Experimental Investigation on the Friction and Wear Characteristics of Palm Seed Powder Reinforced Brake Pad Friction Composites

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Abstract In this research work, palm seed power (0–9 wt%, step of 3%; four composites sample, namely P0, P3, P6, P9) were used to reinforce master batch of friction composite materials containing phenolic resin binder, steel swarf fibre, cashew, alumina, graphite, copper and zinc. The fabrications were as per standard industrial practice via hot compression moulding route. Thereafter, samples were cut and characterized for their tribological characteristics on specifically designed braking dynamometer using grey cast iron disc as per TS 555 and TS 9076 standards. Physical and mechanical properties such as hardness and density of the samples were also determined. Further, multi-criteria-decision-making like Preference Selection Index methods are used to ascertain ranking of material alternatives based on performance criteria. Both the subjective analysis and PSI output are in agreement with each other. Hence, such techniques often found suitable for decision-making or ranking of materials alternatives when performance criteria are of conflicting in nature.

Keywords Palm seed powder · Brake friction materials · Tribology · Dynamometer · Friction · Wear · Composite · PSI · MCDM

Introduction

Friction elements used in places such as brake systems are usually composites formed by the combination of many materials. These composites are referred to as friction composite or brake lining. The materials forming the friction composites are classified according to their nature. These groups are generally binders, reinforcements, abrasives, friction modifiers, solid lubricants, heat conductors and space fillers. In friction composites, phenolic resin is generally used as binder. Reinforcements are a wide variety of fibre materials. In previous studies, the use of many organic and metallic fibres such as aramid fibre, rock wool, steel wool, sisal fibre, glass fibre and kevlar fibre in friction composites was investigated. In abrasives group, high hardness values such as alumina, silica, zircon and quartz are preferred. Materials such as graphite are in the solid lubricant group. Materials such as copper and brass are heat conductors. Materials such as barium sulphate, calcium carbonate and mica, which do not have a distinctive function in the composite, are added to the composite as space fillers. In the friction modifiers group, the use of a wide variety of waste and organic materials in friction composites was investigated. Some of these materials include cashew dust, walnut, hazelnut shell, Calabrian pine dust, waste tire rubber, banana peel powder, periwinkle shell, sisal fibre and rice husk dust. [1–24].

There are several studies on the use of palm pieces in friction composites. Ikpambese and his co-workers [7] produced asbestos-free automotive brake pads using palm kernel fibre and performed the necessary tests. According to the results of their studies, they suggested that palm kernel fibre could be used instead of asbestos in the brake pad formulation. In their study, Ibhadoode and Dagwa [22] emphasized the positive results of using palm kernel shell

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instead of asbestos. Ghazali et al. [23] examined the mechanical and wear behaviour of brake pads produced using palm slag and concluded that palm slag was a potential filler material in brake pads.

Nowadays, material scholars are frequently using multi-criteria-decision-making (MCDM) tool for making material selection whenever selecting criteria are finite and conflicting in nature. Such techniques help in making wiser decisions. Few popular methods are: Analytical Hierarchy Process (AHP) method [25], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method [26], Grey Relation Analysis (GRA) method [27], Preference Ranking Organisation method for Enrichment Evaluations (PROMETHEE) method [28], Elimination Et Choice Translating Reality (ELECTRE) method [29], Multi-Objective Optimization on the Ratio Analysis (MOORA) method [30, 31] and Preference Selection Index method [32–38].

In this study, seed of the *washingtonia filifera* type palm was dried and ground and included in different proportions of a new friction material composition. Necessary friction and wear tests of the composites were performed on a reduced scale dynamometer. The results were compared with the reference composite which does not contain palm seed. Also, the results were analysed using MCDM technique like Preference Selection Index method.

Materials and Methodology

Formulation and Fabrication of Brake Friction Composites

The formulations of the palm seed added friction composites were prepared based on the literature survey and the previous studies of the authors. The fabrication of friction composites containing 9 ingredients was based on keeping parent composition of 7 ingredients constant and varying palm seed powder and barium sulphate accordingly. The parent composition that 66 wt% has included binder (phenolic resin) 20 wt%, fibre (steel swarf) 10 wt%, friction modifiers (cashew, alumina, graphite) 23 wt% and functional fillers (Cu and Zn) 13 wt%. Remaining 34 wt% contained palm seed powder varied from 0 to 9 wt%, and difference was compensated by barium sulphate. All ingredients were sieved, and the average size of particles was 300 mesh (48–84 μm). The palm seed and palm seed powder are shown in Fig. 1. The samples of friction composites were designated as P0, P3, P6 and P9, where “P” represents the palm seed powder and the subscript represents the wt% of palm seed powder in the samples. The samples were fabricated by dry mixing method. In order to get a homogeneous mixture, all ingredients were

mixed for 10 min. After mixing, the mixture was cold pressed by applying hydraulic pressure in the performer. The preforms were placed in the 4 cavities and moulded at room temperature and a uniform pressure of 81 kgf/cm^2 for 2 min duration. The samples were cured under a pressure of 101 kgf/cm^2 for 10 min at a curing temperature of 120 °C. Then, the surfaces of the samples were grinded.

Physical Characterization of Brake Friction Composites

Hardness of composites was measured at five different locations of composite by Rockwell hardness tester on S-scale, and average value was reported. Density of composites was calculated based on Archimedes principle. All tests were repeated thrice, and average value is reported in Table 1.

Tribological Characterization of Brake Friction Composites

A special design dynamometer with 7.5 kW motor was used to evaluate the friction performance of the composites. Specifications of the dynamometer are listed in Table 2. Dynamometer comprises of data acquisition software and has fully computer controllable. Thus, parameters such as rotational speed, braking force, torque and duration can be easily controlled. A grey cast iron disc that composition: 2.5–4% C, 1–3% Si, 0.4–1% Mn, 0.05–1% P and 0.05–0.25% S was used as a counter-face. Brake torque was measured by installed load sensor. Composites were fitted in brake pad calliper assembly. In order to investigate the effect of temperature on friction performance during friction, disc temperature was measured by the non-contact infrared thermometer.

For tribo-test, firstly run-in test was performed until at least 95% contact between disc surface and composite is achieved. Continuous friction process was applied for the main friction test. During this period, the speed was maintained at 6 m/s and applied load was 500 kPa. The test duration is 10 min, and the sliding distance is 3600 metres. Weight loss was determined by measuring the weights of the samples before and after the test. The specific wear rate was calculated according to [39, 40].

$$W_s = \Delta m / L \rho F_n \quad (1)$$

where Δm is the mass loss, L is the sliding distance, ρ is the density of the composite, and F_n is the applied load.

Fig. 1 **a** Palm seed, **b** palm seed powder **Table 1** Hardness and density values of the composites

Properties	P ₀	P ₃	P ₆	P ₉
Hardness (HRS)	94.1	88.5	85.5	95.8
Density (g/cc)	2.562	2.301	2.223	2.017

Table 2 Specifications of the dynamometer

Motor	7.5 kW, AC motor
Min. speed	100 rpm
Max. speed	1450 rpm
Min. pressure	100 kPa
Max. pressure	3000 kPa

Preference Selection Index Method

The multi-criteria-decision-making techniques like Preference Selection Index (PSI) methods [32–38] involve following steps

Step 1: Structuring the Decision Problem It comprises input to PSI method, i.e. determining goal, all the possible material alternatives, criteria and their measures. All things are represented on hierarchy structure as shown in Fig. 2.

Step 2: Formulate Decision Matrix The multi-alternative (say m -alternatives) and multi-criteria (say n -criteria) of the problem are expressed in the decision matrix form

$$D_{m \times n} = \begin{matrix} C_1 & C_2 & \cdots & C_n \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{bmatrix} \end{matrix}$$

where $C_1, C_2, \dots, C_n$ are the n -criteria and

$A_1, A_2, \dots, A_m$ are the m -alternatives.

The element p_{ij} is the performance value of the i th alternative (A_i) with respect to the j th attribute (C_j) where $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$.

Step 3: Normalization of Decision Matrix The entries of the above matrix are normalized (using below principle). Thus, obtained normalized matrix is R_{ij} .

1. If the expectancy is; larger-the-better, then the original attribute performance can be normalized as follows:

$$R_{ij} = \frac{x_{ij}}{x_j^{\max}}$$

2. If the expectancy is; smaller-the-better, then the original attribute performance can be normalized as follows:

$$R_{ij} = \frac{x_j^{\min}}{x_{ij}}$$

where x_{ij} is the attribute measures ($i = 1, 2, 3, \dots, m$ and $j = 1, 2, 3, \dots, n$).

Step 4: Compute Preference Variation Value (PV_j) The obtained normalized matrix R_{ij} is used to compute preference variation value (PV_j) for each criteria with the concept of sample variance analogy using following equation:

$$PV_j = \sum_{i=1}^N (R_{ij} - \bar{R}_j)^2$$

where $\bar{R}_j$ is the mean of normalized value of criteria j , i.e. $\bar{R}_j = \frac{1}{n} \sum_{i=1}^N R_{ij}$.

Step 5: Computation of overall preference value (ψ_j)

The overall preference value (ψ_j) of each criteria is computed using below equation:

$$\psi_j = \frac{\Phi_j}{\sum_{j=1}^n \Phi_j}$$

where $\Phi_j = 1 - \Sigma PV_j$, is the deviation in preference value. For consistency, the sum of overall preference value for all the criteria should be unity, i.e. $\Sigma \psi_j = 1$.

Step 6: Computation of Preference Selection Index (I_i)

Fig. 2 The hierarchy structure of PSI

The Preference Selection Index (I_i) for each alternative is computed using below equation:

$$I_i = \sum_{j=1}^n (R_{ij} \times \Psi_j)$$

Step 7: The computed values of Preference Selection Index (I_i) are used to rank the alternatives according to its descending order and then making related interpretations or recommendations.

Results and Discussion

Frictional Performance of Brake Friction Composite

Friction coefficient, specific wear rate and friction stability parameters should be examined in evaluating the performance of friction composites. The friction coefficient can be examined as a function of the sliding distance, duration or disc temperature. The average friction coefficient change graph as a function of the sliding distance is given in Fig. 3. As shown in the figure, the average friction coefficient decreases with increase in palm seed content and P₃-coded sample containing 3 wt% palm seed powder has the highest average friction coefficient value. Figure 4a, b shows the analysis of friction stability of the composites. Inclusion of palm seed in the friction material composition reduces the friction stability.

In friction composites, it is desirable that the friction coefficient and friction stability are high. However, it is desirable that the weight loss and specific wear rate are low. Temperature is inevitable where friction is present. The occurring high temperature affects the friction

Fig. 3 The change in the average friction coefficient as a function of sliding distance

performance negatively. In addition, undesired chemical changes may occur in the content of the composite by the effect of temperature. Figure 5 shows the maximum temperature on the disc during the test. Accordingly, it was found that the increase in the content of palm seed powder content has a greater influence in the reduction of temperature rise in the disc.

Wear of Brake Friction Composite

Wear properties of composites are shown in Fig. 6a. It is seen that the weight loss is the least in the sample without palm seed powder. However, increase in the content of palm seed powder greatly reduced the wear loss. The specific wear rates of the samples according to Eq. (1) were calculated, and it is seen that the specific wear rate of the palm seed powder-free sample is lower than that of palm

Fig. 4 **a** The change in the average friction stability as a function of duration, **b** friction stability of the composites

Fig. 5 Maximum disc temperature (°C) reached during the test

seed powder added samples as shown in Fig. 6b. In addition, as the amount of palm seed powder in the content increased, the specific wear rate value increased.

Performance Ranking of Friction Composites Using PSI Method

The PSI methods were employed to rank the friction composite specimens, namely P0, P3, P6 and P9 based on

Fig. 6 The wear properties of the samples

their input performance criteria's. Further, the outcome was compared with subjective analysis to judge applicability of PSI method in decision-making in such friction composite materials. Table 3 enlists the used performance criteria, their description and preference. Figure 7 shows structuring of the present case study. The algorithm mentioned in "Preference Selection Index Method" section was used for computation purpose (Tables 4, 5, 6, 7, 8).

Thus, as per PSI method the friction formulations follow following order: $P3 > P6 > P9 > P0$. The discussion over the physical, mechanical and tribological study of the investigated friction composite materials also highlights the performance order: $P3 > P6 > P9 > P0$. Henceforth, both analyses are in agreement with each other. Hence, it could be observed that such MCDM techniques like PSI could possibly be used for making decision by material scientists when there are few alternatives and few conflicting selecting criteria.

Conclusion

In this study, four different friction composites except one containing powder of the *washingtonia filifera* type palm seed were designed and manufactured. No palm seed was added to the sample coded P0. Thus, the results of palm

Table 3 Descriptions of the selection criteria applied in this case study

S. no.	Performance criteria	Description	Preference
1.	Hardness (HRS)	It is the resistance of material against plastic deformation usually by penetration/scratch. Higher hardness improves wear resistance	Maximum
22.	Friction coefficient	It is the ratio of frictional force to normal applied load during when two bodies slides against each other	Maximum
3.	Friction stability (%)	It is the average friction coefficient value during the test run of speicmens	Maximum
44.	Specific wear rate (mm ³ /Nm)	The specific wear rate is defined as the volume loss of the material per unit sliding distance per unit applied normal load	Minimum
5.	Density (g/cc)	It is defined as mass per unit volume of a material	Minimum
6.	Maximum disc temperature (°C)	It is the rise in temperature of disc when brake friction pad slides over it during test	Minimum

seed powder added samples were compared with the sample without palm seed powder.

- When the physical properties of the samples were evaluated, it was seen that the highest hardness value belonged to P9-coded sample containing 9% by weight of palm seed powder. However, there was no linear change in the hardness of other samples with the amount of palm seed powder in the content.
- Density decreased gradually with increase in amount of palm seed powder in the content. It was estimated that the barite was heavier than the palm seed powder because the palm seed powder was balanced with the barite in the content.
- Except the P3-coded sample, the palm seed powder in the content did not affect the average friction

coefficient positively. The same situation was seen in the friction stability percentages.

- The disc temperature measured during the tests of the P0-coded sample containing no palm seed powder was lower than the other samples.
- Considering the wear behaviour, it was observed that the best wear resistance was in the palm seed powder-free sample. As a result, it was seen that palm seed powder could be used in friction composites only 3%.
- The PSI method suggests following performance order: P3 > P6 > P9 > P0 which is in agreement with subjective analysis. Hence, such techniques could possibly be used for making decision by material scientists when there are few alternatives and few conflicting selecting criteria's.

Fig. 7 The hierarchy structure

Table 4 Step 2: Formulate decision matrix

Alternatives (A_i)\performance attributes (PA_j)	Hardness	Friction coefficient	Friction stability	Specific wear rate	Actual density	Max disc temp
P0	94.1	0.409	83.6	1.003E–06	2.562	88.4
P3	88.5	0.467	85	1.995E–06	2.301	146.5
P6	85.5	0.417	81.9	1.997E–06	2.223	111.2
P9	95.8	0.372	80.9	2.108E–06	2.017	102.6
Max(X_j)/Min(X_j)	95.80	0.47	85.00	0.000001003	2.0170	88.40

Table 5 Step 3: Normalization of decision matrix

Alternatives (A_i)\performance attributes (PA_j)	Hardness	Friction coefficient	Friction stability	Specific wear rate	Actual density	Max disc temp
P0	0.982	0.876	0.984	1.000	0.787	1.000
P3	0.924	1.000	1.000	0.503	0.877	0.603
P6	0.892	0.893	0.964	0.502	0.907	0.795
P9	1.000	0.797	0.952	0.476	1.000	0.862
Mean	0.950	0.891	0.975	0.620	0.893	0.815

Table 6 Step 4–5: Compute preference variation value (PV_j) and overall preference value (ψ_j)

Alternatives (A_i)\performance attributes (PA_j)	Hardness	Friction coefficient	Friction stability	Specific wear rate	Actual density	Max disc temp
P0	0.001	0.000	0.000	0.144	0.011	0.034
P3	0.001	0.012	0.001	0.014	0.000	0.045
P6	0.003	0.000	0.000	0.014	0.000	0.000
P9	0.003	0.009	0.001	0.021	0.011	0.002
SUM(PV_j)	0.008	0.021	0.001	0.193	0.023	0.082
Φ_j	0.992	0.979	0.999	0.807	0.977	0.918
Ψ_j	0.175	0.173	0.176	0.142	0.172	0.162

Table 7 Step 6: Computation of Preference Selection Index (I_i)

Alternatives (A_i)\performance attributes (PA_j)	Hardness	Friction coefficient	Friction stability	Specific wear rate	Actual density	Max disc temp	I_i
P0	0.172	0.151	0.173	0.142	0.136	0.162	0.936
P3	0.162	0.173	0.176	0.072	0.151	0.098	0.830
P6	0.156	0.154	0.170	0.071	0.156	0.129	0.836
P9	0.175	0.137	0.168	0.068	0.172	0.139	0.859

Table 8 Step 7: Ranking of alternatives based on largest to smallest I_i

Preference ranking	Alternatives (A_i)	I_i
1	P0	0.936
2	P9	0.859
3	P6	0.836
4	P3	0.830

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