ENHANCED WEAR AND TENSILE PERFORMANCE OF CARBON FIBER-REINFORCED FRICTION PADS FOR AUTOMOTIVE APPLICATIONS

Ragu S[1*], Thayanithi V[2], Jagadeesh G[2], Mohammed Ismail Arif J[2], Kishore S[2] and Sunjaiy Varahan V S[2]

[1]*Assistant Professor, Department of Automobile Engineering, Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, India – 641032.*
[2]*UG Student, Department of Automobile Engineering, Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, India – 641032.*

Abstract: *Composite materials have become indispensable in advanced automotive applications due to their excellent mechanical strength, thermal stability, and wear resistance. In this study, commercial friction pad materials were enhanced by reinforcing them with carbon fibers in varying weight percentages (1.0 to 5.0 wt.%) to investigate improvements in tribological and mechanical behavior. The friction pads were fabricated using a conventional compression molding technique, while carbon fibers were prepared through pyrolytic treatment and uniformly integrated into the friction matrix. Wear characteristics were evaluated using a pin-on-disc tribometer across varying sliding distances (157–942 m) and under three load conditions (50 N, 100 N, and 150 N). Tensile strength was determined using an Instron universal testing machine. The results revealed that the friction pad reinforced with 3.0 wt.% carbon fiber displayed a remarkable reduction in specific wear rate—up to 81% under a 50 N load compared to the unreinforced pad. Additionally, the same composition showed the highest ultimate tensile strength of 371 MPa, representing a 312% improvement over the commercial friction pad. These enhancements are attributed to the homogeneous dispersion of carbon fibers, which significantly improved load transfer, minimized material degradation, and provided superior resistance to mechanical and thermal stresses. The study confirms that carbon fiber reinforcement, particularly at 3.0 wt.%, significantly improve the performance of friction pads, making them highly suitable for use in heavy-duty vehicles and high-performance braking and transmission systems.*

Keywords: **Wear, Friction, Carbon Fiber, Tensile**

1. INTRODUCTION

Composite materials have increasingly replaced traditional engineering materials in automotive, aerospace, and structural applications due to their customizable properties, enhanced durability, and superior mechanical performance. Among various composite systems, fiber-reinforced composites have gained special importance in frictional components, particularly in clutch and brake pad systems, where mechanical strength, thermal resistance, and wear behavior are critical [1,2]. In automotive braking systems, materials are subjected to fluctuating loads, high contact temperatures, and rapid engagement cycles. Conventional friction materials such as asbestos-based or semi-metallic composites often fall short in meeting modern performance requirements due to limitations in thermal degradation resistance, mechanical integrity, and environmental safety [3,4]. Recent advancements have focused on integrating synthetic fibers, particularly carbon fibers, into resin matrices to develop high-performance friction materials. Carbon fibers are known for their exceptional tensile strength, low thermal expansion, and high thermal conductivity, making them ideal reinforcements for thermally stressed environments [5–7]. The incorporation of carbon fibers in weight fractions ranging from 1 to 5 wt.% has been observed to significantly improve the tribological and mechanical performance of brake pad composites [8,9]. The function of carbon fibers in friction materials extends beyond mechanical reinforcement. They enhance the dissipation of heat generated during braking, stabilize the coefficient of friction, and reduce wear loss, all of which contribute to improved operational efficiency and component lifespan [10,11]. Studies using pin-on-disc tribometers for wear testing under constant applied pressure conditions (typically 2 MPa) have shown reduced wear rates and improved frictional stability for carbon fiber-reinforced composites when compared to conventional pads [12–14].

*Corresponding Author

Simultaneously, mechanical testing using universal tensile test machines such as the Instron has validated the increased tensile strength and load-bearing capacity of these composites [15,16]. This is especially important in high-performance vehicles and heavy-duty transportation systems where frequent braking and clutch engagement result in cyclic thermal and mechanical loading [17]. Carbon fiber reinforcement ensures structural stability during such operations and prevents deformation or cracking of the friction pad, thereby improving braking response and overall safety [18]. Another crucial advantage of carbon fiber composites lies in their thermal behavior. Enhanced thermal conductivity and heat resistance ensure that excessive temperatures generated during braking are quickly dissipated, preventing thermal degradation of the material matrix [19]. This feature makes them especially suitable for use in high-speed sports cars, commercial heavy vehicles, and performance motorcycles where thermal loads are typically extreme [20]. Thus, based on the collective findings of previous research, carbon fiber-reinforced friction materials represent a viable path toward the development of environmentally friendly, high-performance, and thermally resilient braking components. The present study investigates the wear resistance and mechanical strength of carbon fiber-reinforced friction pads at varying reinforcement levels (1–5 wt.%) using standardized testing protocols. Both unreinforced and reinforced specimens are tested under a constant applied pressure of 2 MPa to simulate real-world braking conditions, aiming to establish their suitability for modern automotive systems requiring consistent braking performance and efficient power transmission.

2. MATERIALS AND METHODS

2.1. Fabrication of friction pad

The fabrication of commercial friction pads involves a multi-step process that begins with the precise selection and weighing of various ingredients. These include a phenolic resin matrix, reinforcing fibers (such as aramid or steel fibers), abrasive agents, fillers, friction modifiers, and solid lubricants. All ingredients are dry-mixed using a high-speed mixer to ensure uniform dispersion and homogeneity. The mixture is then compacted using a cold pressing operation to form a preform of the desired shape. This preform is then transferred to a hot compression molding press, where it is subjected to pressures ranging from 35 to 50 MPa and temperatures between 150 and 180 °C for a duration of 10 to 15 minutes. This stage allows the phenolic resin to undergo polymerization, providing the mechanical rigidity required for braking applications. After molding, the pads are post-cured in a convection oven at approximately 180 °C for around 4 hours to ensure complete cross-linking of the resin. Following post-curing, the components are allowed to cool, and finishing operations such as grinding and trimming are performed to achieve the final dimensions, surface finish, and fit necessary for installation in automotive braking systems.

2.2. Carbon fiber manufacturing method

Carbon fibers used for reinforcement in friction composites are typically manufactured through the pyrolysis of polyacrylonitrile (PAN) precursor fibers. The process begins with the stabilization of PAN fibers in an oxidizing atmosphere, typically air, at temperatures between 200 and 300 °C. During this phase, the polymer chains undergo cyclization reactions to form a stable ladder structure. This is followed by carbonization, where the stabilized fibers are heated in an inert environment, such as nitrogen, at temperatures ranging from 1000 to 1500 °C. During carbonization, non-carbon elements like nitrogen, hydrogen, and oxygen are expelled, leaving behind a carbon-rich structure. For applications requiring extremely high modulus and thermal conductivity, the fibers may be further graphitized at temperatures exceeding 2500 °C to improve crystalline alignment. After heat treatment, the surface of the carbon fibers is treated chemically or electrochemically to introduce functional groups that enhance interfacial bonding with the resin matrix. A protective sizing agent is then applied to improve fiber handling, compatibility, and shelf life. These fibers are then chopped to lengths between 3 to 6 mm for use in friction pad fabrication.

2.3. Carbon fiber friction pad sample preparation

The fabrication of carbon fiber-reinforced friction pads follows a similar methodology to the commercial pad fabrication, with the key variation being the inclusion of carbon fibers as a reinforcement phase. In this study, carbon fibers were incorporated into the friction pad formulation at varying weight percentages of 1%, 2%, 3%, 4%, and 5%. The base formulation included phenolic resin, abrasive particles, solid lubricants, fillers, and other standard additives. The dry mixing of all ingredients, including chopped carbon fibers (3–6 mm), was carried out in a blade-type mechanical mixer to ensure uniform distribution throughout the mixture. After achieving a homogeneous blend, the material was cold pressed into a preform using a hydraulic press. The preform was then subjected to hot compression molding at a temperature of 160 to 170 °C under a pressure of 40 MPa for about 15 minutes. The heat and pressure initiated the curing of the phenolic resin, embedding the carbon fibers within the matrix. Post-curing was carried out in an oven at 180 °C for 4–6 hours to enhance the thermal and mechanical properties of the composite. After curing, each sample was machined into test specimens of standard size for mechanical and tribological evaluation.

2.4. Wear test

The tribological performance of the fabricated friction pad composites was evaluated using a pin-on-disc tribometer as per ASTM G99 standards. Test specimens were machined into cylindrical pins of 10 mm diameter and 20 mm length, ensuring that the surface to be tested was flat and parallel to the counterface. The disc used in the test was made of hardened EN31 steel with a surface hardness of approximately 60 HRC and a polished finish. During testing, a normal load corresponding to 2 MPa of applied pressure was maintained uniformly across all samples. The sliding speed was kept in the range of 1.5 to 2.0 m/s, and the total sliding distance was maintained between 1500 and 3000 meters depending on the fiber content. All tests were conducted under dry sliding conditions at room temperature (~25 °C) and average ambient humidity (~50%). Frictional force and coefficient of friction were continuously recorded during the test. After testing, wear loss was measured by calculating the weight difference of each specimen before and after the test using a high-precision electronic balance. The wear rate was calculated based on mass loss, sliding distance, and normal load. The wear surface was then examined using optical microscopy and scanning electron microscopy (SEM) to study the dominant wear mechanisms and surface characteristics.

2.5. Tensile test

The tensile strength of the fabricated friction pad specimens was determined using a universal testing machine, specifically the Instron 3369, in accordance with ASTM D638 standards. The test samples were prepared in a standard dog-bone shape with Type I dimensions, which ensured that failure occurred in the gauge section. Before testing, each sample was visually inspected for surface defects and aligned carefully in the grips of the machine to prevent bending stresses. The gauge length was set to 50 mm, and the crosshead speed was maintained at 2 mm/min to ensure quasi-static loading. The load cell used had a capacity of 10 kN, which was sufficient for capturing the entire loading and failure sequence of the composite specimens. During the test, parameters such as ultimate tensile strength, Young's modulus, and elongation at break were recorded in real time using the machine's software. Each test was repeated three times for every composition (including unreinforced and reinforced samples), and the average values were reported for analysis. The tensile data was used to understand the reinforcing effect of carbon fibers on the structural integrity and load-bearing capability of the friction material.

3. RESULT AND DISCUSSION

3.1. Wear characteristics

The wear resistance behavior of friction materials is a primary factor governing the safety, longevity, and reliability of braking systems, particularly under variable load and distance conditions. In this study, the commercial friction pad (FP) and carbon fiber-reinforced friction pad (CF-RFP) composites with varying reinforcement levels from 1.0 to 5.0 wt.% were tested at sliding distances ranging from 157 to 942 meters under loads of 50 N, 100 N, and 150 N. The aim was to investigate how carbon fiber content influences the wear performance and to determine the optimal reinforcement percentage for effective tribological performance. Under a load of 50 N, the neat friction pad displayed the highest specific wear rate throughout the entire distance range as presented in figure 1. When reinforced with 1.0 wt.% carbon fibers, the wear rate reduced by approximately 18–20%, and with 2.0 wt.% reinforcement, the reduction increased further to around 30–48% depending on distance. A significant wear reduction occurred with 3.0 wt.% carbon fiber reinforcement, reaching up to 80% at shorter distances and maintaining a reduction of over 81% at longer sliding distances (942 m) compared to the unreinforced pad. This notable improvement is attributed to the homogeneous dispersion of carbon fibers within the matrix, which effectively resisted surface degradation through improved load distribution and energy dissipation at the contact interface. Interestingly, with 4.0 wt.% and 5.0 wt.% reinforcement, the wear rate increased relative to the 3.0 wt.% composition, indicating that excessive fiber content may lead to agglomeration, disrupting uniform fiber distribution and creating local stress concentrations. These weak zones limit the interfacial bonding, reducing the reinforcement's effectiveness, and leading to a gradual rise in wear rate. At 100 N load, the trend remained consistent. The FP showed accelerated wear, but the addition of carbon fibers significantly enhanced wear resistance. The 3.0 wt.% reinforced composite again exhibited optimal performance with specific wear rate reductions ranging between 65–78% compared to the neat FP. While 2.0 wt.% reinforcement also

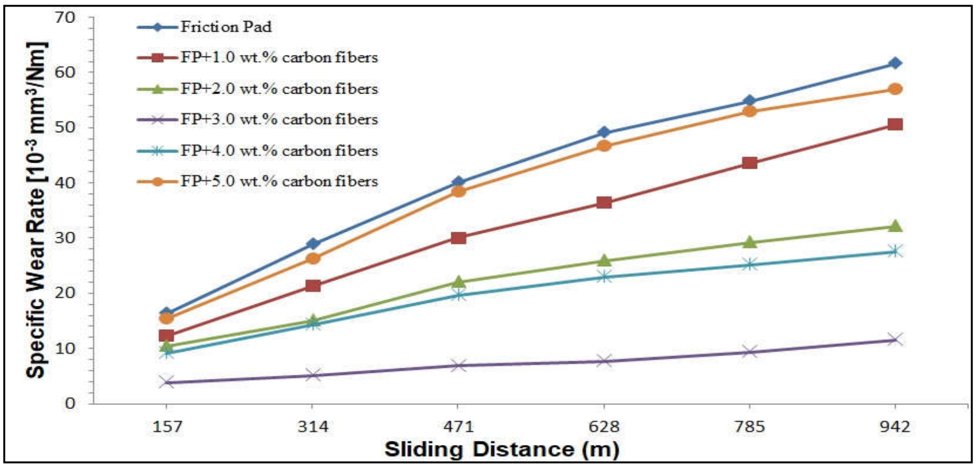

Figure 1. Specific wear rate of friction pad and carbon fibers reinforced friction pad at 50N

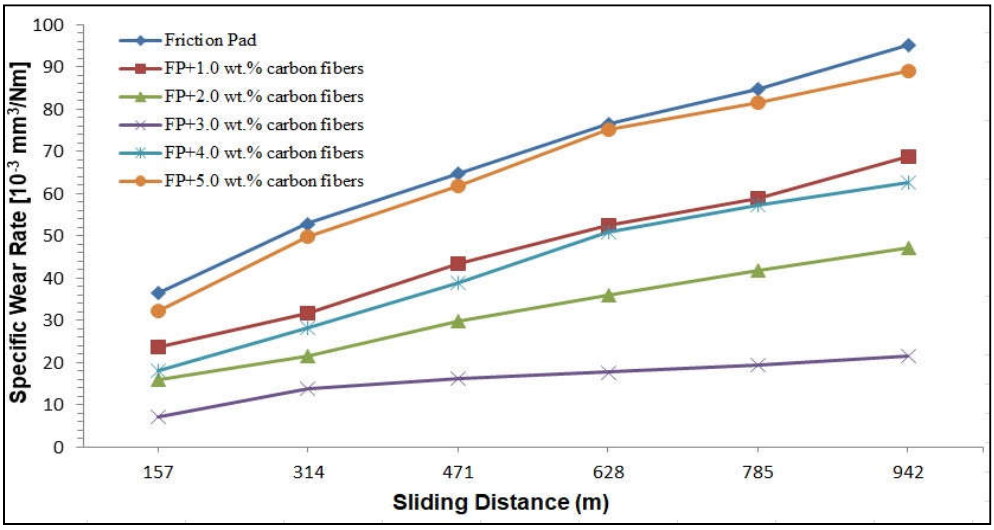

Figure 2. Specific wear rate of friction pad and carbon fibers reinforced friction pad at 100N

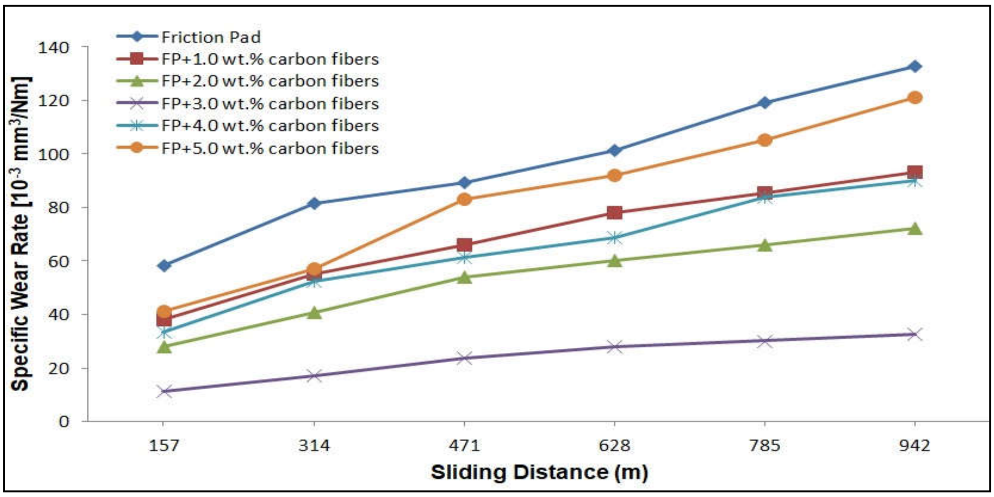

Figure 3. Specific wear rate of friction pad and carbon fibers reinforced friction pad at 150N

performed well, its wear reduction was slightly lower, ranging between 40–55%, depending on distance. The superior wear performance of the 3.0 wt.% composite at this load level reaffirms the critical role of carbon fiber in resisting mechanical and thermal stress, likely due to improved thermal conductivity and load-bearing capacity provided by the carbon phase, which helps dissipate frictional heat and minimize material degradation as shown in figure 2. The load was further increased to 150 N, the influence of reinforcement became even more prominent as shown in figure 3. The neat FP suffered the highest wear due to increased contact pressure and heat generation. The 3.0 wt.% carbon fiber composite showed the most remarkable reduction in wear, achieving over 75% reduction at initial distances and maintaining about 76% reduction at the longest sliding distance compared to FP. This consistent performance under severe loading conditions emphasizes that the optimal carbon fiber content significantly contributes to thermal stability and wear protection. It also highlights the role of uniform fiber-matrix bonding, which effectively restricts crack initiation and propagation even under elevated thermal and mechanical stress. On the other hand, increasing fiber content beyond 3.0

wt.% at 150 N load adversely affected wear resistance. For instance, 5.0 wt.% composites exhibited wear rates close to or higher than 1.0 wt.% composites, demonstrating that excessive fiber loading leads to diminished mechanical synergy due to fiber clustering and inadequate bonding. Hence, the performance is compromised by poor matrix integrity and increased susceptibility to fiber pull-out or matrix fragmentation. Overall, the trend across all three loading conditions consistently indicates that the 3.0 wt.% carbon fiber reinforcement offers the most balanced and effective wear resistance due to homogeneous fiber dispersion, enhanced interfacial strength, and reduced thermal softening. The tribological stability of the CF-RFPs under various operating conditions confirms the potential of carbon fibers as a performance-enhancing reinforcement in frictional composites, especially for high-load automotive applications such as heavy vehicles and sports cars. The study clearly demonstrates that precise control over fiber content and distribution is essential to harness the full benefits of carbon reinforcement in friction materials.

3.2. Tensile characteristics

The tensile strength of a friction material is a critical parameter that determines its structural integrity and ability to withstand mechanical loads during braking and clutch operations. In the present investigation, the commercial friction pad (FP) and its carbon fiber-reinforced variants were evaluated to assess the effect of reinforcement on their ultimate tensile strength (UTS) as shown in figure 4. The unreinforced friction pad exhibited a baseline tensile strength of 90 MPa. With the introduction of carbon fibers at 1.0 wt.%, the tensile strength significantly improved to 182 MPa, registering a 102.2% increase. This improvement indicates the initial positive influence of fiber inclusion on the matrix strength. As the reinforcement increased to 2.0 wt.%, the tensile strength rose further to 231 MPa, reflecting a 156.7% enhancement over the commercial pad. This upward trend continued and peaked at 3.0 wt.% carbon fiber content, where the UTS reached 371 MPa, representing a remarkable 312.2% improvement compared to the unreinforced composition. The substantial increase in strength at this composition is attributed to the homogeneous dispersion of carbon fibers, which enhances load transfer efficiency between the matrix and the reinforcement. The uniform fiber distribution also contributes to crack arrest mechanisms, thereby improving the composite's resistance to failure under tensile loads.

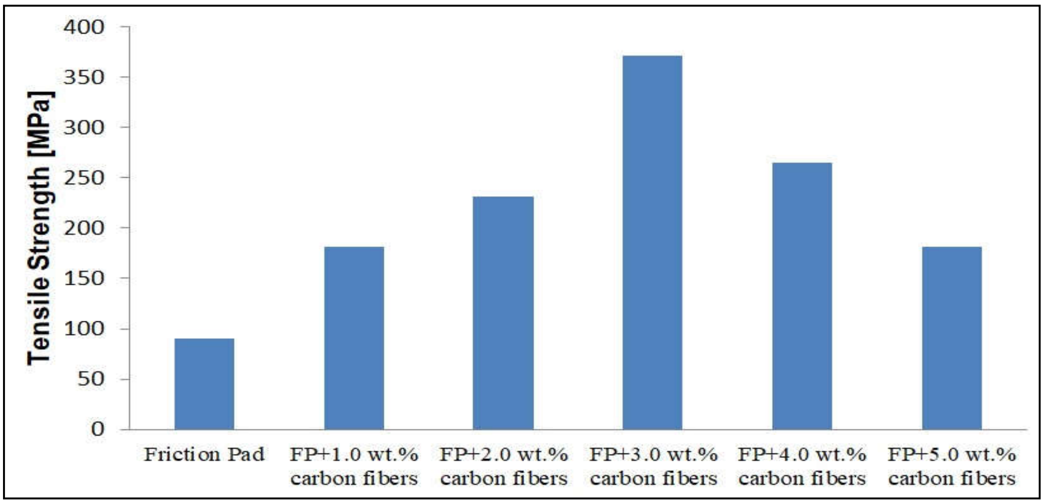

Figure 4 Tensile characteristics of friction pad and carbon fibers reinforced friction pad

However, beyond the 3.0 wt.% reinforcement level, a decline in tensile strength was observed. At 4.0 wt.%, the UTS decreased to 265 MPa, and further dropped to 181 MPa at 5.0 wt.%. This reduction is likely due to fiber agglomeration and poor interfacial bonding, which introduce stress concentration zones within the matrix and hinder effective stress transfer. The excess fiber content, instead of enhancing the matrix, becomes a defect-prone phase, compromising the mechanical integrity. The 3.0 wt.% carbon fiber-reinforced composite demonstrated optimal performance, balancing mechanical reinforcement and structural cohesion. This result highlights the vital role of carbon fiber in enhancing tensile properties when uniformly dispersed, supporting its application in high-performance friction materials.

4. CONCLUSION

1. The carbon fiber-reinforced friction pad with 3.0 wt.% loading exhibited the most effective performance in terms of both wear resistance and tensile strength, making it the optimal composition among all tested variants.
2. Under a 50 N load, the 3.0 wt.% carbon fiber composite demonstrated an 81% reduction in specific wear rate compared to the commercial friction pad, with similar improvements of 65–78% and above 75% observed at 100 N and 150 N loads, respectively.
3. The ultimate tensile strength of the composite increased by approximately 312% at 3.0 wt.% reinforcement, rising from 90 MPa to 371 MPa, showing a significant enhancement in the material's ability to resist mechanical failure under stress.
4. The improvements in mechanical and wear properties are primarily attributed to the homogeneous dispersion of carbon fibers within the matrix, which promoted effective stress transfer, minimized crack propagation, and enhanced thermal stability.
5. Reinforcement levels beyond 3.0 wt.% led to decreased performance due to fiber agglomeration and weak interfacial bonding, indicating that excessive fiber content introduces structural irregularities that diminish the material's integrity.
6. The developed carbon fiber-reinforced friction pad at optimal composition is highly suitable for demanding automotive applications such as heavy vehicles and sports cars, offering improved braking efficiency, superior power transmission, and reliable heat resistance under operational loads.

REFERENCES

1. Jang H., Ko K., Kim S.J., Lee H. "The effect of ingredient morphology on the friction performance of brake friction materials," Wear, Vol. 256, Issue 3–4, pp. 406–414, 2004.
2. Blau P.J., "Compositions, functions, and testing of friction brake materials and their additives," Oak Ridge National Laboratory Report, ORNL/TM-2001/64, pp. 1–78, 2001.
3. Bijwe J., Kumar M., Majumdar N., "Optimization of steel wool and aramid fibre in friction composites for best combination of performance properties," Wear, Vol. 265, Issue 3–4, pp. 699–712, 2008.
4. Karthikeyan R., Vijayarangan S., "Development of natural fiber reinforced brake friction materials using Taguchi method," Materials and Design, Vol. 30, Issue 9, pp. 3203–3210, 2009.
5. Chan D., Stachowiak G.W., "Review of automotive brake friction materials," Proceedings of the Institution of Mechanical Engineers Part D: Journal of Automobile Engineering, Vol. 218, Issue 9, pp. 953–966, 2004.

6. Lee W.J., Kim S.J., Jang H., "Effect of steel wool length on the friction and wear performance of brake friction materials," Tribology Letters, Vol. 30, Issue 2, pp. 109–117, 2008.
7. Lim D.S., Lee W.S., Kim S.J., Jang H., "Effects of phenolic resin, graphite and aramid fiber on the friction and wear characteristics of brake friction materials," Journal of Material Processing Technology, Vol. 136, Issue 1–3, pp. 202–208, 2003.
8. Tanweer S., Jamil M., Ali A., "Mechanical and tribological properties of natural fiber reinforced friction materials: A review," Composite Interfaces, Vol. 27, Issue 4, pp. 387–418, 2020.
9. Zhang S., Li J., Wang Y., "Performance analysis of hybrid fiber reinforced friction materials using Taguchi design," Materials Research Express, Vol. 6, Issue 11, 115309, 2019.
10. Sathishkumar T.P., Satheeshkumar S., Naveen J., "Hybrid fiber reinforced polymer composites – A review," Journal of Reinforced Plastics and Composites, Vol. 33, Issue 5, pp. 454–471, 2014.
11. Sharma S.C., Krishna M., Kamath M.V., "Mechanical and wear behavior of glass and carbon fiber reinforced epoxy composites," Wear, Vol. 253, Issue 3–4, pp. 529–536, 2002.
12. Basavarajappa S., Chandramohan G., Paulo Davim J., "Application of Taguchi techniques to study dry sliding wear behavior of metal matrix composites," Materials and Design, Vol. 28, Issue 4, pp. 1393–1398, 2007.
13. Wahid M., Khalid M., Hassan A., Ismail Z., "Mechanical and wear behavior of basalt and E-glass fiber reinforced epoxy composites," Journal of Reinforced Plastics and Composites, Vol. 32, Issue 2, pp. 1–11, 2013.
14. Jeyakumar P., Aravindan S., Rajadurai A., "Studies on mechanical and dry sliding wear behavior of Al 7075/SiC composite," Materials and Design, Vol. 30, Issue 9, pp. 3497–3502, 2009.
15. Ramesh M., Palanikumar K., Reddy K.H., "Comparative evaluation of mechanical properties of jute and glass fiber reinforced polymer composites," Materials and Design, Vol. 51, pp. 357–366, 2013.
16. Mallesham B., Ramesh C.S., "Friction and wear characteristics of carbon fiber reinforced epoxy composites," Tribology in Industry, Vol. 39, Issue 1, pp. 90–97, 2017.
17. Kumar A., Bijwe J., "Composites containing combinations of ingredients in friction materials: Effects on performance," Journal of Reinforced Plastics and Composites, Vol. 25, Issue 9, pp. 937–948, 2006.
18. Unal H., Mimaroglu A., "Friction and wear performance of polyamide 6 and polyamide 6 composites under dry sliding conditions," Wear, Vol. 255, Issue 1–6, pp. 556–562, 2003.
19. Lee S.W., Kim S.J., Jang H., "Optimization of components in brake lining using Taguchi method," Wear, Vol. 250, Issue 1–12, pp. 82–88, 2001.
20. Muthusamy P., Pitchipoo P., "Effect of fiber reinforcement in polymer matrix brake pad composites – A review," Materials Today: Proceedings, Vol. 33, Issue 5, pp. 2398–2403, 2020.