



Development and Characterization of Epoxy-Based Asbestos-Free Brake Pad Composites Reinforced with Cow Hoof Particulates

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Abstract

The growing global demand for environmentally friendly and sustainable brake pads has intensified the search for viable alternatives to asbestos-based materials. Agricultural and animal waste materials offer advantages such as low cost, wide availability, and reduced environmental impact, making them promising reinforcement options. This study aimed to evaluate the suitability of cow hoof particulates as reinforcement in epoxy-based composites for automotive brake pads. Composites were produced using an epoxy resin matrix, cow hoof particles of varying sizes (150 μm , 250 μm , and 350 μm), and additives including calcium carbonate, graphite, and aluminium oxide. The developed samples were subjected to water and oil absorption tests, compressive strength evaluation, thermogravimetric analysis (TGA), tribological testing, and scanning electron microscopy (SEM). The results revealed that both water and oil absorption increased with increasing particle size, which can be attributed to the formation of more pronounced pore networks and diminished interfacial integrity between the reinforcement and matrix. Compressive strength decreased with increasing particle size, primarily due to weakened particle matrix adhesion and ineffective stress transfer. Thermal analysis confirmed that all samples remained stable within typical brake operating temperatures (450–620 °C). Composites of the newly produced pad was 78% efficient, it maintained stable friction coefficients (0.62–0.79), suitable for braking applications. However, wear increased significantly at loads above 40 N and speeds beyond 3.5 m/s due to tribofilm breakdown, evidenced by grooves, micro-cracks, and delamination. SEM showed finer particles ($\leq 75 \mu\text{m}$) formed dense, uniform structures with better wear resistance, while coarser particles ($\geq 150 \mu\text{m}$) caused porosity, weak bonding, and particle pull-out. Cow hoof particulates demonstrate strong potential as sustainable reinforcement for brake pad production. This study has introduced cow hoof particulates as a previously underutilized animal-waste reinforcement in epoxy-based brake pad composites. It also provides experimental evidence that finer cow hoof particles significantly enhance interfacial bonding, wear resistance, and overall performances of brake pads.

Keywords: Compressive strength; Tribological properties; Cow hoof, Mechanical and Thermal Properties.

1.0 Introduction

The automotive brake system is one of the most important safety features of a vehicle; it is used to slow down or stop a vehicle by changing the vehicle's kinetic energy into thermal energy due to friction between a brake pad and a brake disc. Because of the way they perform, brake pads must provide a consistent level of friction from the beginning of their life cycle to the end of their life cycle, resist wear throughout their life cycle (or until they need to be replaced), and be able to withstand high temperatures during use. Because of these requirements, selecting brake pad material is critical to ensuring reliability and durability of brake pads as well as safety of the vehicle [1]. During many decades, many manufacturers have used asbestos as a reinforcing agent in brake pad material due to the performance characteristics associated with high-temperature stability, strength; and best of all, the ability to create a great deal of friction. The continual use of asbestos in brake pads has created some very toxic health ailments, such as asbestosis and cancer; therefore, asbestos is being heavily regulated and is being phased out of brake pads worldwide [2]-[3].

Due to concerns raised by asbestos use in brake pads, many researchers have initiated research programs to develop environmentally friendly, non-asbestos organic (NAO) brake pads using sustainable materials. In the last several years, many researchers have reported success using agricultural waste materials (agricultural residues) as reinforcers in friction composites. Two examples included the development of friction composite using palm kernel shell and a palm kernel fibre composite; both demonstrate sufficient mechanical strength and wear resistance to be used as brake pads [4]-[5].

Analogous to this, brake pads manufactured from bagasse have been reported to possess mechanical properties similar to traditional asbestos-based brake pads [6]. Other bio-based waste byproducts such as banana peels have been used effectively to produce durable braking pads with acceptable mechanical performance characteristics [7]. Similarly, shells of periwinkles and palm slag have been confirmed to have sufficient thermal stability and wear resistance for use as alternative reinforcement in brake pads.

The development of composite materials made from animal waste is receiving increased attention for creating value-added engineering products from agricultural and animal waste materials (i.e., eggshell particles have been successfully utilized to create braking pads with above-average mechanical performance) [8]. Hybrids of composites produced using a combination of bone and palm kernel were also found to possess superior structural integrity and wear resistance compared to conventional materials [9]. All of these advances are intended to develop materials from previously discarded materials in order to achieve value-added engineering products while simultaneously addressing global environmental issues and supporting sustainable manufacturing processes. As highlighted by recent review studies, eco-friendly brake friction materials have become more significant than ever before, indicating that eco-friendly brake materials could replace current materials without sacrificing performances [10].

Research on modern-day tribology has reported that Natural Fibre Reinforced Composites (NFRC) have shown versatile and consistent coefficients of friction and good levels of wear under a variety of operational conditions, further demonstrating their ability to be used in various automotive applications [11]-[12].

Present research primarily pertains to Plant-based Reinforcements. Limited research has been conducted on using Animal Waste Materials, particularly from cow hoofs. Cow hoofs are a common waste by-product of slaughterhouse operations and present environmental and public health threat when disposed of, especially in many developing African nations. In previous studies, cow hoofs have shown a high potential for use in making composite materials [13]. However, extensive and systematic studies have not been conducted on the performance of cow hoofs in their use as Reinforcements in brake pad composite materials. The influence of Particle Size on critical composite performance properties (such as mechanical strength, moisture absorption, and thermal stability) in brake pad application have not been adequately investigated [14].

The current effort has been undertaken to develop and characterize epoxy-based asbestos-free brake pad composites containing cow hoof particulates and to evaluate the impact of particle size on their mechanical, physical, and thermal performance. The originality of this study includes the full use of cow hoofs as a Reinforcing Material in the production of brake pads with an emphasis on the systematic consideration of the impact of particle size on composite performance. The work provides environmentally and socially sustainable friction material development and engineering processes; and will allow for the viable use of waste vapour (and thus reduce landfill space utilization) and improve resource efficiency with engineering applications.

2.0 Materials and Method

2.1 Material Preparations and Reinforcements

The materials utilized for this study consist of the main components of a brake pad; Cow Hoofs (CH) as reinforcement, epoxy as a binder, Calcium Carbonate (CaCO_3) as a filler and graphite and Aluminum Oxide (Al_2O_3) as frictional additives. The reinforcement enhances the mechanical strength of the composite, while the binder ensures structural stability under mechanical and thermal loads. Fillers improve process ability during fabrication, whereas frictional additives regulate the coefficient of friction and wear behavior of the brake pad. Other materials used are distilled water and sodium hydroxide.

The CH was collected and soaked in a solution of water and detergent in order to loosen any dirt or other material that may have been stuck to it for at least 30 minutes. The reinforcement was then thoroughly washed and dried in the sun until it reached a constant weight before being pulverized in a milling machine. After pulverization, CH reinforcement was treated with a 10% solution of NaOH and then sun-dried until it reached a constant weight. This method was employed to improve the attachment properties of the reinforcement to the resin [14]. The treated reinforcement was then sieved through three different mesh sizes: 150 μm , 250 μm and 350 μm . The selection of these particle sizes is typically guided by both processing and performance considerations such as representation of fine-coarse spectrum, Interfacial behaviour, Tribological relevance and comparative analysis.

2.2 Development of Samples

The production of automotive brake pads involves several sequential unit operations, including the mixing of constituent materials, hot pressing, cooling, post-curing, and final finishing processes [15]-[16]. In this study, cow hoof powder, calcium carbonate, graphite, and aluminium oxide were carefully weighed and thoroughly blended in accordance with the proportions as presented in Table 1. Separately, the epoxy resin and hardener were properly mixed before being gradually introduced into the dry mixture. The mixture of the two components was then stirred manually for approximately five minutes to obtain uniform and homogeneous mixture. The result of mixing the mixture was then put into a metallic mould, covered in aluminium foil to provide an easier way to extract, or demould, the samples after processing. The mould with the resulting mixture was placed inside a hydraulic press and 11 N/mm² was applied to it at 90°C to ensure proper compaction and alignment of the resulting rubber samples.

Following this process, the samples were demoulded and post-cured in an electric oven for 2 hours at 150°C to provide improved bonding and overall mechanical integrity of the composites. The method used here, as described in [17], is very similar to that of other studies. The final formulation of the brake pad is summarised in Table 1, and was derived after 7 different preliminary trial compositions were performed to determine the optimum material combination in terms of mechanical strength, thermal stability and tribological performance. These trials were necessary to determine the optimal composition for fibreglass reinforcement with the resin; based on the results of the previous study [18]. Once the appropriate reinforcement for use with the brake pad was selected, it was then sieved using a set of three sieves (i.e. 150 μm , 250 μm , and 350 μm).

Table 1: Percentage Weight Composition of the Brake Pad Samples

Composition	Resin	Rn	CaCO ₃	Graphite	Al ₂ O ₃	Total
% wt	25	25	30	10	10	100



Plate 1: Cow Hooves

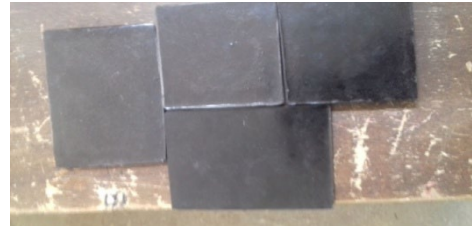


Plate 2: Brake Pad Sample

2.3 Characterization of the Developed Brake Pad

i. Water Absorption Test

A 24-hour water and oil absorption test was performed on the newly created brake pads to see how much fluid they can absorb and thus indicate how long they will be usable and how well they will perform under operating conditions. Each specimen was dried in an oven for 1 hour at 70°C to eliminate all moisture and obtain an accurate measurement of weight before the test. The specimens were individually weighed on a precise scale for initial mass. The specimens were placed into water maintained at a temperature of 30°C, and were permitted to remain submerged in the water for a period of 24 hours at which time they were removed from the water and allowed to drain of excess surface water before measuring final weight [15]. The same procedure was followed for testing oil absorption to determine how the brake pad material reacts with the fluid it will be lubricated with. The percentage of fluid absorbed was calculated based on the change in weight measured from the initial and final weights by using the formulas identified in [16]-[18].

$$\text{Absorption (\%)} = \frac{W_1 - W_0}{W_0} \times 100\% \quad (1)$$

ii. Compressive Strength

The compressive strength of a material is defined as its ability to carry loads that will decrease the size of the material and this property provides an indication of how strong brake pad composite materials will be used in service. This is important for characterizing the structural integrity of the composite brake pads under the conditions expected during use. The compressive characteristics of the developed samples were evaluated using an Enerpac Universal Hydraulic Digital Material Testing Machine, which has a load rating of 100 kN, as shown in Plate I. The tests were conducted according to ASTM D3410/D3410M Standards to ensure that the results were consistent and reliable. The samples were machined to 20 mm \times 20 mm \times 10 mm in order to conform to the dimension requirements of the test equipment and to the standards before testing. Each sample was then placed in between the compression platens of the machine and subjected to an increasing static load until the sample failed. The maximum load the sample could withstand before failing was generated electronically by the digital output of the machine, as reported in [5], and recorded for future analysis. The compressive strength of each sample was then determined by relating the failure load to the cross-sectional area of the specimen, according to the applicable formulation:

$$\sigma_c = \frac{P}{A} \quad (2)$$

Where σ_c = Compressive Strength in MPa; P = Applied Load in N; A = Cross Sectional Area in mm²

iii. Thermo-gravimetric Analysis

To determine the thermal decomposition and stability of the newly developed brake pad composites, thermogravimetric analysis (TGA) was performed. Because brake pads operate at high temperatures while in use, evaluating how well they maintain their physical characteristics will help in assessing the performance of these products. The thermogravimetric analysis was performed using a thermogravimetric analyzer (TGA). This equipment enables the user to measure the mass of a sample as a function of temperature, allowing for the evaluation of moisture evaporating from a sample, as well as other methods of volatilization, and thermal degradation [7].

The small portions of the samples used for testing typically weighed between 10 -14 mg each and were spread uniformly in an open pan that was 6.4 mm in diameter and 3.2 mm in height, thus allowing for accurate measurements and distribution of heat during testing. The samples were tested using a specified temperature program, where the temperature was increased from 30°C to 950°C at a constant rate of 10°C/min. To prevent oxidation from occurring and to ensure most of the weight loss seen was due to thermal decomposition, nitrogen gas was flowing into the furnace at a constant rate of 60 milliliters per minute under atmospheric pressure. Prior to each experimental run, nitrogen was used to purge out the furnace chamber for 30 minutes to create an inert atmosphere thereby reducing any oxidative reactions that might impact the results obtained. The analyzer in real time measured the weight change of the samples as the temperature increased and thermogravimetric (TG) curves were created. TG curves created during the experiment were then processed with Universal Analysis 2000 software from TA Instruments to allow for detailed evaluation of the thermal degradation phases and stability characteristics of brake pad materials created.

iv. Tribological Properties (Coefficient of Friction and Wear Rate)

In brake pad material design and testing, tribological performance is an important factor that impacts the effectiveness of braking performance, wear resistance, stability of operation, and safety in service. The tribological behaviours of the new cow hoof (CH) composite materials were assessed in this study via evaluations of the coefficient of friction (CoF) and the wear rate; both being useful in determining how much friction is produced by the materials and how much material is lost through wear under sliding contact.

The tests used a pin on disc tribometer, which is the most common piece of equipment used for simulating brake pad and disc surface contact interaction. The composite specimens were manufactured to size and placed in contact with a rotating disc under controlled test conditions. The tests assessed various combinations of loads and speeds to mimic actual brake conditions and to evaluate how the composites would respond to any changes in operational parameters. The tests consisted of recording the friction force developed at the interface while assessing the wear rate based on a measurement of material loss. This methodology provided a complete evaluation of the frictional stability and durability of the composite brake pads in realistic service conditions.

v. Microstructural Analysis

The microstructure of the cow hoof (CH) reinforced composites was studied by examining the internal structure and surface morphology of the CH reinforced brake pad composites that were developed. Specifically, the purpose of the microstructural analysis was to understand how well the reinforcement material was dispersed, how well the interfacial bonds were formed, and how the composites performed in terms of wear. Microstructural analysis of composites is essential because they are highly dependent on the structure of the composites to give them their mechanical, thermal and tribological properties.

Microstructural characterization was performed using Scanning Electron Microscopy (SEM) which provides high magnification, high-resolution images of the surface of materials. For microstructural characterization, small pieces of the brake pad samples were removed from the bulk material. The pieces were then cleaned of dust or other contaminants that could reduce the clarity of the images obtained. Where necessary, the samples were lightly polished to ensure a smooth, representative surface before examination. In order to increase the electrical conductivity of the samples and prevent them from charging under the electron beam, the samples were coated with a very thin layer of conductive material (e.g., gold or carbon). The samples were mounted onto specimen stubs for inspection inside the scanning electron microscope (SEM) chamber at the appropriate accelerating voltage, and the images of particle distribution, porosity, cracks, and wear features were captured using magnifications suitable for these types of features. More focus was directed toward worn surfaces of samples post-tribological testing to identify wear mechanisms and their interaction between samples. Furthermore, upon completion of the microstructural analysis, the corresponding mechanical and tribological properties of the composites were compared to give a complete representation of how particle size and distribution influence composite brake pad material performance.

3.0 Results and Discussions

3.1 Characterization Results of the Developed Brake Pad

i. Absorption Tests

The variation of water and oil absorption rates of the developed brake pad samples with respect to sieve grades is shown in figure 1. As can be seen from the results, both water and oil absorption increase progressively

with the increase in particle size; this is likely due to the increase in porosity that is associated with larger particle sizes. As the sieve grade increases, there is less packing efficiency between the cow hoof particulates and the resin matrix which results in the presence of micro voids and interconnected pores in the composite structure. These voids create channels for the ingress of fluids into the composite, thus increasing its absorption capacity.

The coarser samples had higher absorption values indicating poor interfacial bonding between the particles and reduced densification during processing. Previously published studies on natural fibre-based brake pads have also noted similar trends; i.e. increases in porosity have been directly correlated with increases in fluid uptake as well as decreases in durability [16]. Aigbodion *et al.* [5] and Edokpia *et al.* [8] also state that poor particle packing and voiding significantly affected fluid uptake characteristics of composite brake materials. Therefore, when producing brake pads, lower sieve sizes should be used to minimise porosity and maximise resistance to fluid intrusion.

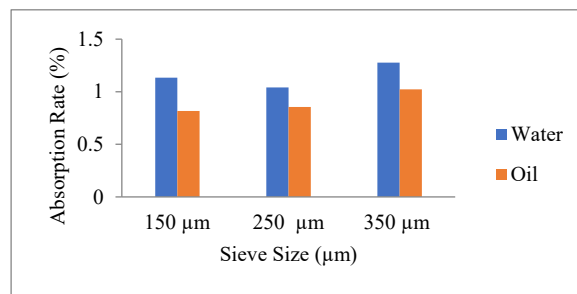


Figure 1: Variation of Absorption Rate with Sieve Grade

ii. Compressive Test

In Figure 2, it can be seen that the relationship of compressive strength versus sieve grade for the developed composites reveals that as the particle size becomes larger (increased sieve grade), the compressive strength decreases. The reason for this reduction in compressive strength is due to the reduction of the interfacial bonding between the resin matrix and the reinforcement particles at larger sieve grades. A larger particle will provide a smaller surface area for bonding to occur and therefore there is not as much interfacial adhesion and therefore will not be able to effectively transfer loads that are applied to the composite.

The increased size of the particles will also create points of stress concentration and disrupt uniform deformation throughout the matrix during compressive loading. The mechanical restraint of the larger particles restricts the movement and deformation of the resin, which leads to premature failure of the composite material. Similar results were found by Edokpia *et al.* [8] with reduced interfacial interaction and particle agglomeration being the primary contributors to the reduction in the mechanical properties of the composite; and it has been shown by other studies that the use of finer agro-waste materials in composite brake pad materials provides better mechanical properties due to the improved dispersion of the particles and a stronger matrix-to-particle interaction (5).

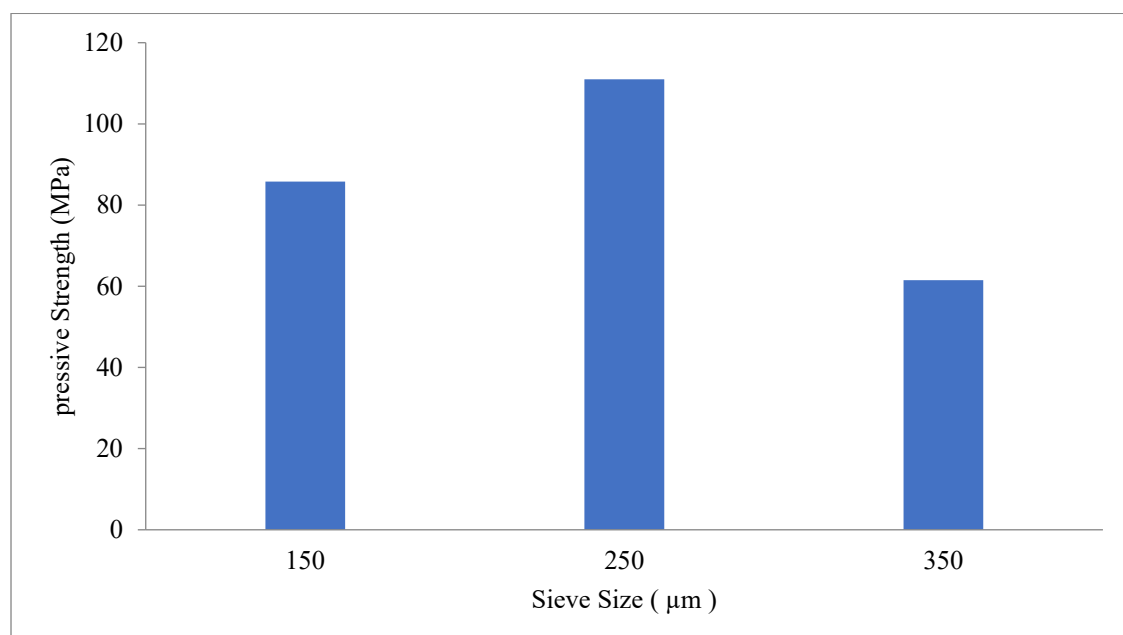


Figure 2: Variation of Compressive Strength with Sieve Grade

iii. Thermo-gravimetric Analysis

During braking there is an area of interface where heat is generated via the contact between the brake pad and the disc due to frictional forces. It is therefore important that the materials of the brake pads can survive these extreme thermal conditions without degradation [17]. Thermograms shown in Figures 3a-c indicate the thermal decomposition characteristics of composite materials that have been developed.

The sample of 150 μm (Figure 3a) revealed three main areas of weight loss. Area one (30-300°C) corresponds to the evaporation of moisture and volatiles with maximum degradation at approximately 140°C. Area two (300-380°C) is related to continued release of bound volatiles, with a peak degradation at about 330°C. Area three (380-450°C) relates to pyrolytic decomposition and oxidation of organic materials; with maximum degradation again at approximately 410°C.

The sample of 250 μm (Figure 3b) displays two stages of degradation. The first stage (30 - 350°C) corresponds with loss of moisture and volatiles, while the second stage (350 - 480°C) represents the thermal decomposition of the composite material itself, having maximum degradation at approximately 260°C and 370°C, respectively. The sample of 350 μm (Figure 3c) also has two-stage degradation; however, an initial stage (30-440°C) presents moisture and volatiles loss with maximum degradation at about 360°C, and a subsequent stage (440-620°C) pertains to oxidation and decomposition with maximum degradation at about 480°C.

Overall, all samples exhibit thermal stability up to temperatures exceeding 450°C, which is significantly higher than the typical operating temperature range of 300–400°C for automotive brake systems [1]. This indicates that the developed cow hoof-based composites possess sufficient thermal resistance for practical applications. Comparable thermal behaviour has been reported for other natural fibre-based brake materials [7] and [12], confirming the suitability of agro-waste reinforcements in high-temperature tribological systems.

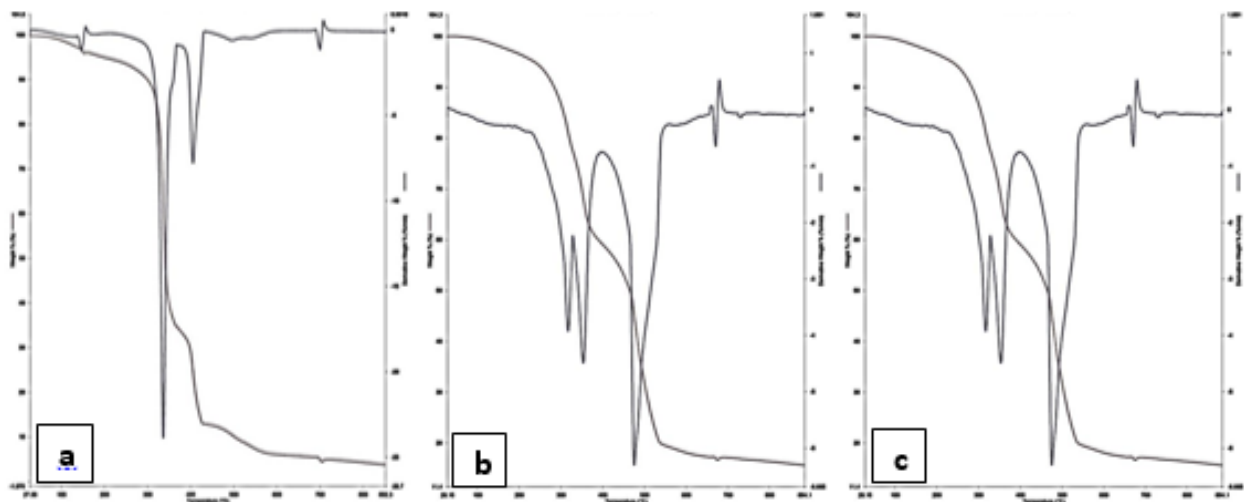


Figure 3: (a) 150 μm (b) 250 μm (c) 350 μm TGA/DTG Patterns of Developed Brake Pad with Different Sieve Grades

Figures 3a, b and c show the thermo-gravimetric analysis of the developed brake pads with 150, 250 and 350 μm sieve grades respectively. Figure 3a shows three zones of weight loss: 30°C to 300°C due to loss of moisture content and volatiles with maximum degradation at 140°C as witnessed in DTG curve, between 300°C to 380°C as a result of further removal of moisture content with maximum weight loss at 330°C and lastly between 380 to 450 (380 to 450? Unit?) Due to pyrolysis and oxidation with maximum weight loss at 410°C. Figure 3b shows degradation in two zones; 30°C to 350°C to loss of moisture content and volatile components with maximum degradation at 260°C and between 350°C to 480°C due to further removal of moisture content with maximum weight loss at 370°C as shown in DTG curve. Figure 3c shows two steps degradation; 30°C to 440°C due to loss of moisture content and volatile components with maximum weight loss at 360°C and between 440°C to 620°C due to further moisture content removal and oxidation with maximum degradation at 480°C as seen in DTG curve. In all the TGA graphs discussed above, it is observed that the mass of the developed brake pad decomposed at higher temperature range of 450°C to 620°C which is higher than the average brake temperature of 300°C – 400°C according to [1].

3.2 Comparison with Existing Brake Pad Materials

Table 2: Comparison of CH Based Brake Pad with other Experimental Brake Pad

Properties	Com Asb. B- BP	PK Based Formulation	Bagasse B- Formula	CBP B- Formula	CH Based Formulation
WA (%)	0.9	5.03	3.48	3.0	1.133-1.277
OA (%)	0.3	0.44	1.11	1.12	0.817-1.023
CS (MPa)	110	103.5	105.6	61.20	46.08-111.85

The comparative data presented in Table 2 show that the developed CH-based brake pads exhibit competitive properties when compared with conventional asbestos-based and other agro-waste-based formulations. The water absorption values (1.133–1.277%) are relatively low and fall within acceptable limits when compared to palm kernel and bagasse-based composites [4]-[5]. Likewise, both the oil absorption values as well as the compressive strength range (46.08 to 111.85 MPa) indicates that the produced composite should be able to meet performance expectations within intended service conditions. Additionally, these findings support that cow hoof particulate offers extensive potential as a matrix reinforcement for creating eco-friendly brake pads.

3.3 Tribological Properties (Coefficient of Friction and Wear Rate)

The tribological characteristics of the developed composites were tested using coefficient of friction (COF) and wear rate measurements while varying the loads and sliding speeds used in this study. It was observed that the COF measures for composite materials fall within the acceptable range of 0.62 to 0.79 (acceptable range for automotive brakes 0.6 - 0.75) [17]. The COF values from both lower load (10 N to 20 N) and sliding speeds (200 to 400 RPM) remained very similar to one another (0.63 to 0.72), illustrating that friction exists in a stable manner as a result of a well-formed, tight tribo-film at the contact interface.

For higher loads (30 N) and speeds (800 to 1000 RPM), the COF increased to approximately 0.79 with a corresponding large increase in wear rate (up to 1.065 mg/N). This change in the wear rates and increased COF are attributed to the failure of the protective tribo-film, thus leading to increased friction between surfaces and the prevalence of abrasive and adhesive wear mechanisms [14] and [17]. The wear rate is directly correlated with both the load applied and the sliding velocity that is used; therefore, when either of this increase, they promote similar conditions for softening of the matrix, particle removal from the composite.

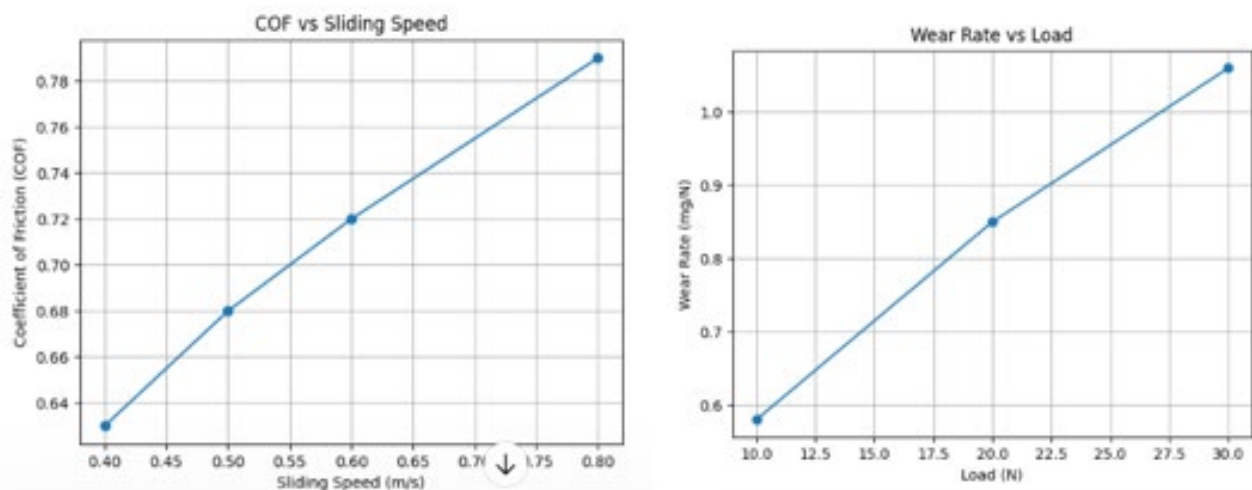


Figure 4: Tribological Properties (a) Coefficient of friction Vs Speed (b) Wear rate VS Load

This confirms the commonly documented relationship between wear loss and friction, with higher friction resulting in greater wear loss [14]. The CH-based composites also provide comparable overall tribological performance to other natural fibre-reinforced brake pads found in previous research [11] and [15], and would therefore likely function well in real-world braking applications.

3.4 SEM Microstructural Analysis

The worn surfaces of the composite brake pad materials developed in this project were electron-microscopically examined using scanning electron microscopy (SEM).

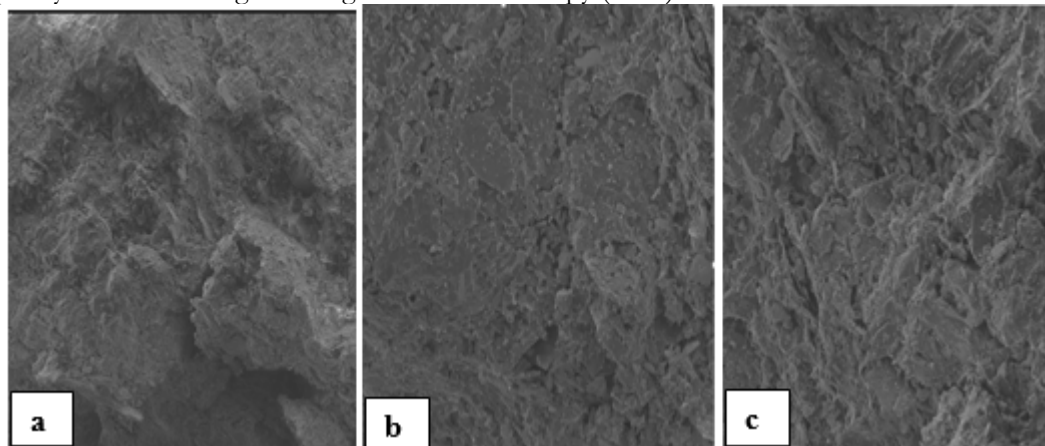


Plate 3: Microstructure of the Developed Brake Pad with Different Sieve Grades (a) 150, μm sieve grades (b) 250 μm sieve grade and (c) 350 μm sieve grade samples at 100X

The SEM images depicted in Plate 3 demonstrate the effects of particle size on both the internal structure and wear characteristics of the composite brake pad materials developed in this study. The differences in appearance of the 150 μm , 250 μm , and 350 μm sieve grades highlight the effect of particle size on surface features, bond quality, and overall tribological behaviour. In the 150 μm sample (Plate 3a), the structure appears to be dense and fairly uniform; the finer particles are evenly dispersed throughout the matrix of the sample. The uniformity of the spreading of the fine particles aids in maintaining a good interface between the particles and the binder, thereby enabling the stress generated during use to be transmitted more effectively and reducing the likelihood of structural deficiencies. The worn surface contains very few voids, little evidence of fracture growth, and almost no detachment of particles; all of which are indicators of improved wear resistance because the fine particles help to maintain a uniform friction layer and reduce the concentration of stress during operation [19]. Characteristics of the 250-micron sample (Plate 3b) show that the material possesses an overall coarser structure; however, it demonstrates less uniform particle size distribution compared to its finer counterparts. In certain regions, there are smaller voids present as well as some clustering of particles, which indicates that there are areas within the composite that have weak bonding characteristics. The wear characteristics observed reflect mild levels of abrasion; there are shallow groove features on the worn surface as well as instances of particle pull-out. The composite does maintain an adequate level of structural stability, so in general a 250-micron particle size appears to be an acceptable compromise between strength and frictional functionality [19].

The microstructure of the 350-micron sample (Plate 3c) shows a much rougher and less uniform configuration than that of the 250-micron sample. The larger particles have an irregular distribution pattern throughout the sample, resulting in clustered areas of larger particles, which decreases the strength of any bonds created in the composite. Higher levels of porosity, more substantial voids, and clear signs of particle separation can be seen in the microstructure image. The worn surface is highly damaged, exhibiting the presence of deep grooves, cracks and significant loss of particles due to wear mechanisms, which is typical for samples subjected to very high wear conditions. Thus, the larger particles tend to diminish the resistance of the composite to wear and therefore create a higher susceptibility to fatigue under frictional loads [19].

In summary, due to the composite material properties exhibited by the different sized particles tested, smaller-sized particles produce a more uniform structure with fewer defects; hence, they perform better when subjected to wear testing. Smaller particles create greater levels of bonding and subsequently contribute to the maintenance of a stable friction layer than do larger particles, thereby increasing the performance of the material. Consequently, either small or intermediate-sized particles will be optimal choices for improved performance in brake pad applications.

4.0 Conclusion

This study provides evidence that cow hoof particulates are a viable reinforcing agent for the manufacture of asbestos-free brake pads. The results showed that the physical, mechanical, thermal, and tribological properties of the composite materials were heavily influenced by the size of the cow hoof particulates. The larger the size of the particulates, the greater porosity of the composite material, which led to increased fluid absorption and reduced compressive strength due to the weaker bond of the interfacial bonds. Thermal analysis demonstrated that the

materials developed have sufficient thermal stability for use in braking, as they can withstand decomposition temperatures far above normal working conditions.

The part of the study that related to tribology showed that the frictional response of the composite materials was acceptable, but wear increased at higher operating conditions. Microstructural analysis confirmed that the composite materials produced from the cow hoof particulates were more homogeneous and free of defects when made from smaller sized particulates, which resulted in greater wear resistance and overall performance. The efficiency of the produced brake pads was 75% compared with other brake pads made from other materials, the CH based composite materials developed in this study had comparable properties, demonstrating their potential as sustainable and cost-effective alternative materials to asbestos based brake pad materials. Thus, this study introduces cow hoof particulates as a previously underutilized animal-waste reinforcement in epoxy-based brake pad composites and systematically establishes the influence of particle size on mechanical, thermal, and tribological behaviour, particularly linking tribofilm stability and wear mechanisms to microstructural characteristics.

It provides experimental evidence that finer cow hoof particles significantly enhance interfacial bonding, wear resistance, and overall performance, while also demonstrating thermal suitability (450–620 °C) and functional braking efficiency (78%), thereby advancing sustainable material alternatives for eco-friendly brake pad development. Furthermore, the study demonstrates that cow hoof is an excellent alternative material for the manufacture of high-performance, asbestos-free brake pads and is a low-cost, environmentally friendly option.

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