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Design, construction and performance of a novel brake pad friction tester

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ABSTRACT

Determination of the tribological behavior of brake pads under real environmental conditions is an important and critical task which can significantly impact the automotive industry. Most studies simulate or measure the variants by indirect methods and accept them as true results. The new computer-controlled, interactive brake pad friction tester presented in this study was developed for this purpose. The major components of the machine, which are operated simultaneously, include: a proportional pressure-controlled hydraulics power pack, a mechanical transmission system with electromagnetic clutch, and a brake and automation control with SCADA computer analysis interface. Compared to other friction testing machines, a very important innovation of the newly developed friction tester allows for the testing of the brake pad samples and measuring of the noise level both to be performed with high precision under real conditions. Moreover, this friction tester is capable of determining the friction coefficients; wear behavior, temperature, and life intervals of brake pad samples. This novel brake pad system is relatively cheaper and measures effective friction coefficients more accurately. **The uncertainty in measurements for friction coefficient and wear rate was approximately calculated as ± 0.0135 and ± 0.170 in all of experiments, respectively.** In this study, the machine performance was carried out to evaluate the friction behavior of non-asbestos brake pad samples reinforced with hazelnut shell powder according to the standard brake lining quality control testing procedure (SAE J661).

1. Introduction

A vast number of traffic accidents today can be blamed on problems related to the brake systems of the vehicles. Specifically, brake pads and the friction materials used in them are the most important components in the brake systems affecting driving security and braking performance [1]. In this regard, brake pads should meet the criteria of driving safety, comfort, and high strength and exhibit a constant friction coefficient, low wear rate, low noise and anti-vibration properties under adverse conditions [2,3]. Brake performance is affected not only by the materials and vehicle hardware design, but also significantly by driver behavior, the vehicle usage, the state of adjustment of the brake system, and the overall environment in which the vehicle is driven. In addition to these considerations, engine braking and the aerodynamics in the wheel system are possible influences on braking control systems. No laboratory test can simulate driving conditions precisely and accurately. In the literature, four different test methods for evaluating automotive brake pads and wear amount have been reported: (1) vehicle road tests, (2) inertial dynamometers, (3) vehicle sliding-pad tests and (4) laboratory tribometers. Among these, the tests conducted using laboratory-type friction devices are generally used. These test devices are of four types: (1) the friction assessment and screening test (FAST) machine, (2) the Chase-type machine, (3) pin-on disc tribometers and (4) inertial dynamometers (ECE R-90 standard test) [4–6]. The basic elements of these friction machines include a means to apply a force, use of conformal contact, and a means to measure frictional torque. Some tests involve constant speed, while others involve deceleration. The use of multiple-load applications is common, as is temperature measurement deceleration. Although a number of researchers are using the laboratory-type devices for determining the wear and friction characteristics of automotive brake pads composed of natural and metal powders, some researchers conduct their experiments by using the simpler friction devices designed for specimen-type pads. Qui et al. [7], Bahari et al. [8], Saffar et al. [9] and Matejka et al. [10] investigated the wear and friction performance of asbestos-free eco-friendly pads. The friction-wear properties of the prepared composites were tested by using a Chase friction performance testing device. For this type of device, the amount of wear and the friction coefficients were determined according to SAE J-661standard recommendations. On the other hand, some other researchers [11,12] tested these properties using FAST-type

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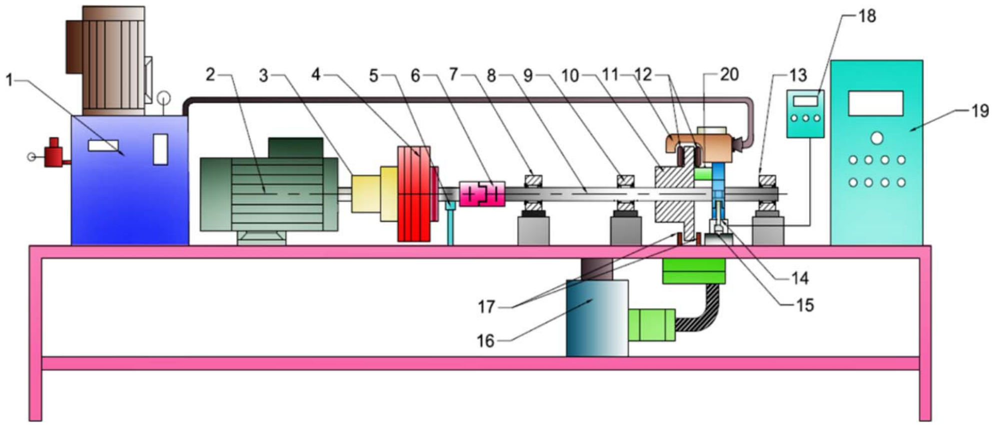


Fig. 1. Schematic diagram of the brake pad friction tester. **(1)** hydraulic unit, **(2)** AC motor-5.5 kW, **(3)** flange coupling, **(4)** clutch option, **(5)** clutch coils, **(6)** couplings, **(7)(9)(13)** bearings, **(8)** main shaft, **(10)** brake disc, **(11)** caliper, **(12)** brake pads, **(14)** caliper mounting apparatus, **(15)** load cell, **(16)** cooling unit, **(17)** heaters, **(18)** amplifier **(19)**, automation unit, **(20)** infrared laser pyrometer.

friction devices. Tayeb et al. [13], Kim et al. [14] and Liew et al. [15] conducted a number of studies on the determination of wear rate with regards to the friction coefficients and weight-loss of small brake pad specimens by using pin-on disc tribometers. This type of device was developed on the basis of the wearing of a material on a pre-determined path by an abrasive material. In their studies, Satapathy et al. [16], Kumar et al. [17], and Jang [19], carried out friction tests using brake dynamometers. Brake dynamometers are mainly Krauss-type advanced devices. In addition to wear, friction coefficients and brake forces, which the other devices can also measure, these devices determine the braking torque. More accurate and reliable friction coefficient results can be obtained by means of providing weight flywheels for the load on one wheel of the vehicle. Mat Lazim et al. [18] have investigated brake pads with different compositions by using small-scale friction testing device. However, the high cost and complex design requirements of these devices limit their usage. Domaç [20], Koç [21], Karaoğlu [22], Timur [23], Mutlu [24] and Kumar [25] developed special test setups for performing the wear and friction tests of specimen-sized pads which were compatible with international standards (SAE J661 and ECE R-90). These setups are computer-controlled and collect the test data by providing brake pressure with hydraulic drive; specimen-size pads are employed instead of full-size pads. These test setups are simpler and consist of fewer compounds in comparison with other types of setups, resulting in lower costs. As all of these tests are conducted on standardized specimens, they may not reflect the tribological response of real components designed with the same material. Recently, efforts for determining the wear and tribological behavior of materials have been centered on testing the full-size components under realistic conditions. Mazza et al. [26] constructed a unique and complicated test setup for investigating the tribological behavior of full-size commercial PTFE-based composites and compared the results with pin-on disc and thrust washer tests. The results of the two test devices were in good agreement.

Analysis of the above mentioned studies shows that the desired wear-friction values have been determined by means of the setups and standard devices developed for testing brake pads. However, some important drawbacks can be observed in the design, manufacture and use of these setups and devices, including inability to work with real pads and basic automation systems, inadequate data transfer systems, inability to provide an adequate vibration environment, insufficiency of required mechanical systems, and absence of interactive access. Thus, existing friction test setups and devices need to be improved in order to adapt to the rapid developments of the automotive brake pad industry. Therefore, in this study, the friction behavior of brake pads manufactured by using organic dusts was investigated by means of a newly developed brake pad test setup. The properties of this setup are superior to those of the existing ones as it is cheaper, able to turn out more reliable and accurate results, able to test real pads and can overcome all the aforementioned limitations.

This study had three primary objectives. The first was to present the development process of the new tester for brake pad friction coefficients and wear as suggested in the SAE J661 standard. The second objective was to test the new design with equipment similar to that used to evaluate the capability of friction testing machines. The third objective was to propose an experimental method for testing and evaluating new organic materials for use in brake pads.

2. Material and method

2.1. Design and development of new brake pad friction tester

For construction of this machine, it was necessary to consider the materials as well as the engineering properties of the clutch pads, and especially the physical and mechanical responses. The machine was designed with the strength and stability of the construction materials in mind so as to comply with the required all standards [2]. The schematic components of the brake pad friction tester developed in this study are shown in Fig. 1, including the general configuration for determining friction and wear behavior. The tester consists of 20 components and was designed according to the real friction and wear behavior influenced by contact of the brake pads with an automobile rotor disc. In this figure, a hydraulic unit with proportional valves directs the oil fluid which controls the open-close movements of the brake pads on opposite sides of the rotor disc by means of a piston. An electric motor (1440 rpm, 5.5 kW) was used to rotate the main shaft supporting a torque of 42.5 Nm and to transmit its motion to the rotor disc. The electro-magnetic clutch pad provides continuous transfer of power at the maximum torque value of the electric motor. The main shaft, 30 mm in diameter, is coupled to the motor and electro-magnetic clutch. The bearings help to guide the main shaft through the axis of the rotor disc. The rotor disc, made of gray cast iron and 240 mm in diameter, and the caliper act to slow down and stop the wheels. A load cell, mounted on the frame carrying the caliper pad assembly, is used to measure the friction force. The automation unit controls the simultaneous operations of the disc speed and temperature, contact pressure, friction force (weight in load cell), friction coefficients, braking time and applications, cooling fans and heaters. In addition, this friction tester is computer controlled and interactive with a SCADA analysis interface. Heaters on opposite sides of the rotor disc adjust the disc temperature to values in the range of 21–450 °C during braking applications. One of the two cooling fans decreases the temperature of the rotor disc, while the other cools the aluminum block of the electro-magnetic clutch pad. Furthermore, the temperature of the rotor disc is precisely measured by a non-contact infrared sensor made to measure the brake pad temperature. The analog output from the sensor is suitably signal conditioned and fed to the interface card of the computer to monitor and control the temperature at which the brake is to be applied. The metal table and blocks were manufactured from AISI 1050 steel. With this

Table 1
Technical specifications of the friction tester.

Parameters	Values
Motor speed	5.5 kW, 1440 rpm, AC
Clutch pad torque	52.5 N.m
Main shaft diameter	35 mm
Max pressure	1–160 bar
Max braking torque	42 N.m
Heaters	1000 W × 2
Cooling fan motor	1.5 kW, 2800 rpm, AC
PLC	Siemens
Control panel	Simatic Panel

friction tester, it is possible to determine the real braking performance and for the brake pads to make contact with the rotor disc by conducting open-close movements. The technical specifications of the brake friction tester are given in Table 1. The tester was also designed and constructed in such a manner as to facilitate its assembly and disassembly for compactness and easy replication. In this study, driving shaft, brake disc and other elements were sensitively tried to adjust by a digital comparator and also, especially, three shaft bearings and a specific-designed coupling with spring were used to induce the mentioned interferences.

In the design of the test equipment, a disc brake using pressure control to adjust the brake pads minimizes the effect of self-locking as well as any thermomechanical or viscoelastic effects. Thus, the measured brake pressure always correlates well with the actual normal load, making the studied cycle a true frictional effect.

2.2. Hydraulic control system

The hydraulic system was designed to provide the required brake pad test force via a high-precision proportional pressure controller and directional control valves. The main proportional integral derivate (PID) device is responsible for controlling the whole hydraulic group fully sequenced with the other system components and test criteria. A highly sensitive pressure transmitter directly and continuously measures the braking piston pressure with an accuracy rate of 0.3%, which results in an operation free of pressure loss and with realistic test outcomes. It is possible to use the results directly in the calculations without any correction factor. The hydraulic unit of the tester is shown in Fig. 2.

2.3. Brake system mechanical design

One of the most important parts of the brake pad tester is the mechanical unit, of a completely new design, the main parts of which include an electric motor, electro-magnetic clutch, couplings, ball bearing-supported drive shaft and brake assembly, load cell, cooling fans, heaters and infrared laser pyrometer (Fig.3a). The functions of these components are described below:

Fig. 2. Hydraulic control system.

- The **electro-magnetic clutch pad** provides the required power transmission from the electric motor with a constant torque and prevents electric motor overloads (Fig. 3b).
- The **brake pad assembly** applies the required hydraulic force to the brake pad and the installed pressure transmitter supplies the real-time pressing force for the tests.
- The **load cells** are sensors that convert force into electrical signals. The drive and measurement values of the brake pad tester are accurate, stable and realistic. The load cell provides the required load measurement and gives feedback to the main PID device for processing.
- The **cooling unit** performs two functions.
  - For the **brake pads**: to keep the brake disc temperature constant at the test values, the cooling fans are used to cool down the disc if required. The disc temperature is continuously measured with the installed highly sensitive infrared laser pyrometer.
  - For the **electro-magnetic clutch**: to maintain performance stability, the electro-magnetic clutch is continuously cooled down by a separate cooling fan controlled by the PID.
- The **heaters** keep the brake disc temperature constant at the test values (21 °C–450 °C), and are used to increase the temperature of the brake disc if required. Disk temperature is continuously measured with the installed highly sensitive infrared laser pyrometer and the value continuously conveyed to the PID device (Fig. 3b).
- The **infrared laser pyrometer** is required to track the measurement of the brake disc temperature. It has a real-time communication with the system PID and this provides stable test conditions and realistic results (Fig. 3b).

2.4. Automation control system

The automation system was designed to control the installed components according to the real-time data sampling of the sensors to create a realistic braking ambiance. With the real-time data collecting ability, the system is capable of supplying the working conditions of the pre-installed test scenarios, or of different scenarios created by the operator. This means that the system can carry out realistic tests with constant or various required temperatures, with different braking forces and a programmable quantity of braking tests. The automation system of the tester is shown in Fig. 4 and the data input and output touch screen panel in Fig. 5. The automation control unit consists of five main parts: (1) the inverter, (2) automation unit (3) the programmable logic controller (PLC), software (4) and (5) the computer (Fig. 4).

The device allows settings for the working ranges of the braking pressure, temperature, disc speed, friction force, braking time, cooling and heating time, which are collected simultaneously. Friction coefficients are automatically calculated for each braking by the software, which has an unlimited data storing ability and can supply very detailed information after a complete scenario. This data can give a Microsoft Excel file output, allowing the operator to process the test results. The whole system is also capable of improving or programming new types of tests. When collection of new data is needed, the system hardware is also capable of installing different types of sensors with analogue or digital inputs. Moreover, the working stages of this automation system are simulated and displayed in green on the interface of the touch panel when the process is activated. In Fig. 5, the touch panel provides to control the braking test conditions such as pressure, absolute speed, temperature, friction coefficient depending on friction force measured by a load-cell and braking cycle and time.

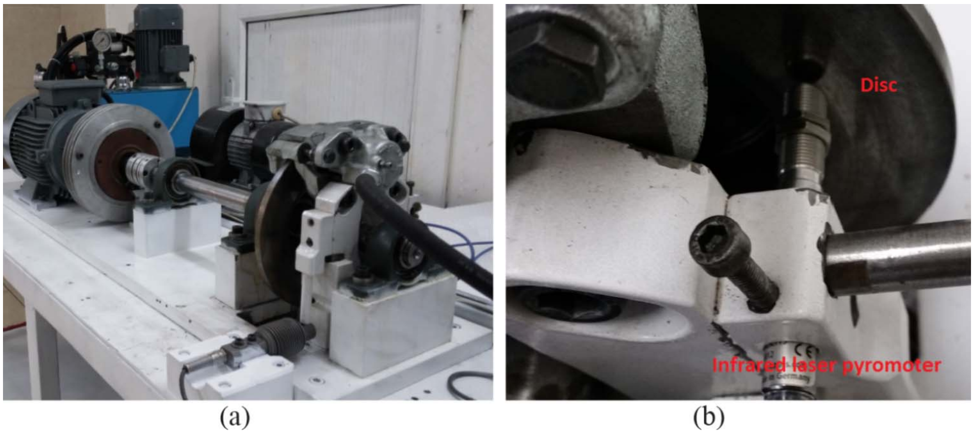


Fig. 3. Brake pad friction tester working in contact conditions: (a) overall view of components **(b) view of attached IR pyrometer.**

3. Discussion

3.1. Friction and wear performance

The friction testing device in this study was developed according to the specifications defined in SAE J661. Simple friction and wear tests were performed to evaluate the reliability and significance of the results of the proposed method and equipment. In total, 12 tests were conducted under different trial conditions including various disc speeds, braking pressures, braking cycles versus friction coefficients and wear rates (given in Fig. 5 and Table 2). The temperature conditions varied between 21 °C and 100 °C in all cases of cold friction coefficients (μ).

In this study, friction coefficients (μ) were calculated by the following formula in Eq. (1).

$$F_s = F_N \cdot \mu \tag{1}$$

F_S = Friction force,
F_N = Normal force,
μ = Friction coefficient.

Friction force (Fs) was measured by using a load-cell in kilo-gram; Summarily, F_N is calculated by pressure in obtained from hydraulics system and brake pad area (Pressure x Pad area). This force which is normal force is applied to brake pad area.

The average of five measurements at least for 12 experiments is used to calculate friction coefficients and wear rate given in Table 2. The uncertainty in measurement of friction coefficient and wear rate is estimated by using average values, variance, standard deviation and standard error based on equations in the following:

$$X_{average} = (X_1 + X_2 + X_3 + X_4 + X_5)/5 \tag{2}$$

N= number of experiments = 5

$$\text{Variance} = S^2 \tag{3}$$

$$\text{Standard Deviation(S. D)} = \sqrt{S^2} \tag{4}$$

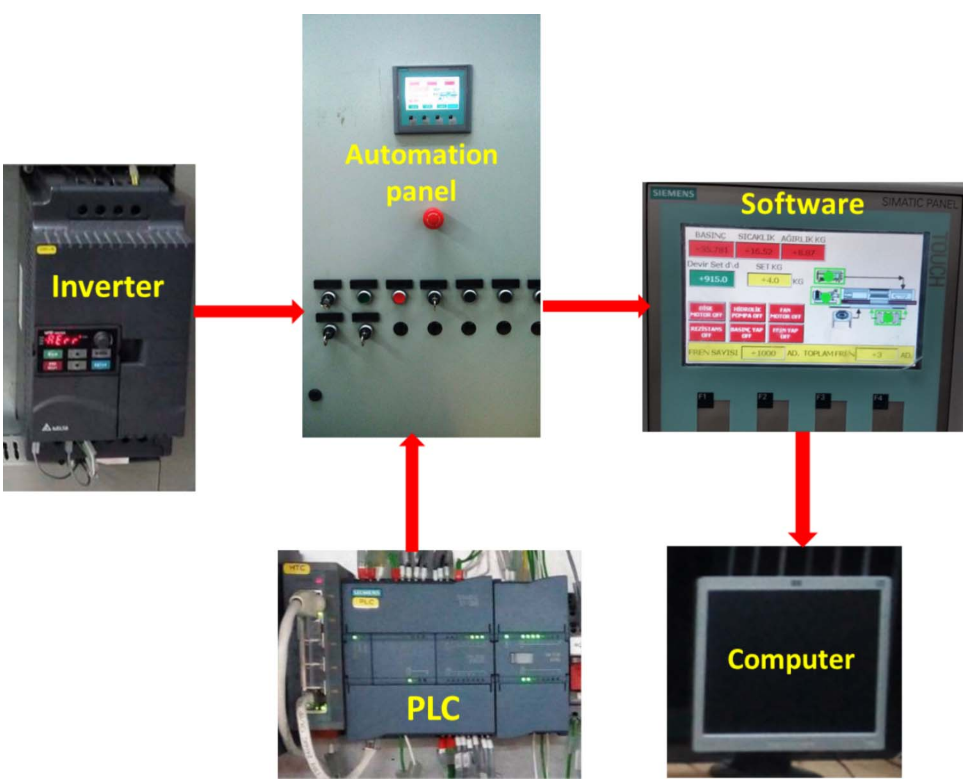


Fig. 4. Working diagram of the automation control system.

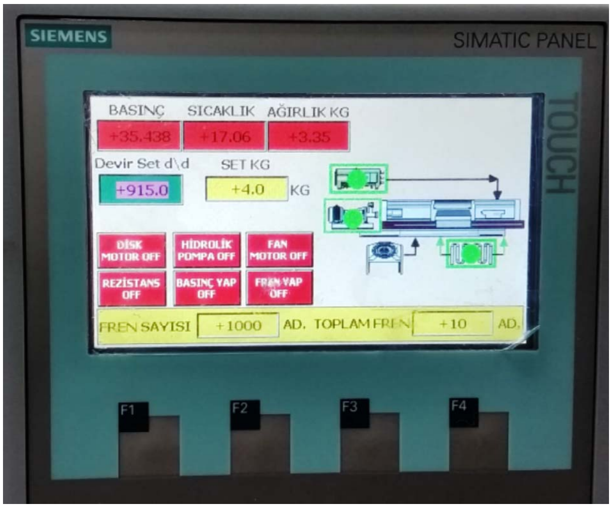


Fig. 5. The touch panel of testing conditions for pressure, speed, temperature and friction coefficient.

$$\text{Standard Error(S. E)} = S.\,D = \frac{s}{\sqrt{N}} \tag{5}$$

For calculation of a single friction coefficient,

Measurement = Best estimation ± uncertainty (For example, 0.502 ± 0.01)

For calculation of a single wear rate;

Measurement = Best estimation ± uncertainty (For example, 1.5 ± 0.165)

In similar way, uncertainty in measurement of the remained experiments for friction coefficients and wear rate according to above equations have calculated and updated in new Table 2.

Although the developed friction tester was capable of performing all tests at temperatures varying in range from 21 °C through 450 °C, only the test results between 21 °C and 100 °C were taken into consideration in this study. Temperatures were measured by infrared laser pyrometer and correlated using a non-contact thermal camera picture as is shown in Fig. 6. Additionally, in Table 2, 1000 cycles correspond to approximately 13,500 m of vehicle road (disc revolution road), whereas 3000 cycles are the equivalent of 26,500 m of vehicle road.

The friction coefficient and wear rate results are given in Table 2, which shows that the μ increased with increasing rotational speed in all cases. The effect of the applied pressure was also crucial on the μ values. Moreover, an increase in the braking cycles rapidly decreased the μ values in the non-asbestos brake pads. Similar trends can also be seen in the wear rate values. The highest wear rate was observed in the sample of Experiment Number 9.

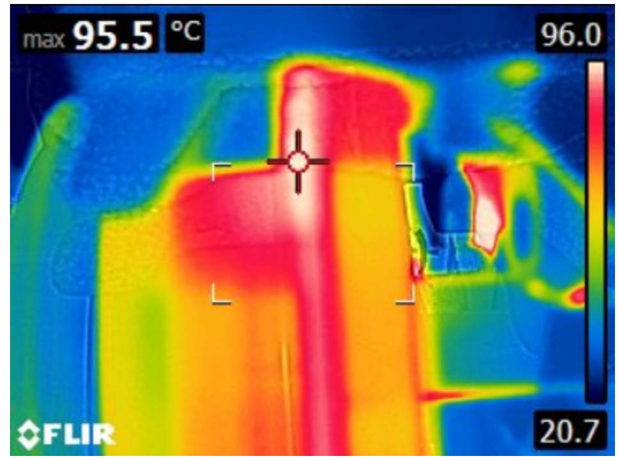


Fig. 6. Brake disc thermal camera temperature gradients.

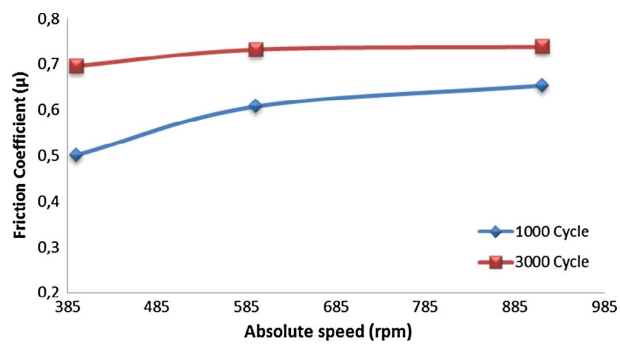


Fig. 7. Variations of friction coefficient according to absolute speed.

The coefficient of friction was plotted as a function of the rotational absolute speed (Fig. 7) in order to compare the friction effectiveness of the different braking cycles. It was observed that the μ values remained in the range of 0.502–0.739. The figure clearly shows that increasing the rotational speed caused significant increases in the friction coefficients for the brake pads containing hazelnut dust. This greater magnitude of the friction coefficients may be attributed to the presence of a higher proportion of hard metal particles (steel fibers) in the hazelnut dust that enhanced the abrasive component by minimizing the adhesive impact of fillers and binders.

Fig. 8 shows the friction coefficients at various applied pressures and indicates that the μ decreased with increased pressure. The rapid change in the μ as a result of pressure was brought about by the components in the friction materials and was attributed mainly to the

Table 2
Braking test conditions and the results.

Experiment Number	Speed (rpm)	Pressure (Bar)	Braking Cycles	Friction Coefficient (μ) (μ) ± 0.0135	Wear rate ($cm^3/N.m \times 10^{-7}$) Wear rate ± 0.17
1	395	10.5	1000	**0.502**	**1.5**
2	595	10.5	1000	**0.608**	**2.2**
3	915	10.5	1000	**0.654**	**3.5**
4	395	30	1000	**0.224**	**2.4**
5	595	30	1000	**0.221**	**3.2**
6	915	30	1000	**0.291**	**0.16**
7	395	10.5	3000	**0.697**	**0.11**
8	595	10.5	3000	**0.733**	**0.10**
9	915	10.5	3000	**0.739**	**9**
10	395	30	3000	**0.239**	**4.1**
11	595	30	3000	**0.244**	**8.1**
12	915	30	3000	**0.258**	**0.17**

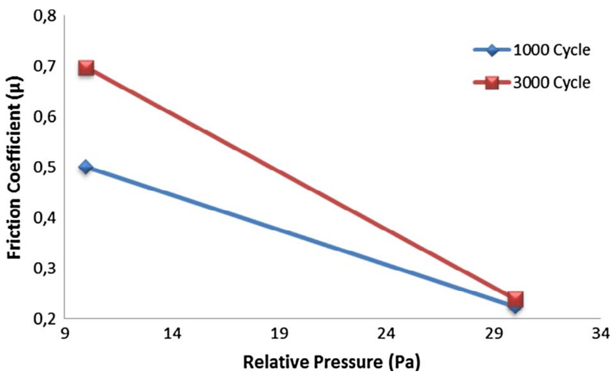
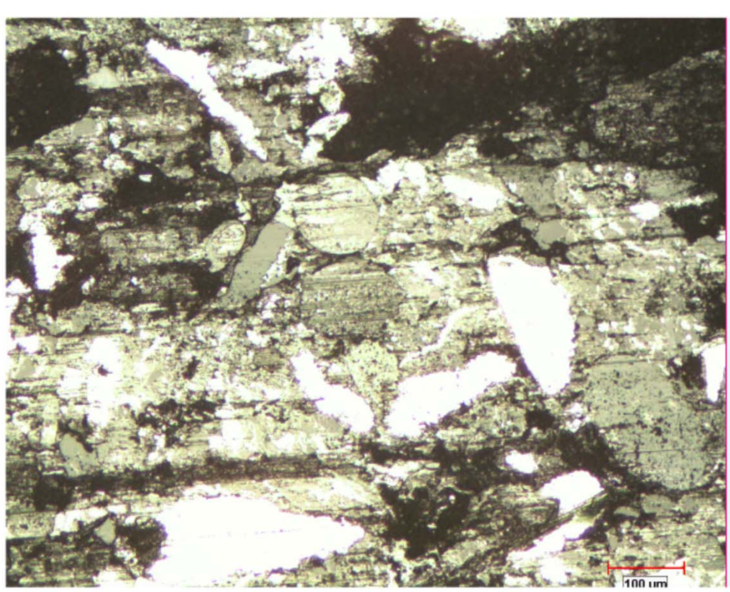


Fig. 8. Variations of friction coefficient according to relative pressure.

effective contact on the sliding surface. The relative contact area occupied by the particles was reduced because when pressure was applied to the surface, the soft elements in the friction material become more exposed to the surface, while the hard particles were pressed into the matrix. There was a significant reduction in the friction coefficients when the pressure was increased. The relationship between the friction coefficients and contact pressure was linear in nature. The difference between 1000 and 3000 cycles could be related with starting friction coefficient value and brake pad surface resistance between two contact areas. This was explained by SAE-J661 sample trial period where 1000 cycles friction coefficient 0.5 μ and 0.7 μ for 3000 braking cycles. Increasing cycles cause serious wear and particle braking away from contact surface and resulting more rough surfaces. Similar results were reported by Tulcidas et al. [27] for various types of particles in reinforced brake pads.

The microstructure of the friction surface of a hazelnut shell dust-reinforced sample is shown in Fig. 9a. The friction surfaces of all samples appeared to be very similar, and were randomly covered with various irregularly dispersed powders. The topography image clearly indicated that the friction contact occurred on the friction layer. The friction layer enrichment with carbonaceous materials was generated from the lignin via thermal decomposition. During the friction process, the pad-disc sliding contact was partially ensured through the thin friction layer [28].

(a)



(b)

Fig. 9. (a) Optical microscopy of new pad with the dusts (b) SEM observation of the friction surface.

4. Conclusions

Compared with other friction testing machines, the developed friction tester can be used effectively to determine the cold and hot friction coefficients, noise level and wear rate of brake pads. The frictional performance of the tester depends strongly on its mechanical design, and hydraulic and automation control systems as well as on rigidly applied testing conditions. The equipment and methods used in developing the brake pad friction tester were proven to be quite advantageous in stabilizing the friction coefficients of the brake pad materials, as well as in improving wear resistance. This friction tester could be used to reduce the time required to determine the friction coefficients and wear rate of brake pad materials while considering their testing conditions, a capability which to date has not been available in any other friction testing machines developed on the same scale.

The eco-friendly brake pads reinforced with hazelnut shell dust were successfully produced and tested, based on SAE J661, using the new friction tester. The friction tester, which was developed to determine the tribological behavior of the organic brake pads, was shown to be adequate under the various test conditions usually observed in a real-life scenario, thus allowing for a true evaluation of the brake pad materials. The uncertainty in measurements for friction coefficient and wear rate has added to ± 0.0135 and ± 0.170 to prove the accuracy of the experiments, respectively. Finally, experimental results showed that the developed friction tester provided a significantly reliable and accurate evaluation of the friction and wear performance of the brake pads produced with organic dusts.

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