International Journal of Innovation in
Mechanical Engineering and Advanced Materials
Vol. 8 (No. 1), 2026, pp. 1-10
Journal homepage: publikasi.mercubuana.ac.id/index.php/ijimeam
DOI: 10.22441/ijimeam.v8i1.33422

Development of Teak Wood Powder–Epoxy Composite for Motorcycle CVT Weight Rollers Application

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Abstract

The development of sustainable materials for automotive components has become increasingly important due to environmental concerns associated with conventional synthetic materials. This study investigates the feasibility of teak wood powder (*Tectona grandis L.F.*) reinforced epoxy composites as an eco-friendly alternative to polytetrafluoroethylene (PTFE) for Continuously Variable Transmission (CVT) weight rollers. The composite was fabricated using a hot-press method with varying composition ratios (60:40, 70:30, and 80:20) and processing temperatures (160 °C, 170 °C, and 180 °C) under a constant pressure of 20 bar. Mechanical performance was evaluated through tensile testing in accordance with ASTM D3039. The results demonstrate that both composition and processing temperature significantly influence tensile strength. The optimal condition—60% teak wood powder and 40% epoxy resin processed at 180 °C—yielded the highest average tensile strength of approximately 25 MPa, surpassing the typical value of conventional PTFE-based rollers (~23 MPa). The improvement is attributed to enhanced matrix–filler bonding and better resin flow at elevated temperatures, resulting in more effective load transfer and reduced void formation. Conversely, higher filler content led to reduced performance due to insufficient matrix continuity and increased interfacial defects. This study provides a significant contribution by demonstrating that teak wood waste can be effectively utilized as a reinforcement material in structural automotive applications. The findings highlight a viable pathway toward cost-effective, sustainable composite design while maintaining competitive mechanical performance. Further investigation on tribological behavior and long-term durability is recommended to support real-world implementation.

Article Info:
Received: 1 May 2025
Revised: 16 June 2025
Accepted: 22 June 2025
Available online: 7 April 2026

Keywords:
composite; motorcycle part; teak wood; hot press; tensile test

1. Introduction

The rapid growth of motorcycle use, particularly in countries such as Indonesia, has increased the demand for transmission components that are not only mechanically reliable but also lightweight, cost-effective, and increasingly sustainable. In automatic motorcycles, the Continuously Variable Transmission (CVT) system is widely adopted because it provides smooth ratio changes, better rider comfort, and good fuel efficiency under urban driving conditions [1]. Within this system, the weight roller plays a critical role because its mass and material characteristics determine the centrifugal response that governs pulley movement, acceleration behavior, and transmission efficiency [2], [3], [4], [5]. Therefore, the selection of weight roller material is not merely a manufacturing issue, but a functional design parameter that directly affects CVT performance.

Commercial weight rollers are commonly produced from metals or synthetic polymers such as polytetrafluoroethylene (PTFE) because these materials offer dimensional stability, acceptable mechanical strength, and wear resistance. However, these conventional materials are less attractive from a sustainability perspective due to their petroleum-based origin, relatively high cost, and limited biodegradability. More importantly, previous studies on CVT rollers have mainly focused on the effect of roller mass, shape, and operating conditions on vehicle performance, rather than on the development of alternative roller materials with lower environmental impact [4], [5]. As a result,

How to cite:

R. D. P. Susilo, M. Fitri, M. S. Yafiq, A. Hamid, and D. Romahadi, “Development of teak wood powder–epoxy composite for motorcycle CVT weight rollers application," *Int. J. Innov. Mech. Eng. Adv. Mater*, vol. 8, no. 1, pp. 1-10, 2026

the material innovation aspect of CVT roller design remains less developed than its performance optimization aspect.

In recent years, natural-filler and bio-based composites have gained attention as potential substitutes for synthetic engineering materials in automotive and structural applications. Earlier studies have shown that lignocellulosic reinforcements can improve the sustainability and reduce the density of polymer composites, but their mechanical performance strongly depends on particle type, filler fraction, interfacial bonding, and processing conditions [6], [7]. For example, natural-fiber and wood-based composites often suffer from weak matrix–filler adhesion, void formation, and non-uniform load transfer, which limit their tensile strength and reliability under service loads. Previous work using natural fillers reported only modest strength levels, indicating that material selection alone is insufficient; the fabrication route and thermal processing parameters are equally important in determining the final composite quality. This suggests that, for functional mechanical parts such as CVT rollers, the challenge is not simply to replace synthetic materials with biomass-derived fillers, but to achieve a composite structure with adequate bonding, strength, and consistency.

Among various lignocellulosic materials, teak wood has particular potential because it is widely available, mechanically durable, and commonly generated as powder waste from woodworking activities. Compared with many other natural fillers, teak powder is attractive because of its relatively high hardness, structural stability, and local availability, making it a promising candidate for value-added composite applications [8], [9], [10], [11], [12], [13]. In addition, teak wood waste offers a practical sustainability advantage: it converts an underutilized biomass residue into a functional engineering material. However, the potential advantage of teak powder over other natural fillers has not yet been sufficiently examined in the context of CVT roller applications. Most published studies on teak-based composites have focused on general mechanical characterization, water absorption, or non-CVT applications such as boards, pads, or structural composite products [14]. Consequently, the relevance of teak powder as a reinforcement for small, load-bearing automotive transmission components remains unclear [15].

Another limitation in the current state of the art is the lack of process-oriented studies that link composite composition and hot-pressing temperature to the mechanical feasibility of bio-based rollers. For CVT roller applications, material suitability depends not only on the selection of reinforcement and matrix, but also on the ability of the manufacturing process to produce sufficient consolidation and interfacial bonding. In particulate composites, inadequate resin content can lead to poor wetting and void formation, whereas excessive filler loading may reduce cohesion and tensile integrity. Likewise, pressing temperature affects resin flow, curing behavior, and particle encapsulation. Despite these known effects, there is still limited published work that systematically evaluates teak wood powder–epoxy composites under controlled hot-pressing conditions for CVT-related use. This indicates a clear gap in the literature: existing studies have not adequately addressed whether teak powder composites can provide the combination of mechanical strength and practical manufacturability required for CVT weight rollers.

This study therefore investigates teak wood (Tectona grandis L.F.) powder reinforced with epoxy resin as an alternative composite material for motorcycle CVT weight rollers. The novelty of this work lies in the use of teak wood powder specifically for CVT roller application and in the systematic evaluation of the combined effects of filler composition and hot-pressing temperature on composite performance. Unlike previous studies that mainly reported general properties of natural-filler composites, this research positions teak powder as a functional engineering reinforcement for an automotive transmission component. The objective of this study is to analyze the mechanical performance of teak wood powder–epoxy composites, determine the effect of composition and

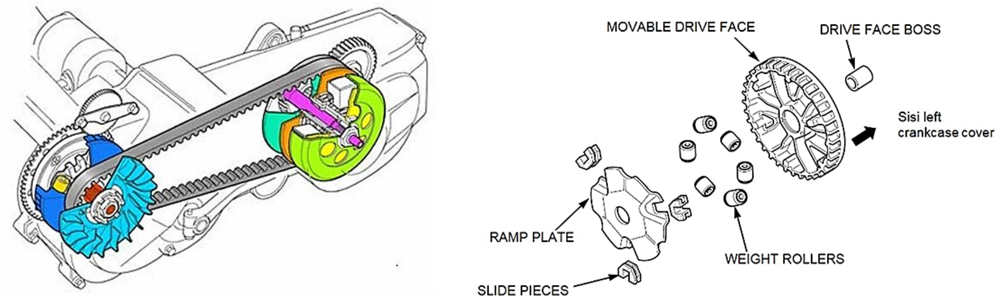


Figure 1. CVT and weight rollers [16], [17].

Figure 2. Damaged CVT roller weights in motorcycles [3].

hot-press temperature on tensile strength, and identify the processing condition that provides the most promising performance for CVT roller material development.

2. Methods

This study employed a controlled laboratory experimental approach to develop and evaluate teak wood powder–epoxy composites as an alternative material for CVT weight rollers. The methodology was designed to systematically investigate the effects of filler composition and hot-pressing temperature on the mechanical performance of the composite. The overall experimental workflow consisted of material preparation, composite fabrication using hot pressing, specimen finishing, and mechanical testing, followed by statistical analysis.

2.1. Materials

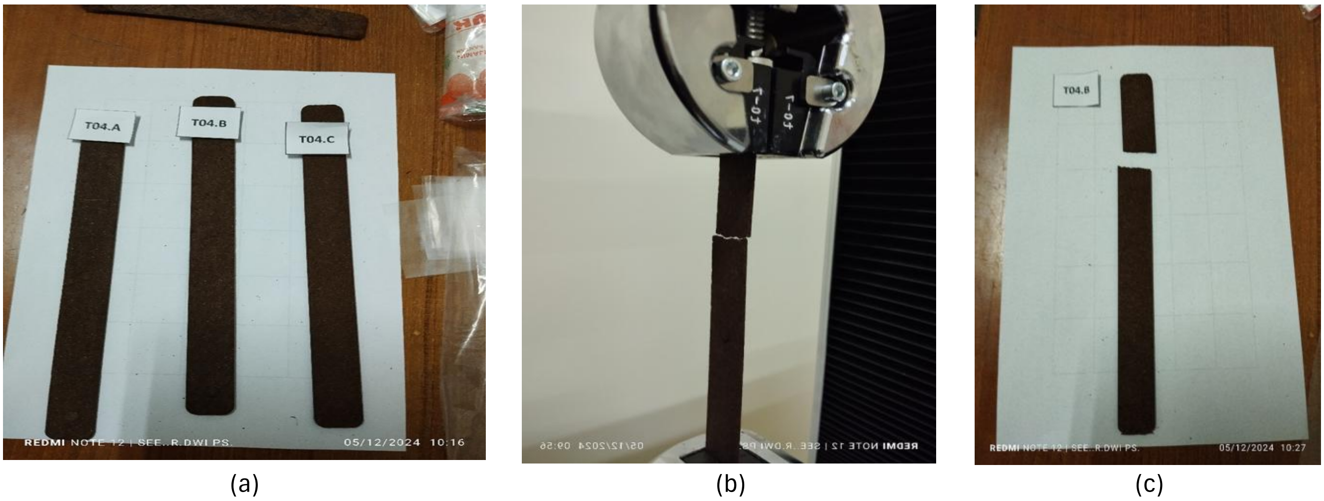
Teak wood (Tectona grandis L.F.) powder was used as the reinforcement material. The powder was sieved to obtain a uniform particle size of 100 mesh and oven-dried at 105 °C for 24 h to remove moisture and improve matrix–filler adhesion. The matrix material consisted of a commercial epoxy resin system combined with a hardener at a weight ratio of 2:1, as recommended by the manufacturer to ensure proper curing. The density of teak wood powder and epoxy resin were taken as 0.72 g/cm^3 and 1.17 g/cm^3, respectively. Composite formulations were prepared based on volume fractions of teak wood powder to epoxy resin at three levels: 60:40, 70:30, and 80:20.

2.2. C*omposite preparation and fabrication*

The required mass of teak powder and epoxy resin for each specimen was calculated based on the target volume fraction and specimen volume. The specimen volume (V_c) was determined using:

(a) (b)

Figure 3. (a) Mold specimen tensile test ASTM D3039, (b) Hot press machine.



(a) (b) (c)

Figure 4. Specimen on tensile test; (a) Before test, (b) During test, (c) After test.

$$V_C = P \times l \times \ t \tag{1}$$

where $P = 250\text{mm}$ (length), $l = 25\text{mm}$ (width), and $t = 2.5\text{mm}$ (thickness), resulting in a total volume of 15,625 mm^3.

The volume fraction of each constituent was calculated using:

$$V_{matrix} = V_C \times P_{matrix} \tag{2}$$

The corresponding mass of each component was obtained using their respective densities.

The teak powder and epoxy resin were manually mixed for approximately 5–10 minutes until a visually homogeneous mixture was achieved. No chemical surface treatment was applied to the filler, allowing evaluation of the baseline interfacial behavior.

The mixture was then placed into a custom-fabricated steel mold designed to produce flat composite specimens. The mold consisted of top and bottom plates with alignment guides to ensure dimensional consistency and uniform pressure distribution during pressing.

Hot pressing was performed using a hydraulic press at three temperature levels: 160 °C, 170 °C, and 180 °C, with a constant pressure of 20 bar (2 MPa) , as shown in Table 1. These temperatures were selected to enhance resin flow and curing kinetics without causing thermal degradation of the lignocellulosic filler. A constant pressing time of 20 minutes was applied for all specimens to ensure consistent curing conditions and eliminate variability associated with time-dependent curing.

After hot pressing, the mold was allowed to cool under pressure to minimize residual stresses and improve dimensional stability. The composite plates were then removed and machined into tensile specimens according to ASTM D3039 dimensions.

Table 1. Composition ratio and hot press temperature combination of the composite.

% Teak Wood [1] (g)	**% Resin Epoxy and Hardener[2] (g)**	**Hot Press Temperature (°C)**
60	40	160
60	40	170
60	40	180
70	30	160
70	30	170
70	30	180
80	20	160
80	20	170
80	20	180

[1] teak wood density.
[2] resin epoxy density.

2.3. Experimental design

A full factorial experimental design was employed to investigate the influence of processing parameters on the mechanical performance of the composite. Two independent variables were considered, namely the teak wood powder content (60%, 70%, and 80%) and the hot-pressing temperature (160 °C, 170 °C, and 180 °C). Each combination of these variables was replicated three times, resulting in a total of 27 specimens to ensure data reliability and repeatability.

The dependent variables evaluated in this study were tensile strength, expressed in megapascals (MPa), and surface hardness, which represent the mechanical performance of the composite material. To maintain experimental consistency, several parameters were kept constant throughout the study, including the particle size of the teak wood powder (100 mesh), the epoxy resin system and its mixing ratio, the applied pressing pressure (20 bar), and the pressing time (20 minutes). This design allows for a systematic assessment of the effects of composition and temperature on the resulting composite properties.

2.4. Mechanical testing

Tensile testing was conducted using a VTS Universal Testing Machine, Model WDW-50E (manufactured in China), in accordance with ASTM D3039. The tests were performed under controlled laboratory conditions with identical loading parameters for all specimens. Surface hardness was measured using a Digital Universal Hardness Tester. Each combination was tested with multiple samples, and the average value was recorded to improve measurement reliability.

2.5. Data analysis and uncertainty

For each experimental condition, tensile strength and hardness values were averaged from three specimens. The variability of the results was quantified using standard deviation to assess repeatability. Statistical analysis was performed to evaluate the influence of composition and temperature on mechanical performance. Analysis of variance (ANOVA) was used to determine the significance of the processing parameters at a confidence level of 95%.

Potential sources of experimental uncertainty including non-uniform particle distribution during manual mixing, variations in specimen thickness after machining, and instrument precision limits during mechanical testing. Efforts were made to minimize these uncertainties by maintaining consistent processing conditions, using calibrated testing equipment, and applying identical procedures for all samples.

3. Results and Discussion

Tensile testing was conducted in accordance with ASTM D3039 to evaluate the mechanical performance of teak wood powder–epoxy composites under varying composition ratios (60:40, 70:30, and 80:20) and hot-pressing temperatures (160 °C, 170 °C, and 180 °C). The objective of this analysis is to determine the combined effect of composition and processing temperature on tensile strength, and to identify the optimal condition for potential application in CVT weight rollers.

3.1. Tensile strength results

The tensile strength results of teak wood powder–epoxy composites under different processing temperatures are summarized in Table 2. Each condition was tested in triplicate, and the average value is used to represent the material performance.

As shown in Table 2, the tensile strength increases with processing temperature, reaching the highest average value of 24.76 MPa at 180 °C. Although the specimen T07 shows a peak value of 36.06 MPa, this value should be interpreted cautiously due to high variability. The relatively large standard deviation at 180 °C (±9.86 MPa) indicates significant inconsistency in the fabrication process, likely caused by non-uniform mixing, void formation, and uneven resin distribution. The stress–strain behavior of the composite is illustrated in Figure 5, which shows a typical brittle response with limited plastic deformation. The curve indicates that the material undergoes elastic deformation followed by sudden fracture, which is characteristic of particulate-filled thermoset composites.

Referring to Table 2 and Figure 5, an increase in hot-pressing temperature from 160 °C to 180 °C results in improved tensile strength. This improvement can be attributed to enhanced resin flow and curing kinetics at higher temperatures. Elevated temperatures reduce epoxy viscosity, allowing better penetration into the inter-particle spaces of teak powder, thereby improving interfacial bonding.

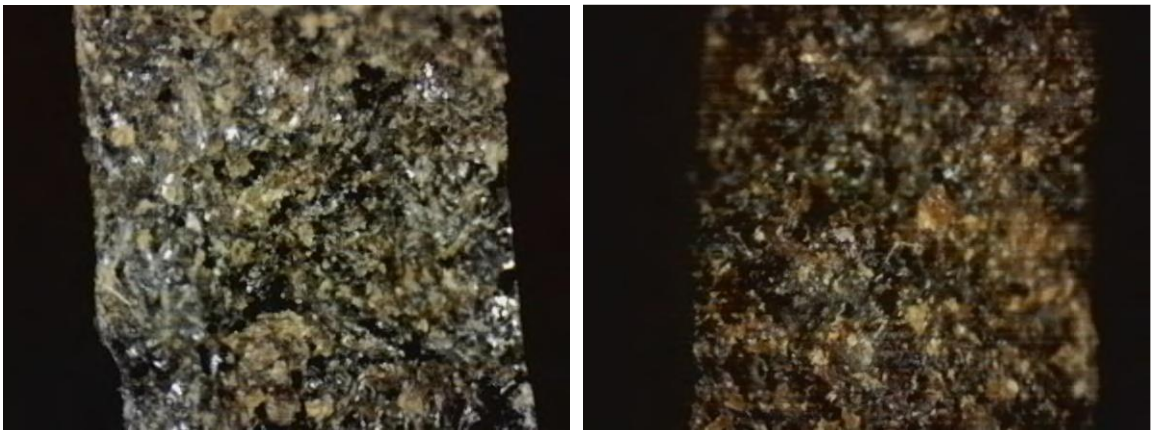
Table 2. Tensile strength of composite specimens at different processing temperatures and composition.

Specimen Code	Weight (g)	Temperature (°C)	Composition (Teak:Epoxy)	Maximum tensile strength (MPa)	Average maximum tensile strength (MPa)
T01.160.1	20.56	160	60:40	20.65	20
T02.160.2	21.12	160	60:40	18.97	
T03.160.3	20.62	160	60:40	20.48	
T04.170.1	18.2	170	60:40	15.07	20.33
T05.170.2	18.61	170	60:40	19.8	
T06.170.3	26.04	170	60:40	25.94	
T07.180.1	26.3	180	60:40	36.06	25
T08.180.2	22.39	180	60:40	18.72	
T09.180.5	22.18	180	60:40	19.51	
T10.160.1	19.5	160	70:30	18.91	20
T11.160.2	21.71	160	70:30	23.46	
T12.160.3	21.8	160	70:30	18.03	
T13.170.1	21.99	170	70:30	24.09	23
T14.170.2	17.04	170	70:30	29.31	
T15.170.3	24.16	170	70:30	16.25	
T16.180.1	19.35	180	70:30	19.23	28.33
T17.180.2	18.8	180	70:30	24.15	
T18.180.3	20.94	180	70:30	12.1	
T19.160.1	18.54	160	80:20	19.05	19.67
T20.160.2	20.56	160	80:20	19.99	
T21.160.3	19.44	160	80:20	20.18	
T22.170.1	19.27	170	80:20	17.94	15.33
T23.170.2	18.87	170	80:20	12.11	
T24.170.3	18.86	170	80:20	16.23	
T25.180.1	19.17	180	80:20	12.3	16.33
T26.180.2	20.76	180	80:20	20.75	
T27.180.3	19.7	180	80:20	16.19	

Additionally, higher temperatures promote a more complete curing reaction of the epoxy matrix, resulting in a stronger crosslinked network. However, the increased variability observed at 180 °C suggests that process control becomes more critical at higher temperatures. Localized overheating or uneven pressure distribution may lead to inconsistent curing and microstructural defects. Although Table 2 focuses on the 60:40 composition, comparison with other tested compositions (70:30 and 80:20) shows that 60:40 consistently provides superior tensile performance. This indicates that sufficient matrix content is essential to ensure effective load transfer.

At higher teak powder content (e.g., 80:20), the epoxy matrix becomes insufficient to fully encapsulate the filler particles. This leads to poor interfacial bonding, increased void formation, and higher stress concentration. As a result, tensile strength decreases significantly. This behavior is consistent with particulate composite theory, where an optimal filler–matrix balance is required to maximize mechanical performance.

The tensile strength obtained in this study (≈25 MPa) is higher than that reported by Reddy et al., who achieved 18.68 MPa for teak-based composites [18]. This improvement suggests that the combination of hot-press processing and optimized composition enhances interfacial bonding and load transfer efficiency. Similarly, Petchwattana et al. demonstrated that teak wood flour composites require improved interfacial compatibility to achieve better mechanical performance [19]. Their work highlights the importance of matrix–filler adhesion, which aligns with the present findings where insufficient resin leads to reduced strength.



(a) (b)

Figure 5. Microstructure of fracture surfaces (50× magnification): (a) specimen no. 8 exhibiting the highest tensile strength, showing a dense structure with darker, glossy regions indicating strong resin bonding; (b) specimen no. 18 exhibiting the lowest tensile strength, showing a lighter wood-dominated surface with a loose structure and evidence of pull-out failure.

Furthermore, Salifu and Olubambi reported that wood-flour composites exhibit improved mechanical properties only when the filler is well-dispersed and properly bonded within the matrix [20]. The results of the present study confirm that excessive filler loading without adequate matrix support leads to performance degradation. The variability observed in Table 2, particularly at 180 °C, indicates that failure is strongly influenced by microstructural heterogeneity. The likely failure mechanisms include; Interfacial debonding, Void-induced crack initiation, and Particle agglomeration. Specimens with better resin distribution exhibit improved cohesion and higher tensile strength, while poorly bonded regions act as crack initiation sites, resulting in brittle fracture behavior as seen in Figure 5.

From an application perspective, the tensile strength achieved in this study exceeds that of conventional PTFE-based CVT rollers (~23 MPa), indicating that teak wood powder–epoxy composites are a promising alternative material. However, tensile strength alone is not sufficient for practical implementation. Additional properties such as wear resistance, friction coefficient, thermal stability, and density, must be evaluated to ensure reliable performance under real CVT operating conditions.

The microstructural observation of the fracture surfaces reveals a clear correlation between composite density, matrix–filler interaction, and tensile performance. As shown in Figure 5(a), the specimen with the highest tensile strength exhibits a relatively dense and compact structure. The darker and more glossy regions indicate well-distributed and properly cured epoxy resin, which enhances interfacial bonding between the teak wood particles and the matrix. This improved bonding facilitates efficient stress transfer, resulting in higher tensile strength. In contrast, Figure 5(b) shows the fracture surface of the specimen with the lowest tensile strength, characterized by a lighter color and a more porous structure dominated by teak wood particles. The reduced presence of epoxy resin leads to insufficient wetting and weak interfacial adhesion. As a result, the composite structure becomes less cohesive, and failure occurs predominantly through a pull-out mechanism, where wood particles are detached from the matrix rather than fractured. This comparison confirms that increasing the teak wood powder content without adequate resin proportion reduces composite integrity. The dominance of pull-out failure in low-strength specimens indicates poor matrix–filler bonding, which is a critical factor limiting mechanical performance in particulate composites.

3.3. Statistical consideration

Statistical analysis using ANOVA was conducted to evaluate the effects of teak wood powder composition and hot-pressing temperature on tensile strength. However, given the relatively limited dataset (three replicates per condition), the statistical interpretation must be approached with caution. In particular, the previously obtained coefficient of determination ($R^2 = 1$) is not physically meaningful and is likely a result of overfitting due to the small number of data points, rather than indicating a true deterministic relationship.

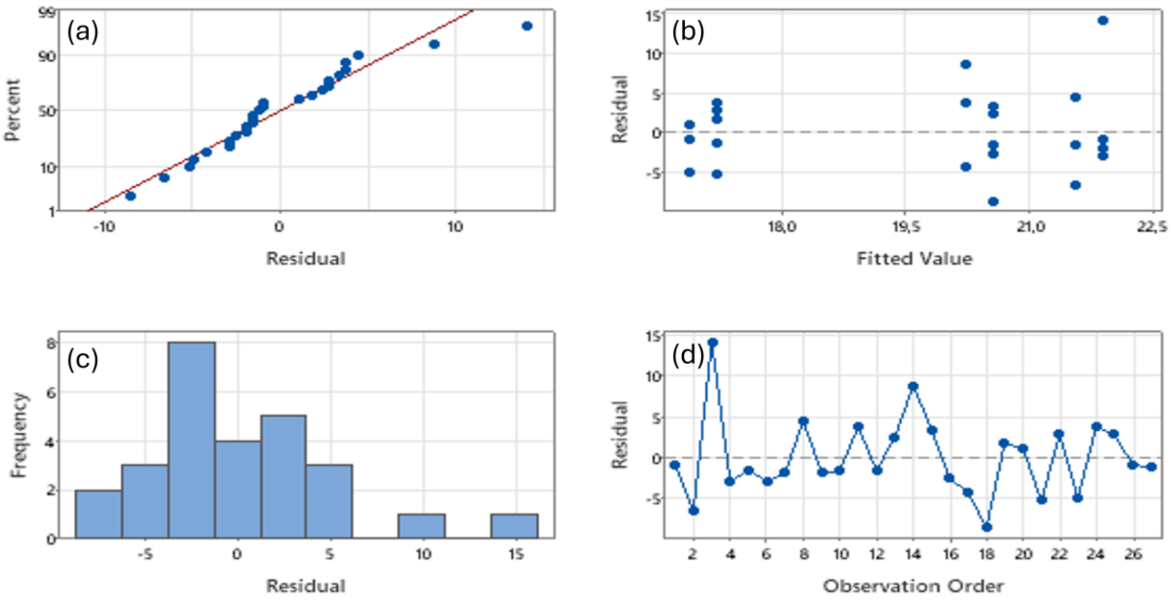


Figure 6. Residual analysis of ANOVA model including (a) normal probability plot, (b) residuals versus fitted values, (c) histogram of residuals, and (d) residuals versus observation order.

To ensure a more reliable interpretation, the analysis emphasizes residual diagnostics and experimental trends rather than relying solely on regression metrics. The residual analysis is presented in Figure 6, which includes the normal probability plot, residuals versus fitted values, histogram, and residuals versus observation order. As shown in Figure 6, the residuals in the normal probability plot follow an approximately linear distribution, indicating that the assumption of normality is reasonably satisfied. This observation is supported by the histogram, which exhibits a near-symmetric distribution centered around zero. Furthermore, the residuals versus fitted values plot shows a random scatter without a discernible pattern, suggesting that the assumption of constant variance (homoscedasticity) is acceptable. The residuals versus observation order plot also indicates no systematic trend, confirming that the data points can be considered independent. These results suggest that the ANOVA model is adequate for identifying general trends in the data, although the limited number of observations restricts the statistical robustness. Therefore, the conclusions derived from this analysis should be interpreted as trend-indicative rather than definitive, and additional experiments with larger sample sizes are recommended for stronger statistical validation.

The effect of teak wood powder composition on tensile strength is illustrated in Figure 7. The results show that tensile strength decreases as the teak powder content increases beyond the optimal composition. The highest tensile strength is observed at the 60:40 composition, indicating that sufficient epoxy matrix is essential to ensure effective particle wetting and load transfer.

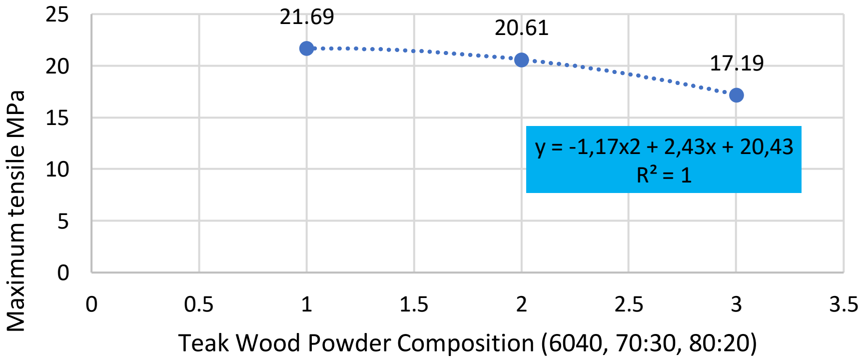


Figure 7. Effect of teak wood powder composition on tensile strength (average values across temperatures).

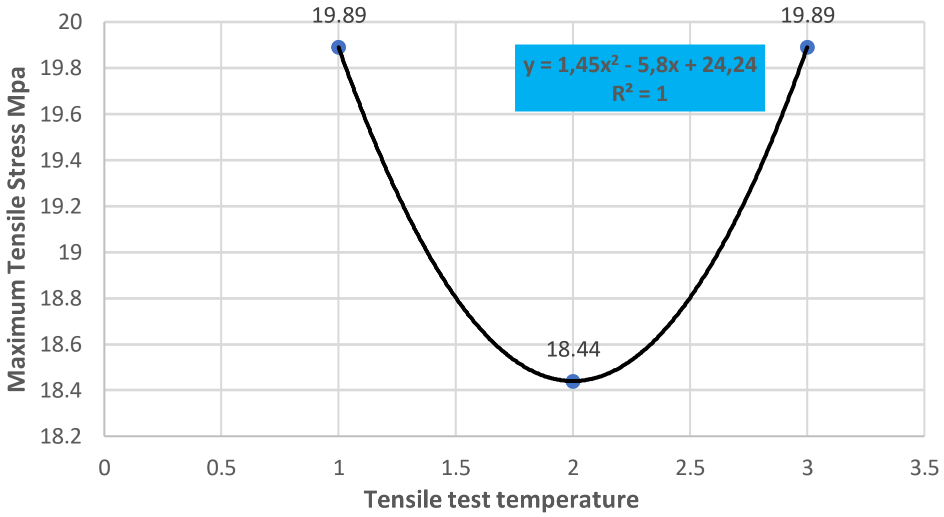


Figure 8. Effect of hot-pressing temperature on tensile strength (average values across compositions).

Although a quadratic regression curve is fitted to the data, the apparent perfect fit (R^2 = 1) should not be interpreted as a physically accurate model. Instead, the curve serves only as a visual representation of the observed trend.

Similarly, the influence of processing temperature on tensile strength is presented in Figure 8. The results indicate a non-linear relationship, with the lowest tensile strength observed at 170 °C, and higher values at 160 °C and 180 °C. The improvement at 180 °C is attributed to enhanced resin flow and curing behavior, which promote stronger interfacial bonding between the matrix and filler. However, the non-monotonic trend suggests that temperature effects are governed by competing mechanisms, including improved consolidation and potential process-induced variability. It is important to emphasize that the regression equation obtained for temperature (e.g., $y = 1.45x^2 - 5.8x + 24.24$, R^2 = 1) should not be interpreted as a perfect predictive model. Instead, it represents a mathematical fit to a limited dataset and does not fully capture the physical complexity of the system.

From the experimental results, the specimen with a 60:40 composition processed at 180 °C achieved the highest average tensile strength of approximately 25 MPa, which is slightly higher than that of conventional PTFE-based weight rollers (~23 MPa). This improvement can be attributed to better resin distribution and stronger interparticle bonding at higher temperatures. Conversely, at a higher teak powder content (80:20), tensile strength decreases significantly, particularly at lower temperatures, due to insufficient resin acting as a binder and the increased likelihood of void formation and weak interfacial adhesion.

4. Conclusion

This study demonstrates that teak wood powder–epoxy composites fabricated using the hot-press method exhibit promising mechanical performance for potential application in CVT weight rollers. The results confirm that both composition ratio and processing temperature significantly influence tensile strength and overall material integrity. The key finding of this research is that the optimal condition—60% teak wood powder and 40% epoxy resin, processed at 180 °C under 20 bar pressure—produced the highest average tensile strength of approximately 25 MPa. This value exceeds the typical tensile strength of conventional PTFE-based CVT rollers (~23 MPa), indicating that the developed composite is mechanically competitive. The improved performance is attributed to enhanced matrix–filler bonding, better resin flow at elevated temperatures, and sufficient matrix content to ensure effective load transfer and reduced void formation. From a design perspective, the results highlight that matrix continuity and processing temperature are critical parameters in achieving high-performance particulate composites. Excessive teak powder content (e.g., 80:20 composition) leads to reduced tensile strength due to insufficient resin for proper particle encapsulation, increased porosity, and weak interfacial bonding. Therefore, an optimal balance between filler and matrix must be maintained to achieve both mechanical performance and material sustainability. In addition to mechanical performance, the use of teak wood waste as reinforcement offers significant environmental and economic advantages, including reduced dependence on synthetic materials and improved resource utilization. This supports the development of more sustainable material solutions in automotive component design. However, it is important to note that tensile strength alone is not sufficient to fully validate the suitability of the material for CVT applications. Future work should focus on evaluating tribological performance (wear resistance and friction behavior), thermal stability, density optimization, and long-term durability under cyclic loading conditions. Furthermore, improvements in processing techniques—such as enhanced mixing methods, filler surface treatment, or the use of coupling agents—should be explored to reduce variability and further enhance interfacial bonding. This study establishes teak wood powder–epoxy composites as a viable and sustainable alternative material, while also providing a foundation for further optimization and application in engineering systems.

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