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Development of Asbestos-Free Friction Lining Material from Palm Kernel Shell

Friction materials are applicable for braking and transmission in various machines and equipment. Their composition keeps changing to keep pace with technological development and environmental/legal requirements. For more than 80 years asbestos has been used as a friction material because of its good physical and chemical properties. However, due to the health hazard associated with its handling, it has lost favour and several alternative materials are being increasingly used. Thus, in this work, a non – asbestos friction material was developed using an agro-waste material base – palm kernel shell (PKS)- along with other constituents. Among the agro-waste shells investigated the PKS exhibited more favourable properties. Taguchi optimization technique was used to achieve optimal friction material formulation and manufacturing parameters. The derived friction material was used to produce automobile disk brake pads. The laboratory brake pads were tested for wear and effectiveness on a car. When compared with a premium asbestos-based commercial brake pad they were found to have performed satisfactorily. However, more pad wear was observed on the PKS pad at high vehicular speeds beyond 80km/hour. The results suggest that palm kernel shell could be a possible replacement for asbestos in friction lining materials.

***Keywords**: friction materials, palm kernel shell, brake pad, Taguchi method*

Introduction

The development of modern friction materials has a history spanning over the past 110 years. Herbert Frood is credited with inventing the first brake lining material in 1897 (Blau, 2001). His invention led to the founding of the Ferodo Company, a firm that still supplies brake lining materials today. In 1901, Herbert patented a block made from layers of textile material impregnated with rubber, if the block was to be used against steel, or wax, if it were to be used against rubber. As the duty of the brakes increased, the cotton tended to char, so in 1908, Herbert replaced it with asbestos. The asbestos was woven into a loose fabric and impregnated with resins and varnishes of high melting point. By 1914, the use of Ferodo brake linings was widespread. In 1920s all friction materials were of the Ferodo type. In 1925, the British Belting and Asbestos (BBA) Limited became known as BBA Group that produced such famous friction material brand names as Mintex, Don, Textar, Frenosa, Bendix Mintex and SBF (Smales, 1995). In the 1930s, Ferodo turned to thermosetting resins and later introduced moulded instead of woven linings. The moulded linings were made by mixing fibre and resin together and also, polymerizing the resin under pressure and temperature. Fillers such as mineral and metal particles, which modify the wear properties of the lining, could be introduced in these linings, and polymers could be used which were impracticable with woven linings (Newcomb and Spurr, 1967).

From the foregoing, asbestos has been used as base material in the manufacture of brake lining materials for close to 100 years. It is still being used by some manufacturers who do not posses the necessary technology or will to change to other materials. Though asbestos has been referred to as a “God given” material for inclusion in friction linings due to its good physical and chemical properties that remain stable over the temperature range experienced by friction materials (Smales,1995), it has been reported that asbestos has serious health risks. Diseases associated with it include asbestosis, mesothelioma, lung cancer and other cancers (Anon, 2004: Norton, 2001).

Efforts have been geared to replace asbestos fibres in friction linings. This is exemplified by the work of Nakagawa et al. (1986), who used metal fibres for inclusion in brake pads to overcome environmental pollution. They developed semi-metallic pad material using chatter–machined short metal fibres because it exhibited excellent properties in view of brake characteristics and resistance to wear. The brake pad contained about 60% by weight of steel fibres with 60μm in diameter and 3mm long. Blau (2001) reported the additive effects of various non-asbestos materials on friction linings. Asbestos – free organic, semi-metallic and metallic friction lining materials are now increasingly being used (Smales (1995), Arita et al. (1987), Jang et al. (2004), Kim et al. (2003), Mathur et al. (2004)).

Thus, to reduce or completely eliminate the health risks posed by asbestos in friction lining manufacture and to reduce the cost of friction linings, this work presents the development of an asbestos-free friction lining material in which an agro-waste (palm kernel shell [PKS]) was used as the base material.

Experiments

Equipment

The major laboratory equipment used was a brake pad test rig, which was manufactured as earlier reported by Dagwa and Ibhadode, (2006) for determining the brake pad wear, brake disk temperature rise, and braking time under different braking conditions. Others included brake pad mould, hydraulic press, Brinell/Rockwell hardness tester, Charpy impact testing machine, Soxhlet apparatus, Lee’s Disk apparatus, and digital photoelectric tachometer.

Materials

The base material for formulation was selected from the following agro-wastes: palm kernel shell (PKS); hyphaene thebaica kernel shell (HTKS); and deleb palm kernel shell (DPKS), after conducting a series of tests. Other materials used included cashew nut shell liquid, carbon black, iron ore, brass chips, ceramics, sulphur, quartz, and calcium carbonate.

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Methodology

Base Material Selection

The following tests were performed to determine the physical and mechanical properties of PKS, HTKS and DPKS to enable the selection of appropriate base formulation material: dimensional properties, moisture content, apparent porosity, coefficient of friction, rupture strength, water and oil soak tests, thermal conductivity, true density, specific heat capacity, sieve analysis, thermal degradation test and compressibility test.

Formulation Tests

Taguchi design method (Kim et al., 2003; Dagwa, 2005) was used to determine the friction lining formulation optimum manufacturing parameters of the brake pad. The brake pad contained ten ingredients. Mechanical property (hardness) and tribological properties (wear and coefficient of friction) were investigated to deduce the optimum manufacturing parameters and optimum friction lining formulation by using the analysis of variance (ANOVA) and Taguchi signal-to-noise ratio (S/N) on the test results (Dagwa, 2005). (Note that the word 'optimum' as used in this paper refers to a set of parameters obtained within a bounded stepped region of tested experimental conditions that gives the best performance characteristics).

The base raw material, PKS, was collected and cleaned thoroughly to remove impurities. It was crushed and ground to a fine powder, and sieved using 125µm sieve. About twenty trial formulations were initially made for preliminary tests. After the trial formulations, a fairly good composition was arrived at, which was used for determining the manufacturing parameters: moulding pressure, moulding temperature, curing time and heat treatment time. This friction lining formulation also served as a starting point for the determination of the optimum friction lining formulation.

Nine brake pads based on this formulation were made using nine different sets of manufacturing parameters derived by the Taguchi method.

Thereafter, twelve sets of brake pads of different compositions were made for determining the optimum level settings of the ingredients. Then further tests were conducted on them, which led to the identification of the optimum formulation for the friction lining.

Brake Pad Tests

(a) Test rig. The test rig was used to determine the performance of the brake pads produced with the optimum manufacturing parameters and optimum composition. The pads were tested for wear, disk temperature rise and disk stopping time. A set of equivalent premium-quality asbestos-based commercial brake pads were subjected to similar test for comparison. Figure 1 shows the schematic diagram of the brake pad test rig. It has a 2.2kW motor with a provision for speed variation by using a stepped pulley. The motor provides the energy required to set the flywheel weights and the brake disc in angular motion. When a set of brake pad is fixed into the brake caliper assembly of the test rig, the system is switch-on and the drive shaft begins to rotate, it is then allowed to attain a desired speed. Thereafter, a manual force is applied on the brake pedal which is similar to that of a motor car. Subsequently the stopping time, temperature of the disc and brake pad material lost are recorded as reported in details by Dagwa and Ibhadode (2005). The speed and brake line pressure ranges were: 6.66 m/s to 13.82 m/s and 0.2 – 0.6 MPa respectively for the test conditions.

(b) Vehicle braking tests. Actual braking tests with the laboratory and commercial, brake pads were carried out at different vehicle speeds of 20, 30, 40, 50, 60, 70, 80, 90 and 100km/hour. The tests were carried out on a Toyota Carina II (Wagon) car. Pad wear, disk temperature rise and stopping time were measured at the above speeds. Constant brake pressure was assured by using a fixed brake pedal travel during the tests.

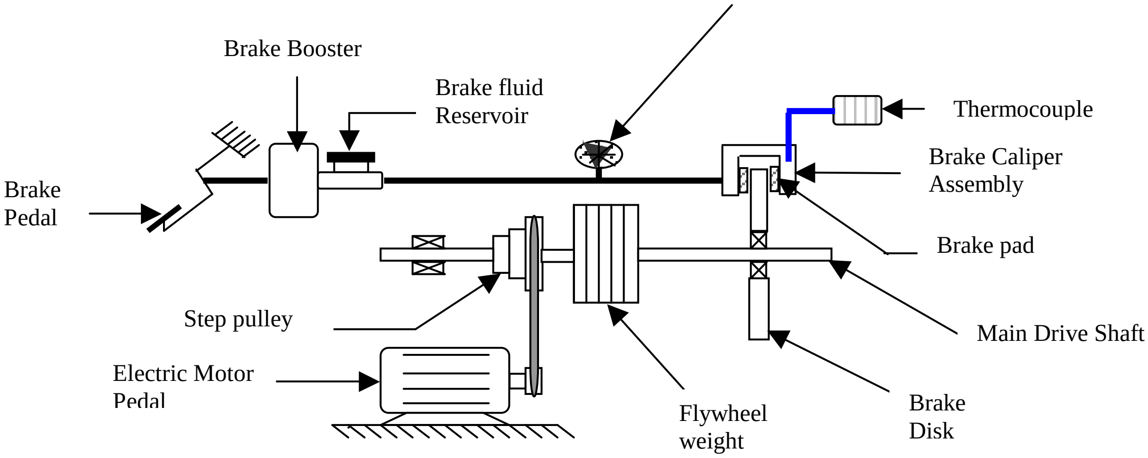

Figure 1. Schematic representation of the brake pad test rig (Dagwa and Ibhadode, 2005).

Experimental Design

The Taguchi Method of experimental design was used. The method uses a special set of arrays called orthogonal arrays. These standard arrays stipulate the way of conducting the minimal number of experiments, which could give the full information of all the factors that affect the performance parameter. The orthogonal array experiments are used as they allow the simultaneous variation of several parameters and the investigation of interactions between parameters. Statistical analysis, such as analysis of variance (ANOVA), is then employed to determine the relationship between the processing conditions and the response value, for example, surface hardness and compressive strength. The main advantage of the Taguchi method is that the number of experiments conducted in most of the cases is lesser than that of any other experimental design method using a statistical approach.

The minimum number of experiments, N_{Tag}, that is required to conduct the Taguchi method is given by (Dagwa, 2005)

$$N_{Tag} = 1 + \sum_{i=1}^{NV} (L_i - 1) \tag{1}$$

where NV = number of variable and L = number of level setting.

The Taguchi method uses a statistical measure of performance called signal – to – noise (S/N) ratio. This is a performance measure to choose control levels that best cope with noise. It takes both the mean and variability into account. Noise is referred to as any cause of variation such as humidity, deterioration of equipment or any factor that is too expensive to control. While “signal” represents the desired target for good product or process. The procedure for applying the Taguchi method is available in the literature (Anon, 2003, Kim,et al.,2003, Zhang et al., 2007).

Physical and Mechanical Properties of Kernel Shells

In Table 1, some physical and mechanical properties of the palm kernel shells tested were presented (Dagwa, 2005). Figure 2 shows the springback effect of the shell particles at various particle sizes. The springback is the recovery in length of a column of compressed shell particles after the removal of the compressing load.

From Table 1, it is seen that PKS has lower apparent porosity and moisture content, better heat resistance than HTKS and DPKS. It also has smaller thickness swell after soaking in water. Figure 2 shows that its particles of less than 400µm did not show any springback effect after the removal of the compressive load. These results indicate that PKS particles have better dimensional stability. In addition to these advantages over HTKS and DPKS, PKS is available in commercial quantity, and is easily processed and ground into fine particles (Ebunilo, 2001).

Results and Discussion

Table 1. Physical and mechanical properties of palm shells (Dagwa, 2005).

S/No.	Property	Value		
		PKS	HTKS	DPKS
1.	**Dimensional Properties**			
1.1	Length, L (mm)	28.5676	43.6588	75.726
1.2	Width, W (mm)	19.7143	20.6903	78.325
1.3	Thickness, t (mm)	16.3977	38.229	51.943
1.4	Sphericity (mm)	0.7415	0.9455	0.892
1.5	Volume (cm^3)	4.4547	39.179	244.768
1.6	Mass (g)	4.9196	30.254	70.883
1.7	Density of Nut	1.1248	0.277	0.286
2.	Apparent porosity (%)	10.98	31.27	43.76
3.	Static Coefficient of friction	0.41	0.40	0.46
4.	**Rupture Strength**			
4.1	Rupture force along thickness (N)	3270.59	12468.35	3721.71
4.2	Rupture force along width (N)	3884.61	12061.08	7071.36
4.3	Rupture force along length (N)	-	17421.6	4987.34
5.	**Water and Oil Soak Tests**			
5.1	Water absorption in 24hours (%)	19.85	61.54	67.30
5.2	Thickness swell in water in 24hours (%)	3.54	6.95	9.23
5.3	Oil absorption in 24 hours %	6.845	34.76	60.67
5.4	Thickness swell in oil in 24 hours (%)	2.33	2.54	4.83
5.5	Moisture content,(%)	7.8325	12.14	11.32
6.	**True Density, g/cm^3**	1.2540	1.09	1.19
7.	Specific gravity	1.1248	1.09	1.19
8.	Specific Heat Capacity(J/kgK)	1099.23	1243.9	1216.47

Note: The values are expressed as mean values.

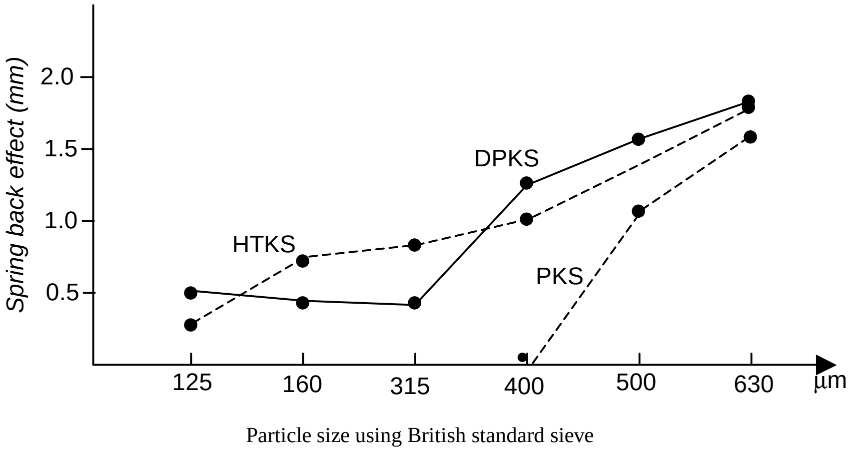

Figure 2. Spring back effect of selected fruit shell particles.

It is known that asbestos is carcinogenic (Smales 1995; Anon 2004; Norton, 2001). However from all available literature and from expert opinion, PKS which has been handled for centuries especially in Southern Nigeria up till date, no report has shown that PKS is carcinogenic. PKS has a coefficient of friction (0.41), which falls within that expected for friction materials (this also applies to HTKS and DPKS). Hence it appears that it could be a possible replacement for asbestos in friction material formulation.

Optimization of Manufacturing Parameters

To determine the manufacturing conditions for the brake pad manufacture, the effects of four factors were studied: moulding pressure, moulding temperature, curing time and post curing heat treatment. Three levels of each factor were chosen to run the L_9 (3^4) Taguchi orthogonal array as earlier reported (Dagwa and Ibhadode, 2006). Table 2 shows the factor levels for the manufacturing parameters obtained by creating equal interval between the manufacturing parameters that are commonly used in brake pad manufacture.

Table 3 shows the experimental design layout using the Taguchi orthogonal array L_9 (3^4). After the selection of the arrays, the variables were assigned to the columns of the orthogonal arrays. The actual experiments were carried out as shown in the randomization column of Table 3.

Table 4 shows the results of the experiments conducted toward identifying the optimum level setting for the manufacturing parameters within the experimental region. Nine specimens of the brake pad were made. Their surface hardness, coefficient of friction and wear were measured. Their corresponding signal – to – noise (S/N) ratios is shown in Table 4 (Dagwa, 2005). The relative importance of the factors was evaluated in terms of their percentage contributions using analysis of variance (not shown here). From Table 4, using the analysis of variance and the averaged values of the signal-to-noise ratios for the manufacturing parameters at different levels [low(-), medium(0), and high(+)] for each of the performance response (surface hardness, wear and coefficient of friction) the optimum settings for the parameters were determined as presented in Table 5. Hence, this is the synergistic effect of S/N ratios for the properties measured that were obtained by using the quality characteristic that is, the large-the-better. The experimental condition having the maximum S/N ratio is considered as the optimal condition as the variability characteristics is inversely proportional to the S/N ratio, that is, reduced variance is achieved at optimal setting (Zhang, 2007). Hence, the optimum level settings were selected as asterisked in Table 5. Therefore, the optimum manufacturing parameters for this formulation are P_m = 16.74MPa, T_m = 160^{o} C, C_t = 8 minutes and H_t = 2 hours.

Table 2. Factor levels for the manufacturing parameters.

Factor	Low Level	Medium Level	High Level
Moulding pressure (P_m), MPa	16.74	22.32	27.90
Moulding temperature (T_m), ^{o}C	150	160	170
Curing time (C_t), minute	6	8	10
Heat treatment time (H_t), hour	1	2	3

Source: Adapted from Dagwa and Ibhadode, (2006)

Table 3. Experimental design layout using taguchi orthogonal array $L_9(3^4)$.

Experiment Number	Moulding Pressure P_m	Moulding temperature T_m	Curing Time C_t	Heat Treatment time, H_t	Randomization
1	1	1	1	1	3
2	1	2	2	2	9
3	1	3	3	3	1
4	2	1	2	3	8
5	2	2	3	1	2
6	2	3	1	2	6
7	3	1	3	2	4
8	3	2	1	3	7
9	3	3	2	1	5

Source: Adapted from Dagwa and Ibhadode, (2006)

Table 4. Experimental results and S/N ratios for surface hardness, coefficient of friction and wear (Dagwa, 2005).

Experiment Number	Surface hardness (Rockwell Scale B)	S/N ratio, db (the large r-the-better)	Coefficient of friction, N	S/N ratio db (the larger the better)	Wear/application , g	S/N ratio for wear, db (the larger-the-better)
1	84	38.49	0.44	-7.13	0.023	32.77
2	64	36.12	0.38	-8.4	0.170	15.39
3	81	38.17	0.39	-8.18	0.037	28.64
4	79	37.95	0.41	-7.74	0.027	31.37
5	80	38.06	0.35	-9.12	0.043	27.33
6	89	38.99	0.42	-7.54	0.023	32.77
7	81	38.17	0.35	-9.12	0.037	28.64
8	82	38.28	0.41	-7.74	0.023	32.77
9	79	37.95	0.43	-7.54	0.017	35.39

Table 5. Signal-to-noise (S/N) response table combined effect of the hardness, coefficient of friction and wear).

Level	Pm	Tm	C_t	H_t
-	4.087*	-3.31	-1.65	-1.74
0	-0.29	3.93*	2.07*	3.81*
+	-2.27	-1.65	1.121	-0.69

Table 6. Ingredients for the Formulation of brake pad.

S/No.	Material	High Level	Low Level
1.	Qucer	a	a – 3
2.	$CaCo_3$	B	b – 6
3.	Cascamite	c	c – 4
4.	Friction modifier	d	d – 3
5.	Carbon black	e	e – 3
6.	Resin improver	F	f – 4
7.	Iron ore	G	g – 5
8.	Modified CNSL	H	h – 2
9.	PKS	I	i – 5
10.	Copper fibre	J	j – 1

Table 7. Taguchi orthogonal array selector L12(210) (Dagwa, 2005).

Exp. No.	Resin improver	$CaC\,O_3$	PKS	Copper fibres	Friction modifier	Carbon black	Iron ore	Qucer	Cascamite	Modified CNSL	Randomi-sation
1.	1	1	1	1	1	1	1	1	1	1	3
2.	1	1	1	1	1	2	2	2	2	2	9
3.	1	1	2	2	2	1	1	1	2	2	1
4.	1	2	1	2	2	1	2	2	1	1	8
5.	1	2	2	1	2	2	1	2	1	2	11
6.	1	2	2	1	2	2	1	2	1	2	2
7.	1	2	2	2	1	2	2	1	2	1	6
8.	2	1	2	1	2	2	2	1	1	1	10
9.	2	1	1	2	2	2	1	2	2	1	4
10.	2	2	2	1	1	1	1	2	2	1	7
11.	2	2	1	2	1	2	1	1	1	2	5
12.	2	2	1	1	2	1	2	1	2	2	12

Table 8. Averaged Signal-to-Noise ratio used for optimum formulation.

Factors	Resin improver	$CaCO_3$	PKS	Copper Fibres	Friction Modifier	Carbon black	Iron Ore	Qucer	Casca-mite	Modified CNSL
Level 1	*41.317	*42.562	38.908	38.944	39.644	*44.346	*41.934	40.166	39.890	*42.278
Level 2	38.74	38.576	*41.568	*42.054	*40.660	37.489	37.86	*40.307	*40.583	38.194

* Indicates the optimum level setting

Optimization of Brake Pad Formulation

Table 6 shows the ingredients and their levels for the brake pad formulation after conducting several trial formulations. The codes “a” to “j” are quantities of ingredients at high-level settings. The other level setting was low–level as indicated in the table. Using the same procedure as in Table 3, the level setting 1 refers to low level, while 2 refers to high level. Hence, Table 7 shows the breakdown of the composition for the friction materials used.

Brake pad specimens were formulated according to the experimental design layout in Table 7. Tribological tests (determination of coefficient of friction and wear rate) on each specimen were carried out. The optimum level settings for the ingredients were determined by using the procedure as stated in the immediate section above shown in Table 8 (Dagwa, 2005). Actual values (in percent volume not presented here) of ingredients indicated by S/N ratios in Table 8 were used for the optimum formulation of the brake pad. Its performance was compared with that of the premium asbestos-based commercial brand of brake pads.

Test of Optimum Formulation Pad

o *Effect f Inertia on Brake Pad Performance*

The test rig was used to perform static tests at a constant speed of 676rpm of the drive shaft and a brake line pressure of 0.3MPa. To generate the different inertia for the tests, the flywheel weights of the test rig were varied from 10kg to 50kg in steps of 10kg. Four braking applications were performed to obtain each set of measurements for pad wear, stopping time and disk temperature rise.

Figure 3 compares the effects of inertia on brake pad wear, brake disk temperature rise and stopping time for the laboratory and commercial brake pads.

The average material loss per application of the laboratory pad (4.4mg) compare well with that of the commercial pad (4.1mg). Blau (2001) reports a value of 3mg for commercial brake pads. The deviations of the laboratory and the commercial pads tested from the quoted value are 46.7% and 36.7% respectively.

The average brake disk temperature rise for the laboratory and commercial pads tested are 2.8^o C each. The average stopping times are 1.0s and 1.06s for the laboratory and the commercial pads respectively.

The above values suggest that the laboratory brake pad may be able to perform as well as the commercial brake pad.

It should be noted in passing that pad wear, disk temperature rise and stopping time increase as the inertia increases. The heavier a vehicle is, the more energy would be required to slow or bring it to rest, and the more braking force acting on the pad. This would give rise to greater pad wear, higher disk temperature rise and higher stopping time.

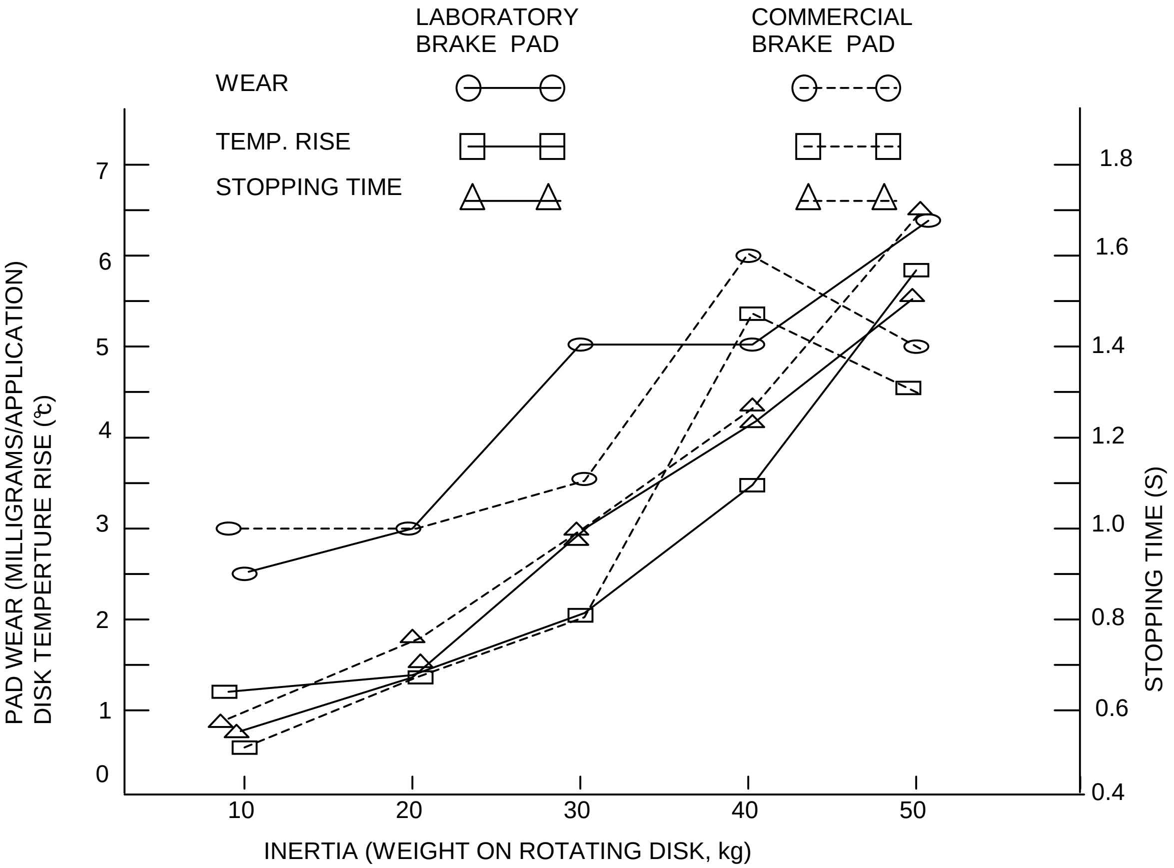

Figure 3. Comparison of laboratory and commercial brake pads under static testing.

- ***Effect of Vehicle Speed on Brake Pad Performance***

Figure 4 presents dynamic road tests which compare the effects of vehicle speed on brake pad wear, brake disk temperature rise and vehicle stopping time after applying the brakes.

The figure shows that the laboratory pad had greater wear than the commercial pad at relatively high speeds especially at speeds higher than 80 km/hour. This may be due to the fact that PKS as a cellulosic material has more volatile elements which volatilizes at higher temperature than the asbestos based commercial brake pad. (The flame resistance test carried out showed that the laboratory pad had 45.7% volatile materially while the commercial one had 8.8% only).

The comparisons for disk temperature rise and stopping time shows that the laboratory brake pad has about the same performance as the commercial pad. The average disk temperature rise and average stopping time for the laboratory pad are 11.6^{o}C and 4.1s respectively, while the corresponding values are 13.1^{o}C and 4.2s for the commercial pad.

- ***Physical and Mechanical Properties of the Optimum Formulation Brake Pad***

Table 9 shows the physical and mechanical properties of the optimum formulation brake pad (Dagwa and Ibhadode, 2007) and commercial asbestos-based brake pad used as control. These values are compared with those quoted in the literature also. The table shows that the compressive strength, hardness, impact strength, specific gravity, wear, coefficient of friction and thickness swell in oil compare well for both the laboratory and commercial brake pads. Also, the laboratory brake pad compare well with quoted values for the compressive strength, shear strength, wear, porosity and coefficient of friction. Poor comparison with other quoted values may arise from test conditions not being the same.

Table 9. Physical and Mechanical Properties of Optimum Formulation and Commercial Brake Pad.

Property	Optimum Formulation Laboratory brake pad (PKS based)	Commercial brake pad (asbestos based)	Quoted values from literature	Deviation of Lab. Pad from mean of quoted values (%)	Deviation of commercial pad from mean of quoted values (%)
Compressive strength (MPa)	103	110	70-125[a]	5.6	12.8
Hardness, Brinell (at 3000kgf)	92	101	-	-	-
Modulus of rupture (MPa)	11.36	-	34-48[b]	72	-
Tensile Strength (MPa)	6.8	-	20-27[b]	71.1	-
Shear Strength (MPa)	2.45	5.46	5.3[c]	40.6	3.0
Impact Strength (J/mm^2)	0.077	0.11	0.0115-0.0154[d]	472.49	717.8
Specific gravity	1.65	1.89	2.1 - 2.4[b]	26.7	16.0
Thermal Conductivity (W/mK)	1.46	0.539	0.47-0.804[b, e]	129.2	15.4
Specific Heat Capacity (J/kgK)	1907	1344	-	-	-
Average wear (mg/application)	4.4	4.1	3.0[f]	43.3	36.7
Porosity (%)	22.45	-	13 - 23[d, g]	24.7	-
Coefficient of Friction	0.43	0.40	0.3 - 0.6[f]	4.4	11.1
Thickness swell in water after 24hrs (%)	5.03	0.9	-	-	-
Thickness swell in oil (SAE 40) after 24hours (%)	0.44	0.3	-	-	-
Flame resistance test after 10 minutes	Charred with 46% ash	Charred with 9% ash	-	-	-

[a](Norton, 2001); [b](Dow, 1985); [c](Singh, 2007); [d](Chand et al, 2004); [e](Newcomb and Spur, 1967); [f](Blau, 2001)[g](Kim et al, 2003)

On the whole, the results suggest that the laboratory PkS – based brake pad possesses mechanical and physical properties similar to asbestos-based brake pad. Thus PKS may be considered as a possible substitute for asbestos in friction lining materials. Further refinement of the formulation to reduce wear at high vehicular speeds and extensive field test on vehicles are recommended.

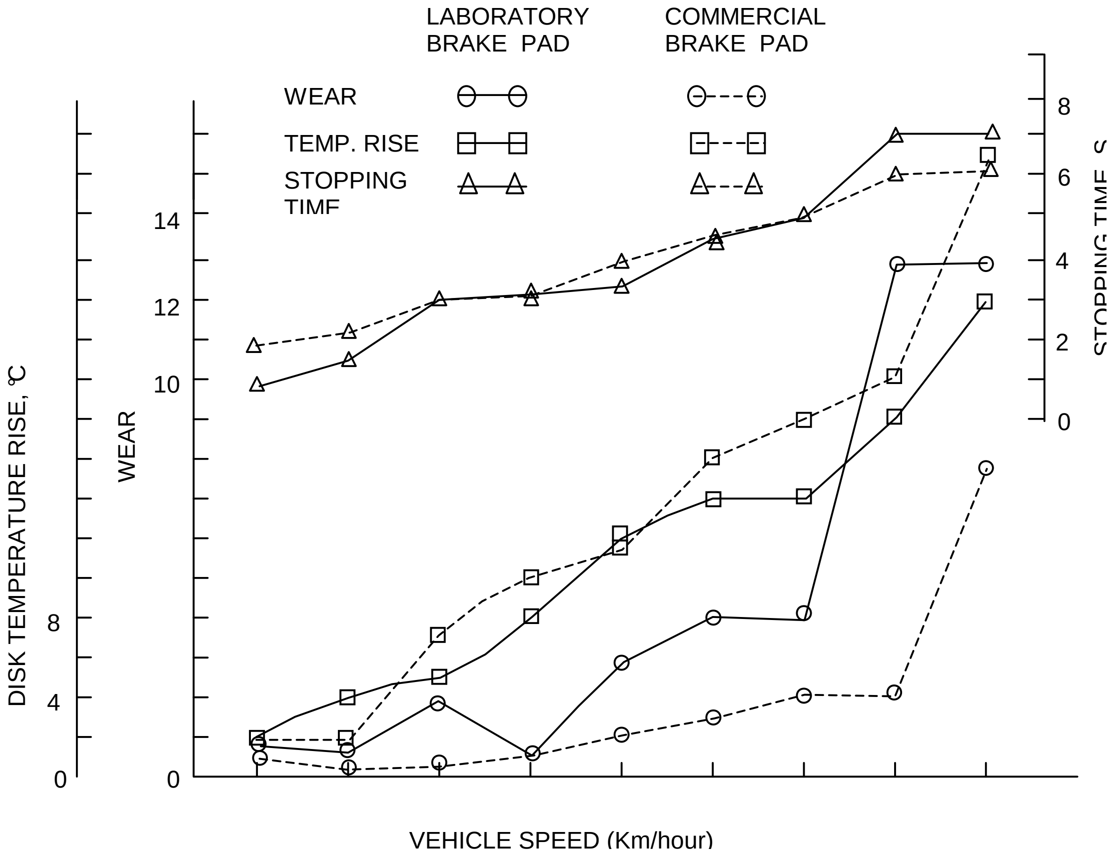

Figure. 4. Comparison of laboratory and commercial brake pads under dynamic testing.

Conclusion

A friction lining material based on PKS as a substitute for asbestos has been developed. The mechanical and physical properties compare well with commercial asbestos-based friction lining material. Its performance under static and dynamic conditions compare well with the asbestos-based lining material. However, further refinement of the PKS lining formulation is recommended in order to have a comparable wear rate at higher vehicular speeds.

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