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Virtual Wear Prediction of Alternative Brake Friction Composites using Finite Element Simulation

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Abstract

This study presents a modelling and simulation approach for predicting the wear of brake friction composites in automotive brake applications. Two alternative brake friction composites are compared for their wear performance through a virtual pin-on-disc mechanism. The pin specimens consist of two developed compositions: one with basalt fibre and calcium carbonate filler, and the other with aramid fibre and barium sulfate filler. Both have common ingredients like phenolic resin, graphite, and friction modifiers. Experimental pin-on-disc wear tests validate comparative wear performance of brake friction composites as per the finite element analysis findings. This indicates their capability for potential applications in automotive brake systems. The research also establishes a methodology for digital development of eco-friendly brake friction materials through optimal formulation of ingredients using Computer Aided Engineering (CAE).

Major Findings: *The aramid fibre-based brake composite exhibits superior wear resistance and friction performance compared to the basalt fibre-based composite. The finite element analysis results were validated by experimental pin-on-disc wear tests. These findings confirm the potential of these composites as eco-friendly alternatives for automotive brake applications.*

Keywords: *Brake Friction Composites, CAE Simulation, Pin on Disc Test, Wear*

1.0 Introduction

The brake systems are certainly important for stopping an automobile and ensuring everyone's safety on the road. The disc brake's effectiveness relies on the friction between the brake pad and the rotor disc. Therefore, choosing the right materials for the composition of a brake friction composite is crucial for productive braking[1]. These brake friction composites are made up of fibres, binders, friction modifiers, and fillers. They play a key role in shaping essential tribological properties of materials[2,3]. To avoid quick wear and a drop in braking performance, the appropriate materials should be selected[4,5]. The wear behaviour of these materials directly affects braking efficiency and longevity.

In this work, current research findings related to wear prediction based on pin-on-disc tests are studied. Virtual wear prediction in brake friction composites is a critical area of research, considering the demand for improved safety and sustainability in automotive brake systems. This study uses CAE tools to simulate the pin-on-disc mechanism setup and provides a robust framework for predicting wear behaviour and material weight loss in friction composites. The wear behaviour of brake materials is influenced by various factors, including thermal dynamics, material composition, and mechanical interactions. As asbestos has outstanding friction and wear characteristics, it is commonly employed as a significant element in brake composite materials. However, its usage has been discouraged due to significant health

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risks[6,7]. In recent years, the emphasis has switched toward discovering alternative materials to replace asbestos-based composites[8-10].

Kumar and Bijwe[11] examined the response of the friction coefficient of brake friction composites to operating variables. Further research has demonstrated the need for knowing composition-specific sensitivity and proposed strategies for improving the effectiveness and durability of friction composite materials[12,13]. Bhanudas Bachchhav *et al.*[13] evaluated the wear performance of non-asbestos friction materials that slid against a grey cast iron disk. The study revealed insights into material wear rates, allowing the selection of appropriate friction materials for braking system applications[10,13].

The material composition of brake friction composites plays a crucial role in determining their wear resistance. The findings from Prasad *et al.*[9] are particularly relevant for the investigation of Aramid-based and basalt-based composites, as understanding the relationship between reinforcement type and wear behaviour can guide the development of more effective brake materials. Another study[14] investigated the impact of bimodal-sized particle reinforcement on the wear, friction, and mechanical properties of brake composites. The findings highlight that the inclusion of bimodal particles enhances wear resistance and mechanical strength, making the composites more suitable for braking applications. Singh *et al.*[15] evaluated phenolic-based non-asbestos organic brake friction composites with various abrasives. It identified aluminium oxide as the most effective abrasive for achieving high friction stability and low fade, while zinc oxide provided superior wear resistance. The study underscores the importance of abrasive selection in optimising brake performance[15].

Another research[16] explored the role of graphitic carbon nitride (g-C_3N_4) in copper-free friction composites for automotive brake pads. The results demonstrated that g-C_3N_4 acts as a soft abrasive, improving friction stability and wear resistance under varying temperature conditions. While previous studies[4,10,13] have established foundational insights into wear mechanisms and predictive modelling, there is a potential for comprehensive comparative studies specifically focusing on fibre and filler-based alternative brake composites. Future research aims to investigate the long-term wear behaviour of aramid-based and basalt-based composites under real-world operating conditions to validate FEA predictions.

2.0 Materials and Methods

2.1 Ingredients for Brake Friction Composites Materials

After considerable review studies[17-20] on the desired properties of elements for brake friction material compositions, the following two crucial combinations were developed for comparative virtual testing and evaluation.

1. Basalt fibre, calcium carbonate filler, resin binder, graphite friction modifier, and balancing ingredients.

Table 1. Formulation of BFC1 composition

Sr. No.	Material	Percentage By weight
1	Basalt	30 %
2	Calcium Carbonate	40%
3	Phenolic Resin	20%
4	Graphite	5%
5	Other fillers (alumina, copper fibres)	5%

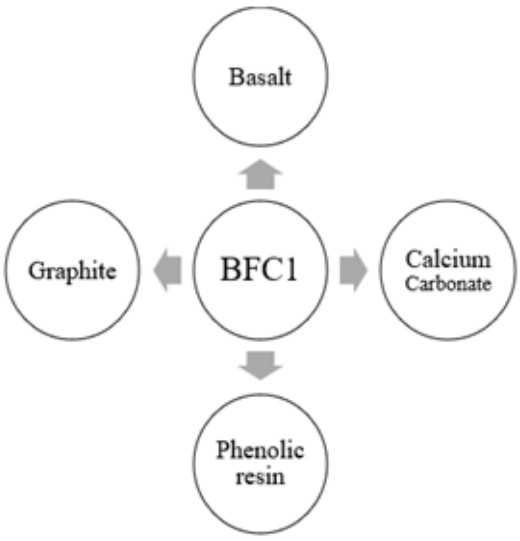


Figure 1. Major ingredients of BFC1.

This composition is represented as Brake Friction Composite 1 (BFC1). The formulation is presented in Table 1.

Figure 1 presents the major ingredients of Brake Friction Composite 1 (BFC1).

2. Aramid fibre, barium sulfate filler, resin binder, graphite friction modifier, and balancing ingredients.

This composition is represented as Brake Friction Composite 2 (BFC2). The formulation is presented in Table 2.

Table 2. Formulation of BFC2 composition

Sr. No.	Material	Percentage By weight
1	Aramid	30%
2	Barium Sulfate	40%
3	Phenolic Resin	20%
4	Graphite	5%
5	Other fillers (alumina, copper fibres)	5%

Figure 2 presents the major ingredients of Brake Friction Composite 2 (BFC2).

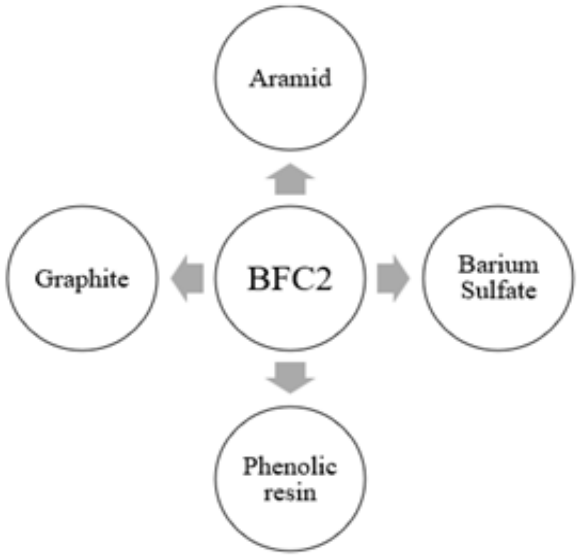


Figure 2. Major ingredients of BFC2.

2.2 Virtual Wear Prediction using Simulation of Pin-on-Disc Setup

Researchers[13,15,18] use the Pin-on-disc tribometer system to develop friction composite materials and benchmark their performance. This method employs a pin-on-disc configuration to measure the wear of materials as they slide against one another[21]. Recent studies have explored various methodologies for wear prediction in brake friction materials. Saurabh A *et al.*[22] conducted a comparative study on semi-metallic and ceramic friction materials using finite element simulation and experimental methods. Their research highlighted the superior performance of ceramic materials under high loading conditions, emphasising their potential for reduced wear and improved friction properties. This study provides a foundation for exploring alternative composites, as proposed in the current work.

Springis G *et al.*[23] reviewed various wear models, including analytical and experimental approaches, to enhance wear prediction accuracy. They identified limitations in classical wear models, such as the inability to account for material fatigue effects and 3D surface texture parameters. The integration of FEA and probabilistic surface modelling, as discussed in their work, helps to develop wear prediction techniques for alternative brake friction composites.

Yan L *et al.*[24] explored the application of FEM in wear simulation, focusing on factors affecting wear behavior and the practical application of the method. Their review underscored the cost-effectiveness and versatility of FEM compared to experimental methods.

Building upon these findings, this study aims to adapt finite element simulation to analyse the wear characteristics of proposed brake friction composites.

For wear prediction, a transient analysis is performed to study the changes in wear behaviour over time. This type of analysis is crucial for understanding materials' behaviour under varying operational conditions, such as changes in load, speed, temperature, or lubrication.

The key steps involved in transient analysis using a CAE tool are listed below.

- Input the material's engineering data.
- Create a CAD model of the pin and disc geometry, followed by FEM meshing of the geometry.
- Identify and specify the contact pairs.
- Assign the contact and target surfaces.

- Control the motion of the target surface as required.
- Apply appropriate boundary conditions.
- Define the solution settings and load steps, then proceed to solve the problem.
- Review and interpret the results.

As per the above steps, a pin-on-disc geometry setup was modelled using CAD software. The pin-on-disc setup has two main parts, as shown in Figure 3. First, a cylindrical pin, which stands upright. The other part is usually a flat, round disc positioned below the pin. The pin specimens used in these tests were 32 mm in length

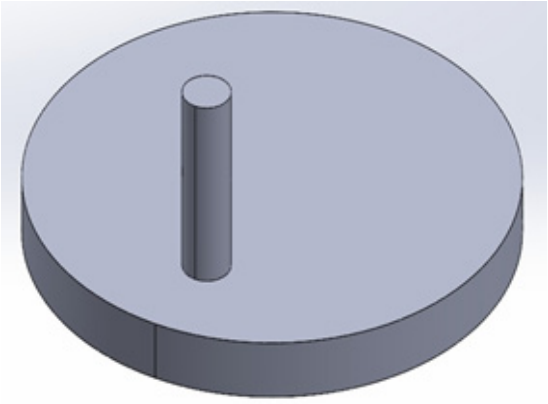


Figure 3. Geometrical model of the pin on a disc setup.

and 10 mm in diameter. The same disc dimensions of 165 mm in diameter and 8 mm in thickness were considered for all the case studies.

To predict the wear loss of the proposed composites virtually, a finite element model was prepared using CAE software. Key factors such as contact pressure, sliding speed, and time were considered for transient structural analysis. To predict wear, the Archard wear equation was utilised, which calculates wear volume based on the load, the distance slid, and the hardness of the materials involved.

Two individual case studies were simulated to evaluate the wear performance of brake friction composites BFC1 and BFC2. In the first case, the BFC1 material properties were assigned to the pin. In the second case, the BFC2 material properties were assigned to the pin. Other conditions were kept the same for the comparative study.

To perform the transient analysis of the developed composites, the ingredients' materials properties of each brake friction composite are considered and combined composite properties are determined separately using the rule of mixtures.

The determined properties of BFC1 and BFC2 are presented in Tables 3 and 4, respectively.

Table 3. Properties of BFC1

Sr. no.	Properties	Values
1	Density	2.644 g/cm^3
2	Young's Modulus	50.420 GPa
3	Poisson's Ratio	0.316

Table 4. Properties of BFC2

Sr. no.	Properties	Values
1	Density	3.034 g/cm^3
2	Young's Modulus	71.095 GPa
3	Poisson's Ratio	0.306

3.0 Results and Discussion

Figures 4 and 5 display results for virtual deformations of BFC1 and BFC2 composites, subjected to a transient structural analysis simulation. Based on the Archard wear law, wear volume is inversely proportional to the hardness of the material. Less deformation typically indicates higher hardness, which reduces wear loss. So,

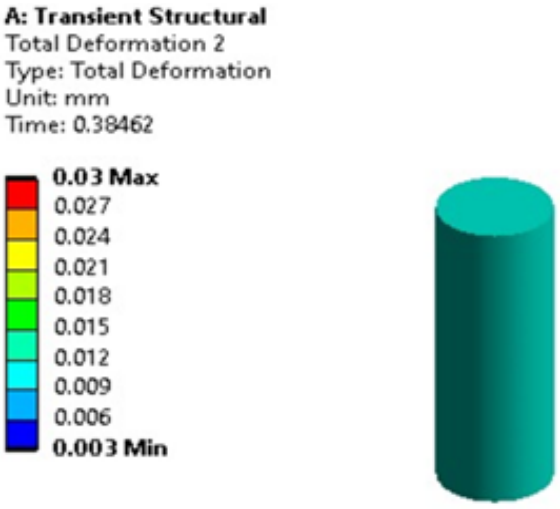


Figure 4. Finite element deformation plot for the pin of BFC1.

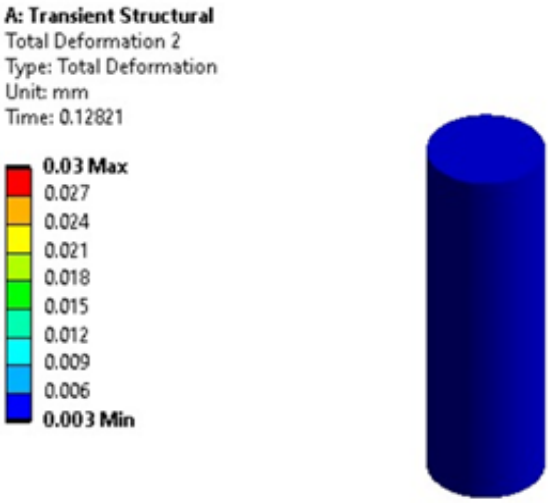


Figure 5. Finite element deformation plot for the pin of BFC2.

less deformation in this study suggests less wear loss due to friction between the pin and disc.

The average deformation in the BFC1 pin case study was much higher than BFC2, which implies better deformation resistance of the BFC2 composition than the BFC1. This generates less stress accumulation, which helps in the wear resistance, rigid and stable braking during high speeds.

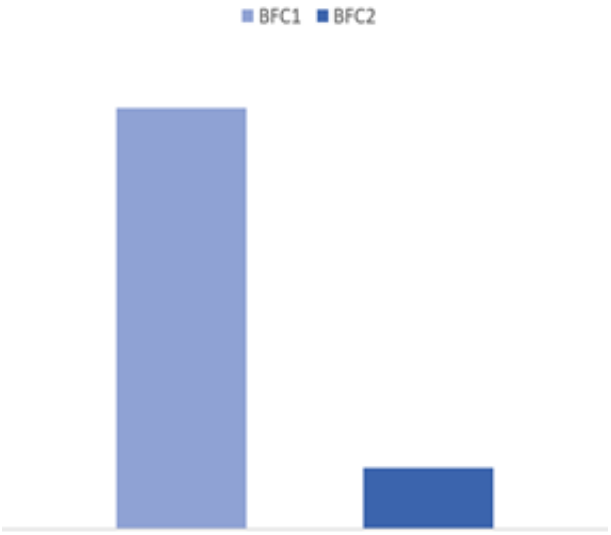


Figure 6. Comparison of predicted wear loss of pin samples of BFC1 and BFC2.

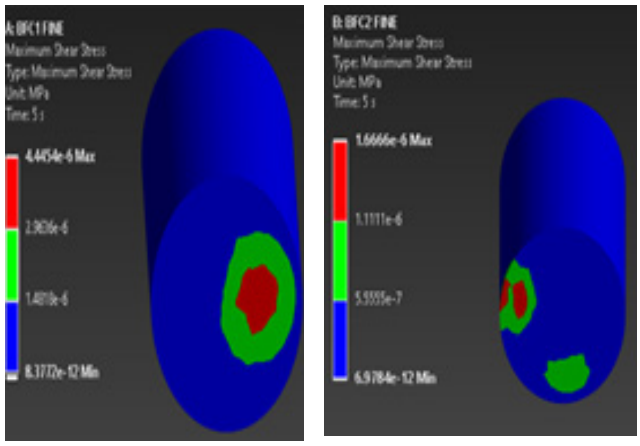


Figure 7. Maximum shear stress plots for pins of BFC1 and BFC2, respectively.

Figure 6 displays a comparison graph for the average predicted wear loss of BFC1 and BFC2 samples. It indicates the BFC1 composition has higher material loss compared to the BFC2. This observation is in agreement with the stronger material properties in the BFC2 composition. The lower wear loss of the BFC2 observed in the wear simulations indicates a lower wear rate in comparison to BFC1. This lower wear rate contributes to better durability of brake friction composite applications.

Figure 7 displays virtual results for maximum shear stress for a pin made up of BFC1 and BFC2 composites subjected to a transient structural analysis simulation.



Figure 8. Comparison of maximum shear stress for pins of BFC1 and BFC2, respectively.

Based on the studies, lower shear stress in the pin of BFC2 suggests less wear loss due to friction between the pin and disc.

Figure 8 displays a comparison graph for the maximum shear stress for BFC1 and BFC2 composites subjected to a transient structural analysis simulation. It indicates the BFC2 composition has better wear resistance compared to the BFC1.

The combination of Aramid fibre with Barium Sulfate filler has been observed to increase the material's abrasiveness. Fillers such as calcium carbonate are known to amplify the abrasive interaction with the counter face, enhancing friction, but also potentially increasing wear[17]. The incorporation of aramid fibres also aids in reducing the overall weight of brake systems due to their low density, thereby improving fuel efficiency[7,10,18]. The inclusion of graphite particles as a friction modifier has been shown to provide stable friction properties and excellent wear resistance[3]. The resin binder is crucial for ensuring proper adhesion of various components and demonstrates high thermal resistance, which is essential for effective braking[20].

These basalt-based (BFC1) and aramid-based (BFC2) brake friction composites were also tested experimentally through a pin-on-disc wear test setup.

Table 5. Pin-on-disc experiment results for the brake friction composites

Properties	Friction coefficient μ	Wear loss (g)
BFC1	0.42	0.084
BFC2	0.48	0.011

As shown in Table 5, the aramid-based brake composite (BFC2) outperformed the basalt-based brake composite (BFC1) in terms of friction and wear performance. Therefore, this experimental study validates the finite element simulation study for comparative wear performance of the developed brake friction composites.

4.0 Conclusion

In automotive brake systems, durable and safe brake friction composite materials are necessarily used for high performance. These composites are engineered by carefully selecting and combining specific materials. In this study, BFC1 is developed for wear performance by combining basalt fibre, calcium carbonate filler, phenolic resin binder, and graphite friction modifier. BFC2 is primarily composed of aramid, barium sulfate, phenolic resin binder, and graphite friction modifier. Comparative finite element and experimental evaluations conducted using a pin-on-disc setup simulation revealed the following key findings:

- Friction Performance: BFC2, which incorporates Aramid fibres known for their high coefficient of friction, demonstrated better friction compared to BFC1, which has basalt fibres.
- Wear Resistance: Aramid fibres contribute to high tensile strength and wear resistance, while barium sulfate provides structural support and hardness. As a result, BFC2 exhibited lower weight loss and less wear rate, thereby enhancing its durability compared to BFC1.
- Eco-Friendly Alternatives: The research suggests that composites based on aramid and basalt fibres, and barium sulfate and calcium carbonate fillers, offer environmentally friendly alternatives to conventional asbestos-based friction materials.

Further research and development can focus on optimising composite formulations to improve the overall performance of brake friction composite materials. Based on these findings, brake system manufacturers can make informed choices for the ingredients used in friction composites. Additionally, researchers can explore the harmonious effects of combining various reinforcement materials to enhance wear resistance. This exploration contributes to continuous innovation and evaluation in developing applications for safe and sustainable automotive braking systems.

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