International Journal of Innovation in
Mechanical Engineering and Advanced Materials
Vol. 7 (No. 1), 2025, pp. 32-42
Journal homepage: publikasi.mercubuana.ac.id/index.php/ijimeam
DOI: 10.22441/ijimeam.v7i1.31092

Effect of Coconut Fiber and Coconut Shell Charcoal Composition on the Properties of PVC- Reinforced Composite Brake Pads

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Abstract

The increasing concern over the health hazards associated with asbestos-based brake pads has driven the development of eco-friendly alternatives using natural fiber-reinforced composites. This study aims to fabricate and evaluate a sustainable brake pad material using coconut fiber as reinforcement, coconut shell charcoal powder as filler, and polyvinyl chloride (PVC) as the matrix. The composite was manufactured using the hot press method at a temperature of 180°C and a pressure of 7 MPa, conditions selected to optimize resin curing and interfacial bonding. A key focus of this research was to investigate the effect of solvent volume (cyclohexanone) used in the PVC resin preparation on the mechanical properties of the resulting composites. Three composite formulations were prepared with a constant composition of 70% coconut fiber, 5% charcoal powder, and 25% PVC resin, but with varying amounts of cyclohexanone solvent (200 mL, 150 mL, and 100 mL). The results revealed that reducing solvent content led to higher resin viscosity, which improved matrix–fiber bonding and increased both tensile strength and surface hardness. The optimal formulation—PVC Resin 3 with 100 mL of solvent—achieved a maximum tensile strength of 7.7 MPa and Shore D hardness of 72.2 HD, both of which meet the SAE J661-1997 standards for brake pad materials. This study confirms that solvent content is a critical factor influencing the density, strength, and durability of the composite. The findings support the feasibility of utilizing coconut-based agricultural waste in producing environmentally friendly brake pads with adequate mechanical performance.

Article Info:
Received: 29 November 2024
Revised: 27 February 2025
Accepted: 8 March 2025
Available online: 5 April 2025

Keywords:
Composite; coconut fiber; coconut shell charcoal; PVC; hot press; brake pad

1. Introduction

The braking system plays a critical role in every motor vehicle, as it directly affects driving safety. As vehicle speed increases, the need for an effective and reliable braking system becomes even more essential [1]. Among the key components responsible for reducing or halting vehicle motion is the brake pad [2]. Traditionally, brake pads have been manufactured using asbestos as a reinforcing material and resin as a binder [3]. However, asbestos poses significant health risks. The dust it generates during wear is toxic and can be inhaled by drivers and nearby individuals. Furthermore, asbestos is known to be carcinogenic, which endangers both end-users and workers in the brake pad manufacturing industry [4], [5].

Due to these health hazards, the development of non-asbestos brake pads with comparable or superior tribological and mechanical properties has become necessary [3]. A promising alternative involves the use of biocomposite materials reinforced with natural fibers [2]. In addition to being environmentally friendly, natural fiber composites offer several advantages such as lower weight, improved strength and durability, as well as resistance to corrosion and wear [6].

This study focuses on utilizing coconut fiber waste and coconut shell charcoal powder as filler materials for the development of non-asbestos brake pads. Coconut fiber waste is abundantly available and often underutilized, despite its high tensile strength and impact resistance [7]. Previous studies have explored coconut fiber-reinforced composites with epoxy resin matrices, fabricated using a conventional cold-press method. However, the resulting brake pads did not meet the performance requirements established by the Indonesian National Standard [4].

How to cite:

A. Pandriana, Kurniawan, and S. Alva, "Effect of coconut fiber and coconut shell charcoal composition on the properties of PVC- reinforced composite brake pads," *Int. J. Innov. Mech. Eng. Adv. Mater*, vol. 7, no. 1, pp. 32-42, 2025

To address these shortcomings, this research proposes modifications to both the reinforcement and fabrication method. First, the coconut fibers will be cut into smaller, uniformly sized segments. This approach is expected to produce a denser and more homogeneous composite structure, thereby improving mechanical performance [8]. Supporting studies have demonstrated that shorter fiber lengths in banana fiber and water hyacinth composites contribute to higher hardness and increased torsional strength, respectively [9], [10].

Second, the fabrication process will transition from a cold-press to a hot-press molding method. Heat-assisted pressing is known to enhance the curing of the binder, which leads to stronger interfacial bonding within the composite [8]. Additionally, this study will replace the epoxy resin matrix with polyvinyl chloride (PVC) resin. PVC offers excellent chemical resistance, superior strength, and higher stiffness compared to many other thermoplastics. Its tensile strength ranges from 40 to 60 MPa, far exceeding the tensile strength requirements for brake pads defined by SAE J661-1997 (4.8 to 15 MPa) [11], [3]. Previous research utilizing PVC resin in wood-powder-based composites through hot pressing has achieved tensile strengths between 11 and 14.5 MPa [12].

Based on this background, the present study aims to develop a non-asbestos brake pad composite using coconut fiber and coconut shell charcoal powder as reinforcements, combined with PVC resin as the matrix and fabricated via the hot press method. The objective is to improve the mechanical properties and meet established performance standards for safe and sustainable braking applications.

2. Methods

This research employed an experimental method to develop composite brake pad materials using coconut fiber, coconut shell charcoal powder, and polyvinyl chloride (PVC) as the matrix. The process involved preparing the raw materials in specific compositions, fabricating test specimens using molds of predetermined dimensions, and conducting mechanical testing to evaluate their performance.

The study began with the preparation of tools and materials, including natural fibers, fillers, and the PVC resin. The raw coconut fibers were cut into shorter lengths to improve mixture density and homogeneity. These materials were then mixed and compacted using the hot press method to form composite specimens suitable for tensile and hardness testing.

Once the specimens were fabricated, they were examined for conformity with dimensional and structural requirements. If the specimens did not meet the specified criteria, the fabrication process was repeated. Conforming specimens were then subjected to tensile and hardness tests to assess their mechanical properties.

The results from both tests were analyzed to evaluate the performance of the composite materials. The findings were interpreted and discussed in relation to previous studies and relevant standards. The research concluded with a summary of observations and recommendations for further development.

2.1. Manufacturing and testing instrumentation

The fabrication of the composite materials in this study involved a series of specialized instruments to ensure consistent processing and compliance with testing standards. The mixing process was carried out using a JLabTech LMS-2003D hot plate stirrer, which was employed to blend cyclohexanone solvent and PVC powder at a controlled temperature, resulting in a homogeneous PVC resin solution.

For specimen molding, a custom-designed mold fabricated from SS400 steel was used, tailored to match the dimensions specified in relevant mechanical testing standards. The composite forming process was performed using a TEFA-brand hot press machine, a hydraulic device capable of applying a maximum pressure of 7 MPa. This machine applied both heat and pressure to consolidate the composite mixture into a solid structure.

To evaluate the mechanical properties of the fabricated composites, two primary tests were conducted. Tensile strength testing was performed using a Universal Testing Machine (UTM) by VTS, rated with a maximum load capacity of 5 kN, and operated in accordance with ASTM D3039 standards. This test assessed the composite's ability to resist axial tensile loads.

Surface hardness testing was carried out using a Shore D durometer with a measurement accuracy of ±0.5 HD, following the procedures outlined in ASTM D2240. This test determined the material's resistance to indentation and permanent deformation.

The use of standardized equipment, as shown in Figure 1, ensured the reliability, repeatability, and validity of the experimental results, allowing for an accurate assessment of the developed composite's mechanical performance.

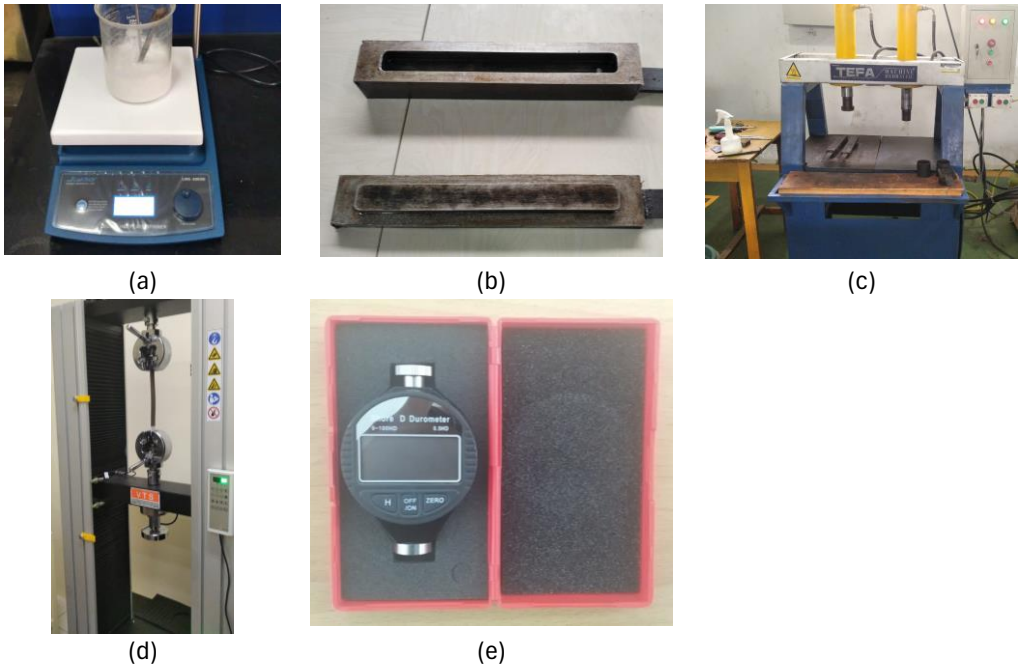

Figure 1. Experimental equipment; (a) Hot plate stirrer, (b) Composite molding, (c) Hot press machine, (d) Universal testing machine for tensile test, (e) Durometer shore D for hardness test

2.2. Material preparation

The composite materials used in this study consist of coconut fiber as reinforcement, coconut shell charcoal powder as filler, and polyvinyl chloride (PVC) as the matrix. The solvent used to dissolve the PVC powder and form the resin is cyclohexanone.

To ensure uniform distribution within the matrix, the coconut fiber was cut into 5 mm lengths. This fiber size enhances dispersion throughout the composite mixture, contributing to better mechanical integrity. The coconut shell charcoal powder was processed by sieving through a 200-mesh screen, resulting in a fine particle size suitable for use as filler, promoting better particle–matrix bonding.

The PVC resin preparation process began by pouring a specific amount of cyclohexanone into a glass measuring cup. This mixture was heated using a hot plate stirrer (JLabTech LMS-2003D) at a minimum temperature of 40°C [13]. Once the desired temperature was reached, 20 grams of PVC powder was gradually added into the solvent. The mixture was continuously stirred until a homogeneous and transparent solution was formed, indicating that the PVC had completely dissolved. The prepared PVC resin was then transferred into glass bottles for storage and later used in composite fabrication.

Figure 2 illustrates the material preparation flow, starting from the cutting and sieving of raw materials to the formulation of the PVC resin. The process ensures that all components are properly conditioned before the molding phase.

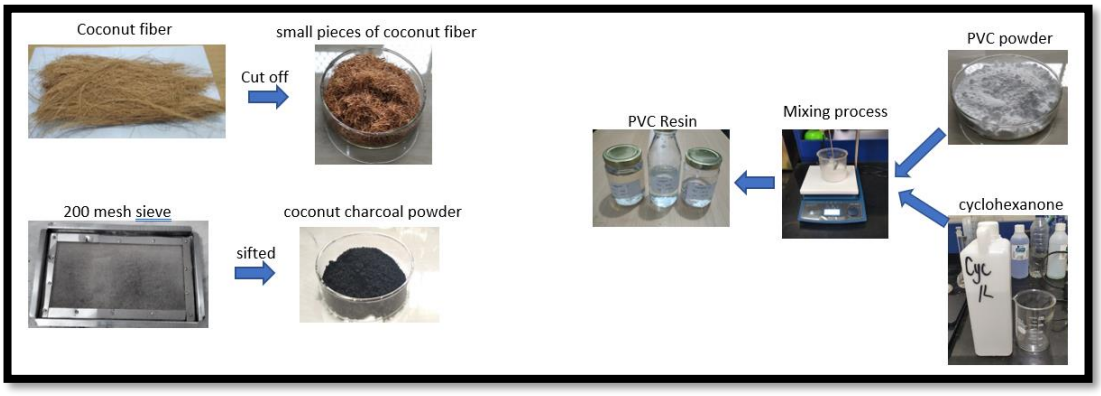

Figure 2. Process flow for preparing composite materials

Table 1. Various PVC resin mixtures

PVC Resin Mixture	PVC Powder (g)	Cyclohexanone (ml)	Cyclohexanone Mass (density 0,936 g/ml) (g)	Total Mass of Mixture (g)	PVC Resin Density (g/ml)
PVC Resin 1	20	200	187.2	207.2	1.036
PVC Resin 2	20	150	140.4	160.4	1.069
PVC Resin 3	20	100	93.6	113.6	1.136

Additionally, three PVC resin formulations were prepared by varying the amount of cyclohexanone added to the fixed 20-gram PVC powder base. These variations were designed to explore the effect of resin density and viscosity on the composite's mechanical and tribological properties. Cyclohexanone, as the solvent, plays a critical role in achieving resin homogeneity, which directly influences the wetting, bonding, and distribution of the reinforcement and filler materials.

The variation in cyclohexanone volume affects the total mass and density of the PVC resin, which in turn is expected to impact the resulting composite's tensile strength, hardness, and wear resistance. Investigating these variations is essential for identifying the optimal formulation that yields brake pad materials with the desired performance and compliance with mechanical standards.

2.3. Composite specimen preparation

The preparation of composite specimens required precise composition calculations to determine the proportions of reinforcement (coconut fiber), filler (coconut shell charcoal powder), and matrix (PVC resin) [14]. These calculations began by determining the volume of the mold, as outlined in Equation (1):

$$V_c = P \times L \times T \quad (1)$$

Where:
V_c = Volume of mold (cm^3)
P = Length of specimen (cm)
L = Width of specimen (cm)
T = Thickness of specimen (cm)

Once the mold volume was determined, the volume fractions for each composite component were calculated using the following equations:
Fiber volume

$$V_s = V_c \times P_s \quad (2)$$

Filler volume

$$V_f = V_c \times P_f \quad (3)$$

Matrix volume

$$V_m = V_c \times P_m \quad (4)$$

Where:
V_s, V_f, V_m = Volume of fiber, filler, and matrix respectively (cm^3)
P_s, P_f, P_m = Percentage of fiber, filler, and matrix in the composite

After determining the volume fractions, the density of each component was used to calculate the corresponding mass, using Equation (5) [15]:

$$\rho = m/v \quad (4)$$

Where:
ρ = Density of the substance (g/cm^3)
m = Mass of the substance (g)
v = Volume of the substance (cm^3)

With all mass values determined, the fabrication process proceeded with heating the mold to 180°C using a TEFA-brand hot press machine. This temperature was selected based on prior studies

using teak wood powder composites, where 180°C was found to optimize resin curing and bonding strength [16].

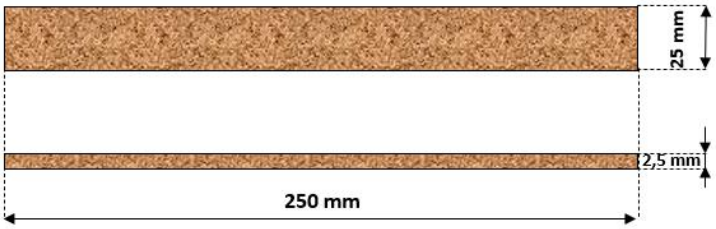

Figure 3. ASTM D 3039 tensile test specimen dimension

Next, the materials — PVC resin, finely cut coconut fibers (5 mm), and coconut shell charcoal powder (200-mesh) were mixed according to the predetermined proportions. The mixture was manually stirred for 5 minutes to ensure even distribution of all components.

Once the mold reached the target temperature, the homogeneous mixture was poured into the mold cavity, which had been designed in accordance with standard specimen dimensions (see Figure 3). The mold was then sealed, and a pressure of 7 MPa was applied using the hot press machine. This pressure was selected based on machine capability and supported by literature findings that increased pressure improves composite hardness and compaction [4], [16]. While previous studies employed pressures ranging from 2.4 MPa (200–350 psi), this study applied a higher pressure to enhance mechanical performance.

The pressing duration was set to be 60 minutes, as preliminary tests showed that durations below this threshold resulted in incomplete drying and suboptimal specimen quality due to insufficient curing of the PVC matrix.

To investigate the effect of resin formulation, three variations of PVC–cyclohexanone mixtures were prepared by maintaining a fixed PVC powder mass (20 g) and altering the volume of solvent. These variations were aimed at evaluating the influence of matrix viscosity and density on the mechanical and tribological behavior of the brake pad composites.

2.4. Testing preparation and equipment setup

To evaluate the mechanical properties of the fabricated composite brake pad specimens, tensile and hardness tests were conducted in accordance with standardized testing procedures.

Tensile testing was performed following the ASTM D3039 standard, which is commonly used for assessing the tensile properties of polymer matrix composites. Specimens were prepared based on the standard dimensions specified in ASTM D3039, which are critical to ensuring accurate and consistent test results. The width and thickness of the specimens were selected according to the guideline to ensure appropriate failure modes and reliable statistical representation of material behavior under axial loading. These dimensional parameters directly influence both the structural response and material strength outcomes during the tensile test [17].

Hardness testing was carried out using the Shore D durometer method, following the ASTM D2240 standard, as shown in Figure 4. This standard specifies that specimens must have a minimum thickness of 6 mm, a minimum distance of 12 mm from any edge, and a flat, parallel surface. These conditions ensure accurate measurement by allowing the durometer's presser foot to make full contact with the specimen surface within a radius of at least 6 mm from the indenter. Proper specimen preparation minimizes boundary effects and ensures that hardness measurements reflect the true material characteristics rather than localized variations or geometric artifacts [18].

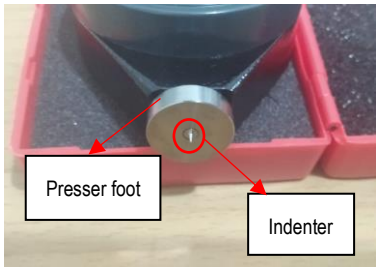

Figure 4. Presser foot and indenter configuration for Shore D hardness testing

3. Results and Discussion

3.1. Determination of specimen composition

In this research, the author conducted an initial experiment to determine the optimal composition by creating three test specimens with composition variations.

Table 2. Composition variations

Composition	Coconut Fiber	Charcoal Powder	PVC Resin
Composition A	70%	5%	25%
Composition B	60%	10%	30%
Composition C	50%	15%	35%

In Composition A (70% coconut fiber, 5% charcoal powder, 25% PVC resin), the composite exhibited the highest density and rigidity among the three formulations. The elevated fiber content enhanced the tensile strength and stiffness of the material, while the resin content was sufficient to ensure good bonding without sacrificing structural integrity. Visually, Composition A appeared denser and more uniform, indicating a well-integrated matrix.

Composition B (60% coconut fiber, 10% charcoal powder, 30% PVC resin) demonstrated a more flexible nature due to the reduced fiber reinforcement and increased matrix content. Although the increased PVC resin improved the composite's viscoelastic properties, the reduced fiber content negatively affected mechanical strength. As illustrated in Figure 5, a visible fracture occurred in the specimen during demolding, indicating reduced reinforcement capability and lower structural strength.

In Composition C (50% coconut fiber, 15% charcoal powder, 35% PVC resin), the specimen displayed the highest degree of flexibility, attributed to the lowest fiber content and highest matrix content. The increase in resin enhanced elasticity but further diminished the composite's stiffness. The specimen's appearance, as shown in Figure 5, suggests a more pliable material with limited load-bearing capacity.

These observations are consistent with prior research findings. For instance, a study utilizing 74% reinforcement and 26% binder in brake pad composites recorded a hardness of 25.1 BHN, which matched that of a commercial RCA brake pad [16]. Similarly, another study using 70% sugarcane bagasse and 30% resin achieved a hardness of 100.5 BHN, indicating the suitability of a high-fiber formulation for effective braking applications [19].

Based on the comparative analysis and mechanical behavior of the specimens, Composition A—comprising 70% coconut fiber, 5% coconut shell charcoal powder, and 25% PVC resin—was identified as the optimal formulation. This composition offers a favorable balance between strength, hardness, and structural integrity, making it suitable for further mechanical testing and brake pad application.

Composition A Composition B Composition C

Figure 5. Composite test specimens with composition variations

(a) (b)

Figure 6. (a) Tensile test specimen, (b) Hardness test specimen

3.2. Solvent effect

Solvents play a crucial role in composite fabrication, particularly during the preparation of the matrix phase. In this study, cyclohexanone was used as the solvent to dissolve PVC powder, enabling the formation of a homogenous PVC resin. A well-dissolved resin ensures uniform dispersion of reinforcement (coconut fiber) and filler (coconut shell charcoal powder), which is essential for achieving optimal bonding and mechanical performance.

However, the volume of solvent used during the resin preparation process can significantly influence the physical and mechanical properties of the resulting composite. An excess of solvent may lead to a lower matrix density and weaker interfacial bonding, while insufficient solvent can result in poor resin flow, leading to inadequate wetting and void formation within the composite.

To evaluate the effect of solvent content, a tensile test was conducted on specimens with a fixed composite composition—70% coconut fiber, 5% charcoal powder, and 25% PVC resin—but with varying amounts of cyclohexanone used in the resin preparation stage. The objective was to determine how differences in solvent volume affected the maximum stress the composites could withstand under tensile loading.

As shown in Figure 7, the tensile testing setup was used to assess the strength characteristics, while visual inspection of the punctured specimen revealed the failure modes and integrity of the matrix-fiber bonding. Differences in fracture appearance across specimens further supported the influence of solvent variation on material behavior.

(a) (b)

Figure 7. (a) Tensile test in progress, (b) Fractured specimen after testing

Table 3. Tensile test results

Specimen	Maximum Stress (MPa)	Average (MPa)	PVC Resin Density (g/ml)
PVC Resin 1	5	4.3	1.036
	5		
	3		
PVC Resin 2	5	5.7	1.069
	8		
	4		
PVC Resin 3	7	7.7	1.136
	8		
	8		
SAE J661- 1997	4.8 - 15	-	-

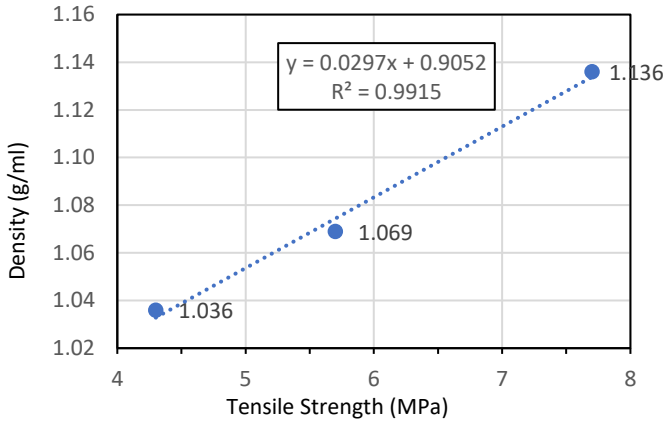

Figure 8. Solvent effect between density of PVC resin and tensile strength

To investigate the influence of solvent volume on composite performance, tensile tests were conducted on three specimens—each with a fixed composition of 70% coconut fiber, 5% coconut shell charcoal powder, and 25% PVC resin, but with varying volumes of cyclohexanone solvent used in the resin formulation.

In PVC Resin 1 (20 grams of PVC powder with 200 mL of cyclohexanone), the tensile test revealed a maximum stress (Rm) of 4.3 MPa. This lower tensile strength is attributed to the excessive solvent content, which resulted in a more diluted resin. The reduced resin viscosity decreased the bonding strength between the matrix and reinforcing materials, leading to a less compact and mechanically weaker composite.

In PVC Resin 2 (20 grams of PVC powder with 150 mL of solvent), the maximum stress increased to 5.7 MPa. The reduced solvent volume led to a thicker resin consistency, allowing for improved fiber wetting and bonding. This enhanced the interfacial adhesion between the matrix, fiber, and filler, yielding a denser composite structure with greater resistance to tensile loads.

The best result was achieved with PVC Resin 3 (20 grams of PVC powder with 100 mL of solvent), which recorded a maximum tensile stress of 7.7 MPa. The lower solvent volume produced a highly viscous resin that effectively encapsulated the fibers and fillers, creating stronger matrix-fiber bonding. As a result, this composition demonstrated superior mechanical integrity and tensile performance.

These findings highlight the critical role of solvent volume in determining the mechanical strength of the composite. As shown in Figure 9, there is a clear trend of increasing tensile strength with decreasing solvent content. Importantly, the tensile strength of PVC Resin 3 (7.7 MPa) satisfies the minimum requirement set by the SAE J661-1997 standard (4.8–15 MPa) for brake pad materials [3]. Although further refinement may be necessary to achieve values closer to the upper limit of the standard, PVC Resin 3 represents the most promising formulation for practical applications.

In addition to tensile testing, the Shore D hardness test was conducted to evaluate the surface hardness of the composite specimens. This test measures the material's resistance to permanent surface deformation when subjected to compressive force. The hardness of the composite is an important parameter in brake pad applications, as it reflects the ability of the material to maintain its shape under pressure, resist wear, and endure friction during braking operations.

The results of the hardness test, combined with tensile strength data, offer a comprehensive understanding of how solvent content in PVC resin affects the mechanical and tribological performance of natural fiber-reinforced composites.

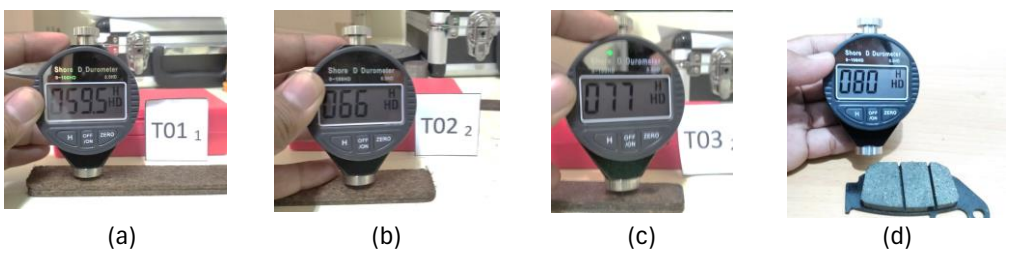

Figure 9. Hardness test of composites with varying solvent volumes; (a) composition A, (b) Composition B, (c) Composition C, (d) Factory brake pad

Table 4. Hardness Shore D test results

PVC Resin	Hardness Shore D (HD)		PVC Resin Density (g/ml)
	Test Result	Average	
PVC Resin 1	59.5 58.5 55	57.7	1.036
PVC Resin 2	66 66 67.5	66.5	1.069
PVC Resin 3	69.5 77 70	72.2	1.136
Factory brake pad	75.5 77 80	77.5	-
SAE J661- 1997	68 – 105 (Rockwell R) 66 – 88 (Shore D)		-

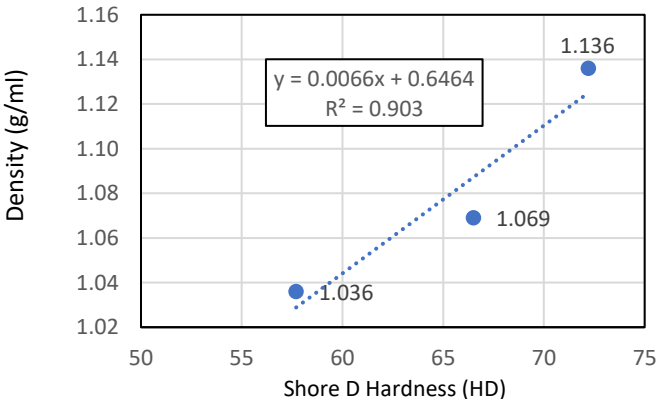

Figure 10. Comparison of Shore D hardness values for composites with different solvent volumes

To complement the tensile strength analysis, Shore D hardness testing was conducted on composite specimens prepared using varying amounts of solvent in the PVC resin formulation. The objective was to assess how solvent content affects the surface hardness of the composite material, which is a critical parameter in brake pad applications where resistance to surface deformation and wear is essential.

In PVC Resin 1 (20 grams of PVC powder with 200 mL of cyclohexanone), the average Shore D hardness value obtained was 57.7 HD. This relatively low hardness is attributed to the high solvent content, which produced a thin and less viscous resin. As a result, the composite structure was less compact, and the bonding between the coconut fiber, charcoal powder, and PVC matrix was weaker. This led to a softer composite with inferior resistance to indentation and mechanical stress.

For PVC Resin 2 (20 grams of PVC powder with 150 mL of solvent), the Shore D hardness increased to 66.5 HD. The reduced solvent volume resulted in a more viscous resin, which allowed better encapsulation of the reinforcing and filler materials. This created a denser and stronger matrix, improving the composite's ability to resist deformation under compressive loads. The increase in hardness indicates improved structural integrity compared to PVC Resin 1.

The highest hardness was recorded in PVC Resin 3 (20 grams of PVC powder with 100 mL of solvent), achieving 72.2 HD. The lower solvent content led to a high-viscosity resin that significantly enhanced interfacial bonding between the matrix and reinforcement components. This produced a highly compact and rigid composite structure, resulting in the best performance among the three tested variations.

When compared to the SAE J661-1997 brake pad hardness standard—ranging from 68 to 105 Rockwell R, which is approximately 66 to 88 Shore D [20], [21], —the results indicate the following:

- PVC Resin 1 (57.7 HD) falls below the minimum threshold, making it unsuitable for brake pad applications due to insufficient surface hardness.
- PVC Resin 2 (66.5 HD) reaches the lower limit of the acceptable range, suggesting potential for application but requiring further optimization for mechanical enhancement.
- PVC Resin 3 (72.2 HD) meets the SAE J661-1997 hardness standard, making it a viable candidate for brake pad materials, with both sufficient rigidity and wear resistance.

These findings confirm that reducing solvent volume in PVC resin not only enhances tensile strength but also improves surface hardness, which are both essential attributes for high-performance composite brake pads.

4. Conclusions

The results of this study demonstrate that the amount of solvent used in PVC resin preparation significantly influences the mechanical performance of coconut fiber-based composite materials. The tensile strength of the composites increased as the solvent volume decreased, due to the formation of a more viscous resin that enhanced interfacial bonding between the matrix, fiber, and filler. Among the tested formulations, PVC Resin 3 (20 grams of PVC powder and 100 mL of cyclohexanone) achieved the highest tensile strength of 7.7 MPa, meeting the SAE J661-1997 standard (4.8–15 MPa). This composition is therefore the most promising for brake pad applications, although further optimization may be required to approach the upper limit of the standard and improve mechanical reliability. The Shore D hardness test also confirmed that lower solvent content leads to a denser, harder composite. PVC Resin 3 recorded the highest hardness value of 72.2 HD, which falls within the SAE J661-1997 standard range of 66–88 HD, making it the most viable candidate among the three compositions. Nevertheless, commercial brake pads, particularly for high-performance applications, often require hardness levels near the upper limit of this standard. Future studies should assess the composite's behavior under extended thermal and mechanical stress to verify its long-term durability. This research contributes to the development of environmentally friendly brake pad materials by utilizing natural fibers (coconut fiber) and biomass waste (coconut shell charcoal powder) as sustainable alternatives to asbestos, reducing the health and environmental risks associated with conventional friction materials. The findings confirm that natural fiber-reinforced composites, when combined with an optimized PVC matrix, can meet basic industrial performance requirements. However, for real-world implementation, further material optimization is needed, particularly in terms of thermal stability and heat dissipation under prolonged braking, wear resistance over extended usage cycles, and the environmental lifecycle assessment of the composite compared to traditional brake pad materials. Future research should focus on refining the composite formulation, conducting performance testing under actual braking conditions, and evaluating sustainability metrics to support commercialization and regulatory acceptance.

Acknowledgements

The authors would like to express their sincere gratitude to Universitas Mercu Buana, especially the Master Program in Mechanical Engineering, for providing the laboratory facilities and academic support essential to the success of this research. Special thanks are also extended to SMKN 7 Tangerang Regency for their valuable assistance in facilitating the material preparation and experimental testing processes. We are equally thankful to the entire research team for their dedication, collaboration, and commitment in method development, data collection, and analysis throughout the study.

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