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Emerging and Unconventional Material in the Manufacturing of Brake Pads- A Review

Dr.Getme Abhijit Sudamrao[1], Mr. Aryan Deulkar[2], Mr.Ashish Kohale[3], Mr.Trikal Gaupale[4], Mr.Vaibhav Sawaitul[5]

[1]Assistant Professor, Department of Mechanical Engineering, J.D. College of Engineering & Management, Nagpur, India.
[2,3,4,5]Student, Department of Mechanical Engineering, J.D. College of Engineering & Management, Nagpur, India.

Abstract
Brake system is one of the most critical safety-related components in every car. It must be imperative that it shows a reliable and consistent performance throughout its lifespan of operation since it has a direct effect of protecting the safety and lives of people using the roadways.

The overall efficacy of a disc brake system in any system is influenced by the friction interface, which in this case is a combination of the brake disc and the brake pads. The brake discs are mostly manufactured using grey cast iron which is regarded as the best thermal conductor, damping and economical. On the other hand, brake pads are multi-layered complex composite materials whose creation strategy has changed significantly since progresses in materials science and fine engineering. These inventions help to carefully customize the type of ingredients, their ratios and bonding techniques to achieve the preferred performance parameters.

The differences in composition and microstructural features have an extreme influence on the key operational characteristics, including thermal stability, durability, and performance in general pad functionality.

It is a rigorous review of the most prominent emerging, unconventional materials currently used or investigated in the sphere of manufacture of railroad brakes pads. It combines their respective and combined effects on friction material behavior especially on thermal behavior, mechanical integrity and environmental consequences. The unique focus is placed on the new and improved, sustainable and non-conventional constituents, including natural fibers, agro-industrial by-products, bio-based fillers, copper-free formulations, and improved hybrid composites, which indicate the new prospects of creating the next-generation brake pads design.

Keywords: brake pads, new friction materials, new unconventional brake pad materials, sustainable brake friction materials, wear, coefficient of friction.

1. Introduction

Brake system is one of the most important safety systems in any motor vehicle. Its basic purpose is to slow down or even stop a moving car, requiring a very high level of performance and consistency in its performance in a wide range of environmental factors, working temperatures, and service periods [1, 2]. This reliable functioning is inherently dependent on the safety of occupants of the vehicle, and the rest of the road users and pedestrians [3].

Modern passenger cars use the disc brakes mainly (Figure 1). The rotating brake disc (rotor) which goes onto the wheel hub forms the friction pair and the brake pads that are mounted in a caliper that is attached to the suspension knuckle or hub carrier make up the friction pair [4]. The releasing of the brake pedal results in creation of hydraulic pressure that forces the pads to squeeze disc and convert kinetic energy into thermal energy through friction. There is an urgent need to ensure the effective dissipation of this thermal energy to the atmosphere to prevent thermal degradation of the surrounding components (e.g. polymeric suspension bushings) or damage to the tires (which might occur) [5-7].

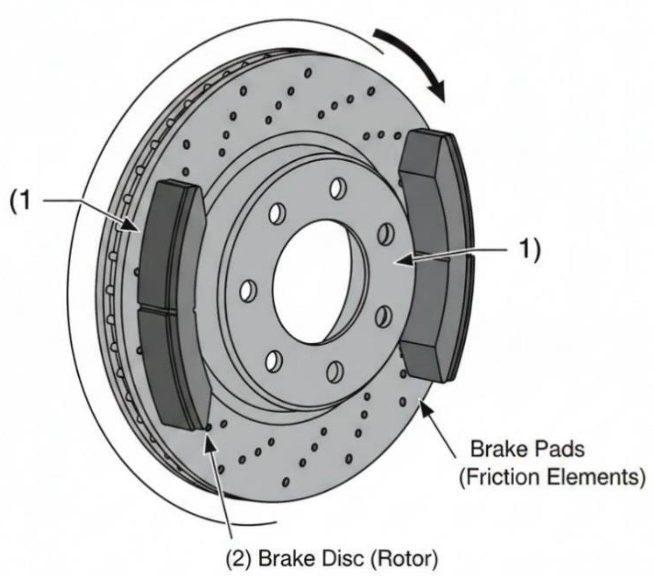

Figure 1: Schematic representation of the disc brake friction pair

Although the widespread construction of brake discs is currently done using grey cast iron as the mainstream material (because of its outstanding thermal conductivity, vibration damping characteristics, and affordability [9]) in the high-performance world, there is a shift towards using more technologically advanced ceramic-matrix composites [10]. On the other hand, brake pads are much more complicated multilayered composites (Figure 2). The main functional element is the friction layer (typically with the thickness of 6-9 mm) that is in direct contact with the disc [11]. This layer is bonded to an underlayer (1-4 mm) which helps to increase adhesion, reduce noise and offer thermal insulation. A thin base coat (<1mm) also enhances attachment to the rigid steel beneath plate, which gives structural strength and allows it to slide accurately on the caliper guides. Noise reduction is often combined with anti-noise shims to reduce noise caused by vibration [12, 13]. There is a significant body of literature related to the materials used in brakes friction but most of the literature regards either limited scopes or traditional compositions. The study of the new trends, such as sustainable and unconventional solutions, has been initiated by recent comprehensive reviews [16, 17, 21]. However, there are still serious gaps to be made-

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especially in regards to incorporation of new, bio-based, agro-industrial waste-based, natural-fiber-reinforced, and copper-free formulations that respond to environmental regulations, health concerns and sustainability demands.

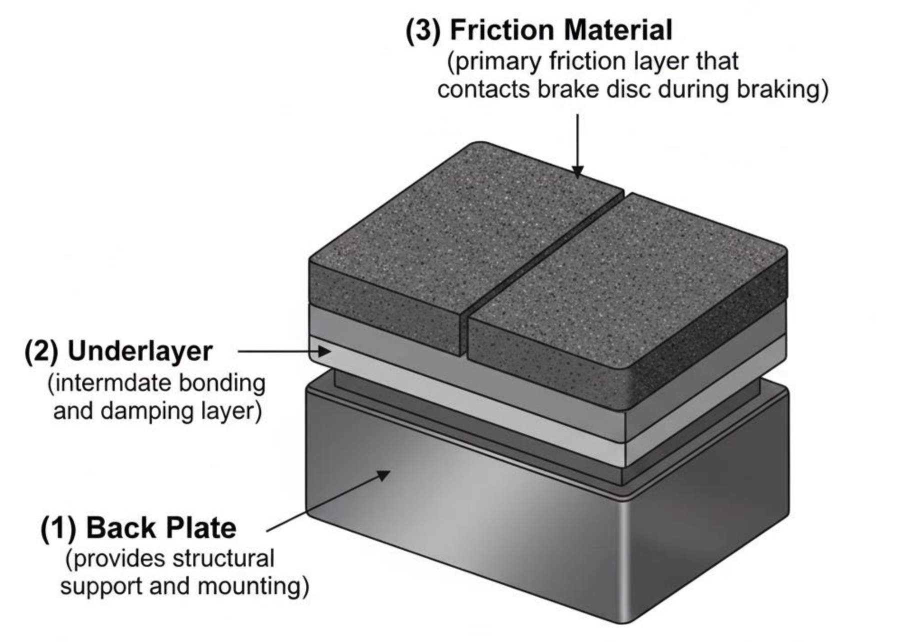

Figure 2: Cross-sectional view of a typical disc brake pad

2. Materials to be used in making brake pads have been classified

Different brake pad manufacturers work with a tremendous number of different raw materials, which are about 2000 various materials [29], each possessing different attributes to the performance of the finished product. An average brake pad will consist of 10 to 20 parts [30]. The problem of finding the best formulation and making accurate predictions about the effect of its application to the finished pad poses an important engineering dilemma that requires a thorough research and high level of practical skills [31]. The choice of materials should consider the use that the pad is to be employed and the working conditions that should be encountered. Moreover, proprietary manufacturing processes, which can be considered as one of the most strongly guarded intellectual property of a manufacturer, can significantly affect the properties of the pad, and sophisticated processes can improve the performance by up to 100 percent [32, 33].

The materials used in brake pads are sometimes classified in terms of a number of criteria. The most functionally relevant classification is to classify them by their contributions to the braking mechanism and ends up with four major types binders, reinforcements (which are typically fibrous), fillers and friction modifiers (including abrasives and lubricants) as illustrated in Figure 3 [28, 34, 35].

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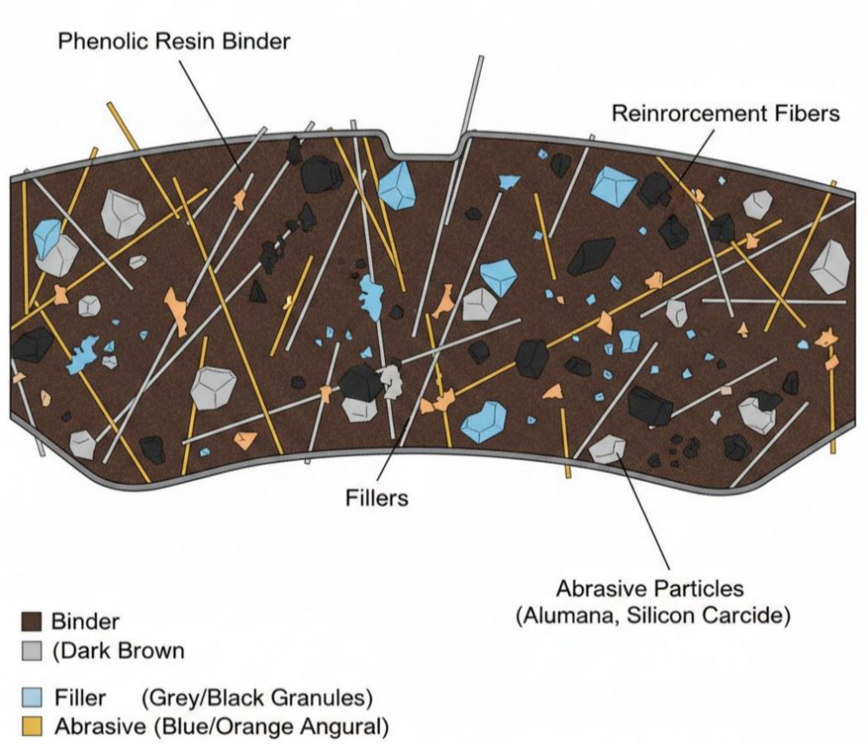

Figure 3: The structure of the brake pad friction material

The binder becomes the continuous polymeric structure which binds all other components to a single composite. The binder should be known to have regular characteristics, high resistance to higher temperatures and a low density (about 20 percent pad volume) [36]. Inertness of the chemical to other elements is essential to avert any reaction that will alter the characteristics of composites or cause delamination [24].

Reinforcements are fibrous materials that increase the mechanical integrity - particularly tensile toughness of the binder matrix. This is because the durability of the pad depends extensively on the reinforcement used. Modern recipes employ as wide a range of safe substitutes as aramid, glass, steel, carbon, and other natural or synthetic fibers [4, 15, 28].

The fillers fill the spaces between the microstructure and are often 10 per cent or more of the volume of the pad. Obviously chosen due to the possibility of cost reduction, density regulation, and high thermal stability, the most popular fillers are vermiculite, perlite, mica, barium sulfate, and calcium carbonate which are appreciated by the ability to endure high temperatures, chemical neutrality, and low cost [23]. The recent studies also tend to explore unconventional and sustainable fillers being found in industrial or agricultural waste products [11, 12, 27].

Another value system of classification differentiates materials depending on their origin: natural or synthetic/artificial.

Natural materials contain [15, 27]:
Plastic (leaves, stems, seeds, and agricultural waste), animal (hair and fur), Metals and alloys (steel, copper, bronze and cast iron).

The synthetic/artificial materials include:
Organic synthetic polymers (e.g. aramids and acrylics); Engineered minerals (e.g. mineral wool); Ceramics; Advanced fibers (e.g. carbon and glass).
The type of constituent is to a large extent determined by its classification of the brake pad [34, 35]:

Metallic pads: These are mostly made of metals (e.g. steel, copper) that are highly strong and also thermally conductive. Semi-metallic pads: It has got the composite of metals and organic substances; it has got the balanced properties.

Non-asbestos organic (NAO) or ceramic pads: This type is made of an organic binder that is reinforced with aramid, glass or ceramic fibers; this type is more durable, high-temperature stable, lightweight and quiet, but more complex and costly.

Carbon-carbon pads: These have the same properties as the ceramic pads except that they have superior thermal-mechanical resistance and low weight; they are best used in high-performance cars, but are more expensive.

Green pads: The use of plant-based or agro-waste additives; low weight offered, low environmental impact, competitive price, and maximum durability.

3. Properties of chosen materials, which are used in production of brake pads
The binder is the continuous polymeric structure in the formulations of brake pads to which reinforcements, fillers and other constituents are amalgamated to provide a composite of structural stability. It is acknowledged that resins are the most common types of binder materials, and their ratios require a careful control to ensure the mechanical reliability and functional performance [5, 6, 22].

Phenolic resins (phenol-formaldehyde) remain the most widely used binders in friction material, often purposely designed with this particular use in mind. Their ratio of the pad volume is usually larger and is favored by high mechanical strength, low cost, low thermal expansion, chemical resistance (to solvents, acids, and water) and low smoke output during combustion [22, 26]. The problem of brittleness is a major limitation but can be overcome by silicone modification which in turn can lead to consequences on other properties [22].

The thermal resistance, as well as the mechanical strength of epoxy-phenolic hybrids, are greater compared to that of these two resins separately [5].

Thermoplastic polyamide resin (obtained based on the fluororesin and calcium carbonate) offers admirable wear properties and a cost-effective production route; however, its weak thermal conductivity limits its feasibility use in brake pads [5].

The innovative solutions include the use of the high-performance resin based on epoxy that can be used as an environmentally friendly resin that can be used as a substitute to the traditional phenolic resin in designed copper-free resin and this way, promote sustainability and performance [6].

Metal matrix composites (MMCs) with silicon carbide (SiC) reinforcement (in particular, in aluminum), in turn, denote a complex alternative to friction linings [20, 29, 32]. These materials are characterized by low density, high mechanical strength, excellent thermal conductivity, and amazing temperature tolerance [20, 29] - qualities that are very beneficial on the use of brake pads. Such challenges include particle distribution, porosity and phase formation [20, 29, 32]. The manufacturing processes (such as mixing liquid metals, infiltration, and powder metallurgy) require special equipment [32].

3.2 Reinforcement

Reinforcement refers to fibrous materials that that considerably increase the mechanical (particularly tensile resilience) strength of the binder matrix. The selection of the materials has a significant influence on the duration of pads and structural strength. Modern recipes have been relying on a wide range of safe substitutes, such as synthetic, mineral, and natural fabrics, reflecting the continuous shift to sustainable and high-performance ingredients [4, 15, 28].

Aramid fibers (such as Kevlar) are unique in having a rigid molecular chain in the axis of the fiber and as a result, have a very high Youngs modulus and specific strength that is superior to steel wire of a similar weight [4]. Aramid fibers, a performance and safe alternative to asbestos, can be used as an efficient component in reinforcing aramid non-asbestos organic (NAO) brake pads. They exhibit exceptional thermal performance and are oftentimes used in hybrid configurations with glass or steel fibers with the aim of driving mechanically beneficial performance at a lower price [4].

Glass fibers have been established effectively in industrial use and have received greater acceptance as an alternative to asbestos following the institute of regulatory limitations. Their beneficial effect on the mechanical properties, especially regarding hardness and abrasion resistance has been proved by empirical studies [15]. They are used to a large extent in the hybrid formulations, commonly with other fibers like coconut or aramid to maximize the features of the entire pads.

The Cocoa bean shells (CBS)- a by-product of cocoa processing, which is a fibrous substance has been explored as a low density, non-toxic, and ecologically sustainable reinforcement [27]. Cocoa-producing regions (such as Nigeria) are numerous and inexpensive to use, as CBS use helps to manage the agricultural waste problem, as well as provide the automobile grade of products. Investigations of pads of different content of CBS (21%, 26 and 31 vol%) show positive qualities such as reduced density (beneficial to construct lightweight) and increased life cycle as compared to the conventional pads [27].
The palm oil production also results in palm kernel shells (PKS) used as another agricultural by-product which have low density, low hygroscopicity, and high levels of stiffness and hardness [15]. These characteristics make PKS a prospective environmentally sustainable friction reinforcing material.

The non-toxic banana peels that are part of up to 40 per cent of the fresh banana weight and often discarded or used as fertilizer are rich in antioxidants and pectin [28]. Pectin is used as a gel-forming substance, and peel powder of bananas increases the hardness and resin-binding properties at high temperatures. Strong interfacial adhesion and low water/oil absorption has been supported by experimental formulations [28].

The shells of periwinkle, which is an unconventional waste in food processing, especially in regions like Nigeria are high in hardness and thermal stability. Upon being ground, these shells have a reduced density compared to that of asbestos, and are under study as a sustainable filler/reinforcement [13]. Prototypes prove to be exceptional in compression resistance, hardness and low water/oil absorption [13].

Ceramic composites (such as C/SiC using silicon carbide as the matrix with carbon fiber as the reinforcement; Al/SiC with an aluminum matrix and SiC particulates) are an indicator of higher order reinforcement options [20, 29, 32]. These materials are superior in terms of durability, less weight, and can withstand heat [20, 29] features highly desirable in the use of brake pads. Issues related to these composite materials are a complicated process of production and cost [29, 32].

3.3 Fillers

Fillers are considered to be an important volume share in a brass of brake pad that plays a major role in space volume filling, reduction of material costs, adjusting density, enhancement of dimensional integrity and support of the overall composite structure. Mostly these fillers are described as either inert or semi-inert particulates that are carefully selected based on their thermal capability, chemical compatibility and cost-effectiveness.

Barite (barium sulfate, $BaSO_4$) is a natural mineral that can be collected at large scale (and is therefore used globally) and is one of the most widely used fillers in friction material because of its high density (near 4.5 g/cm^3), outstanding thermal stability, and minimal changes in properties over a large temperature span, as well as its cost-effectiveness due to its high abundance [23]. Barite is relatively resistant to high temperatures, therefore, its structure does not experience any effect of thermal loading caused by braking. The high percentage of barite usually correlates with the high level of wear performance and homogeneity of the materials [23]. The mentioned features make barite especially beneficial to support the stability of pads and cost-effectiveness under varying operating conditions.

Fly ash a fine particulate by-product generated by the coal burning process in power generation plants and other industrial units is mainly made out of silicon, aluminum and iron oxides, and trace elements and unburned carbon; it is light grey or brown in hue [33]. This has prompted the use of fly ash as a cheap filler in brake pad considering the urgent environmental need to control the waste of coal combustion, and the variability in ash properties because of the differences in coal type and boiler design [33] (mass fractions in a range of a few percent to 55-60 percent). Fly ash as a material is not associated with a high rate of thermal degradation, and, at the same time, provides improved thermal management: the high specific heat storage allows to retain the heat correctly in the ash particles, but its low thermal conductivity restricts the transfer of heat [11, 33]. Besides, the decrease of the specific gravity of fly ash (which is usually 2-3 times lower than in other pad materials) allows achieving considerable weight savings in the end product [11, 33], which is consistent with the modern requirements of lighter braking systems.

Microcellulose, a large amount of organic polysaccharide, is found in trees, and is often used in powdered or micro-fibrillated forms, and decomposes partially during the high temperature curing stages of brake pad production (burn-off) [22]. The process produces a regulated porous microstructure, which minimises the total density and permits lightweight design. The studies of microcellulose-reinforced composites (e.g., 10 wt) indicate that its performance parameters are similar to the traditional pads in terms of mechanical stability and sustainability. Though the use of cellulose-based materials is explored in niche applications in special automotive parts, its use in brakes pads has been an emerging venture, driven by the sustainability agenda and lightweight formulations that are environmentally-friendly [22].

3.4 Abrasives

Friction modifiers such as abrasives, solid lubricants and particular metallic or mineral additives are used to control the characteristics of the brake pad properties such as friction coefficients, thermal characteristics, and acoustics. In this section, some of the most famous examples based on new and unconventional perspectives are explored with a focus on their chemical structure, advantages, limitations, or issues related to sustainability.

Copper remains a major friction modifier in many of the traditional brake pad recipes, and is generally found in concentrations of about 4 percent or above. It is important because of the ability to strengthen the adhesion process and the development of a thermal conductive area on the disc surface despite its relative tenderness in comparison to the binder matrix [24]. Recycled copper, which has been used in electrical motor windings, extracted into segments of 1-2 mm in diameter is a sustainable source of copper procurement [35]. Also, powdered forms, including nano-particles (50-200 nm) and micro-particles (400-600 um) are also being used [35]. However, ecological issues have provoked the adoption of strict rules in such states as California (to 5 by weight in 2021, and 0.5 to 2025) and Washington, which has negative impacts on the aquatic ecosystems (copper). Graphite-titanium composites become viable solutions of low-copper or copper-free ones, which offer improved sustainability and lower noise levels [24].

As a metalloid element with high melting point, low chemical reactivity, and exceptional thermal and electrical insulators, boron is added to formulations in low volume levels (typically 2%), which extends the life of brake pads, which is due to its inherent hardness [18]. It is now under research to use as a possible additive in the advanced formulations.

Graphite, which occurs as a natural, synthetic, or expanded material, is used mainly as a friction material solid lubricant. It is preferred due to the cost efficiency and other constituents compatibility making it a common option used in sustainable designs and design free of copper [24].

Titanium and its alloys like potassium titanate are becoming more and more used as a high-temperature substitute of copper [24]. It also offers lubricating qualities and helps in reduction of total weight of the system because of its low density. It combines with phenolic resins and aramid pulp to produce synergies, which increase the mechanical stability and thermal resistance (potassium titanate (mostly in the shape of whiskers or platelets) [24]. Nevertheless, the issue of cost represents the major impediment, as the barrier to its broad application.

Brass impacts pad properties in an unpredictable way depending on its content and is investigated in the formulations that require a balanced mechanical performance. It adds lubricating properties and increases the density of the brake pads [24].

Cast iron (as crushed chips 1 mm) and steel (as wool, fibers, or powders) are used to strengthen the mechanical properties through improved adhesion [2, 31]. Cast iron is resistant to abrasion, whereas steel is usually added as steel wool, shaped fibers or high-surface-area powders (e.g. RSB 100) to obtain the necessary content to a minimum [35]. These materials are further hardened and their mechanical properties are improved with advanced processing methods like forging and annealing [35]. These materials are also prized in high-performance use [2].

The ceramic qualities of aluminosilicates that have been naturally found as zeolites have been examined as possible fillers and friction modifiers. Zeolites dehydrate during the processing when they are ground to a fine dust and then sintered (5-35 wt%). They offer the chances of enhanced corrosion resistance, and are being researched in sustainable formulations [17].

4. Conclusion

This paper reviews the different materials that are used in the manufacture of brake pads with much emphasis on innovative materials as well as unconventional materials alongside conventional materials. The perfect formula requires a careful choice and an exact distribution of ingredients, which is also an expensive process that is mainly organized by the major manufacturers [9, 17, 25].

The world research activities are continuously advancing to the creation of new compositions and techniques such as the increased use of industrial and agro-food byproducts [11, 12, 27, 33]. Consistent with the requirements of sustainability, future brake pad materials should reduce the consumption of synthetic or artificial components and instead, use environmentally friendly options [6, 16, 25]. The encouraging signs of sustainable candidates, including zeolites [17], banana peels [28], periwinkle shells [13], cocoa bean husks, palm kernel shells, and others [15] derived as they are, show that progress is being made in ensuring vehicles have less harmful effects on the environment and that circular usage of materials is being encouraged [12, 22, 28].

The direct harvesting and re-use of brake wear particles will remain impossible, which is why it is so essential to create profoundly sustainable formulations even at the first development stages [16, 25].

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