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FRICTION AND WEAR OF AUTOMOTIVE FRICTION MATERIALS

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ABSTRACT

The present work discusses the tribological performance of friction composites reinforced by corn and palm fibres at continuous and starting – stopping tests aiming to provide specific relationship between the performances of the two tests. In the friction composites, asbestos is replaced by the corn and palm leaf fibres. The proposed composites contain a mixture of phenolic resin (as matrix), metal powder (iron, copper, and aluminum), graphite, barium sulfate, and silica. Friction coefficient and wear were accurately measured for the two tests (starting-stopping and continuous) to illustrate the effect of the different fibres ingredients and to obtain a relationship between the performances of the two tests. Worn surface of the samples were examined and investigated by SEM scanning electron microscopy for discerning the coherence extent of different agriculture fibres with other components. The tribological properties of the new composite materials were compared with that of three commercial brake linings (brake lining A, brake lining B, and brake lining C), which are Egyptian, Chinese, and Turkish brake linings respectively.

Based on the observations in the present work, it was found that the tested natural fibres can replace asbestos in reinforcing the friction composites, where their friction and wear properties were much better than the commercial brake linings. It was observed that the relationship between the performance of the two tests depends on the fibres content of the composites. The values of wear at continuous test are higher than that of starting – stopping test at the same running distance due to the relatively higher velocity. The results showed that composites containing corn fibres and aluminum powder displayed the highest friction values compared to the other tested composites due to the relatively strong adhesion of corn fibres with aluminum.

KEYWORDS

Friction, wear, automotive friction materials, starting and stopping test, continuous test.

INTRODUCTION

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, [1]. These perform the very same task and claim to be better than others due to their own unique composition.

Automobile braking friction pads are usually composed of more than 10 metallic organic filling and binding ingredients to achieve some acceptable levels of braking objectives (e.g.

maximum value and stability of friction coefficient (μ), solid state lubricity, wear resistance, vibration damping, long life and low initial and maintenance costs). The main solid lubricant constituent is the graphite, whose crystalline structure allows the crystal planes to easily slide over one another without disintegrating as a consequence of the strong bonding forces between individual carbon atoms compared to the relatively weak bonding forces between planes at moderate temperatures, [2 - 4]. At higher temperatures, and due to the increased amounts of adsorbed moisture, the graphite shows a drastic reduction in lubricity and a mild increase in abrasive effects, [5]. The crystalline lamellar structure of graphite allows the crystal planes to slide easily over one another without disintegrating and thus makes it an effective solid lubricant.

An experimental investigation was carried out to examine the tribological behavior of NAO (non-asbestos organic) type brake linings containing different volume ratios of graphite and antimony trisulfide (Sb_2S_3). A scale dynamometer was used for friction tests and particular emphases were given to the effect of applied pressure, sliding speed, and temperature on the coefficient of friction according to the relative amounts of the two solid lubricants, [6]. Results showed that the brake linings with both solid lubricants exhibited better friction stability and less speed sensitivity than the friction materials containing a single solid lubricant. In particular, the brake lining containing higher concentrations of graphite showed better fade resistance than others during high-temperature friction test.

Nowadays however non-asbestos (NAO) formula becomes main stream to overcome the negative effect of asbestos on human respiratory system. A typical brake lining formula includes phenolic resin mixed with metal powder, inorganic fillers and fibres. Natural fibres can replace asbestos in reinforcing the friction materials, [7 - 11]. Eco-friendly brake friction materials were formulated without copper, lead, tin, antimony trisulfide, and whisker materials, [12], to minimize their potential negative environmental impacts. Frictional stability and wear resistance are key performance requirements for heavy truck brake linings. The frictional properties of lining counterface affects the rate of vehicle deceleration, but wear also affects stopping characteristics because uneven or high wear can alter the contact geometry of the lining, change the pattern of frictional heat generation, and degrade the response of the braking system. Inertia dynamometer wear tests are commonly conducted in the linings, [13] industry, but are expensive and time consuming. It is therefore of interest to seek more convenient, lower-cost test methods that still enable wear rates of various linings to be effectively differentiated.

In braking process, kinetic energy is converted to heat energy and the friction lining materials and brake pads absorb this heat energy before being released to the atmosphere, [14]. This accumulated heat energy may cause the automotive friction lining materials to experience high temperatures and this may affect the braking performance. The heat generated in frictional organs like brakes and clutches induces thermal distortions which may lead to localized contact areas and hot spots developments. Hot spots are high thermal gradients on the rubbing surface. They count among the most dangerous phenomena in frictional organs leading to damage and early failure. Hot spots are high thermal gradients on the rubbing surface. It has been shown that the thermo-mechanical solicitation due to these hot spots may induce a cycling of tensile and compressive stresses with plastic strain variations, [15]. Consequently, thermal low cycle fatigue may occur.

Typically, frictional performance is assessed using brake dynamometer testing of full-scale hardware, and the average friction value is then used for the remaining brake system development. This traditional approach yields a hardware-dependent, average friction coefficient that is unavailable in advance of component testing, ruling out true up-front design and leading to redundant lining screening tests. To address this problem, a reduced-scale inertial brake dynamometer was developed to determine the frictional characteristics of lining materials. Design of a reduced-scale dynamometer began with the choice of a scaling relation. In this case, the energy input per unit contact area was held constant between full-scale and reduced-scale hardware. All linear variables were thereby scaled by the square root of the scaling factor, while the pressure, temperature, sliding velocity, and deceleration were kept constant, [16]. Experimental validation of the scaling relations and the reduced-scale dynamometer focused on comparisons with full-scale dynamometer data, particularly the friction coefficient. If similar trends are observed between reduced-scale and full-scale testing, the reduced-scale dynamometer will become an important tool in the up-front design and modeling of brake systems.

The present work discusses the tribological behaviour of the friction composites reinforced by natural fibres at continuous and starting – stopping tests aiming to provide specific relationship between the values of friction and wear observed during the two tests.

EXPERIMENTAL

The test rig used in the present work is a brake dynamometer. The dynamometer has been designed and manufactured to determine the friction coefficient of the tested friction materials. The arrangement of the brake dynamometer is shown in Fig. 1. The dynamometer consists of an electric motor (AC motor of 2.2 KW power and 1500 rpm). Pulley of 50 mm diameter is mounted on motor shaft and drives V – belt drive system. The rotational speed was reduced to 750 rpm. The out put shaft is supported by two bearings. Flywheel of 400 mm diameter and 38 kg weight is mounted to the end of output shaft to achieve inertia of (0.75 kg m^2). Steel disc is assembled to the flywheel of 380 mm outside diameter and 5 mm thickness. Test specimen is held in a specimen holder (chuck) which is mounted in the end of pin supported by load cell to measure the friction force. The contact pressure is applied by weight at the end of the lever. A digital screen is attached to the load cell to detect the friction force. Friction coefficient is determined by the ratio between the friction and the normal forces.

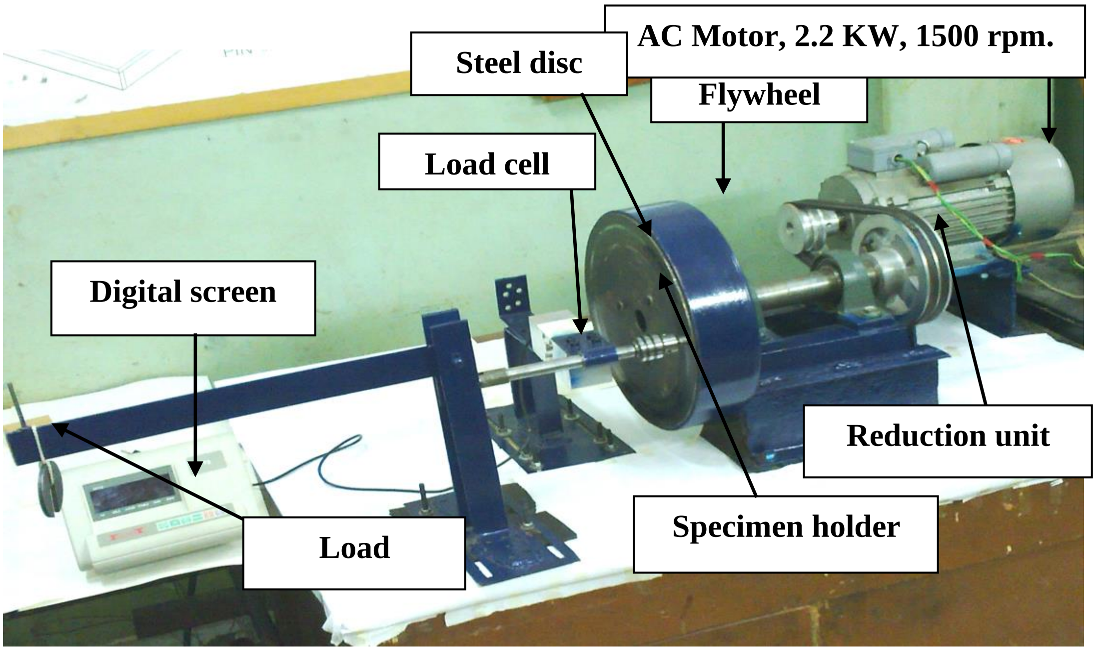


Fig. 1 Arrangement of the brake dynamometer.

The test specimens are asbestos free composites. Test specimens were prepared in the form of a cylindrical pin of 8 mm diameter and 30 mm length. Each specimen contains 20 % wt.

silica, 10 % wt. graphite, and 10 % wt. barium sulfate as well as different contents of organic fibres (corn and palm), metallic powder (Al, Cu and Fe) and phenol formaldehyde resins. The contents of fibres used were 10, 15, 20 and 25 % wt. The Metallic powder contents were 10, 20 and 30 % wt. Test specimens were prepared by the conventional powder metallurgy (P/M) process, which involved the steps of mixing, pressing and sintering.

Two friction tests were carried out at different values of contact pressure. The two tests were continuous and starting - stopping tests. The continuous test was carried out at a constant speed of 12.6 m/s and contact pressure of 1 MPa for sliding time of 60 sec. The starting – stopping test was carried out by starting the dynamometer up to its maximum speed (12.6 m/s) and then stopped to release it motion with its inertia at different values of contact pressure (1, 1.4, and 2.2 MPa). The specimens used contained corn and palm fibres and metallic powder. The tribological properties of the proposed composites were compared with that displayed by three commercial brake linings (brake lining A, brake lining B, and brake lining C), which are Egyptian, Chinese, and Turkish brake linings respectively. For starting – stopping test, the time of stopping is 11, 10 and 9 sec for contact pressure of 1, 1.4 and 2.2 MPa respectively. The material loss of the test specimen during sliding was measured by weighing the specimen before and after test, using electronic balance of ±0.1 mg accuracy. Wear was measured for both the continuous and starting - stopping tests.

RESULTS AND DISCUSSION

The results of friction coefficient are represented in two major types. The first is concerned with tests conducted at continuous tests, whilst the second is concerned with starting and stopping tests. The continuous test was carried out at a constant speed of 12.6 m/s and contact pressure of 1 MPa for a sliding time of 60 sec. The starting – stopping test was carried out by starting the dynamometer up to its maximum speed (12.6 m/s) and then stopped to release it motion with its inertia at different values of contact pressure (1, 1.4, and 2.2 MPa). The specimens used are containing corn, palm fibres and metallic (Al, Cu and Fe) powder.

Figure. 2 shows friction coefficient versus time at continuous test for composites containing corn fibres and 10 % aluminum powder. Composites of 20 % and 25 % corn fibres showed values of friction coefficient up to 0.68 and 0.82 respectively. Those values were higher than that displayed by commercial brake linings. Brake lining A showed friction coefficient up to 0.59, while brake lining B displayed a value of 0.52. Brake lining C displayed lower friction coefficient (0.38) than commercial brake linings. Composites of 15 % corn fibres showed the lowest value of friction coefficient. An increasing trend in friction coefficient was observed as the corn fibres content increased, and this might be attributed to the relatively increased content of the reinforcing material which provided the high strength for the composites. The composites containing 25 % and 20 % corn fibres gave friction coefficient higher than that of commercial brake linings. Figure 3 shows friction coefficient versus time at starting – stopping test for composites containing corn fibres and 10 % aluminum powder. Brake lining B showed the highest friction coefficient value (0.53). A decreasing trend in friction coefficient was observed as the time increased. Brake lining C shows the lowest friction coefficient among composites tested. An increase in friction coefficient was shown as the corn fibres content increased which might be attributed to the increase of the strength of composites. All composites in figure show values of friction coefficient in range within that of commercial brake linings. The values of friction coefficient displayed at continuous test are higher than that displayed at starting – stopping test after duration of 10 Sec.

Composites containing 20 % corn fibres and 30 % copper powder showed the highest friction coefficient at continuous test as shown in Fig. 4. The lowest friction coefficient was obtained for composites containing 10 % corn fiber. A significant increase in friction coefficient was observed as the corn fibres content increased. The friction coefficient slightly decreased with increasing time. In Fig. 6, the maximum values of friction coefficient were observed at 10 wt. % corn fibres for starting – stopping test. Friction coefficient decreased as time increased. All composites containing corn fibres and 30 % copper displayed higher values of friction coefficient than that displayed by commercial brake linings shown in Fig. 2. This observation recommends the application of corn fibres as friction modifier as well as reinforcement in the matrix of the friction composites.

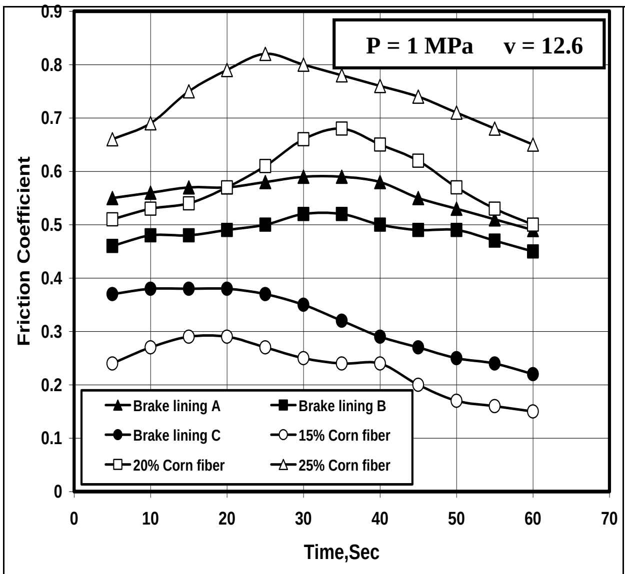


Fig. 2 Friction coefficient - versus time for composites containing corn fibres and 10 % Al, Continuous test.

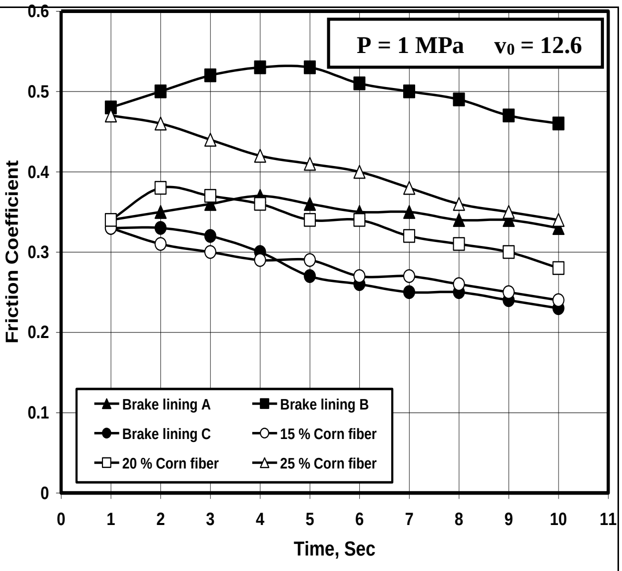


Fig. 3 Friction coefficient - versus time for composites containing corn fibres and 10 % Al, Starting – stopping test.

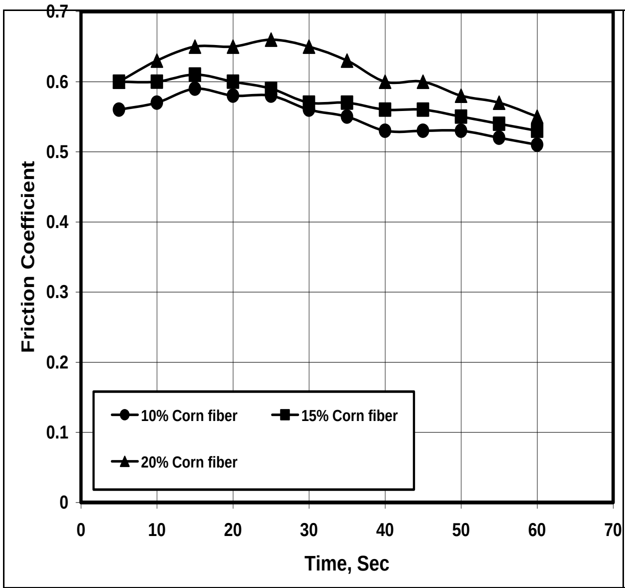


Fig. 4 Friction coefficient - versus time for composites containing corn fibres and 30 % Cu, Continuous test.

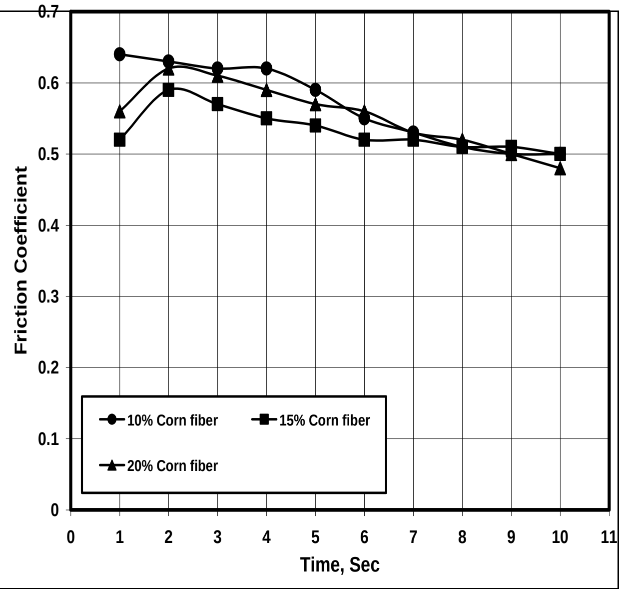


Fig. 5 Friction coefficient - versus time for composites containing corn fibres and 30 % Cu, Starting – stopping test.

The behavior of friction coefficient displayed by continuous test for composites containing corn fibres and 20 % iron powder is shown in Fig. 6. A relatively higher friction coefficient for composites containing 25 % corn fibres was observed. Friction coefficient increased as the corn fibres content increased. For all the tested composites, the friction coefficient was higher than that of other commercial brake linings shown in Fig. 2. Also it can be seen that all composites gave consistent friction during the sliding time. The maximum friction coefficient for composites containing corn fibres and 20 % iron powder was displayed by composites containing 25 % corn fiber at starting – stopping test, Fig. 7. Friction coefficient decreased as the time increased. The lowest friction coefficient among composites shown was displayed by composites containing 15 % corn fibres. Composites containing 10 %, 20 % and 25 % corn fibres showed higher friction coefficient than that displayed by commercial brake linings.

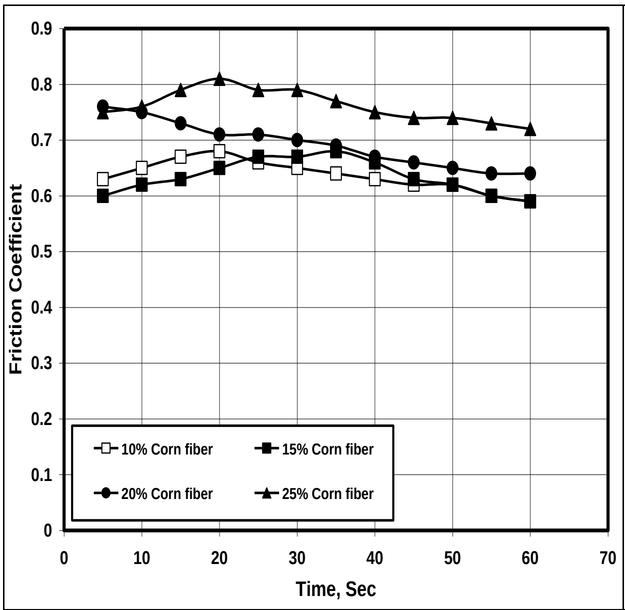


Fig. 6 Friction coefficient - versus time for composites containing corn fibres and 20 % Fe, Continuous test.

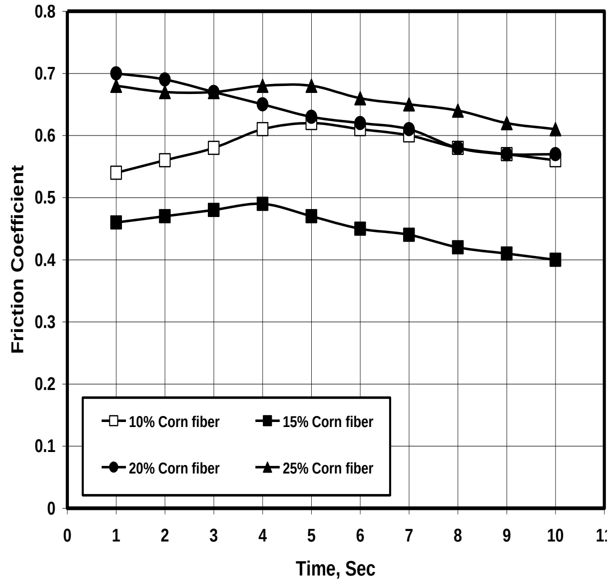


Fig. 7 Friction coefficient - versus time for composites containing corn fibres and 20 % Fe, Starting – stopping test.

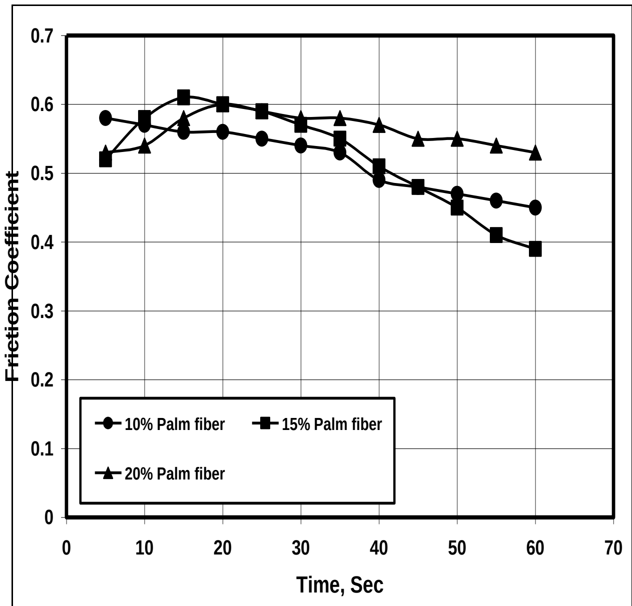


Fig. 8 Friction coefficient - versus time for composites containing palm fibres and 30 % Al, Continuous test.

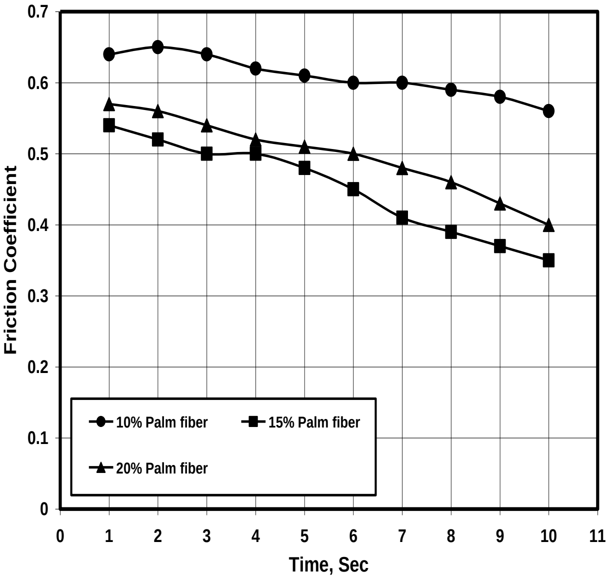


Fig. 9 Friction coefficient - versus time for composites containing palm fibres and 30 % Al, Starting – stopping test.

Friction coefficient displayed by continuous test for composites containing palm fibres and 30 % aluminum is shown in Fig. 8. The average value of friction coefficient for all composites was the same and equal to 0.55. This value was higher than that of brake linings B and C. The friction coefficient decreased with increasing time. The strong bond of composites tested at starting – stopping test and containing 10 % palm fibres and 30 % aluminum powder provided values of friction coefficient up to 0.65 as shown in Fig. 9. It can be seen that coefficient of friction decreased as the time increased. Composites containing 15 % palm fibres showed the lowest friction coefficient among the tested composites. Composites containing 15 % palm fibres and 10 % copper powder showed relatively higher friction coefficient at continuous test, Fig. 10. The lowest friction coefficient was obtained for composites containing 25 % palm fibres. Friction coefficient increased as the palm fibres content decreased. All composites displayed higher friction coefficient than that displayed by the other commercial brake linings. It can be noticed that all composites showed consistent friction during the sliding time. According to Fig. 11, composites tested by starting – stopping test containing 15 % palm fibres and 10 % copper powder showed values of friction coefficient up to 0.77, which was higher than that displayed by commercial brake linings. It can be seen that friction coefficient slightly decreased as the time increased. Friction coefficient increased as the palm fibres content decreased which indicated the good adhesion of the fibres inside the matrix of the friction material.

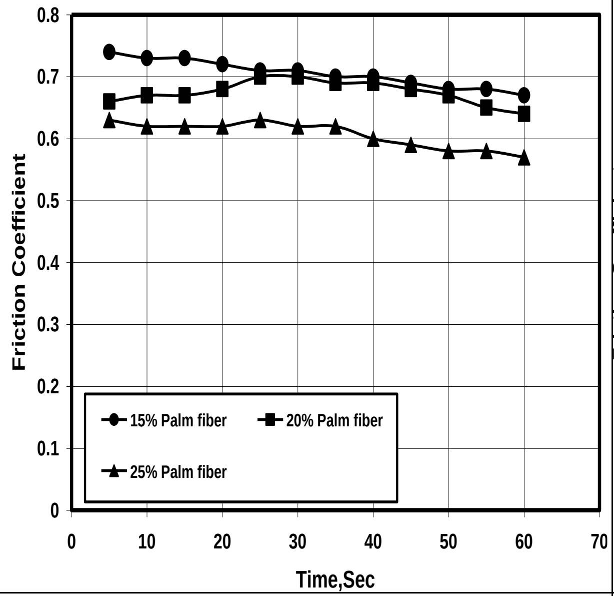


Fig. 10 Friction coefficient - versus time for composites containing palm fibres and 10 % Cu, Continuous test.

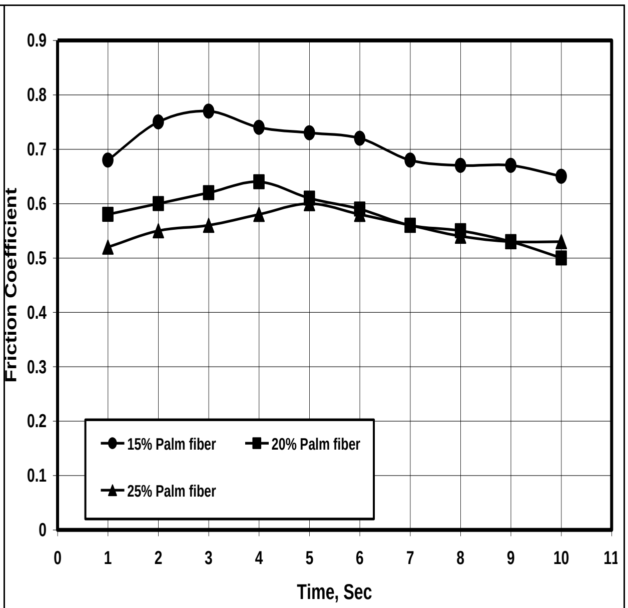


Fig. 11 Friction coefficient - versus time for composites containing palm fibres and 10 % Cu, Starting – stopping test.

For composites tested by continuous test and containing palm fibres and 30 % iron powder, the values of friction coefficient are obtained in Fig. 12. The figure showed significant increase in friction coefficient as the palm fibres content increased except for composites containing of 20 % palm fiber which may be attributed to a weak adhesion between bonding material and fibres. It can be seen that friction coefficient decreased with increasing time for composites containing 10 % palm fibres. Composites tested by starting – stopping test and containing 10 % and 15 % palm fiber and 30 % iron powder showed relatively higher friction coefficient, Fig. 13. Friction coefficient slightly decreased as the time increased. Composites containing 20 % palm fibres showed the lowest values of friction coefficient due to the waxy layer of the palm fibres.

After studying friction coefficient for continuous and stopping tests, it can be concluded that the ratio between friction coefficient displayed in starting – stopping and continuous test

$(\mu_{stopping} / \mu_{continuous})$ depends on the fibres content in composites. This ratio was displayed for starting – stopping and continuous test at a time of 10 second as shown in Figs. 14 and 15. A relationship can be extracted to give specific information about the comparison between tests carried out on pin on disc and dynamometer. Table 1 shows a useful relationship between the results of friction coefficient obtained from starting – stopping and continuous test.

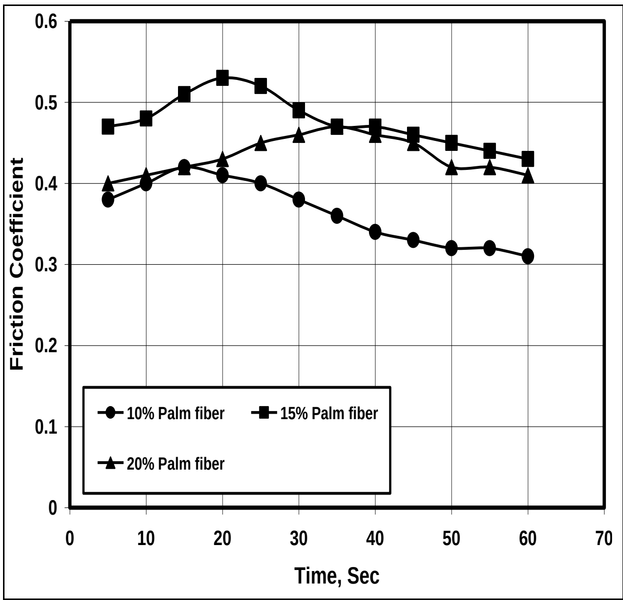


Fig. 12 Friction coefficient - versus time for composites containing palm fibres and 30 % Fe, Continuous test.

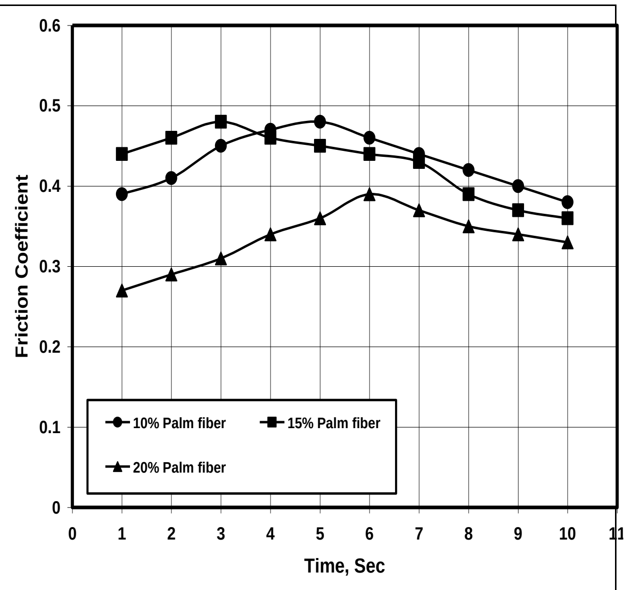


Fig. 13 Friction coefficient - versus time for composites containing palm fibres and 30 % Fe, Starting – stopping test

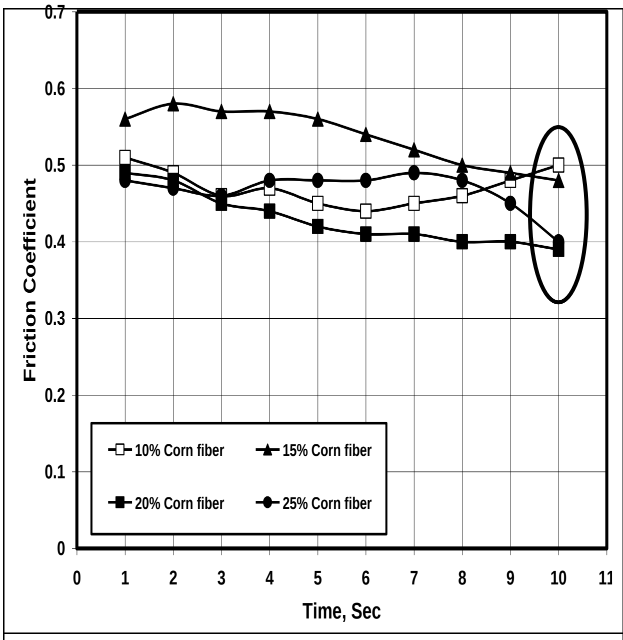


Fig. 14 Friction coefficient - versus time for composites containing corn fibres and 20 % Al, Starting – stopping test.

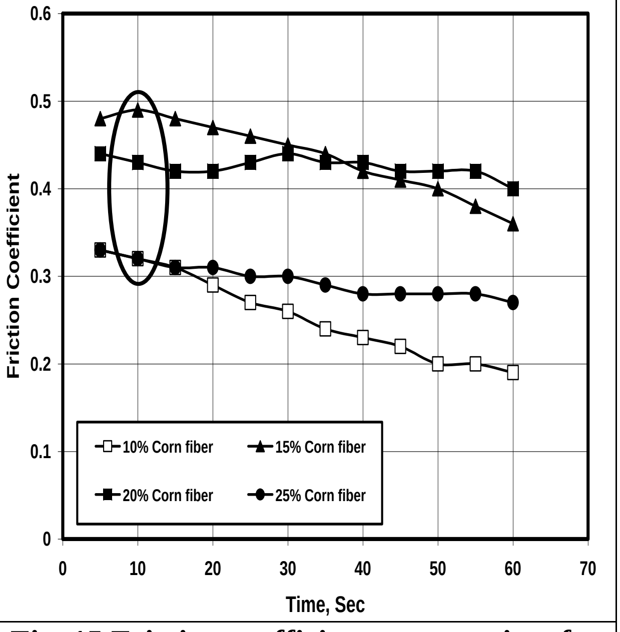


Fig. 15 Friction coefficient - versus time for composites containing corn fibres and 20 % Al, Continuous test.

Table 1. The relationship between starting – stopping and continuous test.

Fibres contents %	$(\mu_{stopping} / \mu_{continuous})$ at 10 sec
10	0.85 – 1.20
15	0.70 – 0.95

20		**0.65 – 0.90**
25		**0.50 – 0.90**
Without natural fiber	**Brake lining A and C**	**0.60**
	Brake lining B	**0.95**

From the above Table, it can be concluded that the ($\mu_{stopping} / \mu_{continuous}$) ratio decreased with increasing fibres content in composites. Composites without natural fibres such as commercial brake lining A and C displayed the same friction ratio (0.6). But brake lining B obtained a ratio of 0.95. Figure 16 showed the relationship between friction coefficient displayed in starting – stopping ($\mu_{stopping}$) and continuous ($\mu_{continuous}$) tests. It can be noticed that the friction ratio ($\mu_{stopping} / \mu_{continuous}$) decreased with increasing fibres content. For composites containing 10 % natural fibres, 93 % of test specimens displayed ($\mu_{stopping} / \mu_{continuous}$) ratio in range of (0.85 to 1.2) and the average ratio was 1.05. For composites containing 15 % natural fibres, 87 % of test specimens displayed ($\mu_{stopping} / \mu_{continuous}$) ratio in range of (0.7 to 0.95) and the average ratio was 0.86. For composites containing 20 % natural fibres, 85 % of test specimens displayed ($\mu_{stopping} / \mu_{continuous}$) ratio in range of (0.65 to 0.9) and the average ratio was 0.82. For composites containing 25 % natural fibres, 80 % of test specimens displayed ($\mu_{stopping} / \mu_{continuous}$) ratio in range of (0.5 to 0.9) and the average ratio was 0.75.

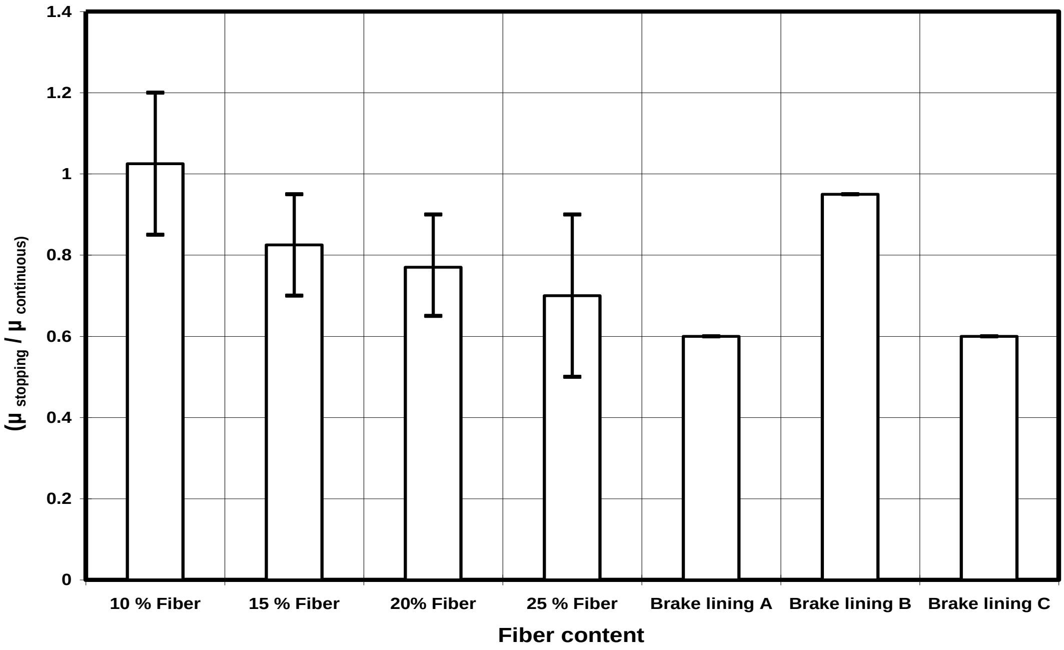


Fig. 16 Relationship between friction coefficient displayed in starting – stopping and continuous test.

Wear of brake pads is strictly correlated with pad lifetime, and it is an important development issue for car brake manufacture. Here, comparison between wear deduced from continuous (v = 12.6 m/s) and also from starting – stopping test (v_0 = 12.6 m/s, a = - 1.454 m/s^2) was made at the same running distance. Figure 17 showed the wear of composites containing corn fibres and 10 % aluminum powder. It can be seen that the values of wear at continuous test were higher than that observed from starting – stopping test at the same running distance due to the relatively higher velocity. Composites containing 15 % corn fibres showed the lower values of wear (9 mg for continuous and 8 mg for stopping) than that of other commercial brake lining due to the good adhesion of the fibres to the bonding material. On the other side, composites containing 25 % corn fibres showed relatively higher wear at continuous test. The increase of wear may be attributed to low content of aluminum powder and bonding material. The values of wear for commercial brake linings at the two tests are shown in Table 2. Wear for composites containing palm fibres and 20 % iron powder is shown in Fig. 18. It can be noticed that the values of wear at continuous test were higher than that of starting – stopping test at the same running distance due to the relatively higher velocity. Composites containing 20 % palm fibres showed quite good wear resistance for stopping test. A higher value of wear among composites tested was obtained for composites containing 25 % palm fibres due to the reduction of adhesion between bonding material and fibres. All of composites shown for continuous and stopping test gave good wear resistance. After studying the comparison between wear for continuous and stopping tests, it can concluded that the ratio between wear displayed by starting – stopping test and that displayed by continuous test (Wear $_{\text{stopping}}$ / Wear $_{\text{continuous}}$) depends on the fibres content in composites. A relationship can be extracted from the results obtained from starting and continuous tests to give specific information helps in the comparison between tests carried out on pin on disc and dynamometer. Table 3 shows the relationship between starting – stopping and continuous test.

Table 2. Values of wear for commercial brake linings at the same running distance.

Commercial brake linings.	Wear for continuous test (mg)	Wear for starting – stopping test (mg)
Brake lining A	51.75	15
Brake lining B	63	20
Brake lining C	13.5	5

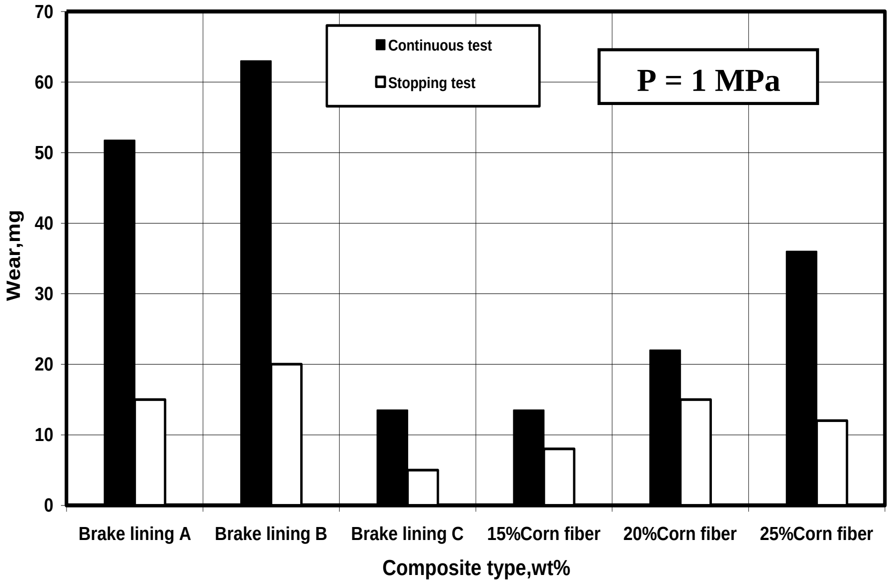


Fig. 17 Wear of composites containing corn fibres and 10 % Al.

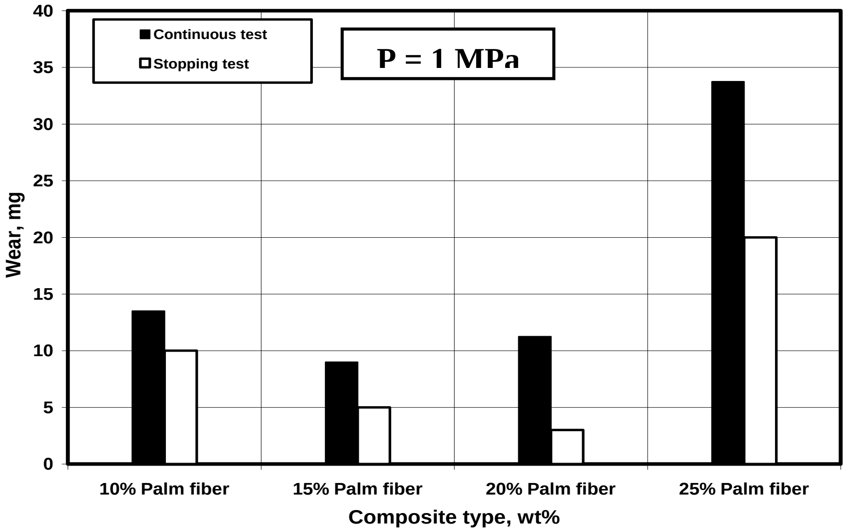


Fig. 18 Wear of composites containing palm fibres and 20 % Fe.

Table 3. Relationship between wear displayed in starting – stopping and continuous test at the same running distance.

Fibres content %		**(Wear$_{\text{stopping}}$ / Wear$_{\text{continuous}}$)**
10		**0.44 – 0.80**
15		**0.20– 0.70**
20		**0.20 – 0.60**
25		**0.10 – 0.55**
Without natural fibres	**Brake lining A**	**0.29**
	Brake lining B	**0.31**
	Brake lining C	**0.37**

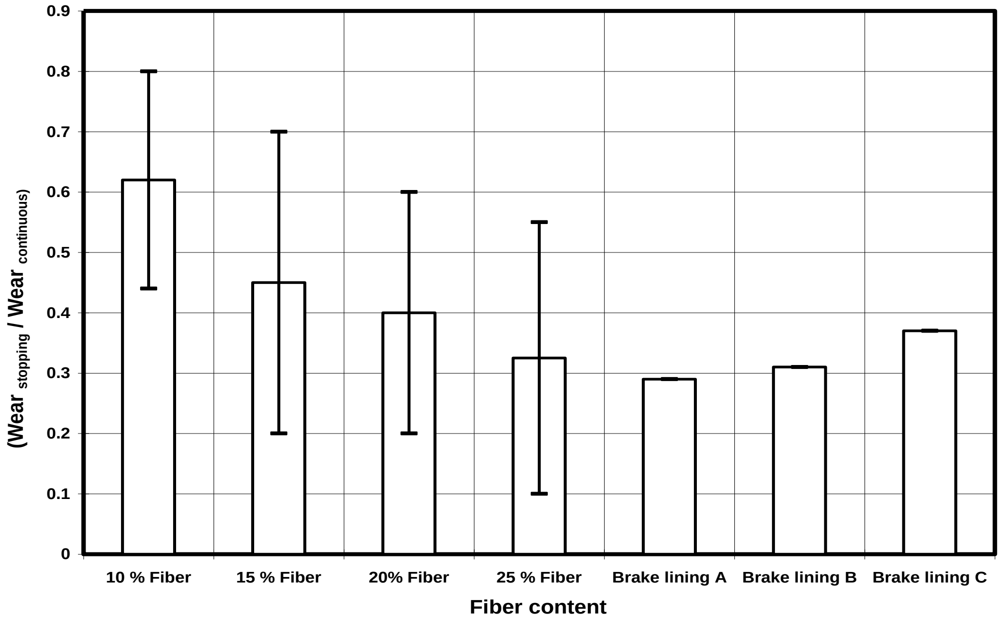
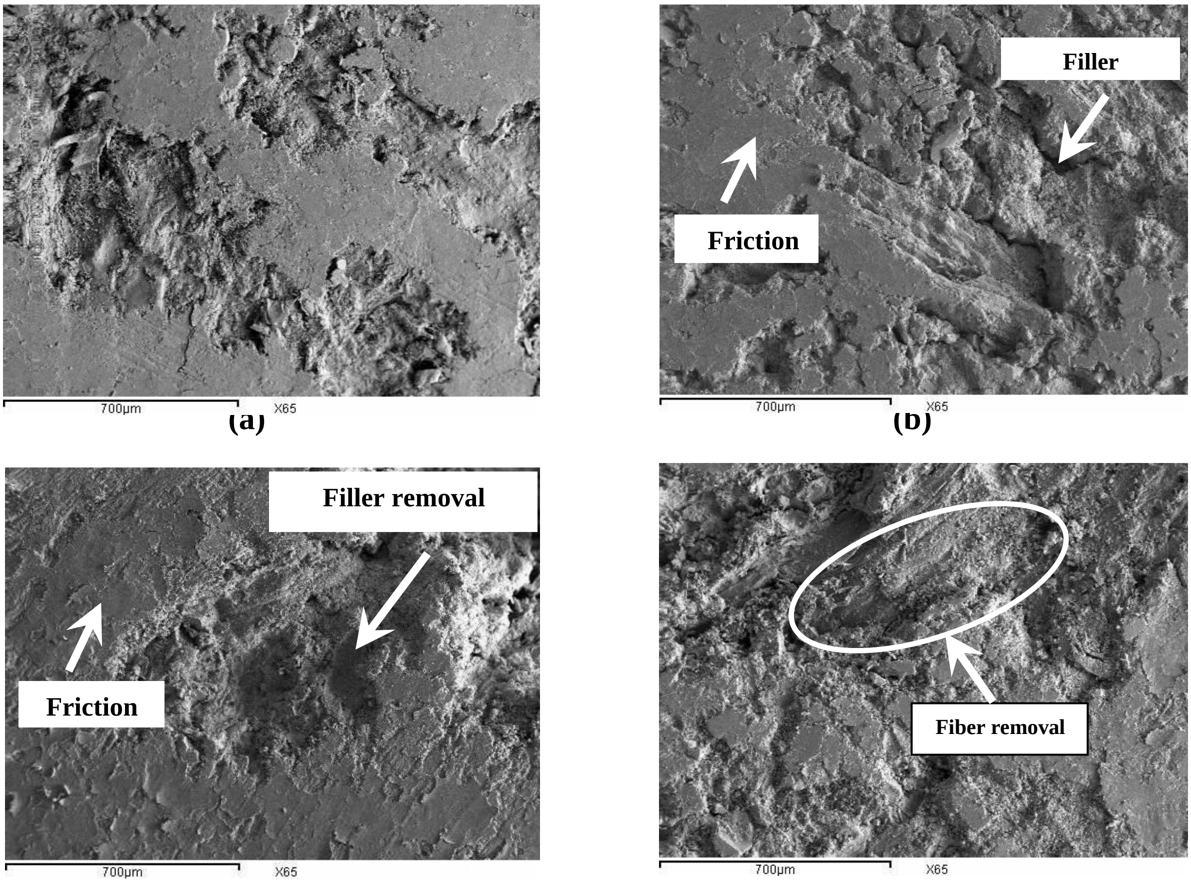


Fig. 19 The relationship between wear displayed in starting – stopping and continuous test.

From Table 3, it can be seen that wear ratio (Wear$_{\text{stopping}}$ / Wear$_{\text{continuous}}$) decreased with increasing fibres content in composites. Composites without natural fibres such as brake linings A, B and C displayed wear ratio of 0.3 approximately. Figure 19 showed the relationship between starting – stopping and continuous test performance. For composites containing 10 % natural fibres, the wear ratio (Wear$_{\text{stopping}}$ / Wear$_{\text{continuous}}$) was in range of (0.44 to 0.8) and the average ratio was 0.59. For composites containing 15 % natural fibres, the wear ratio (Wear$_{\text{stopping}}$ / Wear$_{\text{continuous}}$) was in range of (0.2 to 0.7) and the average ratio was 0.53. For composites containing 20 % natural fibres, the wear ratio (Wear$_{\text{stopping}}$ / Wear$_{\text{continuous}}$) was in range of (0.2 to 0.6) and the average ratio was 0.34. For composites containing

25 % natural fibres, the wear ratio (Wear $_{\text{stopping}}$ / Wear $_{\text{continuous}}$) was in range of (0.1 to 0.55) and the average ratio was 0.33.

Scanning electron microscopy (SEM) was used to examine the friction surface of the tested specimens. SEM micrographs of selected specimens are illustrated in Fig. 20 after the tests.
The worn surface of the test specimen containing 15 % corn fibres and 30 % Cu after wear test at speed of 12.6 m/s and contact pressure of 1 MPa is shown, Fig. 20, a, where the good wear resistance produced durable and smooth friction film. The worn surface of test specimen containing 10 % palm fibres and 20 % Fe after wear test at speed of 12.6 m/s and contact pressure of 1 MPa is shown in Fig. 20, b, where the friction film and filler removal were shown. Deep wear tracks were observed on the wear surface of the specimen which was attributed to the weak binding between palm fibres and resin. Severe matrix failure is observed due to waxed fiber nature; hence less fiber matrix adhesion was expected. The worn surface of the specimen containing 15 % corn fibres and 30 % Al after wear test is shown in Fig. 20, c. The voids were expected to be due to loosening of fibres and metallic particles during the wear test. Matrix failure and fiber removal shown in Fig. 20, d, were observed from the worn surface of a specimen containing 20 % corn fibres and 30 % Fe after wear test.



(a) (b)

(c) (d)

Fig. 20 SEM micrograph of some tested specimen

CONCLUSIONS

Based on the experiments carried out in the present work, the following conclusions can be withdrawn:

1. The relation ship between starting – stopping and continuous test performance depends on the fibres content inside the composites.

2. The ratio between friction coefficient displayed by starting – stopping and that displayed by continuous test decreased with increasing the fibres content inside the composites due to increasing the strength.
3. The ratio between wear displayed by starting – stopping and that displayed by continuous test depends on the fibres content inside the composites and decreased with increasing fiber content.
4. The best wear resistance was displayed by composites containing 15 % palm fibres with 20 % iron powder for each starting – stopping and continuous tests.
5. The corn fibres gave the highest friction coefficient with aluminum powder at continuous and starting – stopping test due to the relatively strong adhesion of corn with aluminum.
6. The best results were displayed by composites containing 25 % corn fibres with 10 % aluminum powder for each starting – stopping and continuous tests.

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