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RECENT PROGRESS AND EVOLUTION IN THE DEVELOPMENT OF NON-ASBESTOS BASED AUTOMOTIVE BRAKE PADS- A REVIEW

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ABSTRACT

Asbestos has been a significant reinforcement material in producing automobile friction components due to its physical and mechanical properties. However, the replacement of asbestos and other toxic metals employed in producing conventional friction components has been called for due to health and environmental concerns. Research in this area has led to the development of more efficient non-asbestos-based organic friction materials for automobiles. In this study, recent progress in the manufacture of non-asbestos-based, eco-friendly automotive brake pads is reviewed. A thorough classification of conventional and non-conventional friction materials used in the development of brake pads is presented, and the production method and the roles of friction materials in the mechanical and tribological properties of the manufactured pads are discussed. The study shows that the performance of brake pads manufactured from plants, animals, or plants and animal materials (hybrid) varies depending on the physical, chemical and mechanical properties of the plants and animals.

Keywords: Brake pads, Eco-friendly, Seashells, Asbestos, Fibres, Mechanical and tribological properties

1. Introduction

The brake is an important safety component in automobiles. It is applied to stop or retard the motion of vehicles. The life of vehicle occupants and road users depends mainly on the functionality of the brake; therefore, brakes must always be reliable and efficient [1-2].

Evolution in the brake system design, brake linings and brake pads depends largely on the physicochemical properties of the materials composing the brake linings and pads. Camel hair, cotton fibres and elm wood were the earliest materials used in automobiles (vehicles produced between 1890-1910) before the introduction of cotton-based material composites [3]. Friction materials should be able to absorb and dissipate heat to the atmosphere and subsequently maintain integrity under different working conditions [4-6] as excess heat adversely affects the braking system [7]. Due to the inability of early friction materials to efficiently withstand heat and control vehicle speed, automobile manufacturers faced the challenge of redesigning the brake system and finding appropriate friction materials to meet evolving needs of the brake system.

Modern light-duty vehicles are manufactured with rear drum and front disc brake systems. The brake consists of a calliper with two flat pads on either side, pressing against a rotating disc when a braking force is applied (see Figure 1). The rotor is connected to and rotated with the hub carrying the wheel. The calliper, which houses the brake pads, provides the means for forcing the pads into contact with the rotor. It causes friction, transforming the disc's kinetic energy to heat energy.

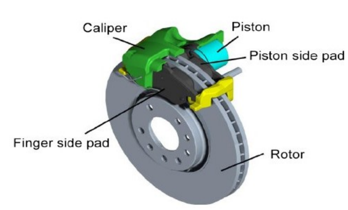

Fig. 1 Typical automotive disc brake system [8]

Asbestos fibres were the major friction material used in vehicles with front disc brake systems from the early 19th century through the 20th century. In 1906, a renowned automotive brake industry, Raybestos,

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invented the US's first asbestos-based automobile brake pads [9,10]. The brake pad is a composite of woven asbestos fibres and brass wire. Herbert Frood also introduced the first asbestos-based brake linings in the United Kingdom in 1907 [11]. Unlike cotton or hair, asbestos fibres possess good physicochemical and mechanical properties [12]. Mechanical and tribological tests on asbestos-based friction linings showed they could maintain their integrity under high braking temperatures and vehicular speeds [3]. These superior properties of asbestos-based linings encouraged their widespread usage until certain diseases were linked to prolonged exposure to asbestos dust.

Several scientists discredited using asbestos material due to its cancerous nature [13-24]. It was shown that prolonged exposure to asbestos dust results in asbestosis [25], mesothelioma and other cancerous diseases [26-31]. Consequently, the US Environmental Protection Agency gave a ban on the use of asbestos in the late 1900s, resulting in a great revolution in the automobile industry.

Alternatives to asbestos in brake pad production exist, as reviewed in several scientific journals. Abutu et al. [32] presented an overview of automobile brake pads produced from non-hazardous reinforcement materials. They studied the various production methods and properties of automobile brake pads produced from conventional agro-based products. Arman et al. [33] reviewed the composition of brake pads produced from different agricultural wastes- banana peels, palm wastes, aramid fibres, flax fibres etc. The effects of binders on the tribological properties of the formulation were considered. Also, Lawal et al. [34] reviewed various formulation methods, asbestos alternatives materials and properties of the brake pads composites. They also investigated the effect of a locally manufactured plant gum binder on the tribological properties of a cashew nut shell reinforced brake pad as an attempt to obtain a substantially green-based brake pad. A survey of different manufacturing methods and characterization of asbestos-free brake pads was conducted by Saindane et al. [35]. The various production and characterization methods, binders, reinforcement materials, fillers, and friction modifiers used in developing brake pads were studied based on the number of research publications available. Borawski [36] concentrated on conventional and unconventional materials used in brake pad production and their impact on the properties of the developed brake pads. Other review articles on materials proposed for manufacturing brake pads and other friction components include the works of [3, 37-44].

This paper presents an up-to-date review of non-asbestos-based automotive brake pads development. A thorough classification of conventional and non-conventional materials used in the development of brake pads is presented, and their roles in the mechanical and tribological properties of the pads are discussed. Furthermore, the performance of selected automobile brake pads manufactured from plants, animals and a hybrid of plant and animal materials is investigated in this study.

2. Classification of brake pad materials

The physicomechanical and tribological properties of brake pads and other friction components depend on the constituents' properties and production method. Bijwe [37] identifies three basic classifications of friction materials: metallic, carbon-carbon composites and organic polymeric (resin-bonded) friction materials. Figure 2 shows the classification and various subdivisions of friction materials.

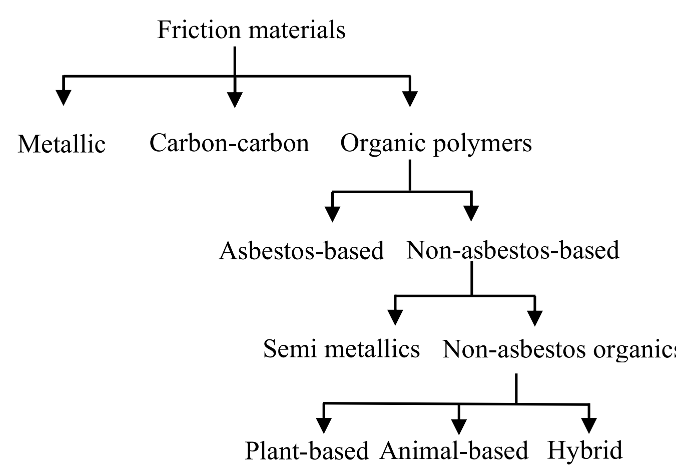

Fig. 2 Classification of friction materials.

Metallic brake pads are made from sintered brass, copper, iron steel and ceramics alloys. They are used on heavy-duty trains and high-speed aircraft that require extreme thermal stability.

Carbon-carbon composites consist of carbon fibres and carbon-reinforced matrices. They are used in racing cars, high-technology vehicles, trains and aircraft where structural integrity is needed than cost. Carbon-carbon friction materials are desirable due to their high friction coefficient, low wear rate, resistance to high temperatures and lightweight. However, they are very expensive to manufacture.

Organic polymeric (resin-bonded) friction materials consist of different organic materials bonded together by resin. They are the most commonly used friction materials on modern-day passenger vehicles. Materials used to manufacture organic polymeric friction components are categorized as reinforcement materials, binders, fillers and friction modifiers, depending on their role in the braking process [45-47].

Binder holds the composite together under various mechanical conditions. It makes up about 20% volume of the entire brake pad composite [37]. The choice of binder depends on the production process. It is a very important ingredient of brake pad composites as it greatly influences the overall properties of the brake pads [48-50]. To achieve desired brake pad performance, binder addition during formulation should be precisely determined as excessive binder reduces the coefficient of friction at high temperatures and significantly increases hardness. At the same time, too little binder reduces the pad's durability [51,52]. Resins are the most commonly used binders in brake pad production. The properties, advantages and disadvantages of various resins used in manufacturing brake pads are listed in Table 1.

Fillers are added to fill up the entire volume of the pad. They make up approximately 10% volume of the brake pad composite. Fillers reduce the overall cost of production without negatively affecting the required properties of the brake pads. Conventional and unconventional materials that can be used as fillers for brake pad production are listed in Table 2.

Friction modifiers can be abrasive or nonabrasive. They increase or decrease the friction coefficient and influence the mechanical properties of brake pads. Abrasive powders like alumina or chromium oxide increase friction coefficient, while solid lubricants such as graphite are added to moderate it. Abrasive like copper are often used to enhance heat dissipation. Common abrasives used in brake pad production are listed in Table 3.

Reinforcement materials provide strength to the composite matrix. They are usually organic or inorganic fibres that determine the brake pads' unique frictional characteristics, structural integrity and thermal stability [86]. Fibrous materials like Asbestos, Aramid, Acrylic, Basalt, Cellulose, Rockwool, a hybrid of Kevlar and Steel etc., have been used as reinforcement materials in the past [87-92]. Modern research involves the use of eco-friendly and readily available reinforcements in manufacturing.

Based on the type of reinforcement, organic polymeric friction materials are divided into asbestos and non-asbestos-based (Fig. 2). Asbestos-based friction materials were widely used in the 19th century due to the unique physical and mechanical properties of asbestos fibres. However, the proposed ban on the use of asbestos redirected the focus of researchers and manufacturers to the use of asbestos alternatives. Non-asbestos-based organic friction materials are grouped into metal-reinforced, semi-metallic (resin-bonded metallics) and fibre/shell-reinforced friction materials. Semi-metallics are asbestos-free friction materials containing 30 to 65% metal shavings (copper, steel, brass) bonded with resin. They are best suited for heavy-duty vehicles although they can also be applied to light-duty vehicles. They have strong stopping power and can withstand high-temperature exposure. However, semi-metallic friction materials are noisy during application, with a high wear rate propensity. Fibres/shell-reinforced friction materials are made from glass, carbon, Kevlar or organic fibres bonded together by appropriate resin. They are commonly used on light-duty vehicles. They are less expensive and produce less brake noise during operation. However, they produce a reasonable amount of brake dust and wear quickly, requiring frequent replacement.

The mechanical and tribological properties of bast fibres reinforced polymer composites have been investigated [94-100], and it was established that the organic fibres positively influence the performance of the composites.

Kumar et al. [101] developed a polymer composite from various bast fibres combination bonded by epoxy resin. The wear behaviour of the developed polymer was found to improve with higher fibre content in the composition. Ilanko and Vijayaraghavan [102] developed three brake pad samples from flax fibres, basalt and flax-basalt hybrid. They found out that the basalt-reinforced brake pads performed better due to high wear resistance and improved thermal properties of basalt. Salem et al. [103] investigated the mechanical performance of hybrid bast and basalt fibre-reinforced composites for automotive applications.

Table 1 Selected materials used as fillers in brake pad development

Resin	Properties	Advantages	Disadvantages
Phenolic [53, 54]	Most commonly used resin for friction materials. The volume of phenolic resin in a formulation has an inverse effect on the coefficient of friction and wear rate.	Inexpensive with good mechanical properties More resistant to solvents, acids and water than other resins.	It is brittle Degrades easily at high temperatures.
Epoxy [34, 55, 56]	Highly used in industries. They are produced from reactive polymers that contain epoxide groups. Epoxy resin has two components- a base and a hardener- that are combined in specific ratios.	High corrosion resistance They are less affected by water and heat than other polymeric matrices	High cost of production Long curing time and handling difficulties.
Polyester [57]	Polyester resins are thermoplastic resins created by a combination of polyhydric alcohol and polybasic acids in the presence of heat.	Inexpensive compared to other resins Cures faster than most resins Excellent physical and chemical properties	Highly brittle Poor mechanical and tribological properties compared to other resins. The finished cure is most likely weaker than that of epoxy.
Condensed Polynuclear Aromatic (COPNA) [58, 59, 60]	A novel heat-resistant resin Often used in the manufacture of friction materials.	Excellent thermal stability Self-lubricating properties	Brittleness Poor processability Poor solubility Poor mechanical properties [61] High cost of production
Cyanate ester [62]	Produced from cyanide monomers	Resistant to high temperature Dampens vibration Chemically neutral	High cost of production Brittleness.
Polyamide [63]	It is produced from fluorescein and calcium carbonate. They contain an amide group as a recurring part of their molecular chains.	Easily produced. Therefore they are inexpensive, strong and lightweight. Offers good wear and chemical resistance.	They are very good thermal isolators limiting their usefulness in the production of brake pads.

Table 2 Selected materials used as fillers in brake pad development

Fillers	Properties	Advantages	Disadvantages
Barites ($BaSO_4$) [52], [11]	Barites are inert minerals with high density. They can be mined from different places in the world and therefore are not expensive.	An increased $BaSo_4$ ratio in a brake pad composition reduces wear rates [64]. It is resistant to high temperature as it does not easily change its properties at temperatures above 300°C [65].	High density High % $BaSo_4$ results in a low coefficient of friction [66]
Limestone ($CaCO_3$) [11]	Odorless, fine white powder compound	Less expensive than barites	Not stable at high temperature
Zinc oxide [11]	White powdered in an organic compound	Offers good resistance to wears	It can cause scratches on the disc or drum
Vermiculite [67]	Golden-Silver, light a weight natural mineral, non-toxic, and expanded at high temperatures.	Speed up the joining of other components. Reduces brake noise The influences friction coefficient and wear rate.	Very expensive

Table 3 Selected materials used as abrasives in brake pad development

Abrasives	Properties	Advantages	Disadvantages
Copper [69-71]	Effect on tribological performance dispersion it's content the formulation	It increases the thermal conductivity and heat resistance of the pad. Improves friction coefficient Reduces adhesion	May produce undesirable noise [68] Harmful to humans
Boron [72-74]	It is a metal characterized by a high melting point. It has low chemical activity.	Reduces wear It tends to stabilize the coefficient of friction Resistant to high temperature	Low thermal conductivity, which may lead to overheating of the brake pad
Graphite [11, 75-77]	Graphite is a naturally occurring form of crystalline carbon. Does not easily react with other materials; hence, they are commonly used in the production of various lubricants.	Excellent lubricative properties Inexpensive Reduces braking noise Good heat conductor	Adverse effect on coefficient friction at high temperature
Titanium [78-80]	Titanium is a shining white metal with low density, high strength and high corrosion resistance. Highly suitable abrasive for brake pad production	Excellent mechanical properties. Brake pads are less susceptible to brake fading Reduces brake noise Resistance to high temperature Good lubricant properties	Very expensive Hence titanium based brake pads are higher in price
Brass [81-83]	Made from a combination of copper and zinc in varying proportions	Increases operation life of brake pad Good lubricating properties and high thermal conductivity	Very expensive High density Reduces friction coefficient
Cast iron [84, 85]	Usually in the form of iron fillings. Comprises about 2-5% volume of the brake pad composite	It has a positive effect on the overall tribological properties of the brake pad. It increases the friction coefficient	It increases the wear rate of the pads

3. Development in non-asbestos organic fibre/shell-reinforced brake pads

Due to health healthiness and economic benefits, organic fibres/shells are gaining widespread recognition as asbestos alternatives in the automobile industries. Many organic fibres/shells have been employed in developing brake pads with good physicomechanical and tribological properties. In this study, conventional and non-conventional organic fibres and shells proposed for the development of automobile friction materials are reviewed under three categories: plant-based, animal-based and plant-animal hybrids.

3.1 Plant-based organic fibres/shells reinforced brake pads

3.1.1 Bast leaf fibres

Bast fibres are soft woody fibres obtained from the stem of dicotyledonous plants like flax, hemp, jute, ramie, and kenaf.

The mechanical and tribological properties of bast fibres reinforced polymer composites has been investigated [94-100] and it was established that the organic fibres positively influence the performance of the composites. Kumar et al. [101] developed a polymer composite from various bast fibres combination bonded by epoxy resin. The wear behavior of the developed polymer was found to improve with higher fibre content in the composition. Ilanko and Vijayaraghavan [102] developed three brake pad samples from flax fibres, basalt and flax-basalt hybrid. They found out that the basalt reinforced brake pads performed better due to high wear resistance and improved thermal properties of basalt. Salem et al. [103] investigated the mechanical performance of hybrid bast and basalt fibre reinforced composites for automotive applications.

3.1.2 Miscanthus Grass

Miscanthus are lignocellulosic materials used as sources for energy production, biofuels, and bioremediation. Mostly grown as source of renewable energy, they are now being used as reinforcement materials in friction materials development.

Unaldi [104] studied the effect of compression pressure on the density and hardness of organic brake pads developed from powdered miscanthus reinforcement materials. The miscanthus plant was cut to about 1cm and dried before grinding to powder.

3.1.3 Banana Peels

Idris et al. [105] developed an eco-friendly brake pad free from asbestos using banana peels. The agricultural waste material (banana peels) was dried and grinded to powder form (uncarbonized). The newly developed brake pads' morphology, mechanical properties and wear properties were tested and found to be adequate replacements of conventional commercial brake pads.

3.1.4 Orange peels

A plant-based organic brake pad reinforced with orange peel dust was developed by Charles and Devaprasad [106] using the hand lay-up fabrication method. Mechanical and tribological tests on the developed samples show uniformity with commercial asbestos-based products.

3.1.5 Bagasse

Bagasse is the main by-product of the sugar cane industry. It is the sugarcane's dry fibrous remains after the juice has been extracted. This low-cost, readily available agricultural waste is important for economic and environmental purposes. Aigbodion et al. [53] developed an asbestos-free brake pad using Bagasse as the reinforcing base material. Different tests were conducted on the produced brake pad, and the results obtained show that different sizes influence the performance properties of brake pads and that brake pads produced from Bagasse of 100μm sieve grade with the composition of 70% bagasse to 30% resin can be used as an adequate replacement for asbestos-based brake pads.

3.1.6 Cashew nutshell

Cashew nut is an essential organic material for developing friction components. The shells are cleaned, dried to remove moisture, and grinded to different mesh sizes.

The friction particles are used as a stability agent in brake products. They can absorb heavy impact and act as a cushioning agent of the engaging property of the lining. Cashew nutshell dust can easily decompose into the surface lining at various elevated temperatures controlling wear and acting as a protective device by reducing excessive temperature. Hence, they have varied uses as fillers, reinforcement materials and friction modifiers in brake pad production [107]. Lawal et al. [34] used local gum as a binder in developing a cashew nutshell-based automobile brake pad rather than other scholars' conventional phenolic or epoxy resin binders. Lawal et al. [108] later extended the study to investigate the effect of the local-based resin (Nigerian Plant Gum) on the performance of the cashew nutshell brake pads.

3.1.7 Palm Kernel Shell/Fibres

Palm kernel shells and fibres are high lignocellulosic agricultural waste from processing crude palm oil [109]. They are used in many engineering applications for reinforcement, fillers, additives, activated charcoal, and biofuel generation. Ibhadode and Dagwa [110] used palm kernel shells to develop asbestos-free brake lining materials. The Taguchi optimization technique obtained the best friction material formulation and other manufacturing variables. Olele et al. [111] also studied the possibility of using palm kernel shells (PKS) to produce brake pads. Different particle sizes were used to obtain different samples of brake pads and were subjected to various tests. It was found that particle sizes influence the performance of brake pads. Ikpambese et al. [55] analyzed the performance of asbestos-free brake pads from palm kernel shell fibres (PKFs) mixed with epoxy resin and other ingredients. The properties of the produced brake pads were investigated. The result showed that palm kernel fibres can be efficiently used as the perfect replacement for asbestos in brake pad production.

3.1.8 Coconut Shells/Fibres

They are highly lignocellulosic materials used as reinforcement and fillers of polymeric composites. They are also used as additives, activated charcoal and for biofuel generation. In a study by Ossia et al. [112], coconut shells (CS) were investigated as a possible replacement for asbestos-based brake pads. The CS-based brake pad was tested for its physicomechanical properties and compared with a commercial brake pad used as a control sample. As the grain size decreases, the results show improved interfacial bonding between the CS-based matrix and the binder. Hence, the 90 μm grain-size formulation was proposed as a good alternative for asbestos since it performed better than asbestos based samples in all tests except thermal conductivity and stability. Apasi et al. [113] also developed brake pad using agricultural waste-coconut shell as base material. The properties of the developed brake pad were studied under several testing conditions and were found to be a possible replacement for conventional asbestos-based brake pads.

3.2 Animal-based organic shells reinforced brake pads

3.2.1 Cow Bones and Hooves

Oladele and Adewole [114] determined the effect of grain size on cow bone-reinforced polyester composites. They found out that the finer the grain size, the higher the strength of the composite, while the coarser particles lead to improved toughness of the composite.

Adegbola et al. [54] developed cow bone-reinforced automobile brake pads using phenolic resin as a binder. They found that the smaller grain-size samples gave better mechanical properties and compared favourably with commercial samples. Bala et al. [56] developed an automotive asbestos-free brake pad using pulverized cow hooves as the base material with other ingredients like epoxy resin, barium sulphate, graphite and aluminium oxide. The produced brake pad was subjected to several tests and compared to existing commercial brake pads.

3.2.2 Periwinkle Shells

Using compression moulding, Amaren et al. [115] developed asbestos-free brake pads from periwinkle shell particles.

The samples were subjected to a wear test, and it was found that the particles' size can influence the brake pads' properties. Elakhame et al. [116] produced periwinkle shell-based brake pads by compression moulding. The obtained results showed that periwinkle shell particles can be effectively used to replace asbestos in the manufacture of brake pads.

3.2.3 Snail shells

Ossia and Big-Alabo [117] developed asbestos-free automotive brake pads from African-giant snail shells. The mechanical properties of the developed brake pads were found to be of superior quality compared to the control brake pad. Using the grey relational analysis, Abutu et al. [118] investigated the effects of some parameters on the properties of brake pads developed from sea snail shells. Their study found that the produced brake pads can be used effectively as substitute for asbestos-based brake pads and that process parameters like moulding pressure, temperature, curing time and heat treatment time significantly affect the mechanical properties of the produced brake pads.

3.3 Hybrid organic fibres/shells reinforced brake pads.

Abhulimen and Orumwense [119] investigated automobile brake pads' mechanical and tribological properties developed from snail shells and rubber-seed husks. Characterization of the hybrid-developed brake pads confirms that grain size profoundly affects mechanical and tribological properties.

Onyeneke et al. [120] produced automobile asbestos-free brake pads from a hybrid of periwinkle and coconut shell for a brand of vehicle (Audi 90 model). The results from the series of tests showed that the hardness, bonding strength and wear rate of the produced brake pads are compared well with commercial asbestos-based brake pads.

Atmika et al. [121] developed an eco-friendly friction lining from hybrid composite reinforced basalt, shells, and alumina. The hybrid composite possessed improved wear and absorption properties than conventional asbestos-based products.

4. Mechanical and tribological properties of non-asbestos organic brake pads

The mechanical and tribological properties of selected non-asbestos-based organic brake pads were investigated and compared with asbestos-based products. The plant-based brake pads studied are banana, palm kernel shells (PKS), palm kernel fibres (PKF) and bagasse-based. The animal-based brake pads are developed from cow bone, snail, and periwinkle shells, respectively. Two hybrid products considered in this study are snail shells + rubber-seed husks (S+R) and Basalt+ Shells+ Alumina (B+S+A), respectively. Animal-based brake pads show a better coefficient of friction than plant-based and hybrid brake pads, as shown in Fig 3. However, the friction coefficient of all organic products compares well with asbestos-based products. Banana and snail shells have low wear rates (Fig 4). The other organic products compared well with asbestos except cow bone-based brake pads with a very high wear rate. Plant-based, animal-based and hybrid brake pads compare favourably with asbestos in terms of hardness except for palm kernel fibres and snail shells (Fig 5). Snail shell-based friction materials have very low compressive strength (Fig 6) compared to others. Plant-based products tend to have higher swelling rates in water and oil than animal-based products (Fig 7 and 8). Asbestos shows better swell rate properties than organic brake pads. Except for palm kernel fibres, all other organic-based brake pads are lighter than asbestos products (Fig 9). Thermal conductivity results show that asbestos-based brake pads are more thermally stable than plant, animal or hybrid products (Fig 10).

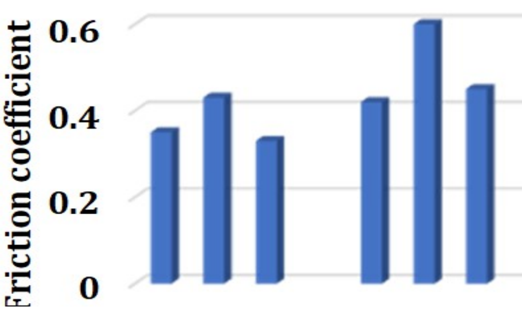

Fig. 3 Friction coefficients of selected plant-based, animal-based and hybrid brake pads

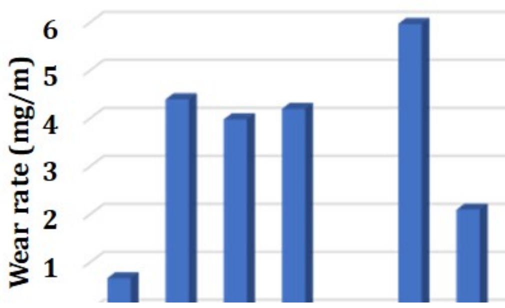

Fig. 4 wear rates of selected plant-based, animal-based and hybrid brake pads

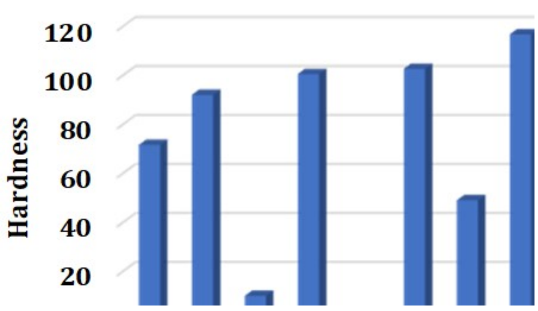

Fig. 5 Hardness (HBN) of selected plant-based, animal-based and hybrid brake pads

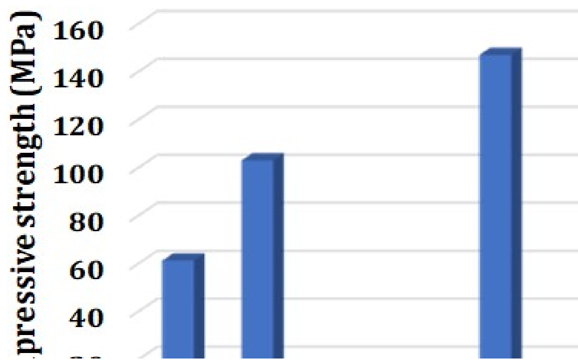

Fig. 6 Compressive strength of selected plant-based, animal-based and hybrid brake pads

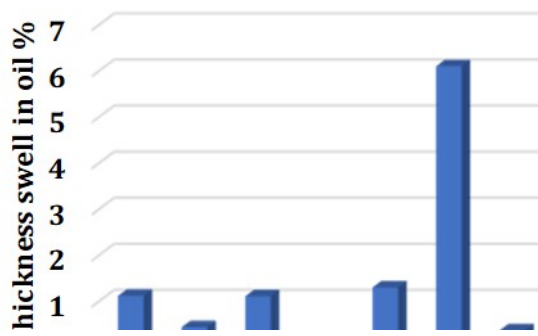

Fig. 7 Thickness swell in water of selected plant-based, animal-based and hybrid brake pad

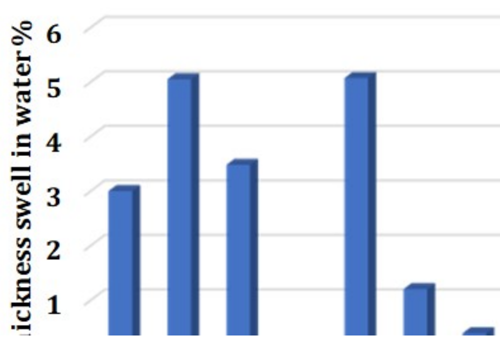

Fig. 8 Thickness swell in oil of selected plant-based, animal-based and hybrid brake pad

The performance of plant-based, animal-based, and hybrid brake pads varies depending on the physical, chemical and mechanical properties of the plants or animals. The main drawback of conventional asbestos-free brake pads is the high wear rate and low thermal conductivity (Fig. 21).

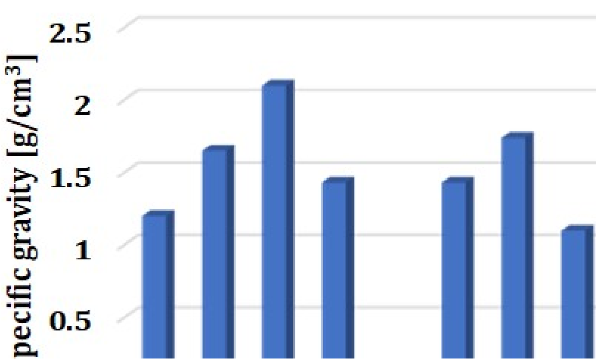

Fig. 9 The specific gravity of selected plant-based, animal-based and hybrid brake pad

Fig. 10 Thermal conductivity of selected plant-based, animal-based and hybrid brake pads

However, considering the combined effects of plants and animal properties, hybrid brake pad products compete favourably with asbestos regarding friction coefficient, wear, hardness and compressive strength. It is observed that non-asbestos organic-based products have low swelling rates and high thermal stability, especially at high braking speeds. It has affected its industrial applicability and commercialization. However, non-asbestos organic friction materials are preferred in terms of health and environmental healthiness.

5. Conclusion

There is a growing need to find sustainable, eco-friendly reinforcement materials for brake pad production due to the health and environmental implications of asbestos and other toxic metal-reinforced brake pad composites. Many biodegradable industrial and agro wastes have been explored and proposed as substitutes for hazardous reinforcement materials used in commercially available brake pads. The review paper presents an elaborate classification of friction materials used in brake pad production, the production methods, and the mechanical and tribological properties of developed brake pads are presented. Organic friction materials are further classified in this study into plant-based, animal-based and plant-animal hybrid. The performance of hybrid brake pads (friction coefficient, wear rate, hardness and compressive strength) is highly commendable compared to asbestos products due to the combined effects of plants and animal characteristics.

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