

SUSTAINABLE BRAKE PAD COMPOSITES REINFORCED WITH DATE PALM FIBER FOR ECO-FRIENDLY AUTOMOTIVE APPLICATIONS

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Graphical abstract



The change in brake pad shape due to thermal overload.

Abstract

The braking system is a vital component of any vehicle, directly impacting the safety of passengers and surrounding property. Given its pivotal role, the braking system is one of the main interfaces between the driver and the vehicle, making it essential for engineers and researchers to deeply understand and continuously improve its components. Among these components, the brake pad is of particular importance in determining the overall braking performance. This study focuses on optimizing brake pad materials to improve the efficiency of disc brakes under different operating conditions. Four brake pad samples, including a locally manufactured brake pad without date palm fiber (A) and three brake pad samples with added date palm fiber (B, C, and D), were manufactured using natural asbestos substitutes and containing different percentages of date palm fiber—namely 0%, 2.3%, 4.6%, and 6.9%, respectively. Experimental results reveal that higher percentages of date palm fiber lead to lower braking force, primarily due to a lower coefficient of friction. It is worth noting that sample (B), which contains 2.3% date palm fibers, showed the best performance, providing an ideal balance between braking force and frictional properties.

Keywords: Date palm fibre, Disc brake, Brake pads, Coefficient of friction, temperature

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1.0 INTRODUCTION

With the rapid advancement of the automobile industry, modern vehicles are expected to meet increasingly stringent safety and performance

standards. Among the critical systems that ensure both vehicle functionality and occupant safety, the braking system plays an indispensable role. It not only controls vehicle speed under various operating conditions but also ensures the safety of drivers,

passengers, and pedestrians by enabling effective deceleration and stopping. Consequently, the development and optimization of braking systems have become a major focus in automotive research and engineering [1, 2]. This study specifically focuses on the disc brake system, which has become the industry standard in modern vehicles due to its superior performance over traditional drum brakes. The disc brake system comprises several key components, including the brake pad, brake rotor, caliper, and associated hardware. Of these, the brake pad and rotor are especially critical, as they directly interact to generate the friction necessary for braking [3].

The brake pad functions as the primary frictional element; during braking, it presses against the rotor, converting the vehicle's kinetic energy into thermal energy through friction, thereby enabling deceleration or a complete stop. This process generates substantial heat, which must be managed efficiently to prevent brake fade and ensure consistent performance. As such, the brake pad's effectiveness is highly dependent on its material composition, design, and operational conditions, making it a central focus in research aimed at enhancing brake performance, safety, and durability [2, 4,5,6].

Given its crucial role, the brake pad must deliver consistent and reliable performance under a variety of driving conditions. Achieving optimal performance requires precise engineering and the careful selection of materials and additives in appropriate proportions. Materials used in brake pad manufacturing must meet several key criteria, including low wear rates, minimal noise generation, stable friction coefficients across a wide range of temperatures, and resistance to the high stresses and thermal loads generated during braking. Additionally, these materials should maintain performance over time while minimizing environmental impact, making material selection a pivotal aspect of modern brake pad development [7,8,9]. The materials used in the manufacturing of brake pads must fulfill several essential criteria to ensure their effectiveness and longevity. These include minimal wear, low noise generation, a stable friction coefficient across a range of operating temperatures, and the ability to withstand the high stresses and heat generated during braking. In addition, brake pads must maintain their performance over extended usage while minimizing their impact on the environment. Meeting these demanding requirements has made material selection a key focus of research in this field [7, 9-12]. Over the years, considerable research has been devoted to enhancing brake pad materials [10]; Fibers used in brake pads can be broadly categorized into synthetic and natural types, each offering unique benefits and challenges. Asbestos, once a widely used synthetic fiber due to its excellent thermal and mechanical properties, has been phased out in many countries following studies that linked it to severe health risks, including asbestosis and various cancers. The World Health Organization (WHO) has classified asbestos as a carcinogen,

prompting a global push toward safer alternatives [13,14,15].

In response, environmentally friendly and sustainable materials have gained traction. Natural fibers such as flax, kenaf, coconut, and sisal are being increasingly explored as asbestos replacements [8, 16]. These fibers address both environmental and health concerns while also offering promising mechanical and thermal properties suitable for brake applications. Research efforts continue to refine natural fiber-based composites to meet the stringent demands of modern braking systems while supporting environmental sustainability [17,18,19]. Beyond natural and synthetic fibers, modern brake pad development also incorporates advanced materials like carbon composites and polymers. These materials offer benefits such as enhanced friction stability, reduced wear, and consistent performance across a broad temperature range. Carbon composites are especially valued for their durability and thermal stability, making them ideal for high-performance and heavy-duty applications. Polymers, used as binders and friction modifiers, ensure homogeneity in the material matrix and contribute to the structural integrity and overall efficiency of the brake pad [10, 20].

Recent advancements have also introduced nanoparticles into brake pad formulations. Nanoparticles such as nano-oxides, nano-graphite, and carbon nanotubes are being utilized to improve the thermal, mechanical, and frictional characteristics of braking materials. For instance, nano-oxides enhance heat dissipation and wear resistance, nano-graphite improves lubrication and reduces noise, and carbon nanotubes provide exceptional strength and thermal conductivity, resulting in extended service life and improved braking performance [21,22,23]. These innovations not only elevate the functional performance of brake pads but also align with broader industry goals for lightweight, high-efficiency, and eco-friendly vehicle components. Various studies have demonstrated the potential of alternative natural materials in brake pad applications. For example, Bashar *et al.* studied the use of coconut shells and observed that increasing coconut powder content led to decreases in compressive strength, fracture toughness, and hardness [11]; Idris *et al.* investigated banana peels and found that higher peel content improved compressive strength, hardness, and wear resistance [12]; Edokpia *et al.* explored eggshell-based brake pads and reported that formulations containing 15–18% eggshell powder showed enhanced hardness, compressive strength, and wear resistance [13]; High braking temperatures can lead to variations in disc thickness and friction coefficients, resulting in increased wear and reduced system stability, as showed in Figure 1. Therefore, any new brake pad formulation must maintain a stable friction coefficient, low wear rate, and thermal resistance across various operating conditions [24, 25].

2.0 METHODOLOGY

2.1 Materials

In this research, brake pads were designed and fabricated using natural fibers as a sustainable alternative to asbestos, a material widely recognized for its hazardous carcinogenic properties. By incorporating natural fibers in varying proportions, the study aims to evaluate their potential to not only replicate but also enhance the performance characteristics of traditional asbestos-based brake pads. This innovative approach addresses the growing demand for safer and more environmentally friendly materials in the automotive industry. Table 1 presents an overview of the different natural fiber compositions used in the formulation of each brake pad sample, providing a clear understanding of the experimental variations. These compositions were strategically selected to investigate the influence of natural fiber content on key properties such as friction stability, wear resistance, and thermal performance.

Table 1 Different components in four brake pad samples

Samples	A(wt.%)	B(wt.%)	C(wt.%)	D(wt.%)
Date plam	0	2.3	4.6	6.9
Si	3.61	3.61	3.61	3.61
Ti	0.28	0.28	0.28	0.28
Al	1.72	1.72	1.72	1.72
Fe	52.38	52.38	52.38	52.38
Cu	3.49	3.49	3.49	3.49
Zn	2.00	2.00	2.00	2.00
Mg	1.85	1.85	1.85	1.85
Ca	4.97	4.97	4.97	4.97
Ba	8.10	8.10	8.10	8.10
K	0.30	0.30	0.30	0.30
Ce	4.54	4.54	4.54	4.54
P	0.02	0.02	0.02	0.02
S	2.52	2.52	2.52	2.52
Li	13.50	13.50	13.50	13.50
Mn	0.551	0.551	0.551	0.551
Ni	0.056	0.056	0.056	0.056
Sr	0.061	0.061	0.061	0.061
Cr	0.041	0.041	0.041	0.041

2.2 Preparation of Nanomaterials

Date palm fibers were selected as one of the primary materials in this study due to their abundance and cost-effectiveness in Egypt. As a leading global

producer of date palm fruits, Egypt has a substantial agricultural presence of date palm trees, approximately 7 million trees in earlier records, increasing to 14.1 million by 2018. By 2020, the agricultural area dedicated to date palm cultivation had expanded to 113.2 thousand acres. This widespread availability underscores the potential of date palm fibers as a renewable, low-cost, and sustainable resource for various industrial applications, including eco-friendly brake pads [26,27,28]. Figure 1 shows the various parts and components of the date palm tree, highlighting its versatility and potential for use in engineering applications [28, 29].

In this study, the fiber material was obtained from agricultural waste, reinforcing the environmentally responsible nature of the approach. The preparation process began by thoroughly cleaning the raw fibers to remove dirt and impurities. The cleaned fibers were then sun-dried for approximately 72 hours to eliminate moisture content [30]; After drying, the fibers were manually crushed or ground using a coffee grinder to reduce their size. To further refine the material to the nanoscale, a series of sieves with decreasing mesh sizes were employed, ensuring uniform particle size distribution [31]. This multi-step process guaranteed the production of high-quality, fine fibers suitable for incorporation into brake pad composites. Figure 2 presents a visual summary of the sequential steps involved in transforming raw date palm waste into nanoscale fibers for material integration [32, 33].

One of the key advantages of date palm fibers lies in their natural composition, which primarily includes cellulose, hemicellulose, and lignin. These constituents impart valuable mechanical and thermal properties to the fibers, making them highly suitable for a wide range of industrial applications. Cellulose, the predominant component, is well-known for its high strength, rigidity, and thermal stability, critical attributes for enhancing the performance of composite materials. Moreover, as a biodegradable and renewable resource, cellulose is widely regarded as an environmentally friendly material, aligning well with sustainable development goals [34]. Its structural characteristics also make it an excellent candidate for use as a filler and reinforcing agent in polymer-based composites, contributing to improved mechanical integrity and dimensional stability. Lignin, a complex aromatic polymer, complements cellulose by providing additional rigidity and resistance to biodegradation, while hemicellulose acts as a supportive matrix that enhances the flexibility and bonding within the fiber structure. Together, these components create a resilient, naturally derived material that offers both performance and sustainability. Their synergistic contribution not only improves the structural robustness of composite materials but also supports the development of environmentally conscious engineering solutions [35]. Date palm fiber is a material that contains cellulose, lignin, and

hemicellulose. These are attractive materials used as fillers for thermoplastic polymers in different proportions due to their excellent properties. In addition, cellulose is a material characterized by strength, hardness, and thermal stability. Despite these advantages, it is a bio-fiber with weak properties. Therefore, the higher the proportion of date palm fiber, the smaller the sample size, and consequently, its mechanical resistance decreases. Based on this, these proportions were chosen in the study of this research [34,35].



Figure 1 Date palm tree fibers.



Figure 2 Stages of grinding date palm fiber material

2.3 Testing Device

During the test, we first determine the brake oil pressure, rotational speed, and initial operating temperature. We then press the start button to run the test device until it reaches the specified initial operating temperature. After this, we stop the device for a moment to ensure the temperature has stabilized. Finally, the device is run for one minute to conduct the test. We record the resulting braking power values, which are used to calculate the torque and friction coefficient, while the final temperature is determined using the temperature sensor.

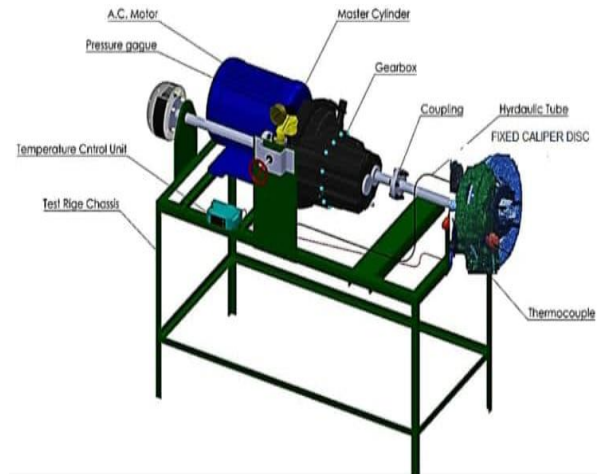


Figure 3 Main components of the test device

The testing apparatus was utilized to assess the effect of incorporating nano-oxides into polymer and graphite-based composites on the braking performance of the developed brake pad materials. By replicating realistic braking scenarios, the device enabled a detailed evaluation of how these additives influenced essential performance characteristics, including friction stability, wear resistance, and thermal behavior. This experimental setup facilitated a comprehensive analysis of the composite formulations, aiding in the identification of optimal material compositions that enhance braking efficiency while ensuring long-term durability. Figure 3 and 4 presents the testing device used for these evaluations, highlighting its critical components and configuration designed to ensure precise and consistent measurement.

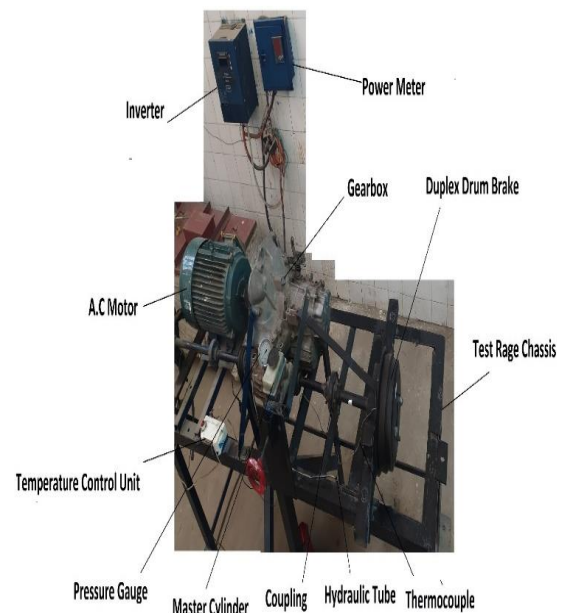


Figure 4 shows the practical testing device

The evaluation used a disc brake system, widely recognized as one of the most efficient and reliable braking technologies available. Disc brakes are commonly used in vehicles and even jet aircraft due to their low sensitivity to water, self-adjusting and self-cleaning capabilities, and excellent performance under a variety of operating conditions. [38] When the brake pedal is depressed, hydraulic pressure is transmitted from the master cylinder to the brake caliper. This pressure activates the caliper piston, which pushes the brake pad against the rotating disc (or rotor) mounted on the wheel hub. The resulting friction between the pad and the disc slows the wheel's rotation, ultimately stopping the vehicle. These are the components of a disc brake system, as mentioned [36].

In laboratory experiments, four brake pad samples were manufactured, including a locally manufactured brake pad without date palm fiber (A) and three brake pad samples with added date palm fiber (B, C, and D), using natural asbestos substitutes and varying percentages of date palm fiber—0%, 2.3%, 4.6%, and 6.9%, respectively. The objective of using date palm fiber was to study its effectiveness as an environmentally friendly alternative to asbestos, a known carcinogen that poses serious health and environmental risks.

The principal goal of this study was to improve the braking performance of the disc brake system while simultaneously promoting the use of eco-conscious materials. Key performance indicators examined included braking force, coefficient of friction, and temperature response under diverse operating conditions. By systematically altering the fiber content in the brake pad formulations, the research sought to determine the optimal composition that achieves superior braking efficiency and thermal stability, while mitigating the risks associated with traditional asbestos-based components.

The performance of each brake pad formulation was assessed using a dedicated testing apparatus designed to simulate realistic operating conditions. The evaluation process employed established theoretical models [37], allowing for accurate quantification of braking parameters.

To determine braking force, the power consumption of the electric motor during both loaded (engaged brake) and unloaded (disengaged brake) conditions was recorded. The braking force was then calculated using the following equation:

$$P_b = P_L - P_{no} \quad (1)$$

Where:

P_b is the brake power (watts), P_L is the electric motor power under brake load (watts), and P_{no} is the electric motor power under no-load brake condition (watts)

Next, the braking torque is calculated using the brake force and angular velocity, as shown in the following equation:

$$T_b = \frac{P_t}{\omega} \quad (2)$$

$$\omega = \frac{2\pi n}{60} \quad (3)$$

Where:

T_b is the Brake torque (N. m), ω is the Angular velocity (rad/sec), and n is the Sliding speed (r. p. m) Thirdly, the braking force is calculated by knowing the braking torque and the average friction diameter, as shown in the following equation:

$$F_b = \frac{T_b}{R} \quad (4)$$

Where:

F_b is the brake force (in Newton) and R is the average friction diameter (in Meters)

Finally, the force at each pressure is calculated by knowing the pressure and the area, as shown in the following equation:

$$P = \frac{F}{A} \quad (5)$$

$$F_n = P \times A \quad (6)$$

$$A = \left(\frac{\pi}{4}\right) \times (d^2) \quad (7)$$

Where P is the brake pressure (in N/m²), F is the brake force (in Newton), F_n is the normal force (in Newton), d is the piston diameter (in Meters), and μ is the coefficient of friction.

Next, the friction coefficient (μ) is calculated by using the braking force and the force at each pressure, as shown in the following equation:

$$\mu = \frac{T_b}{R \times F_n} \quad (8)$$

T_b is the Brake torque (N. m)

R is the average friction diameter (in Meters)

F_n is the normal force (in Newton)

3.0 RESULTS AND DISCUSSION

The experimental test was conducted on four brake pad samples made from natural fibers with different ratios [0%, 2.3%, 4.6%, and 6.9%] of date palm fibers. During the test, various operating conditions were applied, including brake oil pressure levels [2, 4, 6, and 8 bar], operating temperatures [60°C, 90°C, 120°C, and 150°C], and sliding speeds [200, 300, and 400 rpm]. Each test lasted for 60 seconds on all samples under different conditions. The friction coefficient and brake force were calculated using the previously described equations. A summary of the research findings is presented in the following poin.

3.1 Effect of Brake Oil Pressure on Brake Force at Constant Sliding Speed

Figures [5,6,7,8]. illustrate the effect of brake oil pressure on the braking force of the disc brake system at various operating conditions across the four brake pad samples. The experiments were conducted at a constant sliding speed of 300 rpm and a constant temperature of 60°C, with brake oil pressures set at [2, 4, 6, and 8] bar. The experiment time was 60 seconds for all samples. The results show that the braking force increases in all samples as the brake oil pressure rises. Additionally, the results indicate that sample A [0% date palm fibers], exhibits the highest braking force. Sample B [2.3% date palm fibers], provides a suitable braking force under all conditions. However, samples C [4.6%] and D [6.9%] of date palm fibers, respectively, demonstrate lower braking forces. Therefore, from these results, it can be concluded that increasing the amount of date palm fibers in the brake pad leads to a reduction in the braking force under different operating conditions.

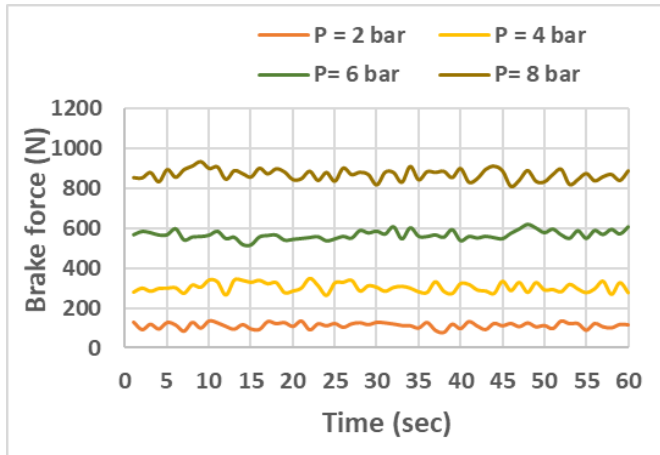


Figure 5 Brake force against time for the disc brake system using sample A (0%) of the brake pad at a sliding speed of 300 rpm, a temperature of 60°C, and various brake fluid pressures

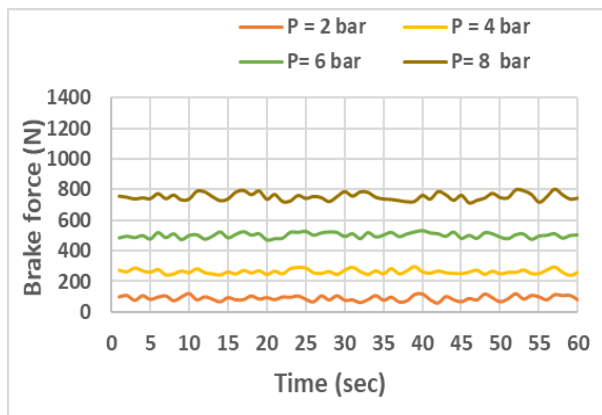


Figure 6 Brake force against time for the disc brake system using sample B (2.3%) of the brake pad at a sliding speed of 300 rpm, a temperature of 60°C, and various brake fluid pressures

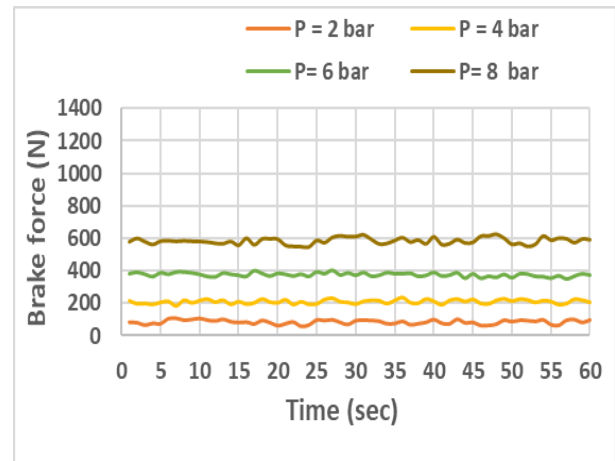


Figure 7 Brake force against time for the disc brake system using sample C (4.6%) of the brake pad at a sliding speed of 300 rpm, a temperature of 60°C, and various brake fluid pressures

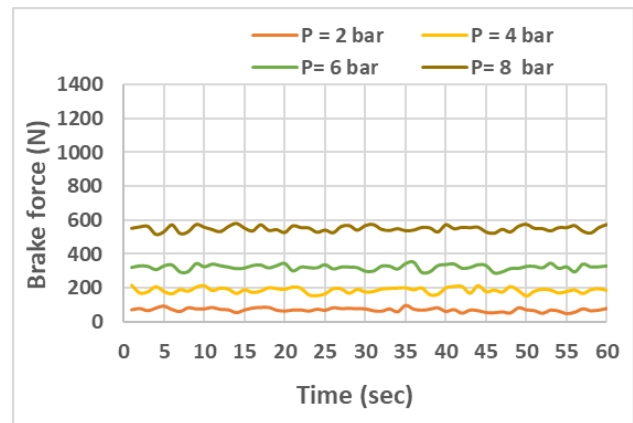


Figure 8 Brake force against time for the disc brake system using sample D (6.9%) of the brake pad at a sliding speed of 300 rpm, a temperature of 60°C, and various brake fluid pressures

The effect of brake oil pressure on the average braking force of the disc brake system was tested across the four brake pad samples. The test results, shown in Figure 9 indicate that the average braking force in all four brake pad samples increased with increasing brake oil pressure. From Figure 9 it can be observed that the average braking force in sample [A] of the brake pad is higher than in the other samples. Increasing the oil pressure from 2 to 8 bar leads to the following increases in average braking force:

1. In sample [A], the increase is 113.13, 306.38, 567.04, and 867.88 Newton, respectively.
2. In sample [B], the increase is 94.21, 259.90, 500.41, and 756.40 Newton, respectively.
3. In sample [C], the increase is 81.71, 207.54, 374.02, and 587.93 Newton, respectively.
4. In sample [D], the increase is 68.60, 184.82, 324.02, and 551.69 Newton, respectively.

The average braking force shows a progressive increase with higher oil pressure across all samples, with the most significant force seen in sample [A].

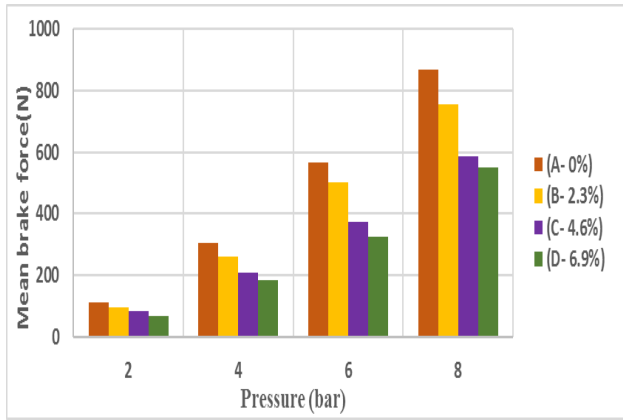


Figure 9 Effect of brake oil pressure on the average braking force in the four brake pad samples for the disc brake system at a sliding speed of 300 rpm and a temperature of 60°C.

The effect of brake oil pressure on the average friction coefficient of the disc brake system was also tested across the four brake pad samples at a sliding speed of 300 rpm and a temperature of 60°C. The test results, shown in Figure 10 indicate that the average friction coefficient increases with increasing brake oil pressure. From Figure 10 it can also be observed that the average friction coefficient in sample [B], remains stable and appropriate under different operating conditions compared to the other brake pad samples. Increasing the oil pressure from 2 to 8 bar leads to the following increases in the average friction coefficient;

1. in sample [A], the increase is 0.25641, 0.34718, 0.42837, and 0.49173, respectively.
2. in sample [B], the increase is 0.21900, 0.29451, 0.36990, and 0.42857, respectively.
3. in sample [C], the increase is 0.18519, 0.23519, 0.28256, and 0.35311, respectively.
4. in sample [D], the increase is 0.15548, 0.20944, 0.24478, and 0.31258, respectively.

Thus, the average friction coefficient increases progressively with oil pressure in all samples, with sample [B] showing the most stable and consistent performance.

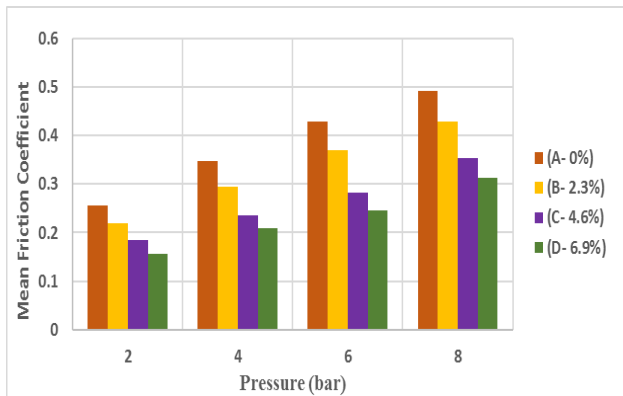


Figure 10 Effect of brake oil pressure on the average friction coefficient in the four brake pad samples for the disc brake system at a sliding speed of 300 rpm and a temperature of 60°C.

3.2 Effect of Brake Oil Pressure on Operating Temperature at Constant Sliding Speed

Figure 11 shows the effect of brake oil pressure on the final temperature of the disc brake system for the four brake pad samples at a sliding speed of 300 rpm and an initial temperature of 60°C. The test results, as shown in Figure 11 indicate that the final temperature increases in all four brake pad samples as brake oil pressure rises. Additionally, from Table 2 it can be observed that the final temperature in samples [B, C, and D], which contain varying percentages of date palm fibers, is lower than the final temperature in sample [A], which contains no date palm fibers. Sample [B] is particularly notable for its effective cooling performance, along with a suitable braking force, leading to a stable and appropriate friction coefficient under different operating conditions.

Table 2 Final temperatures of the four brake pad samples under different operating conditions, with a sliding speed of 300 rpm, an initial temperature of 60°C, and varying brake oil pressures from 2 to 8 bar.

Temperatures Pressure(bar)	T _f (°C) A	T _f (°C) B	T _f (°C) C	T _f (°C) D
2	74	69	67	65
4	80	74	71	69
6	86	79	75	73
8	91	84	80	78

The temperature is determined using a temperature sensor, with an initial temperature of 60°C per minute.

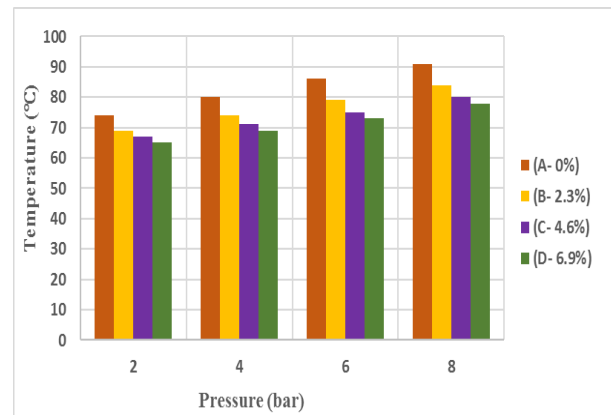


Figure 11 Effect of brake oil pressure on the final temperature of the four brake pad samples for the disc brake system at a sliding speed of 300 rpm and an initial temperature of 60°C.

3.3 Effect of Sliding Speed on Operating Temperature at Brake Oil Pressure

Figure 12 shows the effect of sliding speed on the final temperature of the disc brake system for the four

brake pad samples at sliding speeds of [200, 300, 400] rpm, with an initial temperature of 60°C and a brake oil pressure of 4 bar. The test results, as shown in Figure 12 indicate that the final temperature increases in all samples as the sliding speed rises. Additionally, from Table 3 it can be observed that the final temperature in samples [B, C, D], which contain varying percentages of date palm fibers, is lower than the final temperature in sample [A], which does not contain any date palm fibers, across all sliding speeds [200, 300, 400] rpm. Sample [B] is particularly notable for its effective cooling performance, along with a suitable braking force, which results in a stable and appropriate friction coefficient under different operating conditions.

Table 3 Final temperatures of the four brake pad samples under different operating conditions, with sliding speeds of [200, 300, 400] rpm, an initial temperature of 60°C, and a brake oil pressure of 4 bar

Temperatures \ Speed (r.p.m)	A	B	C	D
	T _f (°C)	T _f (°C)	T _f (°C)	T _f (°C)
200	73	68	65	64
300	80	74	71	69
400	85	79	76	74

High temperatures can cause changes in disc thickness, resulting in unstable friction rates and increased wear on contact surfaces. When developing new brake pad materials, it is necessary to ensure that they provide a stable friction coefficient, low wear, and the ability to withstand varying temperatures under different operating conditions [39, 40].

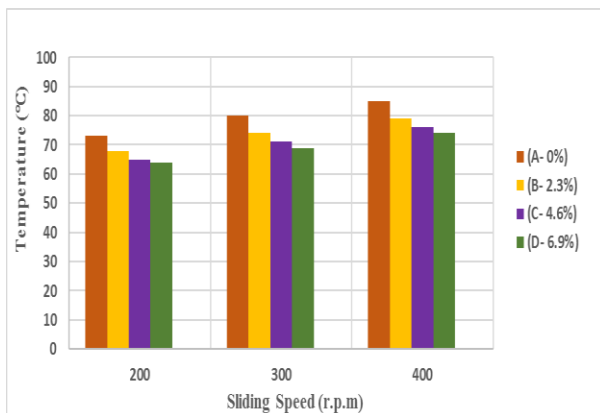


Figure 12 Effect of sliding speed on the final temperature of the four brake pad samples for the disc brake system at sliding speeds of [200, 300, 400] rpm, an initial temperature of 60°C, and a brake oil pressure of 4 bar

3.4 Effect of Date Palm Fiber Ratios on the Coefficient of Friction at Different Temperatures

Natural fibers, specifically date palm fibers, were added to the brake pads in varying proportions. Figure 13 shows the effect of date palm fiber ratios on the

average friction coefficient in the four brake pad samples at temperatures of [60, 90, 120, 150] °C, with a sliding speed of 300 rpm and a brake oil pressure of 8 bar. The test results, as shown in Figure 13 indicate that as the percentage of date palm fibers in the sample increases, the friction coefficient decreases, which in turn reduces both the braking force and the operating temperature.

The results also show that the coefficient of friction decreases in all four brake pad samples as the temperature increases. Specifically, when the temperature rises above 90°C, the coefficient of friction drops due to the weakened properties of the fibers. As the temperature increases, the fiber-based material begins to soften, causing the sample size to shrink and reducing the overall friction.

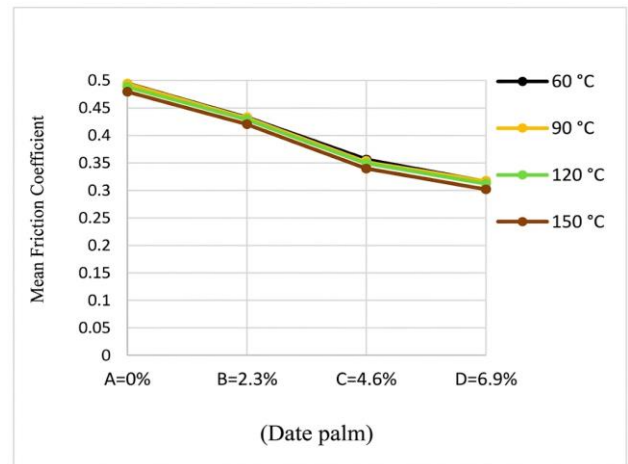


Figure 13 the effect of date palm fiber ratios on the average friction coefficient of the four brake pad samples at different temperatures (60, 90, 120 and 150°C), sliding speed of 300 rpm and brake oil pressure of 8 bar

4.0 CONCLUSION

This study demonstrates that both brake oil pressure and date palm fiber content in brake pad formulations significantly influence braking performance. Increasing the brake oil pressure from [2, 4, 6, 8] bar consistently enhances the braking force and friction coefficient across all samples. However, as the percentage of date palm fibers increases, there is a noticeable decrease in both braking force and friction coefficient, which in turn leads to lower operating temperatures. Specifically, while sample A [0% fiber] achieves the highest braking force, it suffers from unstable friction, increased wear, and elevated temperatures. In contrast, sample B [2.3% fiber] offers a balanced performance with stable friction, reduced wear, and lower temperatures, suggesting it is the optimal composition. Samples C [4.6% fiber] and D [6.9% fiber] show lower braking forces and friction coefficients but benefit from significant temperature reduction, indicating their suitability for applications where effective thermal management is critical.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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