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Investigation on hardness and microstructural behavior of mahogany–brass reinforced bio-composite brake pads under varying compaction pressure

Fatkhurrohman*, Rizqa Ruviana, Musyaroh, Anisah Nurul Izzah
Mechanical Engineering Study Program, Universitas Pembangunan Nasional Veteran Jawa Timur, Surabaya 60294, Indonesia
*Corresponding author: fatkhurrohman.ft@upnjatim.ac.id

Abstract

The gradual elimination of asbestos in brake pad manufacturing has intensified the search for sustainable and non-toxic friction materials. This study presents waste-based bio-composite brake pads reinforced with mahogany sawdust and brass shavings, fabricated using a compaction-sintering approach. The scientific novelty of this study lies in the combined influence of reinforcement composition and compaction pressure on the microstructure-hardness relationship of wood-metal hybrid composites for brake pad applications. The effects of varying mahogany-to-brass ratio and compaction pressure on Shore D hardness and morphological characteristics were systematically evaluated. The results showed that increasing compaction pressure and reinforcement proportion improved composite densification and interfacial bonding, thereby increasing hardness. Increased hardness indicates better structural integrity and load-bearing capacity, which are important mechanical requirements for brake pad materials. The highest hardness value of 76.6 Shore D was obtained at a pressure of 3400 psi with a 4:4 composition, while the lowest value of 70.6 Shore D occurred at 3000 psi with a 1:4 ratio. These findings highlight the role of controlled compaction and balanced hybrid reinforcement in tailoring the mechanical characteristics of sustainable brake pad composites, supporting the potential utilization of wood and metal waste as environmentally friendly friction material components.

Keywords:
Hardness Shore D, bio-composite brake pad, mahogany sawdust, brass shavings, compaction-sintering.

1 Introduction

Brake pads are a critical safety component in vehicles [1][2], and are subjected to repeated mechanical loads and thermal stress during braking [3][4]. The growing demand for automotive components has increased the need for durable and environmentally friendly friction materials [5][6]. Following global restrictions on asbestos due to its serious health risks [7][8], extensive research has focused on developing safer and more sustainable alternatives for brake pad applications.

Composite materials present a promising alternative to asbestos as the primary raw material for brake pad manufacturing [9]. Among these, biodegradable composites or bio-composites offer considerable potential for sustainable brake pad applications by combining natural fibers with environmentally compatible metallic constituents [10]. Mahogany sawdust, a lignocellulosic by product generated by the wood processing and furniture industries, is frequently underutilized or improperly disposed of, leading to environmental concerns [11]. Owing to its cellulose, hemicellulose, and lignin content, mahogany sawdust can enhance interparticle bonding, improve intermolecular adhesion, and reduce moisture diffusion within composite structures [12][13]. In parallel, brass, a copper–zinc alloy, provides high mechanical strength, corrosion resistance, and hardness (approximately 200 HB), enabling strong resistance to surface deformation under load [14]. Its favorable wear characteristics and stability under repeated frictional contact make it a suitable non-ferrous constituent for brake pad systems operating under demanding mechanical and thermal conditions [15][16].

Bio-composites reinforced with natural fibers and industrial byproducts have emerged as promising candidates [17][18]. Various agricultural wastes, including coconut shell powder [19], palm fiber [20], and other lignocellulosic materials, have been incorporated into brake pad formulations with encouraging mechanical and tribological results [21]. These studies demonstrate that natural reinforcements can partially replace conventional constituents while supporting sustainability goals. However, most previous studies have focused primarily on single organic fillers, with limited attention paid to hybrid systems combining wood-based biomass and metal waste. Furthermore, the microstructure-hardness relationship in such hybrid composites, particularly under varying compaction pressures, remains largely unstudied.

Mahogany sawdust is an abundant lignocellulosic waste with potential as a biodegradable reinforcement, while brass shavings, a waste product from machining processes, offer high hardness and mechanical stability. Integrating both into a hybrid composite system can provide a balanced combination of structural reinforcement and load-bearing capacity. However, the effect of reinforcement ratio and compaction pressure on composite densification and hardness characteristics has not been systematically studied for this material combination. Previous studies reported Shore D hardness values of approximately 60 Shore D for brake pads reinforced with coconut shell dust and bamboo fiber [22]. This study can be used as a comparison due to the use of the same reinforcing material derived from bio-reinforcement and the resulting hardness of the brake pads.

Therefore, the objective of this study was to investigate the combined effects of mahogany sawdust-brass composition and compaction pressure on the microstructural characteristics and hardness of sustainable bio-composite brake pads fabricated through a compaction-sintering process. It was hypothesized that increasing compaction pressure and optimizing the proportion of brass reinforcement would improve composite densification and interfacial bonding, thereby enhancing hardness, a key mechanical requirement for brake pad applications.

2 Research methodology

2.1 Materials

The materials utilized in this study consisted of mahogany sawdust collected from Warga Jaya Furniture workshops located in the Kebraon area of Surabaya and brass shavings obtained from lathe workshops of Bengkel Bubut Berkah Teknik in the Demak Timur area of Surabaya. Additionally, polyester resin and magnesium oxide were procured from Fiberglass Supply Depot and Merch as supporting materials for the composite fabrication process.

2.2 Preparation of bio-composite brake pad sample

Mahogany sawdust and brass shavings were sieved sequentially using 80-mesh and 60-mesh sieves to obtain a controlled and relatively uniform particle size distribution. Uniform particle size is essential for improving packing density and interparticle contact, thereby reducing internal porosity and ensuring reproducible mechanical properties in composite systems [23]. Four composition ratios of mahogany sawdust to brass shavings (1:4, 2:4, 3:4, and 4:4 by weight ratio) were prepared to evaluate the influence of organic–metal hybrid reinforcement balance on composite densification and hardness. The total mass of each specimen was fixed at 200 g to maintain consistent compaction behavior and geometry across all samples. Polyester resin (2 ml per specimen) was used as the matrix binder. The resin content was selected based on preliminary trials and previous composite brake pad formulations, in which low to moderate binder fractions are recommended to ensure sufficient particle bonding without excessive matrix dominance which may reduce hardness. Magnesium oxide (2 g) was added as a functional filler to enhance thermal stability and mechanical rigidity, consistent with its use in friction material formulations reported in prior studies. The constituents were mixed using a magnetic stirrer at 30°C for 30 minutes to ensure homogeneous dispersion of metallic and lignocellulosic particles within the binder phase. Homogeneous mixing is critical for minimizing localized agglomeration, which may otherwise influence hardness measurements. The mold cavity dimensions (3 cm × 2 cm × 2 cm) were designed to produce specimens compatible with Shore D hardness testing requirements, ensuring sufficient thickness to avoid substrate influence during indentation. The preparation scheme for the bio-composite brake pad as shown in Fig. 1.

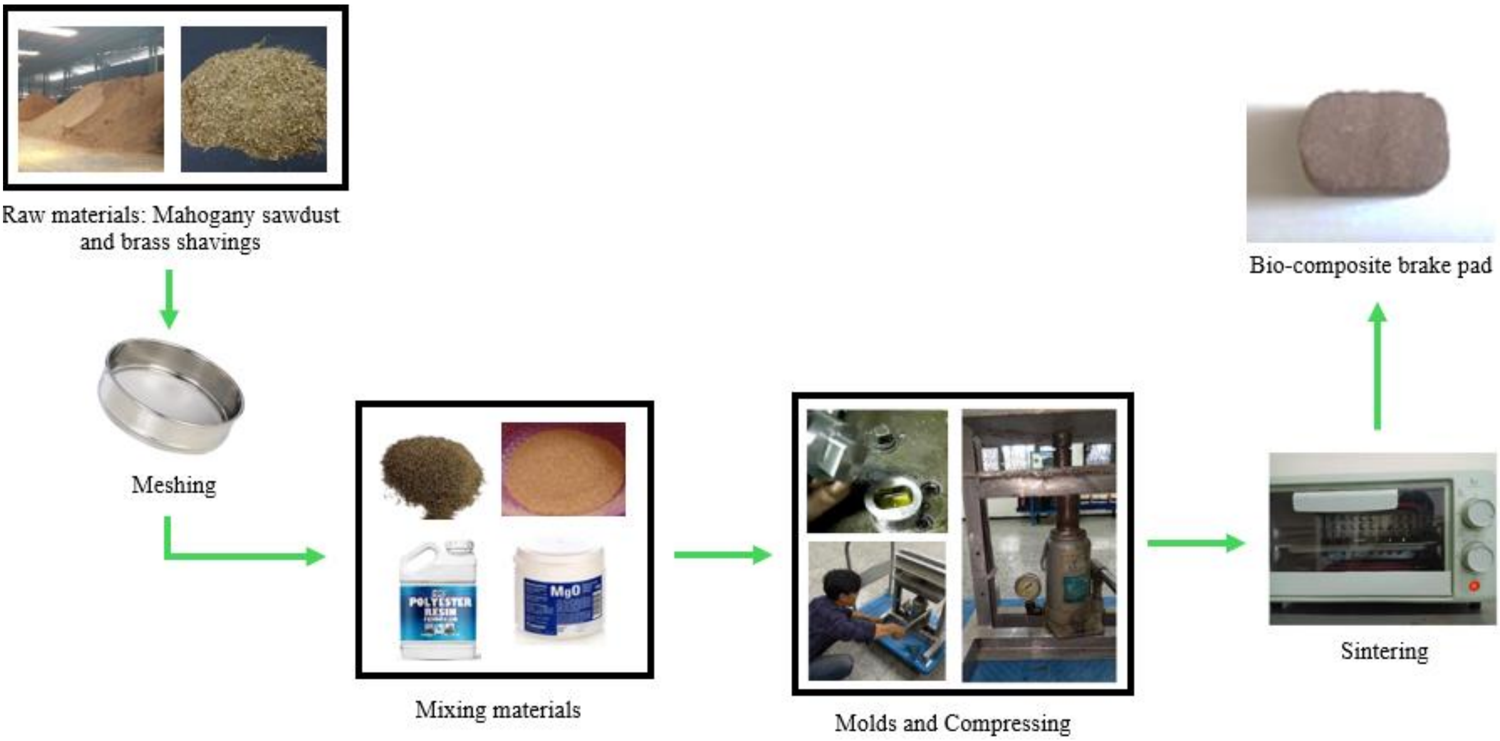

Fig. 1. Systematic preparation of bio-composite brake pad.

2.3 Compaction and sintering fabrication

Compaction was performed using a hydraulic press at 3000, 3200, and 3400 psi (≈20.7–23.4 MPa) for 60 minutes. The selected pressure range was based on reported powder compaction studies indicating that pressures between 10–50 MPa effectively reduce porosity and enhance green density without inducing structural cracking [24][25][26]. Preliminary experimental trials further confirmed that pressures below 3000 psi resulted in insufficient densification, while pressures above 3400 psi increased the risk of binder extrusion and microcracking. Therefore, the selected range was considered appropriate for promoting densification while preserving structural integrity. Sintering (post-compaction thermal treatment) was conducted at 150°C for 30 minutes. This temperature was selected based on the curing characteristics of polyester resin and literature on lignocellulosic composites, where temperatures above 160–180°C may initiate thermal degradation of hemicellulose and lignin components [27]. The chosen temperature ensures adequate binder curing, stress relaxation and interfacial bonding enhancement without degrading the organic reinforcement. This controlled thermal treatment promotes densification and stabilizes the composites's hardness response [28].

2.4 Replication and statistical considerations

For each experimental condition, hardness testing was performed on three independent specimens (n = 3). While this number of replicates is consistent with exploration materials research and preliminary mechanical evaluation studies, it represents a limitation in terms of statistical robustness. The relatively small sample size may reduce the statistical power to detect subtle differences among processing conditions. This limitation has been acknowledged in the Discussion section, and future studies will incorporate larger sample sizes and expanded tribological testing to strengthen statistical reliability.

2.5 Hardness Shore D

The hardness of the fabricated brake pads was evaluated using the Shore D hardness test, according to ASTM D2240-15 [29]. The brake pad molds were produced from metal plates using a rectangular milling process, with outer dimensions of 7 cm × 5.5 cm and an inner cavity measuring 3 cm × 2 cm × 2 cm, and an overall mold thickness of approximately 10 mm. Each sample underwent three hardness measurements, and the average value was recorded to ensure data accuracy. This repetition was necessary because the presence of air bubbles in some specimens could cause the durometer indenter tip to penetrate unevenly, potentially leading to erroneous readings [30] (Fig. 2).

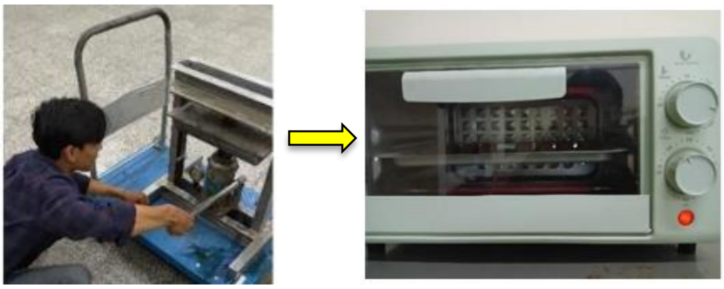

Fig. 2. Compaction and sintering process.

The hardness test was carried out using a Type D Durometer (Teclock GS-720N. This instrument utilizes a sharp-pointed indenter that applies controlled pressure to the specimen's surface [30]. Each specimen was securely positioned on the testing platform to ensure stable measurement throughout the test. The testing procedure involved carefully placing the indenter on the specimen's surface and maintaining the applied pressure for approximately 8 seconds. After this duration, the hardness value was read directly from the dial indicator. The obtained readings, expressed on the Shore D scale, represent the resistance to surface indentation and deformation, providing insight into the mechanical integrity of the fabricated brake pad samples.

3 Results and discussion

3.1 Hardness Shore D of bio-composite brake pad

The Shore D hardness test results for the bio-composite brake pads fabricated from mahogany sawdust and brass shavings are presented in Table 1. This evaluation was conducted to characterize the hardness behavior of the composite material and to assess how variations in material formulation and processing conditions affect its mechanical performance. Shore D hardness was selected as a representative indicator of the brake pad's surface resistance and structural rigidity, which are critical parameters for ensuring adequate wear resistance and dimensional stability during braking operations.

Table 1. Experimental results for the hardness Shore D test. For this dataset, n indicates the sample size, *σ* indicates the sample mean, s is the standard deviation, and SE = s / √n is the standard error

Composition	3000 psi			
	n	σ	s	SE
1:4	3	70.6	0.58	0.33
2:4	3	72	1	0.58
3:4	3	72.6	0.58	0.33
4:4	3	74.3	1.16	0.67
Composition	3200 psi			
	n	Σ	s	SE
1:4	3	71.6	0.58	0.33
2:4	3	72.6	0.58	0.33
3:4	3	73.3	0.58	0.33
4:4	3	75	0	0
Composition	3400 psi			
	n	σ	s	SE
1:4	3	74.3	0.58	0.33
2:4	3	75.6	0.58	0.33
3:4	3	76	1	0.58
4:4	3	76.6	0.58	0.33

The experimental investigation focused on two main variables, namely the composition ratio and the compaction pressure applied during fabrication. Four different mass ratios of mahogany sawdust to brass shavings 1:4, 2:4, 3:4, and 4:4, were employed to examine the effect of increasing metal reinforcement content on hardness. In addition, three levels of compaction pressure, specifically 3000 psi, 3200 psi, and 3400 psi, were applied to study the role of mechanical densification in enhancing particle packing, interfacial bonding, and overall composite consolidation.

For each combination of composition ratio and compaction pressure, three replicate specimens (n = 3) were tested to ensure statistical reliability. The measured hardness data were subsequently analyzed to obtain the mean hardness value (σ), along with the corresponding standard deviation (s) and Standard Error (SE). These statistical parameters provide insight into the consistency, repeatability, and precision of the measurements, thereby strengthening the validity of the observed trends in hardness behavior across different formulations and processing conditions.

At a compaction pressure of 3000 psi, as shown in Fig. 3, the Shore D hardness ranged from 70.6 to 74.3. Specifically, the 1:4 composition exhibited a mean hardness of 70.6 ± 0.33, followed by 2:4 (72 ± 0.58), 3:4 (72.6 ± 0.33), and 4:4 (74.3 ± 0.67). This gradual increase in hardness with higher mahogany sawdust content suggests that the filler enhanced the material's resistance to indentation. The increased mahogany sawdust proportion contributes to a denser and more rigid structure compared to the wood–resin matrix alone. When the compaction pressure was increased to 3200 psi as shown in Fig. 3, a similar trend was observed, with hardness values increasing slightly across all compositions. The 1:4 ratio achieved a mean hardness of 71.6 ± 0.33, while 2:4 and 3:4 recorded 72.6 ± 0.33 and 73.3 ± 0.33, respectively. The 4:4 composition yielded the highest hardness of 75.0, with a negligible standard deviation (s = 0), indicating excellent uniformity in surface consolidation. The improvement in hardness with higher pressure can be attributed to enhanced particle packing, which reduces voids and improves interfacial adhesion between the sawdust and brass particles. At the highest pressure of 3400 psi, as shown in Fig. 3, the hardness values continued to rise, ranging from 74.3 for the 1:4 composition to 76.6 for the 4:4. The results indicate that the influence of compaction pressure intensifies as the filler ratio increases, highlighting a clear synergistic interaction between mechanical densification and the presence of metal powder reinforcement. At higher filler contents, the applied pressure promotes closer particle packing and stronger interfacial contact between the matrix and the metal particles, leading to more effective load transfer and reduced internal porosity. This enhanced densification mechanism suggests that the role of compaction pressure is not merely mechanical but also contributes to optimizing the reinforcing effect of the metal powder within the composite structure.

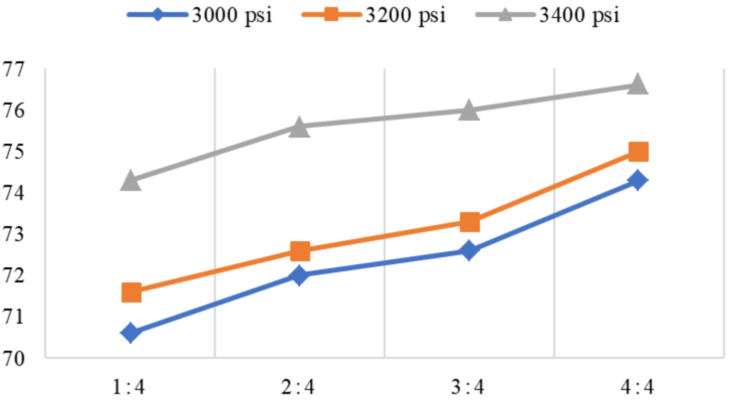

Fig. 3. Shore D hardness results of various compositions.

In addition, the statistical parameters further confirm the robustness of the experimental results. The consistently low standard deviation values (generally around s ≈ 0.58) indicate minimal data dispersion, while the small standard error values (SE ≈ 0.33) reflect high measurement precision across repeated tests. These statistical outcomes demonstrate good repeatability and reliability of the experimental procedure, reinforcing confidence in the observed trends and supporting the validity of the conclusions regarding the combined effects of compaction pressure and filler ratio.

Overall, the data show that composition and compaction pressure influence the hardness behavior of mahogany sawdust and brass shavings bio-composite brake pads. Increasing the proportion of mahogany sawdust enhances the load-bearing capacity of the composite surface, while higher compaction pressure improves densification and particle bonding. The combination of these factors yields a material with superior hardness and potential for wear-resistant applications. These findings are consistent with previous studies reporting that hardness increases with greater metallic filler loading and higher compaction levels. For example, Fadhil and Hadi [31] observed that adding metal or nutshell powder to epoxy matrices improved Shore D hardness due to the filler's rigidity and good interfacial bonding. The hardness obtained was better than that reported by Khafidz [5], who used rice husk. Based on Khafidz's research, with rice husk content of 5 and 10 wt%, the hardness values obtained were 75 and 73.5, respectively. In conclusion, the highest Shore D hardness value (76.6 ± 0.33) was obtained for the 4:4 composition under 3400 psi, indicating that this formulation and processing condition offer the best mechanical surface performance among the tested samples.

Fig. 3 illustrates the Shore D hardness values of the bio-composite specimens fabricated with different composition ratios and consolidated at three compaction pressures, namely 3000, 3200, and 3400 psi. The results demonstrate a consistent and systematic increase in hardness as both the compaction pressure and filler content increase. This trend indicates that the mechanical response of the composite is highly sensitive to processing parameters, particularly the applied pressure during fabrication, which directly influences the final microstructural characteristics of the brake pad material.

At a compaction pressure of 3000 psi, the measured hardness values range from approximately 70.8 to 73.9, indicating a lower degree of densification. When the compaction pressure is increased to 3200 psi, the hardness values show a noticeable improvement, ranging from about 71.8 to 75.1. This enhancement becomes more pronounced at the highest applied pressure of 3400 psi, where the specimens attain the highest hardness values of 74.3 to 76.8. The progressive increase in hardness with pressure suggests that higher compaction levels promote closer particle rearrangement, resulting in a denser composite structure with fewer internal defects.

The observed compositional effect further supports this interpretation, as specimens with higher filler proportions consistently exhibit increased hardness values. A higher filler content contributes to improved material compactness and mechanical rigidity, particularly when combined with sufficient compaction pressure. The concurrent influence of composition and pressure suggests a synergistic interaction between filler reinforcement and mechanical densification, which promotes enhanced interfacial bonding and reduced void formation within the composite. This synergy facilitates more efficient load transfer and improved microstructural homogeneity, thereby enhancing the mechanical integrity of the bio-composite brake pad material, while direct tribological performance requires further experimental validation.

3.2 Surface morphology analysis

The surface morphology of the bio-composite brake pad is examined under a microscope a 500x magnification. Fig. 4 presents the microscopic surface morphology of the indentation regions obtained from the hardness test of the bio-composite brake pads with varying compositions of mahogany sawdust and brass shavings. The micrographs in Fig. 4(a), Fig. 4(b), and Fig. 4(c) correspond to different compaction pressures, and illustrate distinct surface characteristics influenced by the compositional ratio and particle distribution of the reinforcement materials.

The yellowish regions in the images represent the brass particles, while the darker, more fibrous areas correspond to the mahogany sawdust matrix and the polymeric binder phase. The distribution of the brass particles plays a crucial role in determining the overall hardness of the composite. A more homogeneous dispersion of the brass phase, as shown in Fig. 4(b), contributes to improved surface integrity and higher resistance to plastic deformation during indentation. This observation correlates with the higher Shore D hardness values observed for compositions with a balanced ratio of brass-to-sawdust (e.g., 3:4 and 4:4 ratios). In contrast, Fig. 4(a) exhibits a more irregular indentation boundary with noticeable deformation and less compact surface texture. This morphology is attributed to the lower mahogany content (1:4 composition), which reduces the material's ability to resist localized stress and results in lower hardness values. The predominance of lignocellulosic particles (mahogany sawdust) in this composition likely leads to higher porosity and weaker interfacial bonding, consistent with findings by Dirisu et al. [10] and Adetunji et al. [23], who reported similar trends in natural fiber metal particulate composites. Fig. 4(c), representing a higher compaction pressure and greater mahogany content, shows a more refined indentation edge with fewer signs of material displacement around the indentation. This indicates enhanced densification and load-bearing capacity of the composite structure. The presence of well-distributed brass particles (yellow zones) strengthens the surface layer and improves hardness due to the inherent metallic properties of brass, as also supported by Khafidh et al. [6], who noted that metallic reinforcement enhances both hardness and wear resistance in hybrid brake composites.

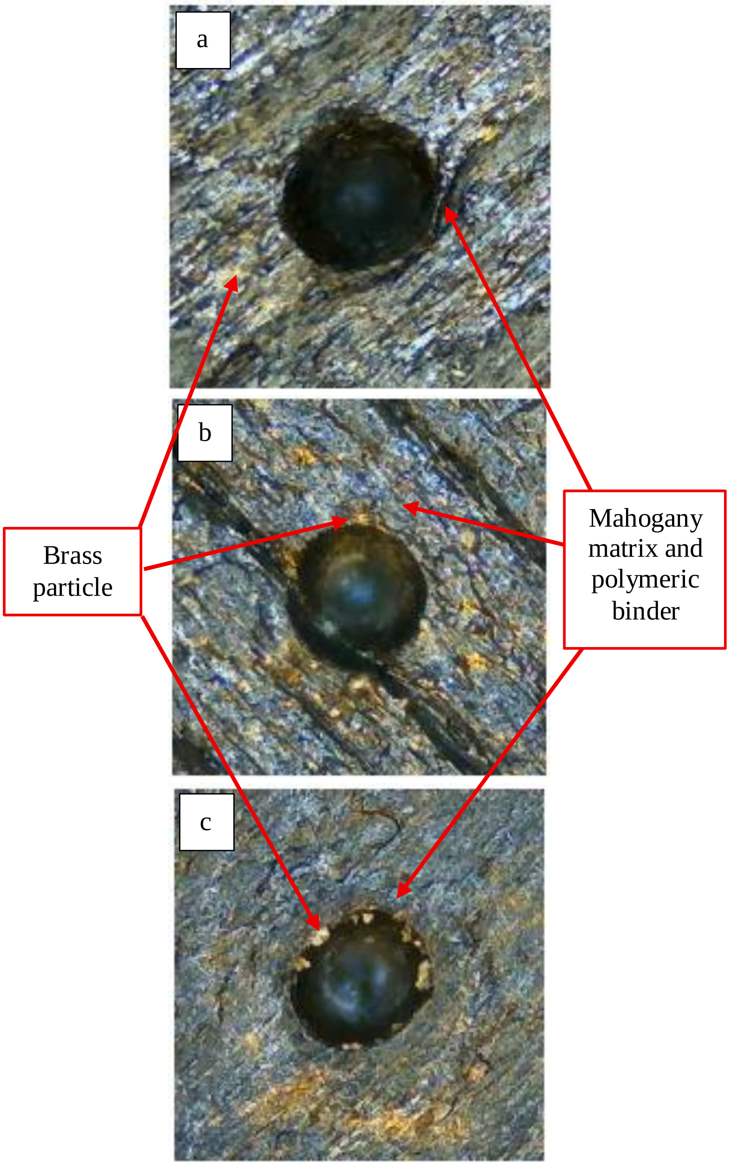

Fig. 4. Indentation points of the hardness Shore D test.

Quantitative image analysis confirmed a reduction in porosity from 12.6% at 3,000 psi to 5.4% at 3,400 psi, indicating effective compaction and the collapse of voids during compaction. This microstructural refinement directly correlated with an increase in Shore D hardness from 68 to 78, demonstrating improved interfacial shear stress transfer and increased resistance to local plastic deformation. These results suggest that, in addition to the compositional ratio of the brake pad components, microstructural compactness also influences hardness. While previous studies on natural fiber-based brake pads have largely attributed hardness enhancement to filler content, the hybrid system demonstrates a different synergistic mechanism. Brass particles serve as a stiffening load-bearing constituent, while mahogany sawdust enhances mechanical locking and matrix adhesion. This combined reinforcement strategy provides a more effective approach to structure-property optimization. However, further tribological evaluation is needed to comprehensively validate the performance potential of the developed sustainable composite.

4 Conclusions

This study successfully developed and characterized bio-composite brake pads made from mahogany sawdust and brass shavings under varying compaction pressures and compositions. The results showed that the composition and compaction pressure influenced the mechanical characteristics of the composites, particularly densification, hardness, and microstructural uniformity. Increasing the compaction pressure from 3000 psi to 3400 psi increased the material densification, which was reflected in higher Shore D hardness values and reduced indentation deformation. Among the studied compositions, a 4:4 ratio of mahogany sawdust to brass shavings showed the highest hardness, indicating improved mechanical integrity and a more compact microstructure. In contrast, lower brass content resulted in increased porosity and decreased hardness. It should be noted that this study focused on mechanical and microstructural evaluations; however, direct tribological performance, such as friction coefficient and wear behavior, was not experimentally assessed and should be addressed in future studies to comprehensively evaluate the braking performance of the developed bio-composite brake pads.

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