PRODUCTION AND CHARACTERIZATION OF HYBRID AUTOMOBILE BRAKE PAD

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ABSTRACT

A brake system is highly imperative for the safe control of an articulated automobile. One of the major components of the automobile system is brake pad which is currently imported into the Nigerian market. This study was aimed at producing brake pads from locally available materials to serve as an alternative to imported pads. Samples of brake pads were produced from a mixture of epoxy resin, kaolin, barium sulphate, steel fibre, fiberglass, silica, alumina, and graphite sourced from local markets. Three samples - A, B, and C – were moulded following the standard practice for brake pad production. The samples were characterized for microstructure, hardness, wear rate, ultimate tensile strength (UTS), and impact strength. The study established that the brake pad made from 16.3% epoxy resin, 13.8% kaolin, 32.6% barium sulphate, 6.5% steel fibre, 10.4% fiberglass, 6.8% silica, 9.2% alumina, and 4.4% graphite performed optimally with a hardness of 4.59 kg/m^2. The optimal brake pad had its wear rate lower than other samples after 210 s of load application, an ultimate tensile strength of 3.60 MPa and impact strength of 0.028 J/mm. SEM image of the sample indicates a homogenous distribution of the binder, fillers and reinforcing materials. Compared to sample B, the conventional brake pad had a higher Brinell hardness value of 18,592 kg/m^2. The results justified that the developed brake pads have sound tribological property as prominent characteristics. The study recommends the application of the optimally produced brake in automobiles for enhanced eco-user friendliness.

Keywords: *Hybrid Brake Pad; Automobile; Alumina; Steel Fibre; Abrasive*

INTRODUCTION

The imperativeness of the brake system in an automobile cannot be overemphasized because it facilitates the safe retardation or stoppage of an articulated automobile. For this action, brake pads are of utmost importance especially as it regards the safety of driver and other occupants (Borawski, 2020). The materials used for the manufacture of brake pad linings depend on the composition of the constituent elements which can either be categorized as metallic, semi-metallic, organic, or carbon-based (Lawal *et al.*, 2019). The use of asbestos became increasingly popular among brake pad manufacturers because of its sound absorption, average tensile strength, and heat resistance, and electrical and chemical damages. However, over the years, asbestos has been considered a carcinogen material that is known to cause malignant lung cancer, mesothelioma and asbestosis (Egeonu *et al.*, 2015; Abutu *et al.*, 2019). Other asbestos-related diseases include asbestos warts caused when the sharp fibers lodge in the skin and are overgrown causing benign callus-like growths (Anaidhuno *et al.*, 2017).

Studies have been directed at replacing products that wear out and release particles such as carcinogens to the atmosphere with materials that are not poisonous (Agunsoye *et al.,* 2018; Ige *et al.,* 2019; Ahmad *et al.,* 2021). Aside from being carcinogenic, asbestos is expensive as a raw material for the production of brake pads and brake lining (Borawski, 2020). Consequently, materials for effective braking systems must be safe, have good thermal properties, high heat capacity, good thermal conductivity, and the ability to withstand high temperatures (Ige *et al.*, 2019). Other pertinent factors are a high coefficient of friction, resistance to corrosion, high wear resistance, and good shear strength (Abdulrahman *et al.,* 2021). Due to these complex factors, composites that can be made by blending biomass materials are best suited for the production of brake pads. Several studies have been reported on the use of biomass for the production of brake pads.

Onyeneke *et al.* (2014) used locally sourced periwinkle and coconut shells as base materials to produce brake pads. The study established that the developed brake pad was comparable to Audi 90 model brake pad in terms of performance. Similarly, Anaidhuno *et al.* (2017) developed a vehicle brake pad using palm kernel, and coconut shells as base materials, epoxy resin as binder, carbon as fiber reinforcement, and cashew shell, copper, aluminum and zinc as abrasives while rubber was used as filler. The study concluded that, compared to the conventional brake pad material with a hardness of 80-85, bonding strength of 25-27 kg/cm^2 and wear rate of 0.03-0.08 mm/min, the developed composite brake pad had a similar hardness and bonding strength as well as a wear rate of 0.025-0.06 mm/min. The results indicated a lower wear rate compared to the conventional brake pad. Agunsoye *et al.,* (2018) produced brake pads from recycled ceramic tile composite using conventional casting techniques and reported improved friction resistance, lower wear rates and excellent thermal stability in comparison to Nissan Jeep Cherokee brake pad. Abdulrahman *et al.* (2021) also produced and characterized brake lining material from agro wastes (palm kernel shell, coconut shell, and canarium sweinfurthii shell powder). The brake pad proved more efficient than the conventional brake pad.

It is established from the literature that materials such as periwinkle, palm kernel, and coconut shells, recycled ceramic tile composite, canarium sweinfurthii shell, eggshell, graphite, aluminum oxide, and epoxy resin have been combined as parent material, binders, fillers, reinforcing agents, abrasives and lubricants to formulate brake pad materials (Ige *et al.,* 2019; Jensen et al., 2024). Other materials include carbon, copper, zinc and cashew nut shell, rubber-dusts-from-shoe, polyester resin, metal chips, carbides, sisal, oil, palm, kapok, bamboo, corn stalk, banana, abaca, sugarcane (bagasse), pineapple, flax, kenaf, jute, rice straw, araldite, and mild steel brass (Lawal *et al.,* 2019). The combinations have yielded improved brake pads compared to the conventional ones. However, the blend of resin as binder, barium sulphate and kaolin as fillers, steel fiber and fiberglass as reinforcing agents, silica and alumina as abrasive, and graphite as lubricant has not been reported. Therefore, this study aimed to produce and characterize hybrid automobile brake pads using locally sourced materials.

METHODOLOGY

Materials Selection

Alumina, barium-sulphate, kaolin, silica, and epoxy resin were mixed, crushed to fine powder with a locally made pestle and mortar, and sieved with a 2 µm mesh. Pieces of steel were obtained from the Mechanical Engineering workshop at the University of Ilorin and ground into particles using a locally made-grinding machine. The fiberglass was manually chopped into 6 mm-long pieces while sulphate was treated with sulphuric acid to ensure a highly pure barium sulphate to withstand the braking temperature of the brake pad. Reason for this is that sulphate has a high melting point of 1580 °C and can withstand high temperature Sulphuric acid was also used to lower the hardness of alumina and steel granules so that the brake pad produced has sufficient hardness to abrade the rotor. The images of all materials used for the brake pad production are presented in Figure 1. Three experimental formulations (A, B, and C) were prepared as presented in Table 1 (Abdulkareem et al., 2019). All compositions were measured with Camry digital weighing balance (Model No: ACS-15-SC71).

Figure 1: Filler [(a) Kaolin (c) Barium sulphate]; *Binder* [(b) Epoxy Resin]; *Reinforcing Materials* [(d) Steel fibre (e) Fibre Glass]; *Abrasive Materials* [(f) Silica (g) Alumina]; *Lubricant* [(h) Graphite].

Table 1: Experimental formulations (wt.%)

Sample	**Composition (wt.%)**								
	Binder	**Fillers**		**Reinforcement**		**Abrasives**		**Lubricant**	**Total (%)**
	Epoxy Resin	Kaolin	Barium Sulphate	Steel fibre	Fibre glass	Silica	Alumina	Graphite	
A	15.7	10.2	36.8	5.6	7.6	7.8	11.5	4.8	100.0
B	16.3	13.8	32.6	6.5	10.4	6.8	9.2	4.4	100.0
C	17.1	14.6	30.4	6.9	12.3	5.9	8.6	4.2	100.0

Moulding of Brake Pad

Samples of brake pads were moulded using a fabricated mild steel mould made of three parts: cylinder bracket (61 mm diameter by 90 mm height), base (13 mm thickness by 130 mm), and plunger (piston) (Figure 2). The base of the mould was designed to accommodate the cylinder bracket firmly and to secure its content during force exertion. The piston - 92 mm in height, 60.50 mm base diameter and 12 mm thick - was designed to fit into the cylinder bracket via which pressure was exerted to compress the sample. The material components of each sample were rigorously mixed, transferred into the mould and compressed severally under 30kN pressure in a compression moulding machine (Model No: 0577-86365889). After the samples were ejected from the machine, they were cured at room temperature for 18 hours (Figure 3(a)) and hardened by heat treatment at 150 $^{\circ}$C for 3 hours in a laboratory oven (Model No: DOF-230F) (Mullaikodi et al., 2020). The brake samples were finally cleaned of rough edges and surface-smoothened to achieve uniform thickness and an acceptable surface finish (Figure 3(b)).

Figure 2: Mould comprising of the cylinder bracket, base, and plunger

(Source: Present Study, 2024)

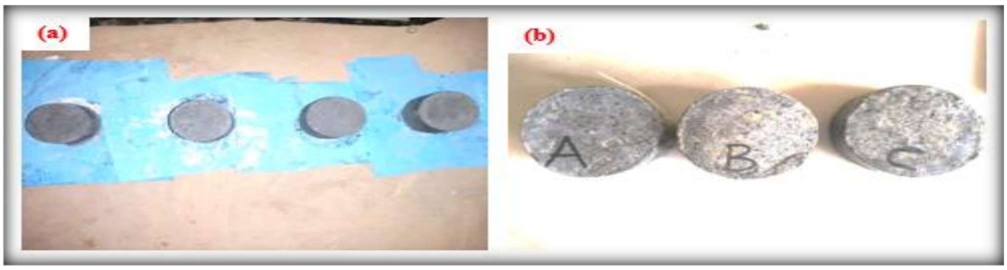

Figure 3: (a) Samples curing after moulding (b) Finished product of the samples

(Source: Present Study, 2024)

Characterizations of the Brake Pad Samples

The microstructural analysis, impact and wear rate tests were conducted on the samples of the brake pads to obtain information about the microstructure and mechanical properties of the samples. The characteristics of the brake pads were validated by comparing them with those of a conventional brake pad.

Microstructural and Elemental Analyses

Microstructural study and elemental analysis were conducted on the brake samples using JEOL scanning electron microscope (Model No: JSM-6510) which had an energy-dispersive X-ray attachment. The morphology of the internal structures and the chemical elements of the samples were evaluated.

Wear Rate

The wear rate of the samples was tested using a Martindale abrasion testing device (Model STM: 105 and developed by Satra Technology). The test was conducted at an operating speed of 50 rev/min, a pre-set cycle of 1000 in 1200 s, and a pressure of 1.26 MPa. The sliding distance (D) and wear rate (Wr) were obtained from Equations (1) and (2), respectively (Abdulrahman et. al., 2021).

$$\text{Sliding distance (D)} = 2\pi Ndt \qquad (1)$$

$$W_r = \frac{\text{Loss in weight (wl)}}{\text{Sliding distance (D)}} \ (\text{mg/m}) \qquad (2)$$

where d, t and N are the disk diameter, time of exposure of the specimen to abrasion test and radial speed, respectively.

Mechanical Properties

The hardness value, tensile and impact strengths were evaluated for all samples. The hardness test was conducted using a direct durometer (Model No: 5019: 01554) while the tensile strength was measured with a tensometer (Monsanto; Serial No-05232) following ASTM D638 type IV standard. The ultimate tensile strength (UTS) was evaluated from the ratio of maximum load to cross-section area. Charpy impact test was conducted on an impact machine (Model No: 412-07-0715269C) based on ASTM E23 standard. The test sample had a size of 55 mm × 10 mm × 10 mm with a notch angle of 45°, a notch radius of 0.25 mm, and a notch depth of 2 mm along the base. The impact strength was evaluated using Equation (3) (Abutu et al., 2019).

$$\text{Impact strength} = \frac{\text{Energy Absorbed}}{\text{Thickness of the specimen}} \qquad (3)$$

RESULTS AND DISCUSSION

Brinell Hardness Testing

Figure 4 shows that the Brinell hardness values of the samples increased with the weight of the reinforcing fibres and binder. Based on the results, sample A has the lowest hardness (3412±2.3 kg/m^2) while sample C has the highest (7,919±1.4 kg/m^2). However, the conventional brake pad has an average Brinell hardness value of 18,592±1.1 kg/m^2 which is largely attributed to the high percentage of carbon content (Mullaikodi et al., 2020). Consequently, additional carbon must be included to raise the hardness of the developed brake pads. The error bars indicate that the hardness is most uniform for sample C and least uniform for sample A.

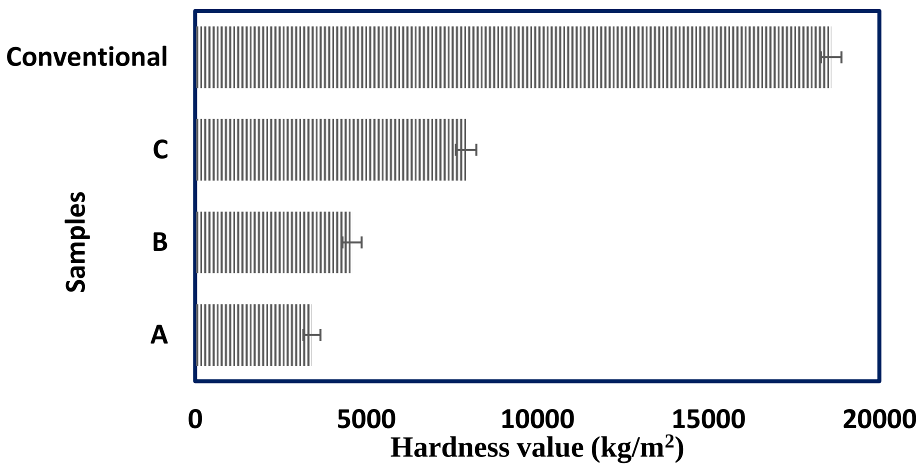

Figure 4: Hardness of the produced samples compared with conventional.

Wear Rate, Ultimate Tensile Strength (UTS) and Impact Test

Figure 5 presents the wear rates of the three brake pad samples that were subjected to a constant load of 35 N for 5 minutes with 30-second intervals. As Ammar et al. (2023) point out, thermomechanical loading is crucial for evaluating brake pad performance. Figure 5 shows a direct proportionality between wear rate and loading duration. Wear rate values for all samples increased as the loading time extended. The figure also showcases the wear behavior of each pad over time. For example, at 180 seconds under the same load, samples A, B, and C have wear rates of 0.039 mg/m, 0.041 mg/m, and 0.043 mg/m, respectively. These values peaked at 5 minutes with 0.087 mg/m, 0.074 mg/m, and 0.091 mg/m for samples A, B, and C, respectively.

Nandiyanto et al. (2023) emphasize the importance of stable friction and wear rate for effective brake pads over extended use. The developed brake pads demonstrate these qualities under consistent testing conditions, exhibiting minimal material loss. This positive performance can likely be attributed to the agglomerates used as binders, particularly the resin and kaolin (Nandiyanto et al., 2023). These findings suggest the suitability of resin and kaolin as effective binders for brake pad production. Figure 6 presents the ultimate tensile strengths (UTS) of the samples which were 2.0217 MPa, 3.6041 MPa, and 1.1195 MPa for samples A, B, and C, respectively. The impact test results (also in Figure 6) yielded values of 0.0233 J/mm, 0.0227 J/mm, and 0.0305 J/mm for samples A, B, and C, respectively. Analyzing Figures 5 and 6 together reveals a proportional relationship between wear rate and ultimate tensile strength. These results collectively support the conclusion that the developed brake pads possess strong tribological properties, a key characteristic for effective braking.

Furthermore, the absence of grooves on the surface of the brake pads, as observed by Abutu et al. (2019) and Ammar et al. (2023) to potentially hinder mechanical properties, might be another contributing factor to the positive mechanical performance exhibited by the brake pads developed in this study. It's important to note that the error bars in Figures 5 and 6 represent the uncertainty associated with the experimental data, the small errors indicate the precision of the measurements.

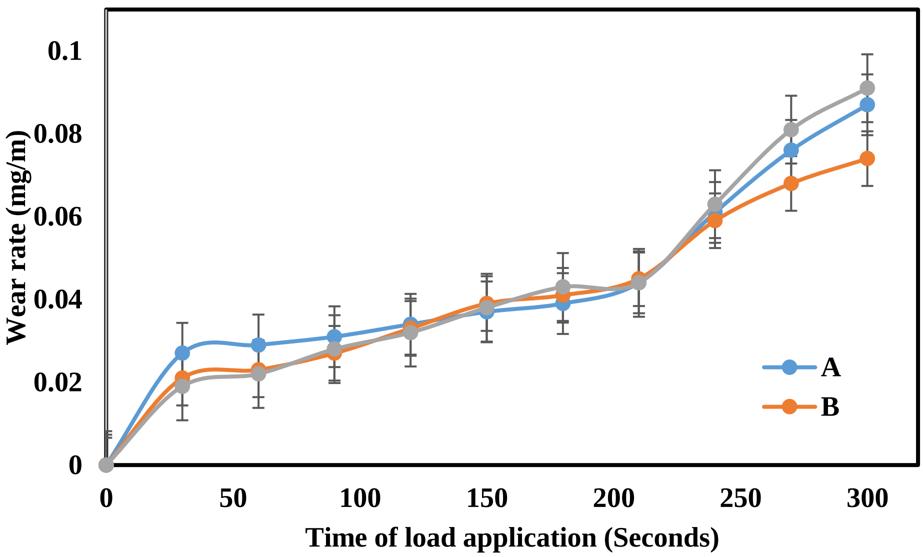

Figure 5: Wear rate over some period of load application

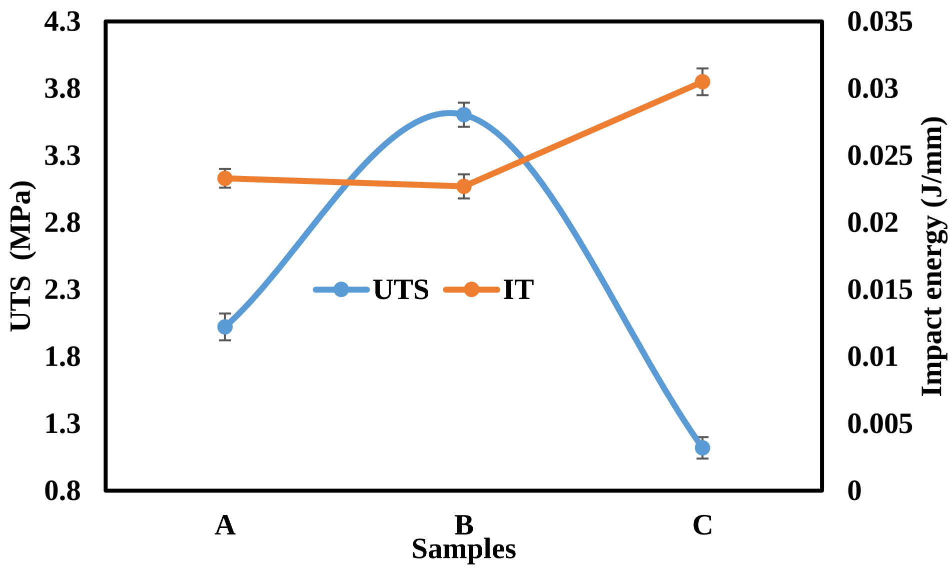

Figure 6: Results of ultimate tensile strength and impact test

Microstructural And Elemental Analysis Of The Brake Samples

Figure 7 shows the SEM images of the three samples along with that of a conventional brake pad (control). For sample A (Figure 7a), the binder is nearly uniformly distributed enabling a low failure rate and moderate fracture strength. For Sample B (Figure 7b), the failure rate is also expected to be low because of the increased volume of the binder and uniform distribution of all materials. A poor attachment between the fibres and the matrix can be seen in Figure 7c confirming the no-uniform distribution of the binder and insufficient compaction of the samples. Consequently, the failure rate is expected to be high. For the conventional brake pad (Figure 7d), large carbon particles were seen to be uniformly distributed although relatively poor adhesion was noted. The presence of pores also indicates that sufficient pressure was not applied during compaction. However, sample B appears to be more homogenous than others implying that the constituents were thoroughly mixed before moulding. It is an indication of a single solid phase having no particle agglomeration (Ilie, and Cristescu, 2022).

Previous studies have reported that the performance of brake pad is largely influenced by the homogeneity and isotropy of their material properties (Agunsoye *et al.,* 2018; Saindane *et al.,* 2023). These properties are exemplified by sample B, thus substantiating the integrity of the brake pad. Compared to sample B, samples A and C exhibit discernable differences as seen in Figure 7a and Figure 7c, since a whole lot of disjointed particles are observable because the particles lack perfect homogeneity. Such a characteristic is due to abrasion of the moving disc when in contact with the brake pad at the instance of wear analysis. These could affect the optimum service condition of the brake pads whereby reduced efficiency and effectiveness dominate.

The dark regions specified by red arrows (X) in Figure 7a signified agglomerated particles and imply that the binder was not perfectly mixed together thus depicting no homogeneity. However, those spots were not as dominant in sample C as observed in sample B. Thus, making sample C have more structural integrity compared to sample B. The agglomerates within those regions exhibit weak bonding because of an insufficient quantity of binder to join the individual particles. Therefore, for enhanced mixing of agglomerates, the electric or automated stirrer is advised for use, since manual stirring is disadvantageous. During the wear analysis, the structure of region X might experience much stress concentration and interference with stress distribution and transfer (Asuke *et al.,* 2014; Agunsoye *et al.,* 2018). The produced brake pads displayed higher wear resistance compared to the conventional pad counterpart. This observation can be attributed to various types of additives and other agglomerates used in the production of each brake pad.

Table 2 shows the elemental composition of all the samples as obtained from EDX analysis. The percentage of carbon, calcium and oxygen contents were in the range of 0 – 0.81, 0.35 - 0.86 and 0 - 0.36, respectively while those of conventional brake pads were 26, 17.59, and 0.63, respectively (Table 2). The 26.0 wt% carbon content in the conventional brake pad provided the needed hardness value. Sample B had 0.81wt% carbon content and was expected to be harder than other samples with zero carbon. The presence of carbon, calcium, and oxygen indicates that the brake pads were produced from both organic and inorganic materials (Irawan et al., 2022) (Table 2).

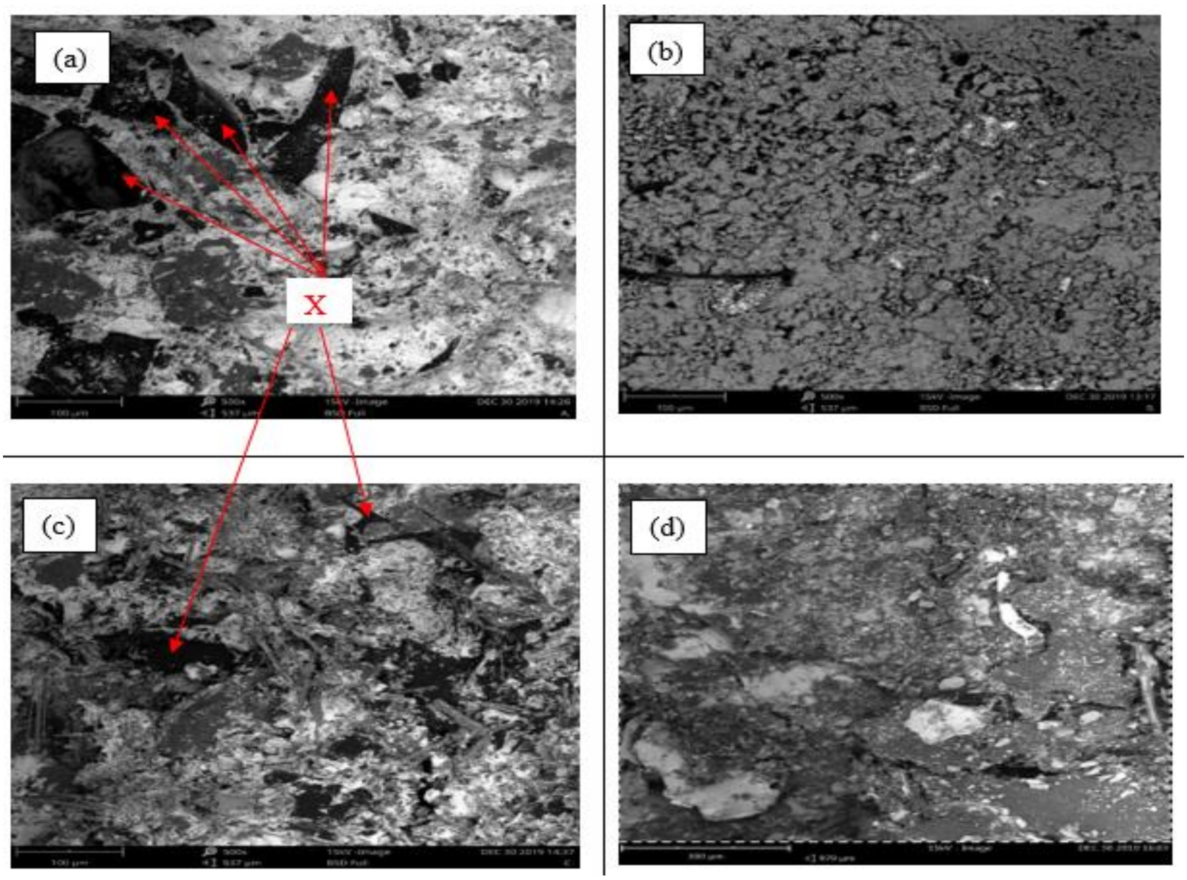

Figure 7: The SEM Images (a) Sample A (b) Sample B (c) Sample C (d) Conventional brake pad

Table 2: Elemental composition for all samples

Elements	Sample A	Sample B	Sample C	Conventional
	Percentage Weight Concentration (wt.%)			
Carbon	0.00	0.81	0.00	26.00
Calcium	0.86	0.35	3.11	17.59
Iron	0.41	9.81	1.88	11.77
Silicon	3.24	0.37	6.57	10.91
Silver	2.00	1.51	2.29	5.74
Potassium	0.93	0.54	1.25	5.18
Magnesium	0.28	0.17	0.46	4.79
Barium	59.03	0.00	53.71	4.31
Aluminum	4.43	0.42	5.91	4.08
Zinc	0.00	0.00	0.00	2.89
Sulfur	0.00	0.43	7.73	2.53
Titanium	3.31	0.72	4.65	1.73
Phosphorus	0.07	0.38	0.67	0.94
Sodium	0.16	0.16	0.30	0.68
Oxygen	0.00	0.36	0.00	0.63
Nitrogen	0.00	0.00	0.00	0.24
Molybdenum	20.59	0.00	0.00	0.00
Tungsten	3.94	0.00	10.79	0.00
Chlorine	0.64	0.59	0.68	0.00
Zirconium	0.12	0.00	0.00	0.00
Tin	0.00	1.69	0.00	0.00
Chromium	0.00	1.01	0.00	0.00
Vanadium	0.00	0.68	0.00	0.00

Comparison of Brake Pad Materials Between the Current and Previous Studies

Table 3 compares the materials used in this study with those employed in previous research. It highlights that while various material categories exist for brake pad production (parent materials, binders, fillers, etc.), none of the reviewed studies utilized all categories. Notably, all studies included at least one binder, with epoxy resin being the most common. In contrast, this study adopted a unique combination filler (kaolin and barium sulphate) to potentially enhance performance.

For reinforcing agents, steel was used in this study, aligning with Nathan et al. (2021). However, while their study incorporated cast iron, this study employed fiberglass, demonstrating potentially superior effectiveness. This study also introduced novel abrasive materials (silica and alumina) and a new filler (barium sulfate) not found in previous research.

Table 3: Materials used by previous studies for brake pad production compared to the present study

Author	Parent material	Binders	Fillers	Reinforcement Agents	Abrasives	Lubricants
Onyeneke *et al.*, (2014)	Palm kernel, and coconut shell	Araldite and epoxy resin	Rubber-dusts-from-shoe	Carbon	Aluminum, copper, zinc, and cashew nut shell	N/A
Egeonu *et al.*, (2015)	Palm kernel shell, and coconut shell	Polyester resin	N/A	N/A	Metal chips and carbides	Graphite
Anaidhuno *et al.*, (2017)	Palm kernel, and coconut shell	Epoxy resin (araldite)	Rubber-dusts-from-shoe	Carbon	Aluminum, copper, zinc, and cashew nut shell	N/A
Agunsoye *et al.*, (2018)	N/A	Gum arabic	Steel slag	N/A	Aluminum chips	Graphite
Abutu *et al.*, (2019)	N/A	Epoxy resin	N/A	Coconut shell	Aluminum oxide	Graphite
Nathan *et al.*, (2021)	N/A	Epoxy resin	Coconut, cashew nut, and egg shell periwinkle shell	Mild steel and cast iron	Brass	N/A
Abdulrahman *et al.*, (2021)	Palm kernel shell, coconut shell, and canarium sweinfurthii shell	Epoxy resin	Carbonate, metal filings and graphite	N/A	N/A	N/A
Present Study, (2024)	N/A	Epoxy resin	Kaolin and Barium sulphate	Steel fibre and fibre glass	Silica and alumina	Graphite

N/A: Not Applicable to the study.

Interestingly, graphite emerged as the common lubricant across all studies, suggesting its continued effectiveness in brake pad production (Onyeneke et al., 2014; Egeonu et al., 2015; etc.).

CONCLUSION AND RECOMMENDATIONS

This study successfully developed and characterized high-performance brake pads using readily available local materials. The formulated pad achieved a promising wear rate (0.074 mg/m), ultimate tensile strength (3.6041 MPa), and hardness (5095 kg/m^2). While these results fall short of conventional brake pads in some aspects, the composition offers a strong foundation for further development. Future research efforts focused on optimizing the material ratios could lead to a locally-sourced brake pad that rivals commercially available options, promoting both economic and environmental sustainability.

Data Availability

Data used in this study is domiciled with the corresponding author and will be made available when requested.

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Author Contributions

O.O.A. conceived, researched, and performed experimentations pertaining to this study. A.T.K. supervised and criticized the work. A.T.B. contributed to the scientific discussion (SEM) of the manuscript. F.M.O. produced the first draft of the manuscript and discussed the results. A.A.O. and A.A.A. reviewed and contributed to the scientific discussion (including the graph plotting) of the manuscript. A.O.O. contributed to the methods presented in the manuscript. O.H.D. and I.P.P updated the introduction of the manuscript and results discussions. All authors reviewed the manuscript.