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# Study on Tribological Investigations of Alternative Automotive Brake Pad Materials

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## Abstract
The aim of this paper is to simulate the process of wear mechanism of brake pad in braking operation to evaluate the weight loss due to wear and the specific wear coefficient for different bake pad materials. It is a key component of transportation including industrial equipment; friction brake plays a critical role in their routine work as well as safety activity. The braking system's role in an automotive is to slow or stop the automobile entirely by converting its kinetic energy to heat energy by friction. The pad and rotor interaction causes friction heat, so the brake pad must absorb heat rapidly to survive high temperatures, but not wear. This work analyzes and discusses various environment friendly and healthy option materials to asbestos. Brake pad friction substance is made up of different materials such as binders, filler content, additives, and reinforcements to satisfy the specifications and adjust their percentage effects on the tribological properties. Over the past few days, the brake pads have been manufactured of asbestos material with enough electrical, tribological, as well as physical properties, but that causes cancer and many other health issues, and therefore, its use is redundant. Three samples with specific mixtures are used with varying ratio of ingredients as well as observing their impact on the tribological characteristics like brake pad friction and wear. Weight loss observed for the asbestos material for the same loading condition is more as compared to the non-asbestos material.

**Keywords** Alternative brake pad materials · Asbestos · Friction material · Tribological properties · Wear rate

## Abbreviations

| | |
|---|---|
| $A$ | Apparent pad contact area, $cm^2$ |
| $a$ | Braking decelaration, m/s |
| $D_f$, $D_m$ | Front wheel and master cylinder diameters, mm |
| $F$, $F_p$, $f$ | Front wheel normal, brake pedal and friction forces, N |
| $f(T_i)$ | Unknown constant at temperature $T_i$ with regard to time i |
| $G$, $G_{01}$, $G_{02}$ | Weight losses per braking, mg |
| $H$, $\Delta H$ | Pad thickness losses, μm |
| $H_0$ | Average pad thickness loss per 1000 km, μm |
| $H_1$ | Original pad thickness, mm |
| $K$, $K_0$ | Apparent specific wear rates (0 = average) $mm^3$/Nm |
| $k_i$ | Wear coefficient at temperature $T_i$ with regard to time i, $mm^3$/Nm |
| $M$ | Brake torque, Nm |
| $m$ | Brake pad mass, kg |
| $N_0$ | Average number of braking's per 1 km |
| $n$ | Total number of different temperature sections |
| $P$ | Brake line pressure, MPa |
| $T_i$ | Braking temperature at time i °C |
| $t$, $\Delta t$ | Braking times, s |
| $U_0$ | Average initial braking velocity, km/h |
| $u_0$, $u_i$, $u_{i+1}$ | Braking velocities at times 0, i and i + 1, km/h |
| $\Delta W$ | Frictional work, J |
| $\alpha$ | Vehicle constant |
| $\beta$ | Amplification coefficient |
| $\Delta\theta$ | Tire rotation angle, rad |
| $\eta$ | Braking mechanical efficiency |
| $\mu$ | Friction coefficient |
| $\rho$ | Pad density, $kg/cm^3$ |

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| | |
|---|---|
| $\Delta s$ | Braking distance for Δt duration, m |
| $R$, $r$ | Effective rotor and front wheel tire radii, mm |

## 1 Introduction

Brake is a critical element of an automotive system from security and performance perspective. Nowadays, disk brakes are mostly used in vehicles because of its faster heat dissipation characteristics as compared to drum brakes. Braking pads are the backing sheets of steel, having friction content which are attached to the surface facing the rotor of the disk brake. Brake pads transform the car's kinetic energy through friction into thermal energy. A couple of brake pad with their friction surfaces facing the rotor are located in the brake caliper. The braking activity begins with the pedal force application, and the caliper grabs or presses the pads into the rotor to slow or stop the automobile. Because of the contact between pad and rotor, heat is generated which transfers the heat in lesser quantity to the disk by friction material which results it into dull gray color [1]. Friction causes the release of energy with material wearing out that result in heating of brake parts and releases wear particles. Therefore, wear of brake pads lead to the decrease in performance of the brakes which generates the need for the replacement of brake pads [2]. Brake pads are exposed to the heat. It is important to develop brake friction materials with exceptional tribological properties to have good performance characteristics at higher temperatures [3]. In automotive braking systems, the friction forces between stationary pads and a rotating disk allows the vehicle to stop. Friction also induces energy dissipation, associated with wear of pad material, which leads to thermal loading of the brake parts and release of wear particles in the environment. The friction coefficient (COF) and wear of the system are based on the properties of the friction layer in the pad-disk contact area, which in turn relays on the structure and functionality of the matting materials [4].

Of brake pads, friction materials (Fig. 1) are composites that would include up to 30 various ingredients. Generally, such components are categorized by four main classes: fiber reinforcement, friction additives, fillers, and binders [4–6]. In order to withstand such a higher temperature, the brake pad surface must absorb the heat radially and maintain a high friction coefficient. The brake pad material should be fully consistent with rotor material to maintain good friction quality, wear rate, vibration, and noise [7]. Automotive brake pad systems require good wear resistance, strong friction coefficient for their useful life, higher thermal conductivity, and lower thermal expansion characteristics. Asbestos is historically used for brake pads due to its wide range. For enhancement, the composition of brake pads is constantly changed to obtain these properties. The reinforcing components are used to get the structure with mechanical strength [8, 9]. Glass fiber or aramid is usually applied to strengthen the load. Fillers are used in large amounts to regulate the composition and also to reduce the costs that are also rising. Functional fillers are added to the composition to increase specific characteristics like fade resistance. Binders are used to hold all the constituents together [10, 11]. The binder resin used such as phenolic resin should be heat resistant to compensate the released heat at the contact area. Frictional additives such as lubricants and abrasives are added to improve the coefficient of friction and eliminate the undesired film created throughout working [12, 13].

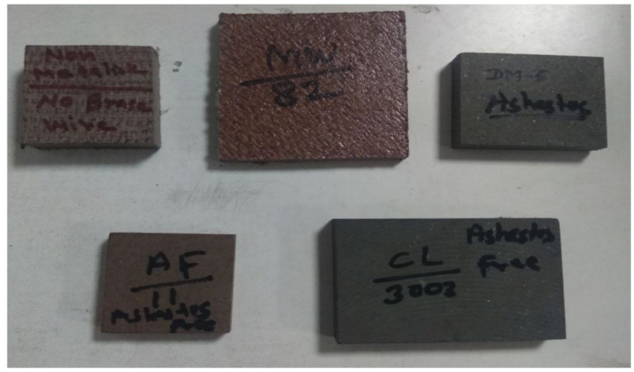

**Fig. 1** Brake pad materials

Over the years, multiple scientists have researched the wear process caused in braking systems. These are quite unclear as there are differences in these unique and complex systems.

Tiwari [14] studied composite materials for automotive brakes with main aspects of friction & wear. An attempt has been made to simplify the complexities and to develop an understanding of the material aspects of friction materials while emphasizing current trends. Deshmukh, et al. [15] studied the three different compositions of semi-metal brake pads for dry friction wear speed. Three compositions have been assigned in this paper and EDX obtains comprehensive compositions of all three materials on the scanning device for electron microscopy. At the end, the wear rate and friction coefficient are used to equate these three materials. The relation between brake pad surface topography and the incidence of squeals was examined by Erikson, et al. [16]. Upon interrupting the experiment under both quiet and squealing circumstances, an analysis of the brake pad surface was performed. The brake pads used for the trials were reinforced organic pads in two sets of metal fiber. One of the combinations was the generic composition for the output. Osterle and Bettge [17] explored the use of topographical inspection techniques including a confocal laser scanning microscope and an interference microscope and also micro-analysis and surface layer characterizing approaches like electron microscopy scanning, light microscopy, and focused ion beam.

The wear resistance of cast iron used for the brake disk rotors was analyzed by Cueva, et al. [18]. The authors examined the wear resistance of three different kinds of gray cast iron (gray iron grade 250, high carbon gray iron and titanium alloyed gray iron) used for the brake rotors and equated them with the data obtained with a compact graphite iron (CGI). Friction coefficients for brake material pairs vary from 0.07 to 0.7, according to Anderson [19], but generally most automobiles work in a smaller range. Typical friction coefficient values vary from approximately 0.3 to 0.6. Saffar, et al. [20] worked with a variety of rubber content to investigate mechanical, physical, frictional, wear, and fade properties and determined that COF is higher for rubber-based material compared to high-speed, wear-resistant resin base. Singh, et al. [21] conducted experiments for mechanical, physical, and tribal characteristics with phenolic composites based on lapinus aramid fiber. Bijwe [22] examined steel and brass introduction, leading to an increase in composite density and particle size relative to barite. Idris et al. [23] used banana peels as a substitute to asbestos and phenolic resin (phenol formaldehyde) as a binder to develop a new brake pad. The resin ranged from 5 to 30 wt% at 5 wt% intervals. A review of the brake pad's structure means study of visual, mechanical, and wear properties. The tests, which included 25 wt% of uncarbonized banana peels and 30 wt% carbonized, provided the best properties.

From collected works and analysis, it is seen that wear rate of metallic, non-metallic, and composites show fluctuating behavior under various working circumstances. Again, it is seen that for low wear rate of different materials, the process parameters have to be optimized. Hence, the objective of this paper is to simulate the wear mechanism in brake pads to estimate the wear rate of different materials of brake pad under different loading conditions.

## 2 Wear Analysis During Vehicle Braking

Vehicle braking usually occurs intermittently and maybe even irregularly. Several different factors seem to influence the wear of brake material like braking stress, speed, temperature, traffic frequency, road condition, and driving and braking methods. Performance coefficient is one of the main criteria for determining brake surface performance, relying heavily on applied pressure, sliding.

Consider a car that runs without wind on a flat concrete (dry) roadway. Its speed decreases shortly after a stop signal from the initial braking velocity $u_0$ to zero [5]. If the braking deceleration $a$ is assumed as constant, the braking time $t$ is determined as,

$$t = \frac{u_0}{a} \tag{1}$$

From a different point of view, $t$ can be divided into $n$ equal parts and each $t$ has the same temperature, i.e.,

$$\Delta t = \frac{t}{n} \tag{2}$$

By using Eqs. (1, 2), the braking distance $\Delta s$ for $\Delta t$ duration is given below as,

$$\Delta s = \frac{\left(u_{i+1}^2 - u_i^2\right)}{(2a)}$$

$$= \left[\frac{2n - 2i - 1}{2n^2}\right]\frac{u_0^2}{a} \tag{3}$$

where $i = 0,1,2,3....(n-1)$ and, $u_i$ and $u_{i-1}$ are the braking velocities at times $i$ and $i+1$ ,respectively.

The corresponding tire rotation angle in *radian* is given by,

$$\Delta\theta = \frac{\Delta s}{r} \tag{4}$$

The servo machinery increases the brake pedal force $F_p$ $\beta$ times, and then the line pressure from the master cylinder is transported to the brake line pressure $P$ in the front wheel cylinder, leading in normal force $F$ being expended on the pads after pressing the brake pedal. The pads press the rotor's inboard and outboard surfaces so that the generated surfaces avoid the movement of the wheels and gradually slow down the vehicle. The friction force $f$ of the front wheel is represented as,

$$f = 4\mu F$$

$$= \frac{4\mu \times \beta F_p \eta \times \pi\left(\frac{D_f}{2}\right)^2}{\pi\left(\frac{D_m}{2}\right)^2}$$

$$= \frac{4\eta\beta\mu F_p {D_f}^2}{D_m^2} \tag{5}$$

The number *4* represent the four pads that undergo the same normal forces on the front axle.

The brake torque $M$ can then be written as follows:

Torque = Effective friction radius × friction force

$$M = R \times f \tag{6}$$

The corresponding work done by the friction force $\Delta W$ is given by,

$$\Delta W = M \times \Delta\theta \tag{7}$$

Thus, the linear relation between the pad thickness loss $\Delta H$ and work done by a brake for a certain brake temperature is expressed as,

$$\Delta H = \frac{1}{A}\Delta W f(T_i) \tag{8}$$

Pad thickness loss is given by,

$$H = \frac{2\eta\beta R\mu F_p u_0^2}{arA}\left(\frac{D_f}{D_m}\right)^2 \sum_{i=0}^{n-1}\left(\frac{2n-2i-1}{n^2}\right)f(T_i) \tag{9}$$

The weight loss is more significant than the thickness loss, taking into account the possible swelling of the pad volume. The corresponding loss of pad weight per braking $G$ is, therefore, determined by,

$$G = \frac{\alpha\mu F_p u_0^2}{a}\sum_{i=0}^{n-1}\left(\frac{2n-2i-1}{n^2}\right)f(T_i) \tag{10}$$

With $\alpha = \frac{2\eta\beta\rho R}{r}\left(\frac{D_f}{D_m}\right)^2$ = constant term

Wear coefficient $k_i$ at time $i$ is as follows:

$$k_i = \frac{\Delta \mathrm{HA}}{4\mathrm{PR}\frac{\Delta s}{r}}$$

$$= \mu f(T_i) \tag{11}$$

By using Eqs. (10 and 11), we get,

$$K = \sum_{i=0}^{n-1}\left(\frac{2n-2i-1}{n^2}\right)\mu f(T_i)$$

$$= \sum_{i=0}^{n-1}\left(\frac{2n-2i-1}{n^2}\right)k \tag{12}$$

$K$ is defined as apparent specific wear rate in order to distinguish from $k_i$. Due to $\sum_{i=0}^{n-1}\left(\frac{2n-2i-1}{n^2}\right) = 1$, Eq. (10) can be written as,

$$G = \frac{\alpha K F_p u_0^2}{a} \text{ with } \alpha = \frac{2\eta\beta\rho R}{r}\left(\frac{D_f}{D_m}\right)^2 \tag{13}$$

The Eq. (13) represents weight loss of material during vehicle braking.

$$G = \left(\frac{mH_0}{1000N_0H_1}\right) \tag{14}$$

$$\left(\frac{mH_0}{1000N_0H_1}\right) = \left(\frac{\alpha K F_p u_0^2}{a}\right)$$

$$K = \frac{mH_0 a}{1000N_0H_1\alpha F_p u_0^2} \text{ with } \alpha = \frac{2\eta\beta\rho R}{r}\left(\frac{D_f}{D_m}\right)^2 \tag{15}$$

The Eq. (15) is used to estimate the average specific wear rate.

## 3 Experimentation and Methodology

### 3.1 Sample Preparation

Brake pad material is very necessary for a vehicle braking system to operate safely and reliably. In general, brake pad products are divided into two subgroups: asbestos and metallic. Metallic brake pad materials are also graded as low metal and semi-metallic materials. Due to the cycle of high heat creation between the rotor and the ground, all pad material starts to dissolve on the friction layer. Because of the non-uniform dispersion of pressure between the pad and the rotor, the surface temperature of the pad will be non-uniform and the higher temperature regions would have a low friction scale than the lower temperatures [24]. It is difficult to establish a precise technical value of the friction coefficient between the rotors and the brake pads. One of the important features of friction brake pad material is binding strength and it should have a high friction coefficient. Friction brake pad material may have good mechanical properties, higher thermal expansion, and water insolubility, yet it should have suitable chemical composition. Organic-based brake pad material are procured from CO-EFF friction bands Pune. The material is non-asbestos friction material with extremely high amount of organic and inorganic reinforcing fibers system, fine brass fibres, and non-ferrous, organic binding system by special synthetic rubber-modified resins plus NBR rubber [25]. Rectangular blocks (Figs. 2, 3) of square cross-section were machined from the standard bar made of semi-metallic and ceramic materials with the dimensions (Fig. 2) of 76.2 mm × 25.4 mm × 12.7 mm (i.e. , $l \times b \times h$). Table 1 shows the physical properties of three brake pad materials.

### 3.2 Experimental Setup

The rubber wheel abrasion method (Figs. 4, 5) is the most popular approach of measuring the components dry/wet three abrasive body wear. In this experiment, between the sample specimen and rotating rubber wheel, the abrasive of known size and composition at controlled flow rate is

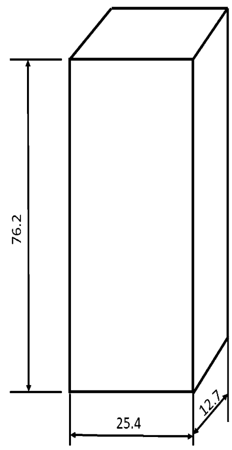


**Fig. 2** Abrasive wear specimen

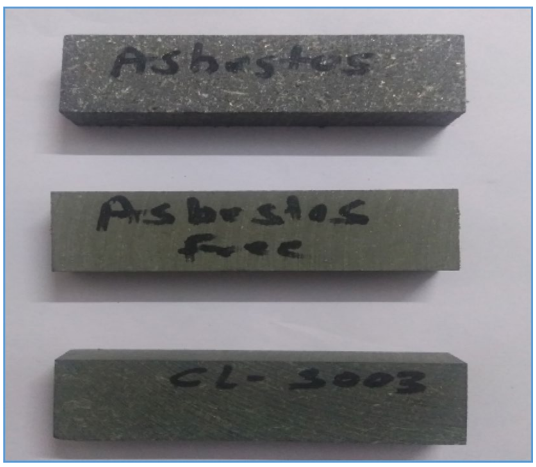


**Fig. 3** Specimen used for testing

inserted. The sample of the experiment may be of any substance or surface covered. The test sample is pushed with a lever arm at a specified pressure against the rotating wheel. The movement of the wheel in the direction of abrasive flow at steady speed abrades the surface of the sample. Instead, using a measuring machine, the mass loss is determined by subtracting the weight of the sample after test run from the weight of the specimen before the examination. Density variation of abraded materials includes calculation of abrasion from volume loss.

The system (Fig. 5) consists of a pan through which, by adjusting the weight, weights can be applied to create a desired pressure on the sample. A chlorobutyl rubber revolving steel disk was connected to the shaft. The sample was to be pushed through the lever [24, 26] against the circumference of the disk. An abrasive medium such as Quartz Sand is supposed to pass between the lining

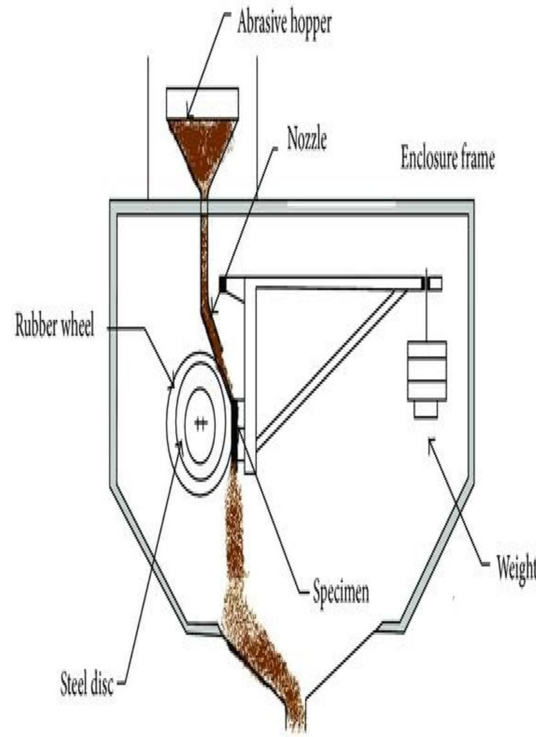


**Fig. 4** Schematic view of dry abrasion tester


**Fig. 5** Experimental setup of dry abrasion tester

material space and the sample. This resulted in an abrasion of three bodies and worn out specimen. The weight

**Table 1** Physical properties of brake pad materials

| Parameters | Asbestos | Asbestos Free | CL3003 |
|---|---|---|---|
| Average COF | 0.4(static)<br>0.45(Dynamic) | 0.38<br>0.4 | 0.34<br>0.36 |
| Compressive strength ($N/mm^2$) | 133 | 170 | 190 |
| Cross braking strength ($N/mm^2$) | 47 | 85 | 85 |
| Density $\times 10^{-3}$ ($kg/cm^3$) | 1.78 | 1.90 | 1.90 |

**Table 2** Vehicle geometric parameters

| Sr. no. | Vehicle parameter | Symbol | Value |
|---|---|---|---|
| 1 | Amplification coefficient | $\beta$ | 3 |
| 2 | Effective rotor radius | $R$ | 96 mm |
| 3 | Front wheel tire radius | $r$ | 282 mm |
| 4 | Front wheel cylinder diameter | $D_f$ | 48 mm |
| 5 | Master cylinder diameter | $D_m$ | 20.64 mm |
| 6 | Original pad thickness | $H_1$ | 12.7 mm |
| 7 | Mechanical efficiency | $\eta$ | 90% |

**Table 3** Estimated vehicle constant

| Material | Density $\times 10^{-3}$ ($kg/cm^3$) | Coefficient of friction (μ) | Estimated vehicle constant $\times 10^{-5}$ (α) |
|---|---|---|---|
| Asbestos | 1.78 | 0.45 | 1.796 |
| Non-asbestos organic | 1.9 | 0.4 | 1.888 |
| CL3003 | 1.9 | 0.36 | 1.888 |

loss between two successive measurements provides the specimen's wear for the test period.

## 4 Results and Discussion

The results of three-body abrasive testing of material have been presented in this section. The tests were carried out for asbestos and asbestos-free material with AFS 50/70 Quartz sand as abrasive media between the wheel and the specimen. The tests were conducted for two materials like asbestos based and asbestos free with different loads for 5 min and each with the constant speed of 200 rpm and 1000 revolutions of rotating wheel. The loads were selected as per the application of force on brake pedal which is distributed on four brake pads. Table 2 shows the geometric parameters of vehicle under consideration.

**Table 4** Material loss

| Material | Load (kg) | Material loss, $H$, (μm) |
|---|---|---|
| Asbestos based | 3.75 | 24,846.999 |
| | 5 | 33,126.33 |
| | 7.5 | 49,693.99 |
| | 15 | 99,387.98 |
| Asbestos free | 3.75 | 22,086.21 |
| | 5 | 29,448.29 |
| | 7.5 | 34,172.43 |
| | 15 | 66,344.87 |
| CL3003 | 3.75 | 19,877.6 |
| | 5 | 26,503.46 |
| | 7.5 | 39,755.192 |
| | 15 | 69,510.384 |

### 4.1 Estimation of Vehicle Constant

Table 3 shows the estimated value of vehicle constant for materials under consideration.

### 4.2 Estimation of Pad Thickness Loss

Table 4 summarizes the estimated pad thickness loss using Eq. (9).

### 4.3 Estimation of Average Specific Wear Rate

Tables 5 and 6 summarize the weight loss and estimated average specific wear rate obtained using Eqs. (13, 15)

### 4.4 Influence of Load and Velocity on Wear Behavior

#### 4.4.1 Influence of Load on Wear of Brake Surfaces

A brake pad's primary requirement is to reduce the car's speed by converting kinetic energy into heat by friction work at the junction between the brake pad and the rotor disk [27, 28]. When a brake-related problem occurs, blame still goes to the brake pads. It is because brake pads tend to be more sensitive to various parameters of braking, including pedal force, vehicle speed, disk temperature, and dry or wet environmental factors [29–31]. The three different frictional brake pad materials (Asbestos based, non-asbestos, CL3003) are evaluated and compared with each other for their weight loss and wear behavior. The friction films on the interface are difficult to form under a low braking pressure (min load). The asperities allocated on the contact interface are deformed and broken in order to create some debris with

**Table 5** Wear rate of brake pad materials for 300 s test run

| Sr. no. | Material | Load (kg) | Weight loss (g) | Wear rate ($mm^3$/s) (Th.) | Wear rate ($mm^3$/s) (Exp.) |
|---|---|---|---|---|---|
| 1 | Asbestos based | 3.75 | 0.035 | 0.0607 | 0.0655 |
| | | 5 | 0.043 | 0.0775 | 0.0805 |
| | | 7.5 | 0.072 | 0.1153 | 0.1353 |
| | | 15 | 0.130 | 0.2283 | 0.2434 |
| 2 | Asbestos free | 3.75 | 0.031 | 0.0520 | 0.0543 |
| | | 5 | 0.040 | 0.0687 | 0.0701 |
| | | 7.5 | 0.047 | 0.0802 | 0.1333 |
| | | 15 | 0.093 | 0.1567 | 0.1631 |
| 3 | CL3003 | 3.75 | 0.028 | 0.0450 | 0.0491 |
| | | 5 | 0.034 | 0.0563 | 0.0596 |
| | | 7.5 | 0.045 | 0.0815 | 0.0824 |
| | | 15 | 0.090 | 0.1488 | 0.1578 |

**Table 6** Wear rate of brake pad materials for 600 s test run

| Sr. no. | Material | Load (kg) | Weight loss (g) | Wear rate ($mm^3$/s) (Th.) | Wear rate ($mm^3$/s) (Exp.) |
|---|---|---|---|---|---|
| 1 | Asbestos based | 3.75 | 0.078 | 0.0721 | 0.0730 |
| | | 5 | 0.099 | 0.0872 | 0.0926 |
| | | 7.5 | 0.129 | 0.1180 | 0.1407 |
| | | 15 | 0.195 | 0.2311 | 0.2801 |
| 2 | Asbestos free | 3.75 | 0.069 | 0.0574 | 0.0605 |
| | | 5 | 0.088 | 0.0749 | 0.0771 |
| | | 7.5 | 0.121 | 0.1460 | 0.1561 |
| | | 15 | 0.187 | 0.1575 | 0.1640 |
| 3 | CL3003 | 3.75 | 0.058 | 0.0501 | 0.0508 |
| | | 5 | 0.084 | 0.0716 | 0.0736 |
| | | 7.5 | 0.098 | 0.0852 | 0.0859 |
| | | 15 | 0.175 | 0.147 | 0.1585 |

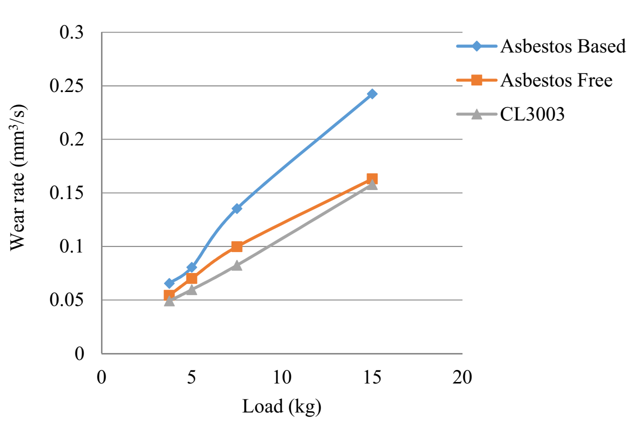


**Fig. 6** Variation in wear rate with load for 300 s test run

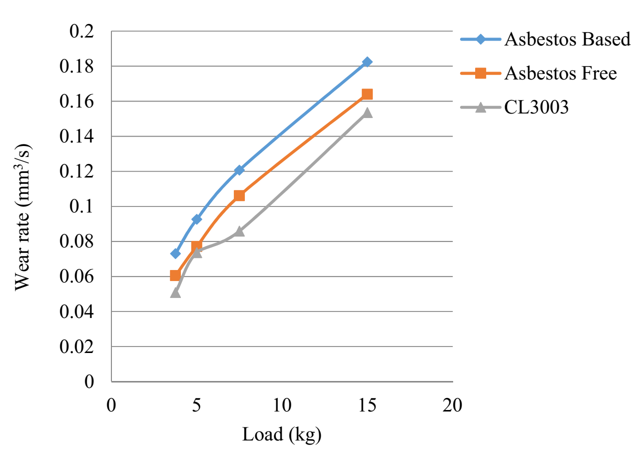


**Fig. 7** Variation in wear rate with load for 600 s test run

the rising load. The debris is easily staged in order to create loose granular films in order to improve the actual contact area.

Figures 6 and 7 display the wear rates observed for all three friction materials under dry continuous braking with gray cast iron disk as a function of load for the 2.3 m/s velocity. The overall pattern of these results is that when load increases at constant sliding speed, wear rate increases. Furthermore, the results indicate that the wear rate is highly calculated by the brake pad type of material or ingredients. The wear characteristics of the brake pad / disk on a macro- and micro-scale relies on the development, growth, and disintegration of contact plateaus, adaptation of the shape, and thermal deformation. In normal braking applications, it is recognized that organic components, fibrous materials, and solid lubricants play a crucial role in maintaining the transfer layer at the friction interface and this transfer layer is, therefore, significant and more consistent at higher pressure. More debris will be shaped, inserted, packed, and filled into the worn surface to produce more granular films when the braking pressure increases to a greater value. These loose granular films can progressively attach to each other in order to establish a dense sheet film with a greater area. The braking pressure is within a low range, the temperature increase will not be apparent, and the strength of the matrix material will be slightly reduced. The temperature will gradually increase with a further increase in braking pressure, which decreases the strength of matrix materials as the wear rate continues to increase.

### 4.4.2 Variation of Weight Loss with Load

Using rubber as lining material and Quartz (AFS 50/70) sand as the abrasive media, the weight loss of the materials (Asbestos based, Asbestos free & CL3003) with respect

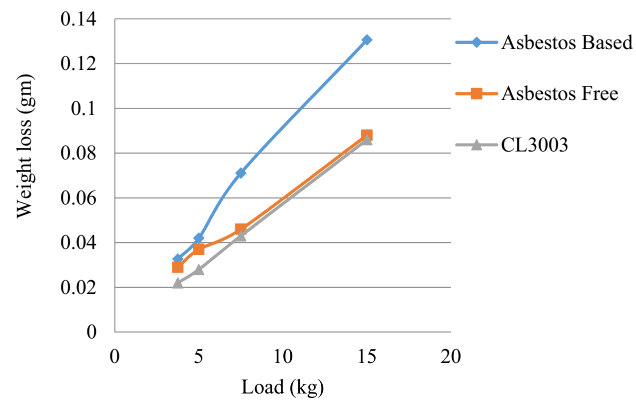


**Fig. 9** Variation of weight loss with load for 300 s test runs (Theoretical)

to time at different loads are shown in Figs. 8, 9, and 10, respectively. The applied pressure (Load) is most significant factor among these three cases. From interaction plot it is observed that as the load increases wear rate is also increases, but with very little amount.

Figures 8, 9, and 10 display the weight loss observed for all three friction materials under dry continuous braking with gray cast iron disk as a function of load for the 2.3 m/s velocity. The overall pattern of these results is that when load increases at constant sliding speed, weight loss also increases. Furthermore, the results indicate that the wear rate is highly calculated from this weight loss by the brake pad type of material or ingredients. For asbestos-based material, the Figs. 8, 9, and 10 shows more amount of loss of material than the other two. So that for the same loading and operating conditions, asbestos-free materials can be used as a substitute for the asbestos material.

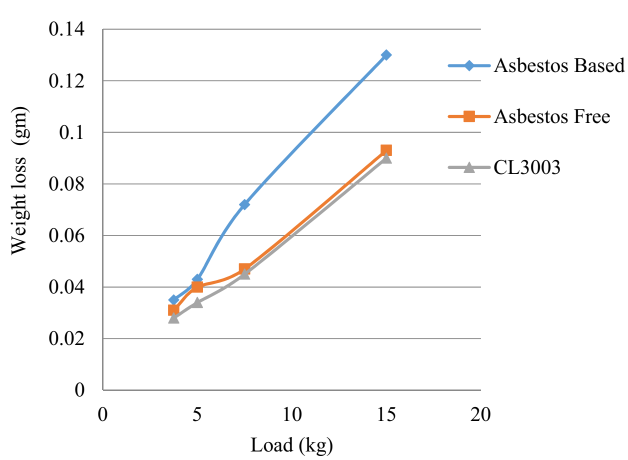


**Fig. 8** Variation of weight loss with load for 300 s test runs (Experimental)

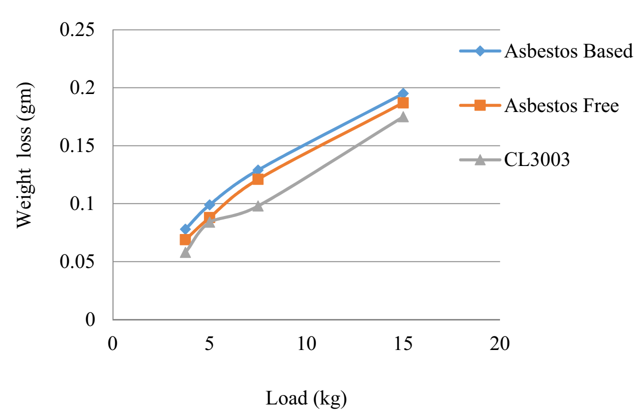


**Fig. 10** Variation of weight loss with load for 600 s test runs (Experimental)

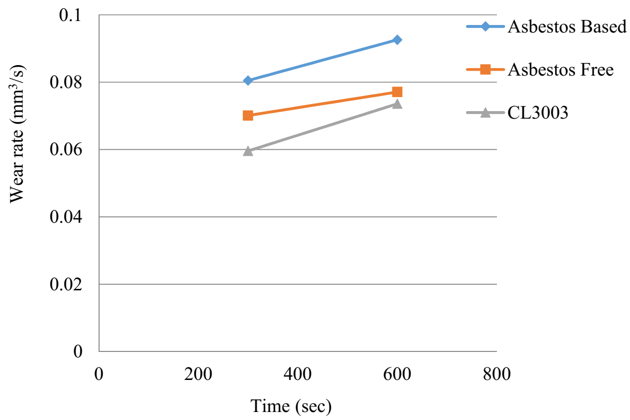


**Fig. 11** Variation of wear rate with time for 5 kg load

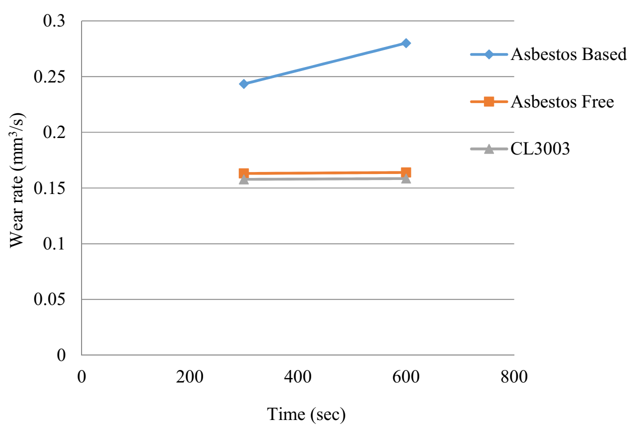


**Fig. 12** Variation of wear rate with time for 15 kg load

### 4.4.3 Variation of Wear Rate with Time

Wear rate of different materials like asbestos based, asbestos free, and CL3003 as a function of time at same load is reported. Figures 11 and 12 show the variation of wear rate with time for 5 kg and 15 kg loads. From Figs. 11 and 12, it is observed that asbestos-based material produces more wear as compared to asbestos free and CL3003 for the same loading and operating condition with respect to time. From Fig. 12 it is seen that there is a linear relationship between weight loss and load [27]. For both the asbestos-free and CL3003 materials, it shows less weight loss as compared to asbestos based for the same loading (15 kg) conditions. With the time, weight loss for the all materials increases linearly.

## 5 Conclusions

- In this work, the tribological characteristics like wear rate for different materials have been studied and compared for their use as a braking material with the help of analysis and dry abrasion tester.
- The load and sliding distance have a significant effect on wear rate. Linear relationship is observed between wear rate and load. This is very helpful for engineers to make changes in composition which should minimize the wear rate by considering this parameter. Also, by taking some precaution during braking, wear rate could be minimized in some cases by adopting good practices while driving.
- Weight loss observed for the asbestos material for the same loading condition is more as compared to the non-asbestos materials.
- The wear rate increases with increase in contact pressure between the brake surfaces under dry condition. As the wear rate of Non-asbestos material and CL3003 material is less as compared to asbestos, they can be a good option for the replacement to asbestos.

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## Compliance with Ethical Standards

**Conflict of interest** The authors declare that there is no conflict of interests regarding the publication of this paper.

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