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Effect of Silicon Carbide (SiC) Nanomaterials on the Performance of the Disc Brake Pads in Vehicles: An Experimental Study

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ABSTRACT:

The braking system is an important vehicle component, primarily responsible for safety by converting kinetic energy into thermal energy through friction. It depends on the materials used in manufacturing the brake pads. The performance of brake pads is significantly influenced by material composition, especially under high-temperature conditions, which typically degrade frictional efficiency. This study investigates the enhancement of brake pad performance by incorporating silicon carbide (SiC) nanoparticles as an abrasive additive. Testing was conducted on a specialized rig utilizing a standard grey cast iron ventilated disc (outer diameter of 241 mm and nominal thickness of 19 mm), consistent with the specifications of a 2005 Hyundai Excel. Four experimental formulations with SiC concentrations of 0, 0.5, 1.5, and 3 vol% were evaluated. The results demonstrate that the 0.5 vol% SiC concentration achieved the most significant improvement, increasing the average brake force by up to 19% and enhancing the friction coefficient compared to unmodified pads. Furthermore, the SiC-infused samples exhibited superior thermal stability and fade resistance at temperatures up to 130°C, outperforming all other tested formulations and demonstrating more consistent reliability under different operating conditions.

Keywords: Ventilating Disc Brake, Brake Pad, Friction Brake, Characteristic Brake, Brake Friction Materials.

1. INTRODUCTION

The braking system is one of the active safety systems in vehicles. It is no hyperbole to say that brakes are one of the most important parts of a car, as the safety of the occupants inside the car depends on the effectiveness of the brake system. Due to the importance of protecting people and buildings, if the brakes fail, the consequences for the vehicle can be catastrophic, for the users and buildings [1]. Braking efficiency depends on many different operating and manufacturing factors, such as disc sliding speed, operating temperature, brake oil pressure, braking time, brake force, material properties, and Friction

coefficient [2]. The brake pad is considered one of the most important safety components on which the vehicle's braking system depends. It is responsible for generating friction during braking, which works to convert the vehicle's kinetic energy into thermal energy. Brake pads are considered one of the most important components for vehicle safety and high braking performance [3]. A typical brake pad formulation consists of over 12 components and over 300 materials used in different brands [4]. These components are divided into five main components: fibers, binders, organics, friction modifiers/additives, and fillers. Brake linings are usually manufactured using asbestos as a filler material; they are thermally stable up to 500 degrees Celsius and enhance surface friction during use. Despite its excellent properties, asbestos has been discontinued due to its carcinogenic properties [5]. A lot of research has been done to develop asbestos-free brake linings. Recent developments in the brake lining industry have focused on finding asbestos-free alternatives to brake pads. This has led researchers to explore the possibility of using certain agricultural waste in the development of brake linings. Some of these agricultural wastes pose a danger to the environment as their disposal is often a concern [6]. Many studies have attempted to test materials such as asbestos and a natural fiber called palm kernel fiber (PKF) for environmental safety using calcium carbonate, graphite, and silicon carbide. Typically, epoxy resin is used as a binder. Composed of 40% epoxy resin, 10% palm residue, 15% calcium carbonate, 10% Silicon carbide, and 25% graphite. A typical brake pad formulation consists of over ten components [7]. The development of automotive brake pads using local raw materials is shown. This custom-designed brake disc friction lining for a 2000 Toyota Camry uses palm kernel powder and coconut shell as base material, epoxy resin, aluminum and copper shell, zinc, and cashew as binder, and carbon fiber reinforcement. It was made as an abrasive and filler for rubber powder generated from shoes. Experimental results showed that, compared with traditional brake lining, the friction coefficient of the pad material is 0.4-0.65[8]. Waste is generated in large quantities around the world, posing a threat not only to human health but also to the environment. Therefore, their efficient, beneficial, and environmentally friendly use is a constant challenge for scientific applications. This article primarily discusses the characterization of periwinkle shell as a potential non-asbestos material for brake pads. The variety of results obtained is comparable to that of asbestos commonly used in the manufacture of brake pads. The obtained results support the possibility of using periwinkle shells as a material to produce brake pads [9,10]. Environmentally friendly brake linings were studied using banana peels. The results of this study show that banana peels can be used effectively in place of asbestos [11-12]. In this experimental study, we developed an environmentally friendly brake using eggshell (ES) as a binder instead of carcinogenic and non-biodegradable asbestos and formaldehyde resins. The following properties were tested: wear rate, thickness, and heat resistance. The best properties were shown by the sample containing 18 wt.% in the ES particles. The maximum decomposition temperature of ES was higher than that of asbestos and many agricultural wastes currently used to make brake pad materials. Eco-friendly brake pads based on eggshells have been developed and evaluated. This formulation can be used in the production of eco-friendly brake pads [13,14,15]. While most recently, a husk-maize-based brake pad as a suitable replacement for asbestos in automotive brake pads was developed [16]. The information provided above provides solutions to reduce the use of asbestos as a brake pad material and find alternatives that give the same desired results. This research aims to develop brake pads using nano-sized powdered silicon carbide. While the developed brake pads were evaluated in terms of frictional and braking force, pressure force, and coefficient of friction, under different operating conditions, such as sliding speed, operating temperatures, braking time, and brake oil pressure.

2. EXPERIMENTAL SETUP

This section relies on two sub-parts: the first part is the preparation of the nanomaterials used in the manufacturing of brake pads, while the second part is the testing device through which the performance of the samples manufactured from the brake pads was measured.

2.1 Basic materials:

Table 1 shows the relative content of materials (vol%) in commercial samples used in the experiments. Silicon carbide was used as an abrasive, a variable, major component. Laboratory experiments were conducted with the use of a disc brake pad without silicon carbide and the use of a disc brake pad with the addition of silicon carbide with 44 nm in size in different proportions; four experimental compositions containing 0 to 3 vol% silicon carbide were selected (SiC-0, 0.5, 1.5, and 3 vol%).

Table 1: Relative content of raw materials in (vol%) of commercial sample.

Main Material	(Wt%)
Silicon	0.11
Iron	70
Phosphorus	0.005
Sulfur	0.01
Manganese	0.619
Chromium	0.030
Titanium	0.297
Niobium	0.029
Phenolic	10
Graphite	7
Baryte	11.9

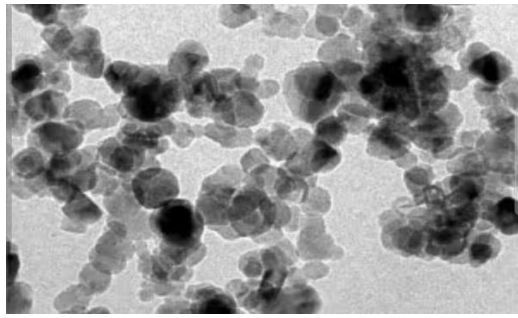
In this study, four brake pads with different formulations were used in laboratory experiments. A commercial disc brake pad has been used to compare three brake pads that were modified by adding a percentage of 0.5, 1.5, and 3 vol% of silicon carbide. Table 2 shows the Relative content of raw materials in formulations 0.5, 1.5, and 3 vol% of silicon carbide of the samples used.

Table 2: Relative content of raw materials in formulations 0.5, 1.5, and 3 vol% of (Silicon carbide) in the samples used.

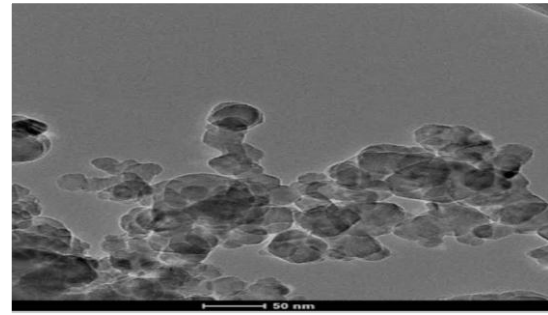
Raw Materials	Samples				(Wt%)
	SiC -0	SiC -0.5	SiC -1.5	SiC -3	
Silicon	0.11	0.11	0.11	0.11	
Iron	70	69.5	68.5	67	
Phosphorus	0.005	0.005	0.005	0.005	
Sulfur	0.01	0.01	0.01	0.01	
Manganese	0.619	0.619	0.619	0.619	
Chromium	0.030	0.030	0.030	0.030	
Titanium	0.297	0.297	0.297	0.297	
Niobium	0.029	0.029	0.029	0.029	
Phenolic	10	10	10	10	
Graphite	7	7	7	7	
Baryte	11.9	11.9	11.9	11.9	

2.1.1 Preparation of nanoparticles:

One type of nanoparticle used is Silicon carbide (SiC) nanoparticles, with sizes ranging from 20-70 nm. A photo of Silicon carbide nanoparticles taken using a transmission electron microscope (TEM) is shown in Figure 1(a, b) (it was conducted at the Cairo National Research Center Laboratories).



(a)



(b)

Figure 1 :(a,b): TEM images of Silicon carbide (SiC) nanoparticles

2.2 The main components of the test rig:

The testing rig is considered the appropriate tool through which the study's objectives can be achieved by means of appropriate measurement procedures. In this study, the testing device was built through the integration of a set of mechanical and electrical devices. The testing device is operated to measure both the braking force and braking torque, as well as the brake pad temperature for four types of brake pads, which were designed with appropriate proportions of nanomaterials. The testing device operates using an electric motor, which is powered by a power meter device to control the speed and torque of the motor to reach the appropriate speeds. The brake disc speeds are then controlled through a gearbox to simulate the different vehicle speeds. The brake pad temperature is measured at various brake pressures, which are controlled using a circular tool to adjust and maintain the brake pressure at the appropriate level. Figures 2 and 3 illustrate the mechanical and electrical components of the testing device, while Figure 4 shows the flow diagram for operating the testing device.

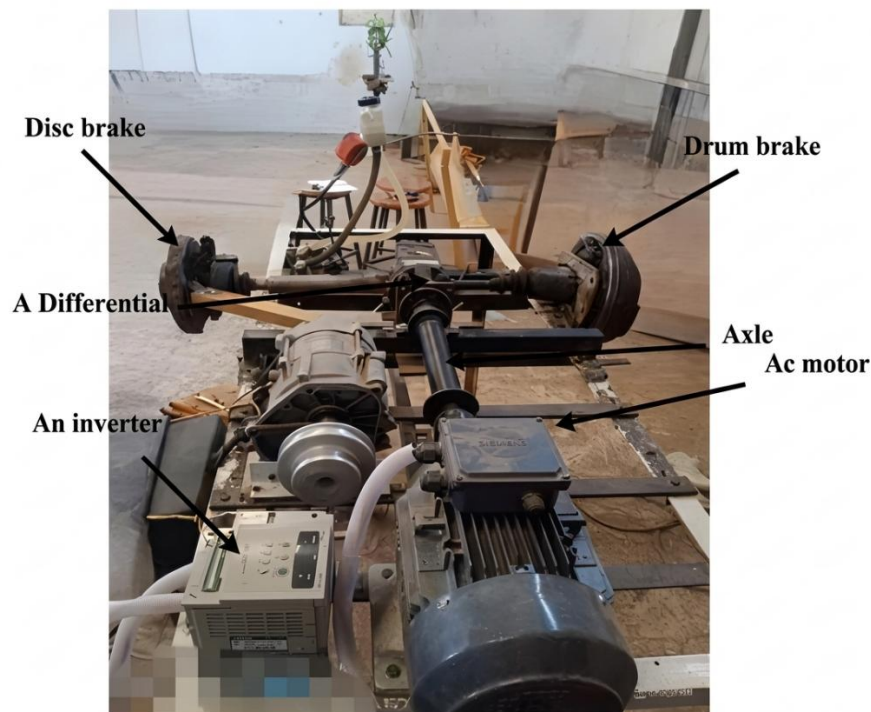


Figure 2: Main components of the test rig.

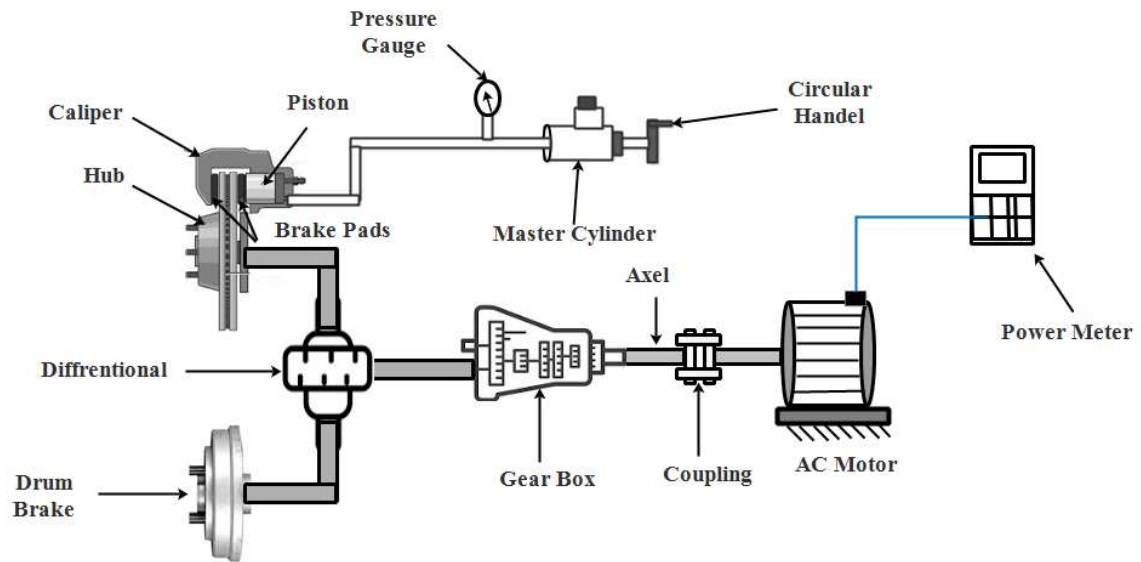


Figure 3: Schematic sketch of the test rig.

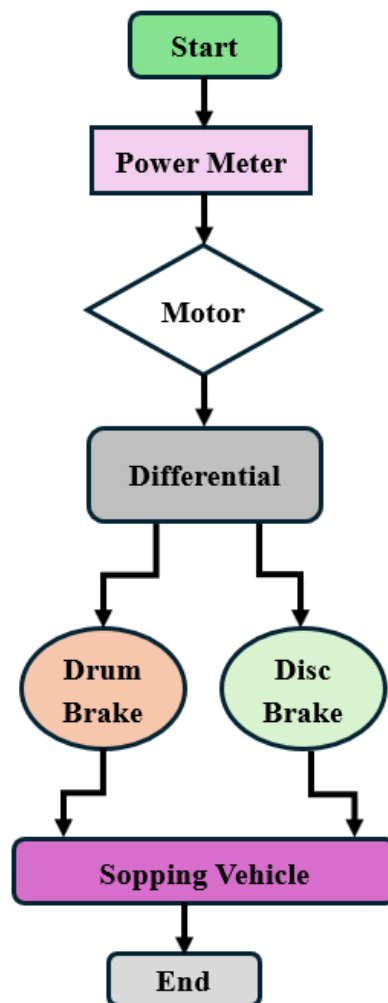


Figure 4: Flowchart of the operation test rig.

First: The disc brake system of the 2005 Hyundai Excel.

A 2005 Hyundai Excel brake is used on the test rig. This brake system is a Floating-type disc brake with a piston on only one side and is also called a sliding disc brake. The main components of the brake system are shown in Figure 5. The braking system consists of a main caliper and piston, a caliper carrier (bracket), caliper slider pins (two), pad holder clips, fixing screws, a braking plate, and the brake pads. The floating disc brake system also has one wheel cylinder, which contains one hydraulic piston.



Figure 5: Disc brake of the 2005 Hyundai Excel.

Second: The normal force generation unit.

Stopping a vehicle weighing up to 1,375 kg requires the driver to press the pedal to create friction with the wheels. What happens between the pedal and the brake pads can determine how much pressure the driver needs to stop the car at a safe distance. Hydraulic braking systems transfer and amplify force. It works on the simple principle that brake oil is incompressible. In a hydraulic braking system, the driver generates force by pressing the brake pedal. Thus, the braking force depends on the applied force (F_n) and the coefficient of friction (μ). The normal force generated should have a constant value during the test under working conditions.

In this study, pressure measurement and normal force calculation were performed. The applied force in a conventional brake system is calculated as the area of the piston head multiplied by the oil pressure. We note that, depending on the oil pressure, the normal force of the conventional brake system varies. See the following equations [17]:

$$A_s = \frac{\pi}{4} D_s^2 \quad (1)$$

$$P = \frac{F_n}{A_s} \quad (2)$$

$$F_n = P * A_s \quad (3)$$

Where:

D_s The piston diameter of the slave cylinder equals (0.052 m)

A_s The piston area of the slave cylinder equals ($2.12 \times 10^{-3} \text{ m}^2$)

F_n The applied force of the disc brake system, which affects the brake pad, was selected with oil pressure values of 2.5, 5, 7.5, and 10 bar during the tests. According to equation (3), these values of pressure equal the applied force of 551, 1103, 1654, and 2206 N, respectively, for the disc brake system.

Third: The kinetic energy generation unit and the temperature measurement unit.

To inspect the performance of your braking system during operation and identify possible solutions that can improve braking performance and control. Brake dynamometers with electric motors come in two designs. The first design is an inertial type of brake dynamometer that has a flywheel attached and can be used to test brake effectiveness at various speeds. The second design is a drag-type brake dynamometer that tests the effectiveness of the brakes only at constant speeds. In this research, a test rig was designed and constructed to test the performance of modified disc brake pads using a drag-type brake dynamometer. Figure 6 shows the kinetic energy generation unit and the temperature measurement unit. The electric motor, which has a maximum power of 10 HP 7.5 KW at 2900r.p.m. using it in the test rig. According to previous studies, sliding speed plays an important role in changing the friction coefficient, leading to differences in braking force [118,19]. Temperature has a significant effect on the effectiveness of the braking system. In this study, a J-type thermocouple with a digital temperature unit attached to the brake pad was used to measure the friction temperature between the brake pad and the rotor disc, as shown in Figure 6. For each experiment, the initial heat of operation is recorded at 40, 70, 100, 130 °C, and the final operation temperature of the commercial disc brake pad without Silicon carbide and the disc brake pad with added Silicon carbide.

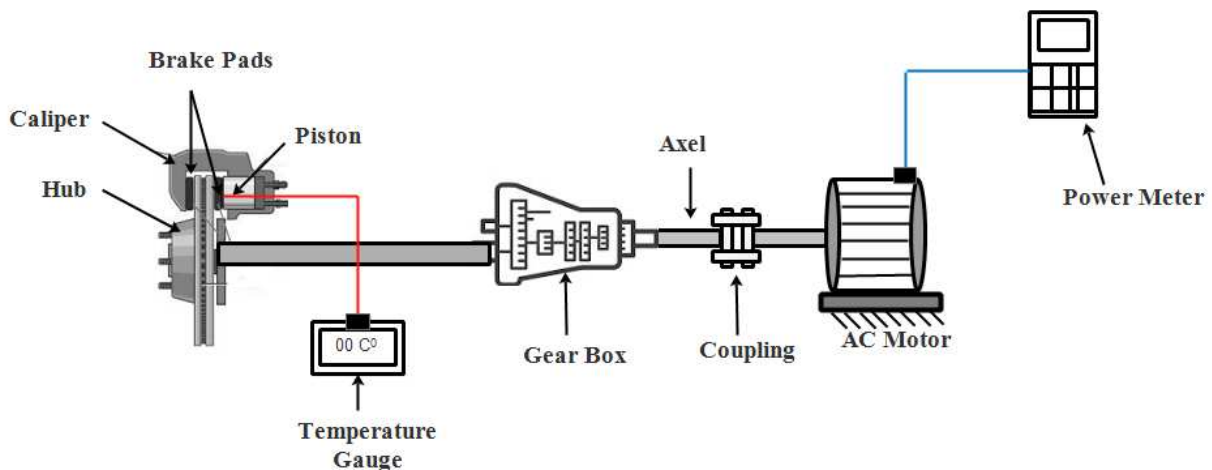


Figure 6: The kinetic energy generation unit and the temperature measurement unit.

Five: Brake torque calculation and speed measurement.

The results of this study are based on several factors, the most important being brake torque. This is a very important factor, as there are many ways to measure braking torque. One such method is to use a torque sensor. There are two ways to directly measure braking torque: measuring the torque and measuring the power consumption of the electric motor during braking. This method measures the sliding speed and calculates the braking torque. In this study. Motor power is measured using a Schneider PM 1200 digital power meter and ranges from 20 W to 300 kW. Figure 7 shows the Digital power meter unit.

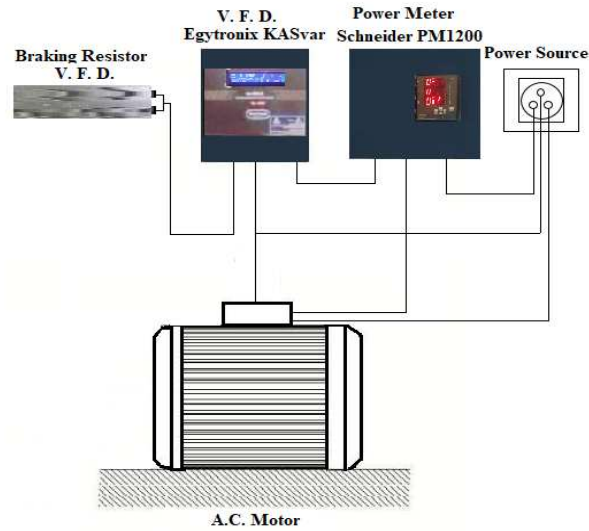


Figure 7: Digital power meter unit.

The important factor that was selected in this study is the rotational speed of the rotor disc during the braking process. The sliding speed system was measured using a DT6234 B digital tachometer with a range of 5 to 100,000 rpm and an accuracy of 0.5%. As shown in Figure 8.



Figure 8: Digital tachometer

To calculate the braking torque by measuring the angular velocity of the rotating disc when a braking force is applied, the sliding speed of the braking system, at different sliding speeds, is 150, 300, 450, and 600 RPM, during different operating conditions. Braking torque can be calculated by knowing the angular velocity of the rotating disc and measuring the brake power using the digital power meter unit during the braking process. See the following equations [17].

$$P_b = P_L - P_{no} \quad (4)$$

Where:

P_b The brake power (watts)

P_L The electric motor power during the braking process (watts)

P_{no} The electric motor power during the operation at no braking load (watts)

$$T_b = \frac{P_b}{\omega} \quad (5)$$

$$\omega = \frac{2\pi n}{60} \quad (6)$$

Where:

T_b The brake torque (N.m)

ω The angular speed of the rotating disc (rad/sec.)

n The sliding speed of the rotating disc (r.p.m)

sex: Brake force and friction coefficient calculations.

To evaluate the performance of the brake system, two very important factors must be calculated: first, the braking force, and second, the coefficient of friction. In a disc brake system, the applied force is produced by a hydraulic cylinder. In this study, the effect of the addition of Silicon carbide in brake pads on the friction coefficient will be examined. Note that a brake pad that contains Silicon carbide has a higher brake force than a commercial brake pad without Silicon carbide. The braking force is calculated in the disc brake system as follows:

$$T_b = F_b \cdot R_{eff} \quad (7)$$

For a disc brake commercial and modified system, there is a pair of brake pads; thus, the total brake torque is:

$$T_b = 2 F_b \cdot R_{eff} \quad (8)$$

$$R_{eff} = \frac{r_i + r_o}{2} \quad (9)$$

Where:

R_{eff} The effective radius of the brake pad, it equals 0.089 m.

r_i The inner radius of the brake pad(m)

r_o The outer radius of the brake pad (m)

F_b The brake force generated at the contact interface (N)

From equation (8) the brake force of the commercial and modified system can be calculated as follows:

$$F_b = \frac{T_b}{2R_{eff}} \quad (10)$$

Where:

F_b The brake force (N)

However, braking force varies depending on the normal force and friction coefficient, which is resulting as following:

$$F_b = \mu F_n \quad (11)$$

The friction coefficient can be calculated as follows:

$$F_b = \mu P A_s \quad (12)$$

$$\mu = \frac{F_b}{P A_s}$$

Where:

μ The friction coefficient.

3. RESULTS AND DISCUSSION

To evaluate the performance of the brake system and its efficiency in different operating conditions, this requires determining the coefficient of friction by which the value of the brake performance factor is determined, which is used in evaluating the performance of the brake system in this study. The impact of different operating standards is verified through laboratory experiments, and these factors are sliding speed and brake oil pressure and the initial friction temperature, to determine the extent of the impact of these parameters on the friction coefficient of the disc brake pad of a Hyundai Excel 2005 model, brake power and laboratory experiments were performed at values for brake oil pressures of 2.5, 5, 7.5 and 10 bar, as well as setting sliding speeds of 150, 300, 450 and 600 rpm tests are done for 60 seconds of braking process and laboratory experiments were carried out in light of the operating conditions mentioned with the use of disc brake pad without Silicon carbide and the use of disc brake pad with the addition of Silicon carbide in different proportions, for experimental compositions containing from 0 to 3 vol% Silicon carbide were tested (SiC-0, 0.5, 1.5 and 3 vol%), the initial operating temperature were measured at 40, 70, 100 and 130°C, brake oil pressure, as well as speed sliding and brake power were measured at every 60 seconds of braking time. For each experiment, the friction coefficient for the disc brake, as well as the brake force, was drawn, and the relationships that were mentioned with time Brakes during each test.

3.1 Effect of brake oil pressure on the brake force at constant sliding speed.

Shows the effect of the brake oil pressure on the brake force of the disc brake pad with the addition of Silicon carbide and without Silicon carbide at a speed of 300 rpm in Figures 9, 10, 11, and 12. It shows that as the brake oil pressure increases, the brake force of the disc brake pad increases without Silicon carbide and with the addition of Silicon carbide, as shown. The four previously presented figures also show that the brake forces of the disc brake pad with the addition of Silicon carbide and without Silicon carbide change with no consistent direction with the brake time at each constant pressure; the variation of the brake force is due to the variation of the friction coefficient with time. SiC-reinforced braking systems exhibit superior braking force and force stability across a range of hydraulic pressures because SiC provides high hardness, wear resistance, and thermal conductivity, and it promotes the formation of a compact tribo-film at the pad-disc interface.

As a highlight, a silicon carbide ceramic can be subject to mild wear in the early stage of contact or under mild testing conditions; a plastically deformed surface is developed through surface smearing; and a friction transfer layer is deposited on if wear debris can have strong enough chemical bonding with silicon carbide, leaving a friction track showing smooth morphology [19]. Under prolonged testing, or even more severe testing conditions, e.g., high pressure/speed, surface cracking is likely introduced during contact sliding [20]. One mechanism responsible for surface cracking under contact is established based on indentation fracture mechanics, indicating that harder abrasive debris, or asperities on the surface of a counterpart, play a key role in initiating radial cracks [21]. Another mechanism is developed and accepted based on the surface tensile stress induced by a moving Hertzian contact and/or possibly thermal strain; such stresses drive pre-existing surface flaws propagation once the stress intensity is larger than the fracture toughness of a ceramic[22].

According to indentation fracture mechanics, surface cracking under contact is promoted by hard asperities or abrasive debris acting as local indenters, which generate radial cracks in a brittle surface. The incorporation of nano-SiC modifies this mechanism by increasing surface hardness and promoting a compact tribo-layer, so that stresses are distributed over many fine contacts rather than a few large asperities; this tends to limit the growth of long radial cracks, although agglomerated nano-SiC clusters can still act as hard debris and initiate local indentation-type cracking.

Figure 13 shows that the effect of the brake oil pressure on the mean brake force of the disc brake pad with the addition of Silicon carbide and without Silicon carbide is explained. The results present that the mean brake forces of the disc brake pad with additional Silicon carbide and without Silicon carbide are increased with increasing brake oil pressure. Also, the mean brake force of the disc brake pad without additional Silicon carbide is less than the mean brake force of the disc brake pad with additional Silicon carbide at each pressure. The average brake forces of disc brake pad without Silicon carbide are 121.440, 271.128, 472.116 and 917.056 N and the mean brake forces of disc brake pad with addition Silicon carbide (SiC- 0.5 vol%) are 141.249, 332.339, 570.067 and 1061.740 N and the mean brake forces of disc brake pad with addition (SiC - 1.5 vol%) are 140.212, 326.011, 562.889 and 1048.353 N the mean brake forces of disc brake pad with addition (SiC - 3 vol%) are 135.661, 320.163, 555.303 and 1029.292 N at brake oil pressure of 2.5, 5, 7.5 and 10 bar respectively. At each pressure, the value of the mean brake force of the disc brake pad with Silicon carbide (SiC - 0.5 vol%) increases by 15 %, 19%, 18% and 14%. And 14%, 17%, 16% and 12.5% respectively for disc brake pad with Silicon carbide (SiC - 1.5 vol%) and 11%, 16%, 15% and 11% according to the value of the average brake force of disc brake pad without additional Silicon carbide.

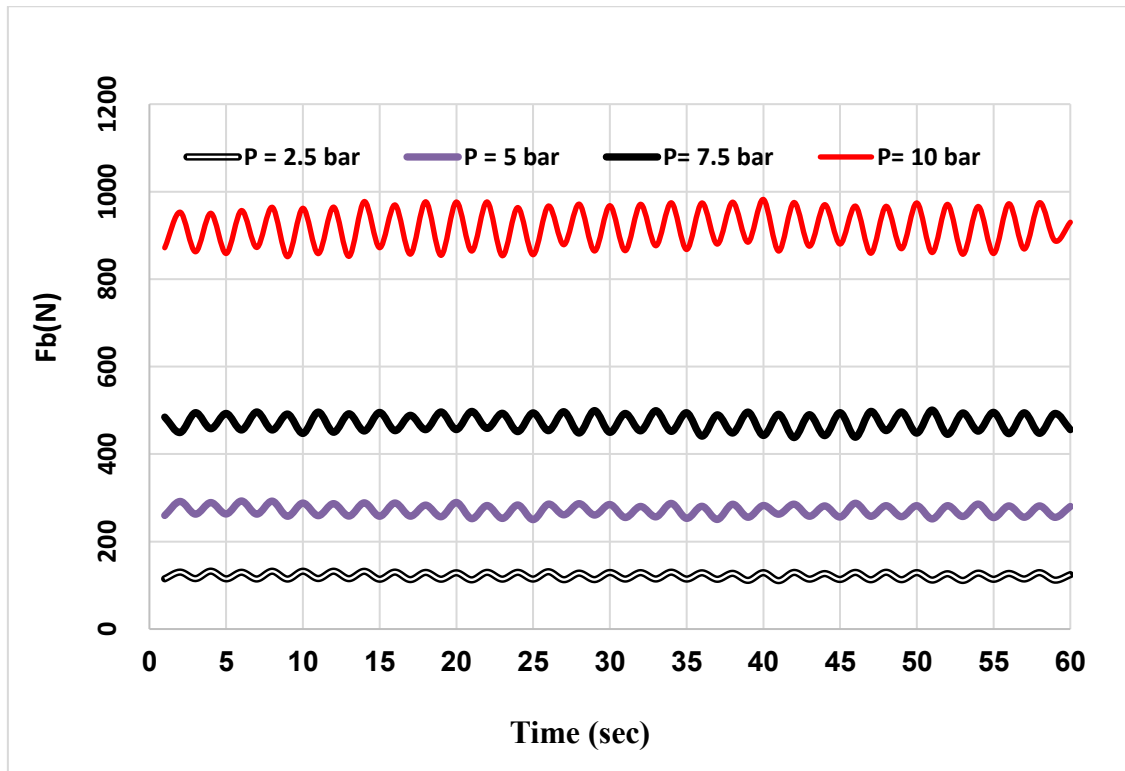


Figure 9: Variation of brake force of the disc brake pad without Silicon carbide (SiC - 0 vol%) as a function of time at sliding speed 300 RPM at different brake oil pressures.

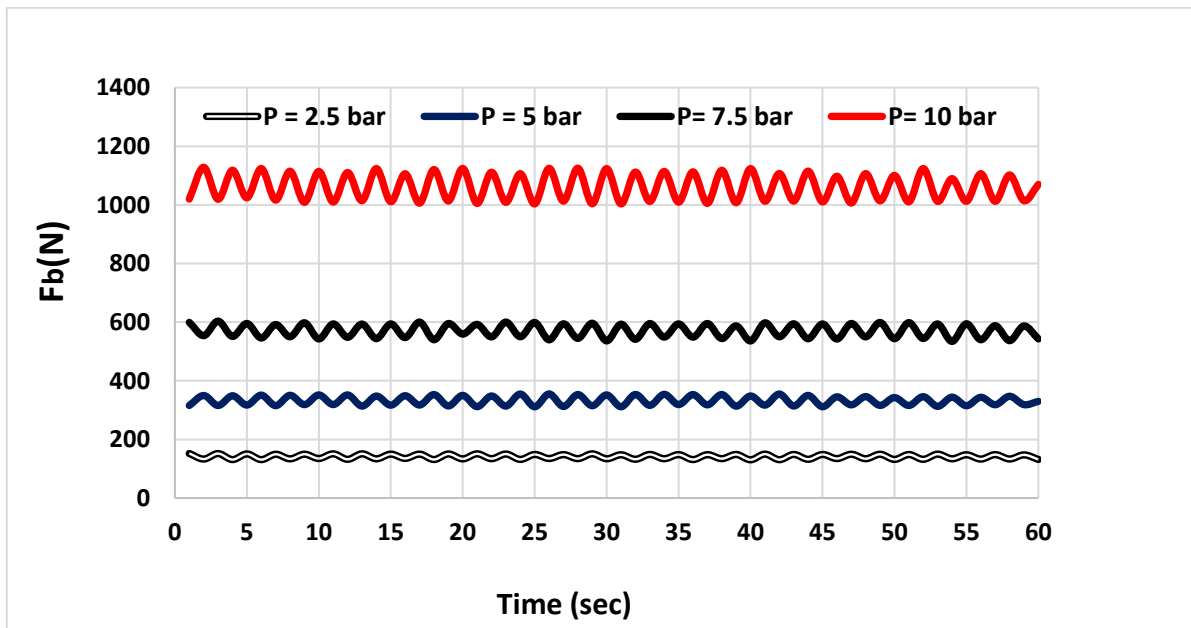


Figure 10: Variation of brake force of the disc brake pad (SiC - 0.5 vol%) as a function of time at sliding speed 300 RPM at different brake oil pressures.

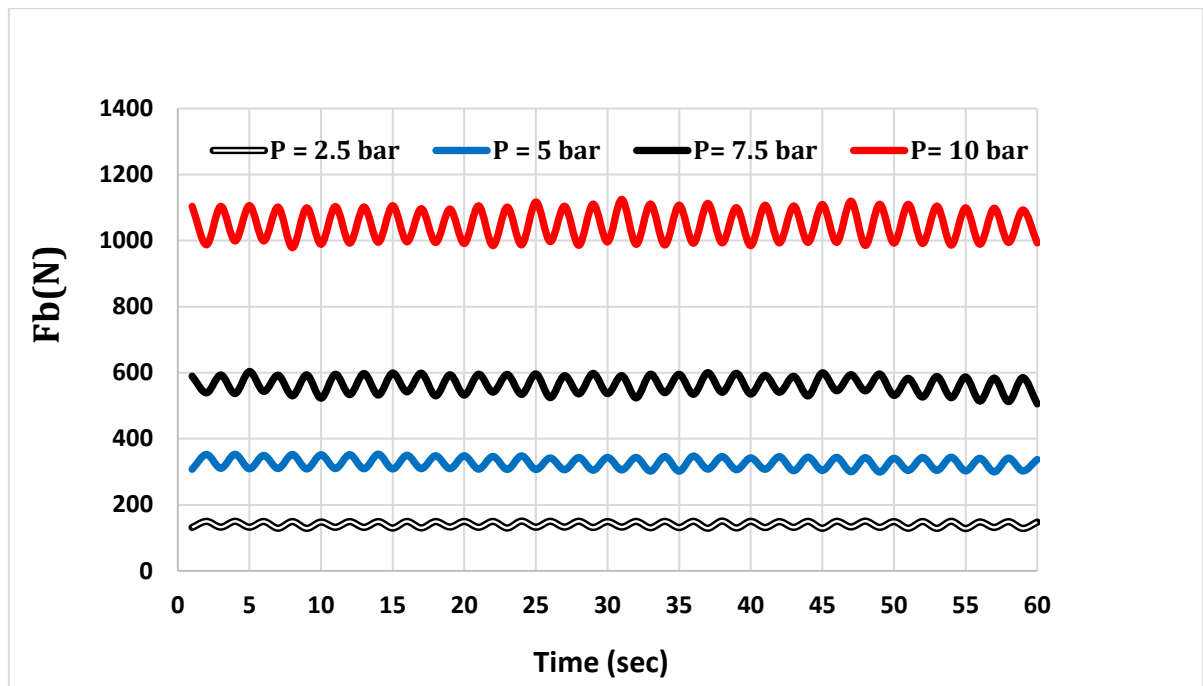


Figure 11: Variation of brake force of the disc brake pad (SiC - 1.5 vol%) as a function of time at sliding speed 300 RPM at different brake oil pressures.

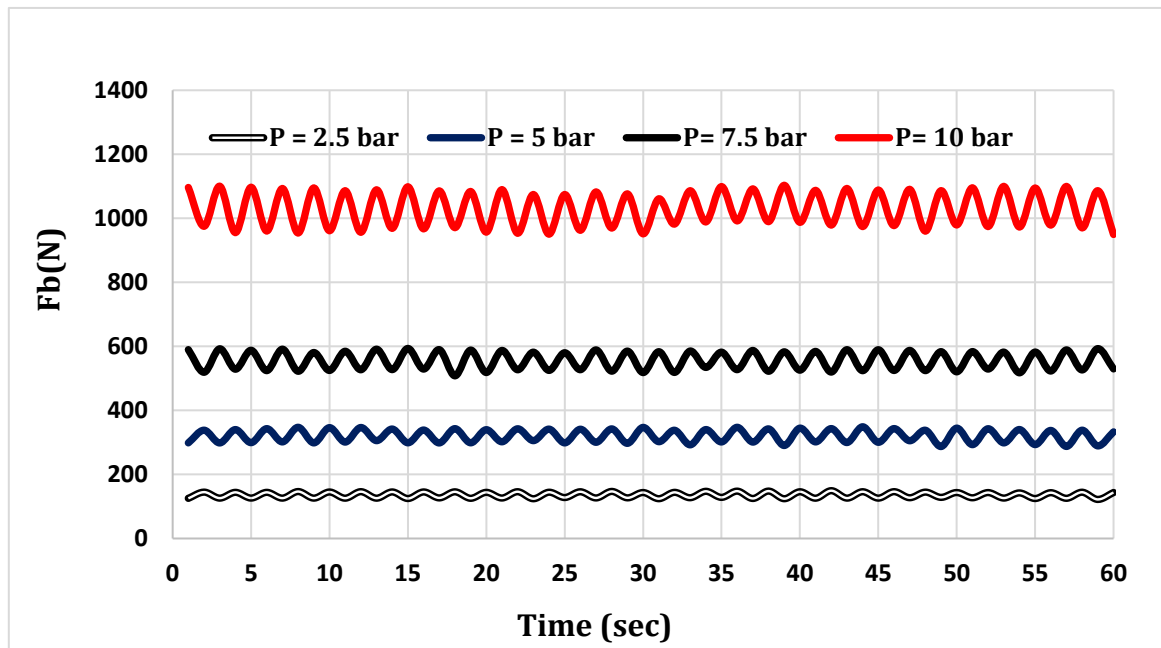


Figure 12: Variation of brake force of the disc brake pad (SiC - 3 vol%) as a function of time at sliding speed 300 RPM at different brake oil pressures.

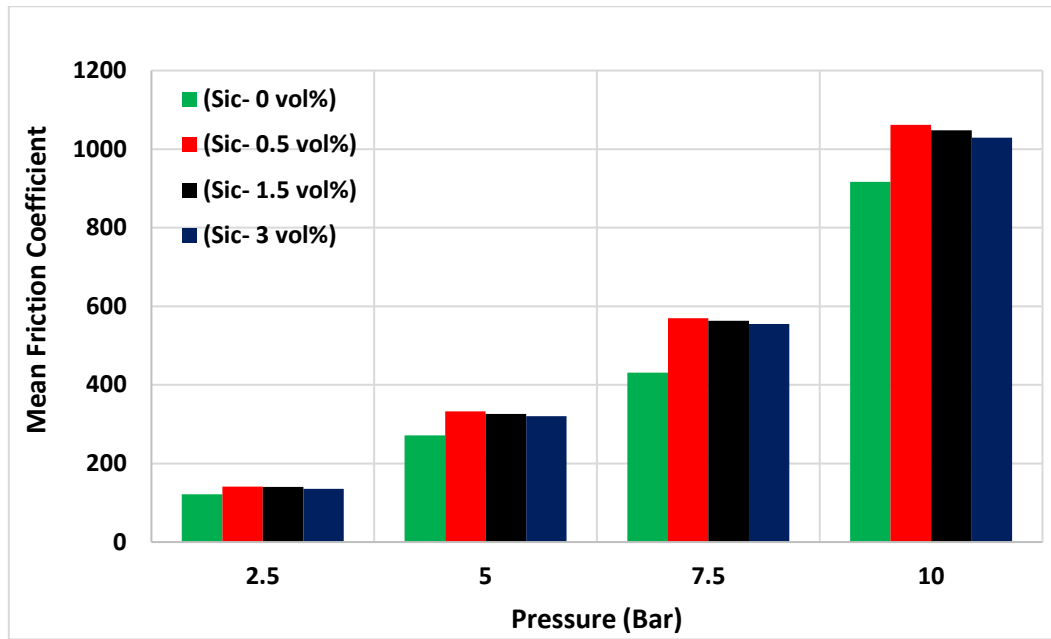


Figure 13: Effect of pressure on the mean brake force of the disc brake pad without Silicon carbide and with the addition of Silicon carbide (SiC from 0 to 3 vol%) at sliding speed 300 RPM.

In Figure 14, the presented results show the effect of the brake oil pressure on the mean friction coefficient of the disc brake pad without Silicon carbide and with the addition of Silicon carbide at a sliding speed of 300 RPM. The results show that, with increased oil pressure, the average friction coefficient of the disc brake pad increases with the addition of Silicon carbide, as well as without Silicon carbide. Additionally, the results indicate that the average friction coefficient of the disc brake pad with additional Silicon carbide is greater than that of the disc brake without Silicon carbide at each pressure. This is because silicon carbide improves the friction coefficient and wear performance. The increase in the oil pressure from 2.5 to 10 bar causes an increase in the mean friction coefficient from 0.220 to 0.415 for the disc brake pad without Silicon carbide, from 0.256 to 0.481 for sample content (SiC 0.5 vol%), and from 0.254 to 0.475 for sample content (SiC -1.5 vol%) and from 0.245 to 0.466 for sample content (SiC -3 vol%).

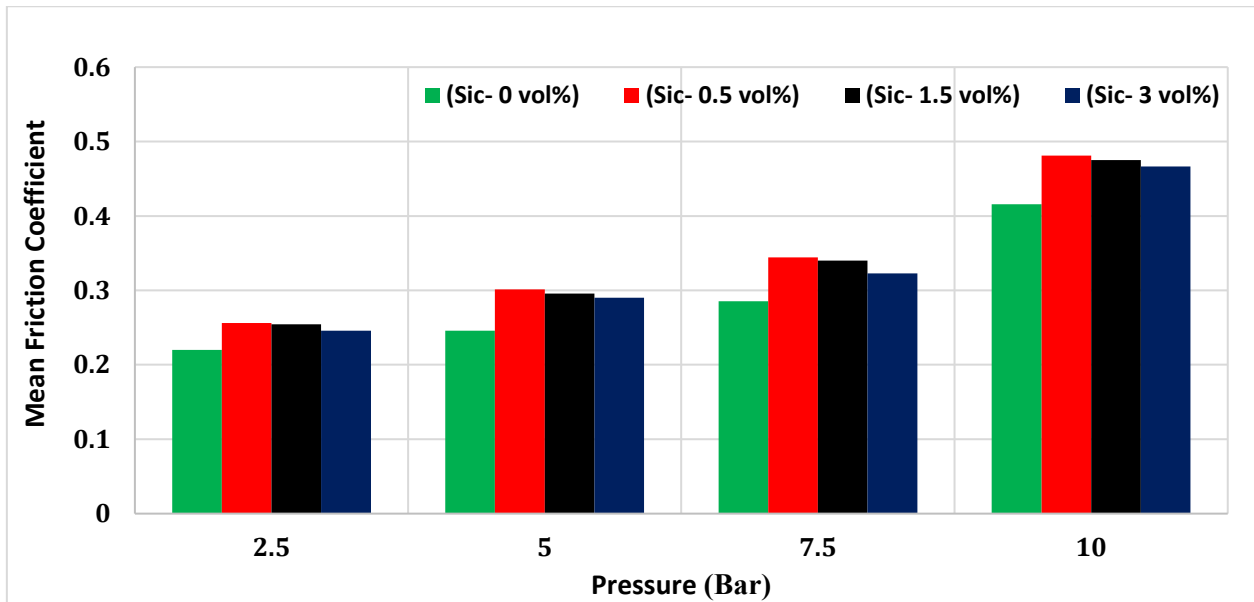


Figure 14: Effect of brake oil pressure on the mean friction coefficient of the disc brake pad (SiC from 0 to 3 vol%), sliding speed 300 RPM.

3.2 Effect of brake oil pressure on operating temperature at different sliding speeds.

In Figure 15 shows The effect of brake oil pressure on the final temperature at initial temperature 40°C of the disc brake pad without Silicon carbide and with addition Silicon carbide at sliding speed 300 RPM, as well The results shown that, As the brake oil pressure increases, the final temperature of the disc brake pad without Silicon carbide and with addition Silicon carbide, because higher hydraulic pressure increases the normal contact force and therefore raises frictional heat generation at the pad-disc interface[23]. Likewise, the final temperature of the disc brake pad without Silicon carbide is less than the final temperature of the disc brake pad with Silicon carbide at each pressure, by the presence of hard SiC particles that increase surface hardness and promote abrasive or ploughing interaction, often increasing frictional response and heat generation during sliding[24][25]. This is due to the increasing friction coefficient in the disc brake pad without Silicon carbide. Due to that, SiC modified the contact mechanics, hardness, and heat-transfer behavior of the pad, leading to higher temperatures for the reinforced samples under the tested conditions[25]. The final temperature of the disc brake pad without Silicon carbide (SiC - 0 vol%) is 55, 60, 68 and 79°C and the final temperature for the sample contain (SiC - 0.5 vol%) is 60, 65, 73 and 83°C and the final temperature for the sample contain (SiC - 1.5 vol%) is 58, 64, 71 and 81°C and the final temperature for the sample contain (SiC - 3 vol%) is 56, 61, 70 and 80°C respectively according to the brake oil pressure of 2.5, 5, 7.5 and 10 bar.

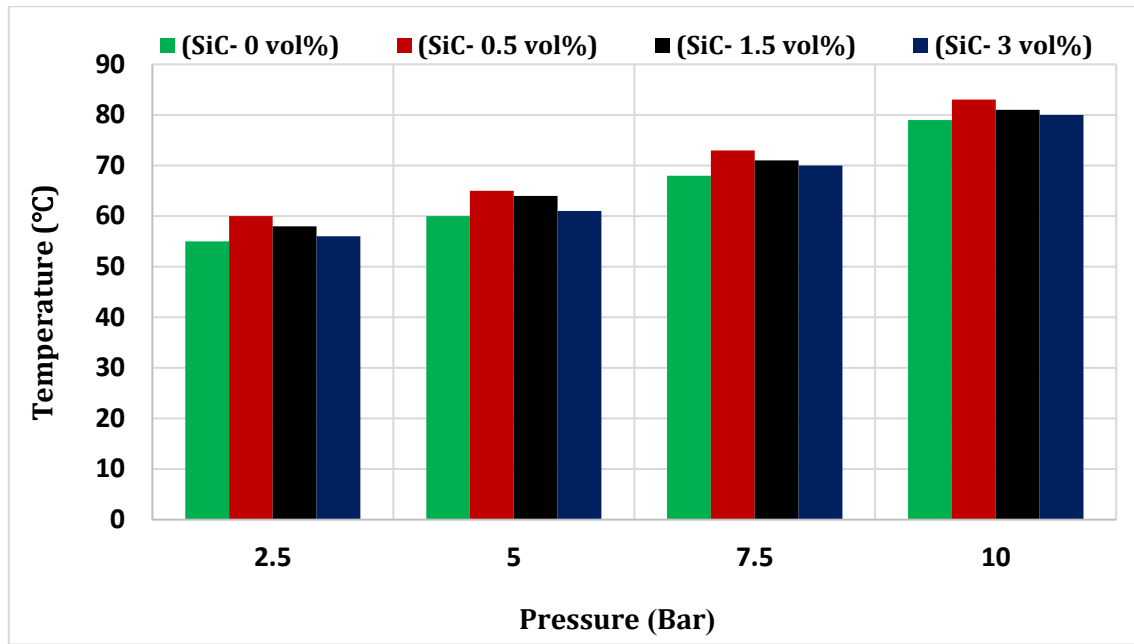


Figure 15: Effect of brake oil pressure on final operating temperature at an initial temperature 40°C at a sliding speed of 300 RPM.

The mentioned temperature values indicate an increase in the final temperature values for disc brake pad with Silicon carbide (SiC - 0.5 vol%) by 8.4%, 7.6%, 6.8% and 4.8%. And 5.1%, 6.3%, 4.3% and 2.5% respectively for disc brake pad with Silicon carbide (SiC - 1.5 vol%) and for disc brake pad with Silicon carbide (SiC - 3 vol%) by 1.7%, 1.6%, 2.8% and 1.2% according to the value of the final temperature of the disc brake pad without Silicon carbide (SiC - 0 vol%).

3.3 Effect of sliding speed on brake oil pressure.

Figure 16 shows the variation of the mean brake force of the disc brake pad without Silicon carbide and with Silicon carbide at different sliding speeds. The results show that the increase in the sliding speed of the rotating disc causes a decrease in the mean brake force of the disc brake pad without Silicon carbide and with Silicon carbide. This was due to a decrease in the friction coefficient. From the results, it can be concluded that the friction coefficient decreases with increasing sliding speed, due to several reasons as follows: Lubricating oxides form at elevated temperatures, and if the surface frictionally melts, the molten liquid can lubricate the asperity contacts. The mean brake forces of commercial disc brake pad (SiC - 0 vol%) are 294.094, 278.076, 266.690, 240.550 N and the mean brake forces for the disc brake pad (SiC - 0.5 vol%) are 347.406, 332.339, 325.015, 287.869 N and the mean brake forces for the disc brake pad (SiC - 1.5 vol%) are 340.205, 326.011, 316.161, 281.830 N and the mean brake forces for the disc brake pad (SiC - 3 vol%) are 327.340, 320.163, 307.519, 276.064 N at sliding speeds of 150, 300, 450, 600 RPM respectively, as well the increase of the sliding speed from 150 RPM to 600 RPM causes a decrease on the mean brake force of the disc brake pad without Silicon carbide from 294.094 N to 240.550 N. And from 347.406 N to 287.869 N for disc brake pad with Silicon carbide (0.5 vol%), from 340.205 N to 281.830 N for the disc brake pad

with Silicon carbide (1.5 vol%) and from 327.340 N to 276.064 N for the disc brake pad with Silicon carbide (3 vol%), Also, the results in Figure (4.30) show that, at each constant speed, the value of the mean brake force of the disc brake pad with Silicon carbide (0.5 vol%) increase approximately by 15.2%, 16.2%, 18.1%, 16.3% respectively, and for disc brake pad with Silicon carbide (1.5 vol%) increase approximately by 13.5%, 14.7%, 15.8%, 13% and for disc brake pad with Silicon carbide (3 vol%) increase approximately by 10%, 13.1%, 13.5% and 13% respectively according the value of the mean brake force of the disc brake pad without Silicon carbide (0 vol%). This is due to the Silicon carbide, which enhances the friction coefficient and brake performance.

As sliding speed increases, the interface temperature rises, promoting thermal degradation or softening of the binder, weakening the bonding between constituents, and changing the real area of contact. In addition, oxide-rich transfer films and third-body layers may form on the rubbing surfaces; although these layers can temporarily stabilize contact, at higher temperatures, they may act as lubricating films or become unstable and detach, causing a reduction in friction and brake force. The presence of SiC improved the brake force at all speeds compared with the unreinforced pad, confirming that SiC enhanced frictional performance[26]. However, the 0.5 vol% SiC pad gave the highest brake force at all sliding speeds, suggesting that a small SiC addition provided the best balance between friction enhancement and friction-layer stability, whereas further increase in SiC content did not produce additional improvement. This interpretation is consistent with published studies showing that SiC influences friction performance and friction-layer formation in brake materials, and that its effect depends on both amount and microstructural characteristics[27].

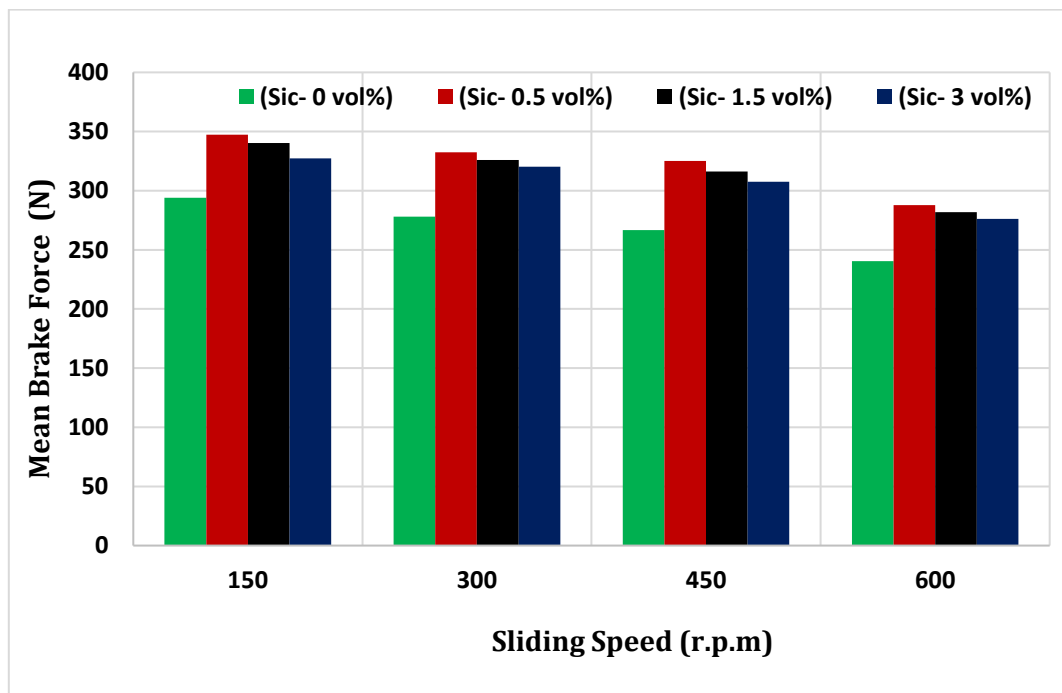


Figure 16: Variation of mean brake force of the disc brake pad with Silicon carbide and without Silicon carbide (Sic - 0 to 3 vol%) as a function of different sliding speeds at pressure 5 bar.

3.4 Effect of sliding speed on operating temperature at different brake oil pressures.

Figure 17 shows the variation of the final temperature of the brake force of the disc brake pad without Silicon carbide and with Silicon carbide at different sliding speeds. The results explain that, with the increase of the sliding speed of the rotating disc, this leads to an increase in the final temperature of the brake force of the disc brake pad without Silicon carbide and with Silicon carbide. In disc brakes, kinetic energy is converted into heat at the pad-disc interface, and the rate of heat generation increases with friction force and sliding speed according to $P=FV$. Qi and Day reported that sliding speed is one of the main factors governing interface temperature, and they also showed that the local maximum temperature depends strongly on the real contact area and the formation of contact plateaus during braking. Therefore, as the disc speed increases, frictional heating becomes more severe, local hot spots develop more easily, and the final temperature of the brake pad rises[28]. The final temperature of the commercial disc brake pad without addition Silicon carbide (SiC - 0 vol%) are 44, 60, 68, 70 °C and for to the disc brake pad (SiC - 0.5 vol%) are 48, 65, 71, 74 °C and for the disc brake pad (SiC - 1.5 vol%) are 46, 64, 70, 72 °C and for the disc brake pad (SiC - 3 vol%) are 45, 61, 69, and 71 at sliding speeds of 150, 300, 450 and 600 RPM respectively. As well, the results in Figure (4.33) shown that, at each constant speed, the value of the final temperature of the disc brake pad (SiC - 0.5 vol%) increase approximately by 8.4%, 7.7%, 4.3% and 5.5% respectively, and for the disc brake pad with addition Silicon carbide (SiC - 1.5 vol%) increase approximately by 4.4%, 6.3%, 2.9% and 2.8% respectively, the disc brake pad with addition Silicon carbide (SiC - 3 vol%) increase approximately by 5.5%, 2.8%, 1.5% and 1.5% respectively over the value of the final temperature of the commercial disc brake pad without addition Silicon carbide (SiC - 0 vol%), This is because it does not contain Silicon carbide, which enhances an increase in the coefficient of friction, which in turn increases the final temperatures of laboratory experiments for samples containing Silicon carbide. The comparison between the pad without SiC and the pads containing SiC indicates that the pad formulation also influenced the thermal response. Research on semi-metallic brake materials has shown that SiC affects friction performance and friction-layer formation, so changing the SiC content can alter both the heat generated during sliding and the stability of the contact layer at the rubbing surface. If your SiC-containing pads recorded higher final temperatures than the pad without SiC, this can be discussed as it can be explained by stronger frictional interaction and greater instantaneous heat generation[29].

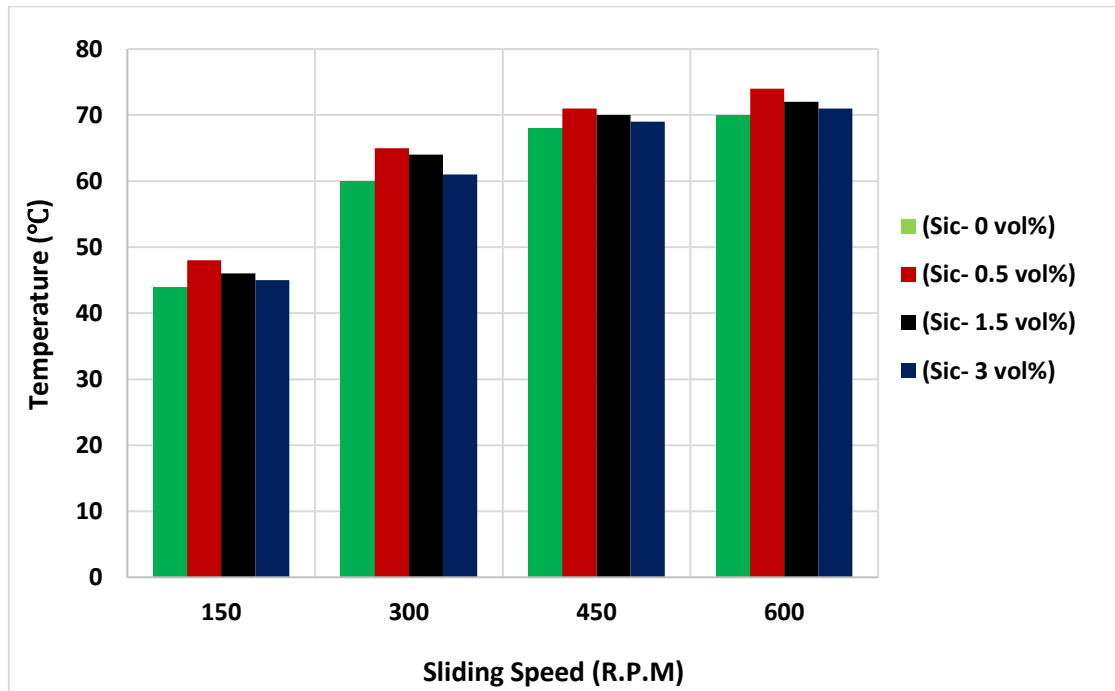


Figure 17: Effect of sliding speed on the final temperature of the disc brake pad, which contains Silicon carbide from (0 to 3 vol%) at brake oil pressure 5 bar.

4.5 Effect of Silicon carbide and initial temperature on friction coefficient at pressure 5 bar at sliding speed of 300 RPM.

The results in Figure 18 show the effects of Silicon carbide on the operating temperature of the commercial and modified brake pad at a pressure of 5 bar at a sliding speed of 300 RPM. The results explain that the samples containing Silicon carbide have a higher coefficient of friction than the conventional sample. The values of the friction coefficient are enhanced by the addition of Silicon carbide into the formulations of modified disc pads. Also, The average friction coefficient of modified brake pad with addition Silicon carbide is more than the average friction coefficient of commercial brake pad without Silicon carbide, with the increasing Silicon carbide from 0 to 3 vol% causes an increase on the mean friction coefficient from 0.252 to 0.290 at initial temperature 40 °C for commercial brake pad without Silicon carbide (SiC - 0 vol%), from 0.243 to 0.281 at initial temperature 70 °C for modified brake pad with addition Silicon carbide (SiC - 0.5 vol%), from 0.238 to 0.271 at initial temperature 100 °C for modified brake pad with addition Silicon carbide (SiC - 1.5 vol%), from 0.230 to 0.260 at initial temperature 130 °C for modified brake pad with addition Silicon carbide (SiC - 3 vol%).

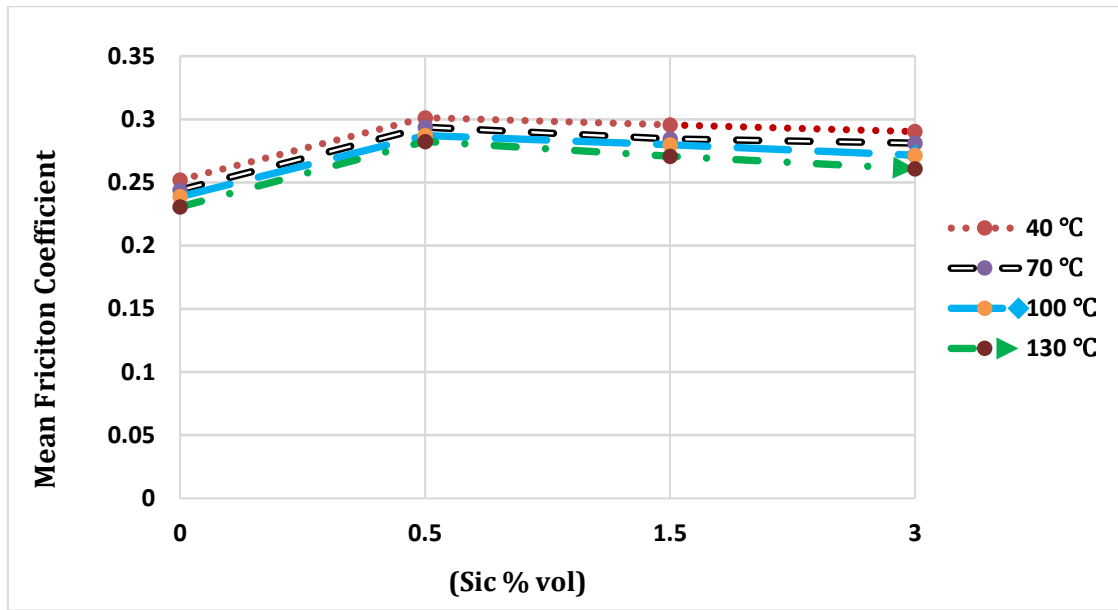


Figure 18: Effect of Silicon carbide and initial temperature on mean friction coefficient of the brake pad which contains Silicon carbide from (0 to 3 vol%) at brake oil pressure 5 bar and sliding speed 300 RPM.

The mentioned mean friction coefficient values indicate an increase in the friction coefficient values for modified brake pad with addition Silicon carbide (SiC - 0.5 vol%) by 16.6%, 17.2%, 17% and 18.4% And 14.5%, 14.4%, 14.6% and 14.8% respectively for brake pad with Silicon carbide (SiC - 1.5 vol%) And for brake pad with Silicon carbide (SiC - 3 vol%) by 13%, 13.5%, 12% and 11.5% respectively, according to the value of the initial temperature 40, 70, 100 and 130 °C of the brake pad without Silicon carbide (SiC - 0 vol%), SiC increases hardness and abrasiveness of the pad surface, helping the material generate and maintain stronger frictional interaction than the pad without SiC. However, as temperature rises, the binder phase can soften, and the contact plateaus or third-body films at the pad-disc interface can become unstable, which lowers the effective shear strength of the contact and reduces friction. Third-body studies on brake pairs confirm that these interfacial films largely control the friction response and that weakly adhered films may detach after braking, causing fluctuations or a reduction in friction performance[30].

5. CONCLUSIONS

Commercial brake pads' overall mechanical and frictional performance is greatly improved by the addition of silicon carbide (SiC) particles. The modified pads continuously performed better than conventional commercial pads at different sliding speeds, oil pressures, and operating temperatures. Interestingly, adding just 0.5 vol% SiC improved the friction coefficient and average braking force the most, resulting in braking force increases of up to 19% over unmodified pads. Although higher SiC concentrations (1.5 vol% and 3 vol%) also

showed discernible advantages over the base material, their performance gains were marginally smaller, indicating that 0.5 vol% is the ideal threshold for this particular additive.

The tribological behavior of all tested materials was consistently influenced by operational variables. Across all sample compositions, raising the brake oil pressure directly increased the mean friction coefficient and the ensuing brake force. On the other hand, the mean brake forces progressively decreased as sliding speeds rose from 150 to 600 RPM, suggesting that standard friction fades at higher rotational velocities. The SiC-enhanced pads maintained a clear operational advantage over the unmodified commercial pads under all tested speed and pressure conditions, despite this fade at high speeds.

During operation, the SiC additives naturally produced more heat because they were successful in increasing frictional resistance. The high-performing 0.5 vol% SiC samples reached the highest peak temperatures as final operating temperatures increased in tandem with the friction coefficients. The altered pads, however, showed outstanding thermal stability. The SiC-infused materials demonstrated their viability and superior fade resistance in high-temperature braking applications by maintaining significantly higher friction coefficients than their commercial counterparts even when initial temperatures were pushed from 40°C to 130°C.

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Author contributions

All authors contributed equally to the conception, design, and execution of the research and to the writing of the manuscript.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical conduct of research.

All experimental procedures and data analyses were conducted according to ethical research standards.

Data availability

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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