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Application of the MULTIMOORA Method to Evaluate Performance Results of Red Mud Reinforced Bronze Matrix Brake Pads

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Research Article

Abstract

The objective of this study is to investigate the effectiveness of the MULTIMOORA method strengthened with AHP to select the most suitable pad material among metal matrix composite brake pad materials reinforced with different proportions of red mud according to the criteria determining the efficiency of brake performance. For this purpose, five different brake pad samples reinforced with red mud, an industrial waste, at different weight ratios (0%, 2%, 4%, 6%, 8%) were produced and the physical, mechanical, and tribological properties of the produced materials were characterized. Tribological characterization tests were carried out in accordance with TSE 555 using a specially designed brake dynamometer. The average coefficient of friction, specific wear rate, friction stability, hardness, density, and TRS values, which represent important performance indicators of the pad material, were used as criteria for the selection of pad material. According to the AHP method, the importance levels of these criteria in terms of brake performance were determined as 0.423, 0.205, 0.205, 0.088, 0.051, and 0.028, respectively. As a result of the evaluation made using the MULTIMOORA and MOOSRA method, it was determined that the RM-8 sample showed the best result in terms of brake performance among all samples. In addition, this material was followed by RM-6, RM-4, RM-0 and RM-2 samples, respectively. The findings of this study indicate that the MULTIMOORA method is an effective and reliable approach for selecting the optimal pad material among alternatives, according to the specified criteria.

Keywords: Brake pad; Metal matrix composite; MOOSRA; MULTIMOORA

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1. Introduction

Brake pads are a critical component in a vehicle's braking system and are designed to ensure safety of driving experience. As such, they play an important role in slowing or stopping a vehicle through frictional force. This is achieved by creating a frictional force on the discs with the brake pad against rotation of disk direction [1]. In recent years, research has been conducted to improve vehicle safety by improving the properties of brake pads [2]. These research efforts are aimed at developing new composite materials that offer better braking efficiency, lower weight, higher wear resistance, better heat transfer capacity, high corrosion resistance, and better mechanical properties for use in vehicle systems [3-7]. For this purpose, intensive studies have been carried out on the development of metal matrix brake pads due to their low specific wear rate, high friction coefficient stability, and high heat transfer [8-10]. Metal matrix brake pads are a composite material comprising a metal matrix and a variety of components, including solid lubricants, reinforcements, and abrasives [11]. Although metal matrix brake pad materials have enhanced features in terms of brake performance compared to polymer matrix brake pad materials, which are widely used in the automotive sector [12, 13] they need to be developed without losing performance in terms of cost [14]. A review of the literature from recent years indicates that industrial and agricultural waste materials are employed in the manufacture of polymer matrix brake pad materials for the purposes of both improving tribological properties and reducing production costs [15-17].

The fact that polymer matrix brake pad materials require low temperature values (180 °C) [16] for production allows the use of reinforcement elements with a wide range of thermal stability from low to high in these materials. Conversely, the necessity for elevated temperatures (>800 °C) [10] during the production of metal matrix brake pad materials restricts the variety of industrial and agricultural waste materials that can be employed as reinforcement elements in these materials. Therefore, reinforcement elements with high thermal stability are preferred in these pad materials. When evaluated from this perspective, fly ash and red mud are evaluated as industrial waste materials that can be used in the production of metal matrix brake pads as reinforcement elements.

Fly ash is a waste product formed at high temperatures (i.e. 1000 °C and above) during the combustion of coal in thermal power plants. Fly ash indicates thermally stable behavior because of its formation in high temperatures. It contains significant quantities of SiO_2, Fe_2O_3, Al_2O_3, and CaO compounds [18]. The rise in global energy demand has led to an increase in coal consumption, resulting in an annual production of approximately 750 Mt of fly ash. However, only 25% of this fly ash is converted into useful products in various sectors, while the remaining 75% is stored as waste and awaits disposal. This situation presents both environmental and economic problems [19].

Red mud, which is rich in Na, Fe, Ca, and Al or bauxite residues, is a waste material generated during the production of alumina from bauxite by the Bayer process. The highly alkaline nature of these waste materials poses a significant environmental risk. Red mud exhibits thermal stability within a range of 500 to 900°C [20]. This, in turn, renders it an appropriate reinforcement component in the advancement of high-temperature-resistant metal matrix composite materials. It has been estimated that approximately 120 Mt of red mud is produced globally each year, with this figure increasing in line with the global demand for aluminum [21]. A negligible proportion (4%) of the red mud produced in China is employed for any purpose and the rest requires large areas for storage, resulting in a large amount of waste accumulation. This situation also has posed a major threat to the environment. It is therefore necessary to enhance the efficiency of the utilization of red mud. In consideration of the aforementioned facts, the utilization of fly ash and red mud in the manufacture of brake pad materials will simultaneously diminish production costs and mitigate the detrimental effects of these waste products on the environment [22].

A review of the literature reveals that the type and ratio of industrial waste materials employed as reinforcement elements in the manufacture of metal matrix composite materials exert a considerable influence on the physical, mechanical, and tribological properties of the resulting composite material [23-25]. In this context, the incorporation of varying amounts and types of waste reinforcement elements into metal matrix brake pad materials gives rise to discernible differences in their braking performance [26, 27]. Consequently, the formulation of an optimal brake pad represents a significant challenge for manufacturers, necessitating the integration of multiple performance criteria. These include an elevated friction coefficient, a reduced wear rate, and enhanced friction stability, which often present conflicting requirements. Given the distinctive brake performance characteristics of each brake pad material, determining the optimal brake pad material that can meet the maximum degree of satisfaction to all the brake performance requirements is a crucial and challenging task [28]. In order to determine the optimal alternative for the solution of these and similar problems, multi-criteria decision-making (MCDM) methodologies, including MOORA, AHP, TOPSIS, VIKOR, ELECTRE, and PROMETHEE, may be employed [29]. The most useful of these methods was the MOORA method in terms of computing time, ease of usage, mathematical computations, consistency, and data type [30]. By adding the full multiplicative form to the MOORA, the new method is named as MULTIMOORA [31]. For solving complex multi criteria problems, it is a statistical method decision support tool [32]. Designed as an extension to MOORA, it provides a powerful approach to multi objective evaluation and prioritization. So, this method is useful in situations where there are a large number of alternatives. MULTIMOORA provides a comprehensive decision using ratio system, reference point and full multiplicative form approaches with alternatives and principles. It facilitates the identification of the optimal choice by normalizing and weighting multiple criteria to rank alternatives. It has a wide range of applications in engineering, management, and other sciences, where a systematic approach is required for the best selection [33]. In the literature, Brauers and Zavadskas [30] utilized MULTIMOORA method for displaying its robustness. Adalı and Işık [31] used the MULTIMOORA and MOOSRA methods for laptop selection. Patnaik et al. [32] studied to determine the most suitable one among the alternatives according to the physical and mechanical properties of composite materials using the MOORA approach. Also, they used the AHP method to calculate weight coefficients for different criteria. Chakraborty [34] applied the MOORA method to six different selection problems. Brauers et al. [35] suggested first fuzzy combination with the MULTIMOORA method. Also, they applied fuzzy approach to ratio system, reference point, and full multicaptive form with different examples. Kracka et al. [36] presented the MULTIMOORA method for heat loss problem for various wall and windows alternatives.

There are multiple alternatives and criteria in selecting automobile friction systems, so the optimal selection emerges as a problem. Therefore, it is necessary to determine the ideal one among distinct options based on MCDM. There are various studies on this subject in the literature. Bhaskar et al. [37] performed a selection process with performance determination criteria for silicon carbide ceramic particle reinforced AA2024 alloy composites using a hybrid AHP and TOPSIS approach. By using the MCDM method, mechanical, and tribological properties of different composite formulations were evaluated and ranked according to their performance. Satapathy and Bijwe [29] displayed an optimization of containing organic fibers composite materials using MCDM approach for friction applications. They also demonstrated the effectiveness of the MCDM in achieving a reliable and efficient selection process. Ahlawat et al. [38] used the Entropy-VIKOR technique for optimization and selection of brake friction composites, which contain raw and milled fly ash in varying proportions based on performance criteria such as coefficient of friction, stability, wear rate, and temperature. Modi et al. [39] presented an optimization process of design of brake discs for all-terrain vehicles using multi-criteria-decision-making methods, specifically the AHP and the TOPSIS. Ishak et al. [40] applied the Fuzzy VIKOR method to select the best natural fiber-reinforced composite material for automotive brake pads to replace asbestos, which has been banned due to its harmful effects. They ranked brake pads with four alternatives of natural fiber-reinforced composites in terms of coefficient of friction, thermal conductivity, hardness, tensile strength, and wear. Jahan et al. [41] carried out a research study focused on the selection of suitable automotive brake materials using different MCDM techniques. They ranked ten alternative natural fibers for manufacturing brake pads based on various criteria, including density, hardness, coefficient of friction, specific wear rate, compressive strength, degradation temperature, and moisture gain. Konada et al. [42] conducted wear tests using a friction test rig to analyze specific wear rate and coefficient of friction at different temperatures and pressures. The experimental results were validated using artificial neural network techniques, and the TOPSIS method was applied to predict the best experimental conditions for achieving lower wear rates and desired coefficients of friction. Singh [43] manufactured and evaluated non-asbestos automotive brake friction composites using varying ratios of waste cement dust and barium sulfate. They employed an integrated multi-criteria-decision-making framework combining the MABAC and AHP approaches to select optimal brake friction composite alternatives based on their tribological properties. Singh et al. [44] developed a hybrid multi-criteria-decision-making framework, specifically using the criteria importance through CRITIC-CODAS approach, to rank automotive brake friction composite materials based on their physical and tribological properties. They evaluated various performance criteria such as density, porosity, compressibility, friction coefficient, fade-recovery performance, friction fluctuation, cost, and carbon footprint. Singh et al. [45] performed evaluation and ranking of different formulations for brake friction materials using the MCDM technique, based on the AHP and the VIKOR method. Yavuz [46] presented research about bio-composites, which are those made from blue-colored cupressus arizonica cones. Also, experimental studies were performed for tribological evaluation utilizing the brake pad samples. In addition, these brake pad samples were evaluated based on their tribological, mechanical, thermal, and physical properties to ensure optimum performance in brake pads using the TOPSIS technique. In the literature review, there are few studies in which the MULTIMOORA and MOOSRA methods were used to optimize brake pad materials. In this study, MULTIMOORA and MOOSRA methods were used to select the optimal alternative among brake pad materials with different amounts of red mud reinforcement. The results of the analysis showed that the multi-criteria-decision-making methods can be used to select the most suitable brake pad material objectively when criteria such as average friction coefficient, specific wear rate, friction stability, hardness, density, and transverse rupture strength (TRS) are considered.

2. Material and Method

2.1. Preparation and production of brake pad samples

In this study, a mixture comprising 68% bronze, 15% iron, 5% graphite, and 12% fly ash was employed for the production of bronze matrix brake pads. The manufacturing process of a bronze matrix brake pad sample involved the use of bronze as the matrix, graphite as the lubricant, iron as the reinforcement, and fly ash as the abrasive component. A novel brake pad materials were developed by incorporating red mud particles, acting as an auxiliary reinforcement element, into the existing composition at varying rates of 0%, 2%, 4%, 6%, and 8% by weight. Brake pad materials were coded as RM-0, RM-2, RM-4, RM-6, and RM-8 according to the proportion of red mud added to the matrix. The fly ash used in the study was supplied from İskenderun Sugözü Thermal Power Plant and red mud was supplied from Seydişehir Eti Aluminium Production Plant. The chemical and physical properties of the powders used in this study are given in detail in the study conducted in the literature [47]. The powders used in the production of brake pads were weighed with a precision scale and the powder mixtures were prepared. The resulting powder mixtures were mixed in the 3D mixer in a plastic bottle at a rotation speed of 40 rpm for 90 minutes to obtain a homogeneous mixture. The homogeneously mixed powders were then sintered at a pressure of 40 MPa for 5 minutes at 800 °C to produce brake pad materials with dimensions of 25x25x7 mm for the wear test specimens and, 10x10x40 mm for the transverse rupture test specimens (Figure 1).

2.2. Physical, mechanical, and tribological characterization of the manufactured samples of the brake pads

The hardness value of the produced samples was determined at five different points of the composite using a Rockwell hardness tester according to the HRM scale, and the resulting values were averaged. Furthermore, the densities of the samples were ascertained through the utilization of the Archimedes method. Each measurement was conducted four times, and the mean value was subsequently calculated. Table 1 lists the hardness and density values of the samples produced. The three-point bending tests were performed on the universal testing machine (Instron 3369, USA) to determine the force required to rupture the brake pad samples produced (Figure 2). Subsequently, the force values were converted to transverse rupture strength (TRS) values according to Eq. (1). Table 1 presents the TRS values of the samples produced.

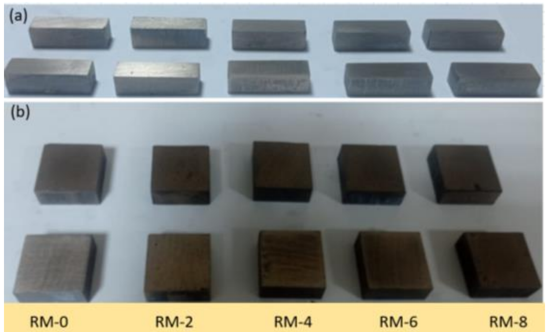
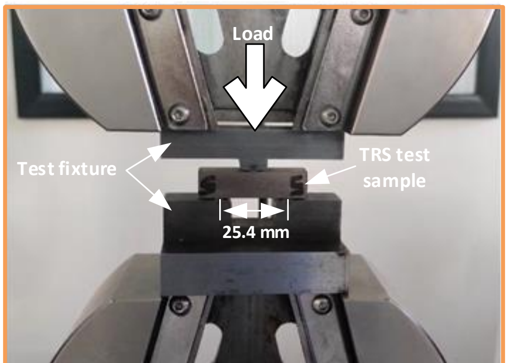


Fig. 1. Produced by hot pressing process: (a) Three-point bending test samples, (b) Friction-wear test samples



$$TRS = \frac{3 \times P \times L}{2 \times T^2 \times W} \qquad \text{(Equation 1)}$$

P: The requisite force for the rupture of material
L: The length between the centres of the support points.
W: Width of the specimen (mm)
T: Thickness of the specimen (mm)

Fig. 2. TRS test set up

The friction-wear tests of the pads were conducted using a brake pad tester that had been specifically designed for this purpose. The tester is basically constituted by a disk/caliper system, a hydraulic unit, a load cell, a computer, and an infrared thermometer, which is used to measure the temperature of the disk surface (Figure 3). Further detailed information regarding the test device can found in other studies by the author [16, 47]. The performance tests that determine the average friction coefficient, friction stability, and specific wear rate values of the pads, were performed at a sliding velocity of 6 m/s and a normal load of 1.05 MPa for a total of 680 seconds under dry sliding conditions. The resulting values are presented in Table 1.

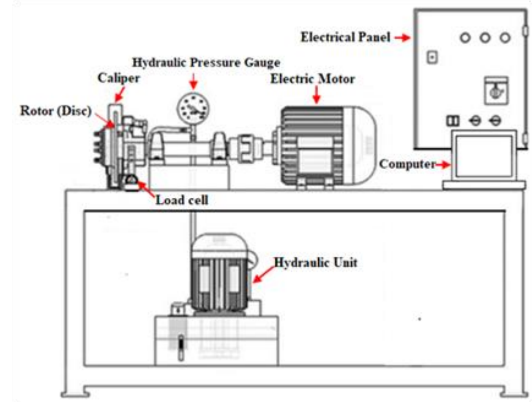


Fig. 3. Friction wear tester [48]

The specific wear rate was calculated in accordance with the methodology set forth in Eq. (2), as defined in TSE 555 standards. The terms set forth in Eq. (2) are elucidated in detail in the author's other studies [16].

$$V = \frac{m_1 - m_2}{2 \times \pi \times R_d \times n \times f_m \times \rho} \tag{2}$$

Frictional stability (FS) was calculated using Eq. (3).

$$FS = \frac{\mu_{ave}}{\mu_{max}} \times 100 \tag{3}$$

In this study, the selection criteria values obtained from the brake pad samples produced are shown in Table 1. These values are presented in detail in another study conducted by the authors [47].

Table 1. Properties of the red mud reinforced brake pads [47]

Samples	RM-0	RM-2	RM-4	RM-6	RM-8
Average COF (μ_{ave})	0.435	0.407	0.384	0.379	0.377
Density (g/cm^3)	5.91	5.80	5.70	5.61	5.53
Friction stability (%)	76.47	78.21	80.07	78.86	80.25
Hardness (HRM)	102.50	105.00	107.00	108.00	110.00
Specific wear rate x10^{-6} (cm^3/Nm)	6.79	8.47	5.19	3.87	3.58
TRS (MPa)	102.14	125.44	128.15	110.00	86.00

2.3. AHP method

AHP is a pioneering and flexible strategy that provides a comparative evaluation and weighting of criteria for decision-making. This hierarchical structuring clearly explains how each factor influences a system. It assists a decision maker in assessing the best choice according to the objective and better understanding of the issue [37]. AHP consolidates all evaluations of various decision makers into the final decision without changing their utility functions by using the pair-wise comparison matrix. It also allows decision-makers to verify their conclusions through consistency checks [39]. To calculate attribute weights, a pair-wise comparison matrix was created using the nine-point Saaty scale is given in Table 2 [49]. The pair-wise comparison matrix is transformed into the normalized matrix by dividing each column element by its column sum. Then, the weights of each criterion become the sum of the weights of each element in each line. The eigenvalue vector is obtained by using the ratio of the weighted sum to the criterion weights of each criterion. By taking the average of the sum of the eigenvalues was calculated for each criterion, so the principal eigenvalue vector (λ_{max}) is obtained. The consistency index (*CI*) is calculated using Eq. (4). Where *n* is criteria number. The consistency ratio (*CR*) is the relationship between the consistency index and the random index number (*RI*) for a matrix of the same size, and it is determined using Eq. (5). The *RI* is selected from the standard value in Table 3. If the value of consistency ratio is less than 0.1, the pair-wise comparison matrix is acceptable [39].

Table 2. Saaty scale [31]

Degree preferences	Priority based on verbal judgment
1	Same significance
3	Minor importance of one over the other
5	Critical or highly significant
7	Proven significance
9	Totally significant
2, 4, 6, 8	Scores between the two judgments

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (4)$$

$$CR = \frac{CI}{RI} \quad (5)$$

Table 3. Values of RI numbers [37]

n	RI	n	RI
3	0.58	9	1.45
4	0.9	10	1.51
5	1.12	11	1.52
6	1.24	12	1.54
7	1.32	13	1.56
8	1.41	14	1.58
9	1.45	15	1.59

2.4. MULTIMOORA method

In the MULTIMOORA method, decision matrix is created by determining the alternatives and criteria. The weighted normalized matrix is obtained by applying the weight coefficients determined by the AHP method. The values are used for the ranking of alternatives using the ratio and reference approaches using the relevant equations. These two methods are known as the MOORA method. With the inclusion of the full multiplicative form, the MULTIMOORA method was created [50]. With the combination of these methods, the best alternative is determined robustly and ranked by three different methods instead of selection by a single method. Schematic diagram of the evaluation methodology for MULTIMOORA is shown in Figure 4. The scheme of MULTIMOORA, which illustrates the application steps of the ratio system, reference point, and multiplicative form that constitute the MULTIMOORA method, is shown in Figure 5.

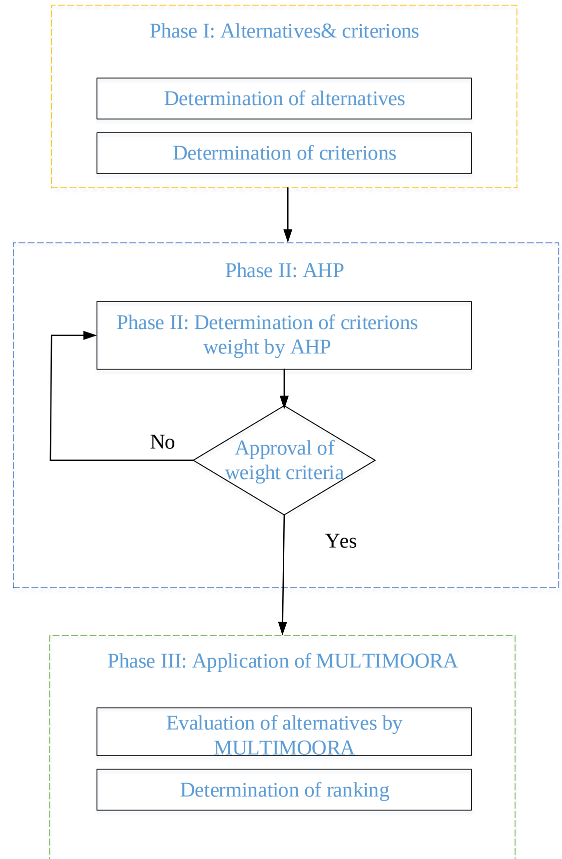


Fig. 4. Schematic representation of the MULTIMOORA method application [45]

2.4.1. The ratio system part of MULTIMOORA method

The ratio system is the first step in the MULTIMOORA method. Before the other steps of the method, the initial matrix is constructed, and this matrix is normalized [50]. To apply MULTIMOORA method, firstly decision matrix *X* is created with X_{ij} that indicates the value of i[th] (i = 1, 2, ..., m) alternative based on j[th] (j = 1, 2, ..., n) criterion [51]. Normalization operation is performed on decision matrix using Eq. (7).

$$X = [X_{ij}]_{mxn} = \begin{bmatrix} X_{11} \ldots. & X_{1i} & & X_{1n} \\ X_{21} \ldots. & X_{2i} & & X_{2n} \\ . & . & .. & . \\ X_{m1} & X_{m2} & & X_{mn} \end{bmatrix} \quad (6)$$

$$X_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}} \quad (7)$$

Where X_{ij}^* is the normalized performance of i[th] alternative on j[th] criterion, j =1,2,...,g indicates the criteria to be maximized and j =g+1, g+2, ..., n shows the criteria to be minimized. These indicators are added if the beneficial value of the indicator is maximum or subtracted if the non-beneficial value is minimum [33]. Thus, the summation index of each alternative is obtained in this way:

$$Y_i^* = \sum_{i=1}^{i=g} X_{ij}^* - \sum_{i=g+1}^{i=n} X_{ij}^* \quad (8)$$

The weighted normalized decision matrix is formed using Eq. (8). Where w_j is the weight of the jth criterion. Values of final preference (Y_j^*) calculated by using Eq. (9), and every ratio is given the rank where the higher index represents the higher rank [32].

$$Y_i^* = \sum_{i=1}^{i=g} w_j X_{ij}^* - \sum_{i=g+1}^{i=n} w_j X_{ij}^* \quad (9)$$

2.4.2. The reference point part of MULTIMOORA method

The Reference point is the second step of the MULTIMOORA method. Reference point approach is based on Tchebycheff Min–Max Metric [52]. Reference points r_j are determined for each criterion based on Eq. (10). While determining reference points, the highest values are chosen for maximization criteria, minimum values are chosen for the minimization criteria [32]. Subsequently, the distance d_{ij} between the alternatives and the reference points are calculated with the utilization of Eq. (11).

$$r_j = \begin{cases} \max_i X_{ij}^*, & for\ criteria\ to\ be\ maximized \\ \min_i X_{ij}^*, & for\ criteria\ to\ be\ minimized \end{cases}$$

(10)

$$d_{ij} = w_j \left| r_j - X_{ij}^* \right| \quad (11)$$

The optimal alternatives are calculated as per the following Equation. Alternatives are sorted and the best alternative with the least total deviation from the reference point is selected [32].

$$P_i = \min_i \{\max_j (d_{ij})\} \quad (12)$$

2.4.3. The full multiplicative form part of MULTIMOORA method

The Full multiplicative form is the third step of MULTIMOORA. It consists of a multiplicative utility function that is maximized and minimized. In this approach, the initial decision matrix is taken into consideration [31]. In contrast to the ratio method and the reference point approach, the initial matrix is not subjected to any normalization during the application of the method [50].

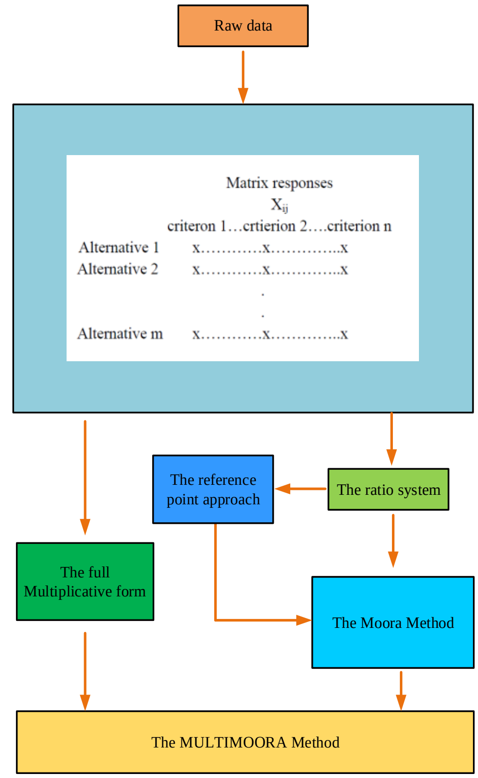


Fig. 5. Scheme of the MULTIMOORA method [31]

The criteria to be maximized (beneficial attributes):

$$A_J = \prod_{j=1}^{g} X_{ij}^{w_j} \quad (13)$$

The criteria to be minimized (non-beneficial attributes):

$$B_J = \prod_{j=g+1}^{n} X_{ij}^{w_j} \quad (14)$$

The overall utility for jth alternative (U_J) is calculated by using Eq. (15). It is ranked as maximum value is the best among the alternatives. Where A_J is product of maximum column, B_J is product of minimum column.

$$U_J = \frac{A_j}{B_j} \quad (15)$$

2.5. The MOOSRA method

The process of the MOOSRA method and the MULTIMOORA method are identical. In the first stage of the MOOSRA method, the decision matrix is constructed with alternatives and criteria. Subsequently, the overall performance value of the alternative (Y_i^*) is calculated as the ratio of the summation of normalized criteria values desired to be maximum and the sum of the values of the criteria considered minimum [53]. The formula is expressed as:

$$Y_i^* = \frac{\sum_{j=1}^{g} X_{ij}^*}{\sum_{j=g+1}^{n} X_{ij}^*} \quad (16)$$

Considering the criteria weights in Eq. (16), this turn into Eq. (17) as:

$$Y_i^* = \frac{\sum_{j=1}^{g} w_j X_{ij}^*}{\sum_{j=g+1}^{n} w_j X_{ij}^*} \quad (17)$$

3. Results and Discussion

The criteria are the average coefficient of friction, specific wear rate, friction stability, hardness, density, and TRS. They were named C1, C2, C3, C4, C5, and C6, respectively. In order to rank the alternative brake pad samples based on performance criteria, a three-stage hierarchy structure was devised, comprising the following stages: goal, criteria, and alternatives, which are illustrated in Figure 6. The preference status according to the importance of the criteria and the descriptions of these preferences [45, 49, 54], are listed in Table 4. The criteria were evaluated pair-wise to ascertain their relative importance according to the Saaty scale detailed in Table 2. The pair-wise comparison matrix of the criteria is listed in Table 5 for brake pad materials. The consistency of these judgments was checked using the Eqs. (1) and (2). It was calculated that less than 0.1. Therefore, the consistency was satisfied. After this step, the weights of the decision criteria were determined based on their importance. The weights of the decision criteria such as average friction coefficient, specific wear rate, friction stability, hardness, density, and TRS were calculated to be 0.423, 0.205, 0.205, 0.088, 0.051, and 0.028, respectively and these values are shown in Table 6. Bhaskar et al [37] determined the importance of decision criteria in their study and stated that the two most important criteria were the friction coefficient and the specific wear rate, respectively. These results are in agreement with our study.

In order to rank with the MULTIMOORA method, firstly the decision matrix was created with the determined alternatives and criteria. Beneficial features were defined as maximum while non-beneficial criteria were defined as minimum. Beneficial criteria are selected as average friction coefficient, friction stability, hardness, and TRS. On the other hand, specific wear rate and density are determined as non-beneficial criteria. Then the decision matrix was normalized. After these operations, weighted normalized matrices were obtained by applying the coefficients previously determined with the AHP method. The decision matrix, normalized decision matrix, and weighted normalized decision matrix are given in Tables 7, 8, and 9, respectively.

Final preference calculations were made for each alternative using Eq. (9) for the ratio system, which is included in the MULTIMOORA method. According to this method, the order was RM-8, RM-6, RM-4, RM-0, and RM-2, respectively. Eqs. (11) and (12) were used to determine the deviation and ranking in the reference point approach. The reference points and matrix of deviations from reference points for beneficial and non-beneficial criteria are given in Tables 10 and 11, respectively. For each of the alternatives, the maximum deviation between them was calculated and the minimum was prioritized. According to MULTIMOORA's reference point approach, RM-4 is the best alternative. For the full multiplicative form (FMF) approach, the utility rating score of each option was calculated utilizing the maximum and minimum values in the numerator and denominator by Eq. (15). According to the full multiplicative form, the RM-8 was the best brake pad among the alternatives. The final ranking was determined, which is shown in Table 12. The other method is the MOOSRA, and the initial stages of it is identical to the MULTIMOORA method. Firstly, normalized decision matrices were weighted [31]. After this stage, the performance scores of the maximum and minimum criteria were computed separately. Maximum criteria summation was divided into minimum criteria summation for each alternative using Eq. (17). Finally, the overall performance score of the alternatives were obtained, as given in Table 13. The order of alternatives for the MULTIMOORA and MOOSRA methods was the same.

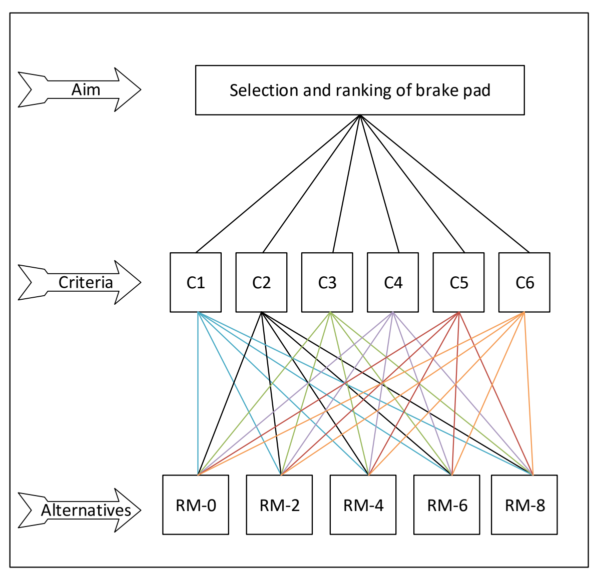


Fig. 6. Hierarchy structure of selection and ranking of brake pad materials [45]

Table 4. Defining importance of the criteria for the brake pads

Criterions	Feature of preference	Brief Despriction
Average friction coefficient	Maximum	It represents the ratio of friction force to normal force, and the appropriate range for vehicles is between 0.3 and 0.6.
Spesific wear rate	Minimum	The specific wear rate describes the loss of mass per unit sliding distance. It is desirable to keep it low for a long service life.
Friction stability	Maximum	Friction stability is the ratio of the average friction coefficient to the maximum friction coefficient, this ratio is desired to be close to unity.
Hardness	Maximum	Hardness is a material property that describes the resistance of a material to plastic deformation through scratching. A higher level of hardness is advantageous in terms of wear resistance. However, too high a hardness is undesirable, as high hardness can cause wear on the counterface disk during friction.
Density	Minimum	It indicates the mass per unit volume. Low densities are acceptable up to the point where they do not degrade the mechanical properties of the pads. The low density is preferred because it means low material weight.
TRS	Maximum	It is defined as the stress at which the material ruptures in a three-point bend test. High TRS values are preferred because high mechanical properties improve wear resistance.

Table 5. Criteria pair-wise comparison matrix for the brake pad materials

Criterions	C1	C2	C3	C4	C5	C6
	Max.	Min.	Max.	Max.	Min.	Max.
C1	1	3	3	5	7	9
C2	1/3	1	1	3	5	8
C3	1/3	1	1	3	5	8
C4	1/5	1/3	1/3	1	3	3
C5	1/7	1/5	1/5	1/3	1	3
C6	1/9	1/8	1/8	1/3	1/3	1

Table 6. Weight coefficients of the specified criteria for the brake pad materials

Criteria	C1	C2	C3	C4	C5	C6
Weights	0.423	0.205	0.205	0.088	0.051	0.028

Table 7. Decision matrix for the brake pad materials

Criterions	C1	C2	C3	C4	C5	C6
Alternatives	Max.	Min.	Max.	Max.	Min.	Max.
RM-0	0.435	6.79	76.47	102.50	5.91	102.14
RM-2	0.407	8.47	78.21	105.00	5.80	125.44
RM-4	0.384	5.19	80.07	107.00	5.70	128.15
RM-6	0.379	3.87	78.86	108.00	5.61	110.00
RM-8	0.377	3.58	80.25	110.00	5.53	86.00

Table 8. Normalized decision matrix for the brake pad materials

Criterions	C1	C2	C3	C4	C5	C6
Alternatives	Max.	Min.	Max.	Max.	Min.	Max.
RM-0	0.490	0.517	0.434	0.430	0.463	0.410
RM-2	0.458	0.645	0.444	0.441	0.454	0.503
RM-4	0.433	0.395	0.455	0.449	0.446	0.514
RM-6	0.427	0.295	0.448	0.453	0.439	0.441
RM-8	0.425	0.273	0.456	0.462	0.433	0.345

Table 9. Weighted normalized decision matrix for the brake pad materials

Criterions	C1	C2	C3	C4	C5	C6
Alternatives	Max.	Min.	Max.	Max.	Min.	Max.
RM-0	0.207	0.106	0.089	0.038	0.024	0.011
RM-2	0.194	0.132	0.091	0.039	0.023	0.014
RM-4	0.183	0.081	0.093	0.040	0.023	0.014
RM-6	0.181	0.060	0.092	0.040	0.022	0.012
RM-8	0.180	0.056	0.093	0.041	0.022	0.010

Table 10. Determined reference points

Criteria	C1	C2	C3	C4	C5	C6
Reference value	0.207	0.056	0.093	0.041	0.022	0.014

Table 11. Deviations for reference point

Criterions	C1	C2	C3	C4	C5	C6
Alternatives	Max.	Min.	Max.	Max.	Min.	Max.
RM-0	0.000	0.050	0.004	0.003	0.002	0.003
RM-2	0.013	0.076	0.002	0.002	0.001	0.000
RM-4	0.024	0.025	0.000	0.001	0.001	0.000
RM-6	0.027	0.010	0.002	0.001	0.000	0.002
RM-8	0.028	0.000	0.000	0.000	0.000	0.005

Table 12. The ranking of the brake pad alternatives by the MULTIMOORA method

	Ratio System	Reference point	Full multiplicative form	MULTIMOORA
	Ranking	Ranking	Ranking	Ranking
RM-0	4	4	4	4
RM-2	5	5	5	5
RM-4	3	1	3	3
RM-6	2	2	2	2
RM-8	1	3	1	1

Table 13. The ranking of the brake pad alternatives by the MOOSRA method

Alternatives	Ranking
RM-0	4
RM-2	5
RM-4	3
RM-6	2
RM-8	1

4. Conclusion

In this study, novel bronze matrix brake pads that can be used as brake pad material in high-performance vehicles were developed using fly ash and red mud as reinforcement elements. The utilization of these materials will lead to notable advancements in automotive technology, primarily due to their cost-effectiveness, minimal carbon footprint, high frictional stability, and low wear rates. The subsequent phase of the study was designed to ascertain the efficacy of the MULTIMOORA and MOOSRA methodologies, as part of the MCDM approach, in identifying the optimal brake pad formulation. To ascertain the most suitable composition, five distinct brake pad formulations were evaluated, each differing in their proportions of red mud reinforcement. The formulations were assessed according to a set of predetermined criteria such as the average coefficient of friction, hardness, friction stability, specific wear rate, and density. Among these criteria, the average coefficient of friction, hardness, and friction stability was defined as maximum, while specific wear rate and density were defined as the criteria to be minimized in the selection process of the optimum brake pad material. The ratio system, reference system, and full multiplicative form methods of the MULTIMOORA model were used in the selection of the optimum brake pad material. According to the ratio and full multiplicative methods, the ranking of the alternatives was RM-8, RM-6, RM-4, RM-0, RM-2; however, the ranking was RM-4, RM-6, RM-8, RM-0, RM-2 in the reference method. When these three methods were evaluated together in the MULTIMOORA model, RM-8 brake pad material was found to be the best among all the alternatives. When the red mud brake pad material alternatives were evaluated with the MOOSRA method, which is another decision-making method, it was seen that the ranking was similar to the MULTIMOORA method.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

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Adem Avcu: Conceptualization, Visualization, Investigation, Methodology, Data curation, Software, Writing - Review & Editing.
Hüsamettin Kuş: Conceptualization, Visualization, Investigation, Methodology, Data curation, Software, Writing - Review & Editing.
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