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Selection of Best Formulation for Semi-Metallic Brake Friction Materials Development

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1. Introduction

Brake friction materials play an important role in braking system. They convert the kinetic energy of a moving car to thermal energy by friction during braking process. The ideal brake friction material should have constant coefficient of friction under various operating conditions such as applied loads, temperature, speeds, mode of braking and in dry or wet conditions so as to maintain the braking characteristics of a vehicle. Besides, it should also posses various desirable properties such as resistance to heat, water and oil, has low wear rate and high thermal stability, exhibits low noise, and does not damage the brake disc. However, it is practically impossible to have all these desired properties. Therefore, some requirements have to be compromised in order to achieve some other requirements. In general, each formulation of friction material has its own unique frictional behaviours and wear-resistance characteristics.

Friction material is a heterogeneous material and is composed of a few elements and each element has its own function such as to improve friction property at low and high temperature, increase strength and rigidity, prolong life, reduce porosity, and reduce noise. Changes in element types or weight percentage of the elements in the formulation may change the physical, mechanical and chemical properties of the brake friction materials to be developed (Lu, 2006; Cho et Al., 2005; Mutlu et al., 2006 & Jang et al., 2004). Earlier researchers have concluded that there is no simple correlation between friction and wear properties of a friction material with the physical and mechanical properties (Tanaka et al., 1973; Todorovic, 1987; Hsu et al. 1997 & Talib et. al, 2006). Therefore, each new formulation developed needs to be subjected to a series of tests to evaluate its friction and wear properties using brake dynamometer as well as on-road braking performance test to ensure that the brake friction material developed will comply with the minimum requirements of its intended application.

Two major types of brake dynamometers are commonly used to evaluate the friction and wear characteristics of the friction materials are the inertia dynamometer and CHASE dynamometer. Inertia dynamometer is used to evaluate a full size brake lining material or brake system by simulating vehicles braking process but it is time consuming and more expensive. On a smaller scale, CHASE dynamometer features low capital expenditure and shorter test time (Tsang, 1985). Chase machine uses a small sample of friction material with a size of 1 inch x 1 inch x 0.25 inch. These brake dynamometers has been used to tests friction materials for quality control, lining development and friction materials property assessments in a lab scale rather then having a series of vehicle tests on a test track or road (Sander, 2001).

The two main types of tests used to evaluate the performance under different loading, speed, temperature and pedal force are, namely, inertia-dynamometer and vehicle-level testing. Inertia-dynamometer test procedures or vehicle testing simulation is used as a cost-effective method to evaluate brake performance in a laboratory-controlled environment. The automotive industry uses inertia-dynamometer testing for screening, development and regular audit testing. Blau postulated that there is no laboratory wear test of vehicle brake materials can simulate all aspects of a brake's operating environment (Blau, 2001). Vehicle testing on the test track is the ultimate judge for overall brake performance testing and evaluation.

Generally, in normal life we cannot avoid friction phenomenon. It still happens as long as there is a relative motion between two components. Even though friction can cause wear of materials, sometimes the process of friction is required such as in the brake system, clutch, and grinding. During a braking process, brake pads or brake shoes are pressed against the rotating brake disc or drum. During this process the friction materials and the brake disc are subjected to wear.

Friction is a continuous process but wear is a more complicated process than friction because it involves plastic deformation plus localised fracture event (Rigney, 1997), microstructural changes (Talib et al., 2003), and chemical changes (Jacko, 1977). Wear process in dry sliding contacts begins with particle detachment from the contact material surface due to formation of plastic deformation, material transfers to the opposite mating surface and formation of mechanical alloyed layers (Chen & Rigney 1985), finally elimination of wear fragments from the tribosystem as the wear debris. Wear mechanism in the operation during braking is a complex mechanism and no single mechanism was found to be fully operating (Rhee, 1973 & 1976; Bros & Sciesczka, 1977; Jacko et al., 1984; Talib et. al. 2007) and the major wear phenomena observed during braking processes were; (i) abrasive (ii) adhesive (iii) fatigue (iv) delamination and (v) thermal wear.

Friction and wear characteristics of friction material play an important role in deciding which new formulations developed are suitable for the brake system. The friction and wear behaviours of automotive brake pads are very complex to predict which depend on the various parameters such as microchemical structure of the pad and the metallic counter-face, rotating speed, pressure and contact surface temperature (Ingo et al., 2004). Composition and formulation of brake pads also play a big role on the friction behaviour, and since composition-property relationship are not known well enough, the formulation task is based on trial and error and thus is expensive and time consuming (Österl & Urban, 2004). Generally brake pads have a friction coefficient, μ between 0.3 and 0.6 (Blau, 2001).

In this work, ten (10) new friction material formulations which are composed of between eight (8) to foureen (14) elements have been developed using power metallurgy technique. In addition, a commercially-available brake pad, labelled as COM, was chosen for comparison purposed. Each sample was subjected to density, hardness, porosity, friction and wear, brake effectiveness and on-road braking performance tests in accordance with various relevant international standards. The best formulation was selected based on the following methodology;

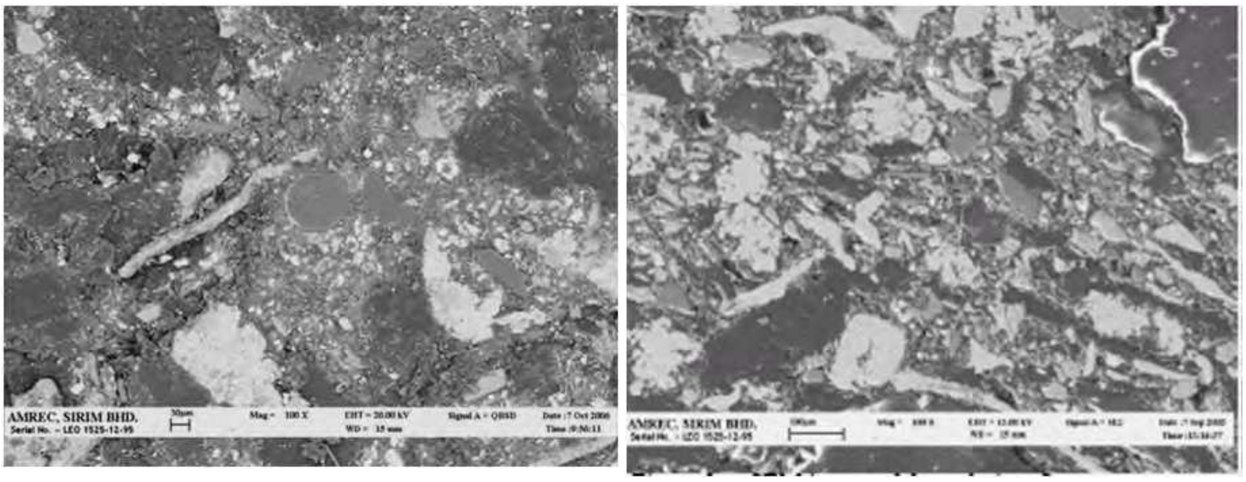
i. First screenings - screening of the developed formulations based on the results of the physical and mechanical tests.
ii. Second screening – screening of the developed formulations based on the results of friction and wear tests performed on CHASE brake lining friction machine.
iii. Third screening - screening of the developed formulations based on the results of brake dynamometer tests.
iv. Final selection - selection of the best developed formulations is based on the compliance with the on-road braking performance requirements.

Correlation among the mechanical, tribological and performance will also be discussed in this work. Wear phenomena on the worn surface after on-the road performance test will be examined and postulated.

2. Materials and method

2.1 Semi-metallic friction materials

Ten semi-metallic brake pad formulations which composed of between eight (8) to fourteen (14) ingredients were produced in this study using powder metallurgy route (Table 1). The powder metallurgy route consists of the following processes, namely, (ii) dry mixing, (ii) preparation of backing plate, (iii) pre-form compaction (iv) hot compaction, (v) post-baking, and (vi) finishing. The prototype samples were marked as SM1, SM2, SM3, SM4, SM5, SM6, SM7, SM8, SM9 and SM10. Figure 1 shows two (2) example microstructure of the newly developed semi-metallic brake pad. It can be seen that the brake pads developed are not a homogenous material. The particle size of each element is not unifrom in size and the distribution of the element is not well dispersed in the matrix.



(a) (b)

Fig. 1. Surface morphology of semi-metallic brake pad; (a) sample SM1, (b) sample SM4

Ingredients	Formulation (Weight %)									
	SM1	**SM2**	**SM3**	**SM4**	**SM5**	**SM6**	**SM7**	**SM8**	**SM9**	**SM10**
Resin	10.0	10.0	9.0	9.0	9.0	9.0	9.0	8.0	12.0	9.0
Kevlar	-	-	2.0	-	2.0	2.0	-	-	-	3.0
Steel fiber	20.0	23.0	31.0	20.0	30.0	31.0	22.0	24.0	22.0	25.0
Organic fiber	5.0	-	-	10.0	2.0	2.0	10.0	8.0	7.0	5.0
Copper fiber	-	-	2.0	6.0	2.0	3.0	6.0	-	8.0	3.0
Graphite	16.0	19.0	7.0	13.0	15.0	7.0	13.0	11.0	16.0	6.0
Antimony	-	-	3.0	-	3.0	3.0	-	-	5.0	
Iron oxide	34.0	24.0	18.0	9.0	16.0	18.0	9.0	15.0	3.0	21.0
Novacite silica	-	3.0	-	3.0	-	-	3.0	2.0	6.0	3.0
Alumina oxide	-	2.0	1.0	5.0	2.0	1.0	2.0	2.0		2.0
Zinc oxide	1.0	-	1.0	-	2.0	-	-	3.0	-	2.0
Rubber	-	3.0	4.0	3.0	3.0	3.0	3.0	3.0	3.0	5.0
White rock	-	-	2.0	3.0	2.0	3.0	3.0	6.0	3.0	3.0
Barium	8.0	10.0	20.0	19.0	8.0	18.0	20.0	14.0	-	7.0
Friction dust	6.0	6.0	-	-	4.0	-	-	4.0	15.0	6.0
TOTAL	100	100	100	100	100	100	100	100	100	100

Table 1. Ingredients of semi-metallic brake pad

2.2 Physical and mechanical tests

Each sample produced is subjected to density, porosity and hardness tests. Density of semi-metallic brake pads was obtained using Archimedes' principle in accordance with Malaysian Standard MS 474: Part 1: 2003 test procedures. Hardness was measured using a Rockwell hardness tester model Mitutoyo Ark 600 in S scale in accordance with Japanese Industrial Standard JIS 4421: 1996 test procedures. The hardness of the samples is the arithmetic mean of ten measurements. Porosity was obtained in accordance with JIS 4418: 1996 test procedures using a hot bath model Tech-Lab Digital Heating.

2.3 Friction and wear tests

Friction coefficient and wear were results were obtained which is in compliance with Society of Automotive Engineer SAE J661 test procedures. In this test, the sample was pressed against a rotating brake drum with a constant rotating speed of 417 rpm under the load of 647 N and subjected to test program as shows in Table 2. Briefly, each sample was subjected to seven test runs with the following sequences; (i) baseline, (ii) first fade, (iii) first recovery, (iv) wear, (v) second fade, (vi) second recovery, and (viii) baseline rerun. The samples thickness were measured and weighed before and after testing. Friction coefficient and wear tests were conducted by Greening Testing Laboratories Inc., USA using CHASE machine.

Test Sequence	Load (N)	Speed (rpm)	Braking mode
Conditioning	440	312	Continuous braking for 20 mins
Initial thickness & mass measurement	222	208	Continuous braking for 5 mins
Baseline run	667	417	Intermittent braking 10 s ON, 20 s OFF for 20 applications
First fade run	667 .	417	Continuous 10 minutes or until 288 °C is attained which ever come first
First recovery run	667	417	10 seconds application at 260, 204 , 149 and 93 °C
Wear run	667	417	Intermittent 20 s ON, 10 s OFF for 100 applications.
Second fade run	667	417	Continuous 10 mins or until 343 °C is attained which ever come first
Second recovery run	667	417	10 seconds application at 316, 260, 204 , 149, 93 °C
Baseline rerun	667	417	Intermittent 10 s ON, 20 s OFF for 20 applications
Final thickness and mass measurement			Repeat initial thickness and mass measurement

Table 2. Friction and Wear Assessment Test Program

2.4 Brake effective tests

The braking performance of the developed semi-material brake pads were determined using brake dynamometer test in accordance with Society of Automotive Engineers standard SAE J2552 issued in August 1999 (available from SAE, 400 Commonwealth Dr, Warrendale, PA 15096, USA). This standard assesses the effectiveness behavior of a friction material with regard to pressure, temperature and speed. Vehicle brake simulations are conducted on an inertia dynamometer, which simulate kinetic energy of the vehicle mass moving at speed. Before the beginning of performance measurement, a burnishing period for conditioning the lining/counterface pairs require more than 200 conditioning stops. After conditioning, dynamometer-based lining tests were subjected to pressure-sensitive stops, speed-sensitive drags, fade and recovery tests. Table 3, briefly shows the test sequences. Dynamometer global brake effectiveness tests were conducted by Greening Testing Laboratories Inc., USA using single end brake brake dynamometer. Each sample was conducted on a new brake rotor. In this study, the focus is only on the friction coefficient and wear characteristics of the sample.

The purpose of this investigation was to evaluate the performance of the semi-metallic brake pads for Proton WIRA using brake inertia dynamometer. Figure 2 shows prototype brake pad and Proton Wira’s drive shaft assembly. The technical specification of the brake effectiveness test is shown in Table 4.

Bil		Snub	Cycle	Speed (km/h)	Pressure (kPa)	Initial temp (^{O}C)
1.	Green µ	30	1	80 to 30	3000	< 100
2.	Burnish	32	6	80 to 30	Varying pressure	< 100
3.	Characteristic 1	6	1	80 to 30	3000	< 100
4.	Speed/press sensitivity	8 8 8 8 8	1 1 1 1 1	40 to 5 80 to 40 120 to 80 160 to 130 200 to 170	Increasing pressure 1000 to 8000	< 100
5.	Characteristic 2	6	1	80 to 30	3000	< 100
6.	Cold	1	1	40 to 5	3000	< 40
7.	Motorway application	1 1	1 1	100 to 5 0.9 V_{max} to 0.5 V_{max}	0.6 g	< 50
8.	Characteristic 3	18	1	80 to 30	3000	< 100
9.	Fade 1	15	1	100 to 5	16000 0.4 g	< 100 < 550
10.	Recovery 1	18	1	80 to 30	3000	< 100
11.	Temp/press Sensitivity 100/80 ^{O}C	8	1	80 to 30	Increasing pressure 1000 to 8000	< 100
12.	Temp/press Ssnsitivity 500/300 ^{O}C	9	1	80 to 30	3000	< 100
	Pressure line 500/300 ^{O}C	8	1	80 to 30	Increasing pressure 1000 to 8000	< 550
13.	Recovery 2	18	1	80 to 30	3000	< 100
14.	Fade 2	15	1	100 to 5	16000 0.4 g	< 100 < 550
15.	Recovery 3	18	1	80 to 30	3000	< 100

Table 3. Brake dynamometer test sequence

Item	Specification
Vehicle System Simulated	1996 Proton Wira 1.5 GL Front
Brake Configuration	single piston, separate function disc brake
Piston Diameter	54 mm
Rotor Diameter x Thickness	236 x 18 mm
Rotor Mass (nominal)	3.7 kg
Rotor Effective Radius	95.88 mm
Axle Load	830 kg
Test Inertia	$34.7\ \mathrm{kg \cdot m^2}$
Static Loaded Radius / Rolling Radius	287.02 mm
Simulated Wheel Load	421 kg
Wheel Rotation	: right hand

Table 4. Technical specifications of the brake effective test

Fig. 2. Semi-metallic brake pad and front axle brake system

2.5 On-road performance tests

In the road performance test, the brake pads were fitted to the brake system of PROTON WIRA 1.5GL with the following test conditions: (i) unladen vehicle, (ii) disconnected engine, (iii) tire inflated to the manufacturer's specifications, (iv) the road was hard, level and dry, (vi) the wind speed was below 5 m/s. The road performance test divided into three types, namely; (i) cold effectiveness test, (ii) heat fade test, and (iii) recovery test.

The on-road braking performance tests on car were performed following closely procedure described in the ECE R13, Annex 3. Modification on the procedure was necessary due to the limitation of the test track conditions (Table 5). Real application testing of the friction materials were carried out using Proton Wira 1.5 (Table 6). Figure 3 shows the test equipment set-up.

PARAMETER	ECE R13	MODIFIED ECE R13
Type-O: Cold brake		
• Initial vehicle speed	120 km/h	100 km/h
• Brake pedal force	65 – 500 N	65 – 500 N
• Engine disconnected	Yes	Yes
• Average temperature	65 – 100 °C	65 – 100 °C
• Vehicle must be laden & unladen	Yes	2 people
Type-1: Fade test		
Heating procedure:		
• Braking speed	120 - 60 km/h	100 - 50 km/h
• Brake pedal force	Equivalent to 3 m/s² deceleration	50% of Type-O
• No. of brake application	15	12
• Vehicle must be laden	Yes	2 people
• Engine connected	Yes	Yes
Hot performance:		
• Initial vehicle speed	120 km/h	100 km/h
• Brake pedal force	Same force obtained in Type-O test	Same force obtained in Type-O test
• Engine disconnected	Yes	Yes
Recovery procedure:		
• Braking speed	50 - 0 km/h	50 - 0 km/h
• Brake pedal force	Equivalent to 3 m/s² deceleration	50% of Type-O
• No. of stops with 1.5 km interval	4	4
• Vehicle must be laden	Yes	2 people
• Engine connected	Yes	Yes
Recovery performance:		
• Initial vehicle speed	120 km/h	100 km/h
• Brake pedal force	Same force obtained in Type-O test	Same force obtained in Type-O test
• Engine disconnected	Yes	Yes

Table 5. Modified ECE R13 test procedure

Fig. 3. Test equipment set-up; (a) *Dewetron DEWE-5000* system, (b) pressure sensor and thermocouple, (c) GPS receiver installed on the roof (d) pedal force sensor.

Manufcaturer	PROTON
Model	Proton WIRA 1.5S
Engine capacity	1,468 cc
Max. Power	66 kW
Max Torque	126NM @ 3000 rpm
Gear system	manual
Wheel size	175/70/R 13
Tire pressure	190 kPa

Table 6. Test car specifications

In the cold test, the test was conducted with the brake lining temperature below 100 ˚C prior to each brake application and comprised of six brakings including familiarization. The brake test was carried out at the initial vehicle speed of 100 km/hr. The test data such as vehicle speed, lining temperature and braking distance were recorded using a brake measuring system from *Dewetron* model DEWE5000. If the pedal force applied is more than 500 N for wheel locking to occur, the brake pad is considered fail to comply with the requirements and the next test (heat fade and recovery test) will not be conducted.

Fade test is used to evaluate the brake performance under high brake material temperature. Prior to this test, the service brake of the test car was heated by successively applying the brake. 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 50 % type-O deceleration. This process was repeated for 12 brake applications. Upon completing this heating procedure, the test vehicle was accelerate to initial vehicle speed of 100km and brake was applied using the same pedal force as in cold effective test of that particular sample. Immediately, the recovery test was conducted with the following test procedure; (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 100km and then brake pedal was applied with the same pedal force cold test.

2.6 Microstructural examination

The worn surface after on-road performance test were analyzed using scanning electron microscope model Leo equipped with a Oxford energy-dispersive X-ray analyzer (EDX).The samples for microstructural examination were cut from a real-size brake pad and coat with platinum using sputter coater to ovoid charging effect during the analysis.

3. Results and discussion

3.1 Physical and mechanical properties

Specific gravity is the relative density of a substance compared to the density of pure water and porosity is the percentage of pore volume with the bulk total volume. Hardness is a measure of material resistance to plastic deformation. The specific gravity, porosity and hardness properties depend on the ingredients and weight percentage used as well as the manufacturing process parameters. Test results of physical and mechanical properties are shown in Table 7 and Figure 4. Ideally, the highest specific gravity should give the lowest porosity and highest hardness reading. But in friction materials this postulation does not apply as shown in this investigation. For example, sample SM6 has the highest specific gravity reading but does producing the highest hardness result. Highest hardness reading was recorded by sample SM1, but this sample is not producing the highest density and the lowest porosity reading (Table 7).

Figure 4 exhibits the correlation among the specific gravity, porosity and hardness. Figure 4a indicates that the specimens with high porosity tend to exhibit low specific gravity. However, Figure 4b shows that there is no simple correlation between hardness with porosity. Brake pad should have a certain amount of porosity to minimize the effect of water and oil on the friction coefficient and to reduce the brake noise. Hardness should be decreased as much as is feasible to increase performance stability and the steel fiber content should be less than 7% in order to reduce rotor thickness variation (Sasaki, 1995). He also found that increasing porosity by more than 10 % could reduce the brake noise. But if the porosity too much, the hardness will be reduced resulting increase in wear rate of friction material. Friction material is not a homogeneous material, when the indenter hits on the metallic component the hardness will be higher, otherwise when it hits on polymeric component the hardness will be lower (Talib et al., 2008). Thus, the hardness of the friction material is not a representative of the bulk property.

Ideally the friction materials developed should have the best physical and mechanical properties in order to get the best brake effective performance. In case of friction materials, this phenomenon does not apply (Todorovic, 1987; Filip et al., 1995; Talib et al., 2006). The physical and mechanical properties of friction material can not be predicted based on type of ingredient used, particle size and shape, weight percentage of the ingredient. It also depends on manufacturing process parameters such as powder mixing duration, compaction pressure, compaction duration, degassing time, and post curing temperature and time. Based on the above observations, the best formulation can not be selected using physical and mechanical properties. The physical and mechanical properties could be used to control the quality of the formulations that has been developed during the manufacturing process. Consistent physical and mechanical properties of the same formulation reveal that the friction material manufacturing process is in control.

Bil	Sample	Specific gravity	Porosity (%)	Hardness (HRS)
1.	COM	2.69	10.4	69.9
2.	SM1	2.76	7.9	85.1
3.	SM2	2.73	2.6	83.8
4.	SM3	2.36	24.2	76.7
5.	SM4	2.30	21.4	70.6
6.	SM5	2.27	20.2	50.0
7.	SM6	3.25	2.5	69.7
8.	SM7	2.75	7.7	69.6
9.	SM8	2.65	9.5	60.5
10.	SM9	2.32	3.1	73.0
11.	SM10	2.43	16.1	51.1

Table 7. Physical and mechanical test results

3.2 Friction and wear properties

Friction material is a heterogeneous material and composed of a few elements. Therefore, the selection of material and weight percentage used in the friction formulation will significantly affect the tribological behaviour of the brake pad [Hoyer et al.1999]. Society of Automotive Engineer introducing two letter codes in classifying the friction material, where first letter represents normal friction coefficient and the second letter represents hot friction coefficient [SAE J886] as shown in Table 8. Normal friction coefficient is defined as average of the four readings taken at 200, 250, 300 and 400ºF on the second fade curve. The hot friction coefficient is defined as the average of the ten readings taken at 400 and 300ºF on the first recovery; 450, 500, 550, 600 and 650ºF of the second fade; and 500, 400 and 300ºF of the second recovery run. Figure 5 shows sample SM5 CHASE test results.

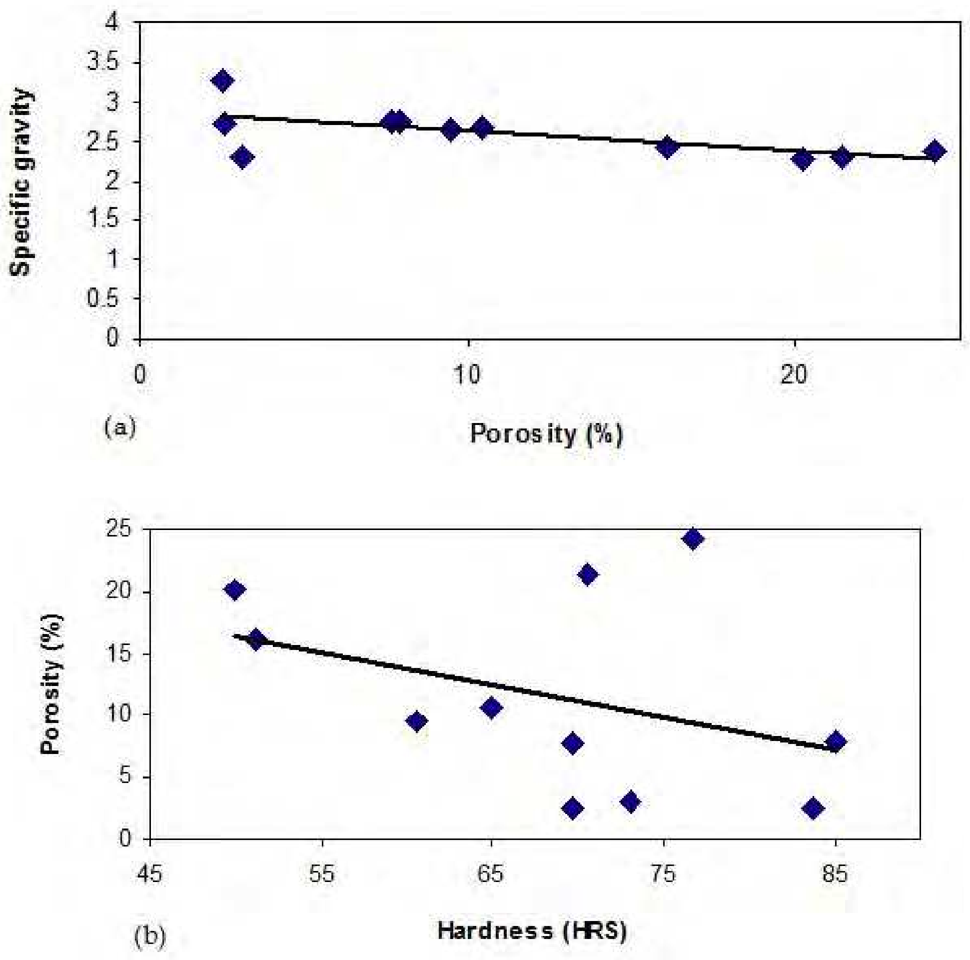


Fig. 4. The relationship between physical properties of friction material used in this study: (a) specific gravity Vs. porosity, (b) hardness Vs. porosity.

Class code	Coefficient of friction
C	Below 0.15
D	Over 0.15 – not over 0.25
E	Over 0.25 – not over 0.35
F	Over 0.35 – not over 0.45
G	Over 0.45 – not over 0.55
H	Over 0.55
Z	unclassified

Table 8. SAE Recommended Practice J866 list for codes and associated friction coefficient

Friction and wear characteristics of friction material play an important role in deciding which new formulations developed are suitable for the brake system designed for a particular vehicle. CHASE test is used in a laboratory for screening of new material formulations prior to inertia dynamometer tests based on friction and wear test results. In deciding which samples are to be subjected to dynamometer tests, the following requirements were set; (a) shall have normal friction coefficient of class E and above, or a hot of class D and above, (b) shall have friction coefficient above 0.15 between 200 and 550 ^{O}F inclusive in second fade, or between 300 and 200 ^{O}F during the secondary fade. These requirements are in line the requirement set by Automotive Manufacturer Equipment Companies Agency, USA.

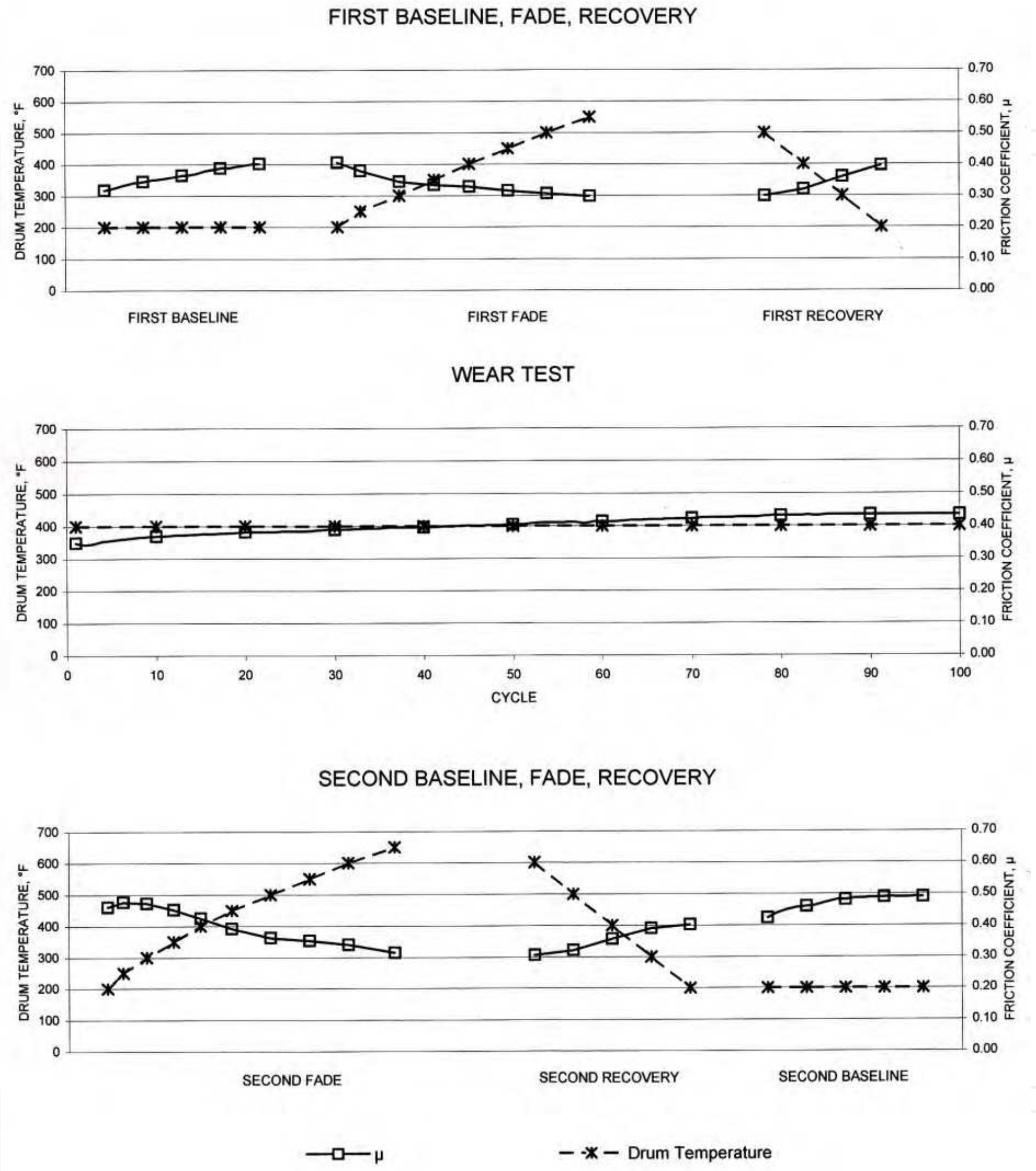


Fig. 5. Friction coefficient characteristic of sample SM5

Test results of friction and wear assessment tests are shown in Table 9 and Figure 6. Analysis of test results showed that all samples developed met with the requirements. During braking, the accumulation of heat will cause high surface temperature on the brake lining materials. The degradation of the polymer materials may cause brake fade in which the friction is reduced as the temperature increased [Begelinger et al. 1973; Rhee 1971]. The ensuing reduction of friction coefficient may also be explained by the shearing of the peak asperities and formation of friction during braking process [Talib et al. 2007]. All hot friction coefficients of the prototype samples reduced except sample SM8. This phenomenon may be due to the formation of metallic layer [Talib, 2001; Scieszka, 1980; Lim et al., 1987] and carbon layer [Begelinger et al., 1973; Zhigao & Xiaofie, 1991]. Sample SM1 and SM2 have lower average thickness loss than the commercial sample. The other eight samples have higher average thickness loss. Even though, higher wear loss resulted in shorter life, the samples which higher average thickness loss will also be subjected to brake effective dynamometer so that correlation thickness loss between these two tests could be made.

Sample	Normal Friction		Hot Friction		Thickness loss (mm)
	μ	Code	μ	Code	
COM	0.422	F	0.385	F	2.79
SM1	0.385	F	0.316	E	0.51
SM2	0.450	F	0.383	F	0.76
SM3	0.459	G	0.352	F	1.52
SM4	0.471	G	0.373	F	2.79
SM5	0.457	G	0.360	F	1.02
SM6	0.417	F	0.345	E	2.03
SM7	0.438	F	0.430	F	3.31
SM8	0.532	G	0.544	G	6.09
SM9	0.374	F	0.322	E	1.27
SM10	0.554	H	0.458	G	5.84

Table 9. Friction and Wear Assessment Test Results

Figure 7 shows the relationship between the hardness with the friction coefficient and average wear. Figure 7a indicates that the sample with high hardness tend to exhibit low friction coefficient. More & Tagert (1952) and Mokhtar (1982) likewise concluded that the coefficient of friction decreased with increase in hardness. Generally, the harder samples were supposed to have a lower average thickness loss. But in this investigation, it was found that this postulation does apply with the friction materials (Figure 7b). Thus, it could be concluded that there is no direct correlation between hardness with average thickness wear loss. Filip et al. (1995) reported that hardness of brake lining materials cannot be simply related to the content of structural constituents, and there is no correlation between hardness and wear resistance.

Figure 8 shows the relationship between the friction coefficient, average thickness loss and porosity. Brake pad should have a certain amount of porosity to minimize the effect of water and oil on the friction coefficient. Sasaki (1995) found that increasing porosity by more than 10 % could reduce the brake noise. It was observed that the sample with high porosity tend to exhibit high friction coefficient. On the other hand, Figure 8b, indicates that there is no direct correlation between average thickness loss with porosity.

During braking, the friction materials wear-off due to friction resistance between the friction materials with the counter face material made of grey cast iron. Wear rate of friction depend many factors such as operating parameters (temperature, speed, braking time), mode of braking (continuous, intermittent braking), wear mechanism in operation during braking (adhesion, abrasion, fatigue). When above the degradation temperature (230 ^{O}C), the

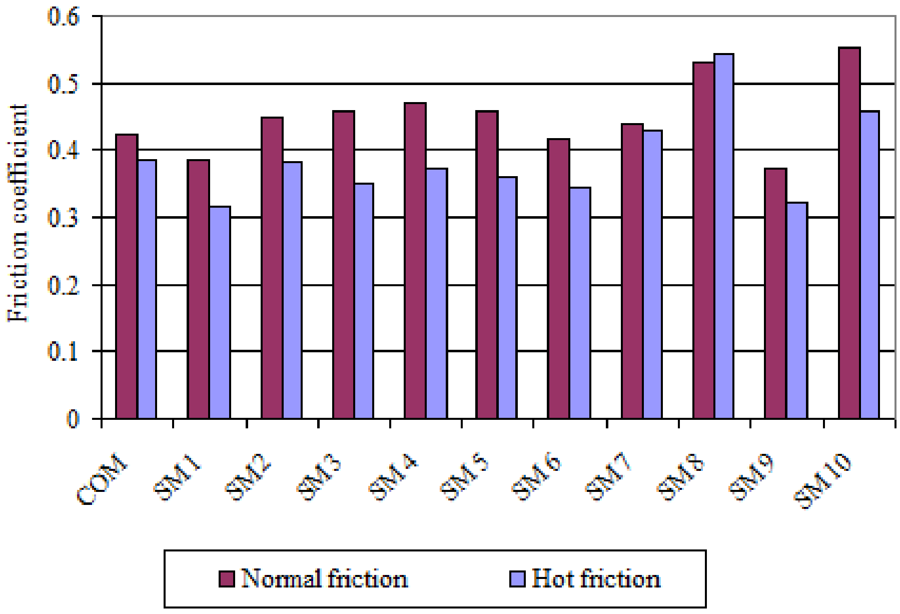


Fig. 6. Normal and hot friction coefficient

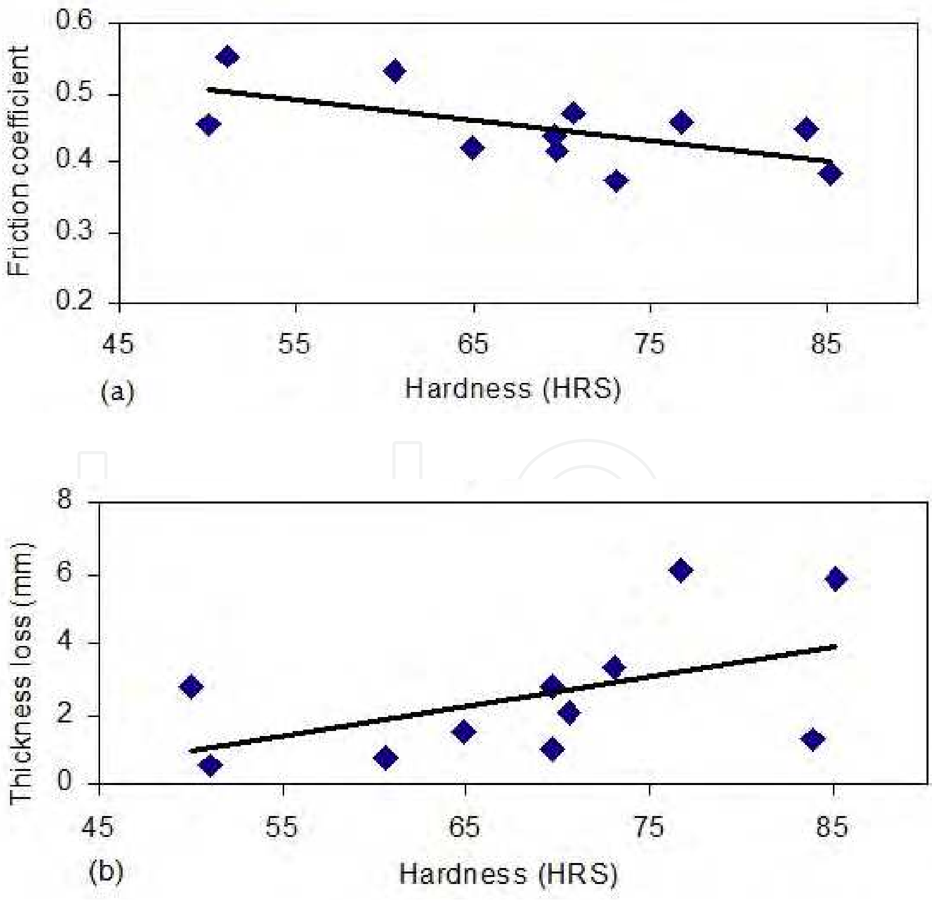


Fig. 7. The relationship between physical properties of friction material used in this study: (a) friction coefficient vs. hardness, (b) average thickness loss Vs. hardness.

binding properties of resin will become weak. As surface temperature increase with increased braking times, the yield strength of the materials will be decreased and leads to change in the wear mechanism and the real contact configuration as well as destruction of friction film. Thus, the wear rate cannot be predicted based on physical and mechanical properties because wear do not depend on material property but rather depends on tribosystem property.

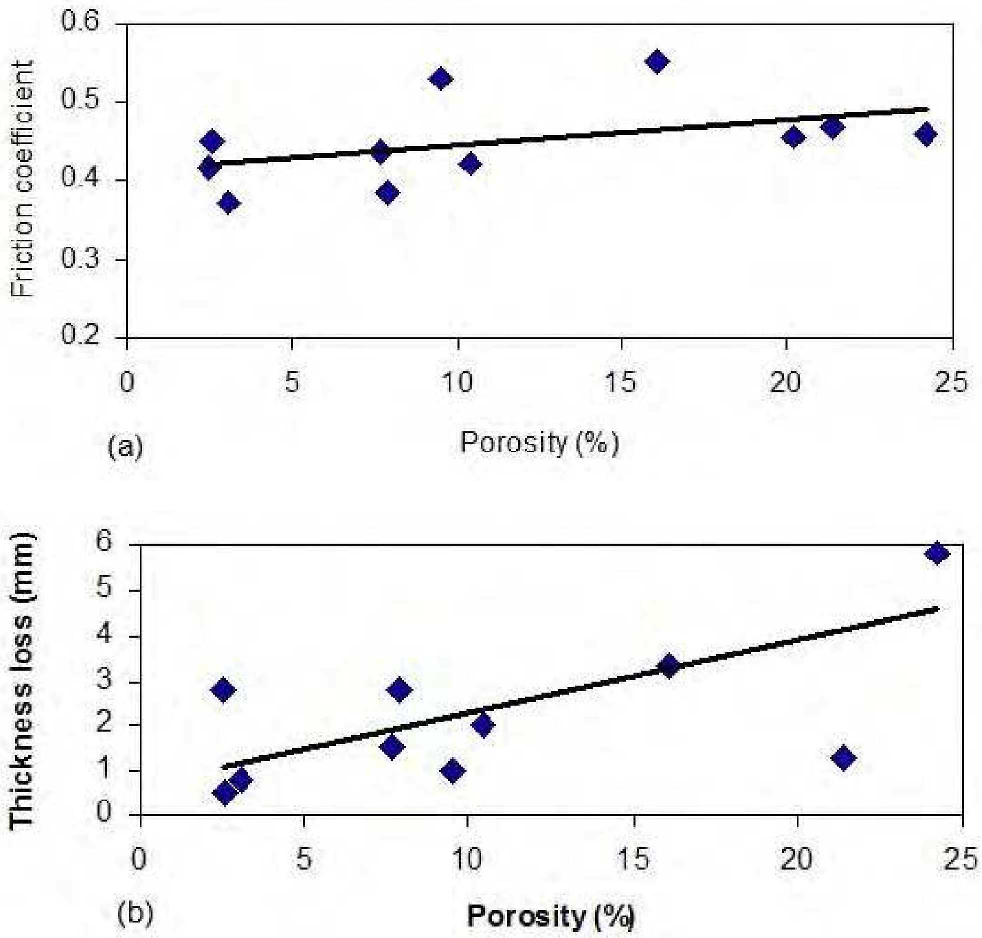


Fig. 8. The relationship between mechanical properties of friction material used in this study: (a) friction coefficient vs. porosity, (b) average thickness loss Vs. porosity.

The friction and wear properties of friction materials depend on a number of different factors such as pressure, speed, interface temperature, composition of friction material and the metal member of the friction pair, duration and length of the friction path, friction material density, its modulus of elasticity, type, design and geometry of friction mechanism [Torovic, 1987]. From the analyses on test data, the following postulation could be made; (i) higher hardness tend to reduce friction coefficient, (ii) higher porosity tend to increase friction coefficient, (iii) there is no simple correlation between average thickness loss with hardness and porosity. So in deciding with formulation can be used in the prototype production, friction and wear test results are the main factor to be considered. Based on test results, it could be concluded that all prototype samples complied with the requirements and will be subjected to brake effective dynamometer tests.

3.2 Brake effective parameters: Friction coefficient and wear

Table 10 shows the friction and coefficient and wear results. Test results show that only sample SM2 and SM9 have a minimum friction coefficient value below than 0.15 during the first fade test sequence. Lower friction coefficient requires a longer braking distance before the vehicle can be stop, which can cause road accident. In this test segment, the temperature was increased from 100 to 550°C under the line pressure of 16 MPa. Under this condition, the brake fade will take place. This fading effect is associated with the decomposition of the organic binder which takes place between 250 and 475 °C (Ramoussse et al., 2001). The friction coefficient of the friction materials will vary with temperature and will fall off dramatically as the contact temperature exceed the maximum organic decomposition temperature depending on the ingredient and weight percentage used. However, in the second fade test, the friction coefficient of the sample SM2 and SM9 have show a better result which is above 0.15, the minimum requirement. Characteristic friction after second fade also shows almost recover to the characteristic friction in the early stage. Thus all the formulation developed will be subjected to on-road performance test.

During braking process, brake pad is pressed against the brake rotor resulting in wear-off the brake pad as well as the rotor material. Brake pad is designed as the sacrificial element due to it low cost and ease of maintenance. Average values of wear detected after completion of the brake effective dynamometer test procedure is given in Table 10. Wear data are different for different formulation due to different ingredient and weight percentage used in the composition. Wear characteristics is difficult to predict because it depend on the physical, mechanical, chemical characteristic as well as the microstructure changes during the braking process.

Sample	Average friction coefficient				
	Characteristic	First fade	Second fade	Characteristic	Thickness loss (mm)
COM	0.50	0.28	0.29	0.32	1.87
SM1	0.42	0.25	0.25	0.31	1.57
SM2	0.42	0.12	0.34	0.39	1.44
SM3	0.42	0.33	0.28	0.33	1.96
SM4	0.44	0.26	0.29	0.36	1.25
SM5	0.45	0.29	0.29	0.34	1.65
SM6	0.42	0.28	0.31	0.34	3.68
SM7	0.43	0.23	0.28	0.33	2.27
SM8	0.47	0.28	0.35	0.36	4.08
SM9	0.36	0.09	0.18	0.32	1.89
SM10	0.48	0.28	0.32	0.26	3.15

Table 10. Brake dynamometer test results

Figure 9 shows example of friction coefficient characteristics under different stops. The friction coefficient characteristics for other samples vary for different stops as apparent from Figure 9. The first and the second characteristic, first and second fade, and recovery sequences reflect on the performance of brake lining. It can be seen from the fade test, the coefficient of friction decreases with increased in temperature. This is attributed to physical and mechanical, chemical and microstructural changes on the contact surface [Scieszka, 1980; Jacko, 1977; Talib et al., 2003; Ingo et al., 2004].

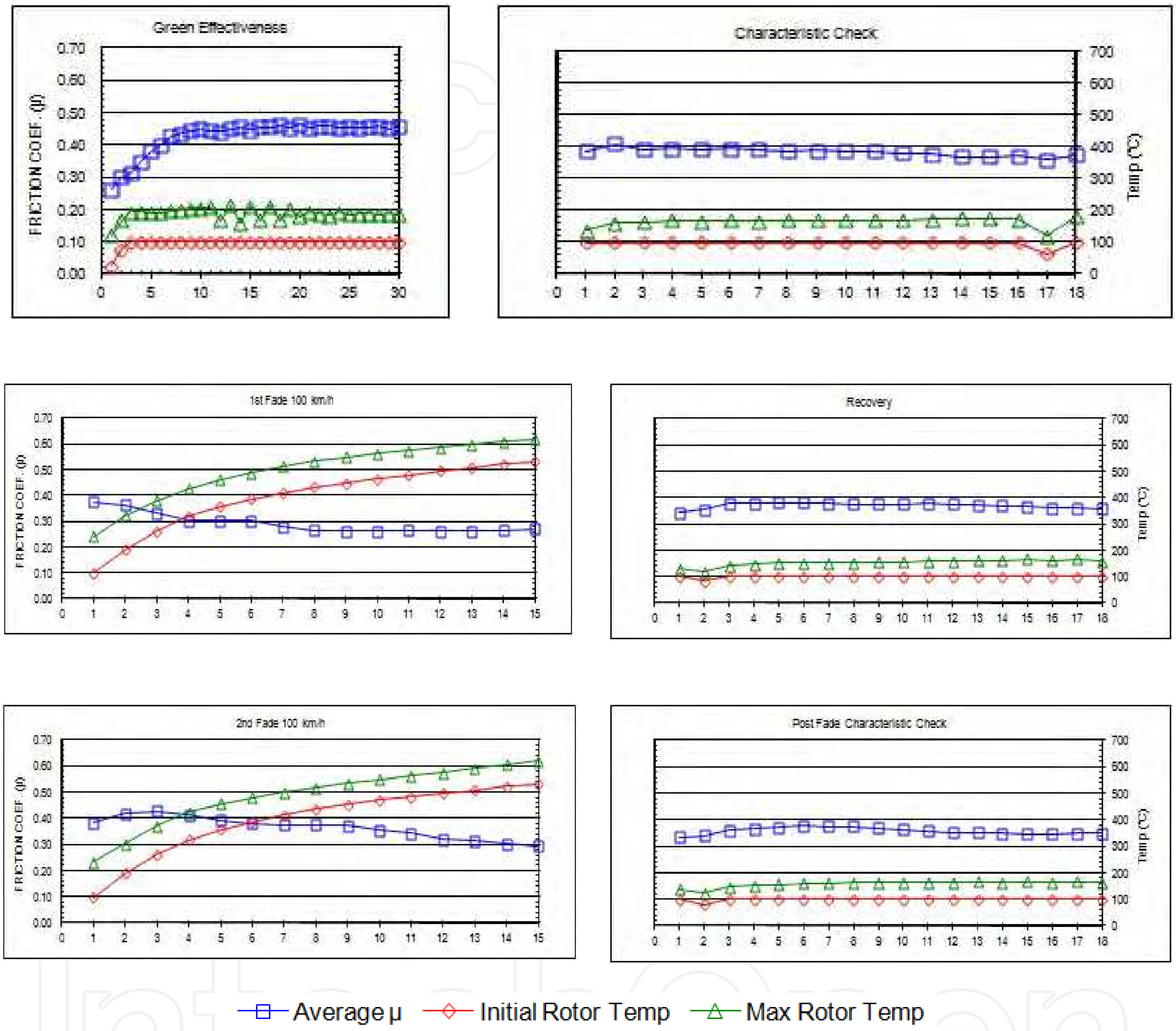


Fig. 9. Characteristic results of brake dynamometer tests

Even though the operating pressure, time and braking sequence of CHASE and dynamometer is not the same, it supposed to produce the friction coefficient results of the same trend for different composition. However, this postulation does not materialise in case of friction materials. It can be seen from Figure 10 that only sample COM, SM1 and SM3 have higher friction coefficient when the samples were subjected to dynamometer tests as compared to CHASE friction coefficient and the variation between friction coefficient reading of CHASE and dynamometer is also not same. Thus, it could be concluded that there is no direct correlation between the friction coefficient between CHASE and dynamometer tests. This was taught due to dependent of friction coefficient with material composition, microstructure and tribosytem.

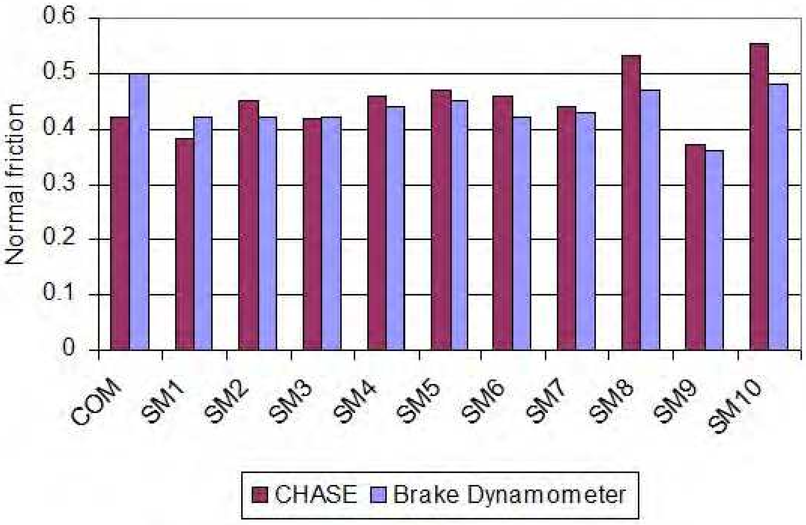


Fig. 10. Bar chart of normal and characteristic friction of CHASE and dynamometer tests.

In case of hot friction, the variation between CHASE and dynamometer results is quite high (Figure 11). This could due to the severity of test conditions applied during dynamometer test. Surface temperature increases when the operating variables such as load, speed and braking time are increased. In the dynamometer test, the surface temperature is increased up to 550°C which much higher compared to CHASE test which is about 300°C. As the surface temperature increases, the polymer materials will degrade. The onset of degradation of the friction material starts at 230 ^{O}C, and the degree of degradation increases with temperature within the range of 269 – 400 ^{O}C [Zhigao & Xiaofei; 1991]. The degradation of the polymer materials may cause brake fade in which the friction is reduced as the temperature increased [Rhee, 1971; Talib 2001]. The high temperature will also decrease the yield strength and leads to changes in the wear mechanism and the real contact configuration [So, 1996]. These phenomena could be the reason why the friction coefficients during dynamometer test much lower than one during CHASE test. The different between the friction coefficients for particular composition is not the same. This could be due to the heterogeneous properties friction materials. Thus, it could be concluded that there no simple correlation between the friction material under high temperature test condition when subjected to CHASE and dynamometer tests.

Figure 12 shows the data of material thickness losses during braking tests on CHASE machine and brake dynamometer. The results show there is no correlation between the two test results. These variations can be due to the fact that CHASE machine uses a small material sample (i.e. 1 inch x 1 inch x 0.25 inch) pressed against a large rotating drum that does not represent the actual size of the lining material in its real intended application. Whereas, the brake dynamometer evaluates a full size brake lining material as it is in real application and thus simulating the actual braking condition of a vehicle. Thus, CHASE machine is not recommended for evaluation of the thickness loss of the developed sample in full size application. Ideally, all friction materials shall be tested and evaluated in all conditions that they may encounter during their service such as under various brake operating parameters (load, temperature and braking duration), road conditions (downhill and winding roads) and wheather conditions (rain, sunshine and snow). For all these, different vehicles will require different friction materials and unfortuantely, CHASE machine perform rather poorly in predicting the actual performance of the materials when they are put into real life application.

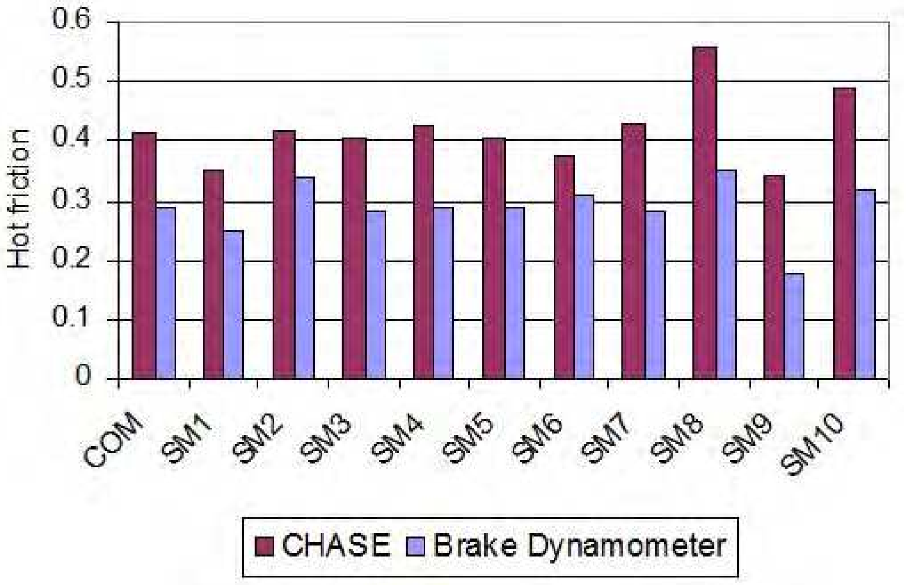


Fig. 11. Bar chart of thickness loss during CHASE and dynamometer test.

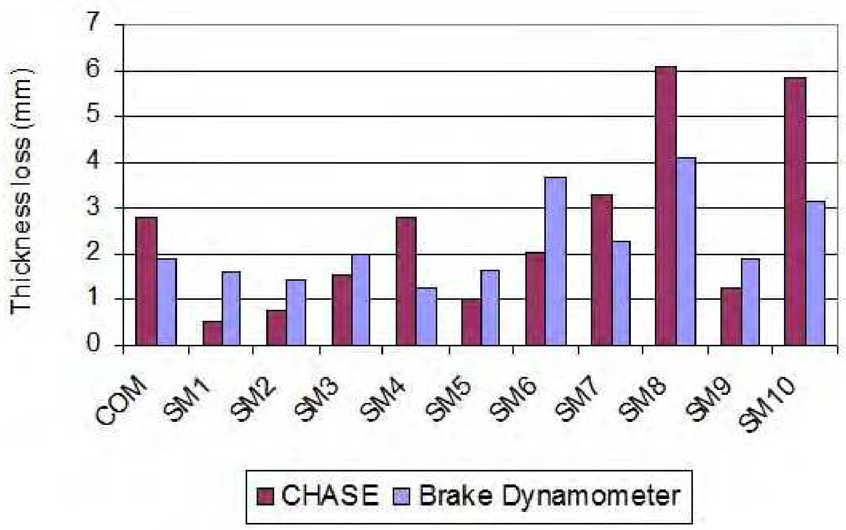


Fig. 12. Bar chart of thickness loss during CHASE and dynamometer test.

3.3 On-road performance

The development and validation of a friction material involve a significant amount of testing in laboratory and on the road. As a vehicle is typically used under various road and driving conditions, 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. Of all the tests carried out during a friction material 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. A brake test is basically a deceleration test carried out between two speeds. Data taken during the test is used to calculate the time taken, distance travelled and deceleration. A few other additional parameters such as brake hydraulic pressure, brake pedal effort and temperature of the friction materials would also be normally measured.

The developed formulations were subjected to on-road test as per ECE R13 and shall achieve a minimum mean fully developed deceleration (MFDD) requirements as shown in Table 11. Alternatively, the braking performance may also be evaluated in terms of the stopping distance. The tests consists of three (3) test modes (cold, fade and recovery) simulating real conditions of brake lining material temperature during its service. Figure 13 shows a typical display of Dewetron DEWE-5000 acquisition system during fade and recovery tests.

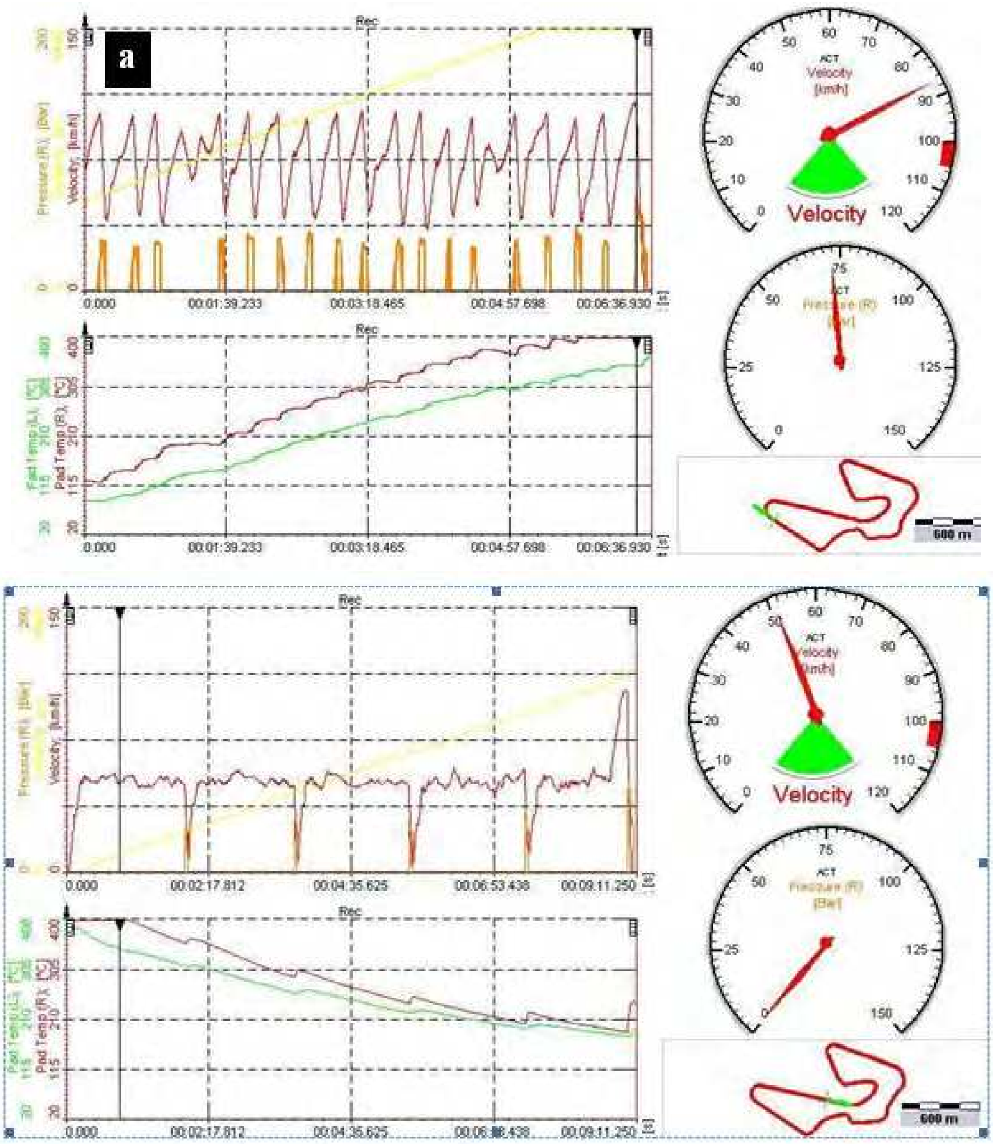


Fig. 13. Display of data acquisition system; (a) fade test, (b) recovery test

Tests	Mean fully developed deceleration (m/s²)
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
Pedal force	Shall be more than 500N

Table 11. Minimum requirements of the performance tests (ECE R13)

Test results of on-road braking performance for all the developed friction material formulation and a commercial pad are shown in Table 12 Figure 14. Out of the 10 prototype and 1 commercial sample tested for on-road performance, four samples do not fully comply with ECE's requirements, namely, sample SM2, SM4, SM7 and SM9. Samples SM2, SM7 and SM9 require pedal forces of 536N, 646N and 980 N, respectively under cold test conditions, which are exceeding the maximum permitted pedal force of 500 N as shown in Table 11. As such, further tests (i.e. fade and recovery) were not performed on these samples and the samples were eliminated. Higher pedal force requires more driver effort to stop the vehicle, which may stress the leg, especially for the lady driver. Sample SM4 does comply with deceleration requirement under fade test with MFDD of 4.18 m/s^2 which is less than the required value of 4.81 m/s^2 (i.e. >75% of 6.43). Test results also show that all other samples (COM, SM1, SM3, SM5, SM6, SM8, SM10) fully comply with cold-, fade- and recovery-tests requirements. Sample SM3, SM5, SM6 and SM8, though, shows higher values of MFDD during recovery tests than the cold effectiveness tests, which is allowed by this regulation which states that the MFDD can go up to 150% of the figure recorded in cold effective test.

Sample	Test Mode	Pedal Force [N]	MFDD [m/s2]	Pad Temp. (deg C)	
				Left	Right
COM	Cold	138	7.65	93	126
	Fade	150	5.49	350	456
	Recovery	133	7.50	184	242
SM1	Cold	254	8.00	161	172
	Fade	230	8.10	212	221
	Recovery	218	8.24	158	140
SM2	Cold	536	8.14	169	177
	Fade	Not performed, F>500 N for Cold Test			
	Recovery	Not performed, F>500 N for Cold Test			
SM3	Cold	114	7.33	103	158
	Fade	120	5.77	394	459
	Recovery	116	7.39	202	260
SM4	Cold	96	6.83	115	110
	Fade	94	4.18	416	312
	Recovery	98	4.95	181	155
SM5	Cold	129	7.46	93	89
	Fade	132	5.73	253	273

Sample	Test Mode	Pedal Force [N]	MFDD [m/s2]	Pad Temp. (deg C)	
				Left	Right
	Recovery	136	7.67	139	137
SM6	Cold	128	8.1	155	154
	Fade	130	7.07	272	260
	Recovery	134	8.38	143	152
SM7	Cold	646	6.02	202	193
	Fade	Not performed, F>500 N for Cold Test			
	Recovery	Not performed, F>500 N for Cold Test			
SM8	Cold	133	7.29	111	99
	Fade	135	5.67	345	289
	Recovery	132	7.32	169	143
SM9	Cold	980	-	292	320
	Fade	Not performed, F>500 N for Cold Test			
	Recovery	Not performed, F>500 N for Cold Test			
SM10	Cold	104	7.05	316	277
	Fade	109	5.72	515	527
	Recovery	117	5.77	333	332

Table 12. On-road performance test results

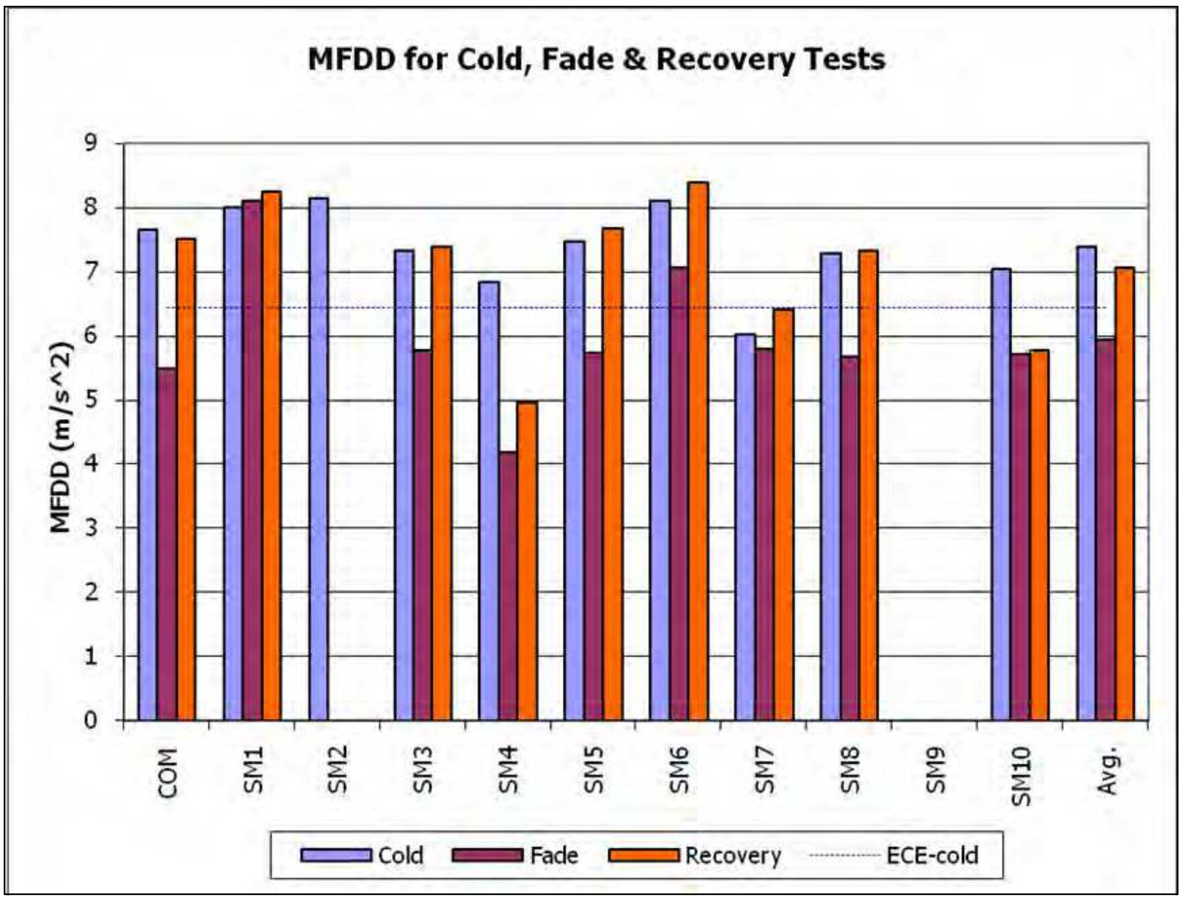


Fig. 14. MFDD for Cold, Fade and Recovery Tests

In the braking process, kinetic energy of a moving vehicle is converted into thermal energy. The generation of heat is due to the friction between the friction materials and brake disc. The heat generated is dissipated to the surroundings by the brake disc and friction materials. The ability of brake disc to dissipate this heat significantly affects the performance and wear life of the friction materials. Heat generated during braking result a phenomenon known as heat fade where the friction fall at elevated temperature. This fading effect is associated with the decomposition of the organic compound. The decomposition of the binder takes place between 250 and 475 °C (Ramousse et al. 2001). This phenomenon results in a reduction of friction as the temperature increased as observed by Rhee 1971 and Talib et al. 2001. This sudden drop of friction results in lower brake performance, in which longer braking distance is required before the moving vehicle can be stopped.

Figure 15 shows that there is no direct correlation between thick loss of prototype brake pad during brake dynamometer and on-road test. The test sequences and braking parameters of the brake dynamometer and on-road tests are not the same. For homogeneous materials, the thickness loss of the two test methods will be producing the same tend. But for friction materials, this postulation does not apply. This was taught due to heterogeneous properties of friction materials, where wear of friction materials is dependent on the mechanical, chemical, thermal properties as well as the microstructure. On-road braking test results give a better picture of the performance of the developed friction material formulations in real life applications as compared with the laboratory test data.

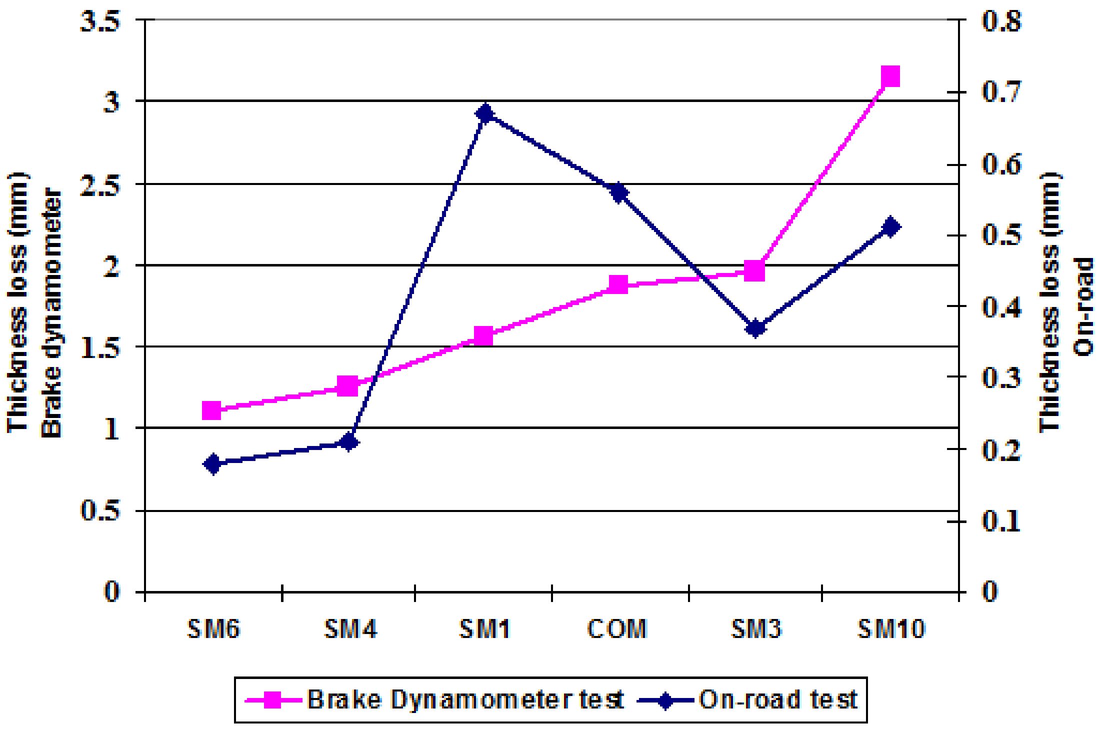


Fig. 15. Thickness loss of brake pad during brake dynamometer and on-road test

3.4 Microstructural

Figure 16, shows the photograph of sample SM6 after subjected to on-road performance test. The pad has pitting, grooving and moderate resin bleed. It was observed there is no flaking or surface cracking evident on the worn surface of brake pad. The surface of rotor has light lining transfer and light grooving.

Fig. 16. Post on-road performance test photograph on brake pad and brake disc

The worn surface after on-road performance test were analyzed using scanning electron microscope equipped with energy-dispersive X-ray analyzer (EDX). Microstructureal examaination on worn surface revealed that the mechanism composed a complex mixture of abrasion, adhesion and delamination as shown in Figure 17. Figure 17a show a manifestation of abrasion wear mechanisms where the harder peak asperities were ploughed into the surface. Figure 17b and c show a manifestation of adhesion mechanism. Adhesion wear mechanism composed a process of two-way transfer during sliding caused the formation of transfer layers on both sides of the sliding surfaces (Figure 17b) as observed elsewhere (Kerridge & Lancaster 1956; Chen and Rigney 1985; Talib et al. 2003) due to mechanical alloying as reported by Chen at el. (1984). Figure 17c shows transfer layers appeared to be sheared and flattened and smeared on their surfaces during then raking process. Thus it can be concluded that the wear surfaces became smoother with increase in braking time. Figure 17d shows a sympton of delamination mechanism where it reveled the wear particles flake off from the wear surface when reaching the critical length.

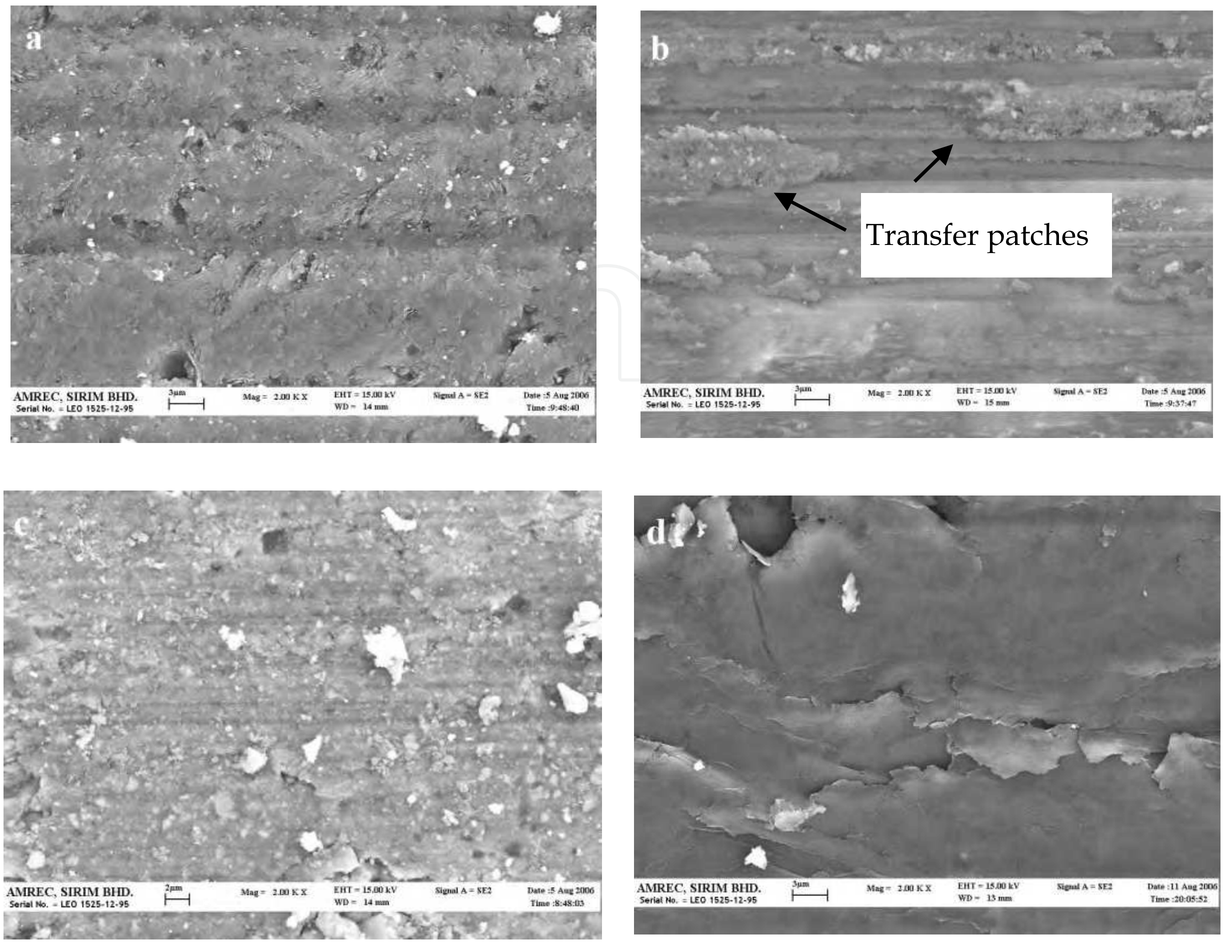


Fig. 17. Wear mechanism observed during braking process; (a) abrasion, (b) adhesion – generation of transfer patches, (c) adhesion – smearing and (d) delamination

4. Conclusions

Characteristic of friction materials is very complex to predict and it is a critical factor in brake system design and performance. To achive ideal brake friction material characteristic such as constant a constant coefficient of friction under various operating conditions, resistance to heat, water and oil fade, low wear rate, posses durability, heat stability, exhibits low noise, and not to damage brake disc, some requirements have to be compromised in order to achieve some other requirements. This can be done by changing the type and weight percentage of the ingredients in the formulation. This works shows

The following phenomena could be postulated based on the physical and mechanical, friction and wear test results using CHASE machine, brake effective test results using brake inertia dynamometer, and braking performance test results;

i. Test results show that there is no simple relationship between the physical and mechanical properties and thus, these test results could not be used to screen the developed samples. The physical and mechanical properties are used for quality control in producing friction material with consistent physical and mechanical properties.

ii. Friction and wear characteristics obtained using CHASE machine could not be simply related to physical and mechanical characteristics.
iii. Friction and wears assessment tests using CHASE brake lining machine can be used for screening of friction material formulations during development as well as for quality control. Thickness loss using CHASE machine cannot be used to predict thickness loss using brake inertia dynamometer.
iv. The test sequence and parameters of brake dynamometer cannot simulate exactly all the braking pameters and enviroment of on-road test condition. Thus there is no simple correlation between the brake dynamometer test results with on-road performance results.
v. The final selection of the best formulation is based on on-road performance test results. However, the prototype samples need to be subjected to endurance tests to ensure that formulations can perform under real life application conditions.

The development and validation of a friction material involve a significant amount of testing in laboratory and on the road. 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. Thus, vehicle testing on the test track is the ultimate measure for the overall assessment of the brake performance testing and evaluation. Out of the ten (10) developed friction formulations, only 6 samples complied with the on-road braking performance requirements. However, further investigations on the performance and wear of the developed brake pads need to be conducted on actual intended application on various real road conditions.

During braking process, the brake pad is pressed against a rotating disc which in turn slows down the rotation of the wheels of a vehicle and thus stops the vehicle. In the process of decelerating a moving vehicle, kinetic energy is converted into thermal energy. This accumulated heat is absorbed by the brake pads and brake disc before being dissipated to the atmosphere. The accumulation of heat causes high surface temperatures in the lining materials and the brake disc which leads to the changes to the mechanical, chemical and wear mechanism. The brake lining materials wear off as a result of friction between the lining materials and the brake disc. Micro-structural changes on the worn surface of the brake reveals that the wear mechanisms operated during braking include adhesion, abrasion and delamination. The wear mechanisms operated during braking are rather complex with no single mechanism was found to be operating fully.

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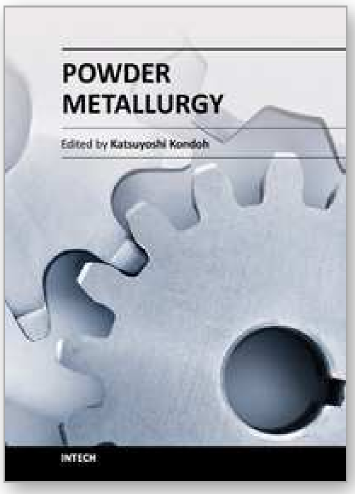

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From high-performance, economical and environmental points of view, Powder metallurgy process shows remarkable advantages in production of parts and components due to their special compositions by elemental mixing and 3-dimensional near net shape forming methods. Powder metallurgy process can be applied to not only metal materials but also ceramics and organic materials, which both are employed as structural and electrical products. Author contributions to Powder metallurgy present excellent and significantly important research topics to evaluate various properties and performance of P/M materials for applying these materials as actual components. In particular, the life estimation of P/M ferrous materials by sliding contact fatigue test and tribological performance evaluation of P/M semi-metallic materials are focused and introduced in this book.

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