Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2025 vol. 27 no. 2 pp. 29–42
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2025-27.2-29-42

NSTU NETI

Obrabotka metallov - Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

A comparative evaluation of friction and wear in alternative materials for brake friction composites

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ARTICLE INFO

Article history:
Received: 17 January 2025
Revised: 17 February 2025
Accepted: 17 March 2025
Available online: 15 June 2025

Keywords:
Non-Asbestos alternatives
Brake friction materials
composite
Wear
Pin-on-disc testing

ABSTRACT

Introduction: this study examines research and development efforts aimed at developing non-asbestos brake friction composites (*BFCs*) to improve the safety and performance of automotive brake systems. The evolution of *BFCs* from asbestos-based materials to safer alternatives is studied, and an analysis is performed to develop alternative material combinations. The critical roles of key components — fibers, binders, friction modifiers and fillers — in creating durable brake friction composites for brake systems is emphasized. A composite material based on basalt fiber with calcium carbonate filler is compared to a composite material based on aramid fiber with barium sulfate filler through pin-on-disc tribological testing. Based on the test results, it is determined that the alternative composite materials show promise for application in brake systems. This work also provides a foundation for further development of eco-friendly brake friction composites by selecting optimal formulations. The present work defines an approach for subsequent research aimed at varying the components and their ratios in the creation of composite materials. This research will further improve the functionality of automotive brake systems. **Purpose of the work:** this research is focused on the development of non-asbestos brake friction composites (*BFCs*) with the goal of improving the safety and performance of automotive brake systems. Eco-friendly alternatives to asbestos are investigated, and the roles of fibers, binders, friction modifiers, and fillers are analyzed. The objective of the research is to identify optimal formulations for creating durable, sustainable brake materials, paving the way for further implementation of innovative solutions in practice. **Methods of investigation:** a pin-on-disc tribological method is used to evaluate wear, friction, and durability, as well as to assess the suitability of the developed materials for use in brake systems. This research is dedicated to analyzing the influence of components (fibers, binders, friction modifiers, and fillers) on the properties of friction composites for brake systems. Two compositions were experimentally studied: basalt fiber with calcium carbonate and aramid fiber with barium sulfate. **Results and discussion:** the results of the research demonstrate the effectiveness of using basalt fiber with calcium carbonate and aramid fiber with barium sulfate as components in friction composites for brake systems. It is shown that these materials provide high levels of wear resistance and friction performance. The potential for further optimization of compositions to improve eco-friendliness and enhance the operational properties of braking systems is emphasized. The obtained results also highlight the importance of component selection for the development of safe and sustainable brake friction composites.

For citation: Kate N., Kulkarni A.P., Dama Y.B. A comparative evaluation of friction and wear in alternative materials for brake friction composites. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2025, vol. 27, no. 2, pp. 29–42. DOI: 10.17212/1994-6309-2025-27.2-29-42. (In Russian).

Introduction

Braking systems are a critical element of automotive safety, ensuring vehicle stopping and safe handling. Their efficiency is critical to ensure the safety of passengers and other road members. In disc braking systems, braking efficiency is determined by the friction between the brake pad and the disc mechanism. Therefore,

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the selection of suitable materials for friction composites of brake pads is a decisive factor in achieving high braking performance [1]. Brake friction composites consist of fibers, binders, friction modifiers, and fillers, which determine their crucial tribological properties [2–3]. Careful selection of materials is necessary to prevent excessive wear and degradation of friction characteristics [4–5].

Evolution of Non-Asbestos Brake Friction Composites

Asbestos, due to its excellent friction and wear-resistant properties, has traditionally been used as the main component of brake composites materials. However, due to serious health hazards, its use has been restricted [6–7]. In recent years, alternative materials have been actively developed to replace asbestos [8–10].

Based on the use of metallic fillers, *Kumar* and *Bijwe* [11] investigated the influence of operating parameters on friction in brake friction composite. The study analyzed the friction characteristics of a non-asbestos organic composite under dynamically varying pressure and speed. It was found that copper powder effectively reduces the sensitivity of friction properties to changes in operating parameters. Further studies have shown the importance of understanding the dependence of friction properties on composite composition and have identified ways to improve the efficiency and durability of friction materials [12]. *Bhanudas Bachchhav* et al. [13] studied the wear performance of non-asbestos friction materials when sliding against a gray cast iron disc. The results of the study provided information on the wear rate of materials and facilitated the selection of suitable friction materials for braking systems [10–13].

Reinforcing Components in Brake Friction Composites

The addition of reinforcing components improves the mechanical and tribological properties of brake friction composites [1]. *Prabhu* et al. investigated the effect of reinforcement with bimodal particles. Composites reinforced with mullite demonstrated higher performance than composites with silica filler [14].

Abrasives in Brake Friction Composites

The selection of abrasive components plays a crucial role in determining the wear resistance of brake composites. *Tej Singh* and *Amar Patnaik* [15] investigated the effect of various abrasives on the performance of non-asbestos brake friction materials. It was experimentally established that friction composites containing aluminum oxide have higher performance characteristics. The results of the study provide valuable insights for the selection of abrasive components in the development of high-performance non-asbestos brake friction composite materials [3–5].

Novel Materials for Brake Friction Composites

Recent studies demonstrate the benefits of incorporating novel materials into the composition of brake composites [10–13]. *Vlastimil Matějka* [16] evaluated the influence of *g-C3N4* on the formation of copper-free friction composites of brake pads. Extensive research has been conducted to develop effective non-asbestos materials [15–19]. The introduction of high-strength components and optimized abrasives demonstrates the prospect of improving tribological properties [20–22]. The use of innovative materials, such as graphitic carbon nitride (*g-C3N4*), opens up opportunities for the development of eco-friendly and high-performance brake pad materials [3–17]. Pin-on-disk tribological tests allow evaluating wear, friction, and durability, determining the suitability of materials for use in braking systems [23–25].

The presented research contributes to the expanding knowledge base regarding brake friction composites by analyzing existing literature, focusing on their tribological properties and wear resistance, and proposing alternative composite solutions for braking systems. The results also outline future research directions in the area of optimized selection of friction materials for braking system applications.

Literature Review

Composition of Brake Friction Materials

Automotive brake friction materials are complex mixtures consisting of numerous components designed to provide the required frictional properties and wear resistance. They can be classified into four main groups:

– *Binders* provide cohesion for all other ingredients.

– *Reinforcing fibers* enhance the strength of the composite matrix.

– *Friction modifiers* provide the required level of lubrication, stabilize the coefficient of friction, and regulate the formation of tribological films on the contact surface.

–*Fillers* are primarily used to reduce the cost of the composite and partially modify the characteristics of the friction material [2, 3].

Fig. 1 schematically presents the key functions of the main components of a brake friction composite. The selection of each ingredient is determined by the need for its properties to meet the required functional requirements.

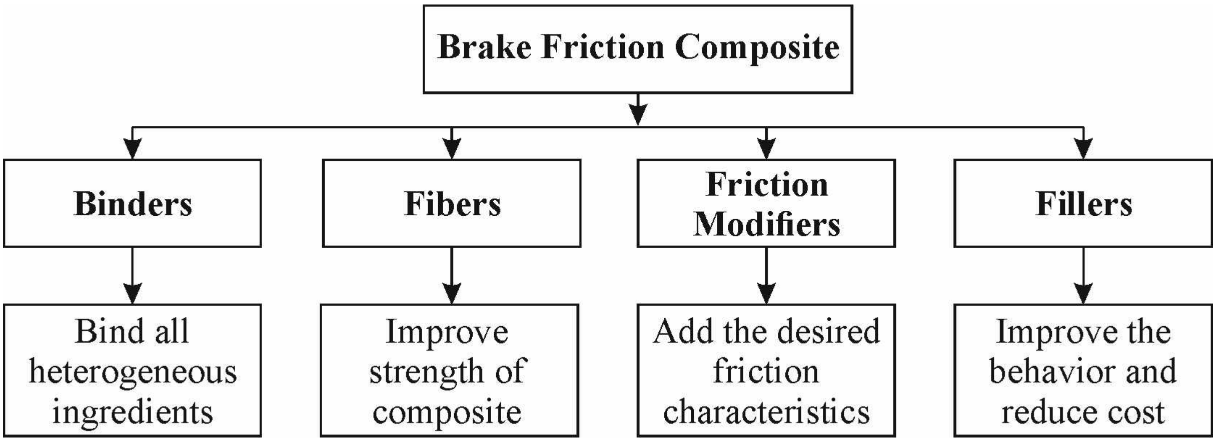

Fig. 1. Key roles of crucial components of brake friction composites

Fibers

Fibers play a crucial role in the composition of brake friction materials, providing the necessary strength and durability under the high loads that occur during braking. The introduction of reinforcing fibers contributes to increasing the overall strength of the material [3]. When selecting fibers for brake pad composites, characteristics such as high strength, friction stabilization, wear resistance, low thermal conductivity, noise absorption, and compatibility with binders are taken into account [7]. Aramid and basalt fibers can be used as reinforcing fibers in brake pad compositions. Aramid fibers, providing high strength and wear resistance, are optimal for heavy-duty braking conditions. Basalt fibers, due to their exceptional heat resistance, are recommended for high-temperature braking modes [9–10].

Fillers

Fillers are important components of brake friction composites, contributing to the reduction of noise and vibration, as well as increasing wear resistance. The introduction of fillers improves the performance characteristics of brake pads friction composites. The most common inorganic fillers include calcium carbonate, exfoliated vermiculite, mica, barium sulfate, kaolin clay, cashew dust, and alkali metal titanates. Calcium carbonate ($CaCO_3$) allows reducing cost and increasing wear resistance, which extends the service life and durability of brake pads. The use of this filler reduces material loss during braking and increases overall wear resistance. Barium sulfate ($BaSO_4$), which has high thermal stability, is often used as a filler because it can withstand extremely high temperatures generated during braking [5–11].

Binders

The main function of binders is to provide cohesion of the composite components and adhesion to other structural elements. Binders provide the necessary structural integrity of the brake pad material when exposed to thermal and mechanical loads. The binder should have good flowability during pressing and curing to ensure uniform distribution and bonding of components. Friction composites are characterized by good adhesion and high heat resistance, which are provided by the use of polymer binders. The choice of polymer binder type is essential for the effective operation of the braking system in a wide range of operating conditions [2–10].

Friction Modifier

Friction modifiers are additives that affect the friction and wear characteristics of brake pads. They play an important role in regulating frictional properties such as noise level, brake pedal feel, and abrasiveness (aggressiveness) towards the counterface. To ensure the efficient operation of the braking system, it is necessary to maintain an optimal ratio of lubricating and abrasive components in the friction material [2–10].

Graphite plays an important role in reducing wear in brake friction materials. It increases the stability of the coefficient of friction over a wide temperature range, minimizes noise, and prevents stick-slip behavior, ensuring smoother braking [3–6].

Selection of Suitable Combinations of Ingredients

Fig. 2 presents the expected properties of components, determining their suitability for use in brake friction composites.

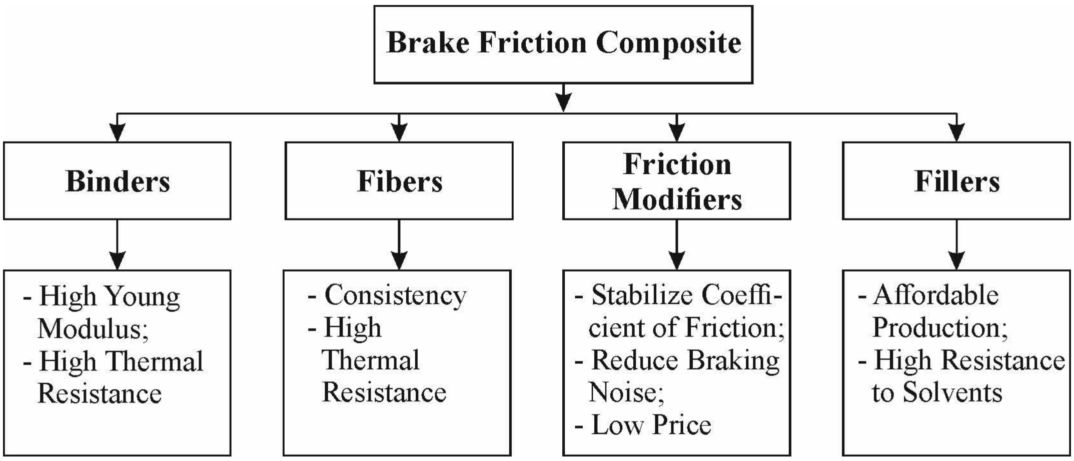

Fig. 2. Expected properties of components in brake friction composites

The selection of optimal combinations of components for brake friction composites is based on the following criteria:

– High braking efficiency: providing the necessary braking force, minimizing noise, and reducing dust and particulate emissions.

– High operational reliability (durability): resistance to wear, high temperatures, and other environmental factors.

Composites based on aramid fibers with copper filler exhibit good operational reliability (durability) due to the high wear resistance of copper and the strength of aramid fiber. This combination provides high braking efficiency, as well as reduces noise and dust emissions [7]. The use of basalt fiber with calcium carbonate filler provides an acceptable level of operational reliability (durability) due to the high heat resistance of basalt and the wear resistance of calcium carbonate [8].

Figs. 3, *a* and 3, *b* show samples of aramid and basalt fibers, respectively. The mechanical properties of aramid and basalt fibers are presented in Table 1 [9].

a *b*

Fig. 3. Aramid Fiber (*a*); Basalt Fiber (*b*) Sheets

Table 1

Mechanical Properties of Aramid and Basalt [22]

Properties	Aramid	Basalt
Tensile strength (GPa)	2.9–3.4	3.0–4.84
Elastic modulus (GPa)	70–112	79.3–93.1
Density (g/cm³)	1.43	2.90

Methods

Based on the analysis of literature data, and considering the role and properties of components, two compositions of brake friction composites were proposed for experimental wear tests. The tribological tests of materials for friction and wear were implemented using the pin-on-disk kinematic scheme. The selected compositions were developed taking into account the unique properties of each component, which allows creating a strong, durable, heat-resistant, and cost-effective friction material. Each component plays an important role in ensuring the necessary characteristics of the braking system.

Material Preparation

1. *BFC1*: basalt fiber, calcium carbonate filler, polymer binder, graphite friction modifier, and balancing ingredients. The proposed composition is based on previous research and includes:

– Basalt: 30 wt. %;
– Calcium carbonate: 30 wt. %;
– Phenolic resin: 20 wt. %;
– Graphite: 10 wt. %;
– Other fillers – alumina: 5 wt. %, copper: 5 wt. %.

2. *BFC2*: aramid fiber, barium sulfate filler, polymer binder, graphite friction modifier, and balancing ingredients. The proposed composition based on previous research and includes:

– Aramid: 30 wt. %;
– Barium sulfate: 30 wt. %;
– Phenolic resin: 20 wt. %;
– Graphite: 10 wt. %;
– Other fillers – aluminum oxide: 5 wt. %, copper: 5 wt. %.

Wear Testing Methodology (Pin-on-Disk Scheme)

Pin-on-disk tribological tests are widely used to evaluate the wear resistance of materials used in braking systems [6, 10, 18]. The essence of the method is to measure the wear of a specimen (pin) when sliding on the surface of a rotating disk under laboratory conditions.

Fig. 4 shows a schematic diagram of the pin-on-disk setup provided by *Ducom Instruments Pvt. Ltd.* The main elements of the setup are: a cylindrical pin pressed perpendicularly against a flat rotating disk, a lever mechanism for applying load to the pin, a linear variable differential transducer (*LVDT*) for measuring wear, and a force sensor for measuring friction force. The linear variable differential transducer and the force sensor are mounted on the lever [18].

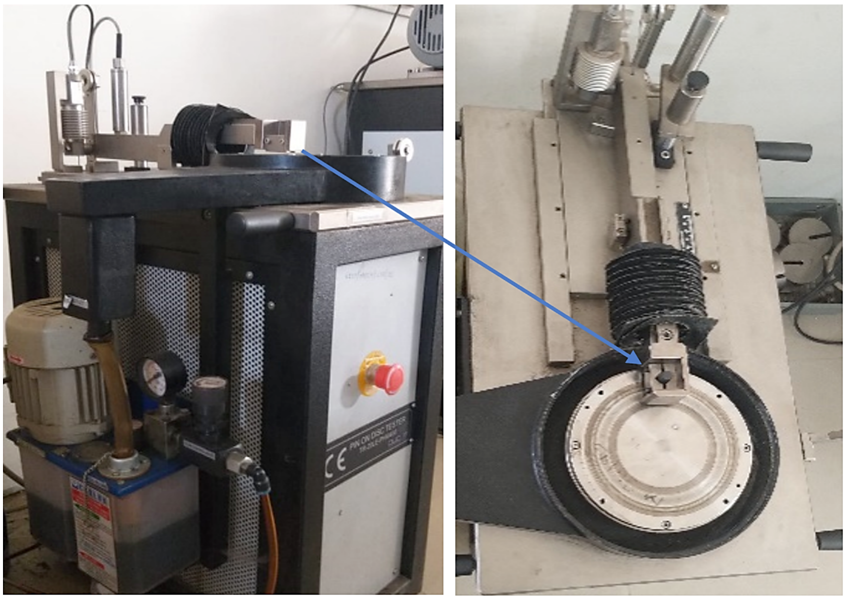

Fig. 4. Pin on Disc Test Setup in Laboratory

During the tests, the normal load (***L***) on the pin was changed stepwise: 10, 50, and 100 N (standard test conditions). The dimensions of the pin specimens were: length – 32 mm, diameter – 10 mm. To ensure comparability of results, the same values of the sliding distance (***d***) and test duration (***t***) were set for both compositions *BFC1* and *BFC2*.

The following parameters were recorded during the tests: friction force (***F***), wear, and other required parameters. The obtained data were used for further calculation of the tribological characteristics of the materials.

The coefficient of friction can be calculated using the following equation:

$$\mu = \frac{F}{L}, \tag{1}$$

where **μ** is the coefficient of friction of the specimen material; ***F*** is the friction force; ***L*** is the applied load.

The volume of the cylindrical pin material is calculated using the following equation:

Volume of the material in the cylindrical pin is calculated by the following equation:

$$V = \pi r^2 h, \tag{2}$$

where ***V*** is the volume of the pin; ***r*** is the radius of the pin; ***h*** is the height of the pin.

The wear rate can be calculated using the following simplified equation:

$$w = \frac{v_f - v_i}{d} \tag{3}$$

where V_f is the final volume of the pin after the test; V_i is the initial volume of the pin before the test; d is the sliding distance.

These equations allow evaluating the wear behavior of the materials under investigation and offer alternative options for brake friction materials.

Results and Discussions

Following extensive research on the selection of optimal components for the brake friction material compositions, two key combinations were selected for further testing and evaluation. The influence of these components on the wear behavior of composites was investigated using the pin-on-disk friction and wear testing method.

Fig. 5 shows the main components of the brake friction composite 1 (*BFC1*), and fig. 6 shows the main components of the brake friction composite 2 (*BFC2*).

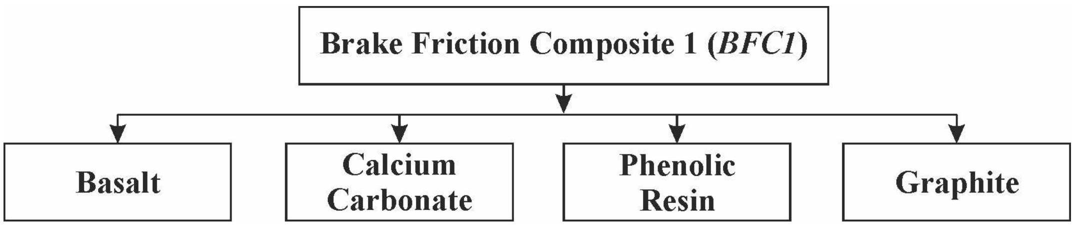

Fig. 5. Major Ingredients of *BFC1*

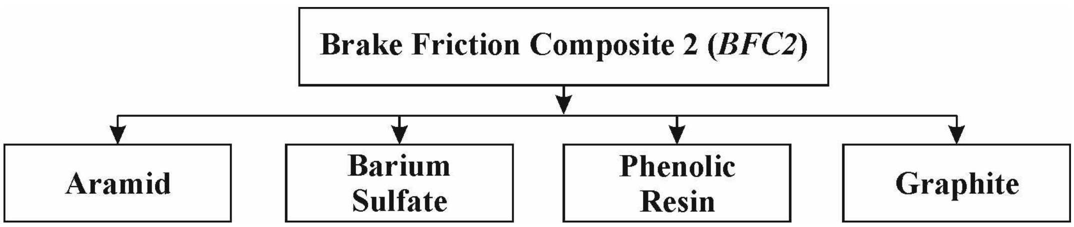

Fig. 6. Major Ingredients of *BFC2*

To evaluate the performance characteristics of the developed composites, the test results of the coefficient of friction **μ** at various applied loads were used. The evaluation of brake friction composites was carried out at three different loads: 10, 50, and 100 N.

Table 2 presents the test results of the average coefficient of friction **μ** for *BFC1* and *BFC2*, and Table 3 presents the test results of the average weight loss (g) for *BFC1* and *BFC2*.

Table 2

Test Results for Average Coefficient of Friction of the *BFC1* and *BFC2*

Composition	Load (N) H	Mean Coefficient of Friction	Average Coefficient of Friction μ
BFC1	10	0.38	0.42
	50	0.43	
	100	0.46	
BFC2	10	0.44	0.48
	50	0.47	
	100	0.52	

Table 3

Test Results for Average Weight Loss of the *BFC1* and *BFC2*

Composition	Load (N) H	Mean Weight loss (g)	Average Weight Loss (g)
BFC1	10	0.042	0.084
	50	0.091	
	100	0.118	
BFC2	10	0.006	0.011
	50	0.010	
	100	0.018	

Fig. 7 displays the coefficient of friction for the *BFC1* and *BFC2*, while Fig. 8 displays the weight loss (g) for the *BFC1* and *BFC2*.

The overall average coefficient of friction **μ** for all applied loads was 0.42 for composite *BFC1* and 0.48 for composite *BFC2*, which corresponds to acceptable values according to engineering standards [19, 20]. For each composite, increasing the applied load resulted in an increase in the coefficient of friction **μ**.

For comparative evaluation of the proposed brake friction composites, the values of the coefficient of friction and mass loss are presented in Table 4.

The higher coefficient of friction of material *BFC2*, revealed by the comparison, indicates its greater effectiveness in braking systems. The greater mass loss during the testing of material *BFC1* in wear tests indicates its lower wear resistance compared to *BFC2*. A higher coefficient of friction contributes to

Fig. 7. Coefficient of Friction for the *BFC1* and *BFC2*

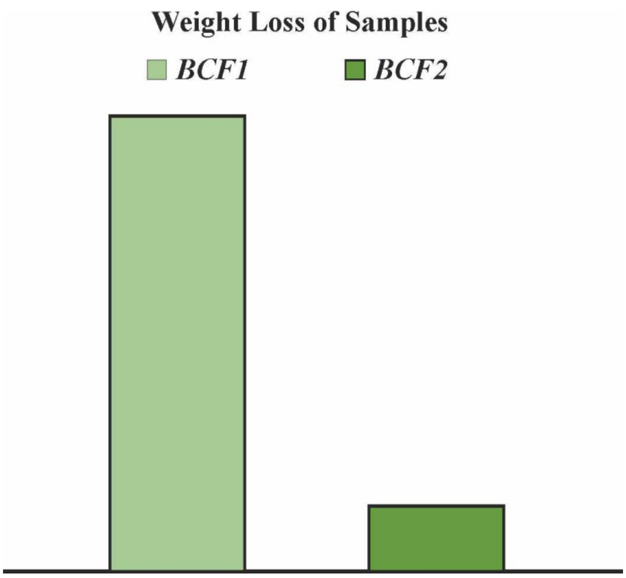

Fig. 8. Weight Loss of Samples for the *BFC1* and *BFC2*

Table 4

Comparison of Properties for the Brake Friction Composites

Properties	Composition *BFC1*	Composition *BFC2*
Friction coefficient **μ**	0.42	0.48
Weight loss (g)	0.084	0.011

improved braking performance, and a lower wear rate contributes to increased durability of brake friction composites.

Widely used ceramic and brass fiber-based brake friction composites were previously tested as a benchmark. In this reference study, the ceramic fiber-based brake friction composite showed better results than the brass fiber-based friction composite. In the current work, the average coefficients of friction for materials *BFC1* (0.42) and *BFC2* (0.48) were higher than that of the benchmark ceramic fiber-based composite (0.38). *BFC2* also demonstrated a lower wear rate compared to the benchmark ceramic fiber-based brake friction composite.

Aramid fibers are used in friction materials due to their high strength and wear resistance. It has been found that the interaction of aramid fibers with barium sulfate-based fillers increases the abrasiveness of the material. It is known that fillers such as calcium carbonate enhance adhesive interaction with the counterface, which increases friction, but can also increase wear [23]. The use of aramid fibers also contributes to reducing the overall mass of braking systems due to their low density, which leads to increased fuel efficiency [7, 10, 19].

The addition of graphite particles as a friction modifier provides stable friction properties and high wear resistance [3, 19]. The polymer binder plays an important role ensuring proper adhesion of various components, as well as possessing high heat resistance, which is necessary for effective braking [20, 21].

Conclusion

Highly efficient friction composite materials with enhanced performance characteristics are used to ensure the durability and safety of automotive braking systems. Achieving these characteristics is ensured by the optimal selection and combination of components in the brake friction composite materials.

The proposed *BFC1* composition was obtained by mixing and pressing the following key components: basalt fiber, calcium carbonate-based filler, phenolic resin binder and graphite friction modifier. The proposed *BFC2* composition mainly consisted of a mixture of aramid fiber, barium sulfate-based filler, phenolic resin binder and graphite friction modifier. Tribological tests of these compositions were carried out on a setup implementing the pin-on-disk scheme. Comparative analysis based on the values of the friction coefficient and wear rate allowed formulating the following key conclusions:

– *BFC2* composite containing aramid fibers demonstrated higher frictional properties compared to *BFC1*, which is due to the higher coefficient of friction provided by aramid fibers.

– *BFC2*, containing aramid fibers (providing high tensile strength and wear resistance) and barium sulfate-based filler (increasing stiffness and load-bearing capacity), demonstrated less weight loss during friction and, as a result, a lower wear rate compared to *BFC1*, which positively affects the operational reliability (durability) of the composite material.

– The results of tribological tests performed within the framework of this study allow recommending aramid and basalt fiber-based composites as eco-friendly alternatives to traditional friction composite materials used in automotive braking systems.

– The results of this study can be used for further improvement of automotive braking systems.

Promising directions for further research are the optimization of composite material compositions to improve the overall performance of brake friction composite materials. The use of the results of this study will allow braking system manufacturers to make informed decisions when choosing optimal components for friction composite materials.

The obtained results also confirm that the development of friction composite materials is a dynamically developing field that requires continuous research and the implementation of innovative solutions to ensure sustainable safety and reliability of automotive braking systems.

References

1. Ahmed K.A., Mohideen S.R., Balaji M.A.S., Rajan B.S. Tribological performance of brass powder with different copper and zinc content in the brake pad. *Tribology in Industry*, 2020, vol. 42 (2), pp. 177–190. DOI: 10.24874/ti.783.10.19.03.

2. Sellami A., Kchaou M., Elleuch R., Cristol A.L., Desplanques Y. Study of the interaction between microstructure, mechanical and tribo-performance of a commercial brake lining material. *Materials & Design*, 2014, vol. 59, pp. 84–93. DOI: 10.1016/j.matdes.2014.02.025.

3. Österle W., Dmitriev A.I. The role of solid lubricants for brake friction materials. *Lubricants*, 2016, vol. 4 (1), p. 5. DOI: 10.3390/lubricants4010005.

4. Liang Y., Wang W., Zhang Z., Xing H., Wang C., Zhang Z., Guan T., Gao D. Effect of material selection and surface texture on tribological properties of key friction pairs in water hydraulic axial piston pumps: a review. *Lubricants*, 2023, vol. 11 (8), p. 324. DOI: 10.3390/lubricants11080324.

5. Kumar M., Bijwe J. Studies on reduced scale tribometer to investigate the effects of metal additives on friction coefficient – temperature sensitivity in brake materials. *Wear*, 2010, vol. 269 (11–12), pp. 838–846. DOI: 10.1016/j.wear.2010.08.012.

6. Saffar A., Shojaei A., Arjmand M. Theoretical and experimental analysis of the thermal, fade and wear characteristics of rubber-based composite friction materials. *Wear*, 2010, vol. 269 (1–2), pp. 145–151. DOI: 10.1016/j.wear.2010.03.021.

7. Aranganathan N., Mahale V., Bijwe J. Effects of aramid fiber concentration on the friction and wear characteristics of non-asbestos organic friction composites using standardized braking tests. *Wear*, 2016, vol. 354, pp. 69–77. DOI: 10.1016/j.wear.2016.03.002.

8. McElheny D., Frydman V., Frydman L. A solid-state 13C NMR analysis of molecular dynamics in aramid polymers. *Solid State Nuclear Magnetic Resonance*, 2006, vol. 29 (1–3), pp. 132–141. DOI: 10.1016/j.ssnmr.2005.08.010.

9. Prasad V.V., Talupula S. A review on reinforcement of basalt and aramid (Kevlar 129) fibers. *Materials Today: Proceedings*, 2018, vol. 5 (2), pp. 5993–5998. DOI: 10.1016/j.matpr.2017.12.202.

10. Xiao X., Yin Y., Bao J., Lu L., Feng X. Review on the friction and wear of brake materials. *Advances in Mechanical Engineering*, 2016, vol. 8 (5). DOI: 10.1177/1687814016647300.

11. Kumar M., Bijwe J. Composite friction materials based on metallic fillers: sensitivity of μ to operating variables. *Tribology International*, 2011, vol. 44 (2), pp. 106–113. DOI: 10.1016/j.triboint.2010.09.013.

12. Kumar M., Bijwe J. NAO friction materials with various metal powders: tribological evaluation on full-scale inertia dynamometer. *Wear*, 2010, vol. 269 (11–12), pp. 826–837. DOI: 10.1016/j.wear.2010.08.011.

13. Bachchhav B.D., Hendre K.N. Wear performance of asbestos-free brake pad materials. *Jordan Journal of Mechanical & Industrial Engineering*, 2022, vol. 16 (4), pp. 459–469.

14. Prabhu T.R. Effect of bimodal size particles reinforcement on the wear, friction and mechanical properties of brake composites. *Tribology-Materials, Surfaces & Interfaces*, 2016, vol. 10 (4), pp. 163–171. DOI: 10.1080/17515831.2016.1262587.

15. Singh T., Patnaik A., Chauhan R., Bíró I., Jánosi E., Fekete G. Performance assessment of phenolic-based non-asbestos organic brake friction composite materials with different abrasives. *Acta Polytechnica Hungarica*, 2020, vol. 17 (5), pp. 49–67. DOI: 10.12700/APH.17.5.2020.5.3.

16. Matějka V., Leonardi M., Praus P., Straffelini G., Gialanella S. The role of graphitic carbon nitride in the formulation of copper-free friction composites designed for automotive brake pads. *Metals*, 2022, vol. 12 (1), p. 123. DOI: 10.3390/met12010123.

17. Park J., Gweon J., Seo H., Song W., Lee D., Choi J., Kim Y.C., Jang H. Effect of space fillers in brake friction composites on airborne particle emission: a case study with $BaSO_4$, $Ca(OH)_2$, and $CaCO_3$. *Tribology International*, 2022, vol. 165, p. 107334. DOI: 10.1016/j.triboint.2021.107334.

18. Deshpande A.R., Kulkarni A.P., Wasatkar N., Gajalkar V., Abdullah M. Prediction of wear rate of glass-filled PTFE composites based on machine learning approaches. *Polymers*, 2024, vol. 16 (18), p. 2666. DOI: 10.3390/polym16182666.

19. Dama Y., Jogi B., Pawade R., Kulkarni A. Vliyanie napravleniya pechati na kharakter iznosa PLA-biomateriala, poluchennogo metodom FDM: issledovanie dlya implantata tazobedrennogo sustava [Impact of print orientation on wear behavior in FDM printed PLA Biomaterial: Study for hip-joint implant]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2024, vol. 26, no. 4, pp. 19–40. DOI: 10.17212/1994-6309-2024-26.4-19-40.

20. Hendre K., Bachchhav B. Tribological behavior of non-asbestos brake pad material. *Materials Today: Proceedings*, 2021, vol. 38, pp. 2549–2554. DOI: 10.1016/j.matpr.2020.07.560.

21. Suresh V., Vikram P., Palanivel R., Laubscher R.F. Mechanical and wear behavior of LM25 aluminium matrix hybrid composite reinforced with boron carbide, graphite and iron oxide. *Materials Today: Proceedings*, 2018, vol. 5 (14), pp. 27852–27860. DOI: 10.1016/j.matpr.2018.10.023.

22. Sethupathi P.B., Chandradass J., Saibalaji M.A. Comparative study of disc brake pads sold in Indian market – impact on safety and environmental aspects. *Environmental Technology & Innovation*, 2021, vol. 21, p. 101245. DOI: 10.1016/j.eti.2020.101245.

23. Chowdhury I.R., Pemberton R., Summerscales J. Developments and industrial applications of basalt fibre reinforced composite materials. *Journal of Composites Science*, 2022, vol. 6 (12), p. 367. DOI: 10.3390/jcs6120367.

24. Zhao X., Ouyang J., Yang H., Tan Q. Effect of basalt fibers for reinforcing resin-based brake composites. *Minerals*, 2020, vol. 10 (6), p. 490. DOI: 10.3390/min10060490.

25. Rajan B.S., Balaji M.A.S., Sathickbasha K., Hariharasakthisudan P. Influence of binder on thermomechanical and tribological performance in brake pad. *Tribology in Industry*, 2018, vol. 40 (4), pp. 654–669. DOI: 10.24874/ti.2018.40.04.12.

26. Yu K., Shang X., Zhao X., Fu L., Zuo X., Yang H. High frictional stability of braking material reinforced by Basalt fibers. *Tribology International*, 2023, vol. 178, p. 108048. DOI: 10.1016/j.triboint.2022.108048.

Conflicts of Interest

The authors declare no conflict of interest.