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Analysis and Characterization of Composites for their potential use in Disc Brake Pad

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Abstract

Brake pads are crucial for vehicle safety, converting kinetic energy to halt motion. They come in types like organic, semi-metallic, ceramic, and metallic. Beyond automotive, brake pads find application in industries such as aerospace, railways, manufacturing, and wind energy for controlled deceleration and safety. This study is primarily concerned with the quality and appropriateness of ceramic brake pads for automotive applications, which are an essential aspect of braking systems for vehicles. The performance characteristics of ceramic brake pads are well established, and this study explores the variables affecting their quality. Under high pressure, brake pad samples are prepared in the study using Powder Metallurgy (PM), which guarantees superior mechanical qualities by removing interface bonding problems. The samples are then sintered at 2850. Hardness, temperature resistance, wear resistance, and Electron Dispersive Spectroscopy (EDS) analysis are all included in the evaluation to ascertain the make-up and distribution of the materials in the brake pad. EDS sheds light on the degree of sintering and the presence of reinforcements. Heat resistance is evaluated using controlled thermal testing, while wear resistance and hardness are determined through Rockwell hardness testing and wear tests, respectively. These measurements are validated for use in automotive disc braking systems for vehicles and motorcycles. The findings are more reliable thanks to statistical analysis done with MINITAB. The study highlights research gaps in environmentally friendly materials, emerging technology impacts, and long-term brake pad durability.

Index Terms: *Ceramic Brake Pads, Disc Braking System, Electron Dispersive Spectroscopy, Vehicle, Wear Resistance.*

I. INTRODUCTION

Brake pads are a critical component of the braking system in vehicles, playing a pivotal role in ensuring safe and reliable braking performance. These essential components are responsible for converting kinetic energy into heat through friction, ultimately leading to the deceleration of the vehicle or its complete stop [1]. They are an essential part of vehicle safety, and understanding their composition, characteristics, and applications is paramount for automotive engineering and safety [2]. Typically composed of a composite material consisting of friction materials, binders, and various additives, brake pads are meticulously designed to deliver optimal braking performance, durability, and noise reduction [3]. The selection of these materials is a careful process, considering factors such as heat dissipation, wear resistance, and environmental impact [4]. These factors are vital in ensuring that brake pads effectively generate friction and achieve a high coefficient of friction between the pad and the rotor [5], which is essential for creating the necessary force to decelerate or stop the vehicle [6]. In essence, brake pads are an important part of vehicle safety, facilitating effective braking performance and ensuring the reliability of the entire braking system [7]. Among the various types of brake pad materials, ceramic brake pads stand out for their performance characteristics, making them a preferred choice, especially in luxury vehicles or performance-oriented applications [8]. Ceramic brake pads are engineered to provide consistent braking performance and reduced noise. Manufacturers carefully engineer the material composition to strike a balance between these factors, ensuring optimal braking efficiency, durability, and user comfort [9]. The specific composition and characteristics of the compound materials used significantly impact the frictional properties, wear resistance, thermal stability, noise levels, and overall cost of brake pads [10]. The ability of these materials to withstand heat and friction without significant deterioration or wear is crucial for the longevity and effectiveness of the braking system [11]. The manufacturing process of brake pads involves a series of intricate steps, aiming to produce high-quality, dependable, and effective braking components. Once the compound material is prepared, it undergoes a shaping process, which includes precision cutting, grinding, and shaping to achieve the final dimensions and surface finish [12-14]. The preparation of the friction material mixture is the first step in forming compound material brake pads [15]. This mixture may also include binders and additives to enhance performance and characteristics. The pressure and heat help compact the mixture into the desired form of the brake pad. The mold cavity is designed to match the shape and contours of the brake pad [16].

Different methods can be employed for mixing compound materials. Dry mixing methods involve tumble mixing, ribbon blending, or vortex mixing, where the components are mechanically or pneumatically agitated in a container [17]. Dry mixing is often used when the compound materials are in powder or granular form and require thorough blending before adding a liquid binder [18].

On the other hand, wet mixing involves adding a liquid binder to the friction materials and additives, creating a slurry or paste-like mixture [19]. The liquid binder helps distribute the components evenly and promotes adhesion [20].

Compression molding is a prevalent shaping technique used in the production of compound material components, including brake pads [21]. This process involves placing the mixture into a mold cavity and subjecting it to high pressure and temperature.

In injection molding, The mixture is first heated and melted, then injected into the mold, where it solidifies and takes the shape of the cavity. Injection molding enables the production of complex shapes with high accuracy and repeatability [22].

Another shaping method is extrusion, which entails forcing the compound material mixture through a die to obtain a continuous shape, such as a rod or profile.

Subsequently, heat treatment and curing processes play a vital role in the manufacturing of compound material components, including brake pads [23]. These processes involve subjecting the materials to specific temperature and time conditions to achieve desired properties, enhance structural integrity, and improve performance characteristics. The purpose of heat treatment is to modify the microstructure of the material, improving its strength, hardness, wear resistance, and resistance to deformation.

II. STATE OF THE ART

Curing, on the other hand, involves subjecting the friction material mixture to controlled temperature and pressure conditions to activate the binders and promote bonding between the friction materials, additives, and binders [24]. The temperature and duration of the curing process are meticulously controlled to ensure the proper cross-linking and polymerization of the binders [25]. These manufacturing processes are essential to produce brake pads with the necessary mechanical properties, durability, and braking performance [26]. The advantages of compound material brake pads over other types make them a popular choice in various automotive and industrial applications. These advantages include excellent friction performance, consistent performance throughout their lifespan, noise reduction, and superior wear resistance [27]. Compound material brake pads also exhibit outstanding thermal stability, allowing them to withstand the high temperatures generated during braking [28]. One crucial parameter in brake pad performance is the friction coefficient, which determines the braking effectiveness. Brake pads with a high friction coefficient provide increased stopping power, allowing vehicles to come to a halt more quickly and efficiently [29]. The ability to generate a high friction coefficient results in better control over the braking process, leading to shorter stopping distances and improved safety [30]. Brake fading, a reduction in braking performance due to excessive heat buildup, is a concern in demanding braking situations. Brake pads with a high friction coefficient exhibit better resistance to brake fade, ensuring consistent and reliable braking performance under challenging conditions [31]. Efficient heat dissipation is vital during prolonged or intense braking, and brake pads that offer improved heat dissipation can efficiently manage and dissipate the heat generated during braking [32]. Brake pads also play a crucial role in minimizing noise and vibration, enhancing comfort, and driving experience. Brake pads that reduce noise and vibration contribute to a smoother and quieter braking operation, making daily commutes and long drives more pleasant [33]. These noise-reducing features help minimize undesirable braking noises, such as squealing or squeaking [34]. Additionally, they help reduce the transmission of vibration through the brake system, ensuring better braking control and precision [35]. While compound material brake pads offer numerous advantages, it is essential to consider their potential drawbacks. These include a higher cost compared to conventional brake pads, the potential for increased wear, dust, and wheel staining, reduced cold performance, wear on brake rotors, and limited availability. The production of compound material brake pads involves complex manufacturing techniques, leading to higher production costs [36]. Aggressive driving behaviors can accelerate wear on these brake pads, resulting in more frequent replacements [37]. However, proper maintenance can mitigate these issues and maximize the lifespan of compound material brake pads [38]. In discussing brake pads, it is essential to consider the environmental impact associated with their production, usage, and disposal. Brake pad materials can have environmental implications; as can the manufacturing processes involved. During braking, brake pads generate dust and particles due to friction, which can have environmental effects. Developing low-dust and low-emission brake pad formulations aims to mitigate this impact during usage [39]. Proper disposal is also crucial to minimize environmental impact, as brake pads may contain materials requiring special handling [40]. Compound material brake pads find applications across various industries and vehicle types. In the automotive sector, they are used in passenger cars, high-performance vehicles, commercial vehicles, and even racing cars due to their exceptional performance characteristics [41], and [42]. Compound material brake pads are also employed in industrial machinery and equipment, rail transportation systems, and aerospace and aviation applications, meeting stringent requirements for high-temperature performance, low wear rates, and braking efficiency [43], and [44]. Passenger vehicles, extensively used for daily commuting, require reliable and consistent braking performance. Brake pads in passenger vehicles must offer reassurance to families during their travels and perform well in various safety scenarios, including emergency braking situations [45]. The passenger vehicles include performance-oriented models designed for an exhilarating driving experience, and compound material brake pads are commonly used in these vehicles to ensure optimal stopping power and control [46]. Commercial vehicles, used for transporting goods and passengers, operate in demanding conditions. They require reliable and robust braking systems, often employing compound material brake pads to ensure effective and reliable stopping power [47]. Delivery service vehicles, such as postal vans and food delivery trucks, rely on brake pads that can withstand frequent stop-start operations and repetitive braking cycles [48]. Buses and coaches used for public transportation also use compound material brake pads to ensure passenger safety and comfort [49]. In the motorcycle and two-wheeler sectors, compound material brake pads play a vital role in ensuring effective stopping power and stability [50]. These vehicles rely heavily on their braking systems for quick and responsive stopping, and compound material brake pads with enhanced friction characteristics provide enhanced stopping power even in challenging situations [51]. Motorcycles and two-wheelers often generate significant heat during aggressive braking maneuvers, and compound material brake pads excel in heat dissipation, reducing the risk of brake fade [52]. These features contribute to safer and more enjoyable riding experiences.

III. PROBLEM STATEMENT AND ITS PROPOSED SOLUTION

In this research paper, in the quest to enhance braking system efficiency and performance, Silicon Carbide (SiC) emerges as a promising alternative to traditional brake pad materials. SiC, characterized by its remarkable attributes including high thermal conductivity, superior wear resistance, and exceptional thermal stability, holds immense potential for demanding braking applications as shown in SiC property table I [53]. Complementing SiC, magnesium compounds are crucial additives in brake pad formulations, serving to disperse heat effectively, reduce brake fade, and ensure consistent performance even under elevated temperatures [54]. These compounds also contribute to improved friction characteristics, amplifying the coefficient of friction for superior stopping power [55]. Moreover, they act as damping agents, diminishing noise and vibrations during braking, thereby delivering a quieter and more comfortable ride [56]. Additionally, trace elements such as sulfur, chlorine, calcium, chromium, and iron play distinct roles in optimizing the frictional properties, wear resistance, and overall performance of brake pads. Careful selection and balancing of these elements by brake pad manufacturers are crucial in achieving the desired material characteristics. Table I shows the properties of silicon carbide.

Table I: Properties of Silicon Carbide (SiC)

Parameters	Value and Unit of Measures
Density	3.1 g/cm^3
Porosity	0%
Color	Black
Flexural Strength	550 MPa
Elastic Modulus	410 GPa
Poisson's Ratio	0.14
Compressive Strength	3900 MPa
Hardness	2800 Kg/mm^2
Fracture Toughness KIC	4.6 $MPa \bullet m^{1/2}$
Maximum use Temperature (no load)	1650 °C
Thermal Conductivity	120 W/m•K
Coefficient of Thermal Expansion	4.0×10^{-6}/°C
Specific Heat	750 J/Kg•K
Dielectric Strength	Semiconductor
Volume Resistivity	10^2–10^6 ohm•cm

IV. PROPERTIES TO BE ANALYSED

In the realm of mechanical and morphological analysis, several key methodologies are employed to comprehensively evaluate brake pad materials:

1. Elemental analysis using Field Emission Scanning Electron Microscopy (FESEM) is employed for its precision and magnification capabilities, enabling a meticulous examination of material surface structure, topography, and elemental distribution. FESEM employs a focused electron beam to produce high-resolution images, shedding light on the material's composition and structure, making it invaluable for scrutinizing properties such as surface roughness, grain boundaries, fractures, and wear patterns [57-60].
2. Secondly, the hardness of brake pads plays a pivotal role in their performance, as greater hardness fosters improved bonding, reducing contact surface area and elevating the coefficient of friction. Figure I shows the sample for hardness. This parameter is measured using various hardness testing machines, including the Rockwell hardness tester, in accordance with ASTM guidelines, with hardness values influenced by composition and manufacturing processes. Notably, resin content positively affects hardness, while the addition of Silicon Carbide (SiC) increases the metallic matrix's hardness, and the choice of friction modifier, like graphite particles, impacts interlayer bonding and pad stiffness [61-65].

Figure I: Sample of Hardness

3. The thermal resistance is assessed through controlled heating and cooling cycles using a thermal testing machine, simulating actual braking conditions to determine the brake pads' ability to maintain structural integrity and frictional properties under elevated temperatures. Figure II

shows the sample for thermal resistance to be analyzed. This evaluation encompasses variables such as temperature rise, heat transfer, thermal conductivity, and thermal stability, crucial for ensuring consistent braking performance and mitigating brake fade resistance. These findings guide manufacturers in optimizing brake pads' thermal stability, heat dissipation, and overall longevity by refining material formulations, designs, and compositions [66], and [67].

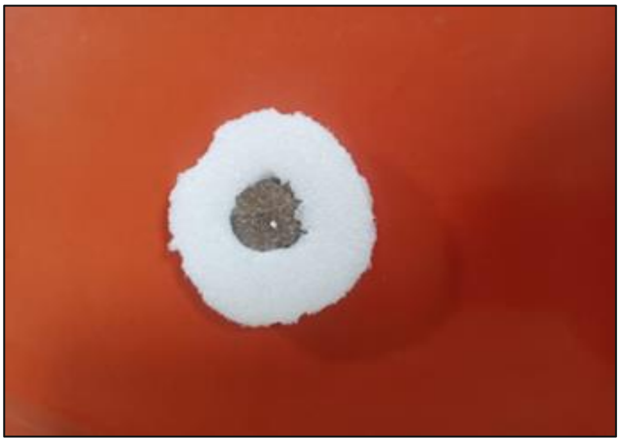


Figure II: Sample of Thermal Test

4. Wear resistance is rigorously evaluated through wear resistance tests conducted with specialized machines. These tests simulate real-world frictional forces by applying controlled rubbing or sliding forces to the brake pads, yielding insights into wear rate, coefficient of friction, and wear debris accumulation. The data garnered from these tests informs manufacturers on enhancing material composition, formulation, and design to bolster wear resistance while maintaining desirable frictional characteristics, ultimately leading to the creation of longer-lasting, lower-maintenance, and high-performance brake pads [68-71].

V. DATA VALIDATION

To validate the measured data, the widely-used statistical software Minitab is employed [72-74]. Renowned for its versatility in data analysis and statistical modeling, Minitab offers a wide array of methods and tools tailored to the specific study goals and data properties, facilitating the creation of reports, graphs, and summary statistics, thus enhancing the comprehension and analysis of brake pad test results. These testing methodologies presented in the research are indispensable for enhancing brake pad efficiency and performance. Evaluation of materials like silicon carbide and magnesium compounds through techniques such as Field Emission Scanning Electron Microscope (FESEM) and hardness testing enables precise selection and optimization, considering properties such as thermal conductivity, wear resistance, and structural integrity. Thermal resistance testing simulates real braking conditions, ensuring consistent performance under elevated temperatures. Wear resistance tests provide insights into friction characteristics, wear rates, and debris accumulation, guiding manufacturers in formulating longer-lasting and high-performance brake pads. Statistical validation using software like Minitab enhances data analysis, facilitating a comprehensive understanding of the results. Overall, these testing procedures are vital for achieving super thermal stability, heat dissipation, and wear resistance, contributing to the development of safer, more durable, and high-performance brake pads.

VI. RESULTS AND DISCUSSIONS

A. Elemental Analysis

For Electron Dispersive Spectroscopy (EDS) analysis, FESEM was employed to ensure precise results. EDS analysis revealed the presence of Silicon Carbide (SiC) particles in the sample containing 6% Si as shown in figure III. The results as shown in table II, indicated that the sample consisted of 47% Carbon, 42% Oxygen, 5% Magnesium, and 3% Silicon. The high percentage of Oxygen (42%) raised concerns about the brake pad's potential brittleness and susceptibility to failure, which could compromise its stopping power. Other trace elements like Sulfur (S), Chlorine (Cl), Calcium (Ca), Chromium (Cr), and Iron (Fe), all below 1%, were considered negligible.

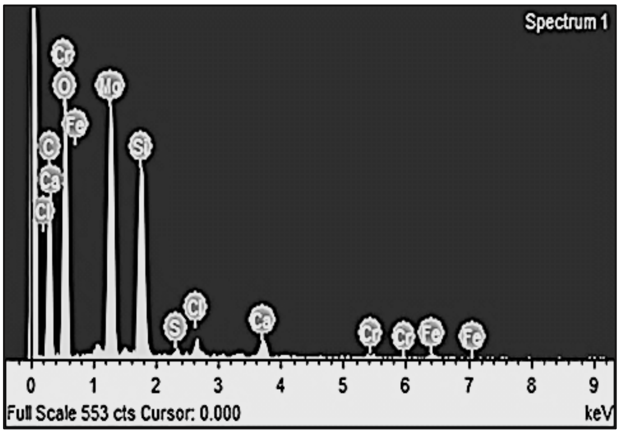


Figure III: EDS Spectrum of Brake Pad Element

Table II: List of Elements in Spectrum

Elements	Weight%	Atomic %
C	37.26	47.33
O	44.57	42.51
Mg	8.99	5.64
Si	6.46	3.51

B. Hardness

In the hardness testing machine as shown in figure IV, an 8x10x11 brake pad sample underwent meticulous evaluation, and a hexagonal cut was employed for precise measurements as previously shown in figure I. Using the Rockwell hardness tester [75], hardness values were recorded at three different points on the sample, yielding the mean hardness values presented in. These values reflected a high level of hardness, indicating the material's resistance to indentation and deformation [76]. Moreover, the hardness test results indicated increased wear resistance, enhanced braking performance, and greater durability, offering valuable insights for engineers and brake pad manufacturers [77-80].

Figure IV: Hardness Testing Machine

C. Thermal Resistance

To find the value of thermal conductivity using Fourier's law, we need to convert the temperature values from Celsius to Kelvin.

Here are the converted temperatures:

- Sample 1:

$$\text{Inlet Temperature}(T1) = 33°C = 33 + 273\ K = 306\ K \quad (1)$$

$$\text{Outlet Temperature}(T2) = 27°C = 27 + 273\ K = 300\ K \quad (2)$$

- Sample 2:

$$\text{Inlet Temperature}(T1) = 40°C = 40 + 273\ K = 313\ K \quad (3)$$

$$\text{Outlet Temperature}(T2) = 29°C = 29 + 273 = 302\ K \quad (4)$$

Now, let us calculate the temperature difference (ΔT) for each sample:

- Sample 1:

$$\Delta T1 = T1 - T2 = 306\ K - 300\ K = 6\ K \quad (5)$$

- Sample 2:

$$\Delta T2 = T1 - T2 = 313\ K - 302\ K = 11\ K \quad (6)$$

Area (A) is given as $30.8mm^2$, which can be converted to square meters:

$$A = 30.8\text{mm}^2 = 30.8 \times 10^{-6}\text{m}^2 \quad (7)$$

The thickness (dx) is given as 11 mm, which can also be converted to meters:

$$dx = 11\ mm = 11 \times 10^{-3}m \quad (8)$$

Now, we can apply Fourier's law:

$$q = \frac{k \times A \times \Delta T}{dx} \quad (9)$$

Where:
q is the heat transfer rate and,
k are the thermal conductivity, we want to find.

For Sample 1:

$$20\ W = \frac{k \times 30.8 \times 10^{-6}m^2 \times 6\ K}{11 \times 10^{-3}m} \quad (10)$$

Simplifying the equation, we find:

$$k = \frac{20\ W \times 11 \times 10^{-3}m}{30.8 \times 10^{-6}m^2} \quad (11)$$

Where:
$k = 1.19\ W/mm.K$

For Sample 2:

$$30\ W = \frac{k \times 30.8 \times 10^{-6}m^2 \times 11K}{11 \times 10^{-3}m} \quad (12)$$

Simplifying the equation, we find:

$$k = \frac{30\ W \times 11 \times 10^{-3}m}{30.8 \times 10^{-6}m^2 \times 11K} \quad (13)$$

Where:
$k = 0.974\ W/mm.K$
Therefore, the thermal conductivity (k) for Sample 1 is approximately 1.19 W/mm.K, and for Sample 2 is approximately 0.974 W/mm.K.

D. Wear Testing

Figure VII shows the wear test results conducted on a 5mm x 5mm x 11mm brake pad sample, the wear resistance testing machine as shown in figure V employed composite disc and diamond ball/pin equipment with specific parameters, including rotation speed, weight applied, and test distance.

Figure V: Break Pad Wear Resistance Testing Machine

The test yielded a minimal wear volume of 0.000 mm^3, indicative of exceptional wear resistance [81], as shown in figure VI.

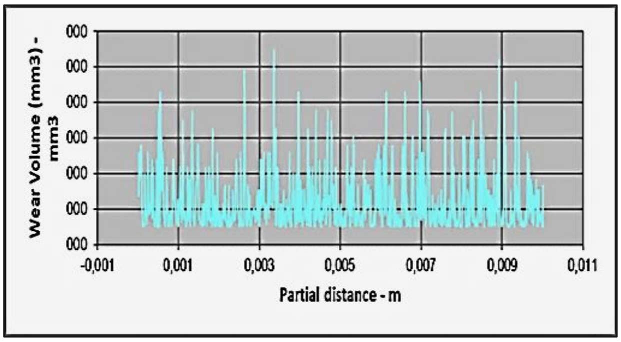
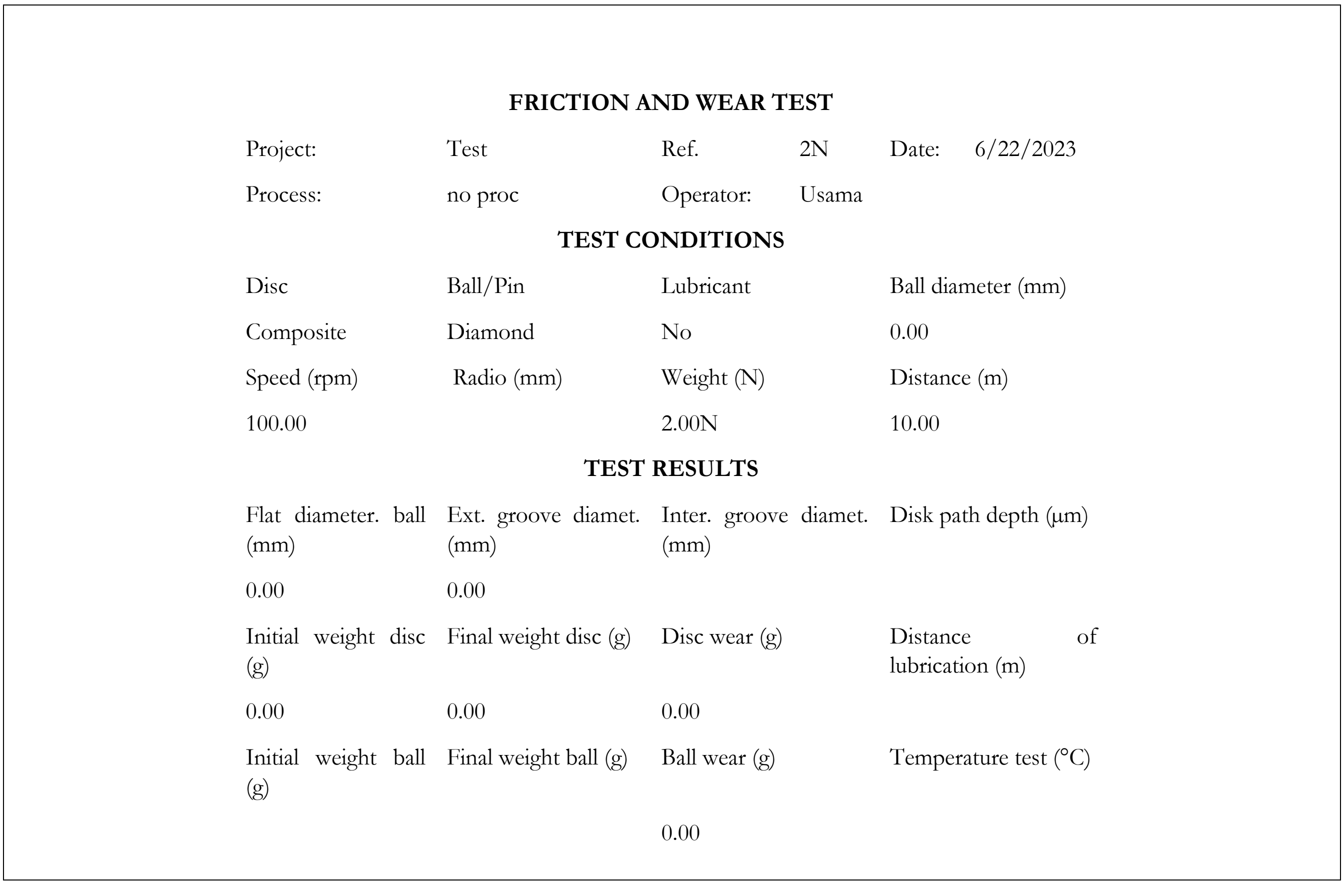


Figure VI: Wear Profile Highlighting Rate of Material Removal at Various Distances

Visual representation of the wear profile highlighted the rate of material removal at various distances, affirming the high wear resistance and longevity of the brake pad sample [82]. These characteristics are pivotal for ensuring a dependable and durable braking system.



FRICTION AND WEAR TEST

Project:	Test	Ref.	2N	Date:	6/22/2023
Process:	no proc	Operator:	Usama		

TEST CONDITIONS

Disc	Ball/Pin	Lubricant	Ball diameter (mm)
Composite	Diamond	No	0.00
Speed (rpm)	Radio (mm)	Weight (N)	Distance (m)
100.00		2.00N	10.00

TEST RESULTS

Flat diameter. ball (mm)	Ext. groove diamet. (mm)	Inter. groove diamet. (mm)	Disk path depth (μm)
0.00	0.00		
Initial weight disc (g)	Final weight disc (g)	Disc wear (g)	Distance of lubrication (m)
0.00	0.00	0.00	
Initial weight ball (g)	Final weight ball (g)	Ball wear (g)	Temperature test (°C)
		0.00	

Figure VII: Wear Test Results

E. Data Validation

To validate the obtained results, a statistical analysis was performed using Minitab software [83]. A matrix plot graph is shown in figure VIII. Depicted the relationship between predicted and actual hardness values obtained from three hardness tests conducted at 10-second intervals. The graph displayed a close alignment between the predicted and actual values, with a predicted hardness value of 162. This alignment underscored the accuracy and consistency of the hardness testing method, affirming its reliability in assessing brake pad resistance. All results for data validation can be provided on demand as supplementary files as it is difficult to show all in this test. The result section unveiled a thorough examination of brake pad materials, encompassing impact, hardness, thermal resistance, wear resistance, and FESEM analysis. Key findings, such as the presence of silicon carbide particles and elevated hardness values indicative of enhanced wear resistance and braking performance, were underscored. Transitioning to broader considerations, the imperative of environment consciousness in brake pad development. Discussion can be on points like environmental considerations, such as reducing emissions, minimizing dust, and promoting sustainability, which are crucial factors in brake pad development. Efforts are being made to develop environmentally friendly brake pad materials and reduce the environmental impact associated with brake pad production, usage, and disposal. Compound material brake pads offer superior braking performance, reliability, and durability. Ongoing research and development efforts aim to further optimize their characteristics and address challenges such as environmental impact and compatibility with advanced braking systems. The continuous advancements in brake pad technology contribute to improved safety, efficiency, and comfort in the field of vehicle braking systems.

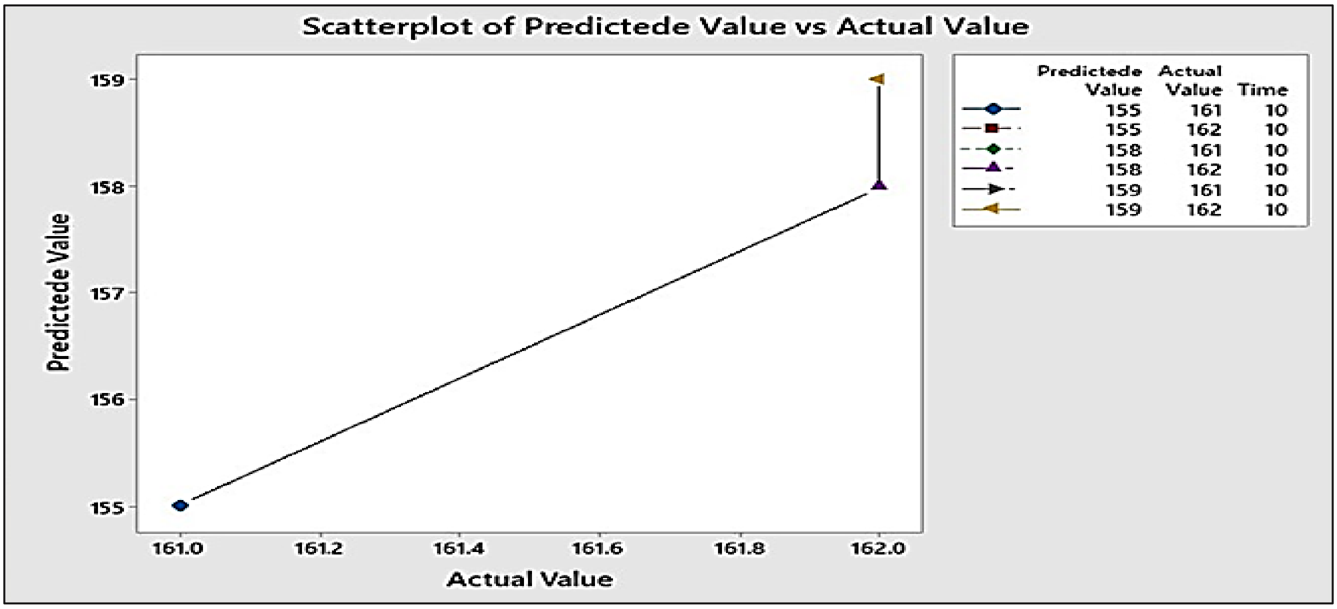


Figure VIII: Actual and Predicted Hardness

VII. CONCLUSION

In conclusion, brake pads are critical components of the braking system in vehicles, providing the necessary friction to slow down or stop the vehicle. The material composition of brake pads, including friction materials, binders, and additives, plays a significant role in their performance and effectiveness. The current study drew the following significant conclusions:

1. The hardness of brake pads affects their resistance to deformation and wear. Brake pads with a higher hardness value exhibit better durability and resistance to frictional forces. The thermal performance of brake pads, including heat dissipation and thermal stability, is crucial to prevent brake fade and ensure consistent braking performance. The intricate interplay between hardness and performance underscores the significance of these characteristics in ensuring extended longevity.
2. Diverse types of compound materials, such as metallic, ceramic, and organic compounds, offer unique properties and characteristics to meet the specific requirements of braking systems. These characteristics contribute to enhanced safety, control, and comfort during braking operations. A nuanced exploration of compound materials reveals the existence of varied options including metallic, ceramic, and organic compounds. Each type boasts unique properties tailored to meet specific requirements within braking systems. The diversity is tailored to meet specific requirements within braking systems.
3. Compound material brake pads offer several advantages, including excellent friction performance, consistent braking performance, reduced noise and vibration, high wear resistance, and efficient heat dissipation. These brake pads go beyond their basic function. They function as a dependable team ensuring safety control, and added comfort during every braking maneuver, making them an indispensable element for a smooth and secure driving experience.
4. Compound material brake pads are widely used in various industries and vehicle types, including passenger vehicles, commercial vehicles, motorcycles, and aerospace applications. These brake pads establish themselves as versatile solutions, highlighting their pervasive influence.
5. Research in brake pad development focuses on material composition, wear behavior, thermal properties, and compatibility with advanced braking systems. The inclusion of elements such as Silicon Carbide (SiC), Magnesium (Mg), and Chromium (Cr) can enhance the performance, durability, and efficiency of brake pads.
6. Advanced testing techniques, such as FESEM and thermal resistance testing, play a key role in better brake pads. These methodologies provide invaluable insights into the microstructure, wear resistance, and thermal behavior of brake pads, facilitating a more nuanced understanding optimization of their performance characteristics.

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Authors Contributions
All the authors equally contributed to this study.

Conflict of Interest
The authors declare no conflict of interest and confirm that this work is original and not plagiarized from any other source. The information obtained from all of the sources is properly recognized and cited below.

Data Availability Statement
The testing data is available in this paper.

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