EFFECT OF HARD PARTICLE GRIFT SIZE ON FRICTION COEFFICENTS AND EMBEDMENT OF AUTOMOTIVE BRAKING SYSTEM

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ABSTRACT

The effect of hard particle grit size on friction coefficients and particle embedment of braking system was investigated using a model brake test rig. Silica sand grit sizes ranging from 180 - 355 µm were used in drag and stop mode braking application and results were compared to the tests without the grit particles in order to determine the changes in friction coefficient (CoF) and the percentage of particle embedment. Sliding speeds of 4 m/s, 8 m/s, 10 m/s and 12 m/s at constant pressures of 0.6 MPa, 0.8 MPa and 1 MPa were applied during the tests. Results showed that the presence of hard particles and grit size has significant effect on the CoF values. The values of CoF tend to reduce when grit particles are present. However, CoF values increase with sliding speed and applied pressure. Wear debris and particle embedment of silica sand was analyzed using SEM and optical microscopy after the test. Particle embedment (PE) of 1- 2 % of the pad area was observed. Fragmentation of hard particle has occurred only at high applied pressures. Also correlation between PE and CoF values was found to be slightly an inverse relationship as small reduction of CoF values with higher percentage of PE was determined.

Keywords: *Braking systems, hard particles grit size, friction coefficients, particle embedment, silica sand*

1.0 INTRODUCTION

The open design and the position of the disc brake close to the road surfaces is often linked to the presence of dirt and hard particles derived from the environment. Hard particles of different sizes and shapes together with other contaminants from outside can enter the brake gap and cause increase or decrease in average friction force and momentary peak values of friction force at the braking interface [1]. Factors such as humidity, presence of dirt and hard particles from the environment can result in the disturbance of the tribological characteristics at the friction interface. They affect not only the tribological processes but also the braking effectiveness. Therefore, these difficult to control

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factors, i.e. dirt and hard particles, represent the serious tribological problems during braking operations [2].

The operation of automotive disc brake is challenging since its function is not only to stop the vehicle at appropriate distance and time, but also to maintain stability, minimum wear, no noise and low emission requirements [3]. The public concern of the health issues and environmental pollution from the brakes has resulted in many changes of the brake pad material composition and design by the brake manufacturers [4-6] . However, the problem associated with brake noise and brake wear are still far from being solved. In addition, the friction behavior during the braking operation is still not yet a fully understood problem. The demand for the coefficient of friction (CoF) to be relatively high but most importantly stable remains a challenging issue for braking research communities. The CoF should be stable irrespective of temperature, humidity, age of the pads, degree of wear and corrosion, the presence of dirt and water spraying from the road [7]. Thus, brake frictional materials are designed to provide stable frictional performance over a range of vehicle operating conditions and to exhibit acceptable durability.During automotive braking, the abrasion at the friction interface is generally caused by hard particles that are included in the brake pad compositions. At the brake interface two modes of abrasion, i.e. two and three bodies can be presented. Some embedded hard particles tend to abrade and function as two body abrasion while the wear debris and other contaminants entering the gap at the brake interface act in three body abrasion mode. The modes of abrasion often changes from two body to three body mode or vice versa [8]. However, during braking, the effect of two-bodies abrasion tends to be a dominating mechanism while the component of three-bodies abrasion is rather small [9]. According to Axen et al. [10] the prerequisite for the two to three body abrasion transition to take place is that the hard particles are sufficiently strong to resist the shearing forces. If the hard particles are crushed then no cutting can take place. Therefore, the abrasion modes and transition between the two and three abrasion modes are important in determining the friction and wear performance of the braking system and they depend on the factors such as particle size, shape volume percent, and particle-matrix bonding strength [11-13] Most manufacturers use abrasive to control the level of friction force, to improve the grip, and to control transfer films build up at the sliding interface [14]. Transfer film build up is due to compaction and agglomeration of the wear particles that remain in the contact. They form the secondary contact plateau and change with time rapidly. Therefore, the transfer films play an important role in brake efficiency and stability. These films are highly dependent on the braking condition and the composition of the brake material [15, 16]. Thus, to understand in detail the transfer film behaviors and characteristics, more information is needed to fully utilize its presence at the brake interface. In general, the main assumption is that the transfer film or third body layers that develop differ in composition from both mating parts of the tribological couple [17].

Despite the fact that brakes operate under a variety of environmental conditions, many laboratory tests for brake materials are conducted in dry conditions and only limited studies included the wet braking conditions [18]. However, studies of the effect of presence of particles and contaminants on the braking system from environment are rather limited in the tribological literature. In addition, most laboratory tests use horizontal pin-on-disk rig which differ from the real orientation of automotive braking system.

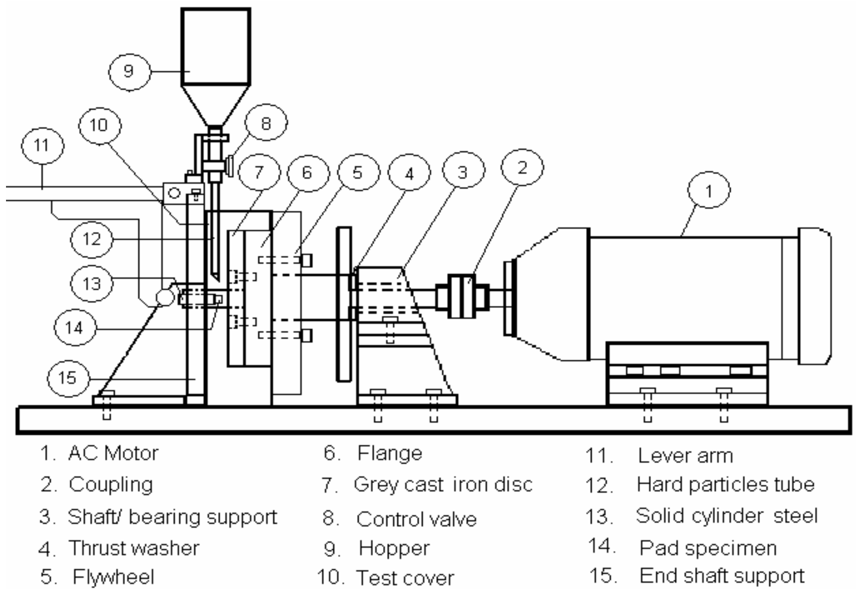
This work is focused on the studies of the effect of hard particles grit size from the environment, i.e. the silica sand, on the friction coefficients and particle embedment of braking system. Experiments were carried out using specially developed model brake test rig at different sliding speeds and applied contact pressures in order to evaluate the particle embedment, to compare the change in friction coefficient and to determine the correlation between particle embedment with CoF using two modes of braking, i.e. the drag and stop modes. Analysis of the fluctuation of friction coefficient was carried out to find possible correlation between presence of hard particles, sliding speeds and applied pressures.

2.0 EXPERIMENTAL WORK

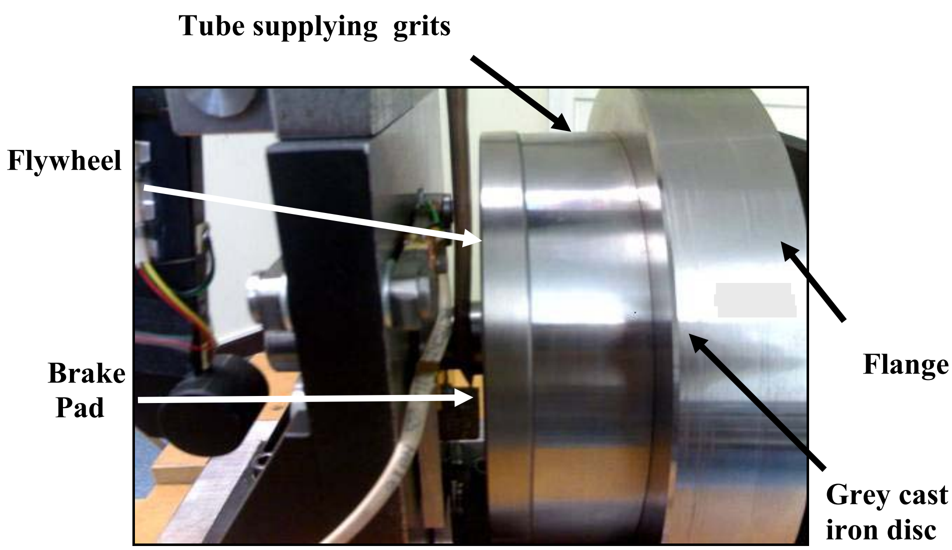
2.1 Brake Test Rig

A specially developed brake test rig was used to conduct the experiments under controlled braking conditions. The test rig consists of a 1 h.p., three-phase, variable speed induction motor (from Baldor) driving a grey cast iron disc mounted vertically on the shaft. This arrangement is to better simulate the contacts encountered during the real brake operation compared to the horizontal pin-on-disc laboratory brake tribotesting. Delta Electronics high performance VF-D series AC motor drive is used to control the speed of the induction motor. A flange and flywheel made of steel are mounted next to the disc brake to ensure better deflection resistance and inertia effect. To absorb any applied force to the motor, a thrust-washer is also used. Solid cylinder steel is used to hold the brake pad and is positioned to the rotating disc at the 3 o'clock position.

A mechanical weight loading system is used to apply braking force to the brake pad specimen via solid cylinder steel. Full bridge strain gauges are fitted to the lever arm and inner side of the end shaft support to record the instantaneous normal force and friction force at the brake interface. A small hopper is fitted at the end shaft support to supply the hard particles through a particle feeder tube which directs the hard particles to the brake gap. A manually control valve is used for regulating the amount of hard particles needed for the test and a transparent cover is used to avoid splashing of the hard particles during the experiments. The schematic diagram with the photo of the test rig is shown in Figure 1.



(a)



(b)

Figure 1: Schematic diagram (a) and picture of the brake test rig (b) used for the drag tests.

2.2 Preparation of Testing Materials

Small squares of 12.7×12.7 mm^2, cut out from a commercial car brake pad, were used in all the experiments. The brake pad total thickness, including the backing plate, is approximately 9 mm. The brake disc is 160 mm in diameter and 10 mm thick, is machined from grey cast iron plate and is a non-ventilated disc type. The radial distance from the center of the pad specimen to the center of the turning disc was 63.65 mm. The arithmetic surface roughness of the discs (R_a), was measured before and after the brake test with a Talysurf profilometer. The pad material was analyzed using EDS and is in the mixture of shiny metallic constituents of steel fiber, barium sulphate and non-metallic particles of silicon oxide within a polymeric binder of phenolic resin as shown in Figure 2. Grey cast iron disc material contains graphite flakes which suggest a typical cast dendritic microstructure [19].

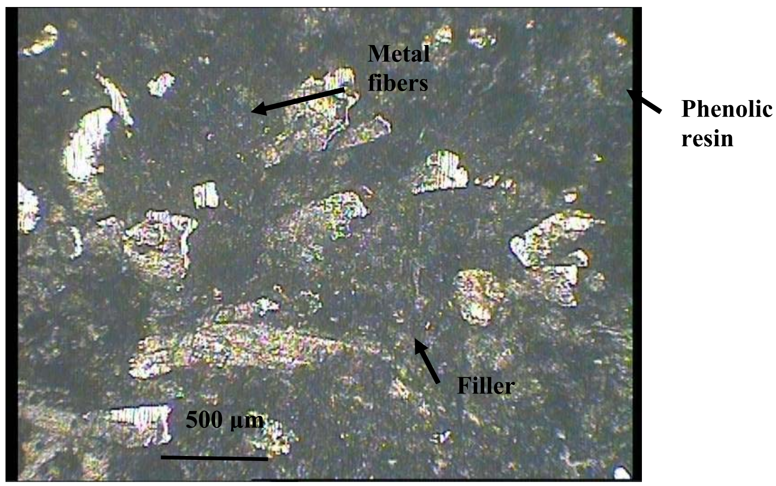


Figure 2: Brake pad random distribution of metal fibers (shiny), fillers (long shape) and binders (dark area) at 20x magnification

Four different sliding speeds of 4 m/s, 8 m/s, 10 m/s and 12 m/s at constant pressures of 0.6 MPa, 0.8 MPa and 1 MPa were used to evaluate the hard particles effects on the change of friction coefficient and particle embedment. Change of CoF values is normally related to the consistency of friction force at sliding interface also known as the friction stability. Thus, friction stability is normally used as an indicator of good braking, since to have a good friction stability means to maintain same level of friction force at different braking conditions. Analysis of the particle embedment was conducted using SEM and optical microscopy to determine the percentage area of particle embedment and to study its relationship with CoF values at different sliding speeds and applied pressures. The details of the tests conducted are shown in Table 1.

Table 1: Testing details for short and hard braking test.

	Short braking (With and without 180-355 µm hard particles)	Hard braking (With and without 180-355 µm hard particles)
Pressure (MPa)	0.6, 0.8	1
Speed (m/s)	4, 8, 10, 12	4, 8, 10, 12
Frequency	3x10s*	3x**

*10 [s] braking is applied for three times.
**braking is applied until the disc stop for three times

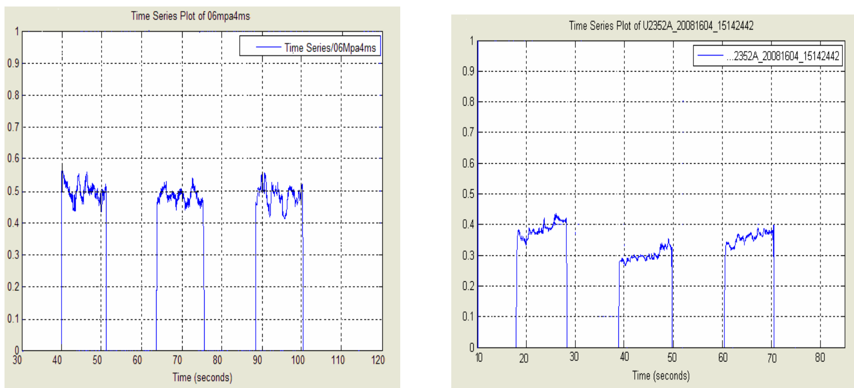
Agilent U2300A Series USB multifunction data acquisition system was used for test data collections. Sliding speed, pad normal force, friction force, and instantaneous friction coefficient were recorded for all the tests. A data sampling rate of 120 Hz was used for all the experiments. Test data was then analyzed and displayed using MATLAB.

3.0 RESULT AND DISCUSSION

3.1 Effect of Hard Particle and Speed on Friction Stability

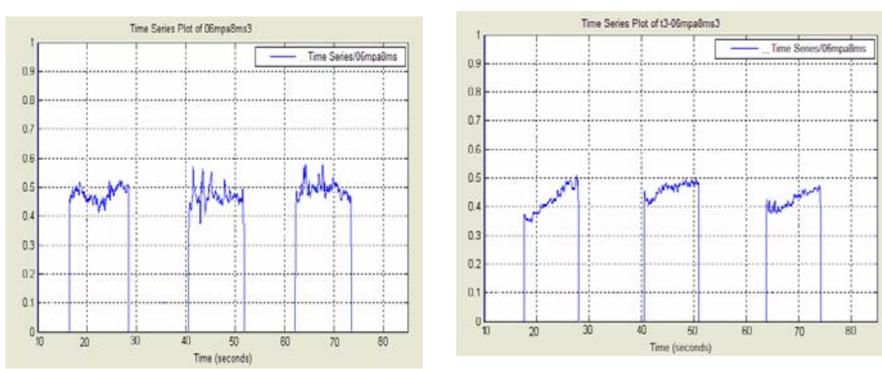
The hard particle effects on friction stability was analyzed and compared to the case where no hard particle was present. Silica sand at a rate of 2.5 $gram.s^{-1}$ was delivered to the brake gap and short duration braking of 10 [s] was applied three times for every test to capture the changes of CoF. Figure 3 and 4 show the changes of CoF measured at 4 m/s (low) and 8 m/s (medium) sliding speeds during the drag test at constant pressure of 0.6 MPa with and without the hard particles. The figure shows that the presence of hard particle tends to lower the CoF especially at lower sliding speed. Average CoF values were reduced to about 0.31-0.38 from 0.47-0.52 for low sliding speed with hard particles present and for medium speed CoF was reduced to minimum average of 0.41-0.47 from 0.52-0.50. This is due to the changes of the effective contact area as the hard particles entered the sliding contact. Hard particles reduce the effective contact area as they themselves become the main contact plateau as shown in the illustration in Figure 5.

The presence of hard particles change the friction mating couple and contact interactions as the interactions are not only between the pad and the disc but with hard particle in between [20] . The hard particles reduced the original effective contact area at the sliding interface by forming the effective contact area themselves before they mixed with other wear debris. Also, at low speeds hard particle had more time to embed and change the effective contact area. The abrupt changes of CoF at the beginning, for both with and without the presence of hard particles, are also related to growth of effective contact area. The CoF values change as the contact plateaus and gaps that form the effective contact area change. Increase in effective contact area results in a higher friction force and this also depends on the compositions of the brake pad and the sliding conditions [21]. However, the CoF values tend to stabilize or reach steady state at later time. In Figure 4, presence of hard particles at medium sliding speed has similar effect but with smaller reduction in CoF. Increase from low to medium speed tends to reduce the effect of hard particles on the CoF values as they moved and mixed with other wear debris more rapidly.



(a) (b)

Figure 3: CoF values at 4 m/s and 0.6 MPa (a) without hard particles and (b) with 180-355 µm hard particles



(a) (b)

Figure 4: CoF values at 8 m/s and 0.6 MPa (a) without hard particles and (b) with 180-355 µm hard particles

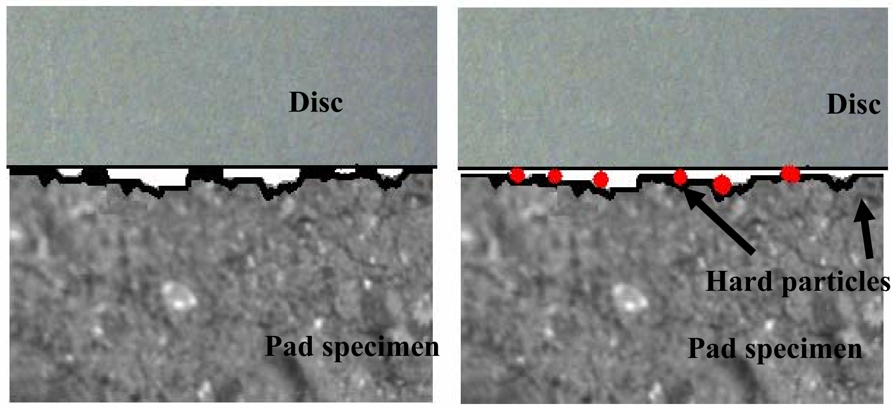
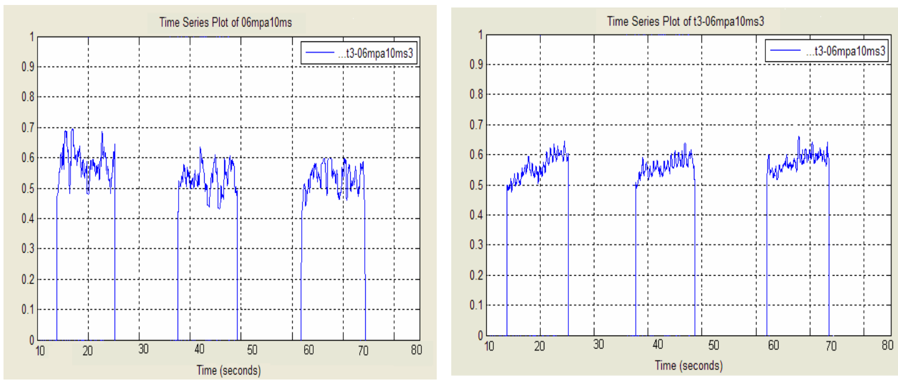


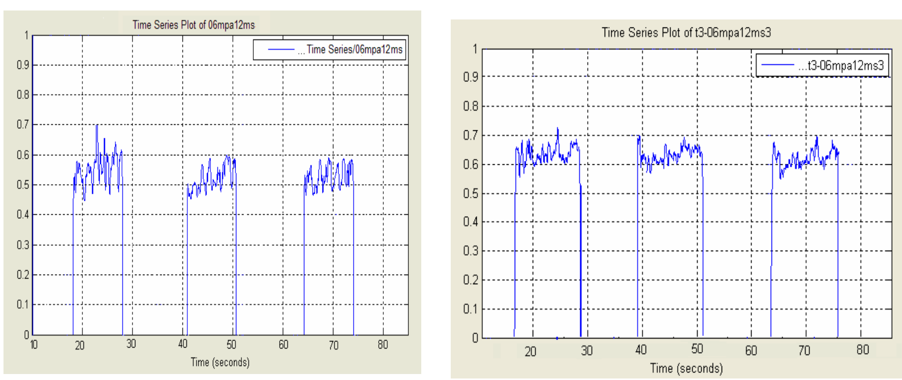
Figure 5: Illustration of how presence of hard particles changes the effective contact areas

Drag test results at higher sliding speeds are shown in Figures 6 and 7. The CoF values for the tests with and without hard particles are higher than for low and medium speed cases. However, compared to the case without hard particles, the CoF values for the test with hard particles of the size between 180 - 355 μm were increased at speeds of 10 m/s and 12 m/s. At higher speed, the hard particle grit size started to significantly affect the CoF values and this is due to their active role in the formation of effective contact area. This results in rapid growth of the effective contact area since these small hard particles roll and mix faster with other wear debris. Thus, they provide reinforcement to the contact area and generate more secondary contact plateaus at the sliding interface. Secondary plateaus composed of compacted wear debris are observed by Eriksson et al. [9]. Higher sliding speed helps to accelerate the rolling and mixing process, with hard particles forming primary contact plateaus themselves and assist in the generation of secondary contact plateaus. Figure 8 shows the primary and secondary contact plateaus at brake pad interface.



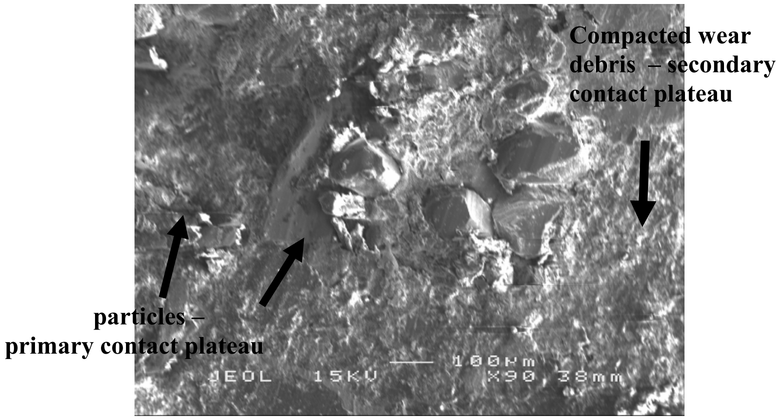
(a) (b)

Figure 6: CoF values at 10 m/s and 0.6 MPa (a) without hard particles and (b) with 180-355 µm hard particles

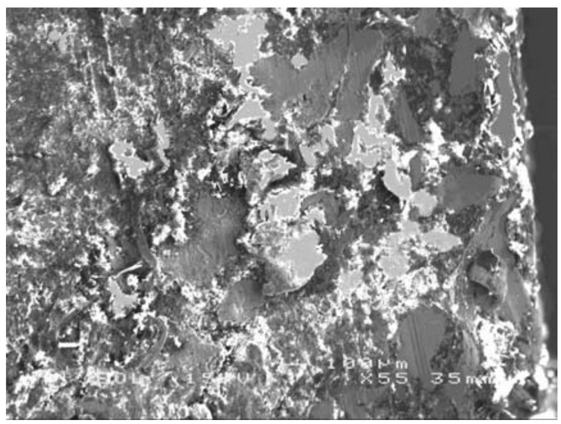


(a) (b)

Figure 7: CoF values at 12 m/s and 0.6 MPa (a) without hard particles and (b) with 180-355 µm hard particles



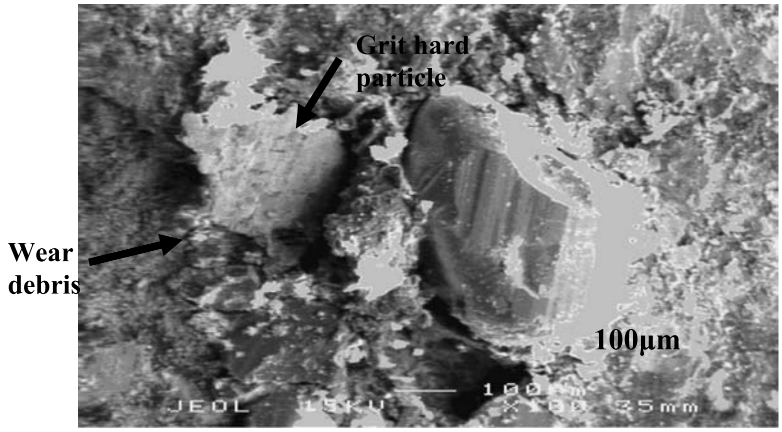
(a)



(b)

Figure 8: SEM images of (a) few embedded hard particles as primary contact plateau and (b) wear debris as secondary contact plateau at pad interface

The stabilization of CoF is related to the formation of secondary contact plateau at the friction interface [22]. Presence of secondary contact plateaus helps to form a stable friction film and thus, braking interface experience lesser disturbance. In addition, embedment of hard particles and wear debris was observed on the brake pad in Figure 9 (a). The embedment of hard particles tends to increase the generation of wear debris because the embedded hard particles will slide against the disc in greater proportion of time. This will enhance the damage of the disc [23]. Wear grooves on the disc caused by the embedded hard particle are shown in Figure 9 (b). The CoF values for drag tests at contact pressure of 0.6 MPa are shown in Table 2.



(a)

(b)

Figure 9: SEM and microscopy images of (a) embedded particle with wear debris and (b) disc wear

Table 2: Drag test results

Pressure, p (MPa)	Sliding Speed, v (m/s)	Ave. COF, μ (No Grit)	Ave. COF, μ (180 - 355 µm)
0.6	4	0.52, 0.50, 0.47	0.38, 0.31, 0.35
	8	0.51, 0.50, 0.52	0.41, 0.47, 0.43
	10	0.60, 0.53, 0.55	0.56, 0.55, 0.58
	12	0.57, 0.55, 0.56	0.64, 0.63, 0.61

3.2 Effect of Hard Particle and Applied Pressure on Friction Stability

The effect of hard particles, at different applied pressures, on friction stability was investigated. Three different pressures of 0.6 MPa, 0.8 MPa and 1 MPa were applied three times for short duration braking of 10 [s] and results were compared to those obtained during tests without hard particles. The CoF values for most cases with hard particle present tend to be reduced. However, changes of CoF were found to be largest at high applied pressures especially at lower speeds. At low and medium speeds, as the pressure increases, CoF values increase slightly. In general, the increase in pressure tends to increase the numbers of particle in contact, thus more effective contact area is involved and there is a small increase in CoF. However, increase in pressure at higher speed tends to decrease the CoF values. This is because increase in pressure has little effect on the CoF compared to the speed increase. In addition, increase in pressure affects the roughness of the disc as the grit will cause more wear damage. Also, CoF at low pressure of 0.6 MPa with grit present exhibits a higher value than without particles for 10 m/s and 12 m/s due to the influence of speed that accelerate the rolling and mixing process. Table 3 shows the results for the CoF values for experiment without hard particles at applied pressure of 0.8 MPa and 1 MPa.

Table 3: CoF comparison with and without hard particle at (a) 0.8 MPa and (b) 1 MPa

Sliding Speed, v (m/s)	Ave. COF, μ (No Grit)	Ave. COF, μ at 0.8 MPa (180 - 355 μm)
4	0.46, 0.44, 0.44	0.38, 0.31, 0.37
8	0.49, 0.48, 0.45	0.46, 0.42, 0.44
10	0.45, 0.46, 0.46	0.47, 0.45, 0.46
12	0.53, 0.55, 0.55	0.42, 0.43, 0.45

(a)

Sliding Speed, v (m/s)	Ave. COF, μ (No Grit)	Ave. COF, μ at 1 MPa (180 - 355 μm)
4	0.45, 0.55, 0.56	0.41, 0.44, 0.43
8	0.49, 0.56, 0.57	0.43, 0.44, 0.44
10	0.53, 0.55, 0.57	0.45, 0.45, 0.46
12	0.55, 0.56, 0.58	0.46, 0.48, 0.49

(b)

3.3 Effect of Sliding Speed and Applied Pressure on Particle Embedment

Study of the particle embedment at different sliding speeds and applied pressures was carried out using SEM and optical microscope. Reports on the nature of grit embedment during abrasion of materials are available [8, 24, 25], but little is published on the embedment of particle grit in brake pad. Factors such as particle shape, size, hardness and pad material may affect the grit embedment [26]; and embedment of particle is one of the main factors that determine the changes of tribological characteristics at the brake interface. The percentage of particle embedment of silica sand of 180 - 355 μm as a function of speed and applied pressure is shown in Figure 10. Four sliding speeds of 4 m/s, 8 m/s, 10 m/s and 12 m/s at constant pressures of 0.6 MPa, 0.8 MPa (drag mode) and 1 MPa (stop mode) were used during the tests. The percentage of embedded particles is higher at low speed than the high speeds at low applied pressures. At the pressure of 0.8 MPa, the same pattern was observed, i.e. higher percentage of grit embedment at low and medium speeds than at higher speeds. However, the particle grit embedment at 1 MPa shows different pattern, i.e. high speed tends to have higher percentage of grit embedment compared to other lower speeds.

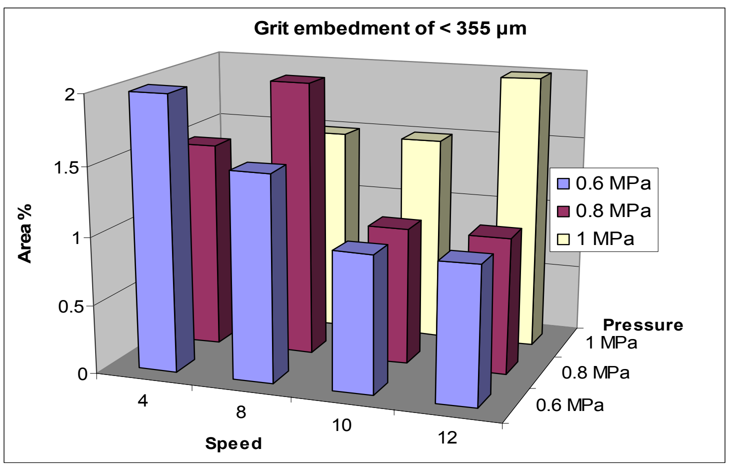


Figure 10: Particle embedment percentage of 180-355 μm particles as a function of speed and pressure.

It can be seen from the results obtained, that speed plays a significant role on the percentage of particle embedment compared to the applied pressures. However, at higher applied pressures, the percentage of grit embedment increases as the particles begin to break up and embed more easily into the pad surface. Some embedded particles were constrained by brake pad as the wear pad deformed to partially cover them. The size of the embedded particles was measured and they were scattered in the size range of 180 to 340 μm. Figure 11 shows particles that were partially embedded below the surface of the brake pad. No fully embedded particle was found at 0.6 MPa and 0.8 MPa for all the speeds tested.

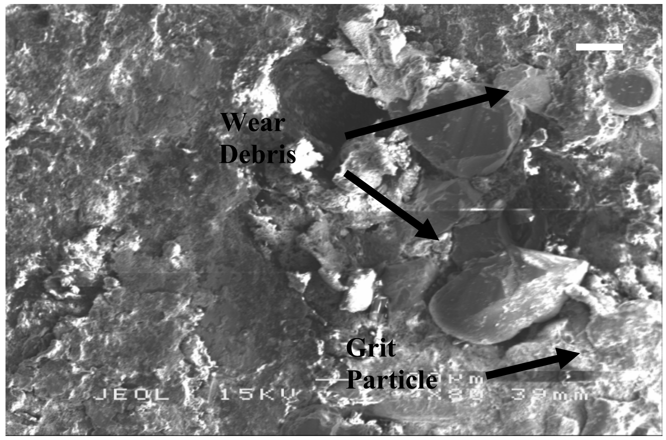


Figure 11: Partially embedded particle below the surface of the brake pad at 0.8 MPa.

Fully embedded particles were observed only at pressure of 1MPa. Figure 12 shows the particle embedment at 1 MPa with some particles were fully embedded and covered by compacted wear debris. The embedded particle grit sizes observed were in the range of 50 to 150 μm and they were smaller than the original particles which suggest occurrence of particle fragmentation. Particle fragmentation is due to the high applied braking pressure. The fragmented particles were also more angular in shape, i.e. thus they were more easily embedded deeply into the holes on the pad surface. These results show that high applied pressure affects the level of particle embedment and cause the particle fragmentation.

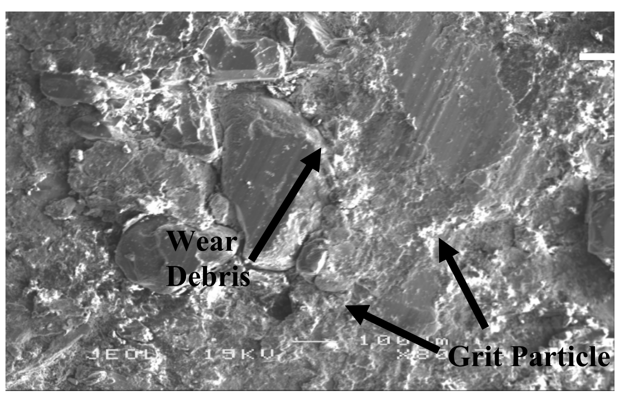


Figure 12: Particle embedment at 1 MPa with fully embedded particle and compacted wear debris.

3.4 Correlation of Particle Embedment with Coefficient of Friction

Study on the relationship between particle embedment (PE) and the coefficient of friction (CoF) at different speed and pressure is also conducted. Figure 13 shows the graph of CoF and PE vs speed. CoF values show the same trends in variation throughout the whole range of speeds. In all the speeds, higher percentage of particle embedment cause lower values of CoF. Higher speeds affect the rapidity of rolling and mixing of the wear debris between the gaps. As the pressure increases, the CoF values also tend to reduce with increase in PE. However, low and medium applied pressure produce higher percentage of PE and CoF at lower speeds. This is in contrast with the high applied pressure case that results in high percentage of PE and CoF values at higher speeds. Half or partly embedded particles were observed in all the cases. However, fully particle embedment is only found at high applied pressure with some fragmentation of hard particles taking place as smaller than original size particle were observed. Fragmentation also may increase the numbers of hard particles between the gap and thus the effective contact area in the sliding contact. This caused the increase of average CoF. Also, more PE may cause more interface gap and reduce the numbers of hard to hard material contact and thus decrease slightly the CoF values. However, factors such as sliding speed and applied pressure may influence the CoF values more than PE.

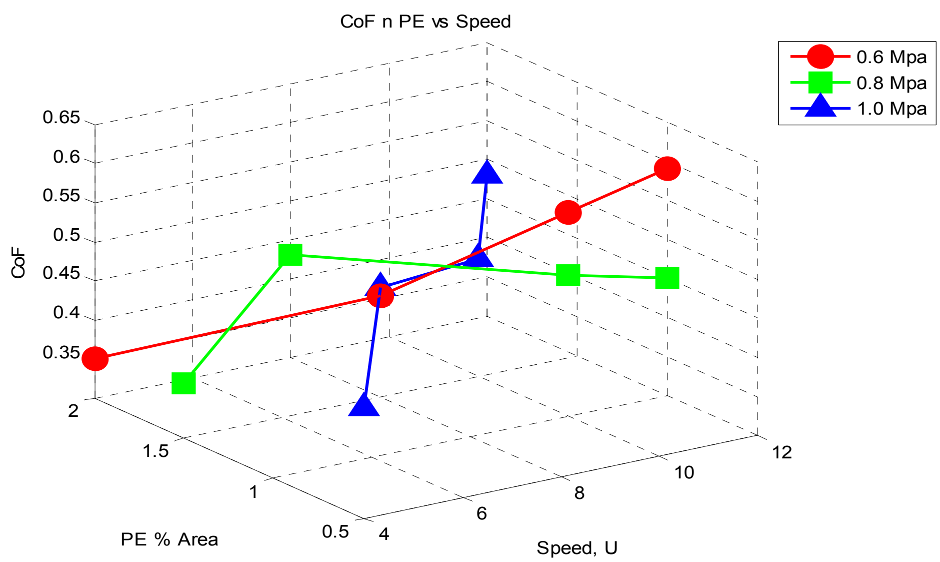


Figure 13: Graph of CoF and PE vs Speed at three different applied pressures

4.0 CONCLUSION

The particle grit size effect on frictional characteristics of braking system was investigated using a specially developed brake test rig. Silica sand grit of the size between 180-355 µm was used during the test to measure the change of friction coefficient and the percentage of particle embedment with different speeds and applied pressures. Experimental results showed that:

- The CoF values depend on the presence of hard particles. The CoF values reduce especially at lower sliding speeds. Hard particles tend to reduce the contact area by forming the new effective contact area themselves before they mixed up with other wear debris.
- CoF values increase with speed and pressure. However, the sensitivity of CoF values depend more on the sliding speed than the applied pressure due to the faster build up of effective contact areas by the hard particles and wear debris produced.
- Sliding speed and applied pressure have significant influence on the level of particle embedment. At lower speeds more particle embedment occurs at lower pressures due to the slower mixing of particles, while at higher speeds more embedment occurs at higher pressures due to the particles fragmentation.
- Small decrease in CoF values with PE may be due to the embedded particles that formed the primary contact area themselves. More embedment means more gap and less hard to hard material contact thus reduce the effective contact area in the sliding contact.

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