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On-Road Braking Performances of Semi-Metallics Brake Friction Materials Developed through Powder Metallurgy Process

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Abstract: *Brake system is used to slow down and finally stop a motor vehicle and friction material is one of the components of the brake system. In this study, eight formulations of brake friction materials were developed through powder metallurgy processes. The samples were subjected to physical, mechanical, friction and on-road performance tests to investigate their mechanical and tribological characteristics and on-road braking performances. The data were then analysed to study the relationship between the tribological characteristics and the on-road braking performance. Test results signify that there are no simple correlations among the physical, mechanical and tribological characteristics of semi-metallic brake friction materials. It was also noticed that there are no simple correlations between the friction characteristics and road performance results. Normal and hot frictions of all the eight samples comply with requirements specified by Automotive Manufacturer Equipment Companies Agency, USA. However, on-road performance test results show that only six out of the eight formulations do comply with requirements of United Nation Economic Commission of Europe Regulation 13. Therefore, it could be concluded that on-road performance test is the ultimate measure in deciding which newly-developed formulations could be used on the road.*

Keywords: Brake friction material, hardness, porosity, friction, wear, road performance

1. INTRODUCTION

Brake system is used to slow down and stop moving motor vehicles in a controllable manner. It also used to hold vehicle stationary when in parking position. During braking process, the brake friction material is pressed against the rotating brake disc or drum which generates heat due to the friction between the friction materials and brake disc. Heat absorbed by the brake pads will be dissipated to the atmosphere through conduction, convection and radiation. The surface temperature, after reaching a maximum value, will arrive at a thermal steady state condition when the rate of heat generated during braking was balanced by the rate of heat loss to the atmosphere.[1] Heat generated during braking results in friction fall at elevated temperature. This fading effect is associated with the decomposition of the organic compounds which takes place between 250°C and 475°C.[2] This sudden drop of friction results in lower brake performance, in which longer braking distance is required before the moving vehicle can be stopped.

The friction and wear characteristics depend on the composition of friction materials and friction material behaviours and the brake design, counterpart materials, operating conditions (speed, applied load, operating temperature), and modes of braking. Friction materials are heterogeneous materials which are composed of between five to 20 different ingredients in the formulation. Each ingredient has its own function and changes in ingredient types or weight percentage may result in changes in physical, mechanical, chemical and braking performance characteristics. Therefore, the selection of ingredients and weight percentages used in the friction formulation will significantly affect the friction and wear characteristics, braking performance, and friction-induced noise.[3,4]

A brake friction material should have characteristics of heat resistance, low wear rate, durable, thermostability, low noise, and does not damage brake disc. It should also have constant coefficient of friction under various operating conditions. However, it is practically impossible to achieve all these in a formulation. Earlier study showed that there is no simple correlation between friction values and wear rates with mechanical, chemical and thermal properties of the friction materials.[5–7] Most of the formulations developed are achieved through trial and error process since there is no rule of thumb, which can be used to predict the wear rate and friction coefficient based on the physical and mechanical properties.[7,8] Therefore each new formulation developed needs to be tested in laboratory as well as on the road to ensure the brake materials developed comply with the requirements set by the authority. In this work, the newly developed friction materials were subjected to physical, mechanical, tribological, and on-road braking performance tests. The correlation of the physical, mechanical, tribological and performance characteristics were reported in this study.

2. EXPERIMENTAL

Eight formulations have been developed through powder metallurgy processes as follow; (1) raw materials selection, (2) mixing, (3) preparation of backing plate, (4) compacting, (5) surface grinding, (6) post-baking and (7) testing. The compositions of the samples are shown in Table 1. Sample T1 is a commercially available semi-metallic brake pad and data gathered from this sample are used as a benchmark. Each sample was subjected to density, porosity, hardness, internal shear strength, friction and on-road performance tests in accordance with standard tests as shown in Table 2. Density of brake friction materials was obtained using a method which applies Archimedes' principles. Hardness was measured using Rockwell hardness tester, model Mitutoyo Ark 600, in the scale *S* with applied load of 100 kgf and ball diameter of 12.7 mm. Internal shear strength is performed on Instron Universal Tensile Machine with a sample size of 20 × 20 × 5 mm. The load is applied gradually until failure at the rate of 4500 ± 500 N/s. The load is applied in a direction parallel to the direction of stress at normal service conditions. Porosity was obtained using a hot bath model Tech-Lab Digital Heating. The test samples with a size 25 × 25 × 5 mm ± 0.5 mm are immersed in the test oil in the container and keep at 90 ± 10°C for eight hours. Porosity is calculated using the following formula:

$$Porosity, \nabla(\%) = \frac{(m2 - m1) \times 100}{\rho V} \quad (1)$$

where,

∇ = porosity (%)
m1 = mass of test sample (g)
m2 = mass of test piece after absorbing oil (g)
ρ = density of test oil (g/cm^3)
V = volume of test sample (cm^3)

Table 1: Weight percentage of ingredients in the composition.

Materials	T2	T3	T4	T5	T6	T7	T8
Resin	10.0	9.0	9.0	9.0	9.0	12.0	9.0
Fibre	32.0	35.0	36.0	38.0	33.0	37.0	40.0
Friction modifier	29.0	24.0	24.0	22.0	26.0	33.0	28.0
Filler	29.0	32.0	31.0	31.0	32.0	18.0	23.0
Total	100	100	100	100	100	100.0	100

Table 2: List of standards.

No.	Tests	Standards
1.	Density	MS 474 PART 1: 2003[9]
2.	Porosity	JIS D 4418: 1996[10]
3.	Hardness	MS 474 PART 2: 2003[11]
4.	Internal shear	ISO 6311 PART 5: 2003[12]
5.	Friction and Wear	SAE J661 Feb 97[13]
6.	Road Performance	UNECE R13[14]

Friction tests were conducted on CHASE brake lining test machine. Samples with dimensions of 25 × 25 × 6 mm were glued to the backing plate and then attached to brake callipers on the brake drum. Each sample was subjected to seven test runs with the following sequences: (1) conditioning (2) baseline, (3) first fade, (4) first recovery, (5) wear, (6) second fade, (7) second recovery and (8) baseline rerun. The sample was pressed against a rotating brake drum with a constant rotating speed of 417 rpm under a constant normal load of 647 N and subjected to test program as depicted in Table 3. Chase friction test is a very useful tool for formulation development, prototype friction evaluation, production process quality control and formulation, as an early assessment before dynamometer testing.

In practice, two-letter friction codes are used in classifying the friction materials, where the first letter represents normal and the second letter represents hot coefficient of friction COF values, as prescribed by Society of Automotive Engineer SAE J886.[15] The normal COF is defined as the average of the four readings taken at 200°F, 250°F, 300°F and 400°F on the second fade curve. The hot COF is defined as the average of the 10 readings taken at 400°F and 300°F on the first recovery; 450°F, 500°F, 550°F, 600°F and 650°F of the second fade; and 500°F, 400°F and 300°F of the second recovery run.

On-road performance tests were performed in accordance with the test procedures as described in UNECE R 13.[14] In on-road performance test, the brake pads were installed to the brake system of a PROTON WIRA 1.5 GL. The road performance test is divided into three types, namely: (1) cold effectiveness test, (2) heat fade test and (3) recovery test. The test data such as vehicle speed, lining temperature and braking distance were recorded using a data acquisition system from *Dewetron* model DEWE5000. During cold effectiveness testing, a brake pad is considered fail to comply with the requirements if the brake pedal force for wheel locking to occur is greater than 500 N. Therefore, further tests, namely, heat fade and recovery tests will not be performed on that particular pad. The developed brake pads will be accepted if it complies with the minimum requirements on the mean fully developed deceleration (MFDD) of road tests as shown in Table 4.

Table 3: Friction and Wear Test Program.

Test sequence	Load (N)	Rotating speed (rpm)	Temperature (°C)	Remarks
Conditioning	440	312	< 95	Continuous braking 20 minutes
Initial measurement	647	0	88–99	Take indicator reading at 667 N load
Baseline run	647	417	82–104	Intermittent braking 10 s ON, 20 s OFF 20 applications
First fade run	647	417	82–288	Continuous and heater ON
First recovery run	647	417	288–82	Continuous and cooling ON
Wear run	647	417	193–204	Intermittent braking 10 s ON, 20 s OFF 100 applications
Second fade run	647	417	82–343	Continuous and heater ON
Second recovery run	647	417	343–82	Continuous and cooling ON
Baseline rerun	647	417		Intermittent braking 10 s ON, 20 s OFF 20 applications
Final measurement	647	0		Repeat initial measurement

Table 4: Minimum requirements of the on-road performance tests.

Tests	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

3. RESULTS AND DISCUSSION

3.1 Physical and Mechanical Properties

Table 5 shows the physical, mechanical and tribological properties of the developed samples. Brake friction materials are non-homogeneous materials, and therefore, there are no simple correlation among the physical and mechanical properties as shown in Table 5 and Figure 1. The same phenomena have been observed by earlier researchers.[5,16,17] Hardness of the friction material depends on type of ingredients, percentage of each ingredients used in the composition and the dispersion of the ingredients in the composition.[16,18] Thus, physical and mechanical properties could not be used to screen the best formulation. However, the physical and mechanical properties are very useful to control the quality of the formulations that has been developed. Consistency in physical and mechanical properties of a formulation indicates good control of the manufacturing process of the brake lining material.

Table 5: Physical and mechanical test results.

No.	Sample	Specific gravity	Hardness (HRS)	Porosity (%)	Internal shear strength (MPa)
1.	A	3.29	68.2	12.88	28.57
2.	B	2.76	85.1	7.86	29.18
3.	C	2.36	76.7	24.16	40.40
4.	D	2.30	70.61	21.37	38.07
5	E	3.25	69.6	2.54	48.38
6.	F	2.57	79.42	3.62	44.30
7.	G	2.32	72.96	3.06	37.62
8.	H	2.43	45.52	16.6	23.23

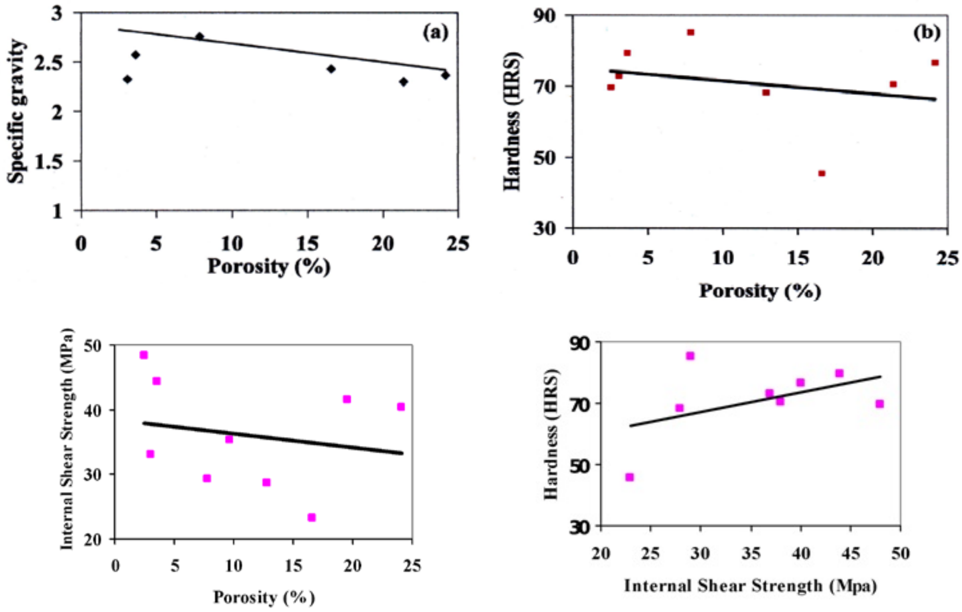

Figure 1: The relationship between physical properties of friction material used in this study: (a) specific gravity vs. porosity, (b) hardness vs. porosity, (c) internal shear strength vs. porosity and (d) hardness vs. internal shear strength.

3.2 Friction Characteristics

In this study, for the friction materials to comply with the requirements of Vehicle Equipment Safety Commission Regulation V-3[19]: (1) shall have normal friction coefficient of class E and above, and a hot of class D and above, (2) shall have friction coefficient above 0.15 between 200°F and 550°F inclusive in second fade, or between 300°F and 200°F during the second recovery fade. CHASE friction test results show that all the eight samples developed have two-letter friction codes higher than the minimum requirement of ED (Table 6). It can be seen in Figures 2 and 3 that all the samples developed have COF of second fade and second recovery higher than minimum requirement of 0.15. Thus, it could be concluded that the all the samples comply with the requirements of Vehicle Equipment Safety Commission Regulation V-3.

Table 6: CHASE test results.

Sample	Normal friction	Hot friction	Friction code	Ave thickness loss (%)
A	0.362	0.332	FE	1.68
B	0.385	0.316	FE	0.12
C	0.447	0.352	GF	2.87
D	0.471	0.373	GF	5.03
E	04.17	0.345	FE	2.90
F	0.515	0.432	GF	4.86
G	0.374	0.322	FE	1.72
H	0.554	0.458	HG	10.20

The CHASE friction data are shown in Figure 2 and Figure 3, which are friction coefficient values of the friction materials at second fade and second recovery, respectively. The first fade characteristic is not discussed because the temperature generated during this braking operation, which were between 93°C to 288°C, below the decomposition temperatures. Figure 2 reveals that the COF of all samples decreased with increasing drum temperature. This phenomenon was due to degradation of organic material as well as transition period of abrasion to adhesion wear mechanism.[20] Whereas, Figure 3 shows that all the samples almost recover to their respective base line friction coefficient readings when the brake drum and the sample are cooled to room temperature.

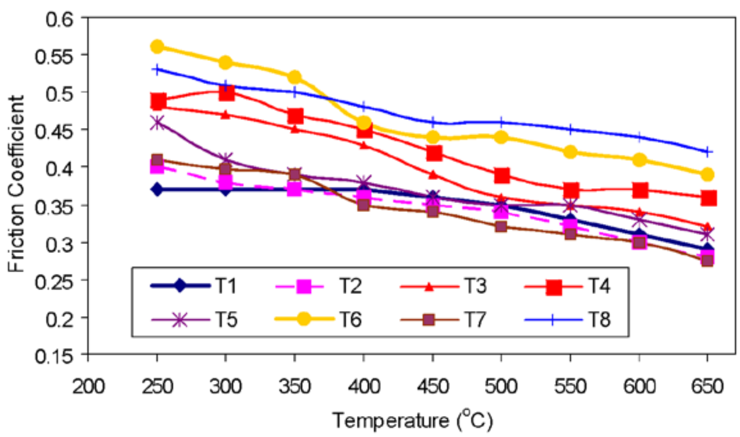

Figure 2. Friction coefficient vs. drum temperature during second fade.

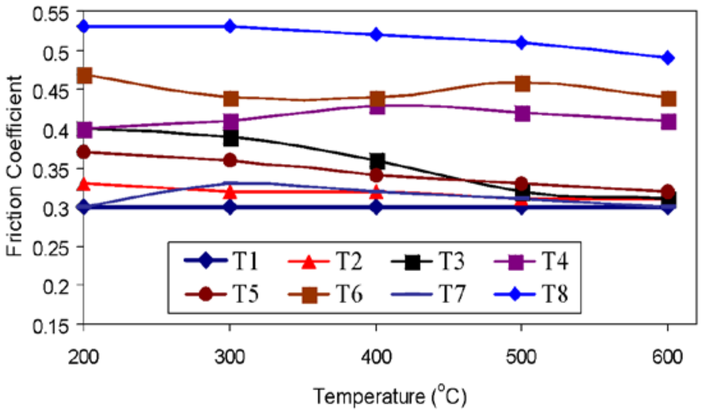

Figure 3: Friction coefficient vs. drum temperature during second recovery fade.

As expected, there is no direct correlation between the mechanical properties and frictional and wear behaviours as shown in Figure 4. The same findings are also reported by the other researchers.[5,16] It was observed that the samples with high porosity tend to exhibit high friction coefficient and increase in average thickness loss. On the other hand, the sample with high hardness tends to have lower COF as well as decrease in the average thickness loss. More & Tagert[21] and Mokhtar[22] also reported that the COF tend to decrease with increasing hardness.

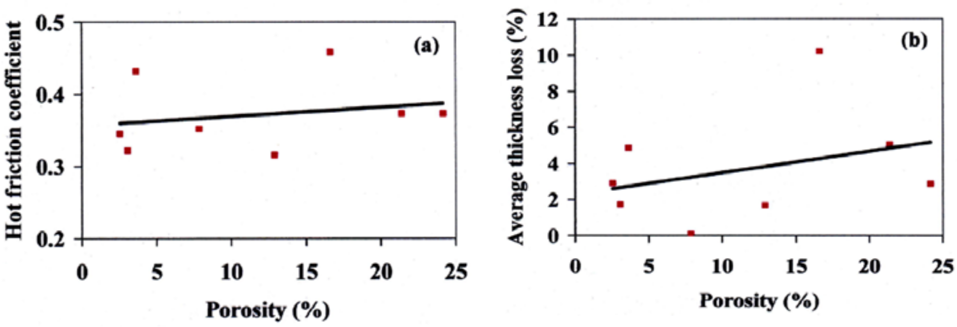

Figure 4: The relationship between physical properties of friction material used in this study: (a) Hot friction coefficient vs. porosity, (b) Average thickness loss vs. porosity (c) Hot friction coefficient vs. hardness and (d) Average thickness loss vs. hardness (*continued on next page*).

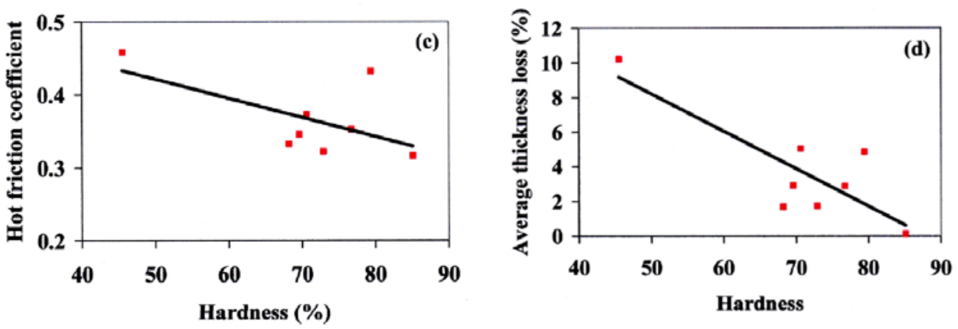

Figure 4: (*continued*).

3.3 Road Performance

Laboratory tests and evaluation show that all the new formulations developed comply with the minimum friction requirement as discussed earlier. However, sample T4 and T7 do not comply with on-road performance requirements as shown in Table 7. Sample T4 do does comply with deceleration requirement under fade test condition. Whereas, sample T7 does not comply the requirement of pedal force applied on the foot pedal which is more than 500 N. Therefore, hot and fade tests were not carried out on sample T7. Higher pedal force requires more drivers' effort to slow down or stop the vehicle, which may stress the leg especially during down-hill driving and winding road condition. Observation was also made on sample T8 which reached brake pad temperature of 515°C, which is the highest among all the samples during fade test. Under this high temperature, most of the organic materials would normally have been decomposed, somehow for sample T8, the braking performance does still comply with the requirement. This indicates that the ingredients and structure of this formulation can still maintain its performance under this high temperature. The heat from this high temperature generated during braking is transferred to the brake fluid and may cause the brake fluid to boil. Typically, the dry boiling point of new brake fluid is around 260°C and the wet boiling point is somewhat lower, depending on the moisture content. When the brake fluid starts to boil, vapour locks are produced that can be compressed and hence the braking performance will drop significantly. Therefore, sample H is rejected. It can be seen from Figure 5 that sample T8 has been subjected to high temperature because of high content of metallic ingredient in the composition. It was observed that there are chipping on the sample T8. The micrograph shows that the worn surface of sample T2 has fine grooving, pitting and light resin bleed as shown in Figure 5(a). However there is no evident of chipping.

Table 7: On-road performance test results.

No.	Sample	Type of tests	Pedal force (N)	MFDD (ms^{-2})	MFDD requirement (ms^{-2})	Temperature (°C)	
						Right	Left
1.	T1	Cold	263	7.70	≥ 6.43	166	181
		Hot	210	5.50	≥ 4.62	260	220
		Recovery	220	7.60	5.39–11.55	105	136
2.	T2	Cold	254	7.90	≥ 6.43	172	175
		Hot	230	6.70	≥ 4.74	212	221
		Recovery	218	8.20	5.74–12.30	158	140
3.	T3	Cold	114	7.40	≥ 6.43	100	154
		Hot	120	5.80	≥ 4.20	394	459
		Recovery	116	7.20	5.04–10.80	202	260
4.	T4	Cold	96	6.83	≥ 6.43	115	110
		Hot	94	3.91	4.09	347	312
		Recovery	98	4.95	4.78–10.20	181	155
5.	T5	Cold	128	8.10	≥ 6.43	155	154
		Hot	130	7.07	≥ 4.86	272	260
		Recovery	134	8.38	5.67–12.15	143	152
6.	T6	Cold	345	6.78	≥ 6.43	127	129
		Hot	346	6.20	≥ 4.08	198	234
		Recovery	360	6.62	4.76–10.17	151	153
7.	T7	Cold	803	5.89	≥ 6.43	415	401
8.	T8	Cold	104	7.05	≥ 6.43	316	277
		Hot	109	5.72	≥ 4.20	515	527
		Recovery	117	5.77	4.93–10.67	333	332

The binder in the brake friction material is used to hold the compositions together and maintain the structural integrity of the brake material during braking process whereupon it is subjected to mechanical and thermal stresses. Polymeric materials such as graphite and rubber are used as modifier to improve the friction and wear characteristics. However, when subjected to high temperature, these materials will decompose which result in brake fade. The decomposition of friction material starts to occur at temperature of 230°C and the degree of degradation increases with temperature within the range of 269°C–400°C.[23] It can be seen from Figure 6 that sample T4 has the highest percentage of fade on road performance test and this sample did not comply with the MFFD requirement. It was also observed that there is no correlation between the percentage of fade on CHASE friction and on-road performance test results.

(a) (b)

Figure 5: Micrograph of worn surface; (a) Sample T2 and (b) Sample T8.

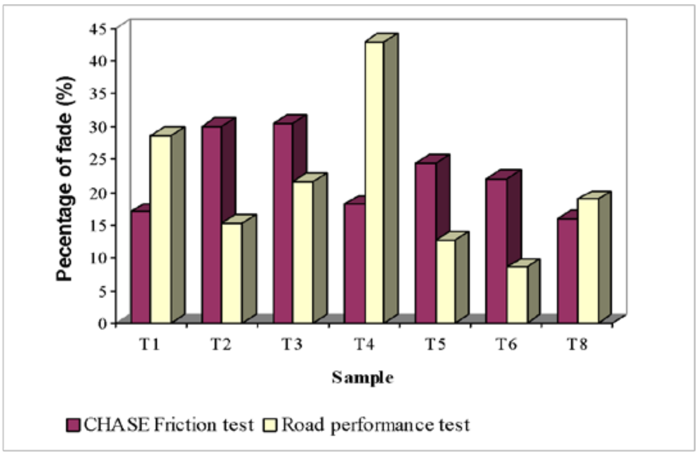

Figure 6: Percentage of fade.

Analyses on test results also show that there is no simple relationship among the physical, mechanical and tribological properties. As friction material is heterogeneous materials, the friction and wear characteristics depend on many parameters such as the ingredients and weight percentage of the ingredients in the formulation, manufacturing process parameters, brake system design and brake application conditions. Test results produced by CHASE friction machine show that all samples developed comply the requirement of COF. However, three of the samples do not comply with the requirement of on-road braking performance tested according to UNECE R13. Thus it could be concluded that on-road performance will be the basis for final decision on whether or not the newly developed formulation can be used on the road.

4. CONCLUSIONS

In this study, eight newly developed brake friction material formulations have been successfully developed using powder metallurgy process. There is no minimum requirement on density, porosity and hardness properties set by the international standards. Analyses on test results show that there is no simple relationship among the physical, mechanical and tribological properties of the friction materials developed and all samples comply with the minimum requirement of COF as specified by Automotive Manufacturer Equipment Companies Agency, USA. As the compliance with the laboratory test requirements does not guarantee the on-road performance, the on-road performance results, where a friction material is tested in its intended real-life applications, is the ultimate deciding factor in selecting the suitability of lining to be used on the road. Therefore, it could be concluded that sample T1, T3, T3, T5 and T6 could be used for further study on the reliability aspect.

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