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Technical paper

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SELECTION OF MATERIALS FOR FRICTION COMPONENTS OF THE BRAKE MECHANISM

ABSTRACT: The aim of this paper is the multi-criteria selection of a friction material for brake mechanism components using the Digital Logic Method. Fourteen alternative friction materials were analysed on the basis of ten mechanical, physical, tribological, thermal, and environmental criteria. In the first stage, the defined limit values of the criteria were applied, after which alternatives M6, M8, and M12 were identified as acceptable. The relative importance of the criteria was determined by pairwise comparison using the Digital Logic Method, followed by the final evaluation of the remaining alternatives. The obtained evaluation index values were 0.001 for M6, 0.026 for M12, and 0.074 for M8, where a lower value represents a more favourable alternative. Based on the results, M6 was identified as the most favourable material within the considered set of alternatives and adopted criteria.

KEYWORDS: friction materials, braking systems, material selection, coefficient of friction

IZBOR MATERIJALA ZA FRIKCIONE KOMPONENTE KOČIONOG MEHANIZMA

REZIME: Cilj rada je višekriterijumski izbor frikcionog materijala za komponente kočionog mehanizma primenom digitalno-logičke metode. Analizirano je 14 alternativnih frikcionih materijala na osnovu deset mehaničkih, fizičkih, triboloških, termičkih i ekoloških kriterijuma. U prvoj fazi primenjene su definisane granične vrednosti kriterijuma, nakon čega su kao prihvatljive izdvojene alternative M6, M8 i M12. Relativni značaj kriterijuma određen je njihovim parnim poređenjem primenom digitalno-logičke metode, a zatim je izvršeno konačno vrednovanje preostalih alternativa. Dobijene vrednosti pokazatelja vrednovanja iznosile su 0,001 za M6, 0,026 za M12 i 0,074 za M8, pri

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čemu niža vrednost predstavlja povoljniju alternativu. Na osnovu rezultata, M6 je izdvojen kao najpovoljniji materijal u okviru razmatranog skupa alternativa i usvojenih kriterijuma.

KLJUČNE REČI: frikcioni materijali, kočioni sistemi, izbor materijala, koeficijent trenja

INTRODUCTION

Friction materials are essential for the operation, safety, and environmental acceptability of modern automotive braking systems. They are complex, multiphase composites that usually consist of four functional groups: binders, reinforcements, fillers, and friction modifiers (Gehlen, G.S. et al. 2026). The materials of the elements forming friction pairs have an exceptionally strong influence on brake quality and, consequently, on the ability of the vehicle braking system to perform its tasks (Todorović, J. 1988).

Brakes and clutches on vehicles differ completely in terms of appearance, purpose, and operating principle, but both systems rely to a large extent on friction. Brakes use friction to reduce speed or bring the vehicle to a complete stop, whereas in clutches friction is used to control power transmission. In these systems, friction is generated by components made of friction materials (Tokai Carbon n.d.).

Friction materials used in brakes play a vital role in braking performance with respect to vehicle speed control and thus ensure the safety of the vehicle and road users. A good brake friction material should have a high and stable coefficient of friction over a wide range of operating temperatures, contact pressures, sliding speeds, and humidity levels. It should also have high wear resistance in order to provide a long service life of the braking element. However, the friction material should have a hardness that does not cause excessive wear of the drum or disc. It should possess high thermal and oxidation resistance because a large amount of kinetic energy is converted into heat during braking. In addition to all the required characteristics, it should also be economical (Talegaonkar, R. P., & Gopinath, K. 2005). Figure 1 summarizes the requirements for friction materials (Todorović, J. 1988).

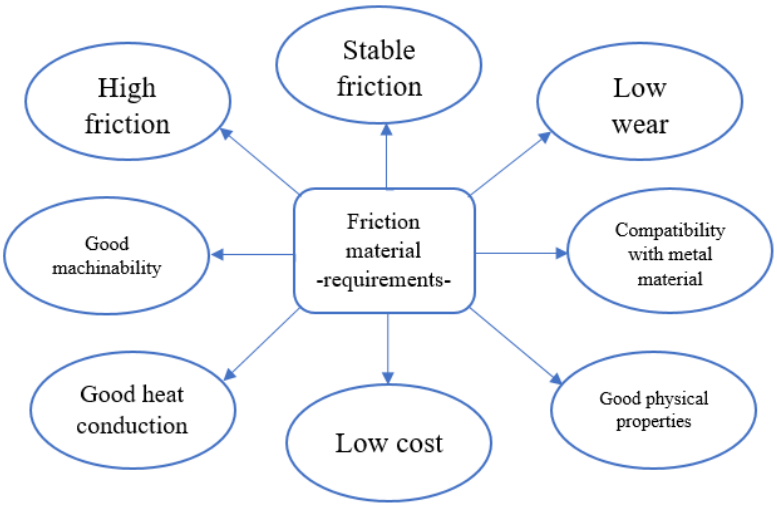


Figure 1 Requirements for friction materials (Todorović, J. 1988)

The above requirements can be satisfied by using several types of materials with different compositions and manufacturing processes. In percentage terms, the contents of the four basic groups in a friction material are as follows:

- binders: 5-25%;
- reinforcements: 20-50%;
- fillers: 0.5-1%;
- friction modifiers: 30-60% (Petar, P. 2025).

Binders play an important role in determining the performance of friction materials. Although they are not the main component by volume or cost, binders represent the “heart” of friction materials. They are used to bind the other components in friction materials and to maintain the structural integrity of the composite under mechanical and thermal stresses (Peng, C. et al. 2025).

The primary task of reinforcements is to provide the friction material with the required mechanical properties, namely strength and toughness. In addition, reinforcements provide the necessary integrity of the friction material

during the manufacturing stage by connecting all ingredients into a mixture that enables subsequent chemical and physical shaping (Todorović, J. 1988).

Fillers are intended to “fill” the friction material mixture, i.e., to provide the required volume in accordance with the design documentation requirements. Since fillers do not significantly contribute to the properties of friction materials, inexpensive minerals, and sometimes metals, are used for this purpose. It is important that the hardness of the filler is not too high, because higher hardness may affect material properties and, in particular, may cause an unfavourable effect of the friction material on the mating metallic element (Todorović, J. 1988).

Friction modifiers are intended to provide the required relationships between the important operating characteristics of friction materials, particularly with respect to friction and wear. Materials of very different origin can be used, including minerals, metals, and organic resins, in various forms and proportions in the mixture (Todorović, J. 1988).

The most widely used friction materials include:

- asbestos friction materials;
- organic friction materials (NAO – Non-Asbestos Organic);
- sintered metallic friction materials;
- semi-metallic friction materials;
- low-metallic NAO friction materials;
- ceramic friction materials;
- carbon-carbon composite (C/C) friction materials;
- carbon-ceramic (C/C-SiC) composite friction materials.

The aim of this study is to perform a multi-criteria selection of the optimal friction material using the digital-logic method for the production of friction components of a braking mechanism. The selection criteria will be based on the mechanical, physical, tribological, thermal and environmental properties of the alternative materials, which have been adopted from scientific studies. The experimental procedure will be presented in greater detail in Section 3.

BRAKING SYSTEMS

The braking system is designed for controlled changes in vehicle speed, stopping the vehicle, and keeping it stationary after stopping. Brakes are one of the most important safety features of any vehicle. (Atlantic Tire Service n.d.) The process of slowing down or stopping a vehicle is generally achieved by friction. (Medium. n.d.) Unlike most machine elements, in which friction is a highly undesirable phenomenon, in motor vehicle brakes friction is one of the fundamental principles of operation and an essential prerequisite for performing the function of the braking system. Friction enables the transformation of kinetic energy into thermal energy, thereby slowing down and stopping the vehicle (Todorović, J. 1988).

The braking system consists of three mechanisms:

- control mechanism – pressure applied by the driver to the brake pedal;
- transmission mechanism – according to the method of transmitting force from the control to the actuator, this mechanism may be mechanical, hydrostatic, pneumatic, or hydropneumatic (combined);
- actuating mechanism – vehicle braking.

The braking system comprises four subsystems (Figure 2).

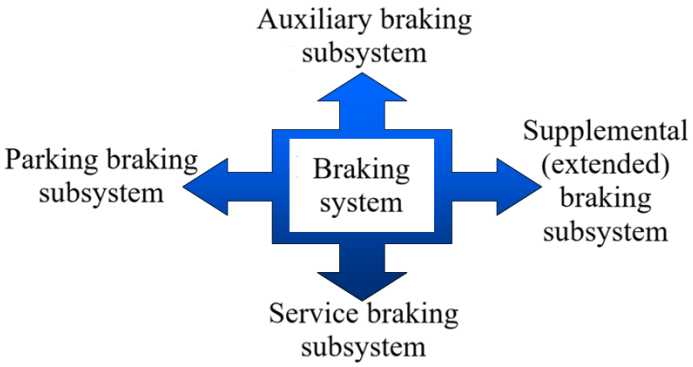


Figure 2 Subsystems of the braking system (Aleksendrić, D. n.d.)

Disc brakes

Disc brakes are standard on most cars today, although, for certain reasons, drum brakes are still used even on more expensive and powerful vehicles. The operating principle of disc brakes is most easily understood by observing a bicycle brake. On a bicycle, the calipers press rubber pads against the rim and thus slow down wheel rotation.

Disc brakes on a car operate in the same way, except that the brake calipers press against a disc located on the wheel hub (Polovni automobili n.d.).

The basic components of a disc brake (Figure 3) are:

- brake pads,
- caliper with piston,
- disc (rotor), mounted on the vehicle wheel hub (howstuffworks n.d.).

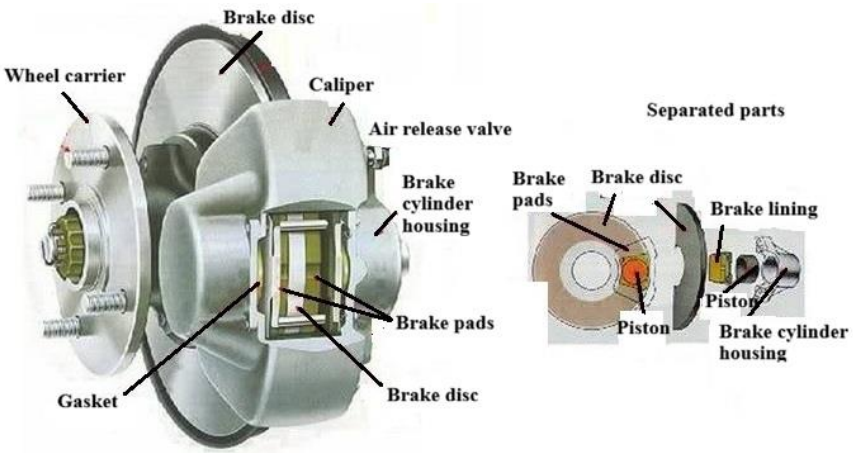


Figure 3 Disc brake (Popravka automobila n.d.)

Drum brakes

Drum brakes are a type of brake commonly used on two-wheeled and four-wheeled vehicles. Their operating principle is almost the same in both types of vehicles. Drum brakes operate on the same principle as disc brakes: the linings press against a rotating surface. In this system, that surface is called the drum (Wuling motors n.d.).

Many cars have drum brakes on the rear wheels and disc brakes on the front wheels. Drum brakes comprise more components than disc brakes and are more difficult to maintain, but they are less expensive to manufacture (howstuffworks n.d.).

The basic components of a drum brake are:

- drum,
- brake linings (brake shoes),
- hydraulic wheel cylinder with piston,
- spring system. (Kwikfit. (n.d.), Akebono. (n.d.))



Figure 4 Drum brake (Akebono. (n.d.))

MATERIAL SELECTION METHODS

In addition to designing the geometry of the components that make up a product, product development also involves selecting the appropriate materials from which those components will be made. Material selection represents an almost constant challenge for designers, regardless of their level of experience in this field (Petković, D. 2016).

The selection of material for a particular product largely determines its functionality. Therefore, the material selection process is very complex and requires expert knowledge. In addition, material cost, product shape, environmental impact, market availability, and other factors further complicate the material selection problem, making it a time-consuming task. The material selection problem often also involves conflicting criteria, such as hardness–toughness or aesthetic appearance–cost, which requires the decision-maker to clearly define the objectives to be achieved.

An inadequate selection of material for a product may lead to premature product failure, resulting in reduced profit, productivity, and company reputation (Petković, D. 2016).

Initial material screening

At the outset, designers consider various initial ideas related to material selection. Ideas that are immediately identified as unsuitable are rejected, while those that appear practical are considered further. Quantitative methods can be used for initial material screening in order to narrow the choices to a manageable number for further processing and evaluation. Initial material screening can be achieved by first classifying performance requirements as:

- rigid requirements – requirements that must be satisfied;
- soft requirements – relative requirements (Farag, M. 2016).

Rigid requirements are those that a material must satisfy in order to be considered at all. For example, metallic materials are eliminated when selecting a material for an electrical insulator. If the insulator also needs to be flexible, the field is narrowed further because all ceramic materials are eliminated.

Soft requirements are those that are subject to trade-offs and deviations. Examples of soft requirements include mechanical properties, specific weight, and cost. Soft requirements can be compared in terms of their relative importance, which depends on the application being studied (Farag, M. 2016).

Comparison and ranking of materials

Selecting an appropriate material is a difficult process that requires handling a large amount of information about material properties. After narrowing the field of possible materials by one or more quantitative methods for initial screening, quantitative methods can be used to further reduce the set of possible materials and match manufacturing processes to several promising candidates that provide good combinations of soft requirements. It is important to emphasize that, at this stage of selection, no quantitative method can replace engineering judgment and experience. These methods are intended only to help engineers make reasonable choices and trade-offs with confidence for a given situation and to ensure that no realistic solution is overlooked (Farag, M. 2016).

Material selection methods can be divided into two groups:

- multi-criteria decision-making (MCDM) methods and
- optimization methods. (Jahan A. et al. 2009)

Multi-Criteria Decision-Making (MCDM) methods comprise a set of techniques and approaches used to support decision-making in situations where multiple criteria or objectives must be taken into account. In many practical situations, decisions cannot be made on the basis of a single criterion because they often involve trade-offs and conflicting objectives (Frank, E. 2024).

MCDM methods have attracted considerable attention and gained popularity in various fields and industries. They are particularly applicable in situations where decisions have significant consequences, where resources are limited, and where stakeholders have different and often conflicting objectives. By incorporating multiple criteria, MCDM methods help decision-makers consider a broader range of factors and make more informed and balanced decisions (Frank, E. 2024).

Multi-criteria decision-making is one of the most accurate approaches to decision-making and may be regarded as a major advancement in this field. It considers various qualitative and quantitative criteria that must be established in order to identify the best solution. For example, cost or price and the quality of products and processes are

among the most common criteria in many decision-making problems. In addition, expert groups assign different weights to the criteria in such problems, based on the importance of each criterion in a particular case (Taherdoost H. et al. 2023).

MCDM methods are divided into three main groups:

- Multiple Attribute Decision-Making (MADM) approaches,
- fuzzy multi-criteria decision-making methods, and
- Multiple Objective Decision-Making (MODM) approaches (Jahan A. et al. 2009).

Multiple Attribute Decision-Making approaches

In contemporary research, material performance is evaluated on the basis of multiple criteria. Selecting the optimal material for an engineering design or manufacturing process from two or more alternative materials on the basis of two or more criteria is a Multiple Attribute Decision-Making (MADM) problem. Decision variables may be quantitative or qualitative. Some criteria can be expressed numerically, such as density or thermal conductivity; some can be expressed as Boolean values (for example, recyclability). In addition, some criteria can only be expressed as a rank (for example, corrosion resistance – poor, good), while others can only be represented by text and images (Jahan A. et al. 2009).

Some of the best-known MADM methods are:

- DLM – Digital Logic Method;
- SAW – Simple Additive Weighting Method;
- AHP – Analytic Hierarchy Process;
- ANP – Analytic Network Process;
- TOPSIS – Technique for Order Preference by Similarity to Ideal Solution;
- ELECTRE – Elimination and Choice Expressing the Reality;
- PROMETHEE – Preference Ranking Organization Method for Enrichment Evaluations;
- VIKOR – Multi-Criteria Optimization and Compromise Solution. (Farag, M. 2016; Jahan, A. et al. 2009; Štirbanović, Z. et al. 2023).

DLM – Digital Logic Method

Before explaining the Digital Logic Method, it is necessary to briefly describe the Weighted Property Method (WPM). The Weighted Property Method is very useful when there are many important requirements (properties) to compare and evaluate. Each material requirement or property is assigned a certain weight depending on its importance to product performance. Numerical values of property β are multiplied by the weighting factor or index α. The sum of the products of the numerical property values and weighting factors represents the performance index γ. The combination of the base material and the corresponding manufacturing process with the highest performance index represents the optimal solution (Farag, M. 2016; Talur, S. 2015).

$$\gamma = \sum(\beta * \alpha) \tag{1}$$

γ – performance index
β – numerical value of the property
α – weighting factor

The weighting factor α represents the relative priorities assigned to material properties. The value of each weighting factor should be assigned according to its importance in the product. (Talur, S. 2015.)

When numerous material properties are specified and the relative importance of a property is not clear, determining the weighting factor may be largely intuitive, which reduces the reliability of the selection. Digital logic can be used as a systematic tool for determining weighting factors. To determine the relative importance of each property or objective, a table is constructed. The properties or objectives are listed in the left-hand column, while comparisons are made in the columns to the right, as shown in Table 1. The table presents the simultaneous evaluation of only two properties at a time (Farag, M. 2016).

When comparing two properties, the more important property is assigned the numerical value one (1), and the less important property is assigned zero (0). The total number of possible decisions is determined by the expression:

$$N = n(n-1)/2 \tag{2}$$

n – number of properties or objectives under consideration

The weighting factor is obtained by dividing the number of positive decisions for each property (m) by the total number of possible decisions (N). In this case (Table 1), Σα = 1.

Table 1 Determination of the relative importance of properties (objectives) using the Digital Logic Method (Farag, M. 2016)

Property (objective)	**Number of possible decisions $N = n(n-1)/2$**										**Positive decisions**	**Weighting factor α**
	1	2	3	4	5	6	7	8	9	10		
1	1	1	0	1							3	0,3
2	0				1	0	1				2	0,2
3		0			0			1	0		1	0,1
4			1			1		0		0	2	0,2
5				0			0		1	1	2	0,2
Total number of positive decisions											10	Σα=1

To increase the accuracy of decisions based on the Digital Logic Method, the evaluation can be modified by assigning grading scores ranging from 1 (no difference in importance) to 3 (large difference in importance). In this case, the total grading scores for each selection criterion are obtained by summing the individual grading scores. The weighting factors are then determined by dividing these totals by their overall sum (Farag, M. 2016).

EXPERIMENTAL INVESTIGATION

Friction materials are marketed under various commercial names, with only some characteristics stated, which can serve as a basic orientation for selection or preliminary decision-making by vehicle manufacturers. Therefore, the final selection of a friction material for a particular brake, vehicle, and expected braking-system operating regimes is based on subsequent detailed analyses and, above all, on experiments covering all relevant requirements.

It should be taken into account that, for each friction material, its composition and manufacturing technology are proprietary information of the manufacturer, so assessments or selection decisions cannot be based on composition alone. However, in many cases, confidentiality regarding friction-material composition is not of key importance because materials with the same basic composition but produced using different technologies can exhibit quite different characteristics, especially under certain operating conditions (Todorović, J. 1988).

This section presents an experiment for selecting materials for friction components of a brake mechanism using the Digital Logic Method.

The friction materials used in the experiment were taken from scientific papers in which researchers experimentally investigated mechanical, physical, and tribological properties using a large number of formulations created by adding different constituents and varying their amounts. The aim was to meet the required braking performance while complying with environmental regulations, i.e., replacing materials that adversely affect human health and the environment. Fourteen materials were adopted for the experiment, and their mechanical, physical, and tribological characteristics are presented in Table 2.

All the presented characteristics of the materials listed in Table 1 represent criteria that will be used for selection.

Therefore, the criteria are as follows:

K1 – hardness
K2 – thermal conductivity
K3 – density
K4 – coefficient of friction
K5 – coefficient of friction stability
K6 – wear rate
K7 – environmental acceptability
K8 – stability under different environmental conditions
K9 – thermal shock resistance
K10 – flame resistance

Table 3 presents all alternatives with the defined criteria.

The Digital Logic Method (Limit Value Method) will be applied to evaluate and select materials on the basis of the defined criteria and their limit values. Starting from the requirements imposed on friction materials for braking systems, a limit or target value was defined for each criterion. Depending on the nature of the criterion, the desirable property may be expressed by a lower limit value, an upper limit value, or a target value toward which the selection should be directed. The alternatives are evaluated on the basis of the limits defined in this way.

Ten previously defined criteria will be considered in the material selection process. Table 4 presents the classification of the criteria according to the type of limit value.

Table 2 Selected materials and their characteristics

Materials / Characteristics/ criteria	M1 (Patil, R.S. et al. 2020)	M2 (Ige, O. E. et al. 2019)	M3 (Ige, O. E. et al. 2019)	M4 (Nwankwo, E. I. et al. 2025)	M5 (Jadhav Sachin, S. P. et al. 2023)	M6 (Kumar, M. et. al. 2010)	M7 (Kumar, M. et. al. 2010)]	M8 (Kumar, M. et. al. 2010)	M9 (Kumar, M. et. al. 2010)	M10 (Adeyemi I. O. et. al. 2016)	M11 (Adekunle A. et. al. 2023)	M12 (Kollur i D. et. al. 2009)	M13 (Kumar M. et. al. 2013)	M14 (Kumar M. et. al. 2011)
Hardness [HV]	162	10.3	13.03	241	180	20	28	22	21	12.27	70	30	25	23
Thermal conductivity [W/mK]	0.429	0.539	0.312	0.126	0.65	2.17	2.51	3.75	1.98	0.239	5.261	2.1	2.3	2.41
Density [g/cm^3]	1.71	1.89	0.85	1.5	1.74	2.2	2.26	2.27	2.09	1.01	0.962	1.153	2.28	2.31
Coefficient of friction	0.28	0.35	0.39	0.40	0.38	0.4	0.43	0.44	0.57	0.32	0.35	0.35	0.41	0.41
Coefficient of friction stability [%]	94.8	71.43	92.21	77.8	33.8	86.1	78	92.3	77	96.3	87.5	92.3	93.5	92.5
Wear rate [mg/m]	7.77	3.8	2.146	4.4	0.0012	0.098	0.222	0.178	0.085	3.934	1.424	0.334	0.183	0.154
Environmental acceptability [scale 1-5]	4	1	5	5	5	3	3	3	4	5	4	3	2	2
Stability under different environmental conditions [scale 1-5]	4	4	3	3	4	4	4	4	3	4	4	4	4	4
Thermal shock resistance [scale 1-5]	4	4	4	3	4	4	4	5	3	3	4	4	4	4
Flame resistance [%]	21.4	100	46	44	75	75	60	80	70	35	70	85	80	80

Table 3 Alternatives and defined criteria

Alternatives / Criteria	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
K1	162	10.3	13.03	241	180	20	28	22	21	12.27	70	30	25	23
K2	0.429	0.539	0.312	0.126	0.65	2.17	2.51	3.75	1.98	0.239	5.261	2.1	2.3	2.41
K3	1.71	1.89	0.85	1.5	1.74	2.2	2.26	2.27	2.09	1.01	0.962	1.153	2.28	2.31
K4	0.28	0.35	0.39	0.40	0.38	0.4	0.43	0.44	0.57	0.32	0.35	0.35	0.41	0.41
K5	94.8	71.43	92.21	77.8	33.8	86.1	78	92.3	77	96.3	87.5	92.3	93.5	92.5
K6	7.77	3.8	2.146	4.4	0.0012	0.098	0.222	0.178	0.085	3.934	1.424	0.334	0.183	0.154
K7	4	1	5	5	5	3	3	3	4	5	4	3	2	2
K8	4	4	3	3	4	4	4	4	3	4	4	4	4	4
K9	4	4	4	3	4	4	4	5	3	3	4	4	4	4
K10	21.4	100	46	44	75	75	60	80	70	35	70	85	80	80

Table 4 Classification of criteria according to the type of limit value

Designation	Criterion	Type of limit value
K1	Hardness	Target value
K2	Thermal conductivity	Lower limit value
K3	Density	Upper limit value
K4	Coefficient of friction	Target value
K5	Coefficient of friction stability	Lower limit value
K6	Wear rate	Upper limit value
K7	Environmental acceptability	Lower limit value
K8	Stability under different environmental conditions	Lower limit value
K9	Thermal shock resistance	Lower limit value
K10	Flame resistance	Lower limit value

The rationale for each type of limit value used to define the criteria is given below.

K1 – hardness – target value – excessive hardness may increase wear of the brake-disc surface, whereas insufficient hardness may lead to increased wear of the friction material itself. Therefore, an appropriate, i.e., target, value is sought.
K2 – thermal conductivity – lower limit value – higher thermal conductivity enables more efficient dissipation of the heat generated during braking and contributes to reducing local heating of the friction material.
K3 – density – upper limit value – lower density contributes to reducing the mass of the friction components. Therefore, an upper density limit is set, assuming that the other functional properties remain satisfactory.
K4 – coefficient of friction – target value – efficient and stable braking requires an appropriate coefficient of friction. An unlimited increase in its value is not necessarily favourable; therefore, a target value is defined.

K5 – coefficient of friction stability – lower limit value – a stable coefficient of friction provides more uniform and predictable braking behaviour. Therefore, higher stability values are more favourable.
K6 – wear rate – upper limit value – a lower wear rate indicates greater resistance of the material to mass loss and a longer service life of the friction component.
K7 – environmental acceptability – lower limit value – greater environmental acceptability is a more favourable property because it reduces the negative environmental impact of the material during production, use, and disposal.
K8 – stability under different environmental conditions – lower limit value – the friction material should retain satisfactory properties under changes in temperature, humidity, and other environmental conditions. Accordingly, higher stability is more favourable.
K9 – thermal shock resistance – lower limit value – greater resistance reduces the possibility of material degradation and damage caused by sudden temperature changes, which is important during intensive braking.
K10 – flame resistance – lower limit value – greater flame resistance reduces the material's tendency to ignite and sustain combustion at elevated temperatures, thereby contributing to the safety and thermal stability of the friction component.

The specific limit values for each criterion must now be determined. These criterion limit values will be used to eliminate unfavourable alternatives. Table 5 presents the criterion limit values.

Table 5 Criterion limit values

Criterion	Limit value
K1	≥ 20 HV
K2	≥ 0.25 W/mK
K3	≤ 2.30 g/cm^3
K4	≥ 0.30
K5	≥ 70%
K6	≤ 1.00 mg/m
K7	≥ 3
K8	≥ 3
K9	≥ 4
K10	≥ 70 %

After the limit values have been defined, the next step is to check each alternative against each criterion. If an alternative fails to satisfy the limit value of even one criterion, it is eliminated from further consideration. Table 6 presents the status of the alternatives on the basis of the limit values.

Table 6 Status of alternatives based on the limit values

Criterion / Alternative	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Alternative status
M1	✓	✓	✓	✗	✓	✗	✓	✓	✓	✗	Does not satisfy
M2	✗	✓	✓	✓	✓	✗	✗	✓	✓	✓	Does not satisfy
M3	✗	✓	✓	✓	✓	✗	✓	✓	✓	✗	Does not satisfy
M4	✓	✗	✓	✓	✓	✗	✓	✓	✗	✗	Does not satisfy
M5	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	Does not satisfy
M6	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**Satisfies**
M7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	Does not satisfy
M8	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**Satisfies**
M9	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	Does not satisfy
M10	✗	✗	✓	✓	✓	✗	✓	✓	✗	✗	Does not satisfy
M11	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	Does not satisfy
M12	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**Satisfies**
M13	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	Does not satisfy
M14	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	Does not satisfy

All considered alternatives were checked against the defined limit values. An alternative is considered acceptable if its values satisfy the specified limit conditions for all criteria. In this way, the initial set of 14 alternatives was reduced to three acceptable alternatives: M6, M8, and M12, as shown in Table 7.

The relative importance of the individual criteria must then be determined. For this purpose, the Digital Logic Method, i.e., a criterion-comparison method, is applied, in which each criterion is compared with every other criterion. For each pair of criteria, the criterion that is more important for material selection is assigned the value one, while the less important criterion is assigned zero. Based on these comparisons, a criterion comparison matrix is formed, as shown in Table 8.

Table 7 Alternatives that passed the elimination stage

Alternatives / Criteria	M6	M8	M12
K1	20	22	30
K2	2.17	3.75	2.1
K3	2.2	2.27	1.153
K4	0.4	0.44	0.35
K5	86.1	92.3	92.3
K6	0.098	0.178	0.334
K7	3	3	3
K8	4	4	4
K9	4	5	4
K10	75	80	85

Table 8 Criterion comparison matrix

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Number of positive decisions P_i	Weighting factor W_i
K1	-	1	1	0	0	0	1	0	0	1	4	0.0889
K2	0	-	1	0	0	0	1	0	0	1	3	0.0667
K3	0	0	-	0	0	0	0	0	0	0	0	0.0000
K4	1	1	1	-	0	1	1	0	1	1	7	0.1556
K5	1	1	1	1	-	1	1	1	1	1	9	0.2000
K6	1	1	1	0	0	-	1	0	1	1	6	0.1333
K7	0	0	1	0	0	0	-	0	0	1	2	0.0444
K8	1	1	1	1	0	1	1	-	1	1	8	0.1778
K9	1	1	1	0	0	0	1	0	-	1	5	0.1111
K10	0	0	1	0	0	0	0	0	0	-	1	0.0222
										Total:	$\sum P_i = 45$	**1.0000**

The weighting factor of each criterion must now be determined. The criterion weighting factor represents the ratio between the number of positive decisions for the i-th criterion and the total number of positive decisions for all criteria. The values of the weighting factors for each criterion are also given in Table 8. This factor is determined using the following equation:

$$W_i = \frac{P_i}{\sum P_i} \tag{3}$$

where:

W_i – weighting factor of the i-th criterion
P_i – number of positive decisions for the i-th criterion
$\sum P_i$ – total number of positive decisions (45 in this case)

After determining the weighting factor of each criterion, the evaluation index M must be calculated for each individual material. The evaluation index M is calculated according to the expression:

$$M = \left[\sum_{i=1}^{n_d} B_i \frac{Y_i}{X_i}\right]_d * \left[\sum_{j=1}^{n_g} B_j \frac{X_j}{Y_j}\right]_g * \left[\sum_{k=1}^{n_c} B_k \left|\left(\frac{Y_k}{X_k}\right) - 1\right|\right]_c \rightarrow min. \tag{4}$$

where:

d, g, and c refer to the lower, upper, and target values of the property under consideration;
n_d, n_g, n_c,... – denote the numbers of lower, upper, and target property values;
B_i, B_j, B_k,... – are the importance factors for the lower, upper, and target property values;
X_i, X_j, X_k,... – *are the lower, upper, and target values of the material properties under consideration;*
Y_i, Y_j, Y_k,... – *are the specific lower, upper, and target property values* (Filetin, T. 2006).

Table 9 summarizes all input data required to determine the evaluation index. The importance factor B is the same as the weighting factor Wi calculated by the Digital Logic Method.

Based on these input data, as well as the previously defined limit and target criterion values, the contribution of individual criteria is calculated for all three remaining alternatives. Depending on the criterion type, the

corresponding equation is applied to calculate the lower-limit, upper-limit, and target-value components. These are, in fact, the elements of the main equation for calculating the evaluation index (Equation 4). Tables 10, 11, and 12 present the obtained calculation results for all three alternatives.

Table 9 Input data for calculating the evaluation index M

Criterion	Criterion type	Limit value X	Importance factor B	M6	M8	M12
K1	Target	20	0.0889	20	22	30
K2	Lower limit	0.25	0.0667	2.17	3.75	2.1
K3	Upper limit	2.3	0	2.2	2.27	1.153
K4	Target	0.3	0.1556	0.4	0.44	0.35
K5	Lower limit	70	0.2	86.1	92.3	92.3
K6	Upper limit	1	0.1333	0.098	0.178	0.334
K7	Lower limit	3	0.0444	3	3	3
K8	Lower limit	3	0.1778	4	4	4
K9	Lower limit	4	0.1111	4	5	4
K10	Lower limit	70	0.0222	75	80	85

Table 9 Calculation results for the lower-limit, upper-limit, and target-value components of alternative M6

Criterion	Lower limit value	Upper limit value	Target value
K1	0	0	0
K2	0.579	0	0
K3	0	0	0
K4	0	0	0.039
K5	0.246	0	0
K6	0	0.013	0
K7	0.044	0	0
K8	0.237	0	0
K9	0.111	0	0
K10	0.024	0	0
Total:	**1.241**	**0.013**	**0.039**

Table 10 Calculation results for the lower-limit, upper-limit, and target-value components of alternative M8

Criterion	Lower limit value	Upper limit value	Target value
K1	0	0	0.008
K2	1.001	0	0
K3	0	0	0
K4	0	0	0.050
K5	0.264	0	0
K6	0	0.749	0
K7	0.044	0	0
K8	0.237	0	0
K9	0.139	0	0
K10	0.025	0	0
Total:	**1.710**	**0.749**	**0.058**

Table 11 Calculation results for the lower-limit, upper-limit, and target-value components of alternative M12

Criterion	Lower limit value	Upper limit value	Target value
K1	0	0	0.030
K2	0.560	0	0
K3	0	0	0
K4	0	0	0.022
K5	0.264	0	0
K6	0	0.399	0
K7	0.044	0	0
K8	0.237	0	0
K9	0.111	0	0
K10	0.027	0	0
Total:	**1.244**	**0.399**	**0.052**

Finally, the final values of the evaluation index for the alternatives are calculated as:

MM6 = 1.241*0.013*0.039 = 0.001
MM8 = 1.710*0.749*0.058 = 0.074
MM12 = 1.244*0.399*0.052 = 0.026

Since the objective for the evaluation index is minimization, as can be seen from Equation 4, the alternative with the lowest value is the most favourable. Table 12 presents the final ranking of the three alternatives.

Table 12 *Final ranking of alternatives using the Limit Value Method*

Alternative	Evaluation index M	Rank
M6	0.001	1
M12	0.026	2
M8	0.074	3

CONCLUSION

Proper material selection is one of the most important steps in the design and development process of any product because it directly determines its functional characteristics: reliability, service life, safety, cost-effectiveness, and manufacturability. No material has ideal properties for all operating conditions; therefore, material selection is always the result of a compromise between different and often conflicting requirements. With the development of new materials and the increasing number of available alternatives, the selection process becomes considerably more complex and requires the application of systematic and objective decision-making methods that enable the simultaneous consideration of multiple criteria.

This paper addressed friction materials. Proper selection of friction materials is of great importance in braking systems because their characteristics affect braking efficiency and the safety of road users. Friction materials must provide a stable coefficient of friction over a wide range of operating temperatures and loads, high wear resistance, adequate heat-dissipation capability, etc. Changes in formulation composition can significantly influence the tribological behaviour of the material; therefore, it is necessary to identify an optimal combination that satisfies the requirements of real operating conditions.

Using the Digital Logic Method, 14 friction materials were evaluated according to ten defined criteria. First, alternatives that did not satisfy the minimum requirements were eliminated using the limit values, reducing the initial set of 14 materials to three acceptable alternatives: M6, M8, and M12. In this way, an initial screening was performed for materials that simultaneously satisfy the specified requirements in terms of mechanical, physical, thermal, tribological, and environmental characteristics. The relative importance of the criteria was then determined using the Digital Logic Method. Final evaluation of the remaining alternatives produced a ranking in which M6 was placed first, M12 second, and M8 third. According to the Digital Logic Method, M6 is the most favorable alternative, indicating that this material provides the best compromise among all the criteria considered.

The obtained result should be interpreted within the framework of the adopted criteria, their limit values, and weighting factors. Future research should focus on sensitivity analysis of the obtained ranking with respect to changes in weighting factors and limit values, as well as on experimental verification of the highest-ranked alternatives under identical test conditions.

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