

Review of automotive brake friction materials

D Chan* and G W Stachowiak

School of Mechanical Engineering, University of Western Australia, Crawley, Australia

Abstract: The gradual phasing-out of asbestos in automotive brake friction materials in many parts of the world has sparked the onset 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 claiming 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 than fundamental understanding. This review strives to eliminate the cloud of uncertainty 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, brake pads, brake shoes, wet and dry braking

1 INTRODUCTION AND SCOPE

In this paper, a review of the materials and constituents currently used in automotive brake friction material 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 States 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 [1]. According to the National Occupational Health and Safety Commission of the Commonwealth of Australia, the use of chrysotile asbestos (the most commonly used form of asbestos) has been banned from 31 December 2003 in Australia. According to the Clean Air and Water Association of the United States, amosite and crocidolite asbestos have already been banned in 1985 in European nations. However, chrysotile asbestos will only be banned starting from 1 January 2005 [2].

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 for asbestos. In the past decade of development, brake friction material 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 pad revolution, each with their own unique composition. This review paper will summarize the current components used in automotive brake friction material for wet and dry braking.

2 BASIC INTRODUCTION TO BRAKE 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 shoe 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 surroundings.

The MS was received on 24 July 2003 and was accepted after revision for publication on 21 April 2004.

** Corresponding author: Tribology Laboratory, School of Mechanical Engineering, University of Western Australia, Crawley, Western Australia 6009, Australia.*

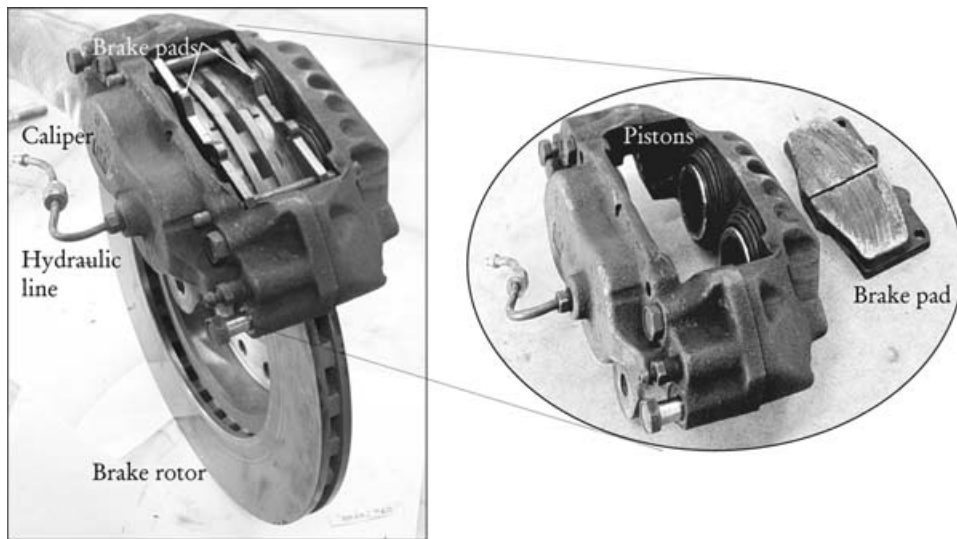


Fig. 1 Typical brake caliper and rotor set-up

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 [3]:

- maintain a sufficiently high friction coefficient with the brake disc;
- not decompose or break down in such a way that the friction coefficient with the brake disc is compromised, at high temperatures;
- exhibit a stable and consistent friction coefficient with the brake disc.

Brake pads typically comprise the following sub-components [3]:

- frictional additives, which determine the frictional properties of the brake pads and comprise a mixture of abrasives and lubricants;
- fillers, which reduce the cost and improve the manufacturability of brake pads;
- a binder, which holds components of a brake pad together;
- reinforcing fibres, which provide mechanical strength.

Figures 2 and 3 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 fibres made of brass whereas sample Y contains harsher ingredients such as zirconium silicate particles and steel fibres.

Complete compositional disclosure of brake friction material is rare because this information is treated as proprietary and manufacturers are not obliged in any way to disclose it to customers. The avenues of compositional 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 Figs 4 to 7. These compositions are divided into the subcomponents 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 6220404 [5] respectively, registered under the United States Patent and Trademark Office. Samples 3 and 4 were used for tribological research purposes and their compositions are described in references [6] and [7]. Sample 3 is manufactured by Ferodo, while the source of sample 4 was not disclosed.

From Figs 4 to 7, it is evident that there is no such thing as a 'typical' brake pad composition because a

Table 1 Classification of brake pads

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.

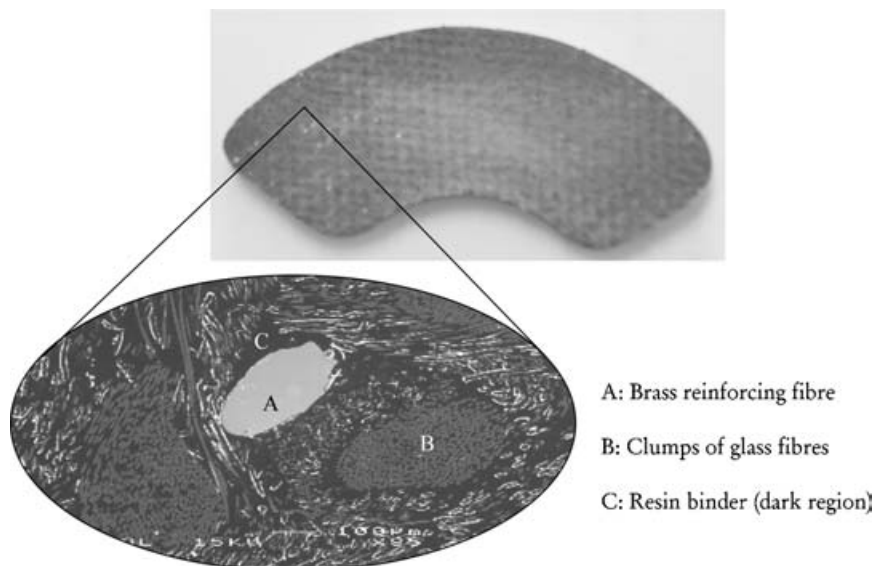


Fig. 2 Example 1: microstructure of brake pad sample X

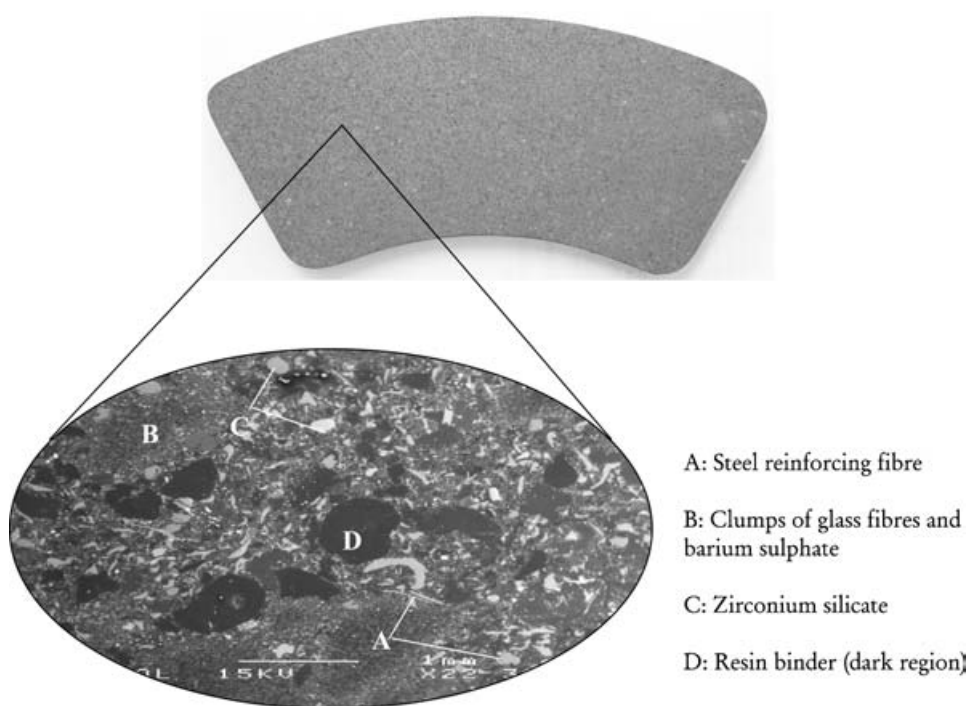


Fig. 3 Example 2: microstructure of brake pad sample Y

composition that can represent the majority of the brake pads in existence will not be accurate. Figures 4 to 7 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.

3 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 of the time, even though they may be unintentionally lubricated (such as braking a car in the rain). The four 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.

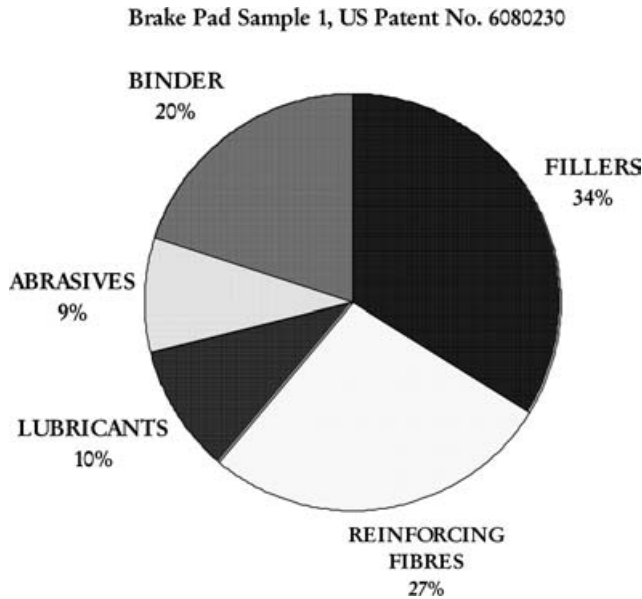


Fig. 4 Composition of brake pad sample 1

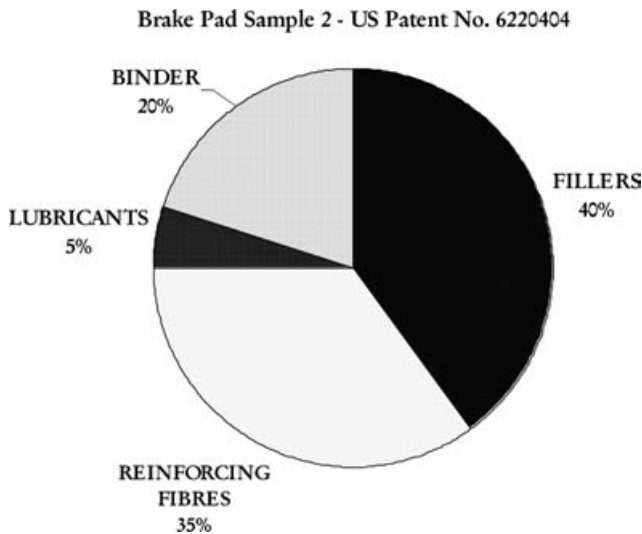


Fig. 5 Composition of brake pad sample 2

3.1 Reinforcing fibres

Asbestos fibres have been used as reinforcing material in brake pads as early as 1908 when English inventor Herbert Froad came up with a combination of asbestos, brass wire and resins for use as a friction lining [8]. Asbestos is cheap and provided friction linings with excellent durability and thermal resilience [9]. This is a 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

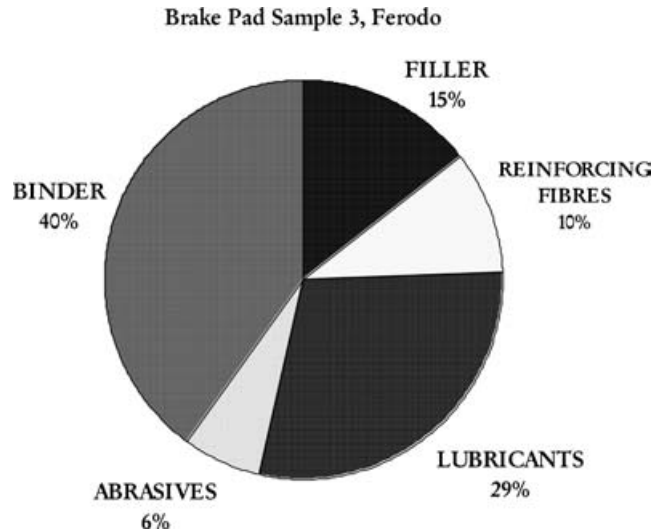


Fig. 6 Composition of brake pad sample 3

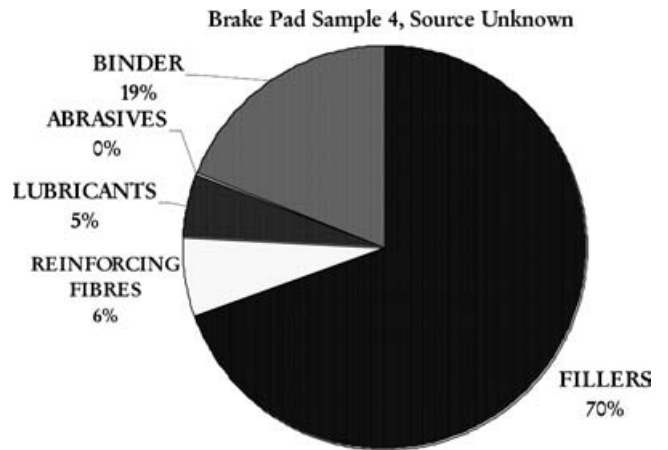


Fig. 7 Composition of brake pad sample 4

on the friction material [10]. 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.

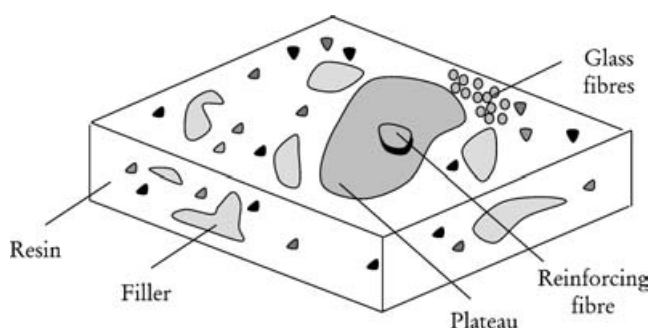
The plateaus are formed by compacted debris and cannot exist without a primary support such as the reinforcing fibre illustrated in Fig. 8 [11]. Therefore, it is reasonable to expect that friction material wear will increase with a decreasing amount of reinforcing fibres, as discovered by Gudmand-Hoyer, Bach, Nielsen and Morgen when they subjected brake pads with varying quantities of fibres to the same braking load [12].

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 use as reinforcing fibres in brake friction

Table 2 Reinforcing fibres

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

**Fig. 8** Enlarged isometric view of a used brake pad

material. Among the different varieties of reinforcing fibres available, it has the highest thermal stability and hardness while being one of 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 brake 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 [13]. 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 brake pads against brake discs is an issue that requires further investigation.

3.1.1 Glass

Glass fibres have been used as reinforcing fibres since the mid 1970s. Being physically strong when bonded together with resinous binders, glass fibres are suitable for use as reinforcing fibres as they also exhibit thermal resilience [14]. Typical glass has a melting point of 1430 °C [15], which is much higher than the melting point of 800–850 °C for asbestos [16]. However, typical glass fibres only have a conductivity of 0.04 W/m K, which is even lower than that of asbestos of 0.15 W/m K [17] and very much less than metallic fibres such as copper. The brittleness of glass means that it cannot be the sole reinforcement in brake friction materials.

3.1.2 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 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 [18]. 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 fluctuations [19], 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 from the frictional surfaces very quickly. Some brake pads contain oxidized or phosphatized fibres, resulting in improved fracture toughness and strength [20].

3.1.3 Aramid

Aramid fibres (a generic expression denoting fibres made from the condensation product of isophthalic or terephthalic acids and *m*- or *p*-phenylenediamine [21]) such as Kelvar 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 [22]. Aramid fibres in pulp form have also been utilized in maintaining the uniformity of the brake pad material mixture during the processing of a moulded brake pad [23]. Another property they have is that of superior wear resistance [24]. 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.

3.1.4 Potassium titanate

Potassium titanate fibres are another type of reinforcing fibre used in brake friction materials. They are fibres prepared from highly refined, single crystals, which have a high melting point (1250–1310 °C) [25]. However, they have the potential to cause mesothelioma [26], 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 fibre inhalation, Hikichi of Akebono Brake Industry has devised a process of producing potassium titanate in the form of powders, with the same frictional performance and strength as fibrous potassium titanate [27]. The powder form is apparently more difficult to inhale than if it were in the fibrous form.

3.1.5 Sepiolite

Sepiolite is a hydrated magnesium silicate mineral that occurs as a fibrous chain-structure mineral [28]. 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 [29]. It retains its microporous and fibrous structure even at temperatures in excess of 1000 °C [30]. Sepiolite is able to absorb traces of fluid between the frictional surfaces.

However, sepiolite is a potential health hazard. It is associated with the development of inflammation in lung and pulmonary interstitial fibrosis, which is also

caused by crocidolite asbestos [31]. As with potassium titanate fibres, they should not be thought of as suitable replacements for asbestos.

3.1.6 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 (aluminium oxide) as well as carbides such as silicon carbide. With a high thermal resistance (melting points ranging from 1850 to 3000 °C [32]), light weight and high strength [33], 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, aluminium brake discs were reinforced by ceramic fibres because the wear rates encountered when using aluminium brake discs against conventional friction materials are unacceptable [34].

3.2 Binders

The purpose of a binder is to maintain the brake pads' 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 for 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 ideal 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.

3.2.1 Phenolic resin

Phenolic resin is probably the most common resin binder used in brake friction material and it is cheap to produce. Phenol resin is a type of polymer formed by a condensation reaction between phenol and formaldehyde, and is able to act as a matrix for binding together different substrates [35]. This condensation reaction may be initiated by acidic or alkali catalysts, resulting in different classes of phenolic resins. For example, phenolic resins produced using an acid catalyst and reacted with insufficient formaldehyde are called novolac resins. When these phenolic resins are cured, they change from a thermoplastic state to a densely, cross-linked thermoset matrix with relatively high heat resistance.

Table 3 Binders

Binder	Advantages	Disadvantages
Phenolic resin	Cheap and easy to produce	Brittle, low impact resistance, highly toxic, decomposes at relatively low temperatures (450 °C)
COPNA resin	High bonding strength with graphite (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 and 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

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 [36]; at temperatures beyond this, it decomposes by charring and evaporation. This process decreases the density of the brake friction material at the wear surface and also increases its porosity, thereby losing its structural integrity [37]. This decomposition into fumes is likely to release its constituents which are poisonous. According to the Occupational 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 [38]. Moreover, Jang *et al.*'s experiment [19] 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 friction material constituents, which forms the basis of the frictional characteristics of the friction material.

The following subsections deal with the resins that have been utilized in an effort to overcome the shortcomings of phenolic resins.

3.2.2 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 [39]. 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 [40] (400–500 °C), although the volume of decomposed gas is in a smaller volume than that of phenolic resin.

3.2.3 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 siloxane resins having enhanced impact resistance, yet these phenolic siloxane resins have equal or better heat and chemical resistance than conventional phenolic resins [38]. Also, silicone-modified resins have the property of preventing the frictional layer from adsorbing water due to its improved water repellency [5].

3.2.4 Cyanate ester resin

Cyanate ester resins, formed from polyfunctional cyanate monomers, are stable at elevated temperatures, chemically inert and have damping properties. However, they are brittle like the phenolic-based resins [41]. According to Ohya and Kimbarya, brake pads that use cyanate ester resins as binders maintain their friction coefficients at elevated temperatures above 350 °C and are also able to maintain good adhesion with the backing plate during service life [42].

3.2.5 Epoxy-modified resin

A pure epoxy resin is unable to withstand high temperatures. At temperatures above 260 °C, typical epoxy resin binders degrade [43]. 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 linear increase in wear above 290 °C. Therefore, epoxy is usually used to modify phenolic resins, resulting in the synergistic effect of having a higher heat resistance than phenolic resin or epoxy resin alone and has a high frictional stability [44].

3.2.6 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 [45]. Such a resin is easily produced using 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 [46], so it is less able to dissipate heat away from the friction surface.

3.3 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 [10]. It is a loose term which could also mean anything used in a large proportion in a brake friction material. For example, certain manufacturers use a large proportion of metal silicates (hard, abrasive particles) in their brake friction material and refer to them as 'fillers' instead of 'abrasives'. 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 material as well as the type of friction material. For example, a metallic pad that generates a lot of braking noise would require more fillers such as cashew and mica (noise suppressors) 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 large amount of molybdenum trioxide to prevent lining cracking. Brake pads with large 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.

3.3.1 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 [47], while vermiculite exfoliates rapidly into flakes at approximately 800 °C [48].

One of the more commonly used fillers is barium sulphate. It imparts heat stability to the brake friction material, at the same time aiding the friction characteristic of the brake friction material [39].

Calcium carbonate is considered to be an alternative to barium sulphate because it has a similar function: it imparts heat stability to the friction material, thereby improving the friction material's brake fade properties [42]. It is the cheaper of the two, but it is not as stable at higher temperatures as barium sulphate [49].

Mica is another commonly used filler. It is able to suppress low-frequency brake noise [50] due to it having a plane netlike structure [51]. 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, aluminium phosphate can be used as a coating on mica powder [52].

Like mica, vermiculite can also suppress noises generated during braking [53]. 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 [51].

Molybdenum trioxide is a recent addition to the family of inorganic fillers. According to Nakajima and Kudo, molybdenum trioxide can prevent thermal fade and cracking of friction lining under high-temperature conditions [54]. It has a relatively high melting point of approximately 800 °C [55]. Others such as Kesavan and Burmester have proposed the use of alkali metal titanates (such as sodium titanate) for use as fillers, claiming that

Table 4 Fillers

Filler	Description
Barium sulphate	Imparts heat stability to friction material, aids friction characteristic
Calcium carbonate	Imparts heat stability to friction material
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 thermal 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

they promote the stability of friction coefficient [56]. Also, the addition of titanium compounds to abrasive particles (such as silicon carbide) has been found to lower its wear rates.

3.3.2 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 [57]. However, these particles, especially cashew, fall off the friction surface easily, leaving behind large pores that eventually crack [58]. To prevent this from happening, the cashew or rubber particles are sometimes coated with an adhesive. Also, certain brake friction material manufacturers use cashew or rubber particles as underlayer material because their low thermal conductivity prevents heat from transmitting to the backing plate of the brake friction material [59]. Cashew particles are also able to reduce fluctuations in friction coefficients, especially at elevated temperatures [19].

3.4 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 conclusions [60]:

1. Brake pads with increased lubricant content show increased stability of the friction coefficient.
2. Brake pads with increased 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 material. 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 material. Metal sulphides do not suffer this problem, although the toxicity of certain compounds such as lead and antimony sulphides is a disadvantage. Therefore relatively safer alternatives such as tin and copper sulphides would be ideal as lubricants.

There has been no mention of any significant advantages or disadvantages of specific abrasives 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 hardnesses. Mild abrasives such as quartz only have a hardness of around 500 HV, zirconium ceramics range from 1000 to 1400 HV and alumina is around the 1750 HV mark.

3.4.1 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 is able to form a lubricant layer on the opposing counter friction material rapidly [61]. 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 powder form. Graphite in the flake form has improved lubrication properties [62], while graphite in the powder form is able to dissipate heat generated during braking more effectively [63].

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 shear strengths [39]. Also, regardless of the type of binder, graphite will increase the overall heat conductivity of the friction material. While this may assist in removing

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 lubricant layer
Metal sulphides	Good lubricating properties, with lower conductivities than graphite; examples include antimony/tin/copper/lead sulphides
Metal oxides/silicates	Abrasives with hardnesses ranging from 500 HV (quartz) to 1750 HV (aluminium oxide); examples include quartz (SiO ₂), zirconium silicate, zirconium oxide, aluminium oxide, etc.

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 application system will occur. It is important to note that the conduction of heat away from 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 materials 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 materials 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 °C [61], 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 [64]. Other examples include copper sulphides and lead sulphides.

3.4.2 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 abrasive 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, aluminium oxide and chromium oxide [65].

4 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 material, 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 material, the fluid trapped within the pores must be quickly released from the friction material [66]. 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 [67].

Table 6 summarizes the three basic types of wet friction materials.

Although the fabric type of material appears to have the best combination of properties, the selection of wet friction material types is very application-specific. For instance, sintered materials have high compressive strengths and are still being used in heavy-duty industrial 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.

4.1 Paper type

The paper type consists of a mat of fibres impregnated with resin. They are typically referred to as the ‘paper type’ because the method of manufacturing these paper type friction materials is similar to that of a normal

Table 6 Different types of wet friction material [68]

Material type	Description
Paper	High porosity; high dynamic friction coefficient (0.10–0.15); low to medium thermal resistance; low compressive strength; material is dried
Sintered	Low porosity; low to medium dynamic friction coefficient (0.05–0.07); high thermal resistance; high compressive strength; material 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-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 transmissions and braking. However, the main trouble with such paper-type friction materials is that they degrade very quickly at temperatures above 150 °C [69], so they are more suitable for automatic transmission applications where the temperatures generated are generally lower than that of braking. There are exceptions to the case—graphitic paper materials can withstand up to 230 °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 strength to the friction material and to provide an open matrix of voids for the resin to fill during resin saturation [70]. 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 [71].

Other components in paper-type wet friction materials include fillers and binders. Fillers such as diatomaceous 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.

4.2 Sintered materials

To eradicate the problem of low-temperature degradation of paper-type wet friction materials, sintered materials are typically used. Sintered materials basically involve curing the friction material instead of drying it. These sintered friction materials allow a higher threshold temperature before friction material 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 a wet environment is that they have high crosslinking densities, thereby reducing the porosity of the friction material. 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 [72].

4.3 Fabric type

The fabric type of wet friction material typically consists of a single ply of woven fabric comprising interwoven strands of yarn. These strands of yarn are spun from

bundles of fibres. Because of the existence of gaps between the individual fibres as well as the yarn strands, the fabric has a high porosity, giving a high flowrate and permeability of fluid. According to Gibson, Mack and Pepper, these gaps channel fluid away from the surface of the fabric during operation, thereby avoiding hydroplaning and assisting in maintaining contact with the opposing surface [73]. 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.

5 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 as 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 mean 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 such as asbestos. Even lesser known toxic substances may be phased out once there is greater public environmental awareness. For instance, the Santa Clara Valley Nonpoint Source Pollution Control Program in the United States has identified vehicle brake pads as a major contributor of copper in stormwater, leading to the southern reach of San Francisco Bay to be labelled as an 'impaired water body' [74]. This is not perceived to be a major problem as the varieties of existing dry friction constituents mean that safer alternatives usually exist. For example, ceramic fibres can be used in place of asbestos fibres. However, one area that needs further investigation would be that of friction material binders. There is a need to develop non-phenolic resin 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 nor any harmful constituents to the surroundings, thereby achieving the pinnacle of environmental friendliness. By the same token, there will also be no ingress of foreign particles 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 coefficients mean that brake maintenance is kept to a minimum. The economic

savings from brake maintenance alone, and possibly lower insurance premiums due to the use of sealed wet brakes, would negate their high manufacturing costs, which are currently only in use on off-road and mining vehicles.

ACKNOWLEDGEMENTS

The authors would like to thank Safe Effect Technologies, a multinational motion control company based in Australia, for supplying the brake components used in the photographs in this work, and the School of Mechanical Engineering, University of Western Australia, for their assistance during the preparation of this paper. Scanning electron microscopy work was conducted at the Centre of Microscopy and Microanalysis in the University of Western Australia with the help of Geraldine Tan, Greg Pooley and Jess Madden.

REFERENCES

- 1 Call for an international ban on asbestos. *Environ. Res.*, May 2000, **83**(1), 79–81.
- 2 UK asbestos ban in force. *Sealing Technol.*, December 1999, **1999**(72), 16.
- 3 Eriksson, M., Bergman, F. and Jacobson, S. Surface characterization of brake pads after running under silent and squealing conditions. *Wear*, 1999, **232**, 163–167.
- 4 Sasaki, Y., Yanagi, M., Todani, Y. and Mita, T. Friction material composition. US Pat. 6080230, 2000 (United States Patent and Trademark Office).
- 5 Hara, Y., Oyama, T., Inoue, M., Mibe, T. and Nakanishi, H. Non-asbestos disc brake pad for automobiles. US Pat. 6220404, 2001 (United States Patent and Trademark Office).
- 6 Filip, P., Weiss, Z. and Rafaja, D. On friction layer formation in polymer matrix composite materials for brake applications. *Wear*, 2002, **252**, 189–198.
- 7 Osterle, W., Griepentrog, M., Gross, Th. and Urban I. Chemical and microstructural changes induced by friction and wear of brakes, *Wear*, 2001, **251**, 1469–1476.
- 8 *Automotive Disc Brake Manual*, 1998, p. 11 (Haynes Publishing).
- 9 Chrysotile asbestos. Priority Existing Chemical Report 9, National Industrial Chemicals Notification and Assessment Scheme, Commonwealth of Australia, 1999, p. 3.
- 10 Eriksson, M., Bergman, F. and Jacobson, S. On the nature of tribological contact in automotive brakes. *Wear*, 2002, **252**, 26–36.
- 11 Eriksson, M., Lord, J. and Jacobson, S. Wear and contact conditions of brake pads: dynamical *in situ* studies of pad on glass. *Wear*, 2001, **249**, 272–278.
- 12 Gudmand-Hoyer, L., Bach, A., Nielsen, G. T. and Morgen, P. Tribological properties of automotive disc brakes with solid lubricants. *Wear*, 1999, **232**, 168–175.
- 13 Dowling, N. *Mechanical Behavior of Materials*, 2nd edition, 1999, p. 144 (Prentice-Hall, Englewood Cliffs, New Jersey).
- 14 Marzocchi, A., Jannarelli, A. E. and Garrett, D. W. Friction materials for brake linings and the like. US Pat. 3967037, 1976 (United States Patent and Trademark Office).
- 15 Avallone, E. A. and Baumeister III, T. *Marks Handbook for Mechanical Engineers*, 10th edition, 1997, pp. 6–142 (McGraw-Hill, New York).
- 16 Chrysotile asbestos. Priority Existing Chemical Report 9, National Industrial Chemicals Notification and Assessment Scheme, Commonwealth of Australia, 1999, p. 8.
- 17 Holman, J. P. *Heat Transfer*, 8th edition, pp. 641–642 (McGraw-Hill, Singapore).
- 18 Hell, M., Jaworek, W., Huppertz, W. and Wieser, D. Friction lining, especially for brakes and clutches, and a method for producing a friction lining. US Pat. 6481555, 2002 (United States Patent and Trademark Office).
- 19 Jang, H., Lee, J. S. and Fash, J. W. Compositional effects of the brake friction material on creep groan phenomena. *Wear*, 2001, **251**, 1477–1483.
- 20 Samuels, G. J. Friction composition and friction element fabricated therefrom. US Pat. 5516816, 1996 (United States Patent and Trademark Office).
- 21 Okubo, H. S., Albertson, C. E. and Nibert, R. K. Asbestos-free friction materials. US Pat. 4446203, 1984 (United States Patent and Trademark Office).
- 22 Smith, W. N. and Boyd, P. Carbonaceous friction materials. US Pat. 5965658, 1999 (United States Patent and Trademark Office).
- 23 Carlson, R. A. and Headley, J. L. Fiber mixtures for brake pads, US Pat. 5871159, 1999 (United States Patent and Trademark Office).
- 24 Brinzey, A. E. Friction materials with universal core of non-asbestos fibres. US Pat. 5041471, 1991 (United States Patent and Trademark Office).
- 25 Kim, S. J., Cho, M. H., Lim, D.-S. and Jang, H. Synergistic effects of aramid pulp and potassium titanate whiskers in the automotive friction material. *Wear*, 2001, **251**, 1484–1491.
- 26 Adachi, S., Kawamura, K. and Takemoto, K. A trial on the quantitative risk assessment of man-made mineral fibers by the rat intraperitoneal administration assay using the JFM standard fibrous samples. *Indust. Health*, 2001, **39**, 168–74.
- 27 Hikichi, A. Friction material. US Pat. 6475614, 2002 (United States Patent and Trademark Office).
- 28 Gonzalez, L., Ibarra, L. M., Rodriguez, A., Moya, J. S. and Valle, F. J. Fibrous silica gel obtained from sepiolite by HCL attack. *Clay Minerals*, 1984, **19** (Mineralogical Society, London).
- 29 Christie, T., Thompson, B. and Braithwaite, B. Clays. Mineral Commodity Report 20, Institute of Geological and Nuclear Sciences, New Zealand.
- 30 Goktas, A. A., Misirli, Z. and Baykara, T. Sintering behaviour of sepiolite. *Ceramics Int.* 1997, **23**(4), 305–311.
- 31 Mossman, B. T. and Sesko, A. M. *In vivo* assays to predict the pathogenicity of mineral fibers. *Toxicology*, 1989, **60**(1–2), 53–61.
- 32 Warren, R. *Ceramic-Matrix Composites*, 1992, p. 2 (Blackie, New York).
- 33 Ceramic fibres (respirable size). Tenth Report on *Carcinogens*, US Department of Health and Human Services, 2002.
- 34 Tsugawa, K., Suzuki, S. and Kubono, H. Friction material. US Pat. 5712029, 1998 (United States Patent and Trademark Office).

- 35 Critchley, J. P., Knight, G. J. and Wright, W. W. *Heat-Resistant Polymers*, 1983, pp. 21–29 (Plenum Press, New York).
- 36 Yesnik, M. A. Friction material comprising powdered phenolic resin and method of making same. US Pat. 5529666, 1996 (United States Patent and Trademark Office).
- 37 Lamport, R. A., Biermann-Weaver, J. M., Jain, V. K. and Shih, P. Resin mixture for friction materials. US Pat. 5753018, 1998 (United States Patent and Trademark Office).
- 38 Kane, J. F. and Mowrer, N. R. Phenolic resin compositions with improved impact resistance. US Pat. 5736619, 1998 (United States Patent and Trademark Office).
- 39 Komori, T., Miyake, S. and Senoo, Y. Brake friction material. US Pat. 4954536, 1990 (United States Patent and Trademark Office).
- 40 Kakegawa, H., Yasuda, T. and Wang, X. Binder composition for friction materials, and friction material. US Pat. 5889081, 1999 (United States Patent and Trademark Office).
- 41 McCormick, F. B., Drath, D. J., Gorodisher, I., Kropp, M. A., Palazzotto, M. C. and Sahyun, M. R. V. Energy-curable cyanate/ethylenically unsaturated compositions. US Pat. 6069219, 2000 (United States Patent and Trademark Office).
- 42 Ohya, K. and Kimbara, H. Disc brake pad. US Pat. 4944373, 1990 (United States Patent and Trademark Office).
- 43 Tsang, P. H., Coyle, J. P., Liu, T. and VanderPoorte, J. G. Method of manufacturing a friction article. US Pat. 4537823, 1985 (United States Patent and Trademark Office).
- 44 Lam, R. C. and Chen, Y. F. Carbon deposit friction lining material. US Pat. 5856244, 1999 (United States Patent and Trademark Office).
- 45 Nagahiro, T. and Umemoto, N. Polyimide based friction material and preparation process of the material. US Pat. 5258441, 1993 (United States Patent and Trademark Office).
- 46 Avallone, E. A. and Baumeister III, T. *Marks Handbook for Mechanical Engineers*, 10th edition, 1997, pp. 6–197 and 4–83 (McGraw-Hill, New York).
- 47 Lide, D. R. and Kehiaian, H. V. *CRC Handbook of Thermophysical and Thermochemical Data*, 1994, p. 26 (CRC Press, Boca Raton, Florida).
- 48 The exfoliation of vermiculite. Report 23, Western Australian Mining and Petroleum Research Institute, 1989.
- 49 Blau, P. Compositions, functions, and testing of friction brake materials and their additives. Technical Report ORNL/TM-2001/64, Oak Ridge National Laboratory, 2001, p. 29; available through NTIS, Springfield, Virginia.
- 50 Yamashita, Y., Nakagawa, M., Ibuki, M. and Kishimoto, H. Friction material for making brake pads. US Pat. 5266395, 1993 (United States Patent and Trademark Office).
- 51 Kimura, K., Goto, Y., Torii, N., Katagiri, H., Miyazawa, H. and Motoyoshi, Y. Friction material for dampers and process for producing the same. US Pat. 5830566, 1998 (United States Patent and Trademark Office).
- 52 Seki, K. Non-asbestos friction material. US Pat. 5217528, 1993 (United States Patent and Trademark Office).
- 53 Nakagawa, M., Yamashita, Y., Ibuki, M. and Kishimoto, H. Friction material and method of manufacturing such material. US Pat. 5268398, 1993 (United States Patent and Trademark Office).
- 54 Nakajima, O. and Kudo, T. Friction materials. US Pat. 6107386, 2000 (United States Patent and Trademark Office).
- 55 Lide, D. R. and Kehiaian, H. V. *CRC Handbook of Thermophysical and Thermochemical Data*, 1994, p. 30 (CRC Press, Boca Raton, Florida).
- 56 Kesavan, S. and Burmester, G. Metal titanates for friction stabilization of friction materials. US Pat. 5891933, 1999 (United States Patent and Trademark Office).
- 57 Kamioka, N., Tokumura, H. and Yoshino, T. Friction material containing BT resin dust. US Pat. 5384344, 1995 (United States Patent and Trademark Office).
- 58 Kinouchi, S., Hara, Y. and Yamaguchi, J. Friction material composition, production of the same and friction material. US Pat. 6372817, 2002 (United States Patent and Trademark Office).
- 59 Nakagawa, M. Disk-brake pad. US Pat. 6193025, 2001 (United States Patent and Trademark Office).
- 60 Jang, H. and Kim, S. J. The effects of antimony trisulphide and zirconium silicate in the automotive brake friction material on friction characteristics. *Wear*, 2000, **239**, 229–236.
- 61 Taylor, A. J., Taylor, S. K., Hubbard, D. A. and Lotfipour, M. Friction pads for use in disc brakes. US Pat. 5725077, 1998 (United States Patent and Trademark Office).
- 62 Takahasi, K., Yoshida, M., Hagiwara, Y., Kondoh, K., Takano, Y. and Yamashita, Y. Titanium and/or titanium alloy sintered friction material. US Pat. 5922452, 1999 (United States Patent and Trademark Office).
- 63 Booher, B. V. Pultrusion method of making brake linings. US Pat. 5156787, 1992 (United States Patent and Trademark Office).
- 64 Huner, R., Melcher, B., Milczarek, R. and Kienleitner, H. Solid lubricants with a tin sulphide and carbon pads. US Pat. 6303545, 2000 (United States Patent and Trademark Office).
- 65 Kobayashi, M. Non-asbestos friction materials. US Pat. 6413622, 2002 (United States Patent and Trademark Office).
- 66 Lam, R. C. Fibrous base material for a friction lining material comprising less fibrillated aramid fibres and carbon fibres. US Pat. 6130176, 2000 (United States Patent and Trademark Office).
- 67 Yesnik, M. A. Non-saturated friction material comprising powdered silicone resin and powdered phenolic resin and method for making same. US Pat. 5639804, 1997 (United States Patent and Trademark Office).
- 68 Llyod, F. A. and DiPino, M. A. Advances in wet friction materials—75 years of progress. SAE Technical Paper Series, SAE Inc., 1980.
- 69 Menard, D., Boutard, J., Guerin, R. and Jacq, G. Friction material designed for fitting to a device employing friction in a liquid medium, and a method of producing such a friction material and the device to which it is fitted. US Pat. 5807518, 1998 (United States Patent and Trademark Office).

- 70 Lee, J. M.** Friction paper containing activated carbon. US Pat. 5989390, 1999 (United States Patent and Trademark Office).
- 71 Kitahara, S. and Umezawa, S.** Wet friction material. US Pat. 6130177, 2000 (United States Patent and Trademark Office).
- 72 Suzuki, M., Mori, M. and Yagi, H.** Wet friction material. US Pat. 6265066, 2001 (United States Patent and Trademark Office).
- 73 Gibson, D. W., Mack, N. B. and Pepper, R. W.** Amorphous carbon coated carbon fabric wet friction material. US Pat. 5952249, 1999 (United States Patent and Trademark Office).
- 74 Engberg, C. C.** The regulation and manufacture of brake pads: the feasibility of reformulation to reduce the copper load to the San Francisco Bay. Palo Alto Regional Water Quality Control Plant, 1995.