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BRAKING PERFORMANCES OF BRAKE PAD FOR PASSENGER CAR

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Abstract. Six prototype brake pads developed through powder metallurgy technique were subjected to on-road performance tests in accordance with Annex 3 Economic European Community Regulation 13 (ECE R13). Each sample was subjected to cold, fade, and recovery tests. Test results show that only sample S2, S14, S27 and S31 comply with the minimum requirements of mean fully developed deceleration (MFDD). Microstructural changes are studied on the worn surface of the brake pad using Field Emission Scanning Electron Microscope (FESEM) and Energy Dispesive spectroscopy (EDS). Microstructural examination on the worn surface revealed that friction layer was discontinuous and did not cover the whole surface. When detailed study is performed on the friction layer, it was observed that several mechanisms of wear such as adhesion, abrasion, and delamination took place during braking process. Generally, surface temperature increases due to the increase in kinetic energy absorbed by the brake pad during braking. The friction coefficient decreases with increasing surface temperature due to degradation of organic materials in the brake pad composition. These wear mechanisms and thermal failures result in plastic collapse in the local region, producing wear particles in different sizes, shapes and chemistry.

Keywords: Brake pad; friction; MFFD; heat fade; on-road performance

Abstrak. Enam pad brek yang telah dibangunkan melalui teknik serbuk metalurgi telah menjalani ujian prestasi di atas jalan mengikut "Annex 3 Economic European Community Regulation 13 (ECE R13)". Setiap sampel telah menjalani ujian sejuk, pudar dan pemulihan. Keputusan ujian menunjukkan hanya sampel S2, S14, S27 dan S31 menepati keperluan minimum purata nyah pecutan terhasil (PNPT). Kajian ke atas perubahan mikrostruktur permukaan haus pad brek telah diperhatikan menggunakan teknik kemikroskopan elektron imbasan (KEI) beserta analisis tenaga terserak Spektroskopi (TTS). Pemeriksaan mikrostruktural ke atas permukaan haus mendapati lapisan geseran adalah tidak berterusan dan tidak menutupi keseluruhan permukaan. Apabila kajian mendalam dijalankan ke atas lapisan geseran, diperhatikan mekanisme haus lelasan, rekatan dan nyah lapisan berlaku semasa proses pembrekan. Lazimnya, suhu permukaan meningkat disebabkan peningkatan tenaga kinetik yang diserap oleh pad/piring brek

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semasa pembrekan. Pekali gesrean menurun dengan peningkatan suhu permukaan disebabkan penguraian bahan organik di dalam komposisi pad brek. Mekanisme haus dan kegagalan haba menyebabkan kegagalan plastik pada permukaan setempat, menghasilkan partikel haus dalam berbagai saiz, bentuk dan kimia.

Kata kunci: Pad brek; pekali geseran; MFFD; pudar haba; prestasi di atas jalan

1.0 INTRODUCTION

Friction materials are composed of a mixture of four main constituents, namely; (i) reinforcing fibers, (ii) binder, (iii) frictional additives, and (iv) filler [1]. Reinforcing fiber such as steel wool, aramid, fiberglass, rock wool, and potassium titanate is used to provide the necessary mechanical strength, rigidity, integrity, and thermal stability at high temperatures. Friction materials typically use a mixture of different types of fibres with complementing properties. Binder such as phenolic resin, novalak resin, and resol resin is used to hold the compositions of a brake friction material together. Frictional additives are added for lowering or increasing the friction levels of the brake pads (graphite, rubber, and metal powder) and for cleaning of the brake drum or disc such as metal chip (brass and zinc), alumina oxide and silica oxide. Frictional additive comprises a mixture of lubricants and abrasive. Finally, fillers such as clay, barytes and calcium carbonate are primarily used to fill-up the space, and reduce the cost by using low cost minerals. It is important to note that certain ingredient in the friction material composition perform multiple functions and may be placed in more than one classification [2].

Each ingredient in the formulation has its own role. Changes in element types or weight percentage of the elements in the formulation may change physical, mechanical and chemical properties of the brake friction materials to be developed. Choa *et al.*, 2005 [3] concluded that the selection of ingredients and weight percentages used in the friction formulation will significantly affect the friction coefficient, wear resistance, and friction-induced noise of the brake pad. In another study, Kim and his co-workers found that the friction characteristics are strongly affected by the type and the amount of solid lubricants in the brake lining [4]. In the process of developing a new formulation, the researchers should compromise some of the properties in order to get the best formulation.

Most of the formulations developed are achieved through trial and error process since there is no wear model available that can predict wear priori from material properties and contact information [5]. There is no simple correlation between physical and mechanical properties with friction and wear characteristics [6]. There is also no simple correlation between; (i) hardness and content of structural constituents, (ii) bulk formulation and friction coefficients [7]. As such, the friction and wear characteristics cannot be predicted based on physical and mechanical properties. Therefore, each new formulation developed shall be subjected to friction and wear assessment tests using brake dynamometer as well as on-road test to ensure the brake pad developed comply with the minimum requirements.

A reduced scale or reduced sample friction testing has been developed to reduce friction materials development cost and time. Friction and wear assessment test using CHASE machine is used in a laboratory scale for screening of new material formulations prior to inertia dynamometer tests. Chase machine uses a small sample (1 inch × 1 inch × 0.25 inch), low cost expenditure and shorter test time as compared with inertia dynamometer. Brake inertia-dynamometer test is used as a cost-effective method to evaluate brake performance in a laboratory-controlled environment rather then having a series of vehicle tests on a test track [8]. However, Blau found that there is no laboratory wear test of brake friction materials which can simulate all aspects of a brake's operating parameters and environment [9]. Thus, vehicle testing on the test track is the ultimate judge for overall brake performance testing and evaluation.

The development and validation of a friction material involve a significant amount of testing in laboratory and on the road. A vehicle is typically used under various road and driving conditions and as such a friction material shall be tested in conditions closely representing these driving conditions. Brake friction material developers will look for quantitative data from these tests to evaluate their material formulations and track the effects of the modifications that are made during the course of the product development. On-road brake test is the final test normally performed to evaluate and validate the formulation as the brake friction material is actually tested under its real life application conditions.

During braking, the brake pad or brake lining is pressed against the rotating brake disc. This clamping action retards the rotation of the brake disc and subsequently, slows down the forward movement of the vehicle and finally stops the vehicle. This process converts the kinetic energy of the moving vehicle into thermal energy. The accumulation of heat will cause high surface temperature on the brake lining materials. High temperature induced on the friction materials can be high enough to decompose the polymeric material by means of high-temperature oxidation process. Over heating of brake friction material compound is the most common form of brake fade. This fading effect is associated with the decomposition of the organic binder. The decomposition of friction material starts at 230°C, and the degree of degradation increases with temperature within the range of 269 – 400°C [10]. The friction coefficient of the friction materials will vary with temperature and will fall dramatically as the contact temperature exceeds the maximum temperature.

Phenolic resins carbonize at approximately 450°C [11] and beyond this temperature; it decomposes by charring and evaporation. The char is not as strong as the original resin, but it is strong enough to bind the ingredients of the friction materials together. The char is removed when the friction material is forced onto the rotating brake disc during braking. Once the char has been removed from the surface, the remainder of the friction material is now fully functioning as normal. Earlier researchers found that the wear mechanisms in forms of abrasion, adhesion, fatigue, delamination and thermal are found to be operated during friction and wear tests on friction materials [12,13]. The purpose of this study was to evaluate the brake performance of the developed brake pads through on-road performance testing. In this work, microstructural changes on the worn surface and the wear mechanisms operated during braking will also be discussed.

2.0 MATERIALS AND METHODS

Prototype brake pads were produced through powder metallurgy technique which consists of the following processes (i) selection of raw materials, (ii) mixing, (iii) preparation of backing plate, (iv) preform compacting (v) hot compacting, (vi) post-baking, (vii) finishing, and (viii) testing. Six prototype brake pads designated as SW1, S2, S10, S14, S27 and S31 were used in this investigation and the elemental compositions are shown in Table 1. The microstructures of the brake disc and prototype samples are shown in Figure 1.

Table 1 Elemental composition of brake pad (% by wt)

MATERIALS	SW1	S2	S10	S14	S27	S31
Phenolic resin	-	10.0	9.0	9.0	9.0	12.0
Organic filler (rubber, friction dust)	13.0	6.0	3.0	3.0	11.0	16.0
Solid lubrication graphite	19.0	16.0	13.0	7.0	6.0	14.0
Metallic fiber (steel and copper)	16.0	20.0	26.0	37.0	28.0	20.0
Mineral fiber (wollastonite, rockwool)	15.0	5.0	13.0	3.0	8.0	13.0
Organic fiber (kevlar)	2.0	-	-	2.0	3.0	-
Abrasive (Fe_2O_3, Mg), Al_2O_3, $SiO_2$2)	15.0	35.0	19.0	19.0	30.0	13.0
Barium sulphate	20.0	8.0	17.0	20.0	5.0	12.0
TOTAL	100	100	100	100	100	100

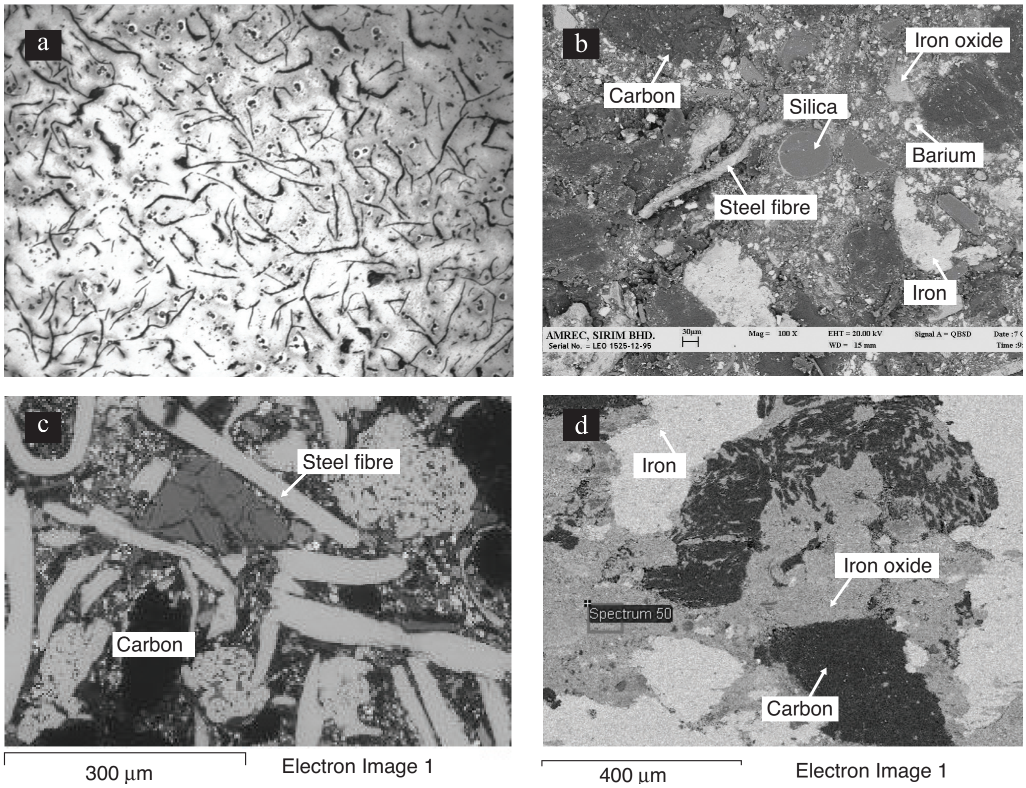


Figure 1 Microstructure of the brake disc and prototype samples; (a) brake disc, (b) sample 2, (c) sample S14, and (d) sample S27

Each brake pad was subjected to on-road performance test in accordance with Annex 3, European Regulation R 13 [14]. The prototype brake pads were installed to the brake system of a PROTON WIRA 1.5 GL. The specifications of the test car are shown in Table 2. The brake lining temperature was recorded using thermocouples embedded 5 mm from the surface of the brake pad, the brake pedal force was recorded using brake pedal force model *HKM PH-100-EX*, and the line pressure was recorded using *BOSCH* pressure transducer installed on the brake hydraulic line. The vehicle forward velocity was measured using *DEWE-VGPS 200* GPS based speed and displacement sensor. All test data such as vehicle speed, pad temperature and braking distance were recorded in real-time using a data acquisition system model *Dewetron* DEWE-5000. Figure 2 shows the test equipment set-up before the test could be performed. The test conditions for the performance are as follows;

(a) the vehicle test speed at the initiation of braking shall be 100 km/hr,

(b) the road surfaces shall be dry, smooth, hard, and level,

(c) the components of the braking system shall be in good order,
(d) any brake servo-assistance shall be disconnected or deactivated,
(e) the wind speed shall be below 5 m/s
(f) the vehicle was unladen

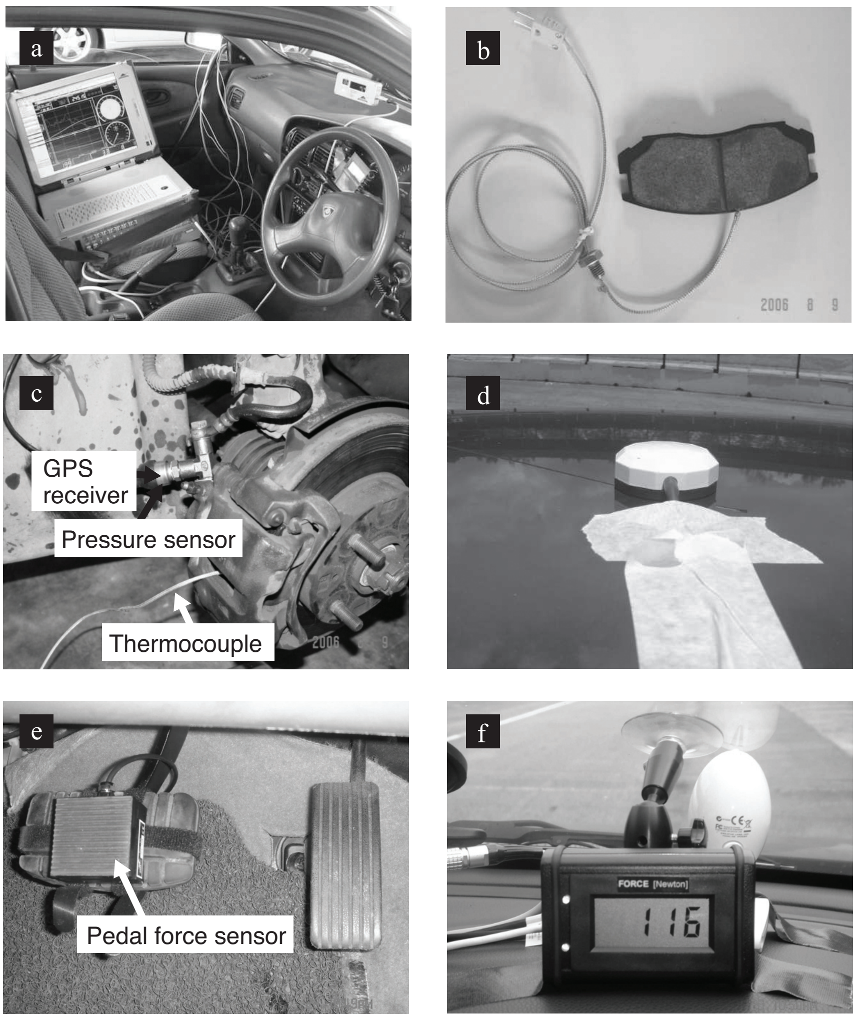


Figure 2 Test equipment set-up; (a) *Dewetron DEWE-5000* system, b) thermocouple installed in the brake pad, (c) installation of pressure sensor and thermocouple, (d) GPS receiver installed on the roof (e) pedal force sensor, (f) pedal force display

Table 2 Test car specifications

Manufacturer	:	PROTON
Model	:	Proton WIRA 1.5S
Engine capacity	:	1,468 cc
Gear system	:	Manual
Wheel size	:	175/70/R 13
Tire pressure	:	190 kPa

On-road performance tests were divided into three phases, namely; (i) cold effectiveness test, (ii) heat fade test, and (iii) recovery test. The new formulations shall have a minimum requirement of the performance test as shown in Table 3. The brake lining temperature shall be kept below 100 ˚C prior to each brake application during the cold effectiveness tests with comprised of six brakings including any needed familiarization.

Table 3 Minimum requirements of the performance tests

Tests	**Mean fully developed deceleration (MFDD) (m/s^2)**
cold effective	6.43
heat fade	75% of that prescribed and 60% of figure recorded in the cold effectiveness test
recovery	not less than 70%, nor more 150%, of figure recorded in the cold effectiveness test

The mean fully developed deceleration (d_m) was determined by using the following formula. The average deceleration with respect to the distance over interval v_b to v_e.

$$d_m = \frac{v_b - v_e}{25.92\,(S_e - S_b)}$$

Where,

v_o Initial vehicle speed (km/h)

v_b vehicle speed at 0.8 v_o (km/h)

v_e vehicle speed at 0.1 v_o (km/h)

S_b distance traveled between v_o and v_b (m)

S_e distance traveled between v_o and v_e (m)

Prior to fade test, the service brake of the test car was heated by successively applying the brake. Fade test is used to evaluate the brake performance under high temperature. The initial speed at beginning of this heating procedure was set at 100 km/hr and speed at the end of braking was set at 50 km/hr with brake pedal force capable of generating about 0.3 to 0.4 g deceleration. This process was repeated for 15 brake applications. Upon completing this heating procedure, the test vehicle was accelerate to initial vehicle speed of 100 km and brake was applied using the same pedal force as in cold effective test for that particular sample. Immediately, the recovery test was conducted with the following test conditions; (a) make four stops from 50 km/hr with the same pedal force applied during heating process of heat fade test. Immediately after each stop, accelerate the vehicle to 50 km/hr and make subsequent stop, (b) accelerate the test vehicle to a speed of 100 km and then brake pedal was applied with the same pedal force cold test. The average thickness losses were the average thickness loss of 10 readings.

The Morphological changes were observed using Field Emission Scanning Electron Microscopy with EDS attachment for elemental analysis on the worn brake pad surface. The samples for microstructural examination were cut from the backing plate of the brake pad after on-road performance test. The samples were cleaned with compressed air and then coated with gold.

3.0 RESULTS AND DISCUSSION

On-road test results show that sample S2, S14, S27 and S31 comply with the minimum requirements of mean fully developed deceleration (MFDD) on cold, fade and recovery performance tests (Table 4 and Figure 3). However, it was observed that sample S10 does not comply with the fade requirements. Lower MFDD during fade test results a longer braking distance, which may not be noticed by the driver during braking process. If the driver noticed this, he presses the brake pedal progressively harder to get the car to slow down. Fade test is used to evaluate the brake performance under high temperature. In the fade test, the service brake is heated by successively applying the brake and causes high surface temperatures in the lining materials. This, in turn causes decrease in MFDD due to the decomposition of the organic materials in the brake friction materials and chemical changes in the friction layer which forms on the friction surface. The organic materials in the composition start to degrade at 230°C and consequently the friction coefficient will be decreased depending on the element and weight percentage used in the formulation.

Table 4 Road performance test results

Sample	Type of test	Pedal force (N)	MFDD (ms^{-2})	Requirement (ms^{-2})	Final temp (˚C)		Average thickness loss (mm)
					Right	Left	
S2	Cold	254	7.9	6.43	172	175	0.12
	Fade	230	8.1	4.82	338	360	
	Recovery	218	8.2	5.39 – 11.55	197	195	
S10	Cold	99	6.9	6.43	114	110	0.23
	Fade	94	4.0	4.82	416	312	
	Recovery	98	4.9	4.83 – 10.35	181	155	
S14	Cold	145	7.9	6.43	136	137	0.18
	Fade	130	7.1	4.82	272	260	
	Recovery	134	8.3	5.53 – 11.85	143	152	
S27	Cold	104	6.9	6.43	308	282	0.51
	Fade	109	5.7	4.82	515	527	
	Recovery	117	5.8	4.83 – 10.35	333	332	
S31	Cold	143	7.4	6.43	154	124	1.18
	Fade	140	4.9	4.82	471	463	
	Recovery	147	7.1	5.18 – 11.1	266	220	
SW1	Cold	1000	6.6	6.43	389	402	*

Sample SW1 does not comply with pedal force requirement. Sample SW1 recorded 1000 N pedal force during cold effective test, which is double the maximum allowable pedal force of which is 500 N. In this case, sample SW1 is considered fail to comply with the pedal force requirements and the next test (heat fade and recovery test) will not be conducted on this sample. Higher pedal force requires more driver effort to stop the vehicle, which may stress the driver leg. For the older and lady drivers, they have to make extra effort to get this higher pedal force. Low pedal force is preferable, particularly in heavy traffic situations where required stop and go, or any time that frequent brake applications such as on downhill driving.

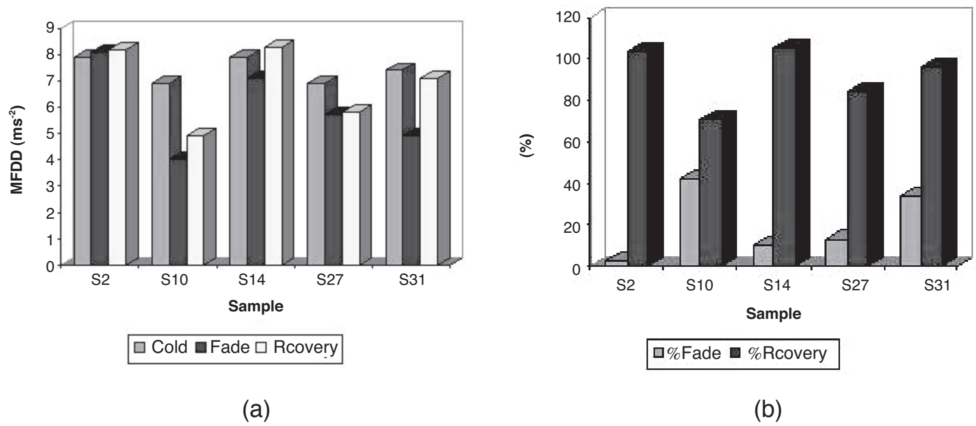


Figure 3 Histogram of brake performance (a) MFDD of test sample during cold, fade and recovery tests (b) Magnitude of fade and recovery

As evident from Figure 3(b) and Table 5, the fade behaviour of sample S10 was the highest (42%) with sample S2 was the lowest (2.5%). It was observed that sample S10 and S27 exhibiting a similar level of cold performance, however their fade properties were dissimilar, sample S10 showed 42% fade as compared to that of the sample S27 (13.2%). An organic material in the composition such as phenolic resin, coke/graphite and rubber are apparently decomposing and interacting with available oxygen as temperature increases and subsequently reduces the friction coefficient. The ability of a brake material to maintain its coefficient of friction in all conditions (i.e cold and hot) is preferable as it does not change the braking characteristics of a vehicle. However, this is not possible to be achieved in practice due to the nature of the brake materials which will always experience brake fade when subjected to high temperature due to the decomposition of the materials. Therefore, variation of friction coefficients, and hence the decelerations, during fade and recovery tests is allowable only to a certain degree as stipulated by the ECE regulation in order to minimize the changes in the braking behaviour of the vehicle.

The organic materials in the composition start to degrade at 230°C and the friction coefficient increased at the early stages of braking, then decreased with braking time and thereafter reached steady state [15]. When the system cooled down by blowing air to the brake system, the friction coefficient of a good friction material should recover to its original value. It was observed that all samples recover to more than 71% of their original performances after recovery tests and all samples comply with the requirement (Figure 3b). Somehow, sample S2 and S14 show over recovery which is allowed by this regulation which states that the MFDD can go up to 150% of the figure recorded in cold effective test. This phenomenon is due to the formation of local carbonisation on the wear surface as observed by Begelinger *et al.* [16] and Talib [13].

Table 5 Fade and recovery characteristics

Type of test	S2	S10	S14	S27	S30
Cold	7.9	6.9	7.9	6.9	7.4
Fade	8.1	4.0	7.1	5.7	4.9
% Fade	2.5	42	10.1	13.2	33.8
Recovery	8.2	4.9	8.3	5.8	7.1
% Recovery	103.8	71	105.1	84.1	95.9

Figure 4 shows that the brake lining temperature of sample S27 is the highest during fade and recovery test but the brake performance still complies with the requirement. This indicates that the ingredients and structure of this formulation is able to maintain its performance under high temperatures. Sample S14 has the lowest brake lining temperature during fade and recovery test. Excessively high temperature during braking may result brake fluid to boils. When this happened, gas is formed and this produces a condition known as "vapour lock". Under this condition, the braking capability will be reduced or, in severe cases, the total loss of braking ability.

Average thickness loss detected in the samples after completion of the road performance tests are shown in Figure 5. It was observed that sample S27 recorded the highest, while sample S2 was the lowest. Wear data are different for different compositions, and this should be attributed to different type and weight percentage of elements used in the compositions of tested brake pads. As a brake pad rubs against a rotor during braking, the two surfaces interact with each other mechanically and chemically. The friction layers are developed between the two mating surfaces as a results of compaction of two-way material transfers for brake pad to brake disc, and vice versa. The composition, mechanical and chemical properties as well as thickness of the friction layer determine the wear rate of the brake pad developed.

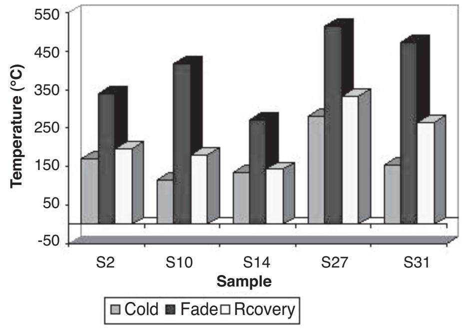


Figure 4 Brake lining temperature

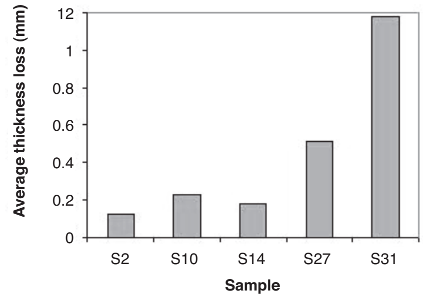
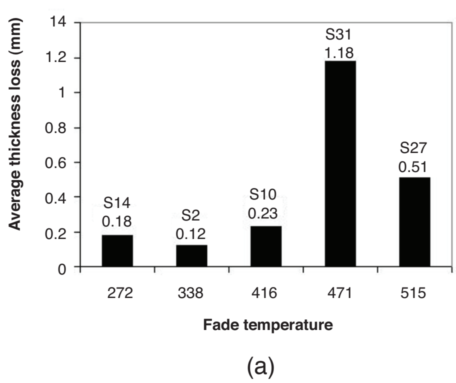


Figure 5 Average thickness loss

Figure 6 shows that the average thickness loss is not directly dependent on the fade temperature developed during braking process (Figure 6a), but could be considered as dependent on the organic composition in the brake pad (Figure 6b). During braking process, the surface temperature increases with braking time either during continuous or intermittent braking. The degradation of the organic ingredients increases with surface temperature and this resulted in the reduction of composition bonding, and structure integrity [17] as well as the destruction of friction layer [18]. This process may have increased the rate of surface failure, thus increasing the average thickness loss, as observed in this work. The onset of degradation of the friction material starts at 230°C, and the degree of degradation increases with temperature within the range of 269 – 400°C [10]. Sample S2 had the lowest average thickness loss may be due to the lubrication effect (16% by wt. of solid graphite lubrication). This sample also has the highest abrasive materials which are wear resistance materials.



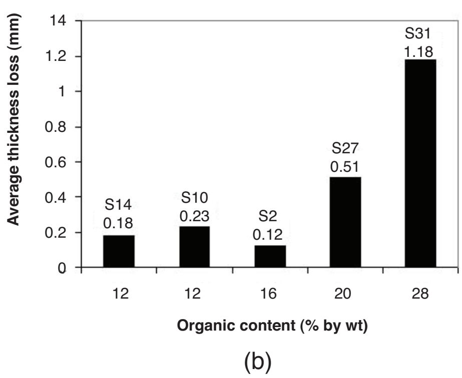
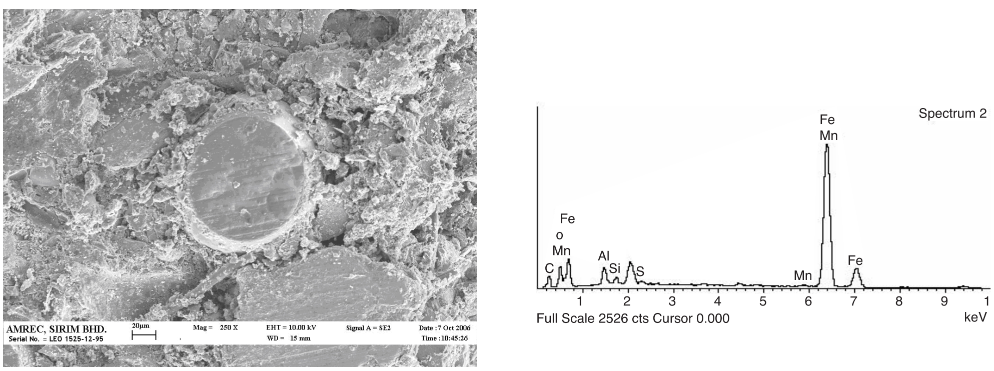


Figure 6 Average thickness loss; (a) Effect of fade temperature, (b) effect of organic contents

In this study, the morphology changes of the worn surface of the brake pads after on-road performance are examined using FESEM. In general, the material surface is rough on microscopic scale and have peaks and valleys. The real contact point is known as the junction while the total area of individual contact is known as the real area of contact. The ratio of real contact area to apparent contact area is very small which is about 10^{-2} to 10^{-5} [19]. The contact area first forms on the wear resistant ingredient in the brake pads such metallic elements, reinforcing fibers and ceramic materials. This phenomenon can be seen in Figure 7. During braking process, wear debris generated will be either released into the environment, or trapped between contact areas. Occasionally, some of the wear debris trapped in the porous areas. As the braking process progresses, the wear debris accumulated and piles up against the contact areas (Figure 8). Subsequently, the contact area grows to form friction patches due to the compaction of wear debris trapped between the sliding surfaces as shown in Figure 9.



(a) (b)

Figure 7 SEM of worn surface (a) contact area, (b) EDS on the worn surface

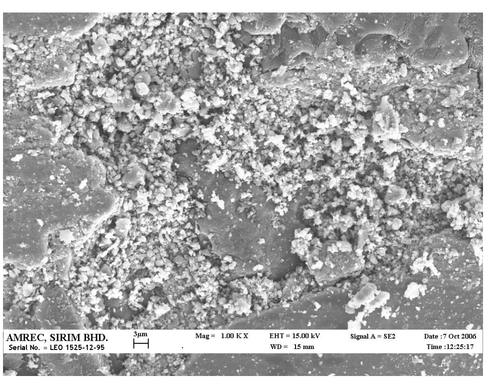


Figure 8 SEM image showing the pile-up of the wear debris on the contact area

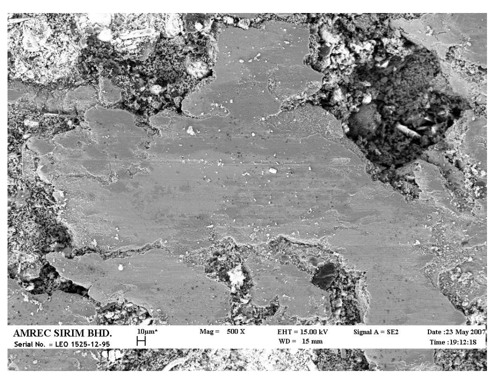


Figure 9 Formation of friction layer

Topography of the worm surface shows that the friction layer does not cover the entire worn surface. Figure 10(a) shows that it does not cover the graphite and coke black areas. The characteristic of graphite and coke microstructure does not allow the wear debris to stick on it, so the wear debris is moved away [20]. Figure 10(b) shows the chemistry of friction layer which developed after mechanical alloying transfer layer process.

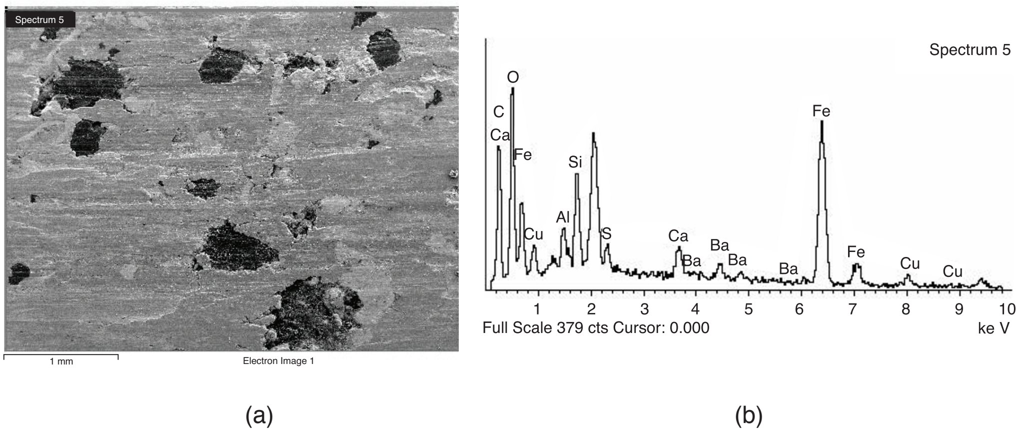


Figure 10 SEM contact surface (a) friction layer, (b) EDS on contact area

Detailed studies on the microstructure changes of the contact areas revealed that the following wear mechanisms were occurred during braking process; (a) abrasion, (b) adhesion and (c) delamination. Abrasion wear mechanism is manifested by the presence of the ploughed marks on the friction layers. Figure 11 shows this wear mechanism did occur during braking process. Generally, the high peak asperities on the brake disc or hard particles were ploughed into the wear surface. There definitely exists a third body at the surfaces of the counterparts (friction material and brake disc) as observed by Sterle [21].

In the early stage of adhesion mechanism, as explained earlier, the contact area grows to form friction patches due to the compaction of wear debris trapped is between the sliding surfaces (Figure 12). Transfer film will continuously form smear and shear on the sliding surfaces as the braking progresses. As the friction patches sheared, causing the friction surfaces to be covered with transfer layers, which had been compacted, smeared, sheared and flattened. Finally the friction materials are covered with a friction film, the composition of which is more like that of the ingredient from the friction material and brake disc as shown in Figure 13.

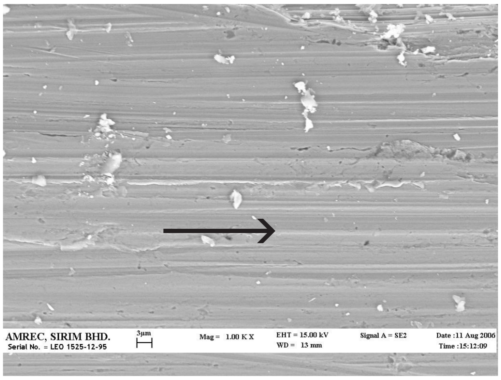


Figure 11 Abrasion mechanism

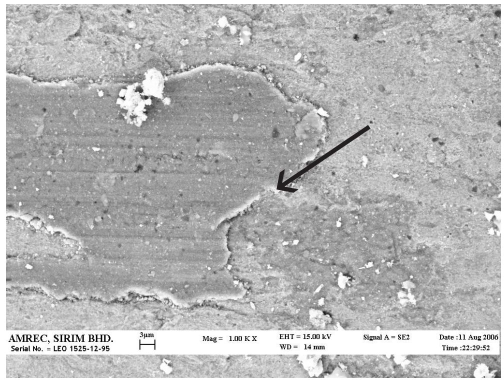
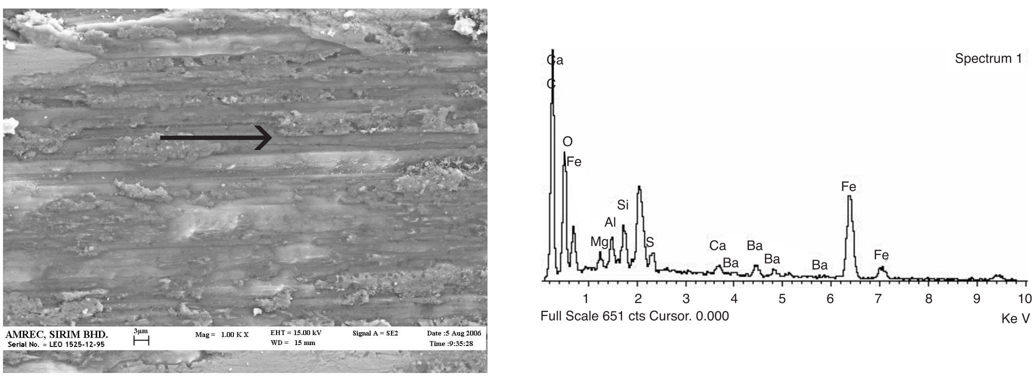


Figure 12 SEM micrograph shows an early stage generation of friction layer



(a) (b)

Figure 13 Formation friction layers, (a) SEM microstructure friction layer, (b) EDS on friction layer

Delamination wear can be observed by the disposal of wear particles from the worn surface and this can be seen in the Figure 14. This theory was postulated by Suh [22] where he found that in the early stage sliding, the morphological changes of the subsurface showed the process of plastic deformation, followed by formation of microvoids, and microcracks. As the sliding progresses, the microcracks propagate parallel to the surface. Finally, the wear particles flake off from the wear surface which subsequently produced wear particles in the shapes of delaminated sheets. Thus, based on the above observations it could be postulated that wear mechanisms occurred during braking are abrasion, adhesion and delamination. These wear mechanisms resulted in the disposal of wear particles from the mating surface. The disposed wear particles have different sizes, shapes and chemical composition as shown in Figure 15. It is observed that the wear particles are composed of ingredients used in the brake pad such iron, aluminum, copper, calcium, barium, silica, sulphur and carbon.

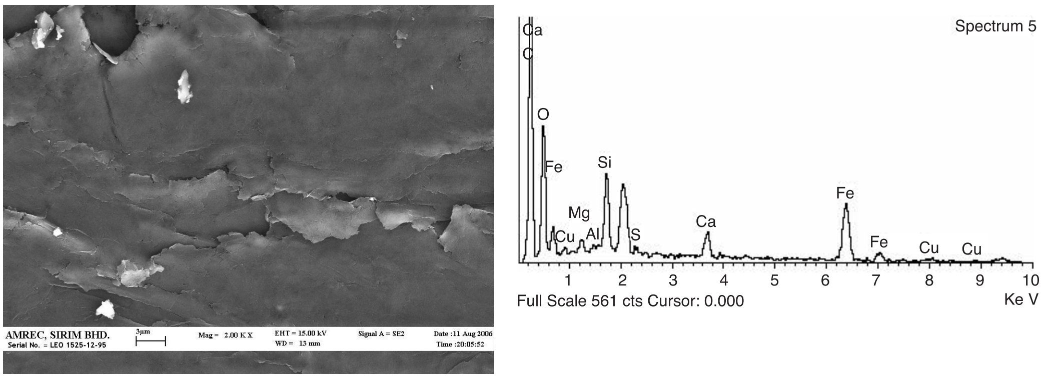
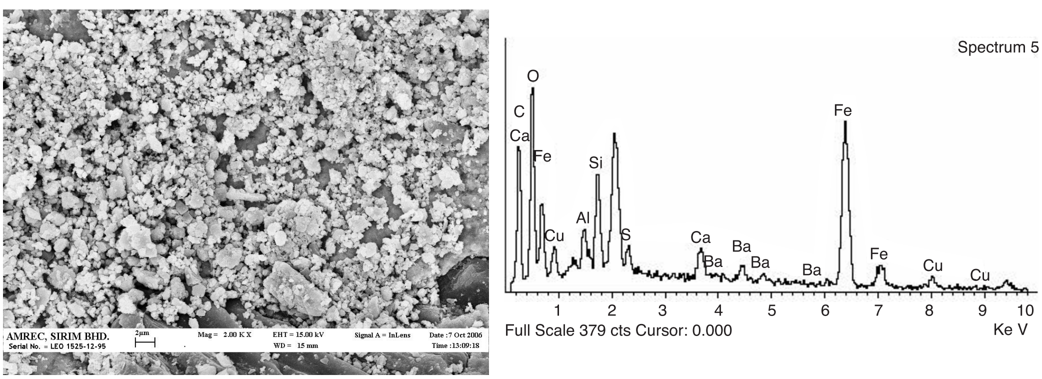


Figure 14 Delamination mechanism



(a) (b)

Figure 15 Wear particles, (a) SEM images of wear particles, (b) Chemistry of the wear partciles

4.0 CONCLUSIONS

In this work, six prototype brake pads were subjected to on-road performance tests in accordance with Annex 3 Economic European Community (ECE) Regulation 13. The samples were developed through powder metallurgy technique. The following phenomena are observed on this work;

(a) Analyses of road performance test results show that sample S2, S14, S27 and S31 comply with the minimum requirements of mean fully developed deceleration (MFDD). Whereas, sample S10 does not comply the MFDD of heat fade requirement, while SW1 exceeds the minimum pedal force requirement.

(b) Microsructure examination on the worn surface reveals that friction layer is discontinuous and does not cover the whole surface, especially on the graphite and coke particles.

(c) Morphological studies on the worn surfaces show that the major wear mechanism in operation throughout the braking process are (i) abrasive, (ii) adhesive, and (iii) delamination.

(d) The surface temperature increases due to the increase in kinetic energy absorbed by the brake pad during braking. Generally, friction coefficient decreases with increasing surface temperature due to degradation of organic materials in the brake pad composition. The degree of degradation increases with increasing of surface temperature.

(e) The average thickness loss is dependent on the surface temperature and organic ingredient in the brake pad composition

(f) The wear particles produced during braking are different in sizes, shapes and composition.

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