Optimum design of brake friction material using hybrid entropy-GRA approach

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Abstract. The effect of Kevlar and natural fibres on the performance of brake friction materials was evaluated. Four friction material specimens were developed by varying the proportion of Kevlar and natural fibres. Two developed composite contained 5-10 wt.% of Kevlar fibre while in the other two the Kevlar fibre was replaced with same amount of natural fibre. SAE J661 protocol was used for the assessment of the tribological properties on a Chase testing machine. Result shows that the specimens containing Kevlar fibres shows higher friction and wear performance, whereas Kevlar replacement with natural fibre resulted in improved fade, recovery and friction fluctuations. Further hybrid entropy-GRA (grey relation analysis) approach was applied to select the optimal friction materials using various performance defining attributes (PDA) including friction, wear, fade, recovery, friction fluctuations and cost. The friction materials with 10 wt% of natural fibre exhibited the best overall quality.

1 Introduction

Generally, a friction material contains a resin binder, fibrous reinforcement, abrasives, fillers and lubricants in varying composition [1]. Asbestos because of its economical issue and met the bulk of fascinating properties of brake friction material are used for years as a fibrous reinforcement [2]. However, the ban on the utilization of asbestos by environmental protection agencies because of its carcinogenic nature had forced the friction industry to hunt alternative of asbestos [3]. Last two decades witnessed a lot of research in the development of asbestos-free brake friction materials [4-10]. In this way the formulation designers start focusing on natural fibres and industrial wastes as a source of raw materials for friction formulations [11-17]. The utilization of such materials will not only be economically viable, but may also result in reduced environmental pollution. A good friction material requires an appropriate set of performance defining attributes (PDAs) namely high and stable coefficient of friction, negligible fading, faster recovery, better wear resistance and low-sensitivity towards load-speed alterations for reliable and safe performance [1]. Therefore assessment of such PDAs and selection of optimal friction material can be regarded as multiple criteria decision-making (MCDM) problem [18-20]. Hence in this work the comparative effect of addition of Kevlar and natural fibre on the tribo-performance of brake friction material is studied and optimal formulation is selected by using MCDM approach.

2 Experimental

2.1 Materials and fabrication of friction specimens

Friction materials based on phenolic resin, Kevlar fibre, Lapinus fibre, graphite, barite, alumina, vermiculite, potassium titanate and natural fibre amounting to 100% by weight were fabricated as per Table 1. Detail of the processing conditions for composite fabrication is briefly reported elsewhere [21-23].

Table 1. Composition and nomenclature of the friction materials specimens.

Composition (wt.%)	Nomenclature			
	K-1	K-2	N-1	N-2
*Parent composition	45	45	45	45
Barite	50	45	50	45
Kevlar Fibre	5	10	0	0
Natural Fibre	0	0	5	10

K: Kevlar fibre, N: Natural fibre
*Parent composition: Phenolic resin, Lapinus fibers, Alumina, Graphite, Potassium Titanate and Vermiculite.

2.2 Tribo-performance evaluation methodology

The tribo-performance of the specimens was evaluated on a chase type friction material testing machine following SAE J661a standard. The details of the testing protocol and testing machine is reported elsewhere [24]. The performance coefficient friction, fade, recovery, wear,

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friction fluctuations and cost were considered as PDA of the evaluation. The detailed description of the various PDAs used in this study is given as:

PDA-1: μ-Performance (Higher-is-better)

It is the average friction coefficient of all fade and recovery cycles.

PDA-2: Wear (Lower-is-better)

It is the loss of material from the specimen during braking. It is calculated as, $\Delta W = W_1 - W_2$, where W_1 the weight of specimen before test and W_2 is the weight of the specimen after test.

PDA-3: %-Fade (Lower-is-better)

%-Fade$=\dfrac{\mu_{\text{Performance}} - \mu_F}{\mu_{Performane}} \times 100$, where μ_F is the minimum coefficient of friction for the fade cycles. Lower %-fade is desirable for good friction composites. The standard range is 0-30%.

PDA-4: %-Recovery (Higher-is-better)

%-Recovery$=\dfrac{\mu_R}{\mu_{Performane}} \times 100$, where μ_R is the maximum coefficient of friction for the recovery cycles. It is desirable in the range of 100-140% for good friction composites.

PDA-5: Frictional fluctuations (Lower-is-better)

Frictional fluctuations are given by $\Delta\mu = \mu_{max} - \mu_{min}$. Where, μ_{max} is the highest coefficient of friction and μ_{min} is the lowest coefficient of friction.

PDA-6: Cost (Lower-is-better)

It is the cost of the composition per kilogram.

2.3 Ranking evaluation methodology

The ranking evaluation methodology consists of three main phases as:

Phase I: Identification of the alternatives, PDAs and decision matrix

Phase II: Weight determination of various PDAs

Phase III: Ranking of the alternatives

Phase I: Identification of the alternatives and PDAs

Here the number of alternatives and performance defining attributes (PDAs) are identified. After the identification of alternatives and criterions the values of experimental results for each alternative is expressed in a decision matrix as:

$$X = \begin{array}{c} \\ A_1 \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{cccc} C_1 & C_j & \cdots & C_n \\ \left[\begin{array}{cccc} x_{11} & x_{1j} & \cdots & x_{1n} \\ x_{i1} & x_{ij} & \cdots & x_{in} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{mj} & \cdots & x_{mn} \end{array}\right] \end{array} \quad (1)$$

where, $A_1,...,A_m$ are the composition/alternatives and $C_1,...,C_n$ are the PDA. Hence, x_{ij} is the value of jth PDA (C_j) for the ith composition/alternative (A_i).

Phase II: Entropy method for weight determination

Entropy method is used for the calculation of weight. This method consists of the following steps [25]:

Step I: The constructed matrix is normalized using following equation:

$$N_{ij} = \frac{x_{ij}}{\sum\limits_{i=1}^{m} x_{ij}} \quad (2)$$

Step II: In this step, the entropy for each PDA is calculated as:

$$e_j = -\kappa \sum\limits_{j=1}^{n} N_{ij} \ln(N_{ij}) \quad (3)$$

Where, κ is a constant and calculated as $\kappa = \dfrac{1}{\ln(m)}$

Step III: Finally the weight of each PDA is calculated as:

$$\varpi_j = \frac{\partial_j}{\sum\limits_{j=1}^{n} \partial_j} \quad (4)$$

Where, $\partial_j = 1 - e_j$ and it is the degree of diversity of the information involved in the outcomes of the jth PDA.

Phase III: Ranking of the alternatives

Grey system theory was developed by Deng and consists following step [26]:

Step-I: In order the make the values free of unit the normalization process is done. The normalized values of each element in the performance matrix can be calculated as follows:

$$X'_{ij} = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \quad (5)$$

$$X'_{ij} = \frac{\max\{x_{ij}\} - x_{ij}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \quad (6)$$

Where $\max\{x_{ij}\}$ and $\min\{x_{ij}\}$ respectively are the maximum and minimum values of the ith PDA. Eq. (5) is used for the larger-the-better PDA; Eq. (6) is used for the smaller-the-better PDA.

Step-II: In this step reference sequence ($\Re_j$) is generated from the normalized matrix by taking the largest normalized value of each PDA as:

$$\Re_j = \max_{i=1}^{m}\{X'_{ij}\} \quad (7)$$

Step-III: Grey correlation coefficient for each term is determined as:

$$\Phi_j = \frac{\min_{i=1}^{m} \min_{i=1}^{n} \Delta_{ij} + \hbar \max_{i=1}^{m} \max_{i=1}^{n} \Delta_{ij}}{\Delta_{ij} + \hbar \max_{i=1}^{m} \max_{i=1}^{n} \Delta_{ij}} \quad (8)$$

Where $\Delta_{ij} = \left|\Re_j - X'_{ij}\right|$ and $\hbar$ is known as the distinguishing coefficient and generally takes the value of 0.5.

Step-IV: Finally a grey relational degree (which is the weighted sum of the grey relational coefficients) is calculated by the following equation:

$$\Omega_i = \sum_{j=1}^{n} \left[\Phi_j \times \varpi_j \right] \qquad (9)$$

Where ϖ_j is the weight of the jth PDA and calculated using entropy method. Therefore, using the grey correlation degrees the friction material formulation sequence can be prioritized and the one with the highest degree of correlation will be identified as the best formulation that represents the optimal solution.

3 Results and discussions

3.1 Experiment results

The tribo-performance evaluation of the fabricated friction composites materials were carried out on a chase type testing machine. The experiment results corresponding to each PDA are listed in Table 2. The performance friction coefficient ($\mu_{Performance}$) (0.586±0.009) and wear performance (1.065±0.055g) remains higher for Kevlar filled friction composite. The $\mu_{Performance}$ and wear performance are observed to decrease for the friction composition having natural fibre content. From fade performance point of view natural fibres (30.39%±5.96) based friction composition proved much

superior to Kevlar fibre based composition where fade remains highest (54.91%±8.52). The recovery performance is observed to exceed 100% irrespective of the fibrous reinforcement. It remains ~110.435±1.525% for Kevlar based composition and increases slightly to 110.735±1.765% for the compositions having natural fibre as reinforcement. Moreover, natural fibres based compositions performed better from friction fluctuations point of view and are much cost effective as compared to Kevlar fibre based compositions.

3.2 Ranking of the alternatives

The decision matrix from Eq.1 is used for the entropy-GRA analysis. The weights of the selected PDAs are calculated by using Eqs. 2-4 and given in Table 3. The weight of PDAs as evaluated by entropy method are PDA-1=0.009, PDA-2=0.078, PDA-3=0.205, PDA-4=0.003, PDA-5=0.185, PDA-6=0.520. After weight calculation, GRA technique is applied to find the optimum composition using Eqs. 5-9. The GRA technique results are shown in Table 6. From this analysis, it was observed that the natural fibre based compositions exhibits the optimal performance.

Table 2. Experimental data of the PDAs.

Alternatives	PDA-1	PDA-2	PDA-3	PDA-4	PDA-5	PDA-6
K-1	0.595	1.12	46.39	108.91	0.329	105.25
K-2	0.577	1.01	63.43	111.96	0.435	169.75
N-1	0.520	1.70	36.35	112.50	0.262	45.25
N-2	0.524	1.20	24.43	108.97	0.175	49.75

Table 3. Weight of PDAs as calculated by entropy method.

Alternatives	PDA-1	PDA-2	PDA-3	PDA-4	PDA-5	PDA-6
Entropy	0.998	0.984	0.959	0.999	0.963	0.895
Weight	0.009	0.078	0.205	0.003	0.185	0.520

Table 4 The normalized decision matrix and reference sequence.

Alternatives	PDA-1	PDA-2	PDA-3	PDA-4	PDA-5	PDA-6
K-1	1.000	0.841	0.437	0.000	0.408	0.518
K-2	0.760	1.000	0.000	0.850	0.000	0.000
N-1	0.000	0.000	0.694	1.000	0.665	1.000
N-2	0.053	0.725	1.000	0.017	1.000	0.964
Reference sequence	1	1	1	1	1	1

Table 5 Grey relation coefficient.

Alternatives	PDA-1	PDA-2	PDA-3	PDA-4	PDA-5	PDA-6
K-1	1.000	0.759	0.470	0.333	0.458	0.509
K-2	0.676	1.000	0.333	0.769	0.333	0.333
N-1	0.333	0.333	0.620	1.000	0.599	1.000
N-2	0.342	0.642	1.000	0.333	1.000	0.932

Table 6 Grey correlation degree and ranking of the formulations.

Alternatives	PDA-1	PDA-2	PDA-3	PDA-4	PDA-5	PDA-6	Grey correlation degree	Ranking
K-1	0.009	0.059	0.096	0.001	0.085	0.265	0.515	3
K-2	0.006	0.078	0.068	0.002	0.062	0.173	0.389	4
N-1	0.003	0.026	0.127	0.003	0.111	0.52	0.790	2
N-2	0.003	0.050	0.205	0.001	0.185	0.485	0.929	1

4 Conclusions

Optimal design of friction material using combined entropy-GRA approach was carried out in this work. The optimal design of friction material was performed in three phases: (1) selection of alternatives and performance defining attributes, (2) weight calculation using entropy method and (3) GRA method is used to rank the alternatives. In this study, Kevlar and natural fibre based friction materials were selected as alternatives whereas; performance coefficient of friction, wear, fade, recovery, frictional fluctuations and cost were selected as performance defining attributes. Based on entropy-GRA results, the ranking of the friction materials from the best to the worst is in the order of N-2, N-1, K-1, and K-2. The specimen N-2 having 10 wt.% of natural fibre was ranked best among all the evaluated friction materials.

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