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ORIGINAL RESEARCH ARTICLE

MECHANICAL CHARACTERIZATION AND PERFORMANCE EVALUATION OF REINFORCED OSSEOUS MATERIALS FOR HIGH-FRICTION AUTOMOTIVE BRAKE PAD APPLICATIONS

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ABSTRACT

Composite brake pad as an alternative to existing conventional brake pads were designed and produced with the aim of addressing the need for ecologically friendly and asbestos-free environment. The brake pads were made via compression molding having cow bone particles reinforced with mild steel chippings. In this study, properties such as density, hardness, tensile, shear, and compressive strength were tested to establish their appropriateness for friction applications in automotive settings. The results showed that the density values varied from 1.566 to 1.801 g/cm³, showing strong compaction and low porosity. Similarly, Hardness tests produced values between 60 and 70 Shore D, demonstrating outstanding resistance to wear, with higher cow bone content resulting in improved hardness compared to metallic chips. It was also observed that the Shear strength ranged from 23.0 to 41.03 MPa while tensile strength ranged from 38.4 to 40.8 MPa, outperforming conventional brake pads and exhibiting sufficient resistance to deformation under load. Also, compressive strength varied from 10.05 to 11.95 MPa indicating adequate resistance to deformation under load. The findings show that cow bone particles greatly improve the mechanical performance of brake pad composites by improving stress transmission, structural stiffness, and resistance to deformation. Overall, these composites have competitive, and occasionally better qualities than traditional and bio-based materials, based on comparisons with previous research. This study provides information on waste valorization with clear understanding by presenting cow bone as a viable, affordable, and environmentally friendly material in the production of high-performance non-asbestos car brake pads.

1.0 Introduction

In the manufacturing of automobiles for the transportation sector, brake efficiency and performance are vital for optimum operation (Limpert *et al*,2011). Brake pads experiences stresses during operation which invariably leads to significant wears and tears, deformation and even complete failure of the brake materials (George.*et al*.2020). Formulation of synergistic composites comprising of reinforcements with osseous materials particularly with cow bones is proposed by this study. It will contribute to improving insight into brake pads performance analysis in high-friction automobiles braking (Abutu *et al*. 2018; Bijwe and Majumdar.2004). However, the relationship between the mechanical performance indices, thermal and frictional behavior in these newly found cow bone composites demand for a robust analytical and experimental approach for their evaluation and optimization.

High friction environment where brake pad plays a crucial role requires materials with unique abrasive resistance, thermal stability and high mechanical strength (Rashid, 2014). However, all these required parameters which makes osseous materials like cow bone a perfect material for its design and fabrication (Blau,2001). Additionally, mineral content and inherent porosity in cow bone help to sustain surface roughness during braking, improving friction stability (Palma-Morales *et al.*2026). Because of these benefits, as well as their minimal environmental impact and biodegradability, cow bone -reinforced composites are a desirable material solution for environmentally friendly braking technologies (Ayogwu *et al*. 2020).

Utilizing waste-derived materials in engineering is increasingly advocated due to sustainability concerns (Roland *et al*. 2017). Osseous materials, in particular, promote the manufacturing of eco-friendly friction compounds that can compete synthetic brake pads (Rajak *et al*. 2019; Ikpambese *et al*. 2016). Mechanical performance of osseous-reinforced materials for high-friction automobile brake applications remains under-researched, despite a rising interest in bio-based composites. Conventional brake pad materials are majorly asbestos-based, metallic or ceramic composites (Chan *et al.*2012; Poh *et al.*2013; Vlastimil *et al.*2013). The drawbacks of conventional brake pads, such as excessive weight, thermal instability, and uneven wear under cyclic loading, have prompted the search for an improved composites with reinforcement (Oesterle and Urban,2006).There are also serious problems associated with the use of these conventional brake pad materials (Jana, *et al.*2011). Since asbestos causes cancer, it is prohibited in many nations. Ceramic or metal substitutes are frequently produced using energy-intensive methods and are not biodegradable these concerns have highlighted the search for sustainable, eco-friendly alternatives (Seung, 2018). The growing demand for environmentally friendly friction materials has sparked substantial research into bio-based composites for application in vehicle braking systems (Okafor *et al*. 2023). Similarly, osseous (animal bone-derived) materials have shown great potential because of their high calcium content, temperature stability, and wear resistance. Experimental studies have verified the effectiveness of osseous reinforcements in improving friction and wear performance during dry sliding situations (Madakson *et al*. 2012). Variety of factors such as mechanical behavior, tribological, and thermal analysis are essential to assess the suitability of osseous-reinforced composites for automotive brake pad applications (Dagwa and Ibhadode, 2026; Miranda-Oporta *et al*. 2023).

Several research emphasized the relevance of bio-based materials in addressing the shortcomings associated with synthetic brake pads have been studied (Azhary *et al*. 2026). Similarly, Afolabi et al. (2016) studied bone ash-based composites and discovered that osseous materials' calcium-rich mineral composition considerably improved wear behavior and thermal resistance. Osseous composites, characterized by a high content of calcium phosphate (in the form of hydroxyapatite) and intrinsic microstructural stiffness, exhibit notable thermal and tribological properties as reported by Mirsalehi *et al*. (2015). Imran *et al*. (2025) investigated epoxy-based friction materials reinforced with coconut-shell charcoal, attaining a peak tensile strength of 28.36 MPa at optimum filler concentrations. They equally noted that excess filler reduced tensile strength due to voids and agglomeration.

Bio-based brake pads should be capable of providing enhanced delamination at high temperatures, as well as specific mechanical strength and heat dissipation (Naidu *et al*. 2023). Natural composites such as animal bone have hierarchical microstructures that maximize load distribution and energy absorption (Rho *et al*,1998; Marthin *et al*, 2019). Friction materials must maintain constant friction coefficients, resist temperature cycling, and retain structural integrity under load in order to be sustainable (Ilie *et al.*2022; Malequeet *et al*. 2010; Nachippan *et al*. 2024)

Numerous investigations have been undertaken regarding the formulation of asbestos-free automotive brake pads utilizing natural and agro-waste reinforcement materials, including palm kernel shell, coconut shell, bagasse, banana peels, rice husk, and other bio-based particulates (Aigbodion, *et al.*2010; Idris, *et al*. 2015, Olabisi *et al.*2023, Osarenmwinda, 2021).These studies primarily aimed to enhance environmental sustainability while preserving satisfactory friction and wear properties for vehicle braking systems. Additionally, Mechanical integrity of brake pads was studied using the impact of binder composition, reinforcement fraction and matrices as parameters (Olabisi *et al*. 2016). The insufficient knowledge of how osseous reinforcement influences the mechanical and tribological characteristics of brake pad materials is another research gap. Additionally, little is known on the influence of bone-particle integration on matrix bonding and structural integrity. Furthermore, experimental data comparing osseous-reinforced brake pads with conventional brake pads is lacking

Thus, this study focuses on developing and characterizing cow bone composite brake pad for automobiles. It aims to conduct an extensive mechanical evaluation of the brake pads made from cow bones reinforced with metal chippings. The findings are expected to advance sustainable brake pad technologies and provide insights into cow bone materials in automotive engineering.

2. Materials and Method

2.1 Sourcing of Cow Bone

10 kg of cow bone were collected in the month of May, 2026 from Edike Market in Agbor, Delta State, Nigeria. It serves as the primary material for this study. These discarded bones create environmental hazards due to their irresponsible disposal following meat extraction, resulting in contamination, unpleasant odors, and unsanitary conditions in the surrounding area. Plate 1 shows the images of the disposed cow bone.

2.2 Sourcing of Metal Chips

10 kg of mild steel chippings utilized as reinforcing materials were sourced in the month of May, 2026 from Andex Fabrications Limited, Onitsha, Anambra State, Nigeria. The metallic chippings were gathered during machining processes within the plant.as shown in Plate 2. These mild steel metallic chips are typically formed as waste material during cutting, drilling, turning, milling, and grinding operations and are commonly thrown away at the end of the day's machining activities.

Plate 1: Cow bones used for study

Plate 2: Mild steel Chips collected during Machining

2.3 Epoxy Resins and Hardener

The 500ml epoxy resin A and epoxy resin B (hardener) utilized as the matrix binding reagents used in this investigation. They were produced by MolyChem, Mumbai in India but were acquired from a vendor in Onitsha, Anambra State, Nigeria. Both materials were of analytical grade quality. While the hardener acted as the curing agent, the epoxy resin was the main binder that held the reinforcing particles together (Dirisu, *et al.* 2024)

Other materials and equipment used includes distill water, cleaning agents laboratory sieves, shore scale durometer hardness tester, compression tester, shear testing machine, digital weigh balance, mechanical press etc.

2.4 Cow Bone Preparation as Matrix Material

To remove dirt, bloodstains, and organic impurities, the cow bones from Edike Market were soaked in acetone for 5 minutes, washed and sun-dried for five (5) days. Heating occurred at 500^{0}C to eliminate remaining organic matter and increase brittleness. A grinding machine was used to ground the bones into powder which was then sieved for consistent particle size of 150µm suitable for composite manufacturing. The sieved bone powder was stored in sealed containers to prevent moisture absorption. All these were done in the Material testing laboratory and workshop belonging to the Faculty of Engineering, University of Delta, Agbor.

2.5 Mild Steel Chippings Preparation

Water and detergents were used to clean the mild steel chippings that were obtained from Andex Fabrications Limited in order to get rid of coolant residues, oil, grease, dirt, and other machining impurities. The metallic particles were cleaned to remove any contaminants. The cleaned metallic particles were dried, mechanically grinded and sieved to produce 110µm homogeneous particle sizes. Before being added to the composite composition, the produced metallic chips were then kept in dry conditions.

2.6 Mold Design and Fabrication

Standard geometrical parameters for disc brake pads were followed according to SAE J661 in the design of the mold for vehicle brake pads shown in Plate 3. With specified intermediate dimensions and slot spacing, it had an overall top width of 144 mm, an internal working width of 120 mm, and a base width of 95 mm. To improve structural compatibility, two Ø15 mm circular pin-hole zones were added. The side profile had a cavity thickness of 3 mm and a height of about 53 mm. To ease molding and lessen the concentration of tension, edge radii were used. In order to provide ideal material compaction and distribution of composite components, the mold was designed to withstand compressive loads and high curing temperatures.

For strength and ease of machining, mild steel was used to fabricate the mold. Several operations like marking, cutting, drilling, grinding, milling, and finishing were carried out. Precise measurement equipment was used to precisely mark the brake pad size on the steel plate. The basic mold shape was achieved by rough cutting, and the required profiles and tolerances were then achieved by milling and grinding. For the brake pad profile, the internal chambers were machined with curves and fillets for effective material flow. The mold was built, examined, and prepared with release agents for use in compression molding.

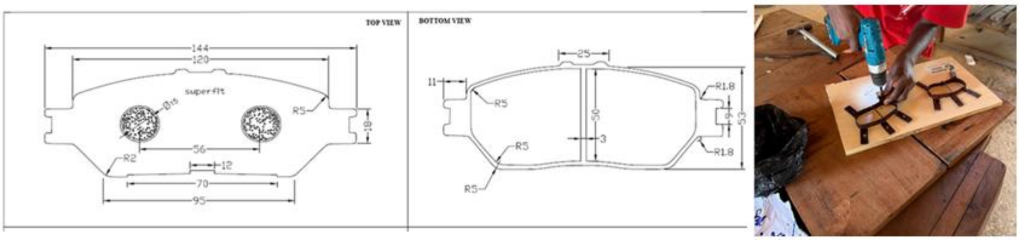

Plate 3: Mold design and Fabrication Processes

2.7 Composite Formulation and Brake Pad Production

The production of cow bone reinforced metal chippings composite brake pad was carried out using compression molding techniques in the Mechanical Engineering Department at the University of Delta, Agbor. Based on a formulation design described in Table 1, the procedure commenced with measuring various ratios of cow bone powder and fine metallic chippings using a digital weighing scale. Before adding epoxy resin and hardener in a 2:1 ratio, those components were properly mixed to provide a uniform distribution.

The inner surface prepared mold was rubbed slightly with oil to ensure easy product removal. It was then filled with the resulting composite mixtures Following ASTM D4703-24 guidelines, compression was applied using a hydraulic press, which strengthened the brake pad structural integrity, decreased porosity, and improved particle bonding. Curing took place at 23^{o}C for seven (7) days Samples were then taken out as seen in Plate 4.

Table 1: Formulations for Brake Pad Production

Materials	Sample A (%/wt)	Sample B (%/wt)	Sample C (%/wt)
Powdered Cow Bone	30	40	50
Metal Chippings	40	30	35
Epoxy Resins	20	20	10
Hardener	10	10	5

Plate 4: Produced Brake Pads

2.8 Characterization of the Developed Brake Pad

2.8.1 Tensile testing

Strength test utilizing a Universal Testing Machine (UTM) with model number WDW-100D manufactured by Chengyu Testing Equipment Co., Ltd, China was performed on the produced brake pad composite adopting the ASTM D638 procedures. For homogeneity, the samples (A, B and C) were kept at room temperature after being machined into typical shapes. Using a vernier caliper, gauge length, breadth, and thickness measurements were made. The test comprised putting the specimen in the UTM, load was applied gradually and continuously at 5 mm/min till fracture and automatically recording the maximum load prior to failure.

$$\delta_t = \frac{F}{A} \qquad 1$$

where δ_t is the tensile stress, F is the force in Newtons and A is area in mm

2.8.2 Hardness testing

Shore Scale durometer Hardness tester manufactured by PTC Instruments, England with model number M-307L was used in accordance with ASTM D2240 to evaluate the brake pad resistance to surface wear and indentation, the samples (A, B and C) thickness was maintained within the ASTM-recommended ranges for accurate measurement and its surface was polished using fine emery paper to produce a smooth, flat finish. The brake pad sample was fixed to the platform during the testing process, and the Shore D durometer was used to apply a standard indentation load of 40N vertically for a dwell time of 15 seconds before the values were recorded. Hardness measurements were made and the mean value recorded.

2.8.3 Density test

The ASTM D792 standard was followed in the density test to determine its mass-to-volume ratio. To get rid of surface impurities, a rectangular specimen was carefully prepared and cleaned. An electronic weighing balance was used to record the mass, and a digital vernier caliper for its dimensions was used for the three samples

$\rho = \frac{M}{V}$, Where ρ, M and V are density, mass and volume respectively 2

2.8.4 Compressive strength test

A Universal Testing Machine (UTM) was used in accordance with ASTM D695 guidelines to assess its ability to withstand compressive stress without failing. For uniform load distribution, specimens were carefully machined. A digital vernier caliper was used to measure the dimensions before testing. In accordance with ASTM D695, the specimens were placed in the center of the UTM, and a compressive load was applied gradually at 1.3 mm/min until significant failure and deformation occurred.

2.8.5 Shear strength test

This test was to evaluate the composite resistance to shearing pressures before it failed. In compliance with ASTM D732 requirements, specimens were machined into conventional rectangular shapes. The surfaces were then polished to provide precise contact and consistent load distribution throughout testing. The specimens were firmly fixed in the UTM shear fixture, where a steady rate of increasing shear stress was delivered until the specimens broke along the shear plane

3. Results and Discussion

3.1 Tensile Test Result

Table 2 shows the tensile strength of the materials tested which vary from 38.4 to 40.8 MPa, demonstrating material homogeneity. Despite having a smaller cross-sectional area, Sample A displayed the maximum tensile strength at 40.8 MPa, indicating that it can sustain higher stress per unit area before fracturing. Additionally, sample C has an intermediate tensile strength whereas sample B, having greater cross-section, produced the lowest tensile strength at 38.4 MPa. Similarly, sample C achieves the highest load as a result of its compact, nearly square cross-section, which may promote uniform stress distribution and reduce concentration. Again, the maximum load was observed to closely ranged from 2.45 to 2.52 kN. It is noteworthy that for constant brake pad performance under service conditions, the relatively small difference in values indicates superior fabrication consistency and a homogenous composite structure as reported by Panchenko *et al.* (2023). According to Edokpia *et al.* (2016), conventional brake pads have a tensile strength of 6.80 MPa. The existing low tensile strength suggests that better friction materials are required to improve mechanical integrity and resistance to cracking under repeated mechanical and thermal loads during braking. Tensile strength increased by roughly 500%, 465%, and 479%, respectively. These substantial improvements highlight that the newly developed pads exhibited improved mechanical performance, which is critical for minimizing delamination, cracking, and structural degradation during repeated braking cycles as reported in Essam *et al.* (2025**).**

Table 2: Tensile Result for the Developed Brake Pads

Samples	Width(mm)	Thickness	Maximum Load (KN)	Tensile Strength (MPa)
A	10	6	2.45	40.8
B	10	6.5	2.50	38.4
C	8	8	2.52	39.4

The tensile strength obtained (38.4-40.8 MPa) was approximately 35-44% higher than the 28.36 MPa reported for coconut-shell charcoal composites by Imran *et al.* (2025). This improvement shows that the cow bone-metal chip reinforcement system provides better load transfer and mechanical strength, indicating that it has potential as a brake pad reinforcement material While the glass-fiber-reinforced epoxy composite brake pads developed by Samuel *et al.* (2021) reported a tensile strengths ranging from 13.79 MPa to 19.17 MPa, the tensile strengths reported in here is between (38.4–40.8MPa) as seen in igure1. This suggests that the hybrid reinforcement system improved matrix-particle interaction and stress distribution which contributed to the improved mechanical performance of the composite brake pad.

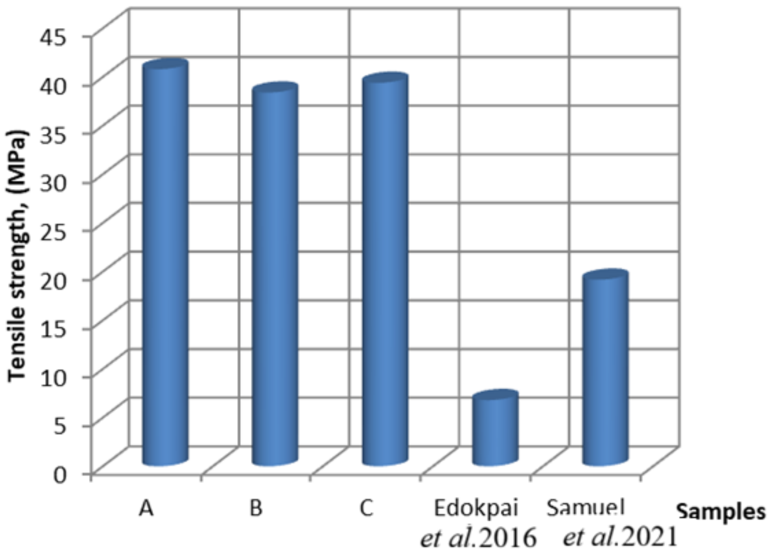

Figure 1: Tensile strength values for the study and Literature reported values in MPa

3.2 Density Results for the Developed Brake Pads

The density measurement for samples in the study was found to range from 1.566 to 1.801 g/cm³ as presented in Table 3. It is observed that Sample A has the highest density compared to Sample C, having the lowest density of 1.5661 g/cm³. It is clear that the higher density (1.80055 g/cm³) as shown by sample A suggests better molding compaction, lower void content, and better particle packing (Iham *et al.,* 2025). It has been reported that increased density is associated with better mechanical strength, wear resistance, and thermal stability (Mark *et al.,* 2020).

Gautam *et al.* (2025) in their work reported the densities of nano-silica-reinforced epoxy composites from 1.13 to 1.90 g/cm³, which is in agreement with the results obtain in this study. Maintaining a proper density is crucial in practical applications since low density can result in increased porosity, decreased mechanical strength, and faster wear (Ademoh *et al.,* 2015)

Table 3: Density Test Result for the Developed Brake Pads

Sample	Length(cm)	Width(cm)	Thickness(cm)	Weight(g)	Density(g/cm^3)
A	2	1.45	1.25	6.527	1.80055
B	2.05	1.55	1.4	7.25	1.62976
C	1.55	1.65	1.5	6.008	1.56611
Average					1.70

3.3 Hardness Results for the Developed Brake Pads

In alignment with ASTM D2240, the standard for assessing semi-rigid composite materials, particularly in friction components, classifies samples A (60), B (70), and C (66) as moderately hard based on their mean Shore D hardness values of 65.33. Variations in the distribution of mild steel chip reinforcement, the degree of matrix consolidation, and the existence of near-surface voids can contribute to the disparities in hardness levels in Table 4. Study by Imran *et al.* (2025) on epoxy-based friction materials reinforced with charcoal from coconut shells revealed a peak hardness of 88.36 MPa at filler concentrations of 90% though resulted in a reduced tensile strength. Furthermore, as shown in Table 4, Sample A, (40% metallic chips, 30% cow bone particles) had a lower hardness value than Sample (40% cow bone particles and 30% metallic chips). Similarly, Sample C, (35% metallic chips and 50% cow bone particle), exhibited higher hardness than Sample A. These findings show that the proportion of cow bone particles introduced into the composite had a significant impact on material hardness in addition to the metallic-chip concentration.

The findings suggest a synergistic interaction between metallic chips and cow bone particles in a composite matrix, with cow bone greatly improving surface resistance and hardness. Increased cow bone content correlates with increased hardness, implying that efficient reinforcing enhances load-bearing capacity and resistance to deformation in brake pad materials. These findings are consistent with reports of Agunsoye *et al.* (2013), who stated that mechanical performance is influenced by the combined proportions of both materials. As a result, the current findings show that the combined effect and relative quantities of cow bone particles and metallic chips have a greater influence on the mechanical performance of the generated composite than each reinforcement alone.

Further investigation reveals that polymer composites reinforced with cow bones and chicken feathers have better mechanical qualities than unreinforced polymers, indicating a reliance on cow bone as reinforcement material that contributes to hardness results(Adah, *et al.*2024) This findings support cow bone particulates as a potential useful reinforcement material in asbestos-free composite brake pads, offering advantages like , mechanical improvement, and chances for waste valorization in the development of sustainable friction materials.

Table 4: Hardness Test Result for the Developed Brake Pads

Sample	Length(cm)	Width(cm)	Thickness(cm)	Weight(g)	Hardness, Shore D
A	2	1.45	1.25	6.527	60
B	2.05	1.55	1.4	7.25	70
C	1.55	1.65	1.5	6.008	66
Average					65.3

3.4 Shear Strength Results for the Developed Brake Pads

The cow-bone-reinforced brake pad composites that were produced had shear strengths value of between 23 and 41.029 MPa as presented in Figure 2. The greatest resistance to shear deformation and interfacial failure was demonstrated by Sample C, which had the maximum shear strength of 41.029 MPa .. The shear strength gradually increased as the amount of cow bone increased, indicating that cow bone particles served both as efficient reinforcing and matrix material. The increased calcium-phosphate and hydroxyapatite content of the bovine bone particles which improved stress transmission and limited fracture propagation under shear loading may be responsible for the improvement (Libonati *et al.* 2013). The findings also show that cow bone reinforcement enhances the brake pad composite structural integrity in addition to its hardness. For high-performance brake pad applications, cow bone can thus be regarded as a viable sustainable reinforcing material.

The shear strength increased by around 78% from Sample A to Sample C in seen Figure 2. This indicates that the increase of cow bone particles as a matrix greatly increased the brake-pad capacity to support loads. Even with a corresponding decrease in metal chip reinforcing particles as seen in Table 1. This improvement in the material mechanical performances is in agreement with earlier hardness findings reported by this study.

The shear strengths reported in this study are equivalent to those of bio-based and polymer-composite brake pads. Findings by Afolabi *et al.* (2015) revealed that integrating cow bone particles into palm-kernel-shell reinforced polymer brake pads increased mechanical performance through better particle reinforcement and matrix interaction caused by the bone particles ceramic-like characteristics.

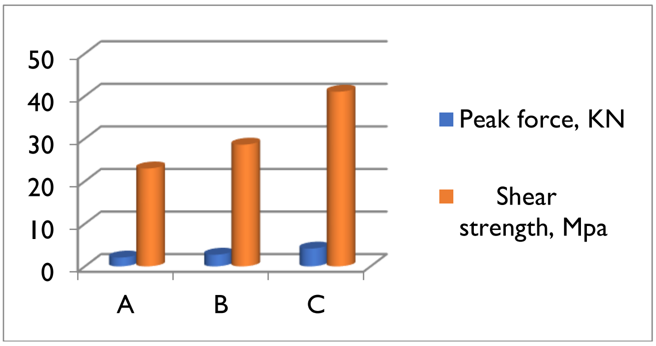

Figure 2: Peak Force and shear strength of cow bone brake pad composites.

Despite having the highest peak force of 4.185KN, Sample C had the greatest shear strength of 41.029 MPa. This suggests that interfacial bonding, particle dispersion, porosity, and stress transfer efficiency all have an impact on shear performance in addition to the applied force (Abay *et al.* 2026). The microstructure of Sample C successfully resisted shear deformation and fracture propagation, indicating that the brake pad composite structural integrity and resistance to shear failure were improved by the matrix cow bone particles. Improvements in interfacial bonding and filler dispersion can greatly increase shear resistance and structural endurance, according to research on epoxy-based friction compounds (Shiqiang *et al*,2015). Consequently, the proposed brake pad has enough mechanical integrity for friction-material applications, according to the shear strengths of 23–41 MPa found in this study.

3.5 Compressive Strength for the Developed Brake Pads

Since brake-pad materials must resist compressive stress during braking, compression strength is crucial. With a peak force of 717 N and the greatest compressive strength of 11.95 MPa, Sample A as shown in Table 5 showed greater load-bearing capabilities, possibly as a result of improved filler dispersion and decreased porosity. On the other hand, despite having a comparable shape to Sample A, Sample B exhibited the lowest compressive strength at 10.05 MPa. Sample C intermediate strength of 10.70 MPa and peak force of 685 N demonstrate how microstructural characteristics and geometry influence compressive performance. The current results are consistent with earlier studies on glass-fiber-reinforced epoxy brake pads by Samuel *et al.* (2021) which revealed compressive strengths of 8 MPa to 12 MPa. According to a comprehensive assessment of eco-friendly brake pad materials by Dirisu *et al.* (2024). Bio-based brake pads typically have compressive strengths ranging from 76 to 120.5MPa, depending on the filler type, binder concentration, and processing circumstances. As a result, the values obtained in this investigation compare favorably to those published for non-asbestos organic brake pads and also bio-composite friction materials reported by Achebe *et al.* (2019).

Table 5: Compressive strength Result for the Developed Brake Pads

Sample	Width(cm)	Thickness(cm)	Peak Force.(KN)	Compressive Strength(MPa)
A	10	6	7.17	119.5
B	10	6.5	6.53	100.4615385
C	8	8	6.85	107.03125

4. Conclusion

This work effectively designed and developed a cow-bone-reinforced composite brake pad and evaluated its potential as a sustainable friction material using a variety of mechanical property studies. The density varied from 1.566 to 1.801 g/cm^3, suggesting significant consolidation. Sample A had the greatest density and structural integrity. Hardness measurements ranged from 60 to 70 Shore D, indicating that cow bone particles made effective contributions to surface durability. Tensile strength measured from 38.4 to 40.8 MPa, outperforming conventional brake pads and demonstrating the efficiency of cow bone as both matrix and reinforcer. Shear strength reached 41.03 MPa, suggesting robust matrix-particle bonding and increased resistance to failure. The compressive strength varied from 100.4 to 119.5 MPa, indicating appropriate load bearing capacity. In all cow bone particles were shown to be an efficient material in brake pads production. These qualities were comparable to those reported for various conventional and bio-based brake pad materials in literature. As a result, cow bone particles have tremendous promise as a long-term, low-cost, ecologically benign, and high-performance material for non-asbestos brake pad manufacture. The findings of this study help to produce eco-friendly friction materials while also boosting the use of agricultural and animal-derived waste resources in sophisticated engineering applications. Future work should focus on microstructural evaluation of the developed brake pad.

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