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## Effect of boron on friction and temperature characteristics of brake pad materials

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### ABSTRACT

Friction material in a brake system plays an important role for effective and safe brake performance. Brake materials contain mainly Alumina and other ingredients. This research attempts to examine mechanical properties of Boron mixed brake pads. Five groups of semi-metallic composite materials were studied. Friction coefficient of Boron mixed and commercial brake pads were significantly different. Average friction coefficient of Boron mixed pads was 0.495, 0.065 higher than commercial pad. Abrupt reduction of friction coefficient which is known as fade was more significant in the commercial pad samples than in Boron mixed pads. Fade occurred in commercial pad sample at the lower temperature as first fade was at 204°C and second was at 159°C resulted from earlier softening and degradation of Alumina material. All Boron pads were more stable and constant than their commercial counterparts. The study shows a slight reduction of friction coefficient at a temperature of 204°C during the first fade and 238°C on the second for Boron mixed pads. Both commercial and Boron mixed brake pads showed normal recovery stage in that they returned to their pre-fade friction coefficient levels with little temperature reduction. Properties of Boron mixed brake pads are better than Commercial brake pads.

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### KEYWORDS

Boron mixed;  
Brake pads;  
Fade;  
Friction coefficient;  
Single material.

### INTRODUCTION

Researchers attempt to investigate various materials in the brake systems to continuously improving the performance of vehicle as well as increasing its safety. The friction materials play an important role for effective and safe brake performance. A single material has never been sufficient to solve performance related issues such as friction force and wear resistance. Com-

mercial brake friction materials contain mainly Alumina and other ingredients. The ingredients contained binders, reinforcing fibers, solid lubricants, abrasives, fillers, additives and metal powders. The current research attempts to examine the mechanical properties of Boron mixed brake pads by comparing them with the commercial brake pads.

Sarikaya et al.<sup>[1]</sup> examined the wear behavior of Aluminum-Silicone-Boron Carbide composite coatings

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with 0-25 wt% Boron Carbide particles for diesel engine motors. The results pointed out that an increase of Boron Carbide particles in Aluminum Silicon coatings was caused on the rising of the micro-hardness values and the decrease of the thermal expansion coefficient of the coatings. It was concluded that wear resistance of the coatings produced using Boron Carbide powders is greatly improved compared with the substrate material. The highest wear resistances of the coatings were also determined in the 20% Boron Carbide coating.

Lu et al.<sup>[2]</sup> investigated the effect of Boron content and wear parameters on dry sliding of nanocomposite Titanium-Boron-Nitrogen thin films. Titanium-Boron-Nitrogen with thin films of 1.4 micrometer in thickness with different Boron contents was deposited on Silicon wafers at room temperature by reactive unbalanced dc-magnetron sputtering. The results show that Titanium-Nitrogen has the highest friction coefficient of approximately 0.93. After the incorporation of a small amount of Boron (<5.3 at %) into Titanium-Nitrogen, the friction coefficient decreased to 0.80. A continuous reduction of friction coefficient was also reported after further increasing Boron content.

Ipek<sup>[3]</sup> in his study compare the wear behaviors of Aluminum-Boron-Carbide (10 wt% B<sub>4</sub>C, 15 wt% B<sub>4</sub>C and 20 wt% B<sub>4</sub>C) particles with Aluminum-Silicon-Carbide (20 wt% SiC) metal matrix composites. In general, the wear rate of composites showed similar trends, with the wear rate of samples increased with the increase in sliding distances. The wear rate of the Aluminum-Silicon-Carbide (20 wt% SiC) composite was the lowest among of test specimens under the wear test condition. Further, Ipek<sup>[3]</sup> explains that Silicon Carbide particle has more effect on wear resistance for Aluminum alloy than Boron Carbide because of good adhering to the Aluminum alloy matrix.

Yi and Yan<sup>[4]</sup> examined the effect of Hexagonal and Calcined Petroleum Coke on friction and wear behaviors of Phenolic resin based friction composites. Specifically, they assessed the effect of Calcined Petroleum Coke (CPC) and Hexagonal Boron Nitride (h-BN) as the friction modifiers to improve the friction and wear properties of Phenolic resin based friction composites. It was observed that the incorporation of CPC led to a gradual increase in the hardness and in the bending

strength of the Phenolic resin based friction composites. It was supposed that the CPC had a strong interfacial bonding strength with the Phenolic resin matrix during the compression at elevated temperature and pressure. Further, it was found that the hybrids of the two friction modifiers were effective to significantly decrease the wear rate and stabilize the friction coefficient of the friction composites at various temperatures by forming a uniform lubricating and transferred film on the rubbing surfaces. The effectiveness of the hybrid of CPC and h-BN in improving the friction and wear behavior of the Phenolic resin based friction modifiers could be attributed to the complementary action of the low temperature lubricity of CPC and the high temperature lubricity of h-BN.

Accordingly, Lu et al.<sup>[2]</sup> documented three important findings in their research. First, both friction coefficient and specific wear rate decreased with incorporation of Boron into Titanium-Nitrogen or increasing Boron content. When the Boron content reached a critical value (<42%), an inverse trend in the wear rate occurred due to formation of soft hexagonal-Boron-Nitride phase in Titanium-Boron-Nitrogen thin films. Second, Wear parameters had great effects on friction coefficient and wear rate. With an increase in applied loading, the friction coefficient increased, however the specific wear rate exhibited an inverse trend, accompanying with an increase in amount of deformed wear debris. Third, Oxygen of water in air participated in and reacted with films and formed mainly Titanium Oxide consisting of Titanium Oxide, Titanium Dioxide and Titanium Trioxide, accompanying with minor amount of Ferum Oxide in debris. The formation of Oxide in debris was believed to have an effect on increasing wear resistance.

Tang et al.<sup>[5]</sup> examined the performance of Aluminum matrix reinforced with 5 wt% and 10 wt% Boron Carbide particles. The findings showed that wear rate of both composite increased with the increase in sliding speed and load. However the composite with 10 wt% Boron Carbide was approximately 40% lower than that of the composite with 5 wt% Boron Carbide appeared under the similar test conditions. This experimental result indicated a significant effect of the Boron Carbide particles on enhancing the wear resistance of these composites.

Hong et al.<sup>[6]</sup> examined wear mechanism of multiphase friction materials with three different Phenolic resin matrices; straight Phenolic resin, Silicon modified Phenolic resin and Boron-Phosphorous (B-P) modified Phenolic resin. Wear tests were carried out using a Krauss Type Friction Tester. Friction stability and wear rate of the three friction materials were compared as a function of temperature up to 400°C and the mechanisms associated with the wear processes at different temperature ranges were analyzed using Arrhenius type plots and worn surface morphology.

## METHODOLOGY

Five groups of locally developed semi-metallic composite friction materials were studied for friction and wear. A semi-metallic commercial brake pad (ZMF) was used as a benchmark. The commercial formulations developed locally were represented by ZMF series. Abrasive material named Aluminum Oxide which existed in ZMF formulation was taken out. It was replaced by consistent different weight percentage of Boron, i.e. 0.6 %, 1.0 %, 1.5 % and 2.0 % and then mixed into the ZMF formulation. In addition, other ingredients measured in their weight percentage were added proportionally. Grouping was made based on these variations. The five groups were referred to as ZMF, ZMF+B0.6%, ZMF+B1.0 %, ZMF+B1.5 % and ZMF+B2.0 %. These compositions were divided into several subcomponents named as abrasives, additives, metal powder, reinforcing fiber, lubricants, fillers and binders.

Brake pad samples were prepared to the sizes of 26 mm x 26 mm x 7 mm. The weight and thickness of brake pad samples were taken before and after the friction test. In order to obtain average thickness value, three measurements were taken at different locations on the brake pad samples. The variations of the thickness were minimized.

Five groups of brake pad samples named as ZMF, ZMF+B0.6%, ZMF+B1.0 %, ZMF+B1.5 % and ZMF+B2.0 % were prepared in actual production process. Typical sizes of samples shown in the Figure 1 was cut for each formulation group and re-shaped to square using grinding machine. A total of 20 pieces of brake pad samples were used to examine their friction and wear behavior.

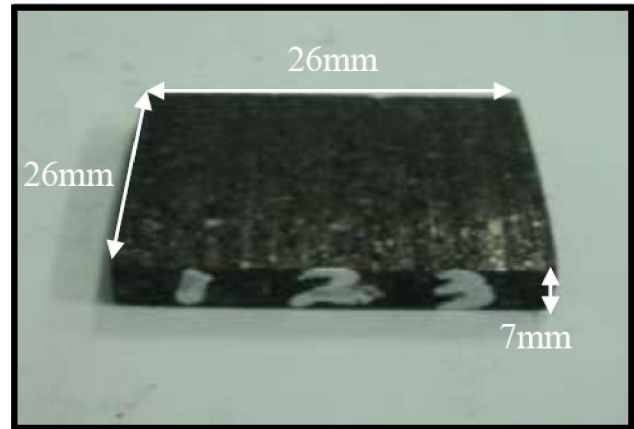


Figure 1 : Test sample used

The friction tests were performed using the friction material test machine called CHASE machine. The CHASE used a pearlitic gray cast iron disc (diameter of 180 mm, thickness 38 mm) and a brake lining test sample with dimensions of 26 mm x 26 mm x 7 mm. The test sample was mounted on the load arm and 150 psi pressure was pressed against the flat surface of the rotating disc. The rotating cast iron disc moved with a constant sliding speed of 417 rpm.

## RESULTS AND DISCUSSION

The TABLE 1 shows comparison test results of Boron mixed and commercial brake pads. The normal/hot friction coefficient test results were summarized from average four samples of Boron and commercial brake pad formulation individually. The results demonstrated that the formulations using Boron mixed brake pads produced higher normal and hot friction coefficient at GG class value than those of the commercial brake pad samples.

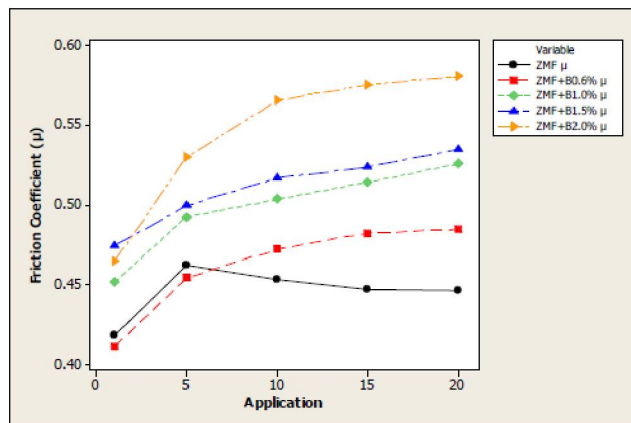
TABLE 1 : Summary of test results

Group of Brake Pad	Normal friction coefficient	Hot friction coefficient
ZMF Regular	0.43 FF	0.41
ZMF + B0.6 %	0.48 GG	0.50
ZMF + B1.0 %	0.51 GG	0.53
ZMF + B1.5 %	0.49 GG	0.50
ZMF + B2.0 %	0.50 GG	0.52

The Figure 2 shows the samples run for first baseline condition. The load was applied to the drum for 10 seconds and released for 20 seconds for 20 applica-

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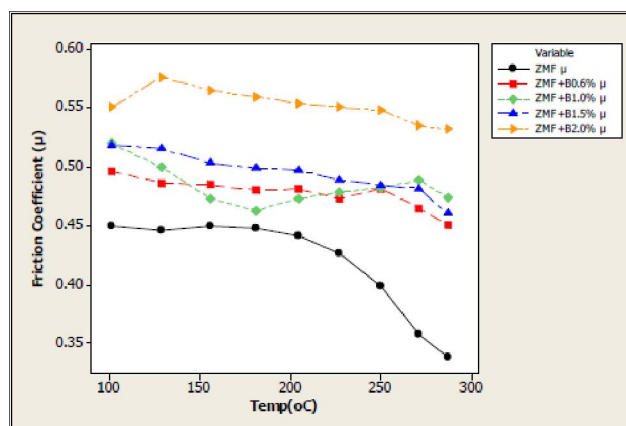
tions with friction readings taken at every fifth application. The temperatures range from 82°C-101°C during the testing procedure. All the friction coefficient of Boron samples increased at the beginning of braking stages until 20 braking applications. Among the Boron mixed brake pads sample ZMF+B2.0% showed the highest trend while ZMF+B0.6% was the lowest.



**Figure 2 : Plots of friction coefficient for first baseline condition**

However the friction coefficient of commercial (ZMF) sample became low at the fifth application and eventually constant after 20 applications. Heat generated during braking caused the surface temperature to increase with braking time which resulting the creating of tribo-films. For the commercial brake pad, tribo-films which were in the forms of Carbon started to created at the fifth application. The increase of tribo-films was accompanied by a decrease in friction coefficient at the fifth application onwards. The similar finding was reported by Shorowordi et al.<sup>[7]</sup> in their studies on the tribo-surface characteristics of Aluminium metal matrix composites (Al-MMC). They suggested that since Carbon in the transfer layer of Al-MMC was in the form of Graphite, the increase in the Carbon content of the transfer layer resulted in a decrease in the coefficient of friction of Aluminium metal matrix composites (Al-MMC).

The Figure 3 shows the changes of the friction coefficient as a function of disc temperature during the first fade condition for all samples. The load was applied continuously for 10 minutes or until the temperature reached 287°C. The coefficient of friction was recorded with each increase in the temperature. Friction readings were taken at average of 23°C intervals.



**Figure 3 : Plots of friction coefficient vs disc temperature**

When the friction coefficient decreases during braking due to the friction heat, the situation is referred to as fade and it is caused by thermal decomposition of ingredients in the brake lining. The current study examined the changes of friction coefficient at temperatures of 101°C to 287°C. It appeared that an overall friction coefficient value declined with the increase in drum temperature. However the reduction of friction coefficient for all Boron mixed brake pads was much more constant and stable as compared to the commercial brake pad. As reported elsewhere in this report, significant reduction of the friction coefficient of the commercial brake pads declined from 0.44 to 0.34, starting at a temperature of 204°C to 287°C. This situation was resulted from the softening of the Alumina fibers at the friction interface during sliding. Jang et al.<sup>[8]</sup> also reported that friction coefficient of friction material containing Alumina fibers was lowering at approximately 200°C, resulted from the softening of Alumina at elevated temperatures. They also found that the flash temperature at the friction interface was much higher than the measured surface temperature and that the friction coefficient dropped due to localized melting of the Alumina fibers.

Meanwhile at the temperature of 204°C, the average reductions of all Boron mixed brake pads were only minimal, reduced only by 0.02 (from 0.50 to 0.48). High thermal conductivity is believed to contribute to the stability of Boron mixed brake pads and fade resistance in high temperature. It is shown that thermal conductivity value for Boron material is 0.27 W/mm K and Alumina is 0.22 W/mm K. Chapman et al. (1999), in their study on the effect of Aluminum-Boron-Carbide for automotive brake pad application using friction

assessment and screening test (FAST) machine reported the similar findings and provided the same explanation. Aluminum-Boron-Carbide showed no evidence of fade with temperature increases since the material has high toughness and thermal conductivity relative to other ceramics.

### First recovery condition

Figure 4 shows friction coefficient during first recovery condition for all samples. During the recovery part of the test the drum was allowed to cool. The brake was applied and friction readings were taken at 50°C intervals. For the first recovery the drum temperature reduced from 271°C to 106°C.

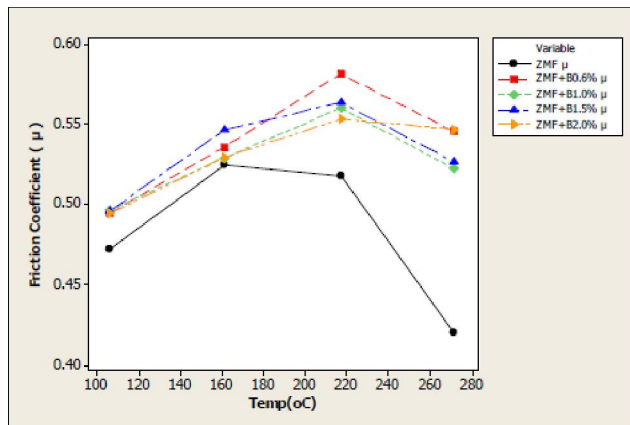


Figure 4 : First recovery plots of friction coefficient

The significant difference of recovery phase was portrayed in the commercial ZMF brake pad sample where the friction coefficient increased from 0.42 to 0.47 at temperatures of 271°C to 106°C. However, for the Boron mixed brake pad samples, the average friction coefficient decreased from 0.53 to 0.49 at the similar temperatures. Friction fade took place at high temperature but recovered rapidly upon cooling. The most desired situation is normal recovery, which is when friction coefficient returns to its pre-fade friction level with a little temperature reduction. Therefore, the recovery condition for both Boron and commercial brake pads were normal as they were able to return to its pre-fade friction coefficient level. Heat generated during braking caused the surface temperature to increase with braking time. During this experiment the onset of degradation of friction material started at 204°C. Therefore during the cooling stage the phenomenon of degradation was diminishing. This finding is congruent with

Zhang and Wang<sup>[9]</sup> findings when they compared the friction performance of brake pad material sliding with Aluminum matrix composite reinforced with Silicone Carbide.

### Wear test condition

The Figure 5 reveals the graph of friction coefficient collected during wear test application. The load was applied for 20 seconds and released for 10 seconds for 100 applications. The temperatures at this stage ranged between 100°C to 106°C.

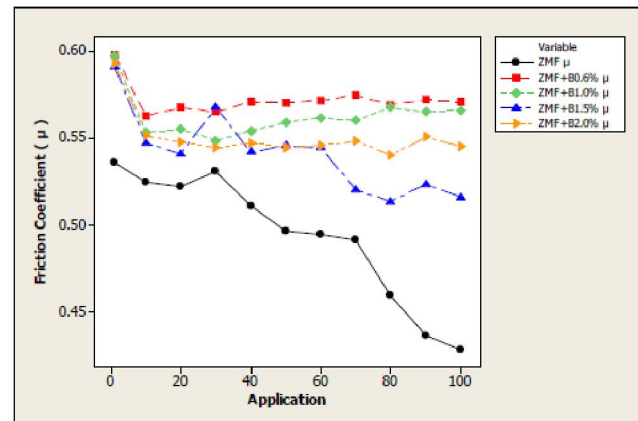


Figure 5 : Plots of friction coefficient during wear test condition

The friction coefficient results showed a trend which is similar to the initial baseline result except for the condition of braking time that was prolonged until 100 applications. Friction coefficient value of Commercial sample ZMF significantly reduced after 30 applications onwards from 0.53 to 0.43. The reduction of friction coefficient for commercial brake pad resulted from the existence of tribo-film that acts as protective layer between both surface and the tribo-film containing plenty of oxygen, which was mainly comprised of various Aluminium Oxides. These oxides commonly have low strength and hardness, which could reduce the friction coefficient. Lu et al.<sup>[2,10]</sup>, in their study on the incorporation of Boron into Titanium Nitrogen (TiN) suggested two factors contributing to the friction coefficient reducing effect of oxides. First, tribo-film acts as protective layer and only occasional metal to coating contact occurs. Secondly, the tribo-film contains a lot of oxygen and is mainly comprised of various Titanium Oxides which eventually reduces the friction coefficient. All Boron samples show high and constant friction co-

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efficient at the beginning of the braking stages caused by direct contacts of the brake pads and rotor surfaces without the formation of tribo-films. However, the friction coefficient significantly drops towards the end of braking applications. It is also worthwhile to note that friction coefficient of Boron sample ZMF+B1.5% only reduced slightly from 0.54 to 0.52 due to the formation of tribo-film at 60 applications.

### Second fade condition

The Figure 6 shows the friction coefficient behavior during the second fade condition. The load was applied continuously for 10 minutes or until 334°C. The coefficient was recorded with every increase of 23°C in the temperature. The friction coefficient value for commercial sample ZMF started to decrease from 0.44 at 159°C to 0.40 at 334°C. The softening of Alumina also occurred at the temperature of 159°C. Beyond this temperature, the degree of material degradation increased. The binding properties of material were weakened, and eventually yield strength of the materials decreased, resulted to the reduction of friction coefficient value. This is similar to Talib et al.'s<sup>[10]</sup> findings which reported that the degree of degradation increased with temperatures within the range of 269°C to 400°C. The significant reduction of friction coefficient for all Boron mixed brake pad samples was observed. The average friction coefficient reduced from 0.58 to 0.48 at the temperatures of 238°C to 334°C. Apparently, the degradation process for all Boron mixed samples occurred in this study is similar to Talib et al.'s<sup>[10,11]</sup>. Hong et al.<sup>[6]</sup> also reported the similar results where they found that decomposition temperature for Boron Phosphorus modified resin brake pad was at 319°C, as opposed to 299°C for the straight resin brake pad.

### Second recovery condition

The Figure 7 shows friction coefficient during second recovery condition for all samples. During the recovery part of the test the drum was allowed to cool. The load was applied for 10 seconds at 50°C increments as the drum cools from 321°C to 104°C.

The graph also shows a trend similar to the first recovery condition. The significant different of recovery phase can be seen for the commercial ZMF brake pad sample where the friction coefficient shows an increasing trend from 0.32 at 321°C to 0.41 at 104°C.

However for the Boron mixed brake pad samples the average of friction coefficient decreased from 0.48 to 0.43 at the similar temperature range. Thus, both Boron and commercial brake pads showed normal recovery when they returned to their pre-fade friction coefficient level.

### Final baseline condition

The Figure 8 shows friction coefficient during final baseline. The load was applied to the drum for 10 seconds and released for 20 seconds for 20 applications, with a drum temperature of 104°C to 82°C. The friction coefficient for all samples show trend similar to initial baseline condition. All Boron and commercial samples experienced increases in friction coefficient at the beginning of the braking stages until 20 braking applications. As explained in the initial baseline stage, friction coefficient increased when direct contacts of the ingredients in the lining and rotor surfaces occur at the friction interface without tribo-films. It was also associated with the increase of the real area of contact during sliding stages.

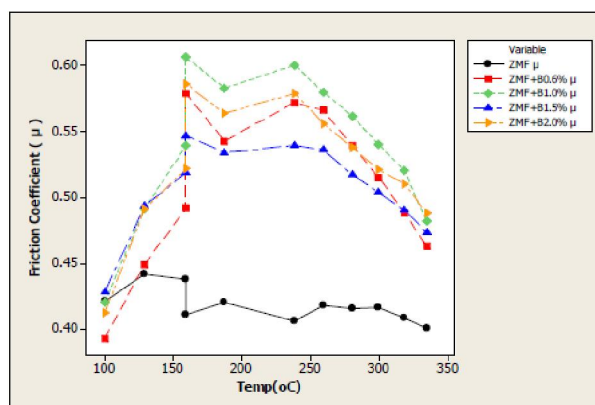


Figure 6 : Plots of friction coefficient during second fade

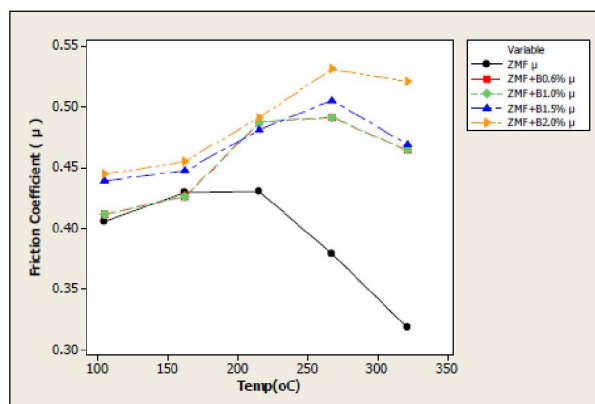


Figure 7 : Plots of friction coefficient during second recovery

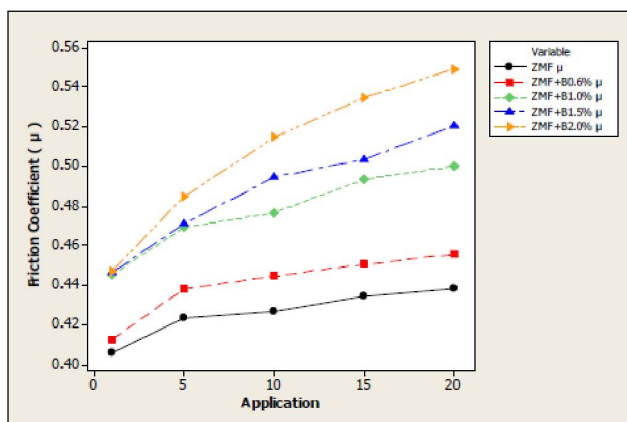


Figure 8 : Plots of friction coefficient during final baseline

## CONCLUSIONS

This study investigates the effect of the Boron on the friction characteristics. Based on the impact factors obtained from this study, it is possible to modify a specific tribology property of a brake friction material by changing the amount of Boron in a systematic manner while expecting possible changes in other tribological properties.

Friction coefficient of Boron mixed brake pads and commercial brake pads were significantly different. The average friction coefficient of all four Boron mixed brake pads was 0.495 (0.065 higher than the commercial brake pads). There was no significant difference in friction coefficient between all four Boron formulations shown by CHASE machine test result.

The abrupt reduction of friction coefficient which is known as fade was more significant in the commercial brake pad samples than in Boron mixed brake pad formulations. Fade occurred in commercial brake pad sample at the lower temperature; i.e. the first fade was at 204°C and the second was at 159°C resulted from the earlier softening and degradation of Alumina material. All Boron formulations were more stable and constant than their commercial counterparts. For Boron mixed brake pads, the study reported only a slight reduction of friction coefficient at a temperature of 204°C during the first fade and 238°C on the second. This was resulted from high thermal conductivity of Boron material. Both commercial and Boron mixed brake pads showed normal recovery stage in that they returned to their pre-fade friction coefficient levels with little temperature reduction.

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