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BIOMASS-BASED COMPOSITES FOR BRAKE PADS: A REVIEW

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ABSTRACT

There is a growing need to develop automobile brake pad materials from sustainable sources. The study of substitute brake pad materials from sustainable sources is an area that requires immediate attention. This is because previous materials used (such as asbestos) are known to have carcinogenic effects. Several studies have investigated alternative materials to asbestos for brake pads. This review paper presents some of the most appropriate environmentally friendly and optimal composites for brake pads. Biomass-based composites from agricultural waste such as natural fibers waste are reviewed. This paper also surveyed the use of substitute materials as filler and binder, such as epoxy resin, phenolic resins, and other adhesives.

Key words: Brake pad, fillers, Natural fiber composite, Agricultural waste, Material properties.

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1. INTRODUCTION

In the past few years several studies have been conducted on the development of non-asbestos brake pads. Uses of palm kernel shell, palm kernel fiber and other biomass precursors have been investigated [1]. The present trend in research for asbestos-free brake pads is to use industrial or agricultural waste (agro-waste) as a raw material source for composite development [2] [3] [4]. Recently, international efforts to address environmental issues and the need to protect the environment has drawn research focus to the use of natural fibers in several applications, including brake pads. Typically, brake pads contain asbestos embedded in a polymer matrix with several other ingredients. Due to its carcinogenic effects on human health and its other harmful properties, the use of asbestos is increasingly being avoided, and therefore new non-asbestos materials and brake pads have been developed [5-8].

The brake pad is one of the most important components of an automobile braking system, as its helps in the conversion of a vehicle's kinetic energy to heat energy. The types of automotive brake pads that are in the market are characterized by metallic materials, semi-metallic materials or non-asbestos organic (NAO) materials [9]. According to Idris et al. [10], a brake pad is a steel back-plate with a friction material bound to the surface facing disk. The effectiveness and performance of brake pads are absolutely dependent on the frictional material used in the process of its manufacture [11]. In recent years, extensive research has focused on environmentally friendly brake pad composites that use natural fiber from agro-waste as a replacement for asbestos fibers [12].

For more than a decade, natural fibers have been used as reinforcing materials [13]. In addition, composite materials have evolved into a cost-effective and potentially eco-friendly substitute for synthetic fiber reinforced composites for use in various parts of an automobile. The availability, comfort and low cost of natural fibers in industrial use have attracted many researchers to study their suitability in meeting the basic specifications of well-reinforced polymer composites for tribological and other applications [14].

Over the years, the production of composite materials worldwide has grown significantly, which means many industries and technology sectors now use the newly formulated polymer composites materials which have successfully replaced traditional composite materials [15]. The investigation of new materials, especially agro-waste, has led to the development of new and low-cost options for the development of brake pads which are commercially viable and environmentally acceptable, including all the properties required.

In addition, studies which investigated the properties of selected agro-waste are reviewed in regard to their application as filler and binder.

2. AGRICULTURAL WASTE

Fibers derived from agro-waste have economic significance and cultural impact throughout the world [16]. Such fibers also have great potential as composite materials because of their high strength, low cost, eco-friendly nature, availability, and sustainability [17, 18]. Fibers derived from agricultural waste have many properties with potential for industrial application, which have led to a great deal of research on how to channel them to useful materials while taking human health and environmental safety into consideration. Agricultural waste, also referred to as biomass, is a potential renewable energy source with several applications which in building materials and multipurpose materials for automobile applications. The use of organic waste and residual materials in polymer composites represents an eco-friendly and significantly high-value substitute [19]. Table 1 shows some agricultural products which have potential as natural fiber resources and their countries of origin

Table 1. Biomass and their countries of origin: Agricultural products as potential natural fiber resources

	Brazil	**China**	**India**	**Indonesia**	**Malaysia**	**Philippine**	**Thailand**	**USA**	**Vietnam**
Banana	6.90	10.55	24.87	6.19	0.335	9.23	1.65	0.008	1.56
Coconut	2.82	0.250	11.93	18.30	0.605	15.35	1.01	NA	1.31
Pineapple	2.48	1.00	1.46	1.78	0.334	2.40	2.65	0.180	0.540
Sugarcane	0.739	125.54	341.20	33.70	0.830	31.87	100.10	27.91	20.08
Rice	11.76	203.29	159.20	71.28	2.63	18.44	38.79	8.63	44.04
Oil palm fruit	1.34	0.670	NA	120.00	100.00	0.473	12.81	NA	NA
Jute	26.71	0.17	1.98	0.007	0.002	0.002	0.06	NA	0.02
Kenaf	14.20	0.08	0.12	4.35	0.01	NA	1.30	NA	8.20
Flax	0.71	0.47	0.22	NA	NA	0.002	0.01	0.004	NA
Sisal	0.25	0.15	0.21	0.03	NA	NA	0.003	NA	0.01
Abaca	1.20	0.65	NA	0.05	NA	0.08	NA	NA	0.01
Kapok	NA	0.06	NA	0.03	0.008	NA	0.07	NA	0.003

Agricultural waste as shown in Figure 1 can be found in many plants, for example oil palm tree, corn stalks, bagasse, bamboo, coir (coconut shell), sugarcane pineapple, banana, rice husk, rice straw and plants (stem, leaf, seed, fruit, stem, grass, reed) [17]. Only 10 % of the potential of these natural fibers are being harnessed and used as alternative raw materials in industry, where the most common applications include bio-composites, bio-medical, automotive parts, and others [20]. The most important fiber waste produced by agricultural activities are cellulose fibers (CF) which have the potential to enhance materials because of their easy availability, lightweight, renewable, degradable, low abrasive properties, and low cost [17, 18, 20]. Cellulose fibers (CF) occurs in combination with other materials for instance lignin, hemicelluloses and pectin [21]. Agro-waste is the most abundant form of natural fiber and has been used in many areas of modern industry These materials vary in relation to conditions of growth and harvesting [22].

Figure 1. Agricultural waste

2.1. Properties of Agricultural Biomass

For more than two decades the characteristics of biomass have been investigated. However, the properties of natural fibers have not been enumerated consistently because of the different fibers utilized, different moisture conditions introduced, and different testing methods. Researchers agree that the properties of agricultural biomass are decided by many variables such as its structure, chemical composition, cell dimensions, microfibril angle, physical properties and mechanical properties. These properties vary widely among plant species and even in the same plant [23]. It is necessary to understand the properties of the fibers in order to elaborate on the use of natural fibers for composites so as to improve their performance.

2.1.1. Chemical Properties

According to Kumar et al. [24], agricultural biomass is mainly made of cellulose, hemicellulose, and lignin, as well as small amounts of pectin, protein, and ash. Cellulose is a semi-crystalline polysaccharide composed of D-anhydroglucose and glycosidic bonds. It offers strength, stiffness and structural stability to the fiber, helping to maintain the structure of the plant, and serves as a determining factor in its mechanical properties. Hemicellulose is a branched and fully amorphous polymer. Lignin is a complex hydrocarbon polymer with aliphatic and aromatic components. Lignin is linked with hemicellulose in agricultural plant cells and plays a role in the natural decay resistance of agro-biomass materials [25]. Table 2 shows the variability in cell wall composition in biomass. The chemical properties of agro-biomass as shown in Table 4 indicates that the polymer content is highly variable, depending on the plant species. The composition, structure and biomass properties depend on the age of the plant, conditions of the soil and other environmental factors which include humidity, stress, and temperature [26]. The polymer chemistry of these fibers affect their characteristics, functionalities and properties [27].

Table 2. Agricultural biomass chemical properties

Composition (%)					
Type of biomass	**Cellulose**	**Extractive**	**Hemicellulose**	**Lignin**	**Reference**
Sisal	43.85-56.63	2	21.12-24.53	7.21-9.20	[28]
Oil palm	44.20-49.60	4	18.30-33.54	17.30-26.51	[26, 29]
Kapok	65.63-69.87		6.66-10.49	5.46-5.63	[30, 31]
Bamboo	73	3	12	10	[26]
Corn stalks	38.33-40.31	5	25.21-32.22	7.32-21.45	[28, 32]
Banana	60.25-65.21	-	48.20-59.2	5.55-10.35	[33, 34]
Abaca	69.23-70.64		21.22-21.97	5.15-5.87	[35]
Sugarcane (Bagasse)	55.60-57.40	10	23.90-24.50	24.35-26.30	[28, 36, 37]
Pineapple	70.55-82.31		18.73-21.90	5.35-12.33	[38]
Flax	69.22-71.65	6	18.31-18.69	3.05-2.56	[28, 35]
Kenaf	37.50-63.00	6.4	15.10-21.40	18.00-24.30	[35, 39, 40]
Jute	69.21-72.35	4	12.55-13.65	12.67-13.21	[28, 35]
Rice straw	28.42-48.33	17	23.22-28.45	12.65-16.72	[32, 41]
Coconut (coir)	36.62-43.21		0.15-0.25	41.23-45.33	[42]

2.1.2. Physical and Mechanical Properties

The physical and mechanical properties of fiber are highly dependent on the growing conditions, chemical composition, extraction methods and its ratio Cristaldi et al. [43] and Huang et al [44]. Table 5 presents a summary of the mechanical and physical properties of different biomasses.

2.1.2.1. Physical Properties

The properties of biomass fibers are strongly affected by their individual material, which play an important role in the consideration of such materials in multidisciplinary applications. Biomass fiber properties associated with important variables include fiber structure, microfibril angle, cell dimension and defects [45]. John and Thomas [46] stated that origin, source, species, and fiber maturity are determined by the size of a single cell in a biomass fiber. The properties of an end product, such as tensile strength, tear strength, drainage, adhesion and stress distribution, are highly dependent on the structural properties of the fiber, particularly fiber length, fiber width and cell wall thickness [47, 48]. In addition, the lumen structure affects the bulk density of fibers, which affects the thermal conductivity and acoustic factors of the fiber end product [49].

2.1.2.2. Mechanical Properties

The processing of natural fibers can occur in various ways to produce reinforcing elements with different mechanical properties. The mechanical properties of natural fibers are affected by many factors, for example, whether fiber bundles or ultimate fibers are being tested. The mechanical properties of the types of fibers from different sources are clearly illustrated (Table 3) while large variation in the mechanical properties of biomass has become a key concern when it comes to commercial use. The large changes in tensile properties during plant growth are also a disadvantage for all-natural products, which is affected by species, fiber structure and environmental conditions.

Table 3. Physical and mechanical properties of certain agricultural waste fibers

Types of fiber	Density gm^{-3}	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	References
Banana	0.65-1.36	51.6-55.2	3.00-3.78	1.21-3.55	[50] [51] [52]
Oil palm	0.7-1.55	227.5-278.4	2.7-3.2	2.13-5.00	[47]
Bagasse	0.31-1.25	257.3-290.5	15-18	6.20-8.2	[37, 53]
Corn stalks	0.21-0.38	33.40-34.80	4.10-4.50	1.90-2.30	[54]
Jute	1.3-1.45	300-700	20-50	1.69-1.83	[55] [56] [57]
Pineapple	1.25-1.60	166-175	5.51-6.76	2.78-3.34	[50]
Coconut (coir)	0.67-1.15	173.5-175.0	4.0-6.0	27.21-32.32	[50] [52]
Rice straw	0.86-0.87	435-450	24.67-26.33	2.11-2.25	[58] [59]
Sisal	1.45-1.5	300-500	10-30	4.10-4.3	[55] [56] [57]
Kapok	0.68-1.47	80.3-111.5	4.56-5.12	1.20-1.75	[60, 61]
Abaca	1.42-1.65	879-980	38-45	9-11	[55]
Flax	1.27-1.55	500-900	50-70	2.70-3.6	[57] [62]
Kenaf	0.15-0.55	295-955	23.1-27.1	1.56-1.78	[63, 64]
Bamboo	0.6–1.1	360.5–590.3	22.2–54.2	4.0–7.0	[65]

The physical and mechanical properties of biomass fibers are very important and allied to the structure of the biomass fibers. Biomass fibers are largely natural organic fibers that exhibit high variability in different properties. This raises different questions in characterizing the quality of the physical and mechanical properties of the fiber. The most important physical property is density, while the mechanical properties of a single fiber are measured by using modulus and tensile strength values. It is very important to reference the development of biomass fibers as a biomaterial and the manufacture of polymer composites [66, 67]. In conclusion, it can be seen from the literature that biomass fibers have good potential as filler/enhancement material in polymer composites. Table 3 gives a comparison of the physical and mechanical properties of selected biomass fibers.

3. ALTERNATIVE FILLER MATERIALS FOR BRAKE PADS

In the production of brake pads there are three types of filler components used, namely, binders, friction modifiers, and reinforcements. The binder is a thermos resin used to bind all other components together to form a thermal stability matrix. The fillers are used to reduce the cost of pads. Reinforcements materials to improve the mechanical strength of the material include mineral fiber, carbon fiber, glass fiber, steel fiber, natural fiber, and ceramic fiber [13]. The friction modifiers are solid lubricants such as graphite and metal sulfides used to control stable friction and wear properties primarily at high temperatures. The objectives for using alternative materials for brake pad are to reduce the use of potentially destructive components in the brake pad material formulation while maintaining friction properties and reducing the pad wear rate. According to Lee and Filip [68], reducing the wear of material will likely reduce the negative environmental impact.

There are several characteristics and criteria that must be considered when selecting composite materials for brake pads. According to Lee and Filip [68] and Matějka et al. [69], the ability of the material to resist brake fade at higher temperatures must be considered when selecting brake pad materials. Lee [70] stated that the material must show good thermal stability and ability to recover quickly from high temperatures or moisture. According to Matějka et al.

[69], the material must exhibit an appropriate value of friction coefficient and good wear resistance.

3.1. Natural Fibers

Natural fibers are fibers derived from natural resources, and can be classified into three categories: plant, animal and mineral fibers [26]. According to Bledzki [71], stems, bark, seeds, and leaves can be used as natural fiber materials.

3.1.1. Maize husks

Ademoh and Olabisi [72], developed a new composite brake pad used maize husks (Figure 2) as a filler material and epoxy resin as a binder. They analyzed the mechanical, physical and tribological properties of the produced brake pad. It was observed that reducing the filler content of the produced composite brake pad increased the hardness, wear rate, tensile strength, compressive strength, and thermal conductivity, while density, the coefficient of friction, water and oil absorption increased with increased maize husk filler content as shown in Figure 3.

Figure 2. Maize husks

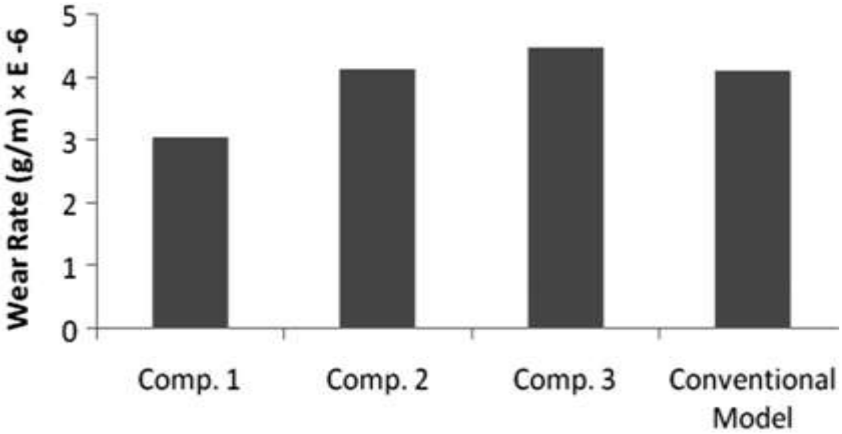

Figure 3. Wear rate analysis of the samples [72]

Studies have shown that reducing the filler content will increase the hardness, wear rate, tensile strength, compressive strength and thermal conductivity of the composite brake pad, while the density and friction coefficient increase with filler wt.%. as shown in Fig 4.

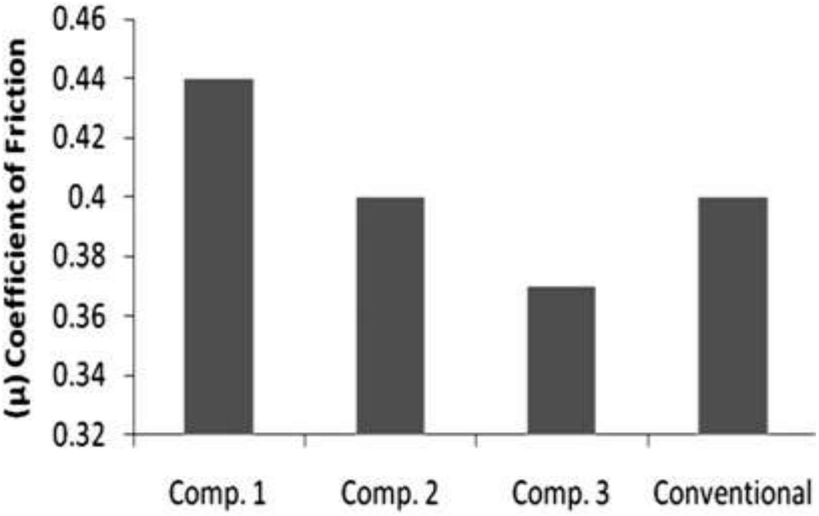

Figure 4. Coefficient of friction analysis of the samples [72]

The properties of the newly developed brake pad from maize husk were compared with asbestos-based brake pad as shown in Table 4. The results showed that the composite brake pad developed is environmentally friendly and is a suitable alternative to asbestos and many agro-biomass friction materials in the automotive brake pad.

Wisdom and Abraham [73] developed an asbestos-free brake pad using corn husks as an alternative filler with a view to replacing asbestos-based brake pads. The corn husks were milled and sieved into sieve grades of 100 μm and 200 μm. The different proportions of the selected corn husk fibers and silicon carbide were mixed together with a fixed ratio of other ingredient such as graphite, steel dust and phenolic resin (phenol formaldehyde) as a binder to produce a brake pad using compressional molding.

The properties such as compressive strength hardness, density, wear rate, flame resistance and porosity of the new brake pad were determined. The results showed that the samples from the 100 μm sieve grade of corn husk fiber gave the best properties. The hardness, compressive strength, density and porosity of the developed samples were observed to decrease with increase in sieve size of the corn husk, while the wear rate and percentage charred increased as the sieve size of the corn husk increased. The results obtained from the developed brake pad were compared with a commercial brake pad and were found to be in close agreement, indicating that corn husks can be used as an alternative filler material in the production of asbestos-based brake pads.

Table 4. Summary of the properties of the brake pads developed from maize husks (MH) compared with asbestos-based brake pads [72]

Properties	Asbestos-based	Maize husks-based
Wear rate (mg/m)	3.800	2.146
Tensile strength (MPa)	7.00	20.22
Hardness	101.0	127.8
Compressive strength (MPa)	110.0	103
Friction coefficient	0.30 – 0.40	0.37 – 0.40
Thermal conductivity (W/mK)	0.539	0.251 – 0.372
Specific gravity (g/cm3)	1.890	0.853
Thickness swells in SAE oil (%)	0.30	0.58
Thickness swell in water (%)	0.9	0.91

3.1.2. Sugar cane fiber (bagasse)

Aigbodion et al. [74] developed a new asbestos-free brake pad using bagasse (Figure 5) as a filler material, with phenolic resin (phenol formaldehyde) as a binder with a view to using it as a substitute for asbestos in brake pads because it is carcinogenic. They also investigated its mechanical, physical and tribological properties, which included hardness, microstructure analysis, density, compressive strength, flame resistance, water, and oil absorption.

Figure 5. Sugar cane fiber (Bagasse) [75]

The microstructure results showed that the resin distribution in the bagasse was uniform. Their results showed that the finer the sieve particle size, the better the properties of the new brake pad. The hardness, compressive strength, and density of the samples produced decreased when the sieve grade increased, whereas the oil soak, percentage charred, water soak and wear rate increased as sieve grade increased. The results show that bagasse can be effectively used as an asbestos substitute in the manufacture of brake pads by using bagasse of 100 µm sieve grade with 70 % and 30 % composition of resin.

3.1.3. Banana

Idris et al. [10] developed a non-asbestos brake pad using banana peel waste (Figure 6) as a filler with phenolic resin (phenol formaldehyde) as a binder. The work varied the resin content from 5 wt% to 30 wt% with an interval of 5 wt%. This work investigated and tested for mechanical, physical, wear, and morphological properties of the new brake pad. The samples containing non-carbonized banana peels (BUNCp) with 25 wt% and carbonized (BCp) sample with 30 wt% gave the best properties in all the samples.

Figure 6. Banana peel [10]

The results of the study (Table 5) showed that hardness, compressive strength, and specific gravity of the samples were increased with increase in wt% of additional resin. The result also showed that water absorption decreased as the wt.% resin increased.

Table 5. Summary of carbonized and non-carbonized based brake pad results compared with asbestos-based brake pads [10]

Properties	Commercial brake pad (asbestos-based)	Laboratory formulation (banana peels uncarbonized at 25% resin)	Laboratory formulation (banana peels carbonized at 30% resin)
Friction coefficient	0.3-0.4	0.40	0.35
Specific gravity (g/cm^3)	1.89	1.26	1.20
Hardness values (HRB)	101	98.8	71.6
Compressive strength (N/mm^2)	110	95.6	61.20
Wear rate (mg/m)	3.80	4.15	4.67
Thickness swell in water (%)	0.9	3.21	3.0
Thickness swell in SEA Oil (%)	0.3	1.15	1.12
Flame resistance (%)	Charred ash 9%	Charred ash 12%	Charred ash 24.67%

From Table 5 it is evident that the carbonized and non-carbonized based brake pads are in good agreement with commercial brake pads. Therefore, these formulations can be used to produce asbestos-free brake pads based on the expected dimensions of the brake pads as per the study (Peugeot 504 brake pad prototype with a length of 77 mm, friction depth of 12 mm and width of 65 mm). The prototype produced from banana peel particles showed that the formulation can be used in the production of automotive brake pads without adding any binder to the formulation. The result of this research revealed that banana peel particles can be used as a substitute for asbestos in the manufacturing of brake pads.

3.1.4. Rice husk dust

Shahril Anuar Bahari et al. [76] investigated the hardness and impact resistance properties of an automotive brake pad produced with rice husk dust (RHD) (Figure 7) as an alternative filler material. The dust was obtained with different sizes of mesh (80 mesh and 100 mesh) with other materials at different percentages of composition (10 % and 30 %). Phenol formaldehyde was used as a binder. Regarding the brake pad composed with fine mesh size, the results showed that a decrease in the percentage of rice husk dust showed an increase in the coefficient of friction, and a decrease in the percentage of rice husk dust in the mixture also decreased the wear rates, therefore rice husk dust increased the frictional performance. Thus, the smaller particle size of rice husk dust performed better as a filler material within a higher percentage of the composition. This study has shown that a high percentage of rice husk dust has a good result on hardness and impact resistance properties.

Figure 7. Rice husk

3.1.5. Pineapple

Felix and Prasanth [77] developed an asbestos-free brake pad using pineapple leaf fiber (PALF) as a filler material. Epoxy resin was used as a binder because it has good mechanical properties. They varied the samples with different percentages of pineapple leaf fiber and examined the compressive strength impact, hardness, flexural, density, and wear. Their results showed that with the increase in the percentage of PALF content, the compressive strength, hardness and wear decreased. Compressive strength, hardness, and wear of different samples decreased with an increase in the percentage of PALF, whereas the water absorption rate increased as the percentage of pineapple leaf fiber increased.

3.1.6. Coconut fiber

Bahari et al. [78] used dried coconut husks (Figure 8) as a filler material and phenolic resin (phenol formaldehyde) as a binder. They determined the friction coefficient and characteristics of the heat resistance of the developed brake pads with size 80 mesh and 100 mesh, as well as the percentage (10 % and 30 %) of coconut husk particles. The results showed that the brake pads with 100 mesh and 10 % coconut husk particles composition had the highest coefficient of friction. In terms of heat resistance, the composition of the brake pad with 100 mesh and 30 % of coconut husk dust showed the highest decomposition temperature which increased the thermal stability due to the high proportion of the coconut husk particles in the composition. The results also showed that the asbestos-free brake pad from coconut husk particles had better heat resistance than commercial brake pads.

Figure 8. Coconut fiber [79]

Maleque et al. [79] used coconut fibers as filler material with phenolic resin as a binder, and reinforced aluminum composites, for the application of automotive brake pads. Four different combinations of coconut fiber content such as BP1, BP2, BP3 and BP4 varied from 0, 5, 10 and 15 volume friction using a metallurgy technique for the development of a new composite material. They examined density, porosity, microstructural analysis, hardness and mechanical properties using a densometer, scanning electron microscopy (SEM), hardness tester and universal testing machine. The properties of the coconut fiber composites improved from the sample with 5 % (BP2) and 10 % (BP3) when they achieved lower porosity, higher density, and higher compressive strength. The compressive strength indicates that the 10 % coconut fiber had the best strength to bear the load applications and the best ability to carry the compressive force. The microstructure showed a uniform distribution of resin and coconut fiber in the matrix. The results showed that 5 % and 10 % had better physical and mechanical properties than other formulations.

3.1.7. Palm kernel fiber

Ikpambese et al. [80] investigated the properties of asbestos-free automobile brake pad filler material produced from palm kernel fiber (PKF) (Figure 9) together with epoxy resin as a binder. They added 100 µm of PKFs in varying percentages with aluminum oxide (Al_2O_3), calcium carbonate ($CaCO_3$) and epoxy polymers and other ingredients to produce the composite. They investigated mechanical properties, physical properties, tribological properties, and microstructure analysis. The composition of 40 % of epoxy resin, 10 % of palm waste, 6 % of aluminum oxide (Al_2O_3), 29 % of graphite and 15 % of calcium carbonate ($CaCO_3$) had better properties than other compositions tested. The results show that the properties of the developed brake pad such as the coefficient of friction, temperature, wear rate, stopping time and noise level, moisture content, specific gravity hardness, surface roughness, porosity, water, and oil absorption rate were stabled with speed increased. Furthermore, the values obtained from the PKF parameters were within the standard requirements for commercial brake pad performance. The researchers' results showed that PKF can be used as a substitute filler material for asbestos brake pads, with epoxy resin as a binder.

Figure 9. Palm kernel fiber [80]

Achebe et al. [3] developed a non-asbestos brake pad material using palm kernel fiber (PKF) as an alternative filler base material in conjunction with epoxy resin as a binder. They investigated the physical and mechanical properties of the three sets of composition made using standard materials, procedures, and equipment to determine their suitability and possible performance. The results of their studied showed that sample C with 40 % PKF content with hardness 178 MPa, compressive strength 96.2 MPa, abrasion resistance 1.67 mg/m) specific gravity 1.8 g/cm3, water absorption 1.86% and oil absorption 0.89% had the best performance rating. The sample C result was used to produce the brake pad. The results obtained were compared with other studies using common brake pads made from other material including asbestos; the result showed that hardness, wear resistance and specific gravity of the composite brake pad increased as the filler content increased, while water and oil absorption decreased as the filler content increased. This showed that palm kernel fiber is a possible alternative material for asbestos as a filler material in the production of automotive brake pads.

3.1.8. Palm slag

Ruzaidi et al. [81] used palm slag as a filler for the production of brake pads with phenolic resin as a binder. They examined properties which include hardness, compressive strength, and wear behavior of the new composite. The results showed that in the composite formulation used to produce the brake pads, palm slag has great potential to replace existing fillers.

Ruzaidi et al. [82] used palm slag (agro-waste) as filler material together with calcium carbonate (C_aCO_3) and dolomite in the brake pad material to increase the performance-to-cost ratio. Phenolic resins were used as a binder with other friction additives. They also investigated thermal properties, compressive strength, and wear behavior. The results showed that the thermal stability of the palm slag material showed a higher performance in the range of 50 °C to 1000 °C compared to the other two fillers. This showed that palm slag can be used as a substitute to the present fillers in composite formulations used to fabricate brake pads.

3.1.9. Lemon peel powder

Ramanathan et al. [83] developed and evaluated an asbestos-free brake pad using lemon peel powder as a filler material and epoxy resin as a binder. They varied the percentage of lemon peel powder, aluminum oxide, and iron oxide composition and made two samples by employing hand molding techniques. They investigated the wear rate, hardness, density, water and oil absorption of the samples produced. The results showed that the first sample with the composition of epoxy resin (40 %), Al2O3 (12.5 %), iron oxide (12.5 %), graphite (1 5%), calcium hydroxide (10 %) and lemon peel powder (10 %) had better properties than the second sample. Lemon peel powder can be used effectively as an alternative filler material for asbestos in brake pad production.

3.2. Shell waste

3.2.1. Cocoa bean shell

Olabisi et al. [84] developed an asbestos-free brake pad using pulverized cocoa bean shell (CBS) as (Figure 10) as filler and epoxy resin as a binder. The mechanical, physical, and tribological properties of the non-asbestos brake pad sample were investigated. The results showed that reducing the pulverized cocoa bean shell filler content of the brake pad increased the wear rate, tensile strength, compressive strength, at the same time as hardness, density and thermal conductivity varied differently. The friction coefficient increased with the increase in the filler wt.%. After an investigation, the outcomes of their work showed that CBS, which is an agro-waste material, can be used as a substitute for asbestos in friction lining and in the production of automotive brake pad material.

Figure 10. Cocoa beans

3.2.2. Coconut shell

Darlington et al. [6] produced an asbestos-free brake pad using coconut shell powder and palm kernel shell from locally sourced raw materials and other additives with polyester resin as a binder. They produced three different samples of brake pads in their study by varying mass compositions of coconut shell powder and palm kernel shell. The results showed that newly developed samples had a density between 2.55 g/cm3 and 2.78 g/cm3 while the commercial brake pad density was 3.36 g/cm3; the wear rate was between 0.2007 g/min and 0.2733 g/min and the commercial brake pad wear rate was 0.1873 g/min; the water absorption was between 0.0399% and 0.0522 % while the commercial pad was 0.0327 %; and, the hardness was between 3.00 and 3.41 while the commercial brake pads was 2.53. The results show that the developed brake pad cannot meet the properties of commercial brake pads due to its high density and high wear rate, but it can be used as a substitute for commercial products due to its environmentally friendly compared to the asbestos brake pad that is carcinogenic nature.

Figure 11. Coconut shell

Bashar et al. [85] produced asbestos-free brake pads using coconut shells (Figure 11) as a filler with epoxy resin as a binder matrix and other ingredients. A series of tests, including tensile, compression, hardness, impact, wear, and corrosion, were performed to determine the composition and optimum performance compared to the widely used commercial Honda brake pad (Enuco) model in Nigeria. Their results showed that a higher percentage of ground coconut shell powder gave lower breaking strength, hardness, compressive strength, and impact strength, indicating that increased coconut powder increased the brittleness of pads.

3.2.3. Palm kernel shell

Fono-Tamo [86] developed a non-asbestos brake pad used palm kernel shell (PKS) (Figure 12) as friction filler material by following the standard manufacture procedures for commercial brake pads. He evaluated the mechanical, physical, thermal and the wear characteristics of the PKS-based brake pads compared with the values of the asbestos brake pads. The properties of the PKS-based brake pad completely fulfilled the NIS 323 standard.

Ibhadode and Dagwa [8] developed asbestos-free friction lining materials using an agro-waste material based on PKS as a filler material and with phenolic resin as a binder and other components. The mechanical and physical properties of the asbestos-free pads were investigated. Among the agro-waste shells that were studied, the PKS demonstrated more favorable properties than others. The performance of the newly developed brake pad, under static and dynamic conditions, was found to be satisfactorily when compared with the asbestos-based commercial brake pad. However, more pad wear on PKS at a high vehicle speed beyond 80 km/hour was evident (Figure 13). Nevertheless, the results indicated that the palm kernel shell may be a possible alternative for friction lining material.

Figure 12. Palm kernel shells [4]

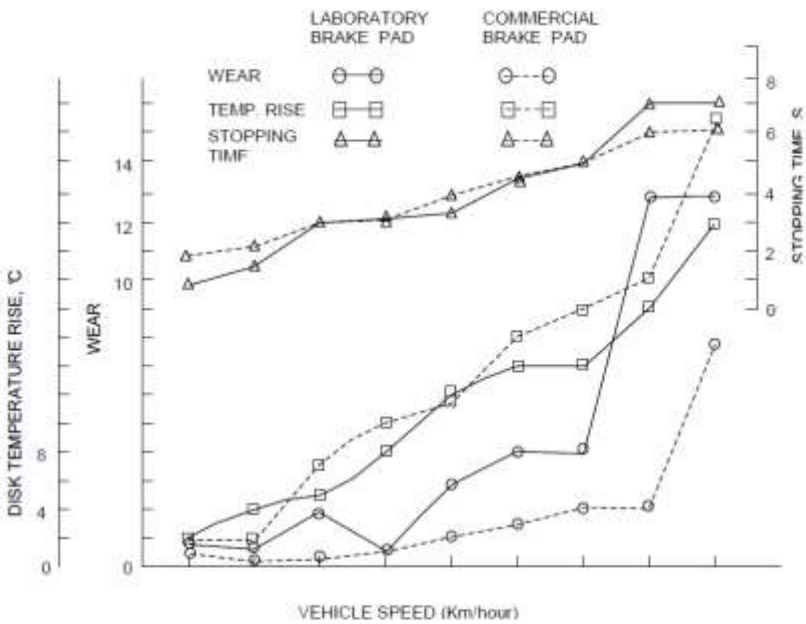

Figure 13. Comparison of laboratory and commercial brake pads under static testing [8]

Mayowa et al. [4] investigated the properties of newly developed brake pad friction material using PKS and cow bone particles as alternative brake pad formulations. The different sizes of the sieved graded palm kernel shell and cow bone were added into 60 % of epoxy resin and 10 % of hardener along with 30 % of different grade sizes at 120 μm, 100 μm and grading below 100 respectively to produce brake pad friction material. Table 8 shows the results.

Table 6. Properties of palm kernel shell and cow bone composite investigated [4]

Properties	Palm Kernel Shell (PKS)	Cow Bone
Hardness	55.7 HRB	46.0 HRB
Oil absorption	2.23 %	4.16 %
Water absorption	5.05 %	5.53 %
Density	1.2 g/cm^3	1.5 g/cm^3
Impact	1.0 J	1.5 J
Wear rate	9.57E-7 g/cm	1.44E-6 g/cm
Tensile strength	23 J/mm^2	21 J/mm^2
Coefficient of friction	0.735	0.677

The study reported that as the particle size increased, the density decreased. The result from the impact test indicated that the impact strength of the higher sieved size samples was relatively increased when compared to the finer particle size sample, and cow bone composite absorbed more water than PKS composite. From the thermogravimetric analysis (TGA) results, it was observed that as the percentage weight loss increased, the temperature also increased from 200° to 500° as the sieved size of the particle increased. All the properties investigated were within the standard requirements for brake pad production.

Samuel et al. [87] used different particle sizes of PKS to develop an asbestos-free brake pad with an idea to replace the use of asbestos-based brake pads. The PKS was sieved into grades of 100 μm, 350 μm, 710 μm and 1mm. The sieved PKS was utilized in asbestos-free brake pad production with a ratio of 35 % to 55 % PKS, 20 % resin, 10 % graphite, 15 % steel, and 0% 20 % SiC by using compression molding. They investigated properties such as hardness, density, microstructure, compressive strength, flame resistance, water, and oil absorption. The result of their study showed that the 100 μm samples of PKS offered better properties than other samples. The microstructure analysis showed that the resin in PKS was regular. Their results showed that the finer the size of the sieve particle the better the properties of the brake pad. When their result was compared with the asbestos-based commercial brake pad, the results are promising. Therefore, PKSa can be effectively used as an asbestos substitute in the production of an asbestos-free brake pad.

Fono-Tamo and Koya [88] developed asbestos-free automobile brake pad materials used factory standard procedures from PKS and more importantly its mechanical properties. The mechanical characteristics of the developed materials were evaluated. The results of developed brake pad showed hardness of 32.34 and shear strength of 40.95 MPa. At the same time, the coefficient of friction was investigated, and the result showed that the pad retained a coefficient of friction of 0.43.

Mgbemena et al. [89] developed an asbestos-free friction lining material for automobile brake pads using pulverized PKS as base filler material and spent workshop metallic cutting fillings as abrasives. Phenolic resin and alkyd resin were used as a binder material in this work. The properties of the newly developed samples of friction lining material were investigated. The thermal and friction surfaces of the samples were characterized using Simultaneous Thermal Analyzer and Optical Stereomicroscopy (ZEISS) respectively, compared to commercially available ones in the market produced by original equipment manufacturers

(OEM). It was established that pulverized PKS-based brake friction lining displayed high wear rate of 0.24 µm and high char content as compared to OEM brake lining materials with a wear rate of 0.16 µm. Also, PKS based brake friction lining demonstrated better thermal stability when it was compared to the OEM materials.

3.2.4. Cashew nut shell

Adeyemi et al. [90] produced asbestos-free automotive brake pads from a composite made of mixed agro-waste materials namely, cocoa beans shells (CBS), maize husks (MH) and palm kernel shells (PKS). The binder used was an epoxy resin. They investigated the physical, mechanical and tribological properties of the new composite. The properties of the mixed agro-waste based brake pad sample were compared with those made of single filler materials such as cocoa beans shell (CBS) based sample pads and maize husks (MH) based sample pads. The result of the analysis showed that as matrix wt.% formulation increased, the friction coefficient, abrasion resistance, and water soak decreased, while the tensile strength and compressive strength increased. However, the density, hardness, thermal conductivity, and oil soak varied inconsistently. The results showed that mixed agro-waste (CBS+MH+PKS) particles can be used effectively as an alternative filler material for asbestos brake pad friction materials.

3.3. Animal Waste

3.3.1. Periwinkle shell

Aku et al. [91] used spectroscopic and wear analysis to investigate the characterization of the periwinkle shell (Figure 14) as asbestos-free brake pad material. The experiment was carried out by using X-ray diffractometer (XRD), thermogravimetric analysis (TGA/DTA), Fourier-transform infrared spectrometry (FTIR), and X-ray fluorescent spectrometry (XRF). They investigated the density, hardness values and wear rate of the periwinkle shell. Their results were compared with asbestos commonly used in the production of brake pads. The results confirmed that periwinkle shell can be used as an alternative material for brake pad production.

Yakubu et al. [92] developed a brake pad using periwinkle shell particles (PSP) as a filler to replace asbestos and investigated thermoset resin as a binder. They varied the PSP size from 710 µm-125 µm and analyzed the wear test, surface morphology, and thermal analysis of the samples. Their results showed that the periwinkle shell particles (PSP) size decreased from 710 µm-125 µm which showed a good interfacial bonding. The wear rate of the brake pad increased as the load and the particle size of the periwinkle shell increased. The coefficient of friction of the developed brake pad was in the same range as the automobile brake pad standard. The PSP had a higher temperature of maximal decomposition than asbestos which showed that PSP can withstand higher temperatures than asbestos. The results of this research work showed that PSP can be successfully used as an alternate filler material instead of asbestos in brake pad production.

Yawas et al. [93] produced brake pads from periwinkle shells as a filler material with phenolic resin as a binder. Five sets of brake pads were produced by using compressive molding with a different sieve size of periwinkle shells (710 µm to 125 µm) with 35 % resin. They evaluated mechanical, physical and tribological properties of the periwinkle shells-based brake pad and compared the values with asbestos brake pads. In their work, they determined the properties and morphology of developing a PSP asbestos-free brake pad and its material was characterized. The results of their research showed that the compressive strength, hardness, and density of the newly developed brake pad samples increased when the particle size of periwinkle shell decreased from 710 µm to 125 µm, whereas the water soak, oil soak and wear rate decreased when the periwinkle shell particle size decreased. The research results indicated that periwinkle shells can be used as a replacement filler material for asbestos in brake pad manufacture.

Figure 14. Periwinkle shell

3.3.2. Snail shell

Abhulimen and Orumwense [94] developed an asbestos-free automotive brake pad with a view to replacing the use of asbestos, snail shell was used as a reinforcement material, while rubber seed husk was used as frictional filler material and epoxy resin as a binder. The pulverized snail shells were sieved into grades of 125 µm, 250 µm, 355 µm, 500 µm, and 710 µm. The composite brake pad was developed in the ratio of 65 v% snail shell, 10 v% rubber seed husk and 25 v% resin by using compression molding. They investigated the characterization of the snail shell through XRD, XRF, differential thermal analysis (DTA), and TGA. They then investigated the properties of the developed brake pad such as density, compressive strength coefficient of friction, hardness, abrasion resistance, and porosity. The microstructure showed equal distribution of the resin in the snail shell, and the results showed that the 125 µm grade of sieved snail shell revealed the best properties. When the results were compared with common asbestos-based brake pads they found that the effect of the developed brake pad was more favorable than the asbestos brake pad. This outcome of the work confirmed that snail shells and rubber seed husk can be used to produce alternative brake pads.

4. RESULTS AND CONCLUSION

This paper studied different agricultural wastes as an alternative to asbestos brake pads. The results show that the performance of the waste materials was almost the same as the asbestos brake pads but without any of the health issues and environmental impact. Brake pad production from biomass materials to substitute asbestos brake pad materials has become the center of research in laboratories, and many studies and investigations are ongoing, although the results from these studies have not yet been translated into commercial applications. Similarly, it is necessary to utilize the combinations of biomass materials at different ratios to further study their effects on the physical, mechanical and tribological properties of brake pad production using these various mixtures. The mechanical and physical properties of the composites are affected by the filler content. In general, studies so far have found that as the composite filler content of the material decreases the properties such as thermal conductivity, hardness, compressive strength and tensile strength of the composite brake pad increase, while the density, water, and oil absorption of the brake pad increases when the filler content of the composite increases.

The studies by Ikpambese et al. [80] and Ibhadode and Dagwa [8] reported that an increase in speed of a vehicle results in an increase in contact pressure between the brake pads and rotor, consequently increasing the wear rate. Table 3 shows the characteristics of the environmentally friendly brake pads manufactured from PKS and PKF. From these studies, it is evident that brake pads using palm kernel fiber (PKF) had a higher wear rate, while the brake pads using palm kernel shell (PKS) had a low friction coefficient.

The mechanical, physical and tribological properties of these brake pads developed from agro-waste biomass materials had certain advantages compared to commercial brake pads. The results obtained from this laboratory work tackles the existing gap in the production of the environmental-friendly and cheap brake pads. Agricultural waste may be effectively used as an alternative component in the production of brake pads when properly used in conjunction with other additives to accommodate the good performance of the brake pads. Then again, concerning their low thermal stability, they should always be considered carefully. In conclusion, an exciting point of these materials is that biomass demonstrates good mechanical properties. Increased use of biomass composites product is expected to have a certain ripple effect in the agricultural sector.

In brake pad applications, the wear resistance improved with the addition of natural fibers as a filler to the friction formulation. Normal load and speed have a significant effect on the wear rate of the brake pad composite. The finer the size of the sieve, the better its properties. The small particle size of natural fibers had a positive result on the composite wear rate. The coefficient of friction result was within the recommended standard for brake pad formulation. Physical and chemical treatments can be used to overcome poor wettability as well as a natural fiber with higher moisture absorption.

Agricultural waste has been used as prospect reinforcement materials for a wide range of applications including brake pad production. The good thing about these materials is that they are waste biomass and present good mechanical properties.

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