Research Article

Critical evaluation/reassessment of (abfm) automotive brake friction materials

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Abstract

The gradual phasing-out of asbestos in automotive brake friction materials (ABFM) in many parts of the world has sparked the onsets of extensive research and development into safer alternatives. As a result, the brake friction industry has seen the birth of different brake pads and shoes in the past decade, each with their own unique composition, yet performing the very same task and claming to be better than others. This suggests that the selection of brake friction materials is based more on tradition and experimental trial and error rather fundamental understanding. This review strives to eliminates and cloud of uncertainly by providing an insight into the pros and cons of the common ingredients and make-up used in contemporary dry and wet friction pads and shoes. In this paper typical brake materials are reviewed and their advantages and disadvantages in contemporary brake applications are discussed.

Keywords: automotive brake friction materials (ABFM) brake pads, brake shoes, wet and dry braking, asbestos, binder, ceramics fibre.

INTRODUCTION

In this paper, an evaluation of the materials and constituents currently used in automotive brake friction materials after the phasing-out of asbestos is presented. Since the 1970s, asbestos had gained widespread acknowledgement as a carcinogen although the introduction of the asbestos ban in the United State only came about in 1989. All forms of asbestos are carcinogenic. This ban was overruled in 1991 due to widespread complaints of the difficulty of finding asbestos replacements-existing uses of asbestos are still permitted, while new applications or uses of asbestos are banned.

Figure 1 shows a typical disc brake commonly found in passenger vehicles. When a driver steps on the brake pedal, brake fluid is effectively pushed against the pistons of the brake caliper, which in turn forces the brake pads against the brake rotor. This clamping action of the brake pads retards the rotational movement of the brake rotor and the axle that it is mounted on. Hence the kinetic energy of the vehicle is converted into thermal energy which is primarily borne by the rotor and brake pads. Drum brakes operate based on similar principles.

Consumer demand and public awareness sparked the onset of extensive research and development into brake pads in the early 1990s as the race was on to find suitable replacements foe asbestos. In the past decade of development, brake friction materials manufacturers have moved away from asbestos in an effort to gain market acceptance. Therefore, a multitude of different brake pads have sprung on to the market in the post-asbestos brake pads revolution, each with their own unique components used in automotive brake friction materials for wet and dry braking.

METHODOLOGY

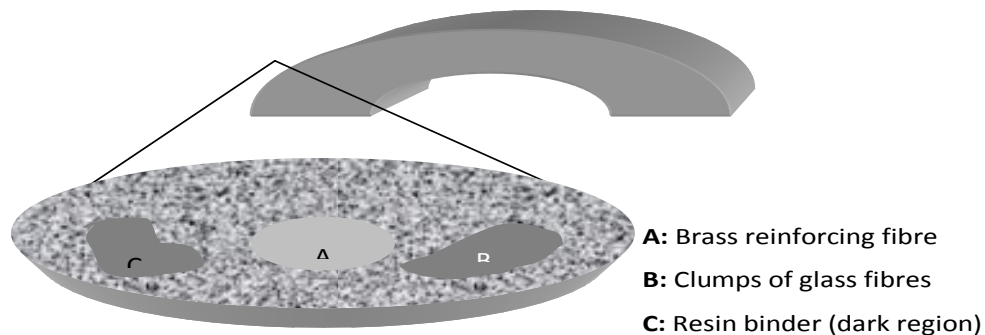### Basic introduction to break friction material

An automotive brake functions by converting the vehicle's kinetic energy into heat energy. During braking, the heat energy is first borne by the two contact surfaces of the brake, namely the brake disc and the brake pad (or drum and shoes in the case of drum brakes), and is then transferred to the contacting components of the brake such as the calipers of the brake, as well as the brake such as the surroundings

    Table 1 shows the general classification of brake pads used in the brake industry. The demands on the brake pads are such that they must (Eriksson et al., 1999).
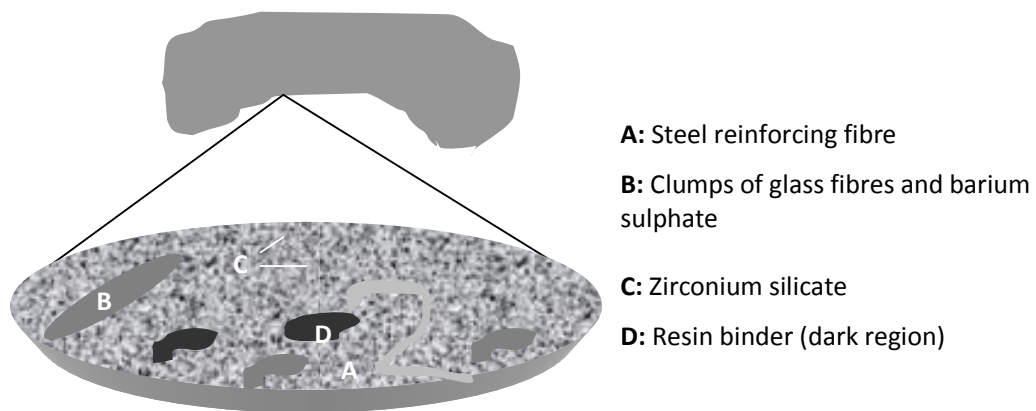
1.   Maintain a sufficiently high down in such a way that the brake disc;
2.   Not decompose or brake down in such a way that the friction coefficient with the brake disc is compromised, at high temperatures;
3.   Exhibit a stable and constituent friction coefficient with the brake disc.
4.   Brake pads typical comprise the following subcomponents (Eriksson et al., 1999).
5.   Frictional additives, which determine the frictional properties of the brake pads and comprise a mixture of abrasives and lubricants;
6.   Fillers, which reduce the cost and improve the manufacturability of brake pads;
7.   A binder, which holds components of a brake pad together;
8.   Reinforcing fibres, which provide mechanical strength.

Table 1. Classification of brake pad

CLASSIFICATION	INGREDIENTS
metallic	Predominantly metallic, such as steel fibres, copper fibres, etc.
Semi-metallic	Mixture of metallic and organic ingredients
Non-asbestos organic	Predominantly organic, such as mineral fibres, rubber, graphite, etc.

A: Brass reinforcing fibre

B: Clumps of glass fibres

C: Resin binder (dark region)

Figure 1. Example 1: microstructure of brake pad sample X

A: Steel reinforcing fibre

B: Clumps of glass fibres and barium sulphate

C: Zirconium silicate

D: Resin binder (dark region)

Figure 2. Example 2: microstructure of brake pad sample Y

Figures 1 and 2 show two different brake pads and their corresponding images taken using a scanning electron microscope. An energy-dispersive X-ray probe was used to identify the constituents present in the brake pads. Brake pad sample X was formulated for use on light motorcycles and is intended to have a moderate friction coefficient; brake pad sample Y was formulated for use on trains and is intended to develop a higher friction coefficient. Therefore sample X contains softer harsher ingredients such as zirconium silicate particles and steel fibres.

Complete composition disclosure of brake friction materials is rare because this information is treated as proprietary and manufacturers are not obliged in any way to disclosure can be narrowed down to academic research papers and patent offices, where information disclosure is a prerequisite for patent application. Sample compositions of certain automotive brake pads based on information from the United States Patent and Trademark Office are shown in Figures 3 to 6. These compositions are divided into the sub compositions as classified above, namely reinforcing fibres, binders, fillers, abrasives and lubricants

The brake pad compositions of samples 1 and 2 are described in US patent numbers 6080230 (4) and (Sasaki et al., 1999). (5) 6220404 (Hara et al., 2001) respectively, registered under the United State Patent and Trademark Office. Sample 3 and 4 were used for tribological research purposes and their compositions are described in references (6) (Filip et al., 2002). (7) (Osterle et al., 2001).Sample 3 is manufactured by Ferodo, while the source of sample 4 was not disclosed.

From Figures 3 to 6, it is evident that there is no such thing as a 'typical' brake pad composition because a composition that can represent the majority of the brake pads in existence will not be accurate.

Composition that can represent the majority of the brake pads in existence will not be accurate. Figures 3 to 6 show that the compositions of brake pads can vary dramatically in terms of their subcomponents; e.g. the fillers can vary from 15 to 69.5 per cent by volume. Moreover, each subcomponent of different brake friction materials will have their own varying ingredients and components; e.g. brake pad sample 1 may contain barium sulphate as the filler while brake pad 2 may use vermiculite instead. Therefore brake friction materials have a myriad of possible compositional variations.
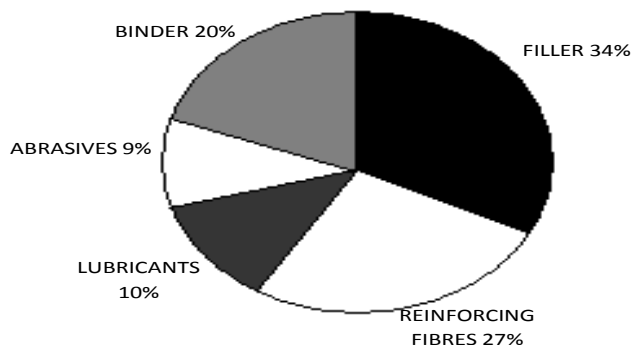
Brake Pad Sample 1, US Patent No. 6080230

Figure 3. Composition of brake pad sample 1
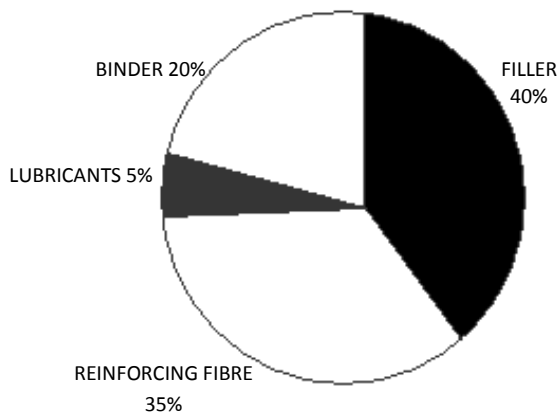
Brake Pad Sample 2 – US Patent No. 6220404

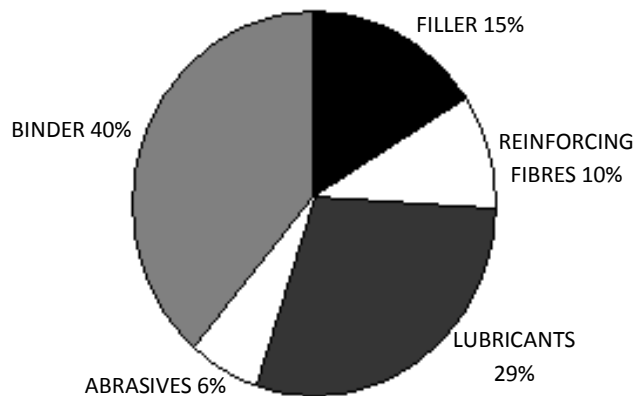**Figure 4.** Composition of brake pad sample

Brake Pad Sample 3, Ferodo

FILLER 15%

REINFORCING
FIBRES 10%

BINDER 40%

LUBRICANTS
29%

ABRASIVES 6%

Figure 5. Composition of brake pad sample 3

Brake Pad Sample 4, Source Unknown

BINDER 19%

ABRASIVES 0%

LUBRICANTS 5%

REINFORCING
FIBRES 6%

FILLER 70%
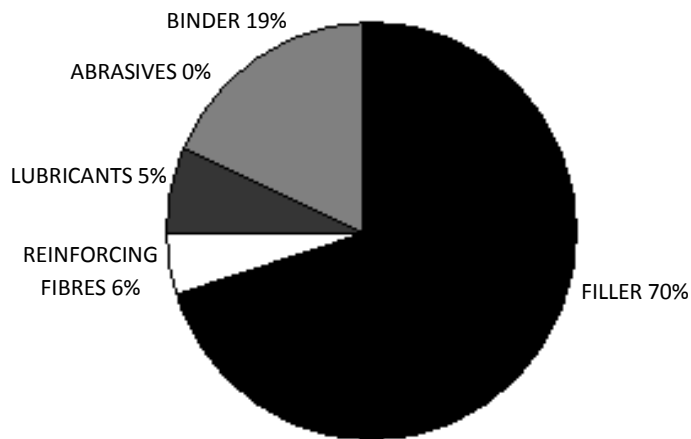
Figure 6. Composition of brake pad sample 4 Reinforcing Fibres

Glass
fibres

Reinforcing
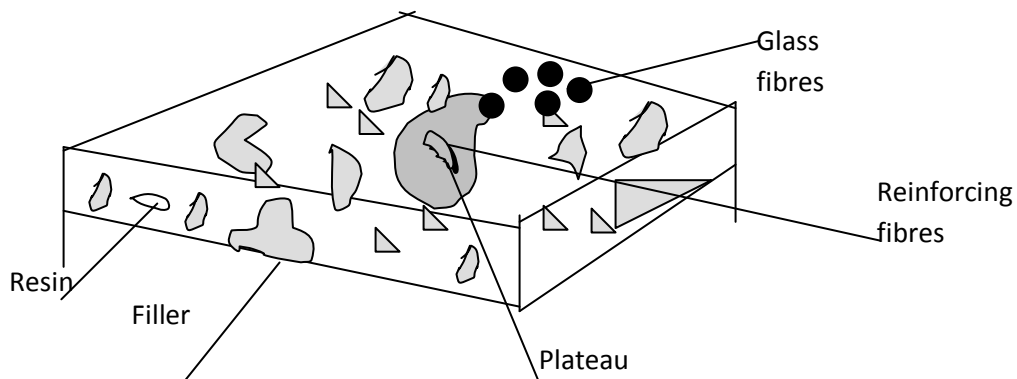fibres

Resin

Filler

Plateau

Figure 7. Enlarges isometric view of a used brake pad

Dry friction materials

This section deals with the materials used in formulating friction linings where the frictional contact surfaces are intended to be dry most the time, even though they may be unintentionally lubricated (such as braking a car in the rain). The four

Table 2. Reinforcing fibres

Components	Advantages	Disadvantages
Glass	Sufficient thermal resilience(high melting point of $1430^{o}c$, but will start to soften at approximately $600^{o}c$	Brittle
Metallic	Thermally resilient steel and copper have melting points greater than $1000^{o}c$	Large amounts may cause excessive rotor war; may corrode
Aramid	Good stiffness to weight ratio, excellent thermally resilient, good wear resistance	Soft, cannot be used without other fibres
Potassium titanate (a type of ceramic)	Thermally resilient(high melting point of approximately $1371^{o}c$); very hard-good wear resistance	Health hazard
Sepiolite	Thermally resilient(high melting point of approximately $1550^{o}c$); able to absorb traces of fluid	Potential health hazard
Ceramic	Thermally resilient(high melting point of approximately $1700\text{-}2040^{o}c$); good stiffness-weight ratio	Brittle

main components of a brake pad, namely the reinforcing fibres, binders, fillers and frictional additives, are discussed below. It is important to note that certain substances perform multiple functions and may be placed in more than one classification.

Asbestos fibres been used as reinforcing material in brake pads as early as 1908 when English inventor Herbert Frood came up with a combination of asbestos, brass wire and reins for use as a friction lining (Auto disc brake manual, 1998). Asbestos is cheap and provided friction lining with excellent durability and thermal resilience (Pilot study). This is key attribute as braking temperatures can reach hundreds of degrees Celsius. In the late 1980s, it was public knowledge that asbestos is a carcinogen and brake pad manufacturers started looking for suitable alternatives.

The purpose of reinforcing fibres is to provide mechanical strength to the friction material. Recent research has shown that the braking load is actually carried by tiny plateaus that rise above the surrounding lowlands on the friction material (Eriksson et al., 2002). These plateaus are formed by the reinforcing fibres surrounded by the softer compacted components. Therefore the importance of the reinforcing fibres in friction material cannot be underestimated. Friction materials typically use a mixture of different types of reinforcing fibres with complementing properties.

The plateaus are formed by compacted debris and cannot exit without a primary support such as the reinforcing fibres illustrated in Figure 7 (Eriksson et al., 2001) is reasonable to expect that friction materials wear will increase with a decreasing amount of reinforcing fibres, as discovered by Gudmand-Hoyer, Bach, Nielsen and Morgen when they subjected brake pads with varying quantities of fibres to the same braking load (Gudmand-Hoyer et al., 1999).

Table 2 summarizes the properties of the reinforcing fibres listed in the following subsections. The figures listed are typical values for that particular reinforcing fibre.

In conclusion, ceramic fibres appear to be the most suitable for the as reinforcing fibres in brake friction material.

Among the different varieties of reinforcing fibres available, it has the highest thermal stability and hardness while being one the lightest materials around.

Ceramic-reinforced brake pads are already being used as original equipment on numerous makes of car; the Akebono Brake Industry Corporation Limited is a manufacturer of original equipment ceramic brake pads for various Japanese car manufacturers and Daimler-Chrysler. Such manufacturers claim that ceramic brake pads have reduced vibration, rotor wear and noise and dust levels compared to other brake pads. In contrast, metallic brake pads have been known to cause excessive rotor wear, high occurrence of brake squeals and high levels of brake dust generation during braking.

The brittleness of ceramic fibres being a shortcoming in brakes pads has not been mentioned in any literature listed in this review. It is probable that the brittleness of ceramic fibres is not a disadvantage in reality-its brittleness may be the reason for its reduced rotor wear despite being the hardest, having a Vickers hardness of more than 1700(Dowln.1999). Again, this is in contrast to metallic fibres, which are softer than ceramic fibres yet encounter the highest rates of rotor wear among all reinforcing fibres. The abrasiveness of ceramic fibres pads against brake disc is an issue that requires further investigation.

Glass

Glass fibres have been used as reinforcing fibres since the mid 1970_{s}. Being physically strong when bonded together with resinous binder, glass fibres are suitable for use as reinforcing fibres as they also exhibit thermal resilience (Mazochi et al., 1976). Typical glass has a melting point of $1430^{o}c$ (Avallone etal 1999) which is much higher than the

melting point of 800-850 ^{o}c for asbestos (Chrysotle Asbestos, 1999). However, typical glass fibres only have a conductivity of 0.04 W/m K, which is even lower than that metallic fibre such as copper. The brittleness glass means that it cannot be the sole reinforcement in brake friction materials.

Metallic

Metallic chips or granules are commonly used as reinforcing fibres and hence they are referred to as Metallic 'fibres' although they may not strictly be thread-like. Examples of metallic fibres include steel, brass and copper. The drawback of using steel fibres is that they will rust, especially if the vehicle has an extended rest period or if the vehicle has extended rest period or it the vehicle has been operating near a coastal environment. Steel fibres attacked by rust will be less resilient, thereby compromising their functionality as reinforcing fibres. Therefore, certain brake pads include metals such as zinc, distributed over the cross-section of the friction lining, thereby forming a sacrificial anode for rusting to occur (Hell et al., 2002). Another drawback of using steel fibres is that they might cause excessive wear of the brake disc if they are present in large proportions. Steel fibres have also been shown to increase friction coefficient fluctuation (Jang et al., 2001). The likely reason being due to the fact that it abrades the transfer film between braking surfaces, which is responsible for friction coefficient stabilization.

On the other hand, a significant advantage of using metal fibres is that they have very high conductivities, able to remove heat form the frictional surfaces very quickly. Some brake pads contain oxidized or phosphatized fibres, resulting in improved fracture toughness and strength (Samuels et al., 1999).

Aramid

Aramid fibres (a generic expression denoting fibres made from the conduction product of isophthalic or terephthalic acids and m- or p-phenyleneddiamine (Okabo et al., 1984) such as Kevlar fibres are also widely used as reinforcing fibres, but they are a different class of fibres in that they are relatively soft fibres. They are very light and exhibit excellent thermal stability, with a very good stiffness- weight ratio. According to Smith and Boyd of R.K.Carbon Fibres, aramid fibres have superior anti-fade properties compared to asbestos (Smith et al., 1999). Aramid fibres in pulp form have also been utilized in maintaining the uniformity of the brake pad materials mixture during the processing of moulded brake pads (Carlson et al., 1999). Another property they have is that of superior wear resistance (Erimzey, 1999). Due to their relative softness, however, it is unlikely that they will be the only fibres supporting the braking load; there would most probably be other harder fibres such as metallic fibres in the friction lining.

Potassium Titanate

Potassium titanate fibres are another type of reinforcing fibres used in brake friction materials. They are fibres prepared from highly refined, single crystals, which have a high melting point (1250-1310°c) (Kin etal, 2001). However, they have the potentials to cause mesthelioma (Adaclu, etal, 2001) a type of cancer that is predominantly caused by asbestos. For this reason, they are not commonly used and should not be thought of as a suitable replacement for asbestos. In an effort to eradicate the danger of potassium titanate fibres inhalation. Hikichi of Akebono Brake Industry has devised a process of producing potassium titanate in the powders, with the same frictional performance and strength as fibrous potassium titanate (Hikichi, 2001). The powder form is apparently more difficult to inhale than if it were in the fibres form.

Sepiolite

Sepiolite is a hydrated magnesium silicate mineral that occurs as a fibrous chain-structure mineral (Gonzales et al., 1984). Due to its porosity, surface charge and cation exchange properties, sepiolite has excellent sorptive properties in water, while also being stable in high-temperature environments (Christie et al., 2002). It retains its micro porous and fibrous structure even at temperature in excess of 1000°c (Goktas et al., 1997). Sepiolite is able to absorb traces of fluid between the frictional surfaces.

However, sepiolite is a potentials health hazard. It is associated with the development if inflammation in lung and pulmonary interstitial fibrosis, which is also caused by crocidolite asbestos (Mossman et al., 1989). As with potassium titanate fibres, they should not be thought of as suitable replacements for asbestos.

Ceramic

Ceramic fibres are a relatively new addition in brake pads compared to metallic fibres such as steel. They are typically made of various metal oxides such as alumina (aluminum oxide) as well as carbides such as silicon carbide. With a high thermal resistance (melting points ranging from 1850 to 3000°c (Warren, 1992), light weight and high strength (Ceramic fibres, 2002), they are very suitable as reinforcing fibres. Their high strength- weight ratio means that they are preferred over metallic fibres, which are much heavier. Not only are they used in brake pads, they are also used to reinforce brake discs as well. In one instance, aluminum brake discs were reinforced by ceramic fibres because the wear rates encounted when using aluminum brake discs against conventional friction materials are unacceptable (Tsugawa et al., 1998)

Binders

The purpose of a binder is to maintain the brake pad's structural integrity under mechanical and thermal stresses. It has to hold the components of a brake pad together and to prevent its constituents from crumbling apart. Table 3 summarizes the properties of the binders listed in this subsection. The figures listed are typical values that particular binder.

   The choice of binders for brake pads is an important issue because if it does not remain structurally intact at all times during the braking operation, the other constituents such as the reinforcing fibres or lubricants will disintegrate. Therefore it has to have a high heat resistance. For this reason, epoxy and silicone modified resins would generally be ideals as the binder for most braking applications. The other binders would have to be application-specific such that their disadvantages would not compromise their functionality.

Table 3. Binders

Binder	Advantages	Disadvantages
Phenolic resin	Cheap and easy to produce	Brittle, low impact resistance, highly toxic, decomposes at relatively low temperature (450°c)
COPNA resin	High bonding strength with graphiye (a common lubricant);therefore has better wear resistance than pure phenolic resin	Decomposes at relatively low temperatures (between 450 and 500°c)
Silicone-modified phenolic resin	Better impact resistance than pure phenolic resin; better heat chemical resistance than pure phenolic resin; enhanced water repellency	Base is still phenolic and highly toxic
Cyanate ester resin	High heat resistance, chemically inert, vibration dampener	Brittle, low-impact resistance
Epoxy-modified phenolic resin	Better heat resistance, than pure phenolic resin	Base is still phenolic and highly toxic
Thermoplastic polyimide resin	Abrasion resistant; does not exhibit thermal fade	Thermal conductivity three times lower than phenolic resin

Phenolic resin

Phenolic resin is probably the most common resin binder used in brake friction materials and it is cheap to produce. Phenol resin is a type of polymer formed by a condensation reaction between Phenols and formaldehyde, and is able to act as a matrix for binding together different substrates (Chritchlay et al., 1983). This condensation reaction may be initiated by acidic or alkali catalyst, resulting in different classes of Phenolic resins for example, Phenol resins produced using an acid catalyst and reacted with insufficient formaldehyde are called novolac resins. When these Phenol resins are cured, they change from a thermoplastic state to a densely, cross-liked thermoset matrix with relatively high heat resistance.

   In high-energy braking applications, the temperature induced can be high enough to decompose the phenolic resin via means of high-temperature oxidation. Phenolic resins carbonize at approximately 450°c (Yesnik, 1996); at temperatures beyond this, it decomposes by charring and evaporation. This process decreases the density of the brake friction materials at the wear surface and also increases its porosity, thereby losing its structural integrity (Lamport et al., 1998). This decomposition into fumes is likely to release its constituents which are poisonous. According to the Occupation

   Health and Safety Administration of the US Department of Labor, formaldehyde is classified as a human carcinogen

that can cause nasal and lung cancer, while phenol causes liver damage and blindness, among other effects.

Another significant disadvantage of phenolic resins is that they are brittle and have a very low impact resistance. Because of this, they are usually modified with tougheners such as epoxy resin or by incorporating wood flour to improve its flexibility (Kane et al., 1998). Moreover, Jang et al., (2002) experiment shows that the larger the quantity of phenolic resin used, the larger the friction coefficient fluctuations will be. A likely reason for this would be the poor thermal stability of phenolic resins. Degradation in binder integrity during higher temperatures would lead to the loosening of the frictional characteristics of the friction materials.

COPNA Resin

COPNA resin is an abbreviation of 'condensed polynuclear aromatic' resin. As the molecular structure is similar to graphite (a lubricant used in brake friction material) the bonding strength between the latter and COPNA resin will be very high (Komori et al., 1990). This means that the structural integrity of graphite-containing brake friction materials will be improved with the use of COPNA resin, giving rise to higher shear strengths than if phenolic resin were used. Its heat resistance is not significantly better than phenolic resin as it decomposes at approximately the same temperature (Kakegawa et al., 1999) (400-500°c), although the volume of decomposed gas is in a smaller volume than that of phenolic resin.

Silicone-modified resin

Silicone-modified resins are typically reacted by reacting silicone oil or silicone rubber with phenolic resins. They are also referred to as phenolic siloxane resins because the base materials are still phenolic. As mentioned earlier, phenolic resins are typically modified with tougheners to reduce their brittleness. However, the original characteristics of thermal and chemical resistance of phenolic resins would be compromised. Kane and Mowrer have succeeded in combining phenolic resins with silicone to form phenolic siloxzne resins having enhanced impact resistance, yet these phenolic siloxzne resins have equal or better heat and chemical resistance than conventional phenolic resins (Kane et al., 1998). Also, silicone-modified resins have the property of preventing the frictional layer from adsorbing water due to it improved water repellency (Hara et al., 2011)

Epoxy-modified resin

A pure epoxy resin is unable to withstand high temperatures. At temperatures above 260°c, typical epoxy resin binders degrade (Tsang et al., 1985). To increase the operating temperatures of epoxy resins, special curing agents have to be used, for example, Shell Chemical Company has a grade of epoxy resin cured with an anhydride agent that is operable at 400°c, despite showing a liner increase in water above 290 ^{o}c. therefore, epoxy is usually used to modify phenolic resins, resulting in the synergistic effect of having a higher heat resistance than phenolic resins or epoxy resin alone and has a high frictional stability (Lam et al., 1999)

Thermoplastic polyimide resin

Thermoplastic polyimide resin is the product of fluoro resin and calcium carbonate. It is abrasion resistant and does not exhibit thermal fade commonly experienced with phenolic-based resins or induce excessive brake disc wear (Nagahiro et al., 1993). Such a resin is easily produced suing injection moulding or other melt-processing methods. Additional heat treatment can improve its heat resistance, as well as mechanical and sliding properties. However, its thermal conductivity is approximately three times lower than that of phenolic resins (Avallone et al., 1997), so it is less able to dissipate heat away from the friction surface.

Fillers

Sometimes referred to as 'space fillers', the fillers in a brake pad are present for the purpose of improving its manufacturability as well as to reduce the overall cost of the brake pad (Eriksson et al., 2002). It is a loose term which

could also means anything used in a larger proportion in a brake friction material. For example, certain manufacturers use a large proportion of metal silicates (hard, abrasive particles) in their brake friction materials and refer to them as 'fillers' instead of abrasive'. This section deals with the two main classes of fillers used-organic and inorganic. Table 4 summarizes the characteristics of the fillers listed in this subsection.

Fillers, while not as critical as other components such as reinforcing fibres, play an important role in modifying certain characteristics of brake friction material. The actual choice of fillers depends on the particular components in the friction materials as well as the type of friction material. For example, a metallic pad that generates a lot of braking noise would require more filler such as cashew and mica (noise suppressor) than barium sulphate (heat stability). On the other hand, semi-metallic brake pads with a mixture of metallic and organic compounds having varying thermal expansion coefficients would require a larger amount of molybdenum trioxide to prevent lining cracking. Brake pads with larger quantities of graphite or antimony sulphide as lubricants would not require alkali metal titanates as a filler. Therefore the specific filler to be used depends on the constituents of the friction material.

Table 4. Fillers

Filler	Description
Barium sulphate	Imparts heat stability to friction materials, aids friction characteristics.
Calcium carbonate	Imparts heat stability to friction materials.
Mica	Suppresses low-frequency brake noise, but causes interlayer splitting in friction material
Vermiculite	Suppresses low-frequency brake noise, but has low heat resistance
Alkali metal titanates	Promotes stability of the friction coefficient
Molybdenum trioxide	Prevents thermals fade and cracking of friction lining under high-temperature conditions
Cashew dust	Suppresses brake noise, but does not adhere well to friction material
Rubber dust	Suppresses brake noise, but does not adhere well to friction material

Inorganic fillers

Typical inorganic fillers include barium sulphate, mica, vermiculite and calcium carbonate. The common property of these fillers is that they possess a relatively high melting point. For example, barium sulphate has a melting point of 1350°c (Lide et al., 1994) while vermiculite exfoliates rapidly into flake at approximately 800°c.

One of the more commonly used fillers is barium sulphate. It imparts heat stability to the brake friction materials, at the same time aiding the friction characteristics of the brake friction material (Komori et al., 1990).

Calcium carbonate is considered to be an alternative to barium sulphate because t has a similar function; it impacts heat stability to the friction materials, thereby improving the friction material's brake fade properties (Ohya et al., 1999). It is the cheaper of the two, but it is not as stable at higher temperatures as barium sulphate (Blau, 2001).

Mica is commonly used filler. It is able to suppress low-frequency brake noise (Yamashita et al., 1993). Due to it having a plane net like structure (Kamura et al., 1998). However, due to its stratified structure, it has a low interlayer strength. As such, mica causes interlayer splitting of the friction lining, especially at high braking loads. To prevent the interlayer splitting of mica, aluminum phosphate can be used as a coating on mica powder (Seki et al., 1993).

Like mica, vermiculite can also suppress noise generated during braking (Nakagawa et al., 1993).it also has a plane netlike structure and resembles mica in appearance. However, it is porous and its wear resistance at high temperatures is compromised.

Molybdenum trioxide is a recent addition to the family of inorganic fillers. According to Nakajima and kudos, molybdenum trioxide can prevent thermal fade and cracking of friction lining under high- temperatures conditions ((Nakagawa et al., 2000). It has a relatively high melting point of approximately 800^{o}_{C} (lide et al., 1994). Other such as Kesavan and Burmester have proposed the use of alkali metal titanates (such as sodium titanate) for use as fillers, claiming that survey promote the stability of friction coefficient (Kasavan et al., 1999) the addition of titanium compounds to abrasive particles (such as silicon carbide) has been found to lower its wear rates.

Organic fillers

Cashew dust and rubber in the form of dust are commonly used examples of organic fillers. Both have similar properties in that they are usually incorporated into brake pads for the purpose of reducing brake noises due to their superior viscoelastic characteristics. (Kamioka et al., 1999). However, these particles, especially cashew, fall off the friction

surface easily, leaving behind large pores that eventually crack (kinouchi et al., 2002). To prevent this from happening, the cashew or rubber particles are sometimes coated with an adhesive. Also, certain brake friction materials manufacturers use cashew or rubber particles as under layer materials because their low thermal conductivity prevents heat from transmitting to the backing plate of the brake friction materials (Nakagawa, 2002). Cashew particles are also able to reduce fluctuations in friction coefficients, especially at elevated temperatures (Jang et al., 2001).

Frictional Additives

Frictional additives are components added to brake friction materials in order to modify the friction coefficients as well as the wear rates. They are divided into two main categories; lubricants, which decrease the friction coefficients and wear rates, and abrasives, which increase friction coefficients and wear rates. It is also important to note here that certain frictional additives may be loosely regarded as fillers by certain manufacturers if they are present in large quantities.

As their name suggests, frictional additives affect the frictional characteristics of brake friction materials greatly. By using brake pads with varying quantities of antimony sulphide (a lubricant) and zirconium silicate (an abrasive), Kim and Jang made the following conclusion (Jang et al., 2000).
1.   Brake pads with increase lubricant content show increase stability of the friction coefficient.
2.   Brake pads with increase abrasive content show increased friction coefficient variation (instability).

Therefore it is important to achieve a compromise between the amount of lubricants and abrasives in brake friction materials. Table 5 gives a summary of the frictional additives.

Metal sulphides appear to be better alternatives to graphite as lubricants. Because of the current high-energy braking demands in the automotive industry, the low bonding strength between phenolic-based resin (most common binder) and graphite would result in accelerated wear of the friction materials. Metal sulphides are a tin and copper sulphides would be ideal as lubricants.

There has been no mention of any significant advantages or disadvantages of specific abrasive in the literature listed in this review. Care has to be taken with the selection of abrasive type and quantity because there are many different abrasives and they have differing hardness's. Mild abrasives such as quartz only have a hardness of around 500HV, zirconium ceramics range from 1000 to 1400HV and alumina is around the 1750HV mark.

Table 5. Frictional additives

Frictional additives	Description
Graphite	Widely used lubricant, available in natural or synthetic forms and as flakes or powder; able to form a self-sustaining.
Metal sulphides	Good lubricating properties, with lower conductivities than graphite; examples include antimony/tin/copper/lead sulphides
Metal oxides/silicates	Abrasives with hardness's ranging from 500HV (quartz) to 1750HV (aluminum oxide); examples include quartz (Si^O_2), zirconium silicate, zirconium oxide, aluminum oxide, etc.

Lubricants

The main purpose of a lubricant is to stabilize the developed friction coefficient during braking, particularly at high temperatures. Commonly used lubricants include graphite and various metal sulphides.

Graphite is widely used as it able to form a lubricant layer on the opposing counter friction materials rapidly (Taylor et al., 1998). This self-sustaining layer ensures a stable friction coefficient. The graphite used in brake friction materials can be of natural or synthetic origin, and can exist in flake or power form. Graphite in the flake form has improved lubrication properties (Takahasi, et al., 1899) while graphite in the powder form is able to dissipate heat generated during braking more effectively (Booher, 1992).

However, graphite cannot be used too liberally in phenolic resins because the bonding strength between graphite and phenolic resin is very weak, leading to low shears strengths (Komori et al., 1990). Also, regardless of the type of binder, graphite will increase the overall heat conductivity of the friction materials. While this may assist in removing the heat away from the friction surfaces, excessive graphite will result in an increase in the temperature of the hydraulic braking fluid. If the temperature of the hydraulic braking fluid is brought to its boiling point, failure of the braking surfaces is a desirable characteristic as long as it does not compromise the functionality of other components that are being heated up.

Metal sulphides such as antimony sulphide are very popular in friction material of today as they are able to provide good lubrication as well as having lower conductivities than graphite. This means that the liberal use of such material is

not likely to cause excessive heating-up of the brake fluid. It is important to note that antimony sulphide, a popular lubricant, has a melting point of 550^o_C (Taylor et al., 1998), and increased friction material porosity and decreased shear strength will result if the friction material temperature reaches this temperature. According to Huner, Melcher, Milczarek and Kienleitner, antimony sulphide is suspected of having carcinogenic properties and recommend tin sulphide as a more suitable alternative (Hunar et al., 2000). Other example includes copper sulphides and lead sulphides.

Abrasives

The abrasives in a friction material increase the friction coefficient while also increasing the rate of wear of the counter face material. They remove iron oxides from the counter friction material as well as other undesirable surface films formed during braking. However, friction materials with higher abrasives content exhibit a greater variation of friction coefficient, resulting in instability of braking torque. Examples of abrasives are hard particles of metal oxides and silicates. The abrasives have to be hard enough to at least abrade the counter friction material, which is typically cast iron. The abrasives typically have Mohs hardness values of around 7-8, and a few examples of the commonly used abrasives include zirconium oxide, zirconium silicate, aluminum oxide and chromium oxides (Kobayaslu, 2102).

Wet friction materials

This section deals with friction materials that are designed specifically for use in a wet environment only, such as wet clutches and oil-immersed brakes. This is in contrast to the 'dry' friction materials which are meant to be operating mostly under dry conditions but also under wet conditions (such as braking a car in the rain). Wet friction materials generally comprise three different types, i.e. paper, sintered and the woven fabric material. Regardless of the types of wet friction materials, they have to exhibit certain properties to be considered for use in Wet friction applications, typically automatic transmission systems and sealed wet brakes.

One important property of the wet friction material is its high porosity to allow a greater fluid permeation capacity. Higher porosity results in a more rapid rate of cooling of the friction material due to a greater volume of fluid inflow and outflow. Upon application of the wet friction materials, the fluid trapped within the pores must be quickly released from the friction material (Lam, 2000). Therefore, it must also be able to maintain its structural integrity under large compressive forces. Another important property is the ability to withstand high thermal energy during application and the ability to dissipate the heat generated during operation. The most basic property they should have is the ability to provide consistent and stable friction coefficients. It should also have a degree of elasticity to promote a more even distribution of pressure which will reduce the likelihood of uneven wear (Yesnik, 1999).

Although the fabric type of material appears to have the best combination of properties, the selection of wet friction materials types is very application-specific. For instance, sintered materials have high compressive strengths and are still being used in heavy-duty industrials clutches despite their low dynamic friction coefficients. This shortcoming can be overcome by having multiple friction surfaces. In other applications, paper materials can be used if there is a large enough quantity of cooling oil to keep the temperature sufficiently low.

Table 6. Different types of wet friction materials (Llyod et al., 1980)

Material type	Description
Paper	High porosity; high dynamic friction coefficient (0.10-0.15); low to medium thermal resistance; low compressive strength; materials is dried
Sintered	Low porosity; low dynamic friction coefficient (0.05-0.7); high thermal resistance; high compressive strength; materials is cured instead of dried.
Fabric	High porosity; medium dynamic friction coefficient (0.09-0.11); medium thermal resistance; medium compressive strength; made of interwoven strands of yarn

Paper type

The paper type consists of a mat fibres impregnated with resin. They are typically referred to as the 'paper type' because the methods of manufacturing these papers type friction materials is similar to that of a normal paper-making process, where fibres are dispersed in an aqueous solution containing a resin. It is spun and dried.

Paper-type friction materials are noted for their extremely low static to dynamic friction coefficient ratios. This results in smoother transitions between stationary and dynamic sliding with minimal vibration and jerkiness. This lack of vibration

means that the paper-type friction materials are very quiet, which is a highly desirable trait in automatic transmission and braking. However, the main trouble with such paper-type friction materials is that they degrade very quickly at temperatures above 150^0_c, (Menard et al., 1998) so they are more suitable for automatic transmission applications where the temperature generally lower than that of braking. There are exceptions to the case-graphitic paper materials can withstands up to 230^0_c without performance degradation.

   One of the most common types of fibres used in such paper-type wet friction materials would be cellulose, mineral and other natural polymers. The purpose of these fibres is to impart strengths ton the friction materials and to provide an open matrix of voids for the resin to fill during resin saturation (Lee, 1999). Synthetic fibres such as aramid fibres are superior in heat resistance to natural polymeric fibres, but are not as widely used due to their cost (Kitahara et al., 2000).

   Other components in paper-type wet friction materials include fillers and binders. Fillers such as diatomatious earth are commonly used to promote fluid flow through the paper material; phenolics and epoxies are examples of typical binders used to impart mechanical and cohesive strength to the paper.

Sintered materials

To eradicate the problem of low-temperature degradation of paper-type wet friction materials, sintered materials basically involve curing the friction material sintered of drying it. These sinteres friction materials allow a higher threshold temperature before friction materials degradation.

Phenolic resins, a type of thermosetting resin, are just as commonly used as binders for wet friction materials as for dry friction materials. Their main shortcoming as binders for friction material in wet environment is that they have high cross linking densities, thereby reducing the porosity of the friction materials. Siloxane-containing resins can be used to overcome this problem, with the disadvantage being the need for a higher curing temperature and consequently higher production costs (Suzuki et al., 2001).

Fabric type

The fabric type of wet friction materials typically consists of a single ply of woven fabric comprising interwoven strands of yarn. These strands of yarn are spun from bundles of fibers. Because of the existence of gaps between the individual's fibres as well as the yarn strands, the fabric has a high porosity, giving a high flowrate and permeability of fluid. According to Gibson et al., 1999, these gaps channel fluid away from the surface of the fabric during operation, thereby avoiding hydro-opposing surface. For this reason, the resin, which is used to bind the fibres together, is usually present in minimum amounts to maximize the gaps available in the fabric.

CONCLUSION

Future Trends

It is envisioned that future developments in the field of brake friction materials will closely mimic the current trends of the automotive industry. The future emphasis on cars will be on lower emissions and fuel efficiency a environmental regulations become more stringent. This shift towards environmentally friendly cars has already seen the release of hybrid cars such as Toyota Prius, Honda Insight and Ford Escape SUV.

   The focus on vehicle fuel efficiency and lower emissions will means that brakes will have to be lighter and not release any toxic and carcinogenic substances into the atmosphere during use. This means that the choice of brake friction materials will need to be more environmentally friendly and not include toxic substances may be phased out once there is greater public environmental awareness. For instance, the Santa Clara Valley Nonpoint Sources Pollution Control Program in the United States has identified vehicle brake pads as a major contributor of copper in storm water, leading to the southern reach of San Francisco Bay to be labeled as an' impaired water body' (Engberg, 1995). This is not perceived to be a major problem as the varieties of existing dry friction constituents means that safer alternatives usually exist. For example, ceramic fibres can be used in placed of asbestos fibres. However, one area that needs further investigation would be that of friction materials binders. There is a need to develop non-phenolic resins binders as current choices are limited.

   Sealed wet friction brakes appear to be the best solution ultimately. As the brake is completely sealed from the atmosphere, there is no egress of brake dust or any harmful constituents to the surroundings, thereby achieving the

pinnacle of environmental friendliness. By the same token, there will be also be no ingress of foreign particular into the brake, so braking performance inconsistencies that arise when the vehicle is stopping in rain, mud or sand will not be an issue. The corrosion of braking components such as the brake disc is also prevented. In addition, minimal pad and rotor wear due to lower braking friction coefficient means that brake maintenance is kept to a minimum. The economic savings from brake maintainers alone, and possibly lower insurance premiums due to the use of sealed wet bakes, would negate their high manufacturing costs, which are currently only in use on off road and mining vehicles.

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