composite in the simulation. This study utilized hexahedron meshes with an average element size of 2 mm to balance computational efficiency and accuracy. The mesh was refined around areas of stress concentration, such as the fiber-matrix interface, to capture the mechanical behavior accurately.

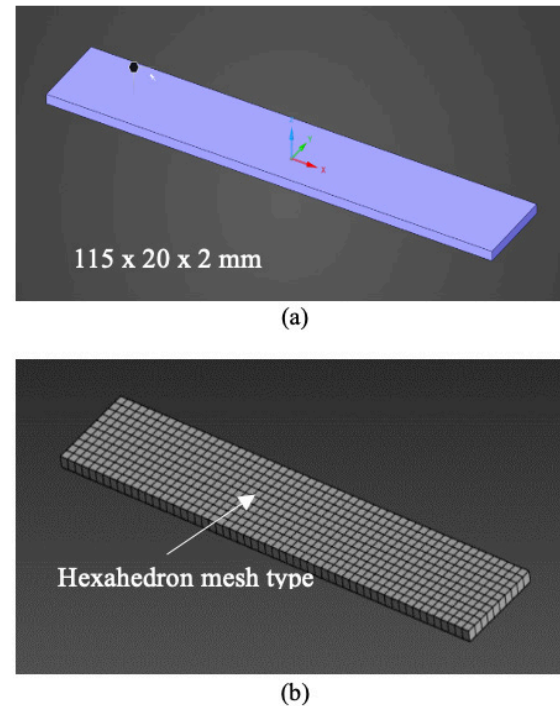


FIGURE 1. Simulation model; (a) geometry and (b) meshing

The simulation setup was then followed by carefully defining the boundary conditions, aligning with the ASTM D790 standards for flexural testing. This is to ensure that the simulation aligns with experiment standards (Tharazi, 2021). A fixed support was applied to one end of the PLA/kenaf composite specimen, preventing any translational or rotational movement. A distributed load at 30 kN was applied on the opposite end to simulate the flexural load. The load was gradually increased to observe the material's response until failure. By following these procedures, the simulation can accurately replicate the experimental processes in the physical realm, such as the flexure impact of the PLA/kenaf composite material. With the simulation environment set up following traditional test methods, the mechanical response of the composite material was then analyzed and predicted using Ansys Static Structural software. This provides valuable insights into its flexural strength, leading to potential optimization for enhanced performance in automotive applications.

TABLE 2. Composite properties

Temperature (°C)	Young modulus, E (MPa)	Poisson ratio, γ	Density, ρ (kg/mm ³)
60	11667	0.16	1.21 x 10 ⁻⁶
90	9107	0.07	
120	7623	0.10	

POST-PROCESSING

The three-point bending test of the PLA/kenaf composite under different parameters was presented with the simulation results using ANSYS software in detail as

shown in Figure 2. This allows comparisons of the flexural strength values related to fiber orientations and temperatures to be made with the simulation response values and hence able to predict the best combinations that can improve and enhance the performance of these composites for automotive applications.

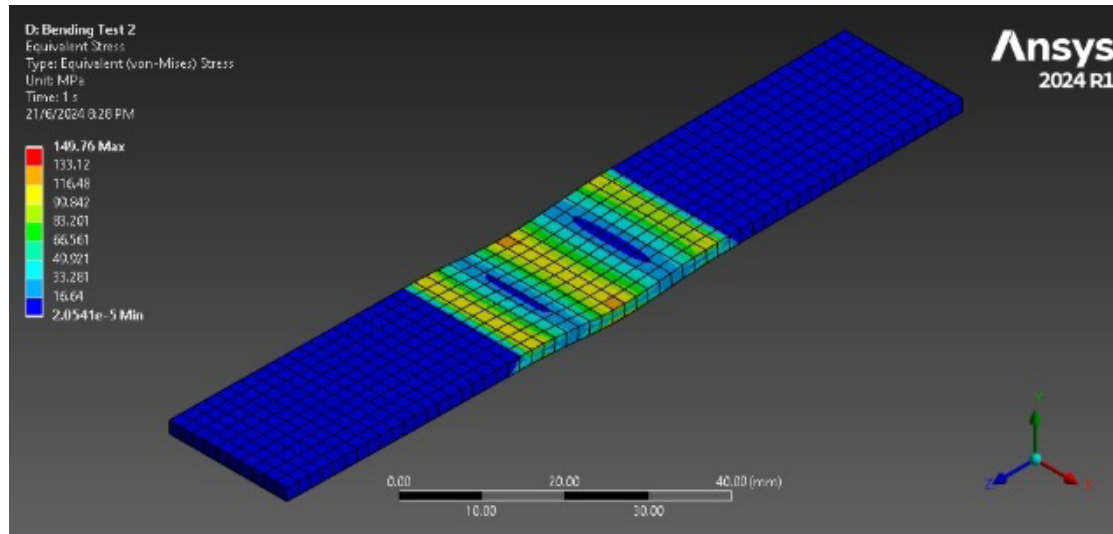


FIGURE 2. The result of the simulation for the three-point bending test

ANALYSIS OF VARIANCE (ANOVA)

ANOVA was conducted on the flexural strength of the PLA/kenaf composite to analyze the impact of each input process parameter and its significance level. ANOVA which stands for Analysis of Variation, is a statistical tool used to assess the relationship between a dependent variable and potential explanatory factors to determine if those factors significantly influence the measurements (Gopalsamy et al. 2009). The F-values and p-values from the ANOVA analysis helped identify the factors affecting the mechanical properties of the composite material. The results of the ANOVA analyses are significant in understanding the impact of different input process parameters on the mechanical properties of the PLA/kenaf composite. This method provides valuable insights for further analysis and improvement of the composite material.

OPTIMIZATION

In this study, response surface methodology (RSM) along with central composite design (CCD) was used to optimize the process parameters of PLA/kenaf composite with the main objective of maximizing flexural strength. Then, the selected optimal parameters were validated with experimental results from a previous study by Tharazi (2021).

RESULTS AND DISCUSSION

RESPONSE FROM POST-PROCESSING

Results from post-processing are presented in Table 3, generated in Ansys Static Structural. The tests were conducted at two midpoints with different fiber orientations and temperatures. The simulation as illustrated in Figure 3, revealed that the flexural strength values ranged from 11.431 MPa to 250.35 MPa. The highest value was obtained from simulation 3 at a fiber orientation of 0° and temperature of 30 °C. The lowest was from simulation 6 at 90° and 90 °C of fiber orientation and temperature, respectively. In general, it can be observed that both factors influenced the responses in the same pattern, where an increase in their values significantly reduced the response. Ranges of the flexural strength generated in this study are sufficient for application in automotive interior parts such as body panels, and inner hood panels where the required strength is around 61 MPa to 67 MPa. It is also appropriate for use in other parts, such as dashboards and baggage covers, where a strength requirement of approximately 30 MPa is needed (Tharazi et al. 2023).

Figures 4 and Figure 5 display the maximum and minimum flexural strength values across the modeled structure from Ansys V2024 R1. The grid-like structure

represents the mesh used for the analysis, where each square corresponds to a finite element (Gupta et al. 2021). The color gradient shows different levels of flexural strength, with cooler colors like blue to green representing lower values, and warmer colors like yellow to red

indicating higher values. This visualization is important for identifying the areas of the structure that experience the lowest and highest flexural strengths, which is crucial for assessing the structural integrity and identifying potential points of failure (Alhijazi et al. 2020).

TABLE 3. Flexural strength results

Run	Controlled factors		Response
	Fiber orientation (°)	Temperature (°C)	Flexural strength (MPa)
1	90	30	15.68
2	45	30	64.7
3	0	30	250.35
4	45	60	20.561
5	0	60	185.09
6	90	90	11.431
7	0	90	82.446
8	45	90	16.233
9	90	60	13.233
10	45	60	20.561

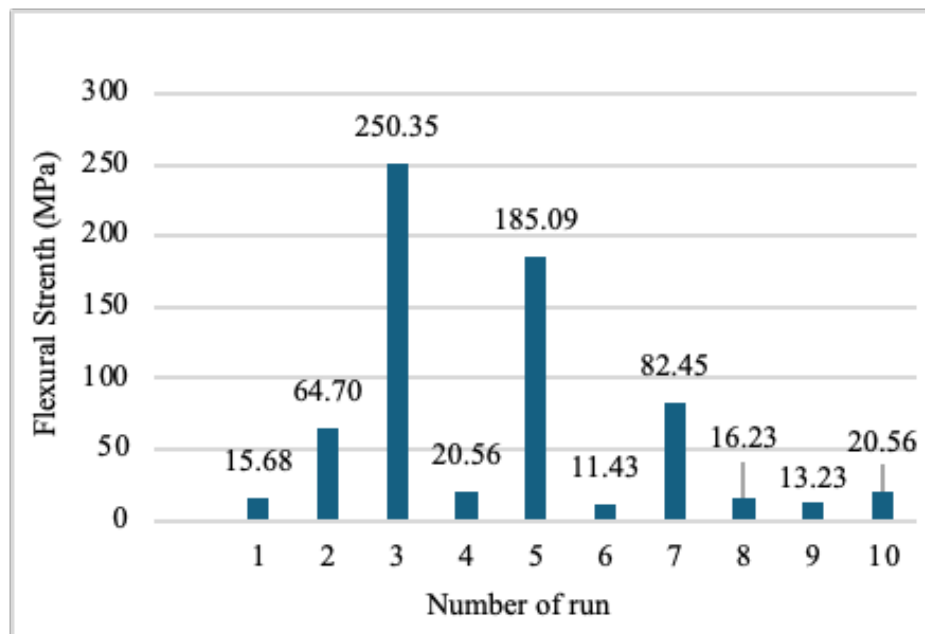


FIGURE 3. Simulation results for flexural strength

As shown in Figure 4, the maximum stress point is 250.58 MPa, located at node 1260 and marked in red contour, indicating high-stress concentrations. The minimum stress point is 5.9755×10^{-05} MPa, found at node 4152 and marked in blue contour, highlighting areas with minimal stresses. The simulation was run under run number 3 with 0° fiber orientation and a temperature of 30°C. These

results show the critical influence of fiber orientation and temperature stability on flexural strength performance in composite materials, providing valuable insights for optimizing structural designs for enhanced durability under bending loads (Ismail et al. 2022).

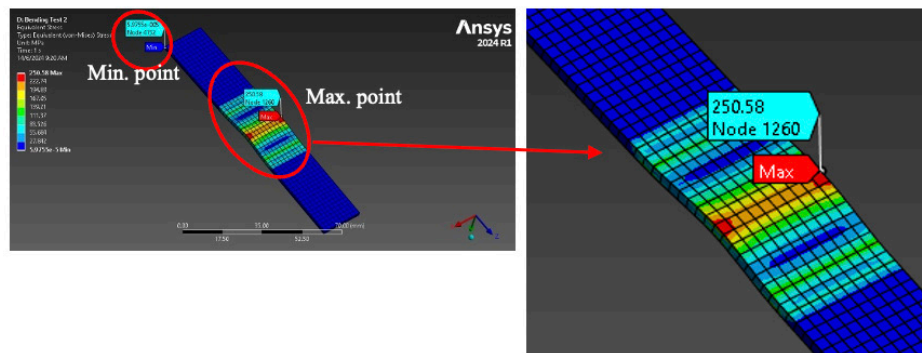


FIGURE 4. Maximum flexural strength

The minimum flexural strength is depicted in Figure 5. The minimum stress point of 11.45 MPa is located at node 1065 and is indicated by a red contour. The lowest stress point, which is $4.4377\text{e-}007$ MPa, is found at node 4016 and is marked by a blue contour. When changing to

a 90° fiber orientation and a temperature of 90°C , the material's flexural strength significantly decreased. This shift typically results in reduced strength along the direction of fiber orientation, with the elevated temperature further contributing to decreased material strength.

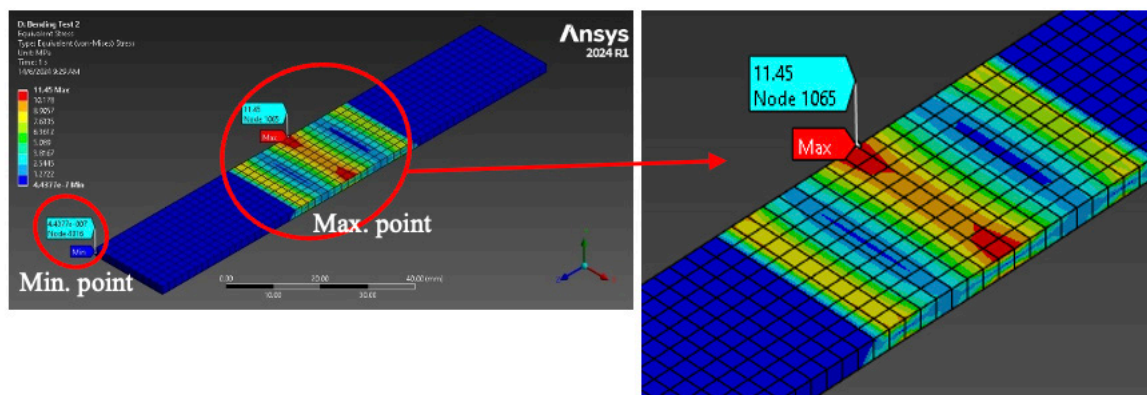


FIGURE 5. Minimum flexural strength

ANALYSIS OF VARIANCE (ANOVA)

ANOVA assesses the individual impact of each factor and explores how interactions between factors behave and influence the response, revealing whether the combined effect of multiple factors is greater, lesser, or different than expected based on their individual effects. ANOVA also facilitates the development of a predictive model that is important for predicting and optimizing the process, based on its robust statistical evidence. For an accurate and reliable model, model reduction was conducted where any non-significant factors or interactions that may reduce the accuracy of a predictive model were excluded or removed (Sulong et al. 2018). The factors or interactions with a p-value greater than 0.05 were considered weakly supported, and interactions with a p-value less than 0.100 were disregarded as not significant.

Table 4 is the ANOVA for flexural strength. The model is significant with the p-value less than 0.05. Based on the F-value, it indicates that fiber orientation has the greatest influence on flexural strength with the F-value of 172.78. It is followed by A^2 , factor B, the temperature and interaction between these factors, AB.

Figures 6(a) and 6(b) illustrate how single factors influence the response. As shown, both factors provide the same trend where the reduction of their value increased the flexural strength. Figure 6(a) also shows the quadratic term of A^2 which indicates that the relationship between fiber orientation and flexural strength is not merely linear but exhibits a non-linear pattern. This non-linear behavior is crucial because it implies that further alignment beyond a certain point may increase or reduce the strength of the composites due to potential issues like fiber buckling or inefficient load transfer.

TABLE 4. ANOVA analysis for flexural strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	62200.86	4	15550.22	70.69	0.0001	significant
A-Fibre Orientation	38007.73	1	38007.73	172.78	< 0.0001	
B-Temperature	8113.59	1	8113.59	36.88	0.0017	
AB	6695.74	1	6695.74	30.44	0.0027	
A ²	9383.80	1	9383.80	42.66	0.0013	
Residual	1099.86	5	219.97			
Lack of Fit	1099.86	4	274.97			
Pure Error	0.0000	1	0.0000			
Cor Total	63300.73	9				
Std. Dev.	14.83					
Mean	68.03					
C.V. %	21.80					
R ²	0.9826					
Adjusted R ²	0.9687					
Predicted R ²	0.9058					
Adeq Precision	24.4654					

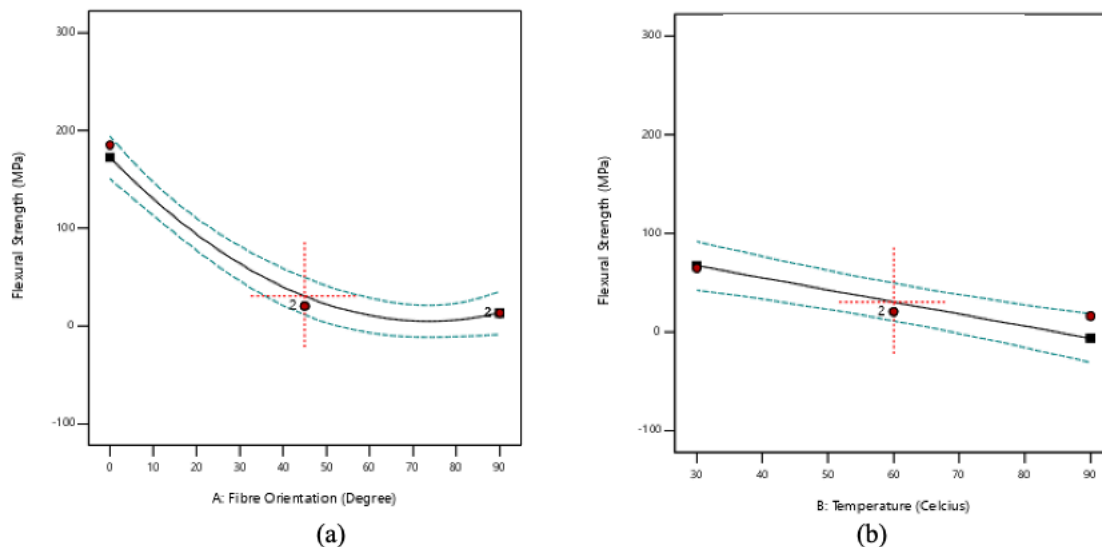


FIGURE 6. The influence of single factors on response; (a) Fibre orientation (°) and (b) Temperature (°C)

The ANOVA findings aligned with Gupta et al. (2021), mentioned that when fibers are aligned with the direction of the applied load, which is at 0° orientation, they can carry the load more effectively, leading to higher flexural strength. While from a study conducted by Li & Huneault (2007), reported that lower processing temperatures enhance the crystallinity of PLA which also improves the stiffness and strength of the PLA matrix, leading to better mechanical properties such as flexural strength. This finding also aligns with Bax & Müssig (2008), mentioned the important influence of processing conditions particularly temperatures on the overall structural integrity of the composites.

From Table 4, the predicted R^2 of 0.9058 shows excellent agreement with the adjusted R^2 of 0.9687, with a difference of less than 0.2. The adequate precision of 24.465 is a good signal, as a precision value greater than 4 signifies an acceptable model. This value is compared to the optimum model value of 21.80%, indicating that the model is satisfactory.

INTERACTION BETWEEN FACTORS

The influence of combined factors over measured response can be visualized and analyzed using a 3D model graph.

A detailed analysis can be conducted to break down the interaction of the observed responses from other factorial interactions in the model graph representation of flexural strength in this study (Syazalee et al. 2022). In Figure 7, it can be observed that changing the value of factor A has a significant impact on the flexural strength at any given value of factor B. As the fiber orientation increases from 0° to 90°, the response decreases. The shape of the curve indicates that factor A is more dominant in this interaction. At 0° of fiber orientation, the reduction of temperatures increases the response. However, the changes were not significant at a fiber orientation of 90°. The highest value of flexural strength, at 253.537 MPa, is achieved at the minimum values of both factors. Interestingly, the highest points of both factors resulted in the lowest flexural strength (Salleh et al. 2018). Thus, it can be said that factor A has a more dominant effect in this interaction.

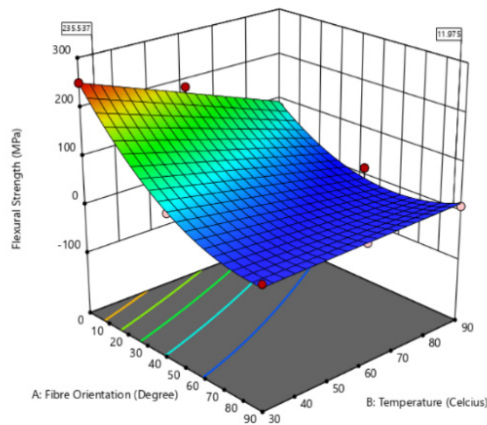


FIGURE 7. 3D-surface model graph of flexural strength

DEVELOPMENT OF MATHEMATICAL EQUATION

ANOVA was also applied to predict the quadratic statistical model in an independent second-order regression. Equation (1) describes the equation in the actual factor.

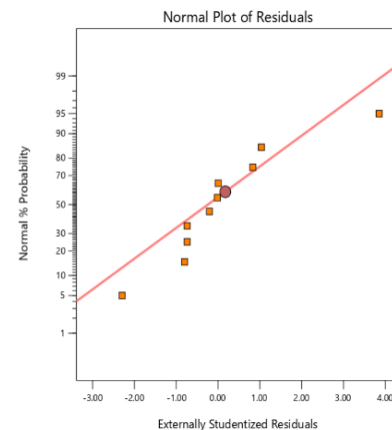
$$\text{Flexural strength} = 328.003 - (6.366 \times A) - (2.59 \times B) + (0.03 \times A \times B) + (0.031 \times A^2) \quad (1)$$

Equation (1) can be applied to understand how the response is expected to change when the factors involved move to different levels. However, it is important to note that this equation should not be used to calculate the relative effects of each term, as the coefficients are scaled to the units of each factor, and the intercept is not centered in the design space (Tharazi et al. 2020). When comparing the simulation results in Table 3 with the predicted values using Equation 1, the average error is 27.18%. The error is

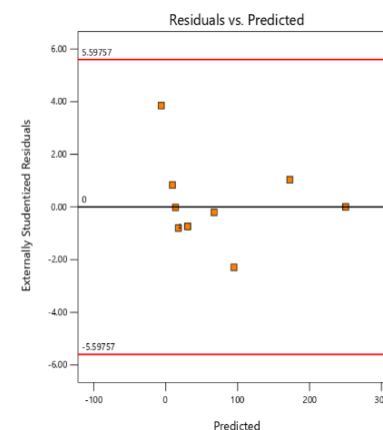
considered high and might be attributed to the inherent complexity of the simulation system and model used. Despite these discrepancies, the model provides valuable insights, and further refinement could enhance its predictive accuracy.

DIAGNOSTIC PLOT ANALYSIS

When assessing the adequacy of the model, it is important to review the following 2 diagnostic plots: normal plot of residuals and residuals vs. predicted plot as shown in Figures 8(a) and 8(b), respectively. These plots provide insight into how well the residuals adhere to a normal distribution and how effectively they fit the data. Any deviations from the straight line in the plots could signal non-normality, suggesting the need for additional adjustments to the model (Sathyaseelan et al. 2022).



(a)



(b)

FIGURE 8. Diagnostic plots: (a) normal plot of residuals (b) residuals vs. predicted

In Figure 8(a), the residuals appear to be well scattered, indicating that this model does not require any further

improvement. Most of the points are randomly located near the straight line indicating that no patterns or large outliers exist in the data. Figure 8(b) shows that the data points fall within the established limits, suggesting the absence of a strong pattern or unusual structure in the model. This indicates a very good fit of the model for the given data, meaning that the assumptions of the regression could be reasonably met. Thus, the model can be used to predict the response, although a few outliers might indicate some areas for further improvement.

OPTIMIZATION USING RESPONSE SURFACE METHODOLOGY (RSM)

In this study, the main aim of the optimization is to identify the best combination of process parameters that could maximize the flexural strength of the PLA/kenaf composite. Table 5 lists 8 solutions with optimum parameters and predicted flexural strengths suggested by the RSM-CCD. As shown, solution number 1 with desirability 1 at fiber orientation of 0° and temperature of 30 °C is predicted to

generate maximum flexural strength at 250.32 MPa. This parameter is also believed could further enhance the overall mechanical properties, structural integrity, and durability of the composite which is important for appliances in the automobile sector (Sreenivas et al. 2020).

The next step is to validate the optimized parameters to ensure the reliability and accuracy of the predictive model. In this validation procedure, the predicted flexural strength of the PLA/kenaf composite is compared with the flexural strength from the simulation work. Such comparison will assist in evaluating the simulation model's accuracy as well as in its validity to predict the mechanical behavior of similar systems in the real world (Uzoma et al. 2023). For comparison with the predicted value, solution number 2 in Table 5 was selected and simulated. Although the first solution had the highest desirability, the second solution was selected to assess the accuracy, as it offered a different parameter set compared to the DOE-generated parameters as in Table 3. With desirability of 0.985, the ramp chart in Figure 9 shows that the flexural strength at 246.65 is expected to be generated at a fiber orientation of 0.674° and temperature of 30 °C.

TABLE 5. 8 solutions for optimum flexural strength

Number	Fiber orientation (°)	Temperature (°C)	Flexural strength	Desirability
1	0.000	30.000	250.316	1.000
2	0.674	30.000	246.649	0.985
3	0.000	40.500	223.125	0.886
4	0.000	43.935	214.229	0.849
5	0.000	64.500	160.975	0.626
6	0.000	66.749	155.151	0.602
7	0.000	70.500	145.438	0.561
8	90.000	90.000	17.589	0.026

From the simulation result, Table 6 shows that the predictive model has an error percentage of 10.31%, which is slightly exceeds the 10% threshold suggested by Hills & Trucano (1999) for model validity. This suggests that while the model can offer valuable insights into the behavior of the material under certain conditions, it may not be entirely accurate for precise predictions. Therefore, the model should be used with caution, particularly in applications where high precision is critical. In this case, the simulated results were further validated by comparing them with the experimental data collected by Tharazi, (2021).

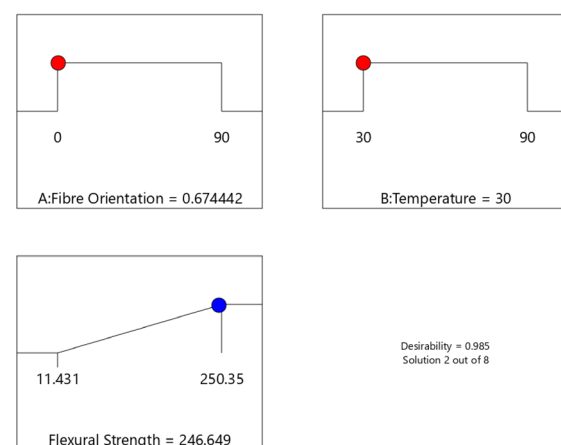


FIGURE 9. The ramp chart for the optimum parameters

TABLE 6. Predicted vs. simulated values

Optimum parameter		Response		Error
Fiber orientation	Temperature	Predicted	Simulated	
0.674°	30 °C	246.65 MPa	275 MPa	10.31%

As exhibited in Figure 10, the flexural strength from simulation and experimental works shows a similar trend for various fiber orientations and temperatures. The blue line represents the simulation data, while the orange line represents the experimental results. It can be observed that as the fiber orientation and temperature increase, the flexural strength decreases significantly. For instance, in the 0/30 combination, the flexural strength was 250.35 MPa in the simulation, while the experimental results showed slightly lower values at higher orientation and temperature combinations at 90/60 and above, with the flexural strength decreasing to almost zero.

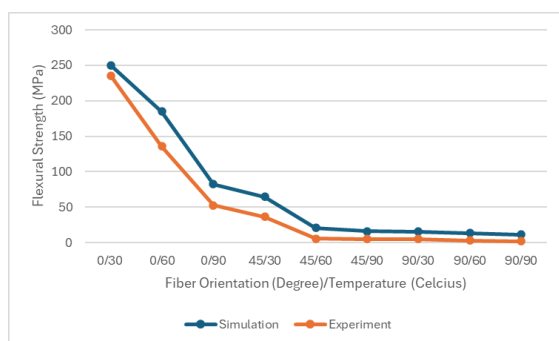


FIGURE 10. Comparison between simulation and experiment results

Thus, it can be said that both simulation and experimental results reveals that higher fiber orientation angles and temperatures have a negative impact on the mechanical properties of PLA/kenaf composites. Despite some minor variations, the two datasets exhibit very similar trends, suggesting a strong correlation between the simulation and experimental data. The consistent prediction of flexural behavior by the simulation model under various conditions indicates that the model accurately represents the real-world scenario (Tharazi, 2021).

CONCLUSION

In conclusion, the simulation works conducted in this study have provided a valuable understanding of the mechanical behavior of PLA/kenaf composite materials which are now widely used in automotive applications. The simulation

works using Ansys Static Structural software have identified the variations of the flexural strength under different combinations of fiber orientation and temperature. Furthermore, the ANOVA findings have revealed that controlled fiber orientation and temperature play a crucial role in determining the flexural strength of PLA/kenaf composites. The interactions between factors have also been examined, with the study identifying key relationships that impact the flexural strength. An optimum set of parameters was also selected based on the suggestion by RSM-CCD where flexural strength at 246.65 MPa is predicted to be achieved at fiber orientation of 0.674° and temperature of 30 °C.

Overall, the combination of simulation works, and ANOVA analysis has provided a comprehensive understanding of the mechanical characteristics of PLA/kenaf composite materials. These findings have significant implications for the automotive sector, where lightweight and high-strength materials are increasingly desired for applications such as interior components, panels, and under-the-hood structures. By optimizing fiber orientation and processing temperatures, manufacturers can potentially tailor the mechanical properties of PLA/kenaf composites to meet specific performance requirements in automotive applications. These findings also can guide future research and development efforts aimed at optimizing the properties of natural fiber-reinforced composites for automotive applications, ultimately leading to more sustainable and high-performance solutions in the industry.

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DECLARATION OF COMPETING INTEREST

None.

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