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REVIEW OF THE DEVELOPMENT OF PERIWINKLE/PALM KERNEL SHELL-REINFORCED EPOXY MATRIX HYBRID COMPOSITES FOR BRAKE PAD PRODUCTION

Oryina Mbaadega INJOR[1*] [0009-0008-9453-0948], Emmanuel Rotimi SADIKU[1] [0000-0002-8504-1041], Moipone Linda TEFFO[1] [0000-0003-0347-7034], Munyadziwa Mercy RAMAKOKOVHU[1] [0000-0002-7196-9674], Victor Ugbetan AGBOGO[1] [0009-0002-3028-2005], Williams Kehinde KUPOLATI[2] [0000-0002-2574-2671]

[1] Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria 0001, South Africa
[2] Department of Civil Engineering, Tshwane University of Technology, Pretoria 0001, South Africa

Abstract

Asbestos has traditionally been used in brake pad production due to its durability, but concerns over its health hazards, non-biodegradability, and high cost have prompted the search for safer alternatives. This study investigates the development of eco-friendly, asbestos-free brake pad composites using agro-waste materials, periwinkle shell (PS) and palm kernel shell (PKS) as reinforcements in an epoxy matrix. The uniqueness of the composites lies in combining the high thermal resistance of PS with the mechanical strength of PKS to create a cost-effective and sustainable friction material. The composites were produced with optimized particle sizes of 100–125 µm in various PS-PKS proportions, and their mechanical and tribological properties were evaluated. Results showed that finer particles reduced porosity, improved wear resistance and enhanced hardness up to 75 HRC for PS and 55.7 HRB for PKS. The best formulations achieved coefficients of friction between 0.35–0.44 and wear rates ranging from 0.017 to 0.170 mm/min, comparable to commercial brake pads. Thermal analysis confirmed that PS remains stable above 600 °C, while PKS decomposes in stages between 54–538 °C. These findings support the viability of PS/PKS-epoxy composites as high-performance, environmentally sustainable alternatives to asbestos-based materials.

Keywords: *Asbestos, Hybrid composite, Periwinkle/palm kernel shell, Brake pad*

Introduction

Brake pad materials are designed composites formulated to provide consistent friction, thermal stability, wear resistance, and durability under varying operating conditions to ensure safe and efficient braking performance. The increasing environmental concerns over non-biodegradable synthetic materials and the harmful emissions from traditional brake pads have driven interest in eco-friendly alternatives. Additionally, natural-based composites offer cost-effective solutions by utilizing abundant agro-waste products especially periwinkle and palm kernel shells, reducing raw material costs and promoting sustainable manufacturing practices [1]. Different machines employ different types of braking materials. All types/brands of vehicles with disc brakes, depend heavily on brake pads as part of their braking systems. Various car manufacturers, including Toyota, Nissan, Honda, Peugeot, Volkswagen, etc., employ brake pads in their braking systems. The steel back plate of these cars has frictional material that is affixed to the side that faces the brake disc [2-4].

*Corresponding author: InjorOM@tut.ac.za

The declaration of the average fuel efficiency standards, for corporations in the 1970's and 1980's, also drives the changes in the formulation of brake pads. This has compelled the auto industry to move away from the back wheel drive to front wheel drive vehicles. This move requires an added front braking scenario that often, leads to elevated temperatures and thus, a priority for the semi-metallic brakes [5]. The braking system plays a fundamental task in all vehicles, primarily functioning to reduce speed or bring the vehicle to a complete stop. Therefore, it must be highly reliable, and its performance should remain consistent throughout its service life [6, 7]. Developing sustainable friction materials is crucial for reducing environmental pollution, conserving non-renewable resources, and promoting the use of biodegradable, renewable alternatives in automobile applications. This study is focused on the development of a hybrid epoxy composite brake pad using periwinkle and palm kernel shells as dual agro-waste reinforcements, optimized for particle size and thermal-mechanical performance as a sustainable alternative to asbestos.

Material Complexity and Evolving Trends in Brake Pad Manufacturing

For an automotive brake system (ABS), the brake pads are friction-complex composites because they comprise of various components that vary in their mechanical, chemical and physical characteristics [8]. The lining material, which is a major part of the brake pad, based on the arrangement of the basic parts, is classified as metallic, semi-metallic and organic, or carbon-based, [9]. Among the many different components that make-up these brake pads, are binders, fibres, fillers, and frictional modifiers or additives (Fig. 1) [10]. The brake pad is typically, composed of several parts and asbestos fibres, encased in a polymeric matrix.

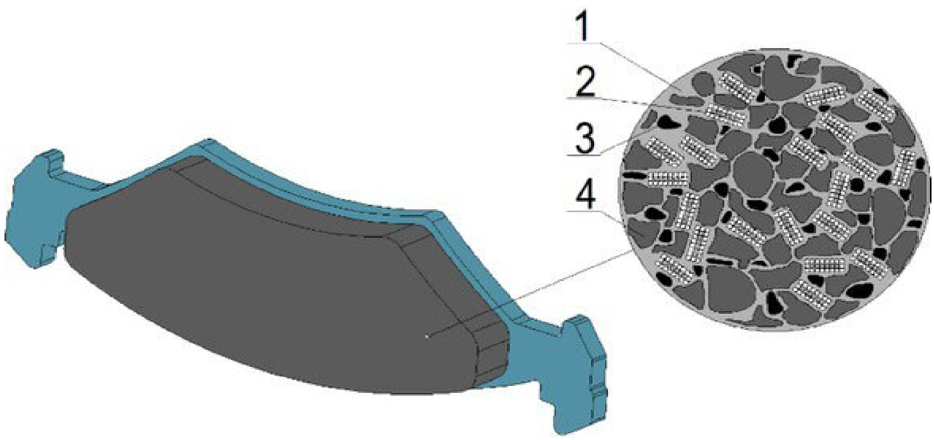

Fig. 1. Brake pad friction material configuration: 1 - Binder, 2 - Fibers, 3 - Filler, 4 – Additive.

Asbestos is a hydrated magnesium silicate and its fibres, occurring genuinely, as mineral, have been used to strengthen the components of frictional materials to confer onto them, the necessary mechanical strength [11]. This is because of its excellent engineering properties, e.g., thermal stability at ~500°C. However, because of the health risks, asbestos use has been discouraged [12]. This is because it can settle in the lungs and initiate certain harmful respiratory conditions. Therefore, the search for non-toxic and cheaper substitutes, becomes imperative. In as much as it is still legal to employ asbestos for brake pads, many brake pad manufacturing industries are pulling away from asbestos; due to concerns that are associated with flying particles in factories and the associated concerns about the waste disposal of the remnant materials that contain asbestos [13].

Brake pad manufacturers employ ~2000 various materials [14], in brake production, each differently, affecting the final product. A standard brake pad comprises between 10 and 20 different materials [15]. The determination of the optimal formulation and the anticipation of its effect on the brake performance, is a challenging process that demands extensive research and specialized knowledge [16]. This decision must also consider the brake pad's intended use and the conditions under which it will operate. Moreover, the manufacturing process plays a vital role in defining the final properties of the brake pad and it is often considered to be a highly protected trade secret, among manufacturers. The use of advanced manufacturing technologies can significantly enhance the tribological performance of brake pads, potentially by up to 100% [17, 18].

Constituents and Classification of Brake Pad Materials

Brake pad materials can be categorized into various ways, with the most critical classification, based on the function each material performs in the braking process. According to this approach, the key constituents are the: binders, additives, fillers, and abrasives [19-21]. The binder functions as the matrix which integrates other components. It must possess a consistently high friction coefficient, strong resistance to extreme or variable temperatures, and maintain a low overall weight [22]. Furthermore, the material should not interact with any other part of the pad, since this could result in alterations to the overall material properties or lead to delamination of the composite. Such issues can severely compromise the braking efficiency. Typically, binders are formulated by using epoxy or silicone resins [23]. Reinforcements are fibrous materials that are incorporated to enhance the mechanical properties of the binder thereby boosting its strength. The choice of reinforcement performs a crucial role in the determination of the brake pad’s durability and structural integrity, and thus, must be produced with careful considerations.

Historically, asbestos was widely used as an effective reinforcing fiber. However, due to its harmful health effects [24], alternative materials to asbestos have been developed and they are now readily available, thereby offering safe and efficient performance [25, 26]. Fillers serve to fill the gaps between other constituents in brake pad composition. Since they can constitute as much as 10% of brake pad’s volume, the selection of an appropriate filler material is essential to ensure optimal performance. The most frequently used fillers consist of vermiculite, perlite, mica, barium sulfate, and calcium carbonate, since these materials resist high temperatures, they do not react with other brake pad components, and they are cost-effective [27].

Depending on performance required, abrasives are incorporated into pads to modify the friction coefficient. Additives, such as steel, cast iron, flame-resistant oxides, silicates, and quartz are commonly used to boost friction between the brake pad and the disc, thereby improving durability due to their hardness. This effect is further strengthened by their interaction with the disc surface, particularly when metallic elements are involved. These materials also create contact zones, which act as primary friction interfaces between the braking components [28, 29]. However, these contact zones generate significant heat due to friction, which can compromise the structural integrity of the brake pad, thereby causing delamination of its components. To counteract this issue, lubricants are incorporated to enhance the pad’s thermal conductivity. These lubricants help to dissipate heat more effectively, from the contact zones, hence, reducing the risk of overheating and therefore, maintaining the performance of friction materials [30-32]. The generally used lubricants include metallic sulfates, such as copper and tin, as well as graphite. The effectiveness of lubrication depends on both the content (typically around 10% of brake pad’s volume, yields optimal performance) and the particle size of the lubricant [33].

Another method for the classification of brake pad materials is by their origin, either natural or synthetic. Natural materials comprise asbestos [34, 35], a mineral that has been historically used, but now banned due to its carcinogenic nature [36], and plant-based substances, derived from leaves, stems, or seeds. Others are animal-based materials, such as hair or fur, and several metals, such as steel, copper, bronze, and cast iron. In contrast, synthetic materials are typically products of organic synthesis, such as aramids and acrylic fibers, or advanced materials, such as mineral fibers, ceramics, carbon fibers, and glass fibers.

Role and Performance of Resin Binders in Brake Pad Composites

Resins are commonly used as binders in brake pad production, thereby serving the essential role of holding all components together. However, they must be incorporated in precise measured quantities to perform effectively, since deviations can compromise the structural reliability and performance of brake pads [37, 38]. Insufficient resin diminishes pad durability, while excessive resin can lower the friction coefficient at higher temperatures and greatly enhance hardness [39, 40]. Resin plays a critical role in brake pad manufacturing by bonding the composite components into a cohesive structure. However, the intense heat generated during a braking scenario can lead to resin degradation, hence, compromising its adhesive strength and the overall integrity of the brake pad [41]. Therefore, thermal stability and the capability to retain the mechanical properties of the pad under harsh braking conditions, rely heavily on the performance of the resin [42]. To enhance both the mechanical and thermal characteristics, ongoing research focuses on the modification of resin formulations through the chemical composition adjustments of the constituents [43, 44].

Phenolic resins are the most extensively used binders in the production of friction materials. While they have limited applications outside this domain, they are integral components to the brake pad formulations, often comprising between 5% and 35% of the pad's volume. Notably, the quantity of resin inversely affects the coefficient of friction (COF) as well as wear rate. Although a reduction of approximately 10% in resin content only resulted in a minor change in the COF, however, it still influenced the overall performance [45]. The extensive use of phenolic resins in the automotive industry is largely attributed to their high mechanical properties and cost-effectiveness [46]. Another important aspect is that this resin exhibits low thermal expansion. In comparison to other resins, it shows greater resistance to solvents, acids, and water, and produces minimal smoke when burned. The temperature at which early degradation occurs, which is significant due to its relationship with brake pad fading, drops from 354∘C for pure resin to 303∘C for cured friction material [47]. The addition of oil or silicone gum can help to decrease its susceptibility to cracking, resulting in a silicone resin. Nonetheless, during this process, various other mechanical properties are compromised [14]. Phenol resin is not the ideal choice for friction amelioration at elevated temperatures. In instances of abrupt braking, the pad temperature can hurriedly reach 700°C, which is by far, surpassing the degradation threshold of phenol resin [48, 49].

The cured condensed polynuclear aromatic (COPNA) resin, offers a slight improvement in thermal resistance. while its decomposition temperature is like that of other resins (400–500 °C), it releases considerably less gas during degradation. This lessens the likelihood of the brake fading. Furthermore, due to its graphite-like structure, the COPNA resin forms a strong bond with graphite particles, thereby enhancing the brake pad's resistance to friction [50, 51]. Cyanate ester resins, synthesized by using cyanide-based monomers, exhibit excellent chemical stability and they are known for their vibration-dampening properties. However, their most notable characteristic is their high thermal resistance. Studies have shown that the addition of ~5% zirconium diboride (ZrB_2), further improves its thermal stability and optimizes its tribological properties, particularly the COF and wear rate [52]. Additional research involving the combinations of graphite and molybdenum disulfide (MoS_2) has demonstrated improvements in the mechanical properties of the resultant product, along with reduced wear rates [38]. Despite their performance benefits, cyanate ester resins are rarely used in friction materials, due to their high cost, which results from a complex manufacturing process [53]. However, their superior properties have led to their growing usage in the electronics industry [54, 55].

Epoxy resins are widely used across various industries; however, their low thermal resistance (degrade at ~260 °C), makes them unsuitable for use in friction materials [56]. Research has shown that at a relatively low temperature of 100 °C, epoxy resins can experience a mass reduction of ~7% [57]. This weight loss is attributed to the release of volatile compounds during the heating process. When exposed to prolonged heating above 400 °C, carbon formation and subsequent oxidation occur. Interestingly, the blending of epoxy with phenolic resins produces a composite material with significantly improved heat resistance and superior mechanical properties when compared to either of the resins, when used alone [56]. Another alternative, i.e., thermoplastic polyamide resin, produced by using fluoresin and calcium carbonate, exhibits excellent wear resistance and thermal stability. In addition to its performance benefits, it offers a cost-effective and simple manufacturing process. Nevertheless, the resin serves as an effective thermal insulator, that is roughly three times, more efficient than phenol resin. This is the reason for its practicality in brake pad production, which is quite limited [56].

Fundamentals and Engineering Significance of Composite Materials

A composite is the arrangement of materials made of the combination/mixture of dissimilar components in a suitable arrangement, with a boundary separating and making them essentially, insoluble in one another with different forms and chemical compositions. Natural plant fibres in composites, have been in existence for centuries [58]. A composite material has engineering relevance when several distinctly different material constituents combine to form a unique material that have exceptional or outstanding characteristics when compared to the singular/individual components. Hence, composite materials are produced by lining-up exceptionally, formidable and rigid ingredients, e.g., fibres and tiny particles in a binder, known as matrix. This class of materials have excellent mechanical properties. One of the constituent parts, allows stress to be incorporated into the reinforcing phase, which creates a strong bond, referred to as matrix. Examples of matrix materials are polymers, ceramic and metals. Another component is the reinforcing phase, referred to as the reinforcement, which can be fibre, particulate or laminar. The distinctive features that composite materials possess, is as a result of the separate components as well as their boundary interaction.

Literatures have identified the factors that control the mechanical behaviour of particulate composites. It is generally, established that the particle size decreases with increased adherence to the matrix, as the reinforcing effect grows. Two polymers can be physically combined to change their properties, or a polymer can be combined with a non-polymeric component. Composites typically, exhibit both high strength and modulus, with a low density. They also exhibit resistance to wear, corrosion, fatigue, creep, and creep rupture [59].

Classification of Composite Materials in Automotive Systems

Composite materials can be generally categorized into three classes, depending on the matrix material. These include metal matrix composites, ceramic matrix composites and polymer matrix composites. Metal matrix composites have a metal, e.g., aluminium, magnesium and titanium as the matrix. Carbon and silicon carbide are used as fibres for reinforcement. The reinforcement is principally, to fit the need of the design. For instance, the addition of silicon carbide, as a fibre, increased the strength and the elastic stiffness of metals, with reduced electrical and thermal conductivities [60].

Metal matrix composites (MMCs) are gaining prominence in modern automotive innovations because of their superior mechanical and thermal properties. These composites are not restricted to braking systems, but likewise utilized in clutches [61], intake manifolds [62], engine blocks [63], and various fuel system components, including the traditional injectors that employ piezoelectric stacks [64, 65] and alternative fuel injectors [66]. Additionally, MMCs serve as substitutes for conventional materials in the fabrication of monocoque-type vehicle frames [67], thereby offering enhanced performance and reduced weight. In brake applications, MMCs are used in the manufacture of brake drums and discs. These components are found, not only in passenger cars [68–70], but also across a range of other vehicles, including motorcycles [71]. In the brake pad friction linings, materials that are predominantly based on aluminum, often reinforced with silicon carbide, are utilized [72]. Their remarkable attributes, including low density, strong mechanical strength, high-temperature resistance, and efficient thermal conductivity [73-75], are the qualities that are often sought after in brake pads. Regrettably, this class of material also comes with its disadvantages.

Challenges, such as uneven distribution of SiC particles, residual porosity, formation of undesirable phases, e.g., aluminum carbide, and exposure to higher braking temperatures, significantly hinder the broad application of metal matrix composites in braking systems [75]. The final characteristic pertains to the elevated friction coefficient when interacting with various materials, and excessive heat could result in material deterioration [76]. A critical challenge in the application of MMCs, lies in their production methods. This includes liquid-metal mixing techniques, where reinforcement particles are incorporated into a molten aluminum matrix, through mechanical stirring. Others are the liquid-metal penetration method, which involves the forcing of molten aluminum or its alloys, into a reinforcement preform, either as a compacted bed or a self-supporting structure; and the solid-state techniques, e.g., powder metallurgy [77]. When compared to the fabrication of resin-based friction materials, these processes require more sophisticated equipment and a deeper level of technical expertise.

Ceramic matrix composites have aluminium silicate, alumina and calcium as matrices, with silicon carbide as reinforcement. Ceramic matrix composites feature low density, high strength, hardness, and ceramic service temperature restrictions. Polymer matrix composites are highly sophisticated when compared to both the metal matrix composites and ceramic matrix composites. They are composed of thermoplastic polymers or thermosets, reinforced by natural carbon, which can be formed into various sizes and shapes. They produce superior properties, such as high stiffness and strength with high resistance to corrosion. Their tremendous strength, low cost, and ease of manufacturing, make them the most widely used composites [78].

Advantages, Applications and Limitations of Composite Materials

The strength, rigidity, and lightweight nature of composite materials are their greatest benefits. In selecting a suitable combination of reinforcement, the properties that precisely, match the specifications for certain uses, can be produced by manufacturers. For example, the modern aviation industry would be less effective without composites; this is because the requirement for materials that are both strong and lightweight, has been the major factor motivating the manufacture of composites. Advanced composites are commonly, used to make parts, such as rotor blades, propellers, wing and tail sections, and considerable numbers of the interior structures and accessories. A few of the smaller aircraft's airframes, as well as the stringers, tail, and body panels of big commercial airplanes, are made entirely, of composite materials [79].

Metals, such as aluminium are more prone, as opposed to composites, to entirely rupture when subjected to stress. This is because, minute fissure in a metal object can expand quickly, and may result to devastating consequences, particularly in aircrafts. However, the fibres in a composite, work to share the stress distributed in the composite and prevent any small crack from spreading. The appropriate composites, are often, very durable and resistant to heat and corrosion. This renders them to be perfectly and adequately ideal for usage in items that are subjected to harsh conditions, e.g., spacecraft, watercraft, and chemical-handling equipment [79]. Due to their ability to be moulded into extremely complicated shapes, e.g., surf, composite materials also provide design versatility.

The only drawback of composites is often, normally their costs. Even though the use of composites improves production processes, the raw materials are rather very costly. It is evident that composites will not completely, replace conventional materials, e.g., steel, but in many cases, they are just what is required. With the development of technology, new applications for composites, will undoubtedly emerge because what composites can do is not known yet [80].

Emerging Role of Natural Fibre Composites in Sustainable Brake Pad Development

The growing awareness in composite materials made of polymers reinforced with natural fibres, is associated to both their industrialized uses and the ultimate research endeavours on these materials. They are cheap, renewable, wholly or partly reusable, and they are eco-friendly. Plants, such as cotton, hemp, flax, jute, sisal, pineapple, kenaf, wood, banana, bamboo, etc., were used before now, as sources of lignocellulosic fibres, and they are more frequently, utilized to reinforce composites. Their accessibility, low densities, low prices and suitable mechanical properties, place them to be preferrable candidates to glass, carbon and artificial fibres, often used to produce composites. The composites produced from natural fibre are more environmentally friendly, and they find applications in the transport industry (aerospace, rail system and automobiles), the defence sector, the construction and building sectors (ceilings, and partitioning of boards), the wrapping/packaging sectors, in the end-user goods, etc [81].

Considerable number of studies are in the domain of developing brake pads, free from asbestos. Agro-waste utilization, such as coconut shell, palm kernel shell (PKS), etc., were previously examined [82-85]. Table 1 shows the summary of some findings on the development of coconut shell to produce brake pad.

Table 1. Summary of some findings on coconut shell-based materials for brake pad production

S/No	Authors	Materials	Findings
1	Olumodeji [86]	Coconut shell and other agricultural waste	They exhibit better friction properties than imported pads
2	Abutu et al. [87]	Coconut shell and Seashell	All of the parameters considered have major impact on the brake pads' mechanical and tribological characteristics, as evidenced by their p-values of >0.010 (1%).
3	Bretotean et al. [88]	Coconut fiber	As the amount of coconut fiber increases, so do the hardness, compressive strength, and longitudinal elasticity modulus.
4	Abutu et al. [89]	Coconut shell	They exhibit steady friction coefficient, improved hardness and minimal wear rate.
5	Apasi et al. [90]	Coconut shell	As the coconut powder increases in the samples, there is increase in the tensile and impact strengths, with a reduction in wear
6	Abutu et al. [91]	Coconut shell and other agricultural waste (asbestos free materials)	The braking temperature of the developed coconut shell brake ≤ 350°C and microstructural analyses confirmed the suitability of asbestos-free pads.
7	Datau et al. [92]	Coconut shell ash and Kyanite particles	The mean particle size in the coconut shell ash microstructure was 26.42 μm, while utilizing it as reinforcing materials, will improve strengthening.
8	Kholil et al. [93]	Coconut fiber, wood powder, cow bone	Composite suitable for motorcycle and light vehicles brake pads with improved thermal and wear properties.
9	Simamora et al. [94]	Candlenut shell and coconut shell	Samples produced have higher hardness and high resistance to wear.
10	Shuaibu et al. [95]	Coconut shell powder & ash, gum arabic	Hardness and density increase while water and oil absorptions decrease as the particle sizes decrease from 450 μm -154μm.

Research around the globe, concentrates on the approaches that employ wastes from agriculture or industry, as sources of raw materials for the sector. The use of these waste materials will be both economical, and result to foreign exchange earnings (in regions where they are available in abundance) and in negative environmental amelioration. Another agro waste is the bagasse, which is the fiber that is left upon forcefully pressing sugar cane to extract the sugar [96]. Bagasse is freely obtainable, and it is not harmful [4]. Some of the bagasse is burnt to provide heat for sugar processing operations. Before now, ~90 percent of empty bunches, fibers, branches, stalks were disposed as trash and burned outside or dumped in waste ponds. As a result, the sugar cane manufacturing industry wastes, adds substantially, to the carbon dioxide emission [13].

Periwinkle Shells as Sustainable Reinforcement for Brake Pad Production

The periwinkle (Turritella communis) is a dark, oval, and hard-shelled aquatic snail that is edible. The outer shell that covers a periwinkle is a naturally occurring structure. This exterior structure protects the winkles from mechanical harm and potential assailants. This structure has many segments, and it is naturally composed of conchiolin, an organic matrix, stuck together with calcium carbonate precipitates [97, 98]. The water-resistant nature of these organic matrix shells, loaded with calcium carbonate, allows the periwinkle shells and their byproducts to have a wide range of uses [99]. Periwinkles are plenty on the rocky coastlines in the surrounding regions of South-South Nigeria, namely: Cross-River, Rivers, Akwa-Ibom and Bayelsa States of Nigeria. There are numerous markets in Nigeria, where they are available for sale. The shells are disposed after consumption, contributing to solid waste in the cities where they are produced, which poses substantial risks to humans and the environment [100]. Consequently, their efficient, favourable, and environmentally friendly use, has long portrayed a problem for scientific applications.

One of the most unconventional materials employed in brake pad production is the periwinkle shell, a food processing by-product that poses environmental and health risks due to the large volumes of waste that it generates. The utilization of crushed periwinkle shells as an alternative for asbestos in brake pad manufacturing, presents a promising solution to the disposal challenge. Studies conducted in Nigeria, evaluated the mechanical properties of periwinkle shell particles smaller than 255 µm, revealed that the material has a lower density compared to asbestos and it demonstrated significant resistance to high temperatures, with its thermal degradation only beginning at temperature beyond 600 °C. Moreover, the material demonstrated significantly, greater hardness, measuring approximately 75 HRC, indicating its superior rigidity when compared to asbestos [101, 102]. Further research conducted in Nigeria, expanded on the earlier findings, by developing multiple brake pad prototypes that incorporated periwinkle shell particles of varying sizes, ranging from 100 - 350 µm. The study identified that particles sized at 100 µm, offered the most favourable properties. These prototypes demonstrated the highest compressive strength and hardness, along with the lowest levels of water and oil absorption. According to the researchers, these performance metrics surpassed those of the commercially available brake pads [103]. Table 2 shows the composition of periwinkle shell particles, while Fig. 2 shows the photograph of the periwinkle shells.

Table 2. Analysis of the elements in the periwinkle shell particles [103]

S/No	Element	Periwinkle shell	Unit
I	SO3	0.30	Wt %
II	CaO	96.09	Wt %
III	Fe2O3	0.79	Wt %
IV	K2O	0.52	Wt %
V	MgO	1.54	Wt %
VI	Na2O	0.10	Wt %
VII	SiO2	0.09	Wt %
VIII	MnO	0.06	Wt %
IX	Cr2O3	0.003	Wt %

Fig. 2. Periwinkle Shells

Properties and Potential of Palm Kernel Shell (PKS) as a Sustainable Reinforcement in Brake Pad Production

Plant fibres, such as shells of coconuts and palm kernels, are hydrophilic because they are made of lignocellulose, which has hydroxyl groups that are highly polarized [104]. When compared to glass fibres, lignocellulosic fibres have several advantages due to their biodegradability, renewable nature, and appropriate unique qualities. Essentially, these fibres have intriguing physical and mechanical characteristics [105].

The Palm Kernel Shells (PKS) are solid rocky endocarps that enclose the kernel and the shells, with varying sizes and structures [106, 107]. There exist two types of these shells, which are "Tenera" and "Dura". In contrast to the Dura type, the hybrid Tenera has a small shell thickness and was created specifically to produce a high oil content [108]. The shell is composed of approximately 21% combustible gas, 45% pyroligneous liquor, and 33% charcoal [109]. The palm kernel shell itself is a material with low moisture product and high density, and it can burn, thereby producing combustion Calorific heat of about 4,200 kcal/kg. The PKS are gotten after the palm oil has been extracted. After breaking the nuts and removing the kernels, the shells are typically abandoned as wastes.

Palm trees are primarily, cultivated in plantations across West Africa. Between 15-18 tons output per hectare of palm tree plantation, renders the PKS a plentiful and low-cost resource. Its minimal density in relation to other organic waste, allows for easy and cost-effective transportation [110]. Due to its fibrous structure, PKS has been investigated as a viable alternative to asbestos in brake pad manufacturing. PKS can make up as much as 40% of the friction layer volume [111]. When processed into powdered form, PKS exhibits low hygroscopicity, along with high rigidity and toughness, which are beneficial in braking applications [9]. Additionally, PKS demonstrates a high coefficient of friction when combined with cast iron brake discs. However, its effectiveness diminishes at elevated temperatures because during a high-speed braking the coefficient of friction drops considerably, as a result of its limited thermal resistance. Furthermore, oxidation heightened the wear of the pad, which occurred drastically faster when compared to the conventional brake pads [112, 113].

Research carried out by Mgbemena et al., [114] identified the initial temperatures of thermal decomposition in three distinct phases, viz: 54.28 °C, 237.14 °C, and 538.57 °C, accompanied by notable weight losses of: 6%, 27%, and 42.37%, respectively. Brake pads designed for cold braking applications that do not reach extremely high temperatures, performed significantly better under these conditions. The particle size of PKS used in pad production, also plays a critical role. Pads that incorporate large PKS particles, exhibited increased hygroscopic absorption and improved wear resistance. However, most favourable mechanical properties, including high hardness, enhanced durability, and low porosity, were achieved when finely grounded PKS material was used [60]. In this modern technological era, bio-based composites provide the potential for environmental benefits, low energy consumption, light weight, insulation, and the capacity to absorb sound and acoustics [115]. Table 3 shows the composition of palm kernel shell particles, while Fig. 3 shows the palm kernel shells.

Table 3. Analysis of the elements in palm kernel shell particles [60]

S/No.	Element	Level Detected (Palm kernel shell)	Unit
I	Br	0.005	Wt %
II	Ca	0.028	Wt %
III	Cu	0.009	Wt %
IV	Cr	0.002	Wt %
V	Fe	0.006	Wt %
VI	K	0.005	Wt %
VII	Mn	0.002	Wt %
VIII	Se	0.003	Wt %

Fig. 3. Palm Kernel Shells

Preparation and Molding of Periwinkle and Palm Kernel Shell-Based Composites

Onyeneke et al [115] reported that crushed periwinkle shell (PWS) and cracked palm kernel shell (PKS) were soaked separately, in distilled water, diluted with 1% (v/v) sodium hydroxide (NaOH) at ambient temperature. After three (3) hours of mechanical stirring, the mixture was filtered, cleaned with distilled water, and dried for twenty-four (24) hours at 80oC in an oven. The cleaned shells of PWS and PKS were burnt separately, in the furnace at a temperature of 500 - 600°C; thereafter the shells were removed from the furnace and cooled for some time before being cut with a hammer into small fragments. These small fragments were thereafter, grounded/pulverized into powder and sieved according to the BS 1377; 1990 standard, with particle sizes ranging from 80 to 150μm [115]. A wooden rectangular mould was prepared to carry out the moulding operation. The grounded PWS and PKS powder prepared were then, mixed in different proportions. Each proportion was mixed with epoxy resin in the desired amount and aluminium filings were added to obtain the required strength and hardness to the mixture. After that, the mixture was transferred into the prepared mould and mechanically pressed. After about 30 minutes, the laminate was taken out of the mould and cut to the required sizes for mechanical testing.

Mathematical Formulation of Volume and Weight Fractions in Composite Laminates

The volume fraction for a particulate (v_p) and for the matrix (v_m) and the weight fraction of a particle (w_p), as well as for the matrix (w_m) of a composite laminate, are defined by using Eq. 1 [99].

$$v_p = \frac{V_p}{V_c} \text{ and } v_m = \frac{V_m}{V_c} \tag{1}$$

where V is the volume of the constituent under consideration, and the particle, composite, and matrix are denoted by the subscripts p, c and m, respectively.

Comparably in Eq. 2:

$$w_p = \frac{W_p}{W_c} \text{ and } w_m = \frac{W_m}{W_c} \tag{2}$$

where w_p and w_m are the weight fractions of particle and matrix respectively, while w_c is the weight of the constituent under consideration, taking into cognizance the subscripts.

A correlation between the weight and volume fractions is shown by bringing forth the density (ρ) of the composite and its components, as shown in Eq. 3 [99].

$$\rho_c = \rho_p v_p + \rho_m v_m \tag{3}$$

The weight fractions of the particle w_p and the matrix w_m, are as shown in Eq. 4 to Eq. 5. [36].

$$w_p = \frac{W_p}{W_c} = \frac{\rho_p V_p}{\rho_c V_c} = \left(\frac{\rho_p}{\rho_c} v_p\right) \tag{4}$$

$$w_m = \frac{W_m}{W_c} = \frac{\rho_m V_m}{\rho_c V_c} = \left(\frac{\rho_m}{\rho_c} v_m\right) \tag{5}$$

At any composite strain, ε_c the preceding fracture, the stresses in the matrix (σ_m) and particle (σ_p) are obtainable, as shown in Eq. 6 to Eq. 7.

$$\sigma_m = E_m \varepsilon_c \tag{6}$$

$$\sigma_p = E_p \varepsilon_c \tag{7}$$

where E_m and E_p represents Youngs moduli of matrix and particle, respectively, while the stress of the composite (σ_c) is given by Eq. 8.

$$\sigma_c = \sigma_p v_p + \sigma_m (1 - v_p) \tag{8}$$

and the components' axial Youngs Modulus is given by Eq. 9.

$$E_c = E_p v_p + E_m\left(1 - v_p\right) \tag{9}$$

Development and Performance of Periwinkle/Palm Kernel Shell Agro-waste Reinforced Composites for Brake Pad Production

Many researchers have examined agro waste materials for brake pad application. Anaidhuno et al., [116] utilized the palm seed, coconut and palm kernel shells as constituents in a composite to produce brake linings. Their result showed improved wear resistance from the wear test result of between 0.025mm/min–0.06mm/min. Rajmohan et al., [117] also used the followings: coconut shells, sugar cane, and snail shells as composite materials to develop brake pad linings. Their findings showed an improved wear resistance, resulting from a wear test result, of between 35.5 x 10-5 mg/m–41.3 x 10-5 mg/m. Amaren et al., [81] examined how the size of periwinkle shell particles affected the asbestos-free brake pad's wear behaviour. Their findings revealed that particles of periwinkle shell can successfully, substitute asbestos in brake pad manufacture because the coefficient of friction obtained in their investigation, fell within the permissible range for automobile brake pads. Afolabi et al., [118] investigated the production of brake pads by utilizing polymer composites reinforced with cow bone and PKS. The study found that both materials exhibited sufficient thermal stability to withstand typical braking temperatures without decomposition. Additionally, hardness tests revealed values of 46 HRB for the cow bone and 55.7 HRB for the PKS, which are comparable to those of conventional materials currently in use. Dagwa et al., [119] characterized powdered PKS for use in composites made of a polymer matrix. Their findings revealed that the properties exhibited by palm kernel shell, encouraged its usage as a friction material. Those properties, include density (1.58 ± 0.07 g/cm3), porosity (6.76 ± 0.42 %) and moisture content (11.16 ± 016 %). Anshuman and Maurya [120] carried out the mechanical analysis of an epoxy-based composite made from biowaste. Their findings indicated that the composite showed excellent abrasion and wear resistance as the hardness increased from 13 Hv to 35 Hv.

In a study conducted by Deepika et al., [113], the development and performance assessment of a composite material for wear-resistant applications was explored. PKS was used as a filler, in combination with sulphur and other conventional brake pad constituents, including calcium carbonate, quartz, iron ore, brass chips, ceramics, cashew nut-shell liquid (CNSL), and carbon black. The PKS filler was pulverized to a particle size of 125 µm. The results demonstrated that PKS exhibited performance characteristics comparable to those of asbestos-based brake linings under a range of speed and inertial conditions.

Fono-Tamo and Koya [9] developed advanced automotive brake pad material, following the normal practices involving palm kernel shell (PKS) in achieving quality properties that are comparable to those of the commercially produced brake pads. Their results showed a shear strength of 40.95 MPa, a hardness of 32.34 MPa, and a notable friction coefficient of ~0.43. These values fall within the acceptable range proposed by Roubíček et al., [12], who suggested that the friction coefficient for brake pad materials should lie between 0.30 and 0.70.

The potential of PKS agro-waste as a substitute for asbestos in brake pad production was effectively, demonstrated by Ibhadode and Dagwa [112]. By using the Taguchi optimization technique, they identified the optimal process parameters, including a moulding temperature of between 150–170 °C, pressure of between 16.74–27.90 MPa, curing times of between 6–10 minutes, and heat treatment durations of between 1–3 hours. The material formulation comprised of 56% reinforcement, 14% abrasives, 24% binder, and 6% friction modifier. The fabricated brake pad was subjected to performance testing, yielding results that are comparable to those of the traditional asbestos-based pads. The measured surface hardness ranged from 64 to 89 HRB, with a coefficient of friction of between 0.35 and 0.44. The wear rates fell into the range of between 0.017 and 0.170, that is consistent with increased wear at speeds above 80 km/h. These findings confirm the effectiveness of PKS-based pads as a sustainable and efficient alternative to the asbestos-based brake materials.

Elakhame et al., [121] explored the use of PKS at varying particle sizes of 100 µm, 350 µm, 710 µm, and 1 mm for the development of asbestos-free brake pads. The brake pad formulations included the followings: between 35%–55% PKS, 20% resin, 10% graphite, 15% steel, and ~20% silicon carbide (SiC), and processed by using the compression moulding technique. Major properties, such as: hardness, density, compressive strength, flame resistance, and fluid absorption were evaluated. Among the tested samples across multiple metrics, the formulation with 100 µm PKS demonstrated the most favorable results. Microstructural analysis confirmed a uniform dispersion of the resin used, indicating improved interfacial bonding, at small particle sizes. When compared to conventional asbestos-based pads, the PKS-based variants exhibited a highly competitive performance, highlighting their potential as eco-friendly, cost effective and efficient alternatives in brake pad production.

Mgbemena et al., [114] developed an asbestos-free friction lining for automotive brake pads by using ground palm kernel shell (PKS) as the primary filler and metallic cutting shavings from workshops as abrasives. Phenolic and alkyd resins were utilized as binders in the formulation. The fabricated samples were subjected to physical, thermal Optical, and tribological tests, which were conducted by using a Simultaneous Thermal Analyzer and Stereomicroscopy (ZEISS). When compared with commercial brake linings, manufactured by the original equipment manufacturers (OEMs), the PKS-based material showed a slightly higher wear rate of 0.24 µm, in contrast to the 0.16 µm observed in the OEM-produced samples. Despite this, the results demonstrated the fact that the PKS-based friction linings possessed promising characteristics for application in eco-friendly, asbestos-free brake pads. However, the PKS-based lining demonstrated enhanced thermal stability and a greater pulverized yield, hence, indicating its resilience under elevated temperature conditions. These findings suggest that, despite the higher wear rate, the PKS-based formulations offered good potential as thermally robust alternatives to the asbestos-containing brake linings.

Singh, et al., [122] studied the absorption characteristics and mechanical properties of coconut shell powder-epoxy composite. Their findings indicated that the composite made with between 20-30% coconut shell powder occupied volume fraction, finds application in the automobile's interior because of its improved strength and low density. Ofem and Umar, [123] researched into how filler the content affected the mechanical properties of CNSL resin composite reinforced with periwinkle shells. Their results showed maximum flexural and tensile strengths at 30% filler content and 400 µm particle sizes, while the maximum impact strength and tensile modulus were observed at an 800 µm particle size with 30% and 40% filler contents, respectively.

Egeonu et al., [124] utilized locally sourced palm kernels and coconut shells to develop high quality asbestos-free disc brake friction lining material that met the Mitshibushi L-300 geometrical specifications. A brake pad that was purchased commercially, served as the control. A trio of separate samples, coded: A, B and C were developed by varying the mass compositions of coconut and palm kernel shells. The result obtained from all the three different samples, compared favourably with the commercially purchased brake pad.

Aku et al., [101] conducted out an in-depth investigation into the suitability of periwinkle shell as an asbestos-free alternative in brake pad production, through both spectroscopic and wear analysis techniques. The study incorporated analytical tools, such as X-ray diffraction (XRD), thermogravimetric/differential thermal analysis (TGA/DTA), Fourier-transform infrared spectroscopy (FTIR), and X-ray fluorescence spectroscopy (XRF), to characterize the material properties. Major properties, such as density, hardness, and wear rate were measured and compared with those of conventional asbestos-based brake pad materials. The findings confirmed the fact that periwinkle shell exhibits favorable mechanical and thermal characteristics, making it a viable candidate for brake pad applications. Furthermore, Obota et al., [125] carried out a comparative study between the different types of abrasive sandpaper that were produced by using palm kernel and periwinkle shells that were locally sourced. This was done to assess their potentials as replacements for imported abrasives sandpaper. Their results revealed that the mechanical and physical properties obtained, were closely at par to the acceptable standards when compared to the imported sandpapers.

Yawas et al., [126] examined the morphological and mechanical properties of asbestos-free brake pads, reinforced with periwinkle shell particles, focusing on the influence of particle size. Their findings revealed that by reducing the particle sizes to between 710 µm to 125 µm, led to notable improvements in the asbestos-contained brake pad compressive strength, hardness, and density. This enhancement in the mechanical properties with finer particles, underscores the capability of periwinkle shell as an effective reinforcement material. The study supports the effectiveness of periwinkle shell as a sustainable and efficient substitute to asbestos, in the production of high-performance brake pads. In the same vein, Yakubu et al., [127] designed an asbestos-free brake pad using periwinkle shell particles (PSP) as reinforcement and thermoset resin as a binder and investigated how different PSP particle sizes (710 µm-125 µm) affected the brake pad performance. The study found that smaller particle sizes enhanced the interfacial bonding between the PSP and the resin matrix, thereby resulting in a better material integrity. While wear rates increased with higher loads and coarser particles, the friction coefficient remained within the acceptable range for standard brake pads. Moreover, the PSP demonstrated a higher decomposition temperature than asbestos, hence, indicating a superior thermal resistance. These findings highlight its potential as an environmentally sustainable and effective replacement for asbestos in brake pad manufacturing. Furthermore, Iwalola et al., [128], Mawuli et al., [129], and Uzochukwu et al., [130], each conducted independent studies on the development of asbestos-free brake pads by using periwinkle shell particles as reinforcement. Their findings consistently confirmed the fact that periwinkle shell is a viable and effective substitute for asbestos, by offering favorable mechanical and thermal properties that are desirably suitable for brake pad applications.

Current Research Gaps in Periwinkle/Palm Kernel Shell Epoxy Reinforced Composites

Despite significant progress in the development of periwinkle shell (PS) and palm kernel shell (PKS) reinforced epoxy matrix hybrid composites for brake pad applications, several critical research gaps do persist. A thorough understanding of their long-term operation under real-life operating conditions, such as thermal cycling and high-speed braking alternatives are still lacking. The interfacial bonding behavior between these natural fillers and the epoxy matrix, also needs deeper exploration to improve durability and mechanical properties. Moreover, there are insufficient modeling and optimization scenarios of multi-filler systems and resin compositions, particularly under varying environmental influences, e.g., humidity and temperature. Standardized testing protocols and consistent benchmarking against the commercial brake pads remain underdeveloped, thereby underscoring the need for uniform evaluation methods and regulatory validation.

Future Trends for Periwinkle/Palm Kernel Shell Epoxy Reinforced Composites

The growing need for sustainable, high-performance brake pad materials has driven major interest in hybrid composites reinforced with agro waste, such as periwinkle shell (PS) and PKS. Future research in this area is expected to focus on the nano-engineering of the reinforcements employed, surface modification techniques, and hybridization with other natural or industrial fillers to enhance the composites mechanical and tribological properties. Advances in epoxy matrix systems, particularly through toughening or bio-based resin modifications, will play a key role in improving the composites thermal and structural stability. The use of advanced manufacturing techniques, e.g., hot pressing and additive manufacturing, combined with computational tools, such as finite element analysis and AI-based modelling, will streamline the optimization of composite formulations. Additionally, efforts should be made to integrate thermally conductive and vibration-damping additives for better heat dissipation and operational safety. Emphasis on life-cycle assessment and cost-performance analysis will also guide the sustainable commercialization of these asbestos-free alternatives. These research trends promise to usher-in a new generation of eco-friendly, efficient, and durable brake pad materials.

Conclusion

The development of periwinkle shell (PS) and palm kernel shell (PKS) reinforced epoxy matrix hybrid composites offers a sustainable and performance-oriented alternative to asbestos-based brake pads. Composites produced with particle sizes between 100–125 µm exhibited the most favorable mechanical and tribological properties, including improved hardness and wear resistance. This particle size range was identified as optimal for interfacial bonding.

The hybrid composite brake pads demonstrated hardness values up to 75 HRC for PS and 55.7 HRB for PKS and compressive strength between 32–41 MPa. The coefficient of friction (COF) was within the acceptable range of 0.35–0.44, satisfying automotive performance requirements.

Thermal analysis revealed that PS maintains structural integrity above 600 °C, while PKS exhibits thermal decomposition between 54–538 °C, indicating their suitability for braking systems subjected to moderate-to-high temperatures.

Future research should focus on long-term durability testing under real-world conditions, finite element modeling for stress distribution, and the incorporation of nano-fillers for improved thermal dissipation.

References

[1] Ige, O. E., Inambao, F. L., Adewumi, G. A. *Biomass-Based Composites for Brake Pads: A Review,* **International Journal of Mechanical Engineering and Technology, 10(3),** 2019, pp. 920–943.

[2] Cho, M. H., Kim, S. J., Kim, D., and Jang, H. *Effects of ingredients on tribological characteristics of a brake lining: An experimental case study,* **Wear, 258**, 2005, pp. 1682–1687.

[3] Jacko, M. G., Tsang, P. H. S., and Rhee, S. K. *Automotive friction materials evolution during the past decade,* **Wear, 100,** 1984, pp. 503–515.

[4] Aigbodion, V., Akadike, U., Hassan, S. B., Asuke, F., and Agunsoye, J. O. *Development of asbestos-free brake pad using bagasse,* **J. Tribol. Ind., 32,** 2010, pp. 12–18.

[5] Irawan, A. P., Fitriyana, D. F., Tezara, C., Siregar, J. P., Laksmidewi, D., Baskara, G. D., Abdullah, M. Z., Junid, R., Hadi, A. E., Hamdan, M. H. M., Najid Najid, N. *Overview of the Important Factors Influencing the Performance of Eco-Friendly Brake Pads,* **Polymers, 14,** 2022, p. 1180. https://doi.org/10.3390/ polym14061180

[6] Jaafar, T. R., Selamat, M. S., Kasiran, R. *Selection of Best Formulation for Semi-Metallic Brake Friction Materials Development,* **In: Powder Metallurgy,** InTech, Shanghai, China, 2012. doi: 10.13140/2.1.1222.2404

[7] Darius, G. S., Berhan, M. N., David, N. V., Shahrul, A. A., Zaki, M. B. *Characterization of brake pad friction materials,* **In: Brebbia CA, Alberto A (eds) Computational Methods and Experiments in Materials Characterization II,** WIT Press, Southampton, UK, 2005, pp.43-50.

[8] Namessan, N. O., Maduako, J. N., and Iya, S. A. *Comparative study of the effects of treatment techniques on the thermal, friction and wear properties of kenaf (Hibiscus Cannabinus) fibre reinforced brake pads,* **African Journal of Science and Technology, 12,** 2013, pp. 44–54.

[9] Fono-Tamo, R. S., and Koya, O. A. *Characteristics of pulverized palm kernel shell for sustainable waste diversification,* **International Journal of Scientific and Engineering Research, 4,** 2013, pp. 6–10.
[10] Borawski, A. *Conventional and unconventional materials used in the production of brake pads – review,* **Science and Engineering of Composite Materials, 27(1),** 2020, pp. 374-396.
[11] Mathur, R. B., Thiyagarajan, P., and Dhami, T. L. *Controlling the hardness and tribological behaviour of non-asbestos brake lining materials for automobiles,* **Carbon Letters, 5,** 2004, pp. 6-11.
[12] Roubicek, V., Raclavska, H., Juchelkova, D., and Filip, P. *Wear and environmental aspects of composite materials for automotive braking industry,* **Wear, 265,** 2008, pp. 167-175.
[13] Amaren, S. G. *Evaluation of the wear and thermal properties of asbestos free brake pad using periwinkles shell particles,* **Usak University Journal of Material Sciences, 2,** 2013, pp. 99 – 108.
[14] Blau, P. J. *Compositions, Functions and Testing of Friction Brake Materials and Their Additives,* Oak Ridge National Laboratory Report, Report no.: ORNLITM-2001/64, US Department of Energy, Tenessee, USA. 2001.
[15] Borawski, A. *Common methods in analysing the tribological properties of brake pads and discs – a review,* **Acta Mechanica et Automatica, 13(3),** 2019, pp. 189–99.
[16] Nagesh, S. N., Siddaraju, C., Prakash, S. V., Ramesh, M. R. *Characterization of brake pads by variation in composition of friction materials,* **Procedia Materials Science, 5,** 2014, pp. 295–302.
[17] Nicholson, G. **Facts about friction: 100 years of brake linings and clutch facings.** 2nd ed, P&W Price Enterprises Inc., Croydon, 1995.
[18] Patel, S. K., Jain, A. K. *Experimental study of brake lining materials with different manufacturing parameters,* **International Journal of Engineering Trends and Technology, 7(4),** 2014, pp. 192–197.
[19] Xiao, X., Yin, Y., Bao, J., Lu, L., Feng, X. *Review on the friction and wear of brake materials,* **Advances in Mechanical Engineering, 8(5),** 2016, pp. 1–10.
[20] Gujrathi, T. V., Damale, A. V. *A review on friction materials of automobile disc brake pad,* **International Journal of Engineering Educ Technol., 3(2),** 2015, pp. 1–4.
[21] Aza, C. A. Composites in Automotive Applications: Review on brake pads and discs. 2014 [cited 2025 April 9] Available from: www.bristol.ac.uk/engineering/media/accis/cdt/news/aza.pdf
[22] Bijwe, J. *Composites as friction materials: Recent Developments in Non- Asbestos Fibre Reinforced Friction Materials,* **Polymer Composites, 18(3),** 1997, pp. 378–95.
[23] Chan, D., Stachowiak, G. W. *Review of automotive brake friction materials,* **Journal Automobile Engineering Part D, 218,** 2004, pp. 953-66. https://doi.org/10.1243/0954407041856773.
[24] Lemen, R. A. *Asbestos in brakes: exposure and risk of disease,* **American Journal of Industrial Medicine, 45(3),** 2004, pp. 229–37.
[25] Ikpambese, K. K., Gundu, D. T., and Tuleun, L. T. *Evaluation of palm kernel fibers (PKFs) for production of asbestos-free automotive brake pads,* **Journal of King Saud University – Engineering Sciences, 28,** 2016, pp. 110–118.
[26] Ganguly, A., George, R. *Asbestos free friction composition for brake linings,* **Bulletin of Materials Science, 31(1),** 2008, pp. 19–22.
[27] Kim, Y. C., Cho, M. H., Kim, S. J., Jang, H. *The effect of phenolic resin, potassium titanate, and CNSL on the tribological properties of brake friction materials,* **Wear, 264(3-4),** 2008, pp. 204–10.
[28] Eriksson, M., Lord, J., Jacobson, S. *Wear and contact conditions of brake pads: dynamical in situ studies of pad on glass,* **Wear, 249(3-4),** 2001, pp. 272–278.

[29] Mitsumoto, M. *Copper free brake pads with stable friction coefficient,* Hitachi Chemical Technical Report; Report No.59, Sponsored by the Social Infrastructure-related Materials Development Center, R&D Headquarters, Japan. 2017.
[30] Kim, S. J., Cho, M. H., Cho, K. H., Jang, H. *Complementary effects of solid lubricants in the automotive brake lining,* **Tribology International, 40(1),** 2007, pp. 15–20.
[31] Gudmand-Hoyer, L., Bach, A., Nielsen, G. T., Morgen, P. *Tribological properties of automotive disc brakes with solid lubricants,* **Wear, 232(2),** 1999, pp. 168–175.
[32] Szpica, D. *New Leiderman-Khlystov Coeficients for Estimating Engine Full Load Characteristics and Performance,* **Chinese Journal of Mechanical Engineering, 32(1),** 2019, p. 95.
[33] Dmitriev, A. I., Osterle, W., Kloss, H. *About the influence of automotive brake pad composition on frictional performance,* **Results of nano-scale modeling. Nanosystems: physics, chemistry, mathematics, 2(2),** 2011, pp. 58–64.
[34] Franck, R. R. **Bast and other plant fibres,** Woodhead publishing, Cambridge, UK, 2005. https://doi.org/10.1533/978184569 0618.
[35] Crosa, G., Baumvol, I. J. Tribology of composites used as friction materials. **In: Friedrich K, editor. Advances in composite Tribology,** Elsevier, Germany, 1993. pp. 583–626.
[36] Loken, H. Y. *Asbestos free brakes and dry clutches reinforced with Kevlar aramid fiber,* SAE Technical paper 800667, 1980. https://doi.org/10.4271/800667.
[37] Mieczkowski, G. *Stress fields at the tip of a sharp inclusion on the interface of a bi-material,* **Mechanics of Composite Materials, 52(5),** 2016, pp. 601– 10.
[38] Bajpai, A., Saxena, P., Kunze, K. *Tribo-Mechanical Characterization of Carbon Fiber-Reinforced Cyanate Ester Resins Modified with Fillers,* **Polymers (Basel), 12(8),** 2020, p. 1725.
[39] Incesu, A., Korkmaz, K., Cetintas, O. O., Kubuc, O., Korkmaz, M., Karanfil, G. *Design of composite brake pads for metro with statistical approach***, In: 2. Uluslar arası Raylı Sistemler Mühendisliği Sempozyumu (ISERSE'13),** 9-11 October 2013, Karabük, Turkey.
[40] Dureja, N., Bijwe, N. J., Gurunath, P. V. *Role of type and amount of resin on performance behaviour of non-asbestos organic (NAO) friction materials,* **Journal of reinforced plastic and composites, 28(4),** 2009, pp. 489-97.
[41] Mieczkowski, G., Borawski, A., Szpica, D. *Static Electromechanical Characteristic of a Three-Layer Circular Piezoelectric Transducer,* **Sensors (Basel), 20(1),** 2019, pp. 1–14.
[41] Bijwe, J., Nidhi, N., Satapathy, B. K. *Influence of amount of resin on fade and recovery behaviour of non- asbestos organic (NAO) friction material,* **International Journal of Water, 23(3),** 2006, pp. 215–22.
[43] Bijwe, N. J., Majumdar, N. *Influence of amount and modification of resin on fade and recovery behavior of non-asbestos organic (NAO) friction materials,* **Tribology Letters, 23(3),** 2006, pp. 215–22.
[44] Bijwe, N. J. *NBR-modified resin in fade and recovery module in non-asbestos organic (NAO) friction materials,* **Tribology Letters, 27(2),** 2007, pp. 189–96.
[45] Yanar, H., Ayar, H. H., Demirtas, M., Purcek, G. *Effect of resin content on tribological behaviour of brake pad composite material,* **Industrial Lubrication and Tribology, 72(2),** 2018, pp. 195–202.
[46] Mieczkowski, G. *Criterion for crack initiation from notch located at the interface of bi-material structure,* **Eksploatacja i Niezawodność, 21(2),** 2019, pp. 301–310.
[47] Menapace, C., Leonardi, M., Secchi, M., Bonfanti, A., Gialanella, S., Straffelini, G. *Thermal behaviour of a phenolic resin for brake pad manufacturing,* **Journal of Thermal Analysis and Calorimetry, 137(3),** 2019, pp. 759–766.
[48] Bijwe, J. *Composites as friction material: recent development in non-asbestos fiber reinforced friction material- a review,* **Polymer Composites, 18(3),** 1997, pp. 378–396.

[49] Cardona, F., Kin-Tak, A. L., Fedrigo, J. *Novel phenolic resins with improved mechanical and toughness properties,* **Journal of Applied Polymer Science, 123(4),** 2012, pp. 2131–2139.
[50] Komori, T., Miyake, S., Senoo, Y. Brake friction material. Patent US4954536, 1990.
[51] Kakegawa, H., Yasuda, T., Wang, X. Binder Composition for Friction Materials, and Friction Materials. Patent US5889081, 1999.
[52] Wu, J., Jia, Z., Yannan, Y. H., Yu, Z. Q. *Investigation on thermal stability and tribological properties of ZrB_2 particles filling cyanate ester resin composites by experiments and numerical simulation,* **Polymer Engineering & Science, 59(3),** 2018, pp. 602–607.
[53] Shivakumar, K., Abali, F., Sadler, R. *Development of cyanate ester-based carbon/carbon composites. ICCM-12,* **Proceedings of the 1999 International Conference on Composite Material,** 5-9 July 1999, Paris, France.
[54] McCormick, F.B., Drath, D.J., Gordisher, I., Kropp, A.M., Palazzotto, M.C., Sahyun, R. V. Energy-Curable cyannate/ethylenically unsaturated compositions, Patent US6069219A, 2000.
[55] Hamerton, I. **Chemistry and Technology of Cyanate Ester Resins,** Springer Science & Business Media, UK. 2012.
[56] Avallone, E. A., Baumeister, T., Sadegh, A. M. **Marks Handbook for Mechanical Engineers,** 11th ed, McGraw-Hill, New York. 2007.
[57] Agunsoye, J. O., Bello, S. A., Bamigbaiye, A. A., Akinboye, I. O. *Recycled ceramic composite for automobile brake pad application,* **Journal of Research in Physics, 1(39),** 2018, pp. 35–46.
[58] Taj, S., Munamar, A. M., and Khan, S. *Natural fiber-reinforced polymer composites*, **Proceedings of the Pakistan Academy of Science, 44,** 2007, pp. 129–144.
[59] Rajiv, V. *Development and analysis of environment friendly brake pad for light motor vehicles,* **International Journal of Advanced Research Trends in Engineering and Technology, 2,** 2005, pp. 935–939.
[60] Saravanan, C., Subramanian, K., Krishnan, V. A., and Narayanan, R. S. *Effect of Particulate Reinforced Aluminium Metal Matrix Composite –A Review,* **Mechanics and Mechanical Engineering, 19(1),** 2015, pp. 23-30.
[61] Szpica, D. *Modelling of the operation of a Dual Mass Flywheel (DMF) for different engine-related distortions,* **Mathematical and Computer Modelling of Dynamical Systems, 24(6),** 2018, pp. 643–60.
[62] Szpica, D. *Simplified numerical simulation as the base for throttle flow characteristics designation,* **Mechanika, 21(2),** 2015, pp. 129–133.
[63] Szpica, D., Piwnik, J., Sidorowicz, M. *The motion storage characteristics as the indicator of stability of internal combustion engine - receiver cooperation,* **Mechanika, 20(1),** 2014, pp. 108–112.
[64] Mieczkowski, G. *Static Electromechanical Characteristics of Piezoelectric Converters with various Thickness and Length of Piezoelectric Layers,* **Acta Mechanica et Automatica, 13(1),** 2019, pp. 30–36.
[65] Mieczkowski, G. *Optimization and prediction of durability and utility features of three-layer piezoelectric transducers,* **Mechanika, 24(3),** 2018, pp. 335–342.
[66] Szpica, D. *Comparative analysis of low-pressure gas-phase injector's characteristics***, Flow Measurement and Instrumentation, 58,** 2017, pp. 74–86.
[67] Kamble, M., Shakfeh, T., Moheimani, R., Dalir, H. *Optimization of a Composite Monocoque Chassis for Structural Performance: A Comprehensive Approach,* **Journal of failure analysis and prevention, 19(5),** 2019, pp. 1252–1263.
[68] Li, W., Yang, X., Wang, S., Xiao, J., Hou, Q. *Comprehensive Analysis on the Performance and Material of Automobile Brake Discs,* **Metals (Basel), 10(3),** 2020, p. 377.

[69] Saravanan, V., Thyla, P. R., Balakrishnan, S. R. *A low cost, light weight cenosphere–aluminium composite for brake disc application,* **Bulletin of Materials Science, 39(1),** 2016, pp. 299–305.
[70] Ismaila, S., Jatau, J. S., Bawa, M. A. *Particulate Reinforced Aluminium Alloy Matrix Composite Brake Rotor – A Review of the Mechanical and Wear Behaviours,* **Journal of Scientific and Engineering Research, 6(7),** 2019, pp. 29–40.
[71] Sadagopan, P., Natarajan, H. K., Praven, K. J. *Study of silicon carbide reinforced aluminium matrix composite brake rotor for motorcycle application,* **International Journal of Advanced Manufacturing Technology, 94(1-4),** 2018, pp. 1461–1475.
[72] Sivananthan, R., Tharun, K., Lokesh, G., Vijayaganapathy, D. *Experimentation on composite brake pads with aluminium reinforcement of SiC and Fly ash,* **International Journal of Pure and Applied Mathematics, 118(24),** 2018, pp. 1–11.
[73] Purkar, A. V., Deore, E. R. *Wear behavior of Aluminium Metal Matrix Composite with Silicon Carbide used for Brake Pads under Dry Friction Condition,* **International Advanced Research Journal in Science, Engineering and Technology, 3(6),** 2016, pp. 72–76.
[74] Szpica, D. *Validation of indirect methods used in the operational assessment of LPG vapor phase pulse injectors,* **Measurement, 118,** 2018, pp. 253–261.
[75] Bracamonte, L., Withers, J., Smith, T. *Lightweight, Wear Resistant, High Thermal Conductivity Metal Matrix Composite Brake Rotors,* SAE Technical Paper, ATS-MER, LLC, Michigan, USA, 2018.
[76] Peng, T., Yan, Q., Zhang, X. *Stability of Metal Matrix Composite Pads During High-Speed Braking,* **Tribology Letters, 66(2),** 2018, pp. 1–13.
[77] Nturanabo, F., Masu, L., Kirabira, J. B. *Novel Applications of Aluminium Metal Matrix Composites,* **In: Cooke K, editor, Aluminium Alloys and Composites,** Intech Open, London. 2020. https://doi.org/10.5772/intechopen.86225.
[78] Ishid, H. *Introduction to polymer composite processing,* **Polymer Science, 17(10),** 1970, p. 1807.
[79] Agrawal, P., Kundu, A. K., Purohit, D., Sahu, P., Gautam, N., Sharma, A., Patil, V. *A review paper of composite materials: Advantages and applications*, **International Journal of Advances in Engineering and Management (IJAEM), 4(11),** 2022, pp. 369-370.
[80] Anil, S. R., Mohan, J. R., Vilas, M. S., Mohan, P. S., Patil, A. A. *A research paper of epoxy based composite material from the natural fiber for manufacturing of helmet,* **Journal of Emerging Technologies and Innovative Research (JETIR), 8(7),** 2021, pp. 154-159.
[81] Amaren, S. G., Yawas, D. S., Aku, S. Y. *Effect of periwinkle Shell particle size on the wear behaviour of asbestos free brake pad,* **Results in Physics, 3,** 2013, pp. 109–114.
[82] Muhammed K. O., Orilonise, A., Woli, T. O., Olatinwo, T. F., Abdulazeez, M. A. *Production and tribological evaluation of brake pad made from locally available materials,* **International Journal of Information, Engineering & Technology, 12(9),** 2024, pp. 61-69.
[83] Okyere, A. K., Amedorme, S. K. *Utilization of palm kernel shell, rice straw, rice husk and rice panicle for automotive brake pad,* **International Journal of Engineering Research and Development, 19(1),** 2023, pp. 38-51.
[84] Popoola, O. T., Rabiu, A. B., Ibrahim, H. K., Omoniyi, P. O., Babatunde, M. A., Muhammed, N., Isiaq, F. O. *Production of automobile brake pads from palm kernel shell, coconut shell, seashell and cow bone,* **Adeleke University Journal of Engineering and Technology, 4(2),** 2021, pp. 92 – 101.
[85] Otuu, J. B. *The use of palm kernel shells in the production of automotive brake pads*, **Ebonyi Journal of Science, 4(3),** 2021, pp. 1-17.

[86] Olumodeji, J. O. *Assessment of agricultural waste for production of brake pads,* **International Journal of Engineering Research & Technology (IJERT), 2(11),** 2013, pp. 4070-4079.
[87] Abutu, J., Lawal, S. A., Ndaliman, M. B., Lafia-Araga, R. A., Adedipe, O., Choudhury, I. A. *Effects of process parameters on the properties of brake pad developed from seashell as reinforcement material using grey relational analysis,* **Engineering Science and Technology, an International Journal, 21,** 2018, pp. 787–797.
[88] Bretotean, C. P., Craciun, A. L., Josan, A., Ardelean, E. *Experimental study of sintered friction material with coconut fiber for brake pads*, **Materiale Plastice, 55(3),** 2018, pp. 389-392
[89] Abutu, J., Lawal, S. A., Ndaliman, M. B.,Lafia-Araga, R. A., Adedipe, O., Choudhury, I. A. *Production and characterization of brake pad developed from coconut shell reinforcement material using central composite design*, **SN Applied Sciences, 1,** 2019, p. 82.
[90] Apasi, A., Ibrahim A. A., Abdul-Akaba, T. *Design and Production of a Brake Pad Using Coconut Shell as Base Material,* **International Journal of Advances in Scientific Research and Engineering, 5(3),** 2019, pp. 65-74.
[91] Abutu, J., Lawal, S. A., Lafia-Araga, R. A., Ndaliman, M. B., Oluleye, M. A. *Microstructure and thermal analysis of brake pads developed from asbestos-free materials,* **Arid Zone Journal of Engineering, Technology & Environment, 16(2),** 2020, pp. 375-386.
[92] Datau, S. G., Bawa, M. A., Jatau, J. S., Muhammad, M. H., Bello, A. S. *The potentials of kyanite particles and coconut shell ash as strengthener in aluminium alloy composite for automobile brake disc,* **Journal of Minerals and Materials Characterization and Engineering, 8,** 2020, pp. 84-96.
[93] Kholil, A., Dwiyati, S. T., Siregar, J. P., Sulaiman, R. *Development of brake pad from composites of coconut fiber, wood powder and cow bone for electric motorcycle,* **International Journal of Scientific & Technology Research, 9(2),** 2020, pp. 2938-2942.
[94] Simamora, J. R., Kurniawan, C., Marbun, J., Simamora, P. *Mechanical properties of brake pad composite made from candlenut shell and coconut shell,* **Journal of Physics: Conference Series, 1428,** 2020, p. 012018.
[95] Shuaibu, Y. A., Ameh, S. E., Abubakar, J. A., Musa, A. J., Abubakar, G. M. *Development of asbestos-free brake pad using coconut shell powder and coconut shell ash as filler materials with gum arabic as the binder,* **International Journal of Innovations in Engineering Research and Technology, 10(4),** 2023, pp. 112-120.
[96] Ilori O. O., Ojetoye, A. A., Olagunju, C. B., Olasunkanmi, A. U., Adedokun, O. P., Umama, T. O. *Effect of mechanical and physical properties on brake pads produced from bagasse, banana peels and periwinkle shell,* **LAUTECH Journal of Engineering and Technology, 16(1),** 2022, pp. 100-105.
[97] Adewuyi, A. P., Adegoke, T. *Exploratory study of Periwinkle shell as coarse aggregate in concrete works,* **Journal of Science Resources, 4 (12),** 2008, pp. 1678 -1681.
[98] Badmus, M. A. O., Audu, T. O. K., Anyata, B. U. *Removal of Lead Ion from Industrial Wastewaters by Activated Carbon prepared from Periwinkle Shell (Typanotonus Fuscatus),* **Turkish Journal of Engineering and Environmental Science, 31,** 2007, pp. 251-263.
[99] Njoku, R. E., Okon, A. E., Ikpaki, T. C. *Effects of variation of particle size and weight fraction on the tensile strength and modulus of periwinkle shell reinforced polyester composite,* **Nigerian Journal of Technology, 30,** 2011, pp. 87-93.
[100] Umunakwe, R., Olaleye, D. J., Oyetunji, A., Okoye, O. C., Umunakwe, I. J. *Assessment of the density and mechanical properties of particulate periwinkle shell-aluminium 6063 metal matrix composite (PPS-ALMMC) produced by two-step casting,* **ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering, 10,** 2017, pp. 83–90.

[101] Aku, S. Y., Yawas, D. S., Madakson, P. B. *Characterization of periwinkle shell as asbestos-free brake pad materials,* **Pacific Journal of Science and Technology, 13(2),** 2012, pp. 57–63.

[102] Aigbodion, V. S., Agunsoye, J. O. **Bagasse (Sugarcane Waste): Non-Asbestos Free Brake Pad Materials,** LAP Lambert Academic Publishing, Berlin, Germany. 2010.

[103] Elakhame, Z. U., Olotu, O. O., Abiodun, Y. O., Akubueze, E. U., Akinsanya, O. O., Kaffo, P. O., Oladele, O. E. *Production of asbestos free brake pad using periwinkle shell as filler material,* **International Journal of Scientific & Engineering Research, 8(6),** 2017, pp. 1728-1735.

[104] Brahmakumar, M., Pavithran, C., Pillai, R. M. *Coconut fibre reinforced polyethylene composites: Effect of natural waxy surface layer of the fibre on fibre/matrix interfacial bonding and strength of composites,* **Composites Science and Technology, 65,** 2005, pp. 563–569.

[105] Avérous, L., Le Digabel, F. *Properties of biocomposites based on lignocellulosic fillers,* **Carbohydrate Polymers, 66,** 2006, pp. 480-493.

[106] Alangaram, U. J., Jumaat, M. Z., Mahmud, H. *Ductility behaviour of reinforced palm kernel shell concrete beams,* **European Journal of Scientific Research, 23,** 2008, pp. 406–420.

[107] Ndoke, P. N. *Performance of palm kernel shells as a partial replacement for coarse aggregate in Asphalt concrete,* **Journal of Polymer composites, 25(11),** 1995, pp. 110 - 120.

[108] Dagwa, I., Ibhadode, A. *Some physical and mechanical properties of palm kernel shell (PKS),* **Botswana Journal of Technology, 17,** 2010, pp. 11-15.

[109] Okly, D. A. *Chemical and biological characterization of the by-products of NIFOR palm oil mill,* **In International Oil Palm/Palm Oil Conference Progress and Prospect: Conference II: Technology. – Proc,** 1987, Kuala Lumpur, Malaysia, pp. 434 – 437.

[110] Okoroigwe, E. C., Saffron, C. M., Kamdem, P. D. *Characterization of palm kernel shell for materials reinforcement and water treatment,* **Journal of Chemical Engineering and Materials Science, 5(1),** 2014, pp. 1–6.

[111] Achebe C. H., Chukwuneke, J. L., Anene, F. A. *A retrofit for asbestos based brake pad employing palm kernel fiber as the base filler material,* **Proceedings of the Institution of Mechanical Engineers, Part L:** ***Journal of Materials: Design and Applications,*** **233(9),** 2018, pp. 1906-1913.

[112] Ibhadode, A. O., Dagwa, I. M. *Development of asbestos-free friction lining material from palm kernel shell,* **Journal of the Brazilian Society of Mechanical Sciences and Engineering, 30(2),** 2008, pp. 166–73.

[113] Deepika, K., Bhaskar Reddy, C., Ramana Reddy, D. *Fabrication and Performance Evaluation of a Composite Material for Wear Resistance Application,* **International Journal of Engineering Science and Innovative Technology, 2(6),** 2013, pp. 66–71.

[114] Mgbemena, C. O., Mgbemena, C. E., Okwu, M.O. *Thermal stability of pulverized palm kernel shell (PKS) based friction lining material locally developed from spent waste,* **ChemXpress., 5(4),** 2014, pp. 115– 122.

[115] Onyeneke, F. N., Anaele, J. U., Ugwuegbu, C. C. *Production of motor vehicle brake pad using local materials (periwinkle and coconut shell),* **The International Journal of Engineering and Science, 3,** 2014, pp. 17-24.

[116] Anaidhuno, U. P., Ologe, S., Maduike, F., Mgbemena, C. E. *The development of vehicle brake pad using local materials - (Palm kernel, coconut and cashew shells as base materials),* **IOSR Journal of Engineering, 7,** 2017, pp. 61 – 67.

[117] Rajmohan, B., Arunachalam, K., Sundarapandian, G. *Predict the tribological properties on brake pad using coconut shell/sugarcane/sic powder hybrid composites,* **International Journal of Engineering and Innovative Technology (IJEIT), 7,** 2017, pp. 43-49.

[118] Afolabi, M., Abubakre, O. K., Lawal, S. A., Raji, A. *Experimental investigation of palm kernel shell and cow bone reinforced polymer composites for brake pad production,* **International Journal of Chemistry and Materials Research, 3(2),** 2015, pp. 27-40.
[119] Dagwa, I. M., Builders, P. F., Achebo, J. *Characterization of palm kernel shell powder for use in polymer matrix composites,* **International Journal of Mechanical and Mechatronics Engineering, 12,** 2012, pp. 88-93.
[120] Anshuman, S., Maurya, M. *Preparation and mechanical characterization of epoxy-based composite developed by biowaste material,* **International Journal of Research in Engineering and Technology, 4,** 2015, pp. 397 – 400.
[121] Elakhame, Z., Alhassan, O., Samuel, A. *Development and production of brake pads from palm kernel shell composites,* **International Journal of Scientific & Engineering Research, 5,** 2014, pp. 735-744.
[122] Singh, A., Singh., S., Kumar, A. *Study of mechanical properties and absorption behaviour of coconut shell powder-epoxy composites*, **International Journal of Materials Science and Applications, 2(5),** 2013, pp. 157–161.
[123] Ofem, M. I., Umar, M. *Effect of filler content on the mechanical properties of periwinkle shell reinforced CNSL resin composites,* **ARPN Journal of Engineering and Applied Sciences, 7,** 2012, pp. 212–215.
[124] Egeonu, D., Oluah, C., Okolo, P. *Production of eco-friendly brake pad using raw materials sourced locally in Nsukka,* **Journal of Energy Technologies and Policy, 5,** 2015, pp. 47–54.
[125] Obota, M. U., Yawasa, D. S., Akua, S. Y., Obadaa, D. O. *An assessment on the production of abrasive sandpaper from locally sourced materials,* **Tribology in Industry, 38,** 2016, pp. 176–185.
[126] Yawas, D. S., Aku, S. Y., Amaren, S. G. *Morphology and properties of periwinkle shell asbestos-free brake pad,* **Journal of King Saud University - Engineering Sciences***,* 2013, doi: http://dx.doi.org/ 10.1016/j.jksues.2013.11.002.
[127] Yakubu, A. S., Amaren, S., Saleh, Y. D. *Evaluation of the wear and thermal properties of asbestos free brake pad using periwinkles shell particles,* **Usak University Journal of Material Sciences, 2,** 2013, pp. 99-108.
[128] Iwalola, H. O., Ikpeseni, S. C., Sada, S. O., Ekpu, M. *Performance evaluation of the integration of periwinkle shell, cashew nut dust, and resin for manufacture of brake pad formulations excluding asbestos,* **J. Appl. Sci. Environ. Manage, 28(10),** 2024, pp. 2949-2955.
[129] Mawuli, S. E., Anthony, S., Akintunde, D. O. *Development of asbestos-free disc brake pad using periwinkle shell powder and coconut shell ash as base materials,* **European Journal of Applied Sciences, 10(6),** 2022, pp. 473-491.
[130] Uzochukwu M. I., Aiyejagbara, M. O., Ugbaja, M. I. *Property investigation of cow horn/ periwinkle shell epoxy composite for automobile brake pad linings,* **Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS), 10(3),** 2019, pp. 86-91.

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