Materials Physics and Mechanics 47 (2021) 796-815
Overeview article
Received: September 29, 2021
Accepted: November 8, 2021

THE EVOLUTION OF BRAKE FRICTION MATERIALS: A REVIEW

Naveen Kumar[1]✉, Ajaya Bharti[1], H.S. Goyal[2], Kunvar Kant Patel[3]

[1]Applied Mechanics Department, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India-211004

[2]Mechanical Engineering Department, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India-211004

[3]Electronics and Communication Engineering Department, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India-211004

✉ chaudhary56naveen@gmail.com

Abstract. Today, in the fast-moving world, the focus of all automobile companies is to increase the speed of vehicles to reduce travel time. With an increase in the speed of vehicles, there is an urgent need for the development of friction materials suitable for high-speed braking applications. A historical review of various materials used to date for making brake pads and brake drum/disc is done in the present work. Asbestos was the most suitable and widely used brake lining material, but its carcinogenic nature has forced the health and environment agencies to ban it. Ban on the use of asbestos has forced researchers to develop asbestos-free brake friction materials. Today, the non-asbestos organic type of brake pads is most widely used. But, non-asbestos organic type brake pads wear out rapidly and generate lots of wear debris. Wear debris generated from braking materials is a cause of concern to the health and environmental agencies. So, researchers are working on developing environment-friendly brake friction materials for all-weather high-speed braking applications. Natural fibre or agricultural waste-based brake pads are considered as the future material for brake pads. At the same time, cast iron was the most commonly used material for brake discs or drums. Today, various materials such as aluminium matrix composites, carbon-carbon composites, and ceramic-based materials are used to make brake discs or drums. However, the use of cast iron is still preferred. Aluminium matrix composite is considered the future material for brake discs or brake drums because of its low density and improved braking stability.
Keywords: aluminium matrix composite, brake disc, brake drum, brake pad, non-asbestos organic

***Acknowledgements**. No external funding was received for this study.*

Citation: Kumar N., Bharti A., Goyal H.S., Patel K.K. The evolution of brake friction materials: a review // Materials Physics and Mechanics. 2021, V. 47. N. 5. P. 796-815. DOI: 10.18149/MPM.4752021_13.

1. Introduction

Braking is the process of stopping or deaccelerating a moving vehicle or a rotor. A system comprising various devices or equipment used for braking is known as the braking system [1]. The braking system is one of the most important parts of any vehicle (i.e., car, bus, train, airplane, etc.) because the braking system's failure can lead to the loss of life of many. The

http://dx.doi.org/10.18149/MPM.4752021_13

braking system works on the principle of conservation of energy. During braking operation, a vehicle's kinetic energy is converted into heat energy by rubbing a frictional material with the moving body other contact-less processes [2]. Based on the contact nature, there can be two types of braking systems: direct-contact braking and contactless braking systems. Different types of braking systems are shown in Fig. 1.

In a direct-contact braking system, a stationary frictional material is pressed against the rotating or moving device [3]. So, due to the relative motion between the moving device (rotor) and the stationary frictional material (pressed against the moving device), there is a frictional force against the moving device's direction of motion. This opposing force is responsible for the deceleration of the vehicle. Finally, the moving device stops when all the moving device's kinetic energy is converted into frictional heat. Two main components of a direct-contact braking system are a stationary brake pad and a device rotating with the moving device (wheel of the vehicle) [4]. A rotating device can be a brake disc or brake drum.

In a contactless braking system, there is no direct contact between the moving device and the braking system. Electro-magnetic devices are used for braking operation without any physical connection with the rotating device. When magnetic flux is applied across a conducting device, there is a generation of eddy current in the conducting material [5]. Eddy current applies an opposing force; hence there is an eddy current heating in the material. In this way, the rotating device's kinetic energy is converted into heat energy, and as a result, the rotating device stops. There are various advantages of contactless braking systems over the direct-contact braking system: high efficiency, less frequent replacement, uniform braking force, etc. But the contactless braking system is not feasible for petroleum-fuel-based vehicles. Also, there is a sudden failure in the contactless braking system, leading to an accident. On the other hand, there is continuous wear of braking materials (i.e., brake pad and brake disc/drum) in the direct contact braking system. If wear-out pads and disc/drum are replaced regularly, then there are fewer chances of sudden failure of the braking system [6]. The brakes are applied mechanically in the direct-contact braking system; hence, the direct-contact braking systems are more reliable than the contactless braking system. Because of the above reasons, the use of the contactless braking system is limited.

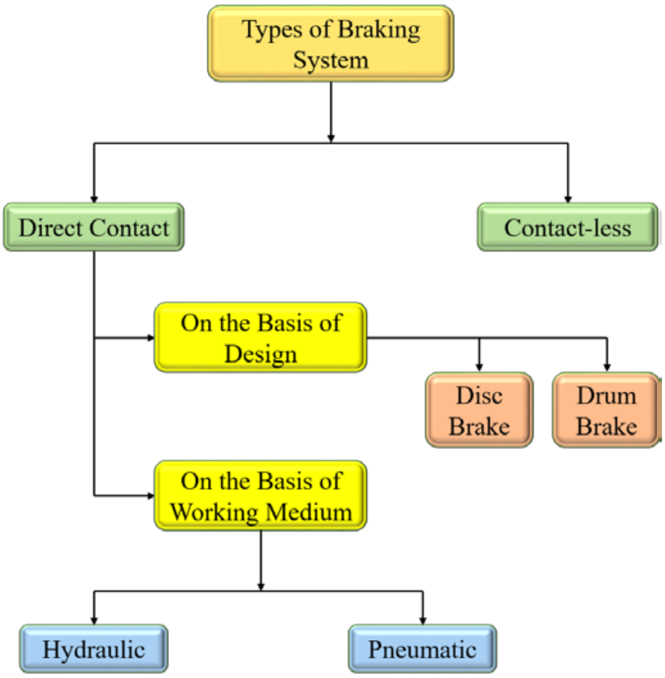

Fig. 1. Types of the braking system

Cotton soaked in a bitumen solution; the first brake lining material was invented by Herbert Frood in 1897 [6,7]. It was used for braking applications in automobiles and railways. Later on, wood and leather were also used for braking applications in railways [8]. Then, Frederick Willian Lanchester, the English engineer, invented the disc-brake. In disc-brakes, a metal or composite disc is rigidly fixed to the rotating wheel, and a frictional material (brake pad) is pressed against the brake disc. The brake disc and brake pad's engagement produces an opposing frictional force; this force is used to deaccelerate the rotating vehicle. The invention of the brake disc was path-breaking in the field of baking technology. In 1903 automobile companies, i.e., Renault and Mercedes introduced a variation in the design of the existing braking system (disc-brake) that led to drum-brake development. In the drum-brake, a hollow cylindrical drum (metallic or composite) is rigidly fixed to the rotating wheel, and braking pads are pressed against the drum's inner circumference. There are various advantages of drum-brakes over disc-brakes, such as increased contact area of friction materials, cheap, and less input force. In the present work, different materials used over the years for brake pad and brake disc/drum are reviewed in detail in the next sections.

2. Materials Used for Brake Disc/drum

The brake disc/drum is the most important and critical part of the braking system because 70% of brake wear starts from the brake disc or drum [9]. The brake disc/drum material should have high strength, high wear resistance, high thermal conductivity, low thermal expansion, and high thermal stability [9]. Today there are so many different materials that are being used for making brake discs and brake drums. These materials can be classified into five different categories, i.e., gray cast iron, steel, carbon-based materials, aluminum-based materials, and ceramic-based materials. Figure 2 shows the percentage use of different materials for making brake disc/drum (science direct). Still today, cast iron and steel remained the most preferred material for making brake discs/drums (almost 70%). The use of ceramic-based and aluminium-based materials for making brake discs/drums is increasing.

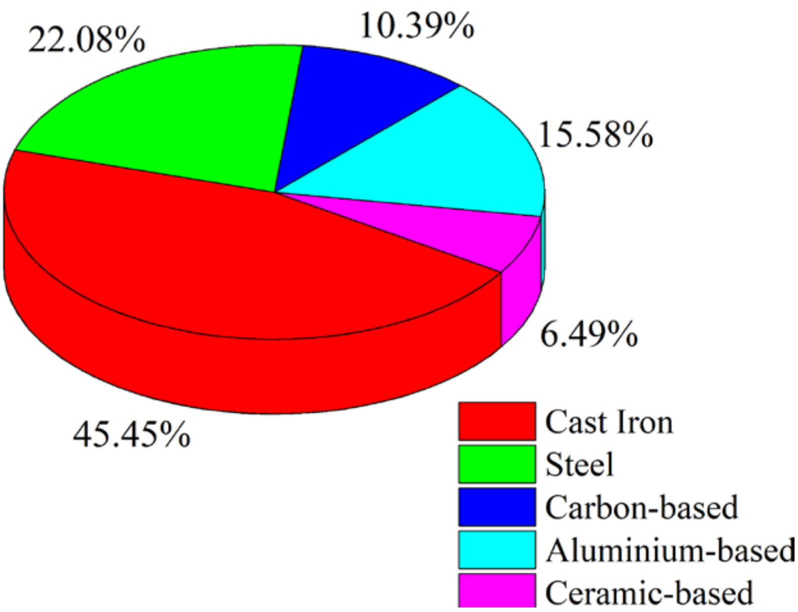

Fig. 2. Use of different materials for making brake discs/drums

Cast Iron. Gray cast iron was the first material used for making brake disk/drum [6,10]. Even after hundreds of years, cast iron is still one of the brake disc's preferred materials [11-14]. In the last 100-120 years, so many different materials are developed as a replacement for cast iron in brake discs, but cast iron remained the most used material for brake discs [15-25]. A high preference for cast iron as a brake disc material is due to its low cost, low wear rate, less noise, steady coefficient of friction, high thermal conductivity, long life, and sufficient corrosion resistance [25-35]. High-carbon gray iron alloyed with molybdenum and niobium, used as the disc material for heavy trucks and passenger cars, has low strength [35-37]. Compact graphite iron (CGI), which is being used as a brake disc in the Europium railroad, can be a better alternative to gray iron for making brake discs [38].

One of the major issues with cast iron as a material for brake discs and brake drums is the high density. Because of the high density, the weight of the un-sprung mass of brake assembly is very high. The dynamics of braking are highly dependent on the un-sprung mass [39]. High un-sprung mass is the main reason for poor brake dynamics. Because of the above problem, researchers are working on the development of lightweight material for brake disc/drum from the beginning so that the brake dynamics can be improved. Another problem encountered with the gray cast iron disc is the reduction in the coefficient of friction in wet conditions [40]. That can be a reason for the accident. So, a braking material that can work well in both the dry condition and the wet condition needs to be developed.

Steel. Steel is another widely used material for brake disc/drum [13,17,41]. Because of its high strength, excellent corrosion resistance, high thermal stability, and high wear resistance, steel is used as a braking material for heavy-duty applications such as aircraft, trains, and trucks [42-49]. Panier et al. investigated the hot spot in the 28CrMoV5-08 forged steel (used in railways brake disc) [50]. The main reason for the hot spot generation can be the thermal distortion due to frictional heat. So, a high thermal resistance is required in the brake disc's material to avoid brake failure. Desplanques et al. analyzed a sintered metal matrix composite brake pad's wear behavior against the 28CrMoV5-08 forged steel brake disc used in railways [51]. It was observed that a third body is produced during the braking operation and separates the brake disc and brake drum. Hence, the wear behavior is mainly dependent on the third body formed.

Camacho et al. also investigated the wear behavior of steel brake discs against the brake pad [52]. The third body layer formed between the brake pad and brake disc and highly influenced the wear behavior. Wu et al. done investigated the failure mechanism of GS24CrNiMo445V steel brake discs used in high-speed trains on snowy days. It was observed that the hard SiO_2 and Fe_2O_3 particles included in ice were the main reason for the abrasion of brake discs and led to the generation of swarf. So, a high abrasion-resistant material for brake discs is required for high-speed trains to avoid failure. Zhang et al. studied the tribological behavior of 30CrSiMoVA alloy steel against the copper-based brake pads during emergency braking in high-speed trains [53,54]. It was observed that the copper-based brake pads tribo-couple exhibits fading behavior [53]. Zhao et al. also investigated the similar fading behavior of metal matrix composite brake pad against the steel disc. Xiao et al. also observed the significant effect of the third body formed between the Cu-based brake pad and 30CrSiMoVA alloy steel on the wear behavior of tribo-couple [55].

Carbon-based Materials. Carbon-based materials are also one of the most commonly used materials for making brake discs [56]. Carbon-based materials have very high thermal resistance and high wear resistance. Because of its excellent thermal and wear resistance, the carbon-carbon brake system is used mostly in aircraft and racing cars [24]. Blanco et al. stated that the carbon-carbon brake system could be used satisfactorily for twice the aircraft landing number compared to steel brake systems [41]. Carbon-carbon brake discs have low coefficient friction at operating temperatures below 400°C-500°C [57,58]. To enhance the coefficient of friction and wear resistance, reinforcements such as SiC are reinforced in the carbon matrix to produce C-C/SiC brake discs. C-C/SiC brake discs have superior properties compared to the carbon-carbon brake disc, and these are used widely for making brake discs for high-speed trains and racing cars.

Kermc et al. have done a comparative study on the thermal and wear behavior of C-C/SiC and gray cast iron against the Metal Matrix Composite (MMC) brake pad [59]. Very high heat was generated in the braking system consisting of a carbon-based disc and MMC brake pad compared to the heat generated in the braking system consisting of a gray cast iron disc. But, the friction coefficient was higher and steady in the case of a braking system consisting of C-C/SiC-based braking.

Podratzky et al. designed and experimentally characterized the military-helicopter disc brake [45]. It was observed that in the case of the carbon-fiber composite brake disc, the coefficient of friction and wear rate increased with an increase in the temperature and sparks generated. Zhao et al. investigated the metal matrix composite brake pads' wear behavior against the steel disc and C-C/SiC disc [60]. It was observed that the brake pad's wear rate against the C-C/SiC disc was significantly less in comparison to the wear rate of the pad against the steel disc. So, C-C/SiC is a better material for the brake disc against the metal matrix composite brake pad.

Aluminium-based Materials. Because of the high density of cast iron or steel, low-density aluminium alloy-based brake disc materials are being developed to improve brake dynamics [61]. Sallit et al. used two aluminium alloys, Duralcan (AS10G) and hyper-eutectic alloy (AS18UNG), to make a brake disc. SiC was used as a reinforcement to enhance the wear resistance [62]. Various post-processing effects such as annealing and aging were investigated on the wear properties of prepared composites. Results obtained were promising, thus leading to the development of aluminium-based brake discs and brake drums.

Jang et al. investigated the effect of reinforcement of metal fibers in a non-asbestos organic brake pad on the wear behavior of cast-iron brake disc and aluminium-based brake disc [63]. Aluminium-based discs were produced by reinforcing 20% SiC in A356 aluminium alloy. The wear trend of aluminium-based disc was found out to be the same as a cast-iron disc. The high-temperature fade resistance of the aluminium-based disc was maximum with the copper-fiber reinforced brake pad. Shorowordi et al. used aluminium matrix composite reinforced with 13% SiC/B_4C as brake discs [64]. The wear behavior of the fabricated brake discs was investigated against phenolic resins-based brake pads. It was observed that a compact transfer layer formed between the composite brake discs and phenolic brake pads and reduced the wear rates. Uyyuru et al. also developed the aluminium matrix composites reinforced with different weights of SiC, intending to replace cast iron in brake discs [65]. The wear behavior of aluminium matrix brake discs against polymer matrix composite brake pads was investigated. It was observed that a tribo-layer formed due to the brake pad's interaction with the brake disc and affected the wear behavior significantly [66].

Blau et al. investigated the wear behavior of four different combinations of frictional materials (brake disc and brake pad) [2]. Gray cast iron, C/SiC, Al/SiC, and Fe_3Al Alloy were used as brake disc materials. Commercial brake pad used in trucks was used as counterparts for gray cast iron and Fe_3Al alloy discs, C/SiC brake pad was used as counterparts against C/Sic brake disc, and commercial brake pads used in automobiles were used as counterparts against aluminium matrix brake discs. The coefficient of friction obtained for aluminium matrix composite brake disc against commercial brake pad counterpart was minimum. Hence, the force required for braking was maximum in the case of the aluminium brake disc.

Natarajan et al. do a comparative study on the wear behavior of grey cast iron and aluminium matric composite (reinforced with 25% SiC) brake disc against a semi-metallic brake pad [67]. It was observed that the wear rate in the case of the aluminium matrix composite brake disc was less in comparison to the grey cast-iron brake disc. Also, the friction coefficient was 25% higher in the aluminium matrix composite brake disc. Natarajan et al. have done a comparative study on the tribological properties of aluminium matrix composite brake drum and cast-iron drum brake [39]. It was observed that the temperature rise in the case of the aluminium matrix composite brake drum was slightly higher than the temperature rises in the cast-iron brake drum.

Kushal et al. investigated various aluminum-based materials' mechanical and tribological properties to check the suitability for making brake drums [68]. It was observed that the deformation and the temperature rise were minimum in the case of controlled expansion aluminium alloy. So, a controlled expansion alloy can be used to make brake drums in light-duty vehicles. Natarajan et al. also investigated the tribological properties of aluminium-based brake drum against non-asbestos organic brake liner (consisting of aluminium alloy insert) and asbestos brake liner [69]. It was observed that the thermal expansion of the aluminium brake drum was higher in the case of a non-asbestos brake liner because of the high heat generation. But the steady-state temperature was low in the case of non-asbestos organic brake liner. Gowthami et al. have done a comparative study on the tribological behavior of three different brake disc materials, i.e., cast iron, steel, and aluminium alloy, used in trucks [3]. It was observed that the deformation and the maximum temperature rise were minimum in the case of aluminium alloy brake discs. So, cast iron can be replaced by aluminium alloy to make brake discs for trucks; by doing this, a nearly 58% reduction in brake disc weight can be achieved.

Ceramic-based Materials. Zhang et al. fabricated a composite material consisting of a porous ceramic mixture (56%) and aluminium alloy (44%) as a replacement of cast-iron in brake rotors [70]. The wear behavior of the fabricated composite brake rotor against the phenolic resin brake was investigated. It was observed that the wear rate and friction of coefficient were high compared to the cast iron rotor. Podratzky et al. found SiC brake discs or ceramics brake discs superior to the carbon-fiber composite brake discs for military helicopter and other heavy-duty applications because of low wear rate and negligible spark generation [45]. Bian et al. investigated two C/SiC/Si ceramic brake discs' tribological behavior containing 53.1% SiC/Si and 17.7% SiC/Si in the water-spray environment [71]. A higher coefficient of friction (0.5) was observed in ceramic brake discs containing 53.1% SiC/Si. So ceramic brake can be used effectively in a moist environment also. Gunay et al. reviewed the materials used in railways for brake discs and brake pads [48]. It was found out that the cast iron and aluminium alloy-based disc brakes are suitable for low-speed trains (speed below 200 km/h) only. In high-speed trains (speed above 400 km/h), ceramic and steel brake discs are used because of their high thermal and wear resistance. Hence, ceramic materials are thought to be the future materials for braking because all the countries' focus is to develop high-speed trains and vehicles to reduce travel time. Jiang et al. investigated SiC/Al ceramic brake disc's tribological properties against the C/SiC brake pads used in high-speed trains [72]. It was observed that the SiC/Al-C/SiC tribo-couple is suitable for emergency braking in high-speed trains.

3. Materials Used for Brake Pad or Brake Lining

The brake pad is the stationary friction material rubbed against the rotating brake disc or brake drum. Some of the properties required in a brake pad are lightweight, corrosion resistance, low wear rate, low noise, long life, and low cost [73]. Over the years, so many materials are used for making brake pads. Some of the brake pad/lining materials are given in Table 1 with an approximate year of first use. Asbestos is one of the most suitable materials for brake drums, but asbestos has some health issues [64,74-76]. There are mainly two types of asbestos, serpentine asbestos (chrysotile) and amphibole asbestos (crocidolite). It was found that wear-out particles of chrysotile asbestos brake pads have a high carcinogenic effect on the car mechanics who replace brake pads [77]. Hence, the use of asbestos-based brake pads was banned by the Environment Protection Agency in 1986. So, it becomes a challenge for research communities to develop asbestos-free brake pads.

Bernstein et al. have done a comparative study on health issues caused by two types of asbestos (chrysotile and crocidolite) [78]. An opposing result to previous studies was found out. It was observed that the chrysotile asbestos does not cause lung infection on inhalation for a short period. In contrast, crocidolite asbestos had a half-life of more than 1000 days and caused a severe inflammatory response. The release of other heavy metals such as copper, iron, antimony, etc., from brake pads, is also harmful to the environment [31,47,79]. So, researchers are working on the development of eco-friendly brake pads.

Table 1. History of brake pad/lining materials [6,8]

Brake Pad or Brake Lining Material	Approximate Year of Fist Use
Cast iron or steel	Before 1870
Cotton or hair belting	1897
Asbestos	1908
Molded materials to replace steel or cast iron	1930
Flexible organic materials	1930
Semi-metallic materials	1950
Non-asbestos organic	1960
Carbon fibers	1991

There are mainly four types of brake pads used widely, metallic or semi-metallic brake pads, Non-asbestos Organic (NAO) brake pads, Metal Matrix Composite (MMC) brake pads, and ceramic or carbon-carbon brake pads [80]. The most commonly used materials for making brake pads or brake lining are shown in Fig. 3. It can be observed that non-asbestos organic brake pads are most widely used today because of their low cost and environment-friendly nature.

Metallic or Semi-Metallic Brake Pads. Metallic pads consist of metal or metal alloys. Simultaneously, semi-metallic brake pads contain a high amount of metals or metallic fibers (20%-80%) [81]. Iron, copper, brass, and tin are the most commonly used metals. Cast iron or steel-based metallic pads are widely used in heavy-duty braking applications such as railways, aircraft, etc. [48]. Kukutschova et al. investigated the wear behavior and wear debris of semi-metallic brake pads against the gray cast-iron brake disc [13]. It was observed that the wear debris consisted of a high percentage of metals and metallic oxides. Ferrer et al. have done a comparative study on the tribological behavior of sintered alloy brake pad and cast-iron brake pad against the railway brake disc [82]. The brake pad consists of iron, copper, chromium, tin, and graphite. It was observed that the sintered alloy brake pad has an 80% higher coefficient of friction in comparison to the cast-iron brake pad. Sintered alloy pads produce low roughness in the brake disc in contrast to cast iron brake pads. The noise produced was also low in the case of a sintered brake pad. Vasconcellos et al. characterized the third body layer formed between the cast-iron brake disc against two different types of semi-metallic brake pads [21]. Magnetite and pyrite were detected on the surface. These phases have a significant effect on the wear behavior of brake couples. Tayeb et al. investigated the wear behavior of four different non-asbestos semi-metallic brake pads against a cast-iron disc in a water spray environment [24]. It was observed that the brake pad consisting high amount of steel fibers saw a constant coefficient of friction in the water spray environment. So, the brake pad's high metallic fiber content is better from the safety point of view, but high steel content induces high disc wear.

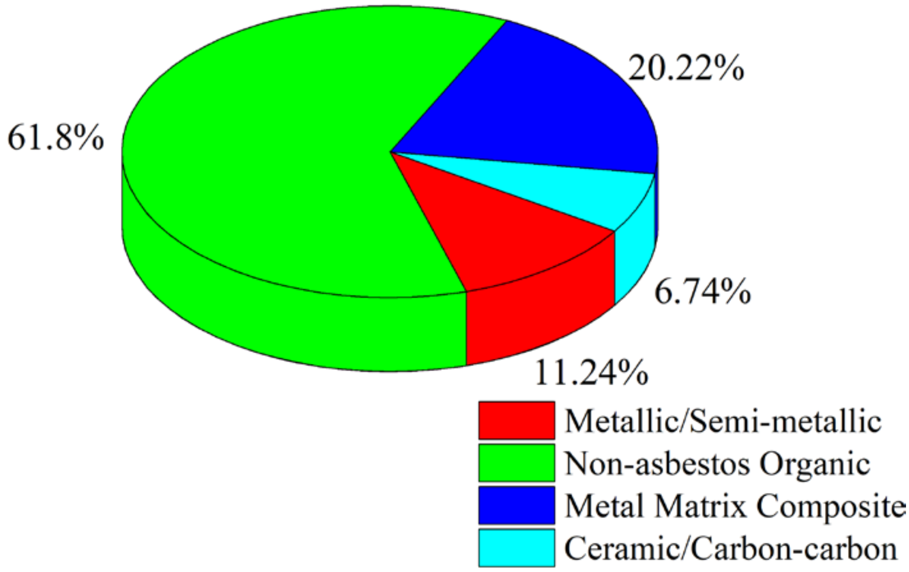

Fig. 3. Materials used for making brake pad or brake lining

Wahlstrom et al. investigated the wear behavior of three different types of brake pads, i.e., nano-porous, low-metallic, and NAO against the cast-iron brake disc [27]. It was observed that the wear nano-porous brake pad release 3-7 times fewer airborne particles. Hinrichs et al. investigated semi-metallic brake pads' wear behavior against the gray cast-iron brake disc [28]. It was observed that the coefficient of friction was erratic; this was due to the lack of magnetite, and a high amount of cementite in the third body formed. So, the amount of cementite should be less to obtain a stable coefficient of friction. Shupert et al. studied the effect of brake pad wear dust originating from a low metallic brake pad on the aquatic plant Salvinia molesta Mitchell [83]. It was observed that the wear debris could be a serious cause of marine plant species' growth. Hendre et al. fabricated two brake pads, i.e., semi-metallic type (metallic fibers bonded by resin) and NAO type [84]. A comparative study on the mechanic and tribological properties of fabricated pads and asbestos-based commercial brake pad were done. It was observed that the fabricated brake pad's mechanical properties were higher in comparison to the asbestos-based pad. The coefficient of friction of the asbestos-based pad was higher than the coefficient of friction of fabricated pads.

Non-asbestos Organic Brake Pads. Asbestos-free organic materials are the most commonly used material for brake pads [77]. Almost 80% of brake pads used in automobiles are NAO type. There are various contents in organic brake pads, such as a binder, fibers, abrasives, lubricants, fire-resistant materials, and other reinforcements [18-20,23,50,62,65,66,80,85]. The composition of a non-asbestos organic brake pad is given in Table 2.

Effect of metallic fibers. Hoyer et al. fabricated three different NAO brake pads with and without metallic threads [86]. The fabricated pads' wear behavior was investigated; it was observed that the no-friction film was formed during the low-duty cycle. As the thermal stability of NAO-type brake pads without metallic fibers is less, Yevtushenko et al. investigated the effect of the addition of steel fibers and copper fibers on the tribological properties of NAO-type brake pads [87]. It was observed that the temperature rise was high, even after the addition of high thermal conductivity metal fibers. So, the addition of metallic threads was found ineffective in reducing the temperature rise. Eriksson et al. also investigated NAO brake pads' surface characteristics containing metallic fibers [15,88]. Jang et al. also fabricated low copper fiber NAO brake pads containing 15 different ingredients [16,89]. Steel fibers used in NAO brake pads are the reason for high brake disc/drum wear. Jang et al. fabricated NAO brake pads with three different types of metallic fibers, i.e., aluminium, copper, steel fibers [63]. It was observed that the Cu-based brake pad saw better fade resistance. Also, a steel fiber-based brake pad saw erratic friction due to large metal transfer against an aluminium brake disc. Darius et al. also fabricated four different NAO brake pads with varied compositions for light rail transit [80]. It was observed that the friction of the coefficient was high, and the wear rate was less for the brake pad containing a high amount of barium and iron.

Table 2. General composition of non-asbestos organic brake pad

Constituent	Characteristic Name
Fiber	Organic/Inorganic/Metal
Fillers	Barytes/Vermiculite/clay/Iron Oxide
Abrasives	Mica/SiC/Zirconium Silicate/Quartz
Binders	Rubber/Resin
Reinforcements	Sulfides of Copper/Lead/Antimony

Effect of processing parameters. Kim et al. optimized the process parameters to fabricate the NAO brake pad using the Taguchi design of the experiment [90]. It was observed that the molding temperature and molding pressure were the most influencing parameters in the manufacturing of NAO brake pads. Optimum parameters were molding pressure of 27MPa, molding temperature of 225°C, six-minute molding time, and six hours of heat treatment at 200°C.

Surface characterization. Osterle et al. studied the microstructural and chemical changes in braking material during the braking operation [17]. NAO-type brake pad with quartz as a major constituent was used for the study. It was observed that the third body patches formed contain pad constituents and iron oxide from the disc. Delamination of filler particles was the dominant wear mechanism for the brake pad. Osterle et al. also studied the friction film and friction layer formed on the NAO-type polymer matrix composite brake pads [11]. It was observed that a third body layer formed and separated the brake disc from the brake pad. The third layer formed had a high influence on the wear behavior of the braking couple. Also, constant friction in the range of 0.3-0.5 was achieved after a running time. Blau et al. investigated NAO type brake pads' wear behavior in trucks against a cast-iron brake disc in the water spray environment. It was observed that the coefficient of friction dropped significantly in the wet condition. Dry friction was achieved after 1-2 sec. of sliding. Eriksson et al. investigated the contact and wear behavior of NAO-type brake pads [91]. An NAO-type brake pad consists of so many different materials such as polymer, metal, etc. So, there is a high difference in the hardness of the constituent material. The high difference in constituents' properties, a particular type of surface consisting of micron size plateaus, is formed. These plateaus wore out and developed again during braking.

Effect of various reinforcement. Mutlu et al. investigated the effect of the addition of boric acid on the wear behavior of NAO-type brake pads [92]. It was observed the wear performance of brake pads improved after the addition of boric acid. Marina et al. investigated the effect of potassium titanate on the wear behavior of NAO-type brake pads [34]. It was observed that the wear behavior and grain pull-out reduced. Liew et al. fabricated two types of brake pads, one with asbestos and one without asbestos, and investigated the tribological properties of fabricated pads against the cast-iron disc. It was observed that the non-asbestos brake pad has a stable coefficient of friction. Also, the wear resistance of the non-asbestos brake pad was high compared to the asbestos-based brake pad and commercial brake pad. Baklouti et al. investigated the effect of the addition of glass fibers on the wear behavior of NAO-type brake pads [93]. It was observed that the wear rate decreases after the addition of glass fibers. Also, thermal and mechanical strength improved. Osterle et al. investigated organic type brake pads' tribological properties consisting of solid lubricants such as graphite and molybdenum disulfides [94]. It was observed that the addition of solid lubricants significantly affected the wear behavior of brake pads. Natarajan et al. have done a cooperative study on the tribological behavior of asbestos brake liners and NAO brake liners against aluminium-based brake drums [69]. It was observed that the steady temperature was low in the case of NAO brake liners. But, the brake drum's thermal expression was less more in the case of NAO brake liners because of more heat generation.

Effect of resin. Phenolic resin is the most commonly used binder in NAO-type brake pads. But the life of phenolic resin is short, and there is shrinkage in the final material. Also, various volatile by-products evolve during the processing of phenolic resins. So, Gurunath et al. fabricated a new resin polymerizing by heat-induced ring-opening to replace the Novolac phenolic resin [95]. It was observed that the performance brake pad formed from the new resin was better than the performance of the pad formed from conventional phenolic resin. Joo et al. studied the effect of different types of resins on the particulate emission from the NAO type of brake pads [32]. It was observed that the wear rate and particulate emission were low in the case of heat-resistant resin in comparison to the straight-phenolic resin. So, heat-resistant resin is a better alternative to straight-phenolic resin for the fabrication of NAO-type brake pads.

Environmental impact of Antimony. Uexkull et al. studied the health issue related to antimony (Sb_2S_3), a commonly used constituent of an NAO-based brake pad [96,97]. It was observed that the Sb released in the environment from the friction material could cause human cancer [44]. So, the use of Sb_2S_3 and Sb based materials was deterred. Ertan et al. also fabricated an NAO-type brake pad using a powder metallurgy process [12]. The wear behavior of the brake pad consisting of 15 ingredients was investigated against the cast-iron disc. It was observed that the density of brake pads was mostly dependent on the molding pressure and temperature. Wear resistance of brake pads increased on increasing the molding time. Iijima et al. characterized the brake dust released from the non-steel non-asbestos brake pad to study antimony sulfides' impact on the environment [14]. It was observed that the Sb_2S_3 used in the brake pad oxidized to form carcinogenic Sb_2O_3. Also, Sb particles released from brake pads can be a reason for the enrichment of Sb in the environment [98].

Replacement of Copper. Copper metal fibers (5%-10%) are most commonly added in NAO-type brake pads to increase the thermal conductivity. Also, copper fibers help in the formation of compact third body layers. But, the release of heavy metal copper has some health issues [33]. So, Straffelini et al. suggested some replacements for copper in a review [99]. Graphite is suitable for replacing copper because graphite increases the thermal conductivity and reduces the wear rate. But graphite oxidized to carbon monoxide easily at a higher temperature, which can be because of health issues. Nature fibers can also be used to replace copper in making copper-free eco-friendly brake pads. Mahale et al. used stainless steel swarfs as a replacement for copper fibers in NAO-type brake pads [100]. It was observed that the wear rate and fade resistance of stainless-steel swarf containing brake pads was slightly higher than copper-containing brake pads. Mahale et al. investigated the effect of plasma treatment of stainless steel swarfs on the tribological properties of stainless-steel swarf-containing brake pads [101]. It was observed that the tribological properties improved after plasma treatment because of better adhesion. Lyu et al. fabricated the Cu-free brake pads, and a comparative study was done on the airborne particle generated from the copper-containing pad and copper-free pad [102]. It was observed that the Cu-free brake pads produced more airborne particles.

Eco-friendly Brake Pads. As the emission of asbestos, Cu, Sb, Pb, Zn, etc. to the environment from brake pads is one of the reasons for serious health issues, so the researchers are working for the development of eco-friendly NAO type brake pads using natural fibers [103,104]. Asabe et al. fabricated an NAO-type brake with the addition of coconut shell powder. It was observed that the strength and wear rate improved after the addition of coconut shell powder. But, on further increasing the coconut shell powder content, brittleness increased [7]. Rao et al. fabricated eco-friendly NAO-type brake pads using agriculture waste. It was observed that the wear performance of agriculture-based brake pads was comparable to asbestos-based brake pads and didn't have any health issues [4].

Singh et al. investigated the effect of weight fraction of aramid fibers and lapinus fibers on NAO-type brake pads' mechanical and tribological properties [105]. It was observed that the physical properties increased on increasing the lapinus fibers while the mechanical properties enhanced on increasing the weight fraction of aramid fibers. Yun et al. fabricated the eco-friendly NOA brake pad by reinforcing natural fibers in place of hazardous metallic threads such as copper, brass, etc. The wear behavior of the fabricated pad was investigated [106]. It was observed that the properties of natural fibers-based eco-friendly was comparable to metal fibers-based brake pads. So, natural fibers can easily replace hazardous metallic threads in NAO-type brake pads. Abutu et al. fabricated NAO-type brake pads consisting of sea-shell, epoxy resin, alumina, and graphite [107]. It was observed that the steady coefficient of friction of the fabricate pad was around 0.48. So, manufactured material was found suitable for making automobile brake pads. Pujari et al. fabricated NAO-type eco-friendly brake pads consisting of palm kernal shell, wheat, nile-roses, graphite, alumina, and phenolic resin [108]. It was observed that fabricated brake pads had a low wear rate, low noise, and high friction coefficient. Tamo et al. also fabricated palm kernal shell-based brake pads and observed similar properties [109]. Craciun et al. investigated the effect of varying weight fractions of aluminium metal fibers and coconut fibers (keeping weight fraction of other constituent constant) on the tribological properties of NAO-type brake pads [110]. It was observed that the brake pads having 10%-15% coconut fibers exhibited excellent properties.

Karthikeyan et al. fabricated non-asbestos-type brake pads using kenaf fibers and aloe-vera fibers [73]. It was observed that the deformation in fabricated brake pad material was higher than the deformation and stresses in asbestos-based brake pad material. So further research is required to develop eco-friendly brake pads that can replace asbestos-based brake pads. Lawal et al. fabricated eco-friendly NAO-type brake pads using sawdust [36]. The wear performance of sawdust-based brake pads was comparable with the wear performance of commercial brake pads. So, sawdust can be used to fabricate eco-friendly brake pads. Dadkar et al. manufactured an NAO-type brake pad with the addition of fly-ash as a filler and aramids as reinforcement [111]. It was observed that the recovery response increase after the addition of fly-ash. Xin et al. have done a comparative study on the wear behavior of the sisal fiber-based NAO brake pad and asbestos-based brake pad [112]. It was observed that the wear performance of the sisal fiber-based brake pad was better than the asbestos-based brake pad. So, sisal fiber can replace carcinogenic asbestos for making a brake pad. Zhang et al. fabricated NAO-type brake pads consisting of Cu fiber, glass fiber, and wood fiber in place of steel fibers [70]. Wood fiber improved the bonding between the fibers and binders.

Metal Matrix Composite Brake Pads. Asbestos based are being eliminated because of health issues, and non-asbestos organic pads have a low thermal resistance. So, MMC brake pads are being developed for heavy-duty applications [26,29,113,114]. Chapman et al. fabricated a boron carbide reinforced aluminium matrix composite brake pad [115]. It was observed that the Al/B_4C has very high wear resistance; also, Al/B4C brake pads did not show any fading behavior at high temperatures too. Kermc et al. investigated the MMC brake pad's wear behavior against two types of brake disc material, i.e., gray cast iron and C-C/SiC [59]. It was observed that the temperature rise was very high in the case of the MMC pad used against the C-C/SiC brake disc, but the coefficient of friction was high and steady. So the MMC brake pad instead of the C-C/SiC brake pad can be used against the C-C/SiC brake disc. Stadler et al. investigated the effect of the addition of SiC and graphite on the wear behavior of metal matrix composite brake pads against the C-C/SiC brake disc [57,58]. It was observed that the SiC reinforced MMC brake pad had a low coefficient of friction. The coefficient of friction increased after the addition of graphite despite the solid lubricant nature of graphite. Yevtushenko et al. studied the thermal stresses induced during braking in a brake system consisting of a metal-ceramic brake pad and cast-iron disc [22]. It was observed that the high heat generated during braking induce thermal stress in the brake couple. Desplanques et al. investigated a sintered metal matrix composite brake pad's tribological behavior against the forged steel brake disc [51]. It was observed that the third body layer formed and influenced the wear behavior significantly. Gultekin et al. investigated aluminium matrix composite brake drum wear behavior against the copper matrix composite brake pad reinforced with graphite [24]. Due to copper's high thermal conductivity, heat dissipation was better, and the temperature rise was low. Abhik et al. fabricated an aluminium matrix composite reinforced with SiC for brake pad application [116]. Effect of weight fraction of SiC was observed on the wear behavior of Al/SiC brake pads. It was observed that the wear rate of Al matrix composite reinforced with 10% SiC was minimum.

Tang et al. fabricated copper matrix hybrid-composite brake pads reinforced with graphite, MoS_2, SiC, Fe, and FeCr for railways [117]. The effect of making a hole in the middle of the brake pad was studied on the tribological behavior. It was observed that the noise production reduced, and heat dissipation improved. Xiao et al. also fabricated copper matrix composite pads by reinforcing graphite, MoS_2, Fe, FeCr, etc. [49]. Cu-MMC brake pads exhibited excellent properties, so they can be used for making railway brake pads [118]. Zhang et al. fabricated copper matrix composites reinforced with Fe, graphite, and MoS_2 from brake pad applications [119]. It was observed that the coefficient of friction incre4ased slightly on the addition of MoS_2 (2% by weight). On the other hand, the wear rate decreased significantly (80% decrease) in comparison to the sample without MoS_2. Zhang et al. also studied the fade behavior of the Cu-MMC brake pad against the steel disc used in railways [53]. It was observed that fading became severe when brake applied for a long time. Zhang et al. also investigated the effect of alumina on the wear properties of Cu-MMC brake pads [54]. It was observed that the wear rate reduced, and the coefficient of friction increased after the addition of alumina. Aluminium matrix composites can also be used for brake pads materials [120].

Ceramic or Carbon-carbon Brake Pads. C-C or C-C/SiC brake pads are mostly used against the C-C/SiC or ceramic brake discs [41]. C-C/SiC brake couples are light and used for heavy-duty applications such as aircraft, trains, etc., because of high thermal and wear resistance. The friction of the C-C/SiC friction couple is also high, so it requires a low braking force. Fiber-reinforced Ceramic Matrix Composites (FRCMC) are also used in aircraft brake pads [1]. Ceramic resins derived from polymer (i.e., alumina silicate and silicon carboxyl) are used as a matrix material, while silicon carbide, silicon nitride, and alumina are used as fiber. Podratzky et al. investigated the wear behavior of carbon-fiber composite brake couple and silicon carbide (ceramic) brake couple [67]. It was observed that the wear rate of the carbon fiber-based brake pad was higher than the wear rate of the ceramic brake pad. So, a ceramic brake pad was found to be superior to the carbon-fiber brake pad.

Wang et al. investigated a carbon-based brake pad's tribological properties against the steel rotor in a wet environment [121]. It was observed that the friction coefficient reduced by nearly 30% in wet conditions in comparison to dry conditions; this can be a reason for the accident. Jiang et al. investigated the graphite/SiC brake pad's tribological properties against the SiC/Al brake disc [72]. It was observed that the graphite/SiC brake pads were found suitable for high-speed train braking systems. Ma et al. investigated the effect of the introduction of the ductile phase $FeSi_2$ on the tribological properties of C-C/SiC brake pads [56]. It was observed that the wear resistance of $FeSi_2$ modified C-C/SiC brake pads was higher than the un-modified C-C/SiC brake pads. Also, friction surface in the case of $FeSi_2$ modified C-C/SiC brake pads was maintained even at high pressure, but in the case of un-modified C-C/SiC brake pads, the friction layer destroyed completely.

4. Conclusions

Asbestos is a perfect material for making friction materials such as brake pads or brake lining. But, due to its carcinogenic nature, it has been banned by the environment and health agencies. So, researchers are working on the development of asbestos-free material for braking applications. Non-asbestos organic materials are the most commonly used material for making brake pads. But the thermal stability organic brake pad is low, so the use of the NAO brake pad is limited to light-duty vehicles. In railways and airplanes, MMC or ceramic brake pads are more suitable. As most of the countries are working to develop high-speed trains, there is a high demand for ceramic or MMC brake pads. Emission of Sb, Cu, and other heavy metals from brake pads/discs during braking is also harmful to the environment. So, researchers are working on the development of eco-friendly braking material using agricultural waste or natural fibers. For making brake disc/drum, high density cast iron or steel is most commonly used. But heavyweight of the un-sprung rotating mass is the reason for poor dynamics. So, aluminium matrix composite is considered a future material for brake disc/drum because of its lightweight, high strength, and high wear resistance. The use of

AMCs for brake drum/disc can reduce the braking system's weight, and as a result, brake dynamics will improve.

References

[1] Atmur SD, Strasser TE. *Brakes Rotors/Drums and Brake Pads Particularly Adapted For Aircraft/Truck/Train/and Other Heavy Duty Application*. Patent US5560455; 1996.
[2] Blau PJ, Meyer III HM. *Case Study: Characteristics of wear particles produced during friction tests of conventional and unconventional disc brake materials*. Wear. 2003;255(7-12): 1261-1269.
[3] Gowthami K, Balaji K. Designing and Analysis of Brake Drum. *International Journal for Research in Applied Science & Engineering Technology*. 2016;4(9): 135-142.
[4] Rao RU, Babji G. A Review paper on alternate materials for Asbestos brake pads and its characterization. *International Research Journal of Engineering and Technology*. 2015;2(2): 556-562.
[5] Lee K, Park K. Optimal robust control of a contactless brake system using an eddy current. *Mechatronics*. 1999;9(6): 615-631.
[6] Maluf O, Angeloni M, Milan MT, Spinelli D, Filho WWB. Development of materials for automotive disc brakes. *Minerva*. 2007;4(2): 149-158.
[7] Asabe BD, Madakson PB, Manji J. Material Selection and Production of a Cold-Worked Composite Brake Pad. *World Journal of Engineering and Pure and Applied Science*. 2012;2(3): 92-97.
[8] Blau PJ. *Compositions, Functions, and Testing of Friction Brake Materials and Their Additives*. Oak Ridge: U.S. Department of Energy; 2001.
[9] Hulskotte JHJ, Roskam GD, Denier van der Gona HAC. Elemental composition of current automotive braking materials and derived air emission factors. *Atmospheric Environment*. 2014;99: 436-445.
[10] Thuresson D. Influence of material properties on sliding contact braking applications. *Wear*. 2005;257(5-6): 451-460.
[11] Osterle W, Urban I. Friction layers and friction films on PMC brake pads. *Wear*. 2004;257(1-2): 215-226.
[12] Ertan R, Yavuz N. An experimental study on the effects of manufacturing parameters on the tribological properties of brake lining materials. *Wear*. 2010;268(11-12): 1524-1532.
[13] Kukutschová J, Roubícek V, Maslán M, Jancík D, Slovák V, Malachová K, Pavlíčková Z, Filip P. Wear performance and wear debris of semimetallic automotive brake materials. *Wear*. 2010;268(1-2): 86-93.
[14] Iijima A, Sato K, Yano K, Tago H, Kato M, Kimura H, Furuta N. Particle size and composition distribution analysis of automotive brake abrasion dusts for the evaluation of antimony sources of airborne particulate matter. *Atmospheric Environment*. 2007;41(23): 4908-4919.
[15] Eriksson M, Jacobson S. Tribological surfaces of organic brake pads. *Tribology International*. 2000;33(12): 817-827.
[16] Jang H, Kim SJ. The effects of antimony trisulfide (Sb2 S3) and zirconium silicate (ZrSiO4) in the automotive brake friction material on friction characteristics. *Wear*. 2000;239(2): 229-236.
[17] Österle W, Griepentrog M, Gross T, Urban I. Chemical and microstructural changes induced by friction and wear of brakes. *Wear*. 2001;251(1-12): 1469-1476.
[18] Blau PJ, Jolly BC. Wear of truck brake lining materials using three different test methods. *Wear*. 2005;259(7-12): 1022-1030.
[19] Osterle W, Klob H, Urban I, Dmitriev AI. Towards a better understanding of brake friction materials. *Wear*. 2007;263(7-12): 1189-1201.

[20] Mutlu I, Eldogan O, Findik F. Tribological properties of some phenolic composites suggested for automotive brakes. *Tribology International*. 2006;39: 317-325.
[21] Vasconcellos MAZ, Hinrichs R, Cunha JBMD, Soares MRF. Mossbauer spectroscopy characterization of automotive brake disc and polymer matrix composite (PMC) pad surfaces. *Wear*. 2010;268(5-6): 715-720.
[22] Yevtushenko A, Kuciej M. Temperature and thermal stresses in a pad/disc during braking. *Applied Thermal Engineering*. 2010;30: 354-359.
[23] Österle W, Dörfel I, Prietzel C, Rooch H, Bulthé ALC, Degallaix G, Desplanques Y. A comprehensive microscopic study of third body formation at the interface between a brake pad and brake disc during the final stage of a pin-on-disc test. *Wear*. 2009;267: 781-788.
[24] Tayeb NSME, Liew KW. Effect of water spray on friction and wear behaviour of noncommercial and commercial brake pad materials. *Journal of Materials Processing Technology*. 2008;208: 135-144.
[25] Belhocine A, Bouchetara M. Temperature and Thermal Stresses of Vehicles Gray Cast Brake. *Journal of Applied Research and Technology*. 2013;11: 674-682.
[26] Wahlström J. A comparison of measured and simulated friction, wear, and particle emission of disc brakes. *Tribology International*. 2015;92: 503-511.
[27] Wahlstrom J, Gventsadze D, Olander L, Kutelia E, Gventsadze L, Tsurtsumia O, Olofssona U. A pin-on-disc investigation of novel nanoporous composite-based and conventional brake pad materials focussing on air borne wear particles. *Tribology International*. 2011;44(12): 1838-1843.
[28] Hinrichs R, Soares MRF, Lamb RG, Soares MRF, Vasconcellos MAZ. Phase characterization of debris generated in brake pad coefficient of friction tests. *Wear*. 2011;270: 515-519.
[29] Yevtushenko AA, Kuciej M, Yevtushenko O. Modelling of the frictional heating in brake system with thermal resistance on a contact surface and convective cooling on a free surface of a pad. *International Journal of Heat and Mass Transfer*. 2015;81: 915-923.
[30] Liew KW, Nirmal U. Frictional performance evaluation of newly designed brake pad materials. *Materials and Design*. 2013;48: 25-33.
[31] Verma PC, Menapace L, Bonfanti A, RodicaCiudin, Gialanella S, Straffelini G. Braking pad-discsystem: Wear mechanisms and formation of wear fragments. *Wear*. 2015;322-323: 251-258.
[32] Joo BS, Chang YH, Seo HJ, Jang H. Effects of binder resin on tribological properties and particle emission of brake linings. *Wear*. 2019;434-435: 202995.
[33] Barros LY, Poletto JC, Neis PD, Ferreira NF, Pereira CHS. Influence of copper on automotive brake performance. *Wear*. 2019;426-427: 741-749.
[34] Marina E, Daimon E, Boschetto F, Rondinella A, Inada K, Zhu W, Pezzotti G. Diagnostic spectroscopic tools for worn brake pad materials: A case study. *Wear*. 2019;432-433: 202969.
[35] Lyu Y, Olofsson U. On black carbon emission from automotive disc brakes. *Journal of Aerosol Science*. 2020;148: 105610.
[36] Lawal SS, Bala KC, Alegbede AT. Development and production of brake pad from sawdust composite. *Leonardo Journal of Sciences*. 2017(3):47-56.
[37] Mackin TJ. Thermal Cracking in Disc Brakes. *Engineering failure Analysis*. 2002;9: 63-76.
[38] Cueva G, Sinatora A, Guesser WL, Tschiptschin AP. Case Study: Wear resistance of cast irons used in brake disc rotors. *Wear*. 2003;255: 1256-1260.
[39] Natarajan N, Vijayarangan S, Rajendran I. Fabrication, testing and thermal analysis of metal matrix composite brake drum. *Int J Vehicle Design*. 2007;44: 339-359.

[40] Blau PJ, McLaughlin JC. Effects of water films and sliding speed on the frictional behavior of truck disc brake materials. *Tribology International*. 2003;36: 709-715.
[41] Blanco C, Bermejo J, Marsh H, Menendez R. Chemical and physical properties of carbon as related to brake performance. *Wear*. 1997;213: 1-12.
[42] Rao VTVSR, Rajaram LS, Seetharamu KN. Temperature and torque determination in brake drums. *Sadhana*. 1993;18: 963-983.
[43] Hohmann C, Schiffner K, Oerter K, Reese H. Contact analysis for drum brakes and disk brakes using ADINA. *Computers and Structures*. 1999;72: 185-198.
[44] Ingo GM, D'Uffizi M, Falso G, Bultrini G, Padeletti G. Thermal and microchemical investigation of automotive brake pad wear residues. *Thermochimica Acta*. 2004;418: 61-68.
[45] Podratzky A, Bansemir H. Design and experimental characterization of modern helicopters rotor brakes. *Aerospace Science and Technology*. 2007;11: 360-369.
[46] Li Z, Han J, Yang Z, Pan L. The effect of braking energy on the fatigue crack propagation in railway brake discs. *Engineering Failure Analysis*. 2014;44: 272-284.
[47] Abbasi S, Wahlström J, Olander L, Larsson C, Olofsson U, Sellgren U. A study of airborne wear particles generated from organic railway brake pads and brake discs. *Wear*. 2011;273: 93-99.
[48] Günay M, Korkmaz ME, Özmen R. An investigation on braking systems used in railway vehicles. *Engineering Science and Technology, an International Journal*. 2020;23: 421-431.
[49] Xiao Y, Zhang Z, Yao P, Fan K, Zhou H, Gong T, Zhao L, Deng M. Mechanical and tribological behaviors of copper metal matrix composites for brake pads used in high-speed trains. *Tribology International*. 2018;119: 585-592.
[50] Panier S, Dufrénoy P, Weichert D. An experimental investigation of hot spots in railway disc brakes. *Wear*. 2004;256: 7764-7773.
[51] Desplanques Y, Roussette O, Degallaix G, Copin R, Berthier Y. Analysis of tribological behaviour of pad–disc contact in railway braking Part 1. Laboratory test development, compromises between actual and simulated tribological triplets. *Wear*. 2007;262: 582-591.
[52] Camacho JRL, Morales GJ, Ramón CC, Martínez VV, Romero IH, Méndez JVM, et al. A study of the wear mechanisms of disk and shoe brake pads. *Engineering Failure Analysis*. 2015;56: 348-359.
[53] Zhang P, Zhang L, Fu K, Wu P, Cao J, Shijia C, Qu X. Fade behaviour of copper-based brake pad during cyclic emergency braking at high speed and overload condition. *Wear*. 2019;428-429: 10-23.
[54] Zhang P, Zhang L, Fu K, Wu P, Cao J, Shijia C, Qu X. The effect of Al2O3 fiber additive on braking performance of copper-based brake pads utilized in high-speed railway train. *Tribology International*. 2019;135: 444-456.
[55] Xiao JK, Xiao SX, Chen J, Zhang C. Wear mechanism of Cu-based brake pad for high-speed train braking at speed of 380 km/h. *Tribology International*. 2020:150: 106357.
[56] Ma X, Fan S, Sun H, Luan C, Deng J, Zhang L, Cheng L. Investigation on braking performance and wear mechanism of full-carbon/ceramic braking pairs. *Tribology International*. 2020;142: 105981.
[57] Stadler Z, Krnel K, Kosmac T. Friction behavior of sintered metallic brake pads on a C/C–SiC composite brake disc. *Journal of the European Ceramic Society*. 2007;27: 1411-1417.
[58] Stadler Z, Krnel K, Kosmac T. Friction and wear of sintered metallic brake linings on a C/C-SiC composite brake disc. *Wear*. 2008;265: 278-285.
[59] Kermc M, Kalin M, Vizintin J. Development and use of an apparatus for tribological evaluation of ceramic-based brake materials. *Wear*. 2005;259: 1079-1087.

[60] Zhao S, Yan Q, Zhang TPX, Wen Y. The braking behaviors of Cu-Based powder metallurgy brake pads mated with C/C–SiC disk for high-speed train. *Wear*. 2020;448-449: 203237.

[61] Gultekin D, Uysal M, Aslan S, Alaf M, Guler MO, Akbulut H. The effects of applied load on the coefficient of friction in Cu-MMC brake pad/Al-SiCp MMC brake disc system. *Wear*. 2010;270: 73-82.

[62] Sallit I, Richard C, Adam R, Valloire FR. Characterization Methodology of a Tribological Couple: Metal Matrix Composite/Brake Pads. *Materials Characterization*. 1998;40: 169-188.

[63] Jang H, Ko K, Kim SJ, Basch RH, Fash JW. The effect of metal fibers on the friction performance of automotive brake friction materials. *Wear*. 2004;256: 406-414.

[64] Shorowordi KM, Haseeb ASMA, Celis JP. Velocity effects on the wear, friction and tribochemistry of aluminum MMC sliding against phenolic brake pad. *Wear*. 2004;256: 1176-1181.

[65] Uyyuru RK, Surappa MK, Brusethaug S. Effect of reinforcement volume fraction and size distribution on the tribological behavior of Al-composite/brake pad tribo-couple. *Wear*. 2006;260: 1248-1255.

[66] Uyyuru RK, Surappa MK, Brusethaug S. Tribological behavior of Al–Si–SiCp composites/automobile brake pad system under dry sliding conditions. *Tribology International*. 2007;40: 365-373.

[67] Natarajan N, Vijayarangan S, Rajendran I. Wear behaviour of A356/25SiCp aluminium matrix composites sliding against automobile friction material. *Wear*. 2006;261: 812-822.

[68] Kushal M, Sharma S. Optimization of Design of Brake Drum of Two Wheeler through Approach of Reverse Engineering by Using Ansys Software. *IOSR Journal of Mechanical and Civil Engineering*. 2015;12(4): 70-75.

[69] Natarajan MP, Rajmohan B. Heat Dissipation and Temperature Distribution of Brake Liner Using Steady State Analysis. *Applied Mechanics and Materials*. 2013;249-250: 712-717.

[70] Zhang SY, Qu SG, Li YY, Chen WP. Two-body abrasive behavior of brake pad dry sliding against interpenetrating network ceramics/Al-alloy composites. *Wear*. 2010;268: 939-945.

[71] Bian G, Wu H. Friction performance of carbon/silicon carbide ceramic composite brakes in ambient air and water spray environment. *Tribology International*. 2015;92: 1-11.

[72] Jiang L, Jiang Y, Yu L, Yang H, Li Z, Ding Y, Fu GF. Fabrication, microstructure, friction and wear properties of SiC3D/Al brake disc−graphite/SiC pad tribo-couple for high-speed train. *Trans Nonferrous Met Soc China*. 2019;29(9): 1889-1902.

[73] Karthikeyan SS, Balakrishnan E, Meganathan S, Balachander M, Ponshanmugakumar A. Elemental Analysis of Brake Pad Using Natural Fibres. *Materials Today: Proceedings*. 2019;16: 1067-1074.

[74] Erdinc M, Erdinc E, Cok G, Polatli M. Respiratory impairment due to asbestos exposure in brake-lining workers. *Environmental Research*. 2003;91: 151-156.

[75] Blake CL, Orden DRV, Banasik M, Harbison RD. Airborne asbestos concentration from brake changing does not exceed permissible exposure limit. *Regulatory Toxicology and Pharmacology*. 2003;38: 58-70.

[76] Langer AM. Reduction of the biological potential of chrysotile asbestos arising from conditions of service on brake pads. *Regulatory Toxicology and Pharmacology*. 2003;38: 71-77.

[77] Venkatesh S, Murugapoopathiraja K. Scoping Review of Brake Friction Material for Automotive. *Materials Today: Proceedings*. 2019;16: 927-933.

[78] Bernstein DM, Rogers R, Sepulveda R, Kunzendorf P, Bellmann B, Ernst H, Phillips JI. Evaluation of the deposition, translocation and pathological response of brake dust with and without added chrysotile in comparison to crocidolite asbestos following short-term inhalation: Interim results. *Toxicology and Applied Pharmacology*. 2014;276(1): 28-46.
[79] Abbasi S, Olander L, Larsson C, Olofsson U, Jansson A, Sellgren U. A field test study of airborne wear particles from a running regional train. *Journal of Rail and Rapid Transit*. 2012;226(1): 95-109.
[80] Darius GS, Berhan MN, David NV, Shahrul AA, Zaki MB. Characterization of brake pad friction materials. *WIT Transactions on Engineering Sciences*. 2005;51: 43-50.
[81] Figi R, Nagel O, Tuchschmid M, Lienemann P, Gfeller U, Bukowiecki N. Quantitative analysis of heavy metals in automotive brake linings: A comparison between wet-chemistry based analysis and in-situ screening with a handheld X-ray fluorescence spectrometer. *Analytica Chimica Acta*. 2010;676: 46-52.
[82] Ferrer C, Pascual M, Busquets D, Rayón E. Tribological study of Fe–Cu–Cr–graphite alloy and cast iron railway brake shoes by pin-on-disc technique. *Wear*. 2010;268: 784-789.
[83] Shupert LA, Ebbs SD, Lawrence J, Gibson DJ, Filip P. Dissolution of copper and iron from automotive brake pad wear debris enhances growth and accumulation by the invasive macrophyte Salvinia molesta Mitchell. *Chemosphere*. 2013;92: 45-51.
[84] Hendre KN, Bachchhav BD, Bagchi HH. Frictional Characteristics of Brake Pad Materials Alternate to Asbestos. *International Journal of Engineering and Advanced Technology*. 2019;9(2): 694-698.
[85] Roubicek V, Raclavska H, Juchelkova D, Filip P. Wear and environmental aspects of composite materials for automotive braking industry. *Wear*. 2008;265: 167-175.
[86] Hoyer LG, Bach A, Nielsen GT, Morgen P. Tribological properties of automotive disc brakes with solid lubricants. *Wear*. 1999;232: 168-175.
[87] Yevtushenko A, Kuciej M, Wasilewski P. Experimental study on the temperature evolution in the railway brake disc. *Theoretical & Applied Mechanics Letters*. 2019;9: 308-311.
[88] Eriksson M, Bergman F, Jacobson S. Surface characterisation of brake pads after running under silent and squealing conditions. *Wear*. 1999;232: 163-167.
[89] Jang H, Lee JS, Fash JW. Compositional effects of the brake friction material on creep groan phenomena. *Wear*. 2001;251: 1477-1483.
[90] Kim SJ, Kim KS, Jang H. Optimization of manufacturing parameters for a brake lining using Taguchi method. *Journal of Materials Processing Technology*. 2003;136: 202-208.
[91] Eriksson M, Lord J, Jacobson S. Wear and contact conditions of brake pads: dynamical in situ studies of pad on glass. *Wear*. 2001;249: 272-278.
[92] Mutlu I, Oner C, Findik F. Boric acid effect in phenolic composites on tribological properties in brake linings. *Materials and Design*. 2007;28: 480-487.
[93] Baklouti M, Cristol AL, Desplanques Y, Elleuch R. Impact of the glass fibers addition on tribological behavior and braking performances of organic matrix composites for brake lining. *Wear*. 2015;330–331: 507-514.
[94] Österle W, Deutsch C, Gradt T, Gil GO, Schneider T, Dmitriev AI. Tribological screening tests for the selection of raw materials. *Tribology International*. 2014;73: 148-155.
[95] Gurunath PV, Bijwe J. Friction and wear studies on brake-pad materials based on newly developed resin. *Wear*. 2007;263: 1212-1219.
[96] Uexkull Ov, Skerfving S, Doyle R, Braungart M. Antimony in brake pads-a carcinogenic component? *Journal of Cleaner Production*. 2005;13: 19-31.
[97] Varrica D, Bardelli F, Dongarrà G, Tamburo E. Speciation of Sb in airborne particulate matter, vehicle brake linings, and brake pad wear residues. *Atmospheric Environment*. 2013;64: 18-24.

[98] Hu X, He M, Li S. Antimony leaching release from brake pads: Effect of pH, temperature and organic acids. *Journal of Environmental Sciences*. 2015;29: 11-17.
[99] Straffelini G, Ciudin R, Ciotti A, Gialanella S. Present knowledge and perspectives on the role of copper in brake materials and related environmental issues: A critical assessment. *Environmental Pollution*. 2015;207: 211-219.
[100] Mahale V, Bijwe J, Sinha S. A step towards replacing copper in brake-pads by using stainless steel swarf. *Wear*. 2019;424-425: 133-142.
[101] Mahale V, Bijwe J. Exploration of plasma treated stainless steel swarf to reduce the wear of copper-free brake-pads. *Tribology International*. 2020;144: 106111.
[102] Lyu Y, Leonardi M, Wahlstrom J, Gialanella S, Olofsson U. Friction, wear and airborne particle emission from Cu-free brake materials. *Tribology International*. 2020;141: 105959.
[103] Jadhav SP, Sawant SH. A review paper: Development of novel friction material for vehicle brake pad application to minimize environmental and health issues. *Materials Today: Proceedings*. 2019;19: 209-212.
[104] Abutu J, Lawal SA, Ndaliman MB, Araga RAL. An Overview of Brake Pad Production Using Non–hazardous Reinforcement Materials. *Acta Technica Corviniensis – Bulletin of Engineering*. 2020;11(3): 143-156.
[105] Singh T, Patnaik A. Performance assessment of lapinus–aramid based brake pad hybrid phenolic composites in friction braking. *Archives of Civil and Mechanical Engineering*. 2015;15: 151–161.
[106] Yun R, Filip P, Lu Y. Performance and evaluation of eco-friendly brake friction materials. *Tribology International*. 210;43: 2010-2019.
[107] Abutu J, Lawal SA, Ndaliman MB, Araga RAL, Adedipe O, Choudhury IA. 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*. 2018;21(4): 787-797.
[108] Pujari S, Srikiran S. Experimental investigations on wear properties of Palm kernel reinforced composites for brake pad applications. *Defence Technology*. 2019;15: 295-299.
[109] Tamo RSF. A Mathematical Model for the purpose of analysing the Thermal Stress Characteristics of PKS-Based Brake Pad with MATLAB. *Materials Today: Proceedings*. 2018;5: 12534-12544.
[110] Crăciun AL, Bretotean CP, Băneasă CB, Josan A. Composites materials for friction and braking application. *IOP Conference Series: Materials Science and Engineering*. 2017;200: 012009.
[111] Dadkar N, Tomar BS, Satapathy BK. Evaluation of flyash-filled and aramid fibre reinforced hybrid polymer matrix composites (PMC) for friction braking applications. *Materials and Design*. 2009;30: 4369-4376.
[112] Xin X, Xu CG, Qing LF. Friction properties of sisal fibre reinforced resin brake composites. *Wear*. 2007;262: 736-741.
[113] Kermc M, Kalin M, Vizintin J, Stadler Z. A reduced-scale testing machine for tribological evaluation of brake materials. *Life Cycle Tribology*. 2005;48:799-806.
[114] Wang WJ, Wang F, Gu KK, Ding HH, Wang HY, Guo J, et al. Investigation on braking tribological properties of metro brake shoe materials. *Wear*. 2015;330-331: 498-506.
[115] Chapman TR, Niesz DE, Fox RT, Fawcett T. Wear-resistant aluminum-boron-carbide cermets for automotive brake applications. *Wear*. 1999;236: 81-87.
[116] Abhik R, V. U, Xavior MA. Evaluation of Properties for Al-SiC Reinforced Metal Matrix Composite for Brake Pads. *Procedia Engineering*. 2014;97: 941-950.
[117] Tang B, Mo JL, Xu JW, Wu YK, Zhu MH, Zhou ZR. Effect of perforated structure of friction block on the wear, thermal distribution and noise characteristics of railway brake systems. *Wear*. 2019;426-427: 1176-1186.

[118] Wu Y, Liu Y, Chen H, Chen Y, Xie D. An investigation into the failure mechanism of severe abrasion of high-speed train brake discs on snowy days. *Engineering Failure Analysis*. 2019;101: 121-134.
[119] Zhang P, Zhang L, Wei D, Wu P, Cao J, Shijia C, Qu X. Adjusting function of MoS2 on the high-speed emergency braking properties of copper-based brake pad and the analysis of relevant tribo-film of eddy structure. *Composites Part B*. 2020;185: 107779.
[120] Kumar N, Bharti A, Saxena KK. A re-investigation: Effect of powder metallurgy parameters on the physical and mechanical properties of aluminium matrix composites. *Materials Today: Proceedings*. 2021;44(1): 2188-2193.
[121] Wang F, Gu KK, Wang WJ, Liu QY, Zhu MH. Study on braking tribological behaviors of brake shoe material under the wet condition. *Wear*. 2015;342-343: 262-269.

THE AUTHORS

Kumar N.
e-mail: chaudhary56naveen@gmail.com
ORCID: 0000-0002-6918-4384

Bharti A.
e-mail: abharti@mnnit.ac.in
ORCID: 0000-0003-2809-9674

Goyal H.S.
e-mail: hsg@mnnit.ac.in
ORCID: 0000-0003-0243-9570

Patel K.K.
e-mail: kunvarkantpatel@gmail.com
ORCID: 0000-0003-4812-3694