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ORIGINAL ARTICLE

Grain Size Effect on Compression Behavior in Basalt–Wheat Straw Epoxy Brake Pads Using Response Surface Method

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Abstract

Background/Objectives: Due to the carcinogenic nature of asbestos, the development of eco-friendly, lightweight brake pads using agricultural waste and natural minerals has become vital. However, such formulations often suffer from poor mechanical strength. This study investigates the optimization of particle sizes of wheat straw fiber and basalt materials to enhance the compressive strength of a novel, lightweight brake pad formulation. **Method**: This research investigates the optimization of brake pad friction materials via RSM, focusing on the particle size effects of constituents: basalt (B), sand (S), steel (St), wheat straw fiber (WS), and graphite (G). A novel, non-traditional casting fabrication route is introduced. Comprehensive physical and mechanical characterization, including density, porosity, and compressive strength testing, validates the performance of the produced composites. **Findings**: RSM analysis revealed that optimized particle sizes—basalt at 168.75 μm, sand at 225 μm, steel at 337.5 μm, wheat straw fiber at 225 μm, and graphite at 112.5 μm—yielded significant performance improvements. Notably, sample S6 achieved a compressive strength of 114.77 MPa, porosity of 3.84%, density of 1.31 g/cm^3, and water absorption of 0.27%. **Novelty:** Specifically, the achieved compressive strength surpassed 39% higher than reported in the literature. The findings highlight the significant influence of particle size variation on porosity and compressive performance, unlike density variation. This study demonstrates that controlled particle size distribution improves the mechanical performance of eco-friendly brake pads, offering a high-performance, sustainable alternative.

Keywords: Basalt; Compression Strength; Particle Size; Wheat Straw

1 Introduction

Modern automotive brake pads are highly engineered composite materials designed to meet increasingly stringent requirements for safety, performance, and ecological sustainability. Historically, asbestos was the primary reinforcement fiber due to its excellent thermal stability and cost-effectiveness; however, its carcinogenic nature and the severe health risks associated with airborne asbestos dust have led to widespread global bans. This shift has necessitated the development of non-toxic, eco-friendly friction materials that can serve as effective replacements without compromising mechanical integrity. Current material advancements are increasingly focused on organic fibers and plant residues due to their abundant availability, low cost, and unique capacity for carbon sequestration. Given the high frequency of use and the significant environmental risks posed by traditional friction materials, there is an urgent need for extensive research into sustainable, high-performance alternatives derived from renewable biological sources[(1)]. Historically, the use of asbestos and various heavy metals in friction materials has been identified as a primary cause of severe respiratory diseases, including lung cancer and chronic infections. Recent data from the World Health Organization (WHO) indicates that air pollution—of which airborne particulates from carcinogenic brake pads are a significant component—is linked to approximately 7 million premature deaths annually. This represents a critical environmental health risk, contributing to nearly 7% of global mortality[(2)]. To mitigate these risks, international frameworks have been established to limit the use of hazardous materials. While the Paris Agreement focuses broadly on reducing greenhouse gas emissions, more specific regulations, such as the EU's Euro 7 standards, now directly target non-exhaust emissions, including particulate matter (PM) from brakes. These legislative shifts emphasize the mandatory ban of hazardous substances and their replacement with safer alternatives[(3)]. Consequently, research has shifted toward sustainable friction materials, specifically the integration of plant fibers into brake pad formulations. This transition supports a circular and green economy by reducing the industrial carbon footprint, repurposing biomass waste, and providing a sustainable economic model through the conversion of natural waste into high-value functional products.

Brake pads serve as a critical component within automotive braking systems, as they are responsible for generating the frictional force required to decelerate and stop a vehicle[(4)]. Beyond basic friction, high-performance brake pads must possess high compressive strength to withstand intense braking forces, alongside a low-to-moderate density. Furthermore, controlled porosity is essential to facilitate effective heat dissipation and minimize operational noise. Among these properties, compressive strength and stiffness are the most significant factors for structural integrity and system response. High compressive strength is necessary to resist the substantial normal forces applied during braking maneuvers[(5)]. Simultaneously, high stiffness and a low strain rate directly improve braking effectiveness by reducing brake pedal travel, maintaining precise caliper clearances, and preventing the over-displacement of braking fluid. These mechanical characteristics ensure a consistent hydraulic volume and a more responsive, reliable braking system.

Recent research into natural fiber-reinforced friction materials has revealed significant challenges in achieving the density, porosity, and strength required for automotive standards. Recent investigations into natural fiber-reinforced friction materials have evaluated hybrid systems comprising alkali-treated kenaf and jute woven fibers. While these composites, fabricated via vacuum-assisted resin infusion with bisphenol-A epoxy, offer renewable alternatives, they often struggle to meet stringent industrial benchmarks[(6)]. Specifically, reported densities (1.28–1.50 g/cm^3) and water absorption rates (14.42–29.36%) deviate significantly from the industry standards of 1.89 g/cm^3 and 0.9%, respectively[(7)]. These discrepancies underscore the necessity for alternative reinforcements, such as wheat straw fiber, which may offer a more favorable balance of physical properties and moisture resistance. Other studies have explored hybrid reinforcements with varying success. A composite utilizing carbon black, metal chips, and coconut fibers via the casting method achieved a compressive strength of up to 120.52 MPa, yet suffered from low density and inconsistent water absorption[(8)]. Similarly, hybrid jute/sisal composites reached a compressive strength of 102.26 MPa—approaching the 110 MPa standard of commercial asbestos pads—while maintaining competitive density and absorption rates[(9)]. Despite these advancements, performance gaps remain prevalent. Research on date palm fibers and other bio-composites reported compressive strengths ranging from 70 to 77 MPa, consistently falling achieve of commercial requirements[(10)]. Furthermore, while some formulations achieved high strength (120.5 MPa), they often resulted in higher specific gravity (2.081), which negatively impacts vehicle weight, unsprung mass, and can induce undesirable noise, vibration, and harshness (NVH) levels. A critical observation across these studies is that increasing the complexity of the formulation or the number of ingredients does not linearly improve performance, highlighting the need for optimized constituent particles and constituent ratios.

1.1 Research gap

In this study, a novel friction composite is developed through a unique formulation of hybrid reinforcements—comprising basalt, wheat straw fiber, sand, and steel particles—integrated within a graphite-enhanced epoxy resin matrix. This research addresses the persistent trade-off between mechanical strength and weight in friction materials by systematically optimizing particle size to enhance interfacial bonding and structural packing. Unlike traditional formulations, this multi-constituent approach serves a dual function: providing robust frictional stability while achieving a significant reduction in density and increase in stiffness. By bridging the gap between bio-based sustainability and industrial performance, this work provides a scalable pathway for engineering lightweight, high-performance brake pads that surpass the mechanical limitations. The novel contribution of this research is the development of a high-performance brake pad composite utilizing NaOH-treated wheat straw fiber (WS) as a primary organic filler. While traditional friction materials rely on energy-intensive molding pressures, this study introduces a unique pressureless casting technique that achieves superior structural integrity and mechanical response. By leveraging the advanced manufacturability of commercial epoxy resin in a hybrid natural fiber-polymer matrix, the resulting composite surpasses existing literature in strength-to-weight ratio, exhibiting significantly reduced density and lower porosity compared to conventional alternatives reported in contemporary literature.

The significance of this work is twofold: it addresses a critical engineering need for lightweight friction materials while solving a mounting environmental crisis. WS is currently the largest harvested crop byproduct in history, with global food security initiatives further accelerating its abundance. In Ethiopia, a historical center of crop diversity, wheat production has surged to over 28 million tons—more than double previous records [11]. Despite this volume, approximately 30% of wheat straw is currently managed through non-green practices, such as open-field burning, which releases significant CO_2 and burdens landfills. By repurposing this vast, underutilized biomass into a value-added industrial component, this research provides a foundational step toward a circular economy, transforming agricultural waste into a sustainable solution for the automotive sector.

Building upon the current need for sustainable friction materials, this research aims to replace hazardous components with a novel, high-performance green composite. The primary objective is to evaluate the synergistic effects of a unique hybrid formulation—comprising basalt, sand, steel, wheat straw fiber, and graphite—on the mechanical and physical properties of brake pads.

To achieve this, the study focuses on the following specific objectives:

- Systematic Particle Size Optimization: To investigate the influence of varying particle sizes (112.5-337.5μm) for each constituent on the structural packing and interfacial bonding of the composite.
- Novel Fabrication via Pressureless Casting: To develop and validate an energy-efficient casting technique as a viable alternative to traditional, energy-intensive compression molding.
- Performance Characterization: To quantify the impact of constituent granularity on compressive strength, porosity, and density, ensuring the results meet or exceed industrial safety standards.
- Statistical Correlation and Mathematical Modeling: To employ Analysis of Variance (ANOVA) to establish a robust statistical relationship between grain size and compressive performance.
- Predictive Framework Development: To derive a mathematical model that optimizes the balance between mechanical integrity and weight reduction, providing a predictive tool for the future engineering of bio-based friction materials.

2 Methodology

2.1 Materials

The materials in this research on brake pad formulation have been classified into six ingredients and processed separately. Those materials are steel particles: which is grinding swarf of steel as filler material, basalt and river sand micro-powders as abrasive material, Wheat straw (*Triticum aestivum*) fiber as reinforcing fiber which is known industrialy as Alkali-Treated Wheat Straw Fiber (ATWS), graphite dust particles industrialy known as dry lubricant powder as friction modifiers, epoxy resin as binding material: a mixture of unsaturated polyester derived from phthalic anhydride, glycols, and maleic anhydride and a monomer, most commonly styrene as commercialy obtained binding material, and hardener, methyl-ethyl-ketone peroxide (MEKP) for hardening were used to harden the epoxy during brake pad casting.

The research methodology encompassed materials collection, drying process at 100 °C, sieving, grinding, alkali treatment of wheat straw fiber(using alkaline medium 5%NaOH), and characterization of materials, which were done before composite formulation. Sieving and storing of materials based on three particle sizes for each material was done in order to use for the subsequent formulation of the brake pad. Steel particle chemical composition analysis is among the basic tests on the constituent materials of the brake pad.

The brake pad composition was fixed, and the RSM experimental design based on particle size variation was performed with replicated center points of particle size. The brake pad manufacturing process using casting method was performed. The brake pad test specimen was fabricated for various tests of the brake pad sample, including SEM morphological observation, density, porosity, compressive strength, and XRD (of the optimal sample) investigation of the brake pad.

2.2 Material Processing

2.2.1. Steel

Steel pallets were sourced from Ethiopia, Kality Metals Factory in Addis Ababa. The material was milled using a grinding wheel, and the resulting steel particles were separated from non-magnetic impurities through magnetic separation. The collected steel particles were sieved, and fractions with sizes of 225, 281.25, and 337.5 μm were isolated and retained for subsequent brake pad formulation.

The heavy metal concentration in the steel sample was quantified using an Optical Emission Spectrometer (OES) available at Kality Metals Factory, Addis Ababa, Ethiopia. For analysis of the steel sample, a small amount was taken from the steel billet and subjected to electrode spark discharge energy. This process vaporized a minute amount of material, generating plasma. The intensity of specific wavelengths and spectral lines emitted by the plasma was measured and used to determine the elemental composition using the principle of spectral analysis.

The compositional analysis of the steel particles used in the brake pad formulation, as presented in Table 1, reveals no significant level of heavy metal concentration, such as copper, in the sample, with the heavy metal concentrations being less than 5%.

Table 1. Elemental composition of steel particles

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al	Co	Nb	Ti	V	w	Fe
wt.%	0.01	0.021	0.01	0.09	0.013	0.01	0.01	0.084	0.005	0.003	0.005	0.005	0.003	0.00001	0.03	99.70099

2.2.2. Basalt

The mineral basalt, known as mafic, extrusive igneous (volcanic) rock, was sourced from local suppliers in Ethiopia, Bale Zone, and industrially aggregated by jaw crushing process. After the collection of the basalt aggregate, a cleaning process using distilled water was carried out, and dried in the sunlight. The basalt milling process was performed using a ball mill located in the mechanical operations laboratory of the chemical engineering laboratory at Adama Science and Technology University. The pulverized basalt was manually sieved, and particles with sizes of 112.5 μm, 140.63 μm, and 168.75 μm were separately retained for use in brake pad formulation. The abrasive properties of basalt were crucial for its role in brake pads, as it contains abrasive compounds such as Al_2O_3, Fe_2O_3, and SiO_2, which are required for brake pad for improving physical and compressive performance.

2.2.3. Wheat straw fiber (WS)

Wheat straw fiber (WS) was obtained from local suppliers in a farmland located in Ethiopia, the Bale Zone, southeastern Oromia Regional State. The collected straw fiber was cleaned with distilled water and dried in sunlight for one day. Subsequently, the dried fiber was milled using a rotational milling machine and sieved manually. Particle sizes of 225 μm, 281.25 μm, and 337.5 μm were isolated and stored for brake pad formulation. Additionally, wheat straw fiber particles in the size range of 255–337.5 μm were soaked in a 5% NaOH solution for 30 minutes to enhance fiber surface interfacial adhesion with epoxy resin and enhance the compressive strength of the brake pad.

2.2.4. River Sand Particle

River Sand (natural silica sand), commonly used for the construction of concrete, was used as a brake pad abrasive ingredient. The natural sand is composed mainly of quartz (SiO_2), which was collected from the ZIWAY province. The sand was cleaned using distilled water and dried in sunlight. The milling operation was performed on the sand using a ball-milling machine. The milled sand particles were sieved manually using the ASTM standard sieves obtained from the soil laboratory at Adama Science and Technology University. Finally, sand particles of (225, 281.25, and 337.5) μm were stored separately for the brake pad formulation.

2.2.5. Graphite

The artificial Graphite (Synthetic Graphite) was obtained from suppliers from Ethiopia for the solid lubricant constituent of the brake pad formulation. The graphite particles were pulverized using the ball mill apparatus. After the milling process, graphite particles with grain sizes of (112.5, 140.63, and 168.75) μm were stored separately for the brake pad formulation.

2.2.6. Epoxy

Epoxy resin was purchased from World Fiber Glass and Waterproofing Engineering in Addis Ababa, Ethiopia. The hardener methyl ethyl ketone peroxide (MEKP) was also purchased and used as the binder and curing agent of the matrix. The primary advantages of epoxy in brake pad composites include its easy castability as a brake pad sample, good thermal characteristics, high hardness, wear resistance, and excellent chemical resistance properties.

The epoxy cures fast enough when it is mixed with the hardening agent (MEKP). For example, the hardening time is 5 minutes for 4 ml MEKP per liter of Epoxy resin.

2.3 Morphology of particles

The SEM instrument JEOL JCM-6000Plus image, shown in Figure 1, was employed to determine the particle size and effective diameter of ingredients. For instance, sand particles exhibited sizes ranging from 362 to 395 μm, basalt particles ranged from 223 to 439 μm, wheat straw fiber sizes ranged from 142 to 241 μm, and graphite particle are range between 112.5-168.75 μm.

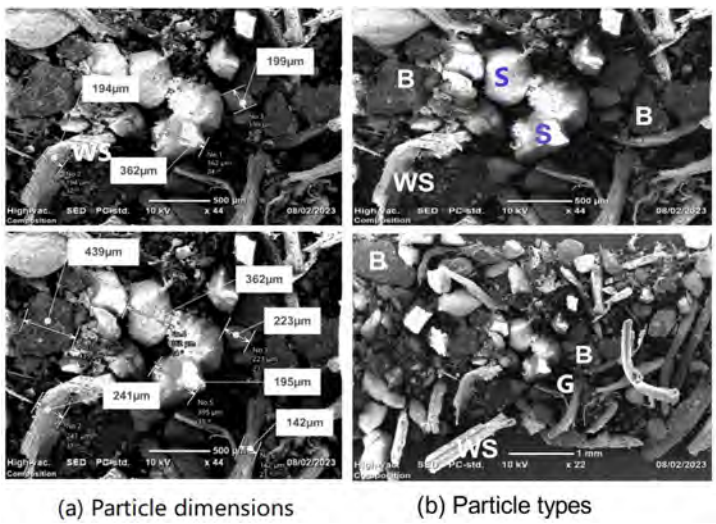

Fig 1. SEM image of particle size

2.4 Experimental design

The particle sizes of basalt, steel, graphite, WS, and river sand formulation and experimental setup are shown in Table 2. The variation of quantity in wt. % of all materials has been constantly added to each formulation. The signal-to-noise ratio is determined by statistically analyzing the variation, and analysis of variance (ANOVA) was used to predict the optimal particle size for the best-performing brake pad sample in compressive strength response.

Table 2. Experimental design

Sample	Mass distribution %	Ingredients	Composition (wt.%)	Particle size(μm)
S-1	99.99	B	10	112.5
		S	4	225
		St	7	225
		WS	3	225
		G	6	112.5
		Epoxy	70	-

Continued on next page

Table 2 continued

		B	10	112.5
		S	4	225
S-2	99.95	St	7	225
		WS	3	337.5
		G	6	168.75
		Epoxy	70	-
		B	10	112.5
		S	4	337.5
S-3	99.96	St	7	337.5
		WS	3	225
		G	6	112.5
		Epoxy	70	-
		B	10	112.5
		S	4	337.5
S-4	99.97	St	7	337.5
		WS	3	337.5
		G	6	168.75
		Epoxy	70	-
		B	10	168.75
		S	4	225
S-5	99.95	St	7	337.5
		WS	3	225
		G	6	168.75
		Epoxy	70	-
		B	10	168.75
		S	4	225
S-6	99.97	St	7	337.5
		WS	3	337.5
		G	6	112.5
		Epoxy	70	-
		B	10	168.75
		S	4	337.5
S-7	99.99	St	7	225
		WS	3	225
		G	6	168.75
		Epoxy	70	-
		B	10	168.75
		S	4	337.5
S-8	99.99	St	7	225
		WS	3	337.5
		G	6	112.5
		Epoxy	70	-
		B	10	140.63
		S	4	281.25
S-9	99.36	St	7	281.25
		WS	3	281.25
		S	6	140.63
		Epoxy	70	-
		B	10	140.63
		S	4	281.25
S-10	99.78	St	7	281.25
		WS	3	281.25
		G	6	140.63
		Epoxy	70	-
		B	10	140.63
		S	4	281.25
S-11	99.89			

Continued on next page

Table 2 continued

		–		
		St	7	281.25
		WS	3	281.25
		G	6	140.63
		Epoxy	70	-
Epoxy	99.66	Epoxy	100	-

2.5 Fabrication of the brake pad composite

This stage involves the design of experiment, design of formulation, mixing process of ingrediants, preparation of epoxy – MEKP solution (before solidified state), Materials mixing with the resin, casting molding process of the brake pad composite and fabrication as shown in processing step of Figure 2 and followed by preparation of compressive strength, density, porosity samples based on brake pad test standards.

For the process of brake pad formulation various tools were used such as electronic weighing balnace, Polystyrene (PS) micro spatula spoon, Polypropylene (PP) stirring sticks, Polyvinyl Chloride (PVC or vinyl) Smurf inorder to cast near neat shaped samples for compressive,dendity, porosity test and finishing and cutiing tolls such as Metal Cutting Circular Saw to machine the brake pad specimen for the slicing of required dimensional tolerance test samples.

A total of 11 specimens were fabricated using various particle sizes of the materials. Furthermore, a neat epoxy sample was prepared separately. After mixing the dry mass of the materials, the epoxy and hardener mix was manually added to a beaker and stirred thoroughly until a homogeneous mixture was obtained. The prepared dry mixture or master batch of the brake pad ingredients was added to the liquid epoxy and manually mixed until a uniform distribution of the materials was achieved in the matrix. Finally, the brake pad samples were cast in molds by pouring. After solidification, the samples were demolded, and specimens for compressive and physical tests were prepared.

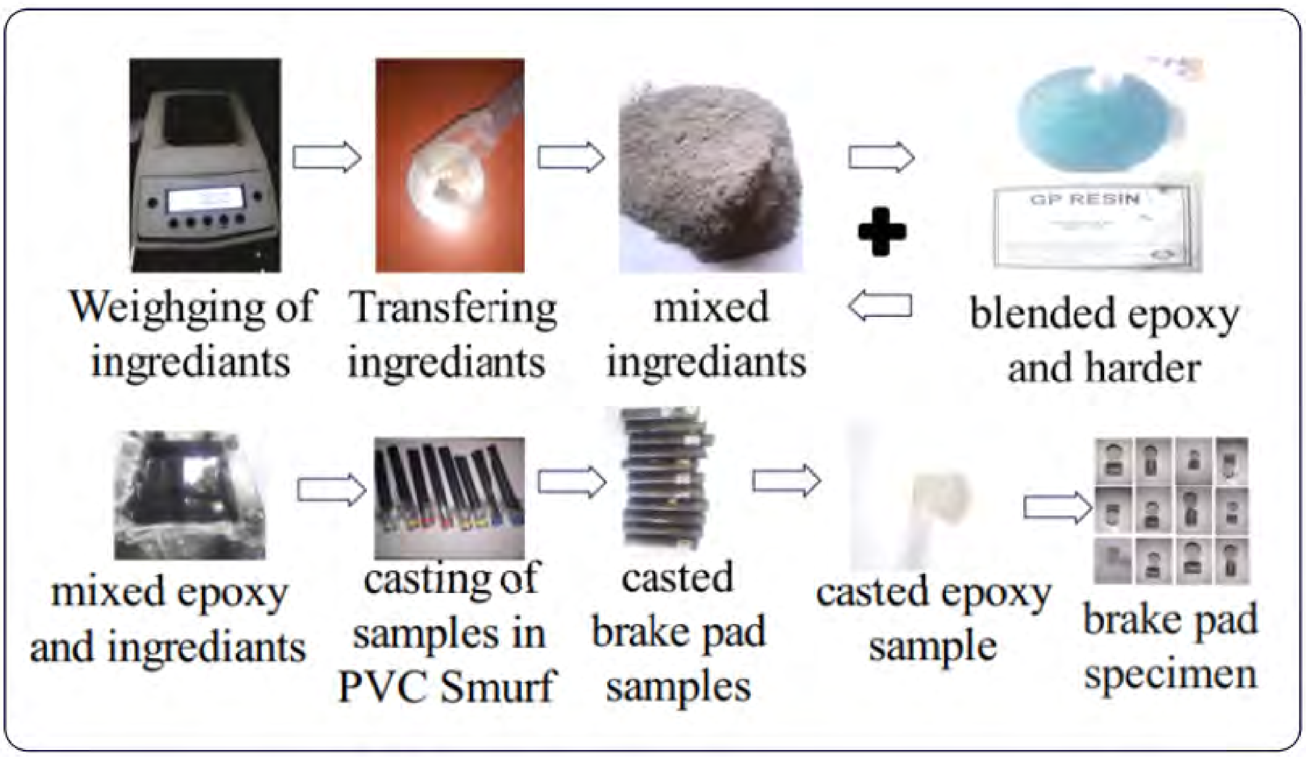

Fig 2. Fabrication process of brake pad composite and test specimen

2.6 Test of brake pad sample

2.6.1. SEM investigation

Morphological Analysis of composites was performed using scanning electron microscopy (SEM). For SEM analysis, the experiment was performed at an acceleration voltage of 10.00; magnification of ×200 at a field of view of 596 μm × 441 μm by JCM-6000 plus (Japan) was used to investigate sample morphology and distribution of materials on the surface of the composite. The SEM micrograph has been utilized to reveal the consistency and microstructure of the composite.

2.6.2. XRD investigation

The brake pad composite sample was studied at the k-alpha radiation using the instrument *(XRD-7000 X-RAY Diffractometer Maxima, Shimadzu Corporation Japan)* operated at Cu-target with an acceleration voltage of 40.0 kV, an accelerating current of 30.0 mA, a scanning drive axis of 2θ, and a scan range of 10-80° was used in phase and the degree of crystallization of the selected optimal brake pad composite sample. The crystallization rate of the brake pad sample and the neat epoxy sample is determined to investigate the degree of crystallization of the matrix and the level of improvement in the structure of the composite.

2.6.3. Compressive strength test

A compression tester (UMT-GUNT WP310, Germany), as shown in Figure 3, was used on Cylindrical specimens of 16.5 mm in diameter and 20 mm in height at a constant loading rate of 0.22 mm/min. The test was conducted according to the ISO 611 protocol.

2.6.4. Density

A density test was performed using ASTM D792-98 using a specimen of cylindrical dimensions 30 mm height by 30 mm diameter. Finally, the density was calculated using Eq.(1).

$$\text{Density} = \text{weight of specimen}/\text{volume of specimen} \tag{1}$$

2.6.5. Porosity

The porosity of the brake pad specimen is calculated using the theoretical and experimental densities. Eqs. (2 & 3) are used to calculate the porosity.

$$\text{Theoretical Density} = \rho_m = (\rho m \times Vm) + \sum_{n=1}^{5} (\rho_r \times V_r) \tag{2}$$

Where: $\rho_{m\,=}$*density of the matrix, and* $\rho_{r=}$ *density of reinforcements;* V_m = *volume fraction of the matrix,* and V_r = *volume fraction of the reinforcement.*

$$\text{Porosity\%} = (\text{Theoretical density of the specimen} - \text{Experimental density of the specimen})/(\text{Theoretical density of the specimen}) \times 100$$

3 Results and Discussion

3.1 Response surface of compressive behavior

The contour plots of (RSM) analysis of compressive strength response illustrate the interactions between particle sizes while holding some particle sizes at constant values, as shown in Figure 4a. The combination of sand (S) and basalt (B) particle sizes of 225 μm and 168.75 μm, respectively, resulted in high compressive performance. Similarly, Steel (St) and basalt (B) at 337.5 μm and 168.75 μm, respectively, result in high compressive strength. Wheat straw fiber (WS) 168.75 μm and Basalt (B) 225 μm result in elevated compressive strength. With graphite (G) 112.5 μm and basalt (B) 168.75 μm sizes, the highest compressive strength is achieved. Generally, the optimal particle sizes for the constituent materials—basalt (B), sand (S), steel (St), wheat straw fiber (WS), and graphite (G)—are 168.75 μm, 225 μm, 337.5 μm, 225 μm, and 112.5 μm, respectively. The Pareto chart in Figure 4b shows that the bars extending beyond the vertical reference line (at a value of approximately 4.3) indicate statistically significant effects of particle size on strength, while those that do not cross the line are insignificant to compressive performance improvement.

The lowest compressive strength is sample S2, which is 58.16 MPa, and S6 exhibits the highest strength of 114.77 MPa, as shown in Figure 5(a–b). This value surpasses the compressive strength of commercial brake pads, having 110 MPa, and sisal-jute fiber epoxy filler-based composites (101.83 MPa)[12]. Similarly, palm kernel-silica-based phenolic resin brake pads and bagasse-based phenolic resin brake pads have a compressive strength of 103.6 MPa[13]. Also, S6 elastic strain of 0.4% as

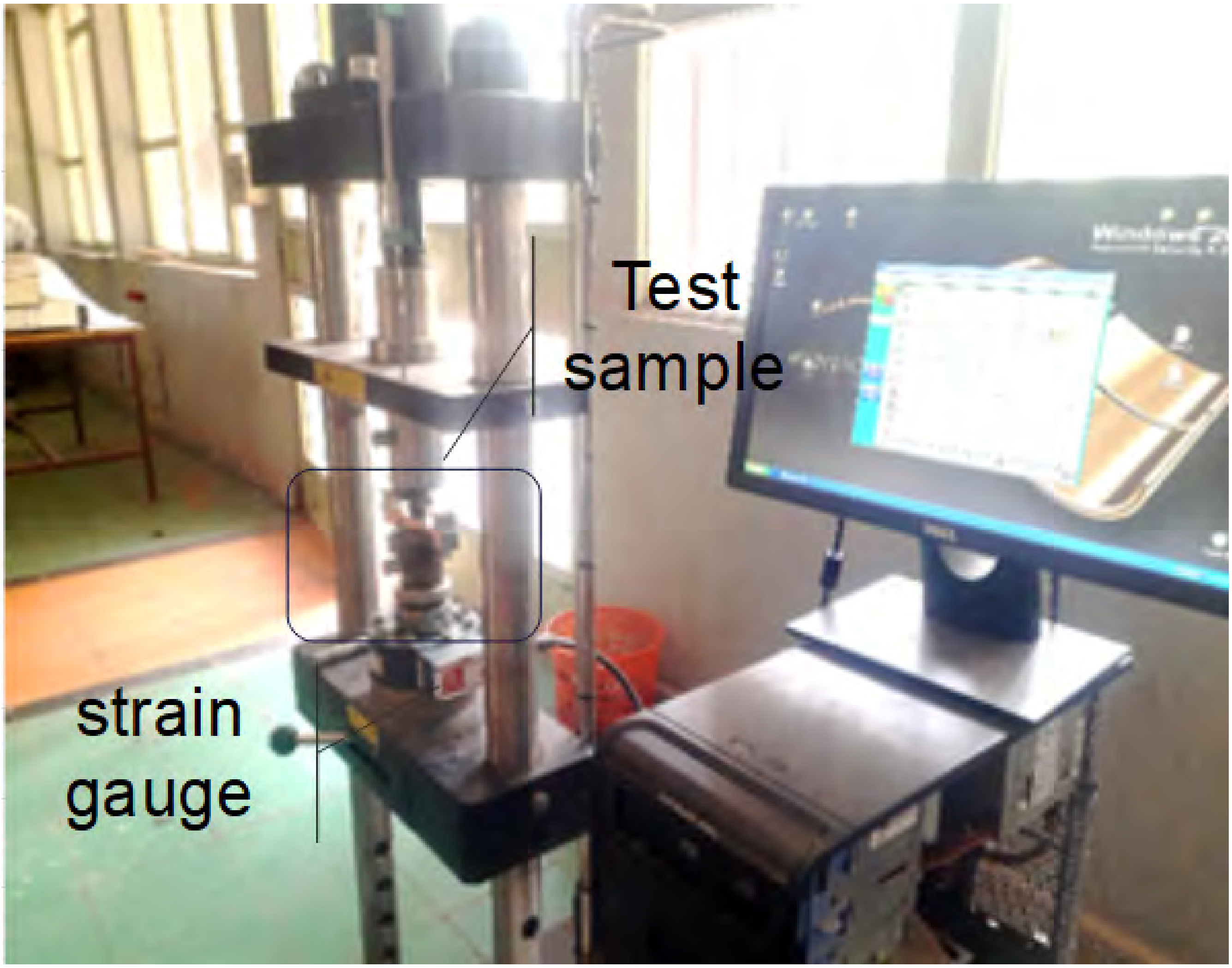

Fig 3. Compressive strength tester UMT-GUNT WP310 machine

compared to the strain rate of the sintered semi-metallic brake pad of 0.21% [4]. Other samples' strength behavior falls between S2 and S6. Figure 5b, the lower strength of S2 can be attributed to its highest porosity of 16.44%, and the range of density across all samples is (1.16-1.31 g/cm^3) as shown in Figure 5c. Porosity varied significantly across all samples (3.58-16.44%), a trend strongly correlated with particle size variability. These fluctuations in cross-sectional and particle dimensions exerted a decisive influence on both porosity and mechanical strength. Specifically, we found that minimizing porosity enhances compressive strength by optimizing particle-epoxy interactions and aggregate packing. Because structural irregularities and voids serve as primary crack initiation sites, improved material dispersion effectively mitigates porosity, thereby enhancing particle-matrix load transfer and arresting crack propagation under high-stress conditions.

3.2 Comparative analysis of performance

Table 3 presents a comparative assessment of the current brake pad composite against various biomass-reinforced polymer counterparts in the literature. The compressive strength achieved in this study notably outperformed previously reported values, such as those for sisal/jute (102.26 MPa [14]), wheat straw (77 MPa [12]), and date palm (70 MPa [10]) based composites. Despite this superior mechanical performance, the developed composite exhibited a lower density and overall weight than traditional bio-composites, which typically range from 1.89 g/cm^3 (sisal/jute [14]) to 2.28 g/cm^3 (abaca [13]). Furthermore, the

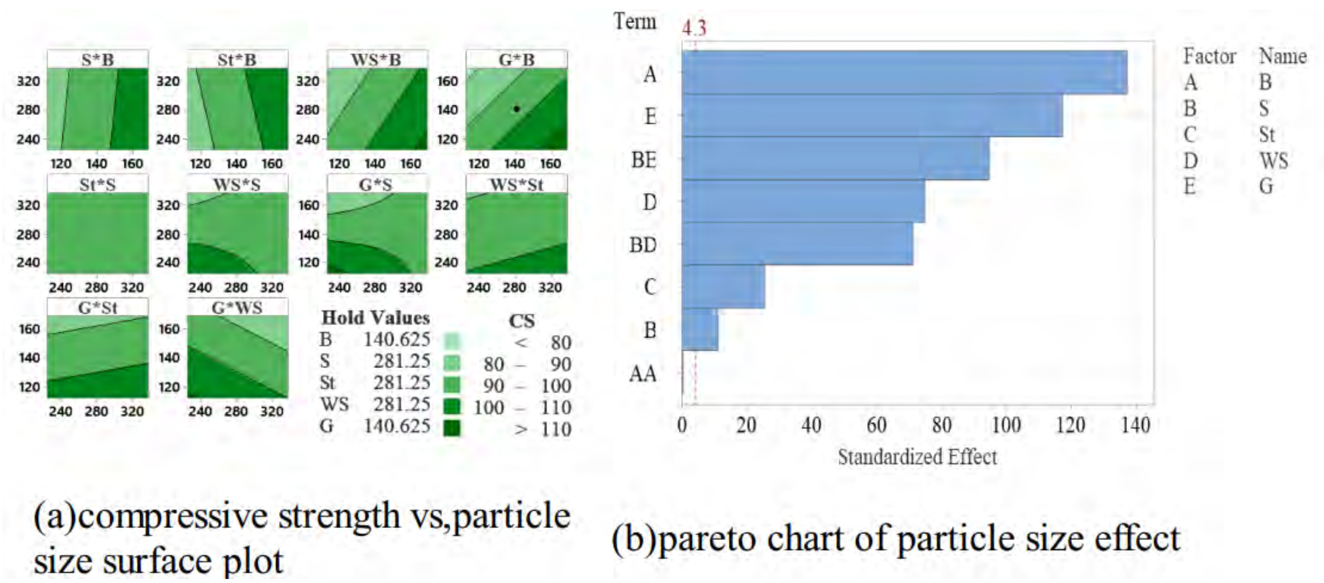

Fig 4. Particle size effect on compressive behavior

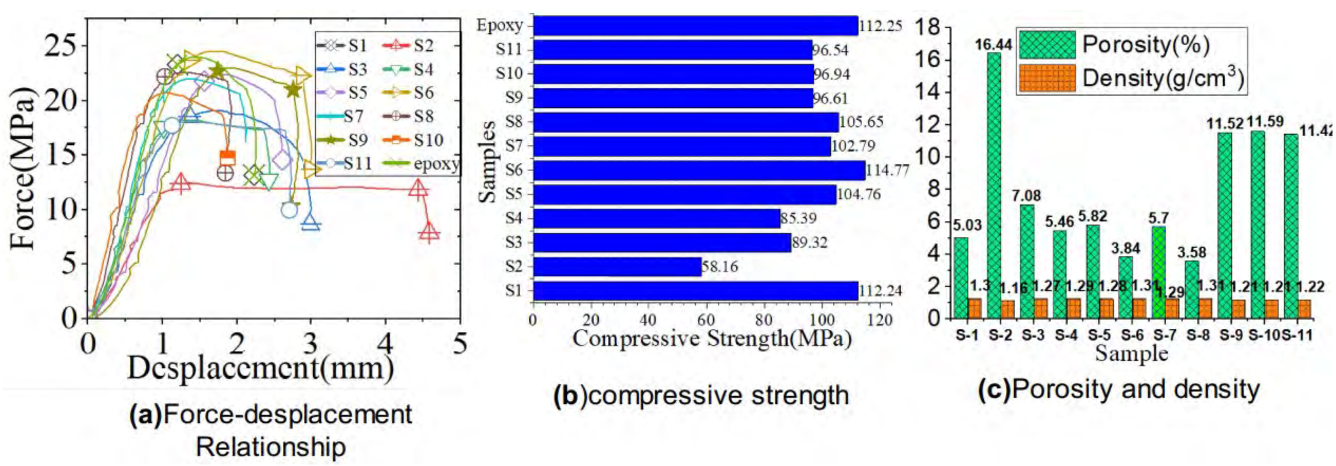

Fig 5. Mechanical and physical behavior of samples

water absorption resistance in this work surpassed that of molluscan shell (29.36% [15]), wheat straw (18.67%), and even high-density abaca-based pads (2.95%), suggesting a more robust interfacial bonding and a less porous matrix structure.

3.3 Analysis of variance

Analysis of variance (ANOVA) was conducted at a 95% confidence level (α = 0.05). The results showed that the p-values for the particle sizes of all constituent materials indicate a statistically significant influence on compressive strength. The most significant interaction effects were the two-way interactions between sand and wheat straw fiber (S & WS) and between sand and graphite (S & G). However, the quadratic term for basalt (B*B) was not significant ($p = 0.712 > 0.05$). The adjusted R-squared value of 99.98% confirms the model's excellent predictive capability. Eq. (4) presents the regression model for the response surface, enabling precise prediction of compressive strength based on particle size parameters.

$$\text{Compressive Strength} = 423.94 + 0.3901\text{B} - 1.12951\text{S} + 0.03422\text{St} - 0.57809\text{WS} - 1.5884\text{G} - 0.000078\text{B}^2 + 0.001699(\text{S} \times \text{WS}) + 0.0045$$

Table 3. Comparative assessment of physical and mechanical properties of various biomass-reinforced brake pad composites

Reinforcement Type	Binder	Compressive Strength (MPa)	Density (g/cm^3)	Water Absorption (%)	Porosity (%)	Ref.
Current Study	epoxy	58.16-114.77	1.16-1.31	0.17-0.85	3.58-16.44	–
Date Palm Fiber	epoxy	70.00	–	–	–	(10)
Sisal & Jute Fiber	epoxy	102.26	1.89	1.64	–	(14)
Wheat Straw (1mm)	epoxy	77.00	–	18.67	–	(12)
Abaca Fiber	Phenol formaldehyde	–	2.28	2.95	3.10-4.18	(13)
Molluscan Shell Waste	phenol-formaldehyde	–	–	29.36	14.51-28.13	(15)
coconut shell & oil bean stalk	epoxy	4.89-120.52	1.136-1.257	0.95 -2.174	–	(16)
Oil Bean & Palm Fiber	epoxy	74.66	–	2.17	–	(17)

3.4 SEM analysis

The morphology investigation was focused on the structural phase observed in the fashion of fracture of the sample reveled britle transition across the epoxy sample. This fracture behavior is underlining investigative analysis of the reinforcing effect of particles localized near the weak region of the matrix, usually distributed in regions of the matrix as a structural feature, as shown in Figure 6. In the Figure, the localized reinforcement of materials is embedded between the regions of weak matrix structure as an impasible obstacle during deformation and crack propagation at the time of compressive load application. Also, the variation in structural surface features across all the samples shows significant variation caused by particle size variation. These variations in compressive strength, density, and porosity—driven by this phenomenon—underline the importance of optimizing particle size and porosity levels.

3.5 XRD analysis

XRD analysis in Figure 7 reveals significant differences in crystallization between the optimal brake pad sample and the neat epoxy. The brake pad sample exhibits a significantly higher degree of crystallinity compared to the predominantly amorphous structure of the neat epoxy. This modification improves the deformation resistance, stiffness, and compressive strength of the brake pad sample compared to the neat epoxy, which is amorphous and mechanically weak. This enhancement effectively inhibits the rapid crack growth observed in the unreinforced resin. The observed enhancement in the physical and mechanical nature of the epoxy matrix due to reinforcement is pivotal for optimizing the structural application of brake pads. Incorporation of an optimal filler size into the epoxy matrix significantly enhanced the composite's structural integrity, improving both compressive strength and stiffness, whilst inhibiting crack propagation to increase fracture toughness.

4 Conclusion

This study establishes a new benchmark for eco-friendly friction materials by demonstrating the synergistic potential of NaOH-treated wheat straw and basalt in a cast-epoxy matrix. Departing from traditional, energy-intensive compression molding, our novel casting approach streamlines manufacturing while delivering superior mechanical integrity. Through Response Surface Methodology (RSM), we identified porosity as the critical determinant of performance; its targeted reduction by 76.64% resulted in surpassing compressive strength of 114.77MPa, a 39% improvement over existing biomass-reinforced brake pads in the literature. Beyond mechanical gains, the transition from brittle to ductile fracture behavior and ultra-low water absorption (0.17-0.85%) underscores the material's durability. These findings provide a scalable pathway for developing high-performance, lightweight composites that significantly reduce the braking system unsprung mass, surpassing the performance of conventional biomass composites documented in recent literature.

5 Abbreviation

Alkali Treated Wheat Straw (ATWS)

Analysis of Variance (ANOVA)

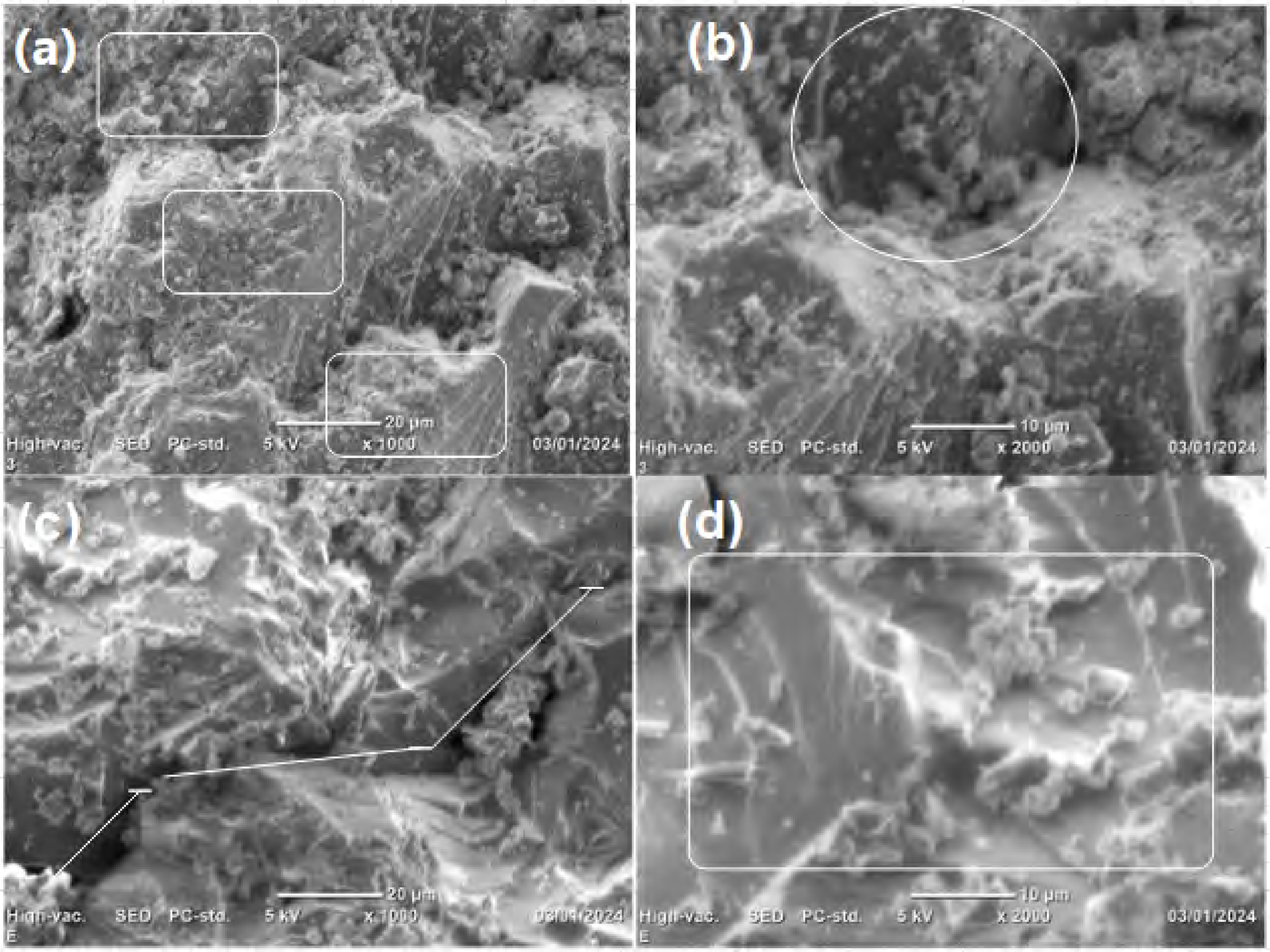

Fig 6. Morphological illustration: (a)variation in microstructure,(b) reinforcing particles,(c) matrix phase change, and (d) matrix structure

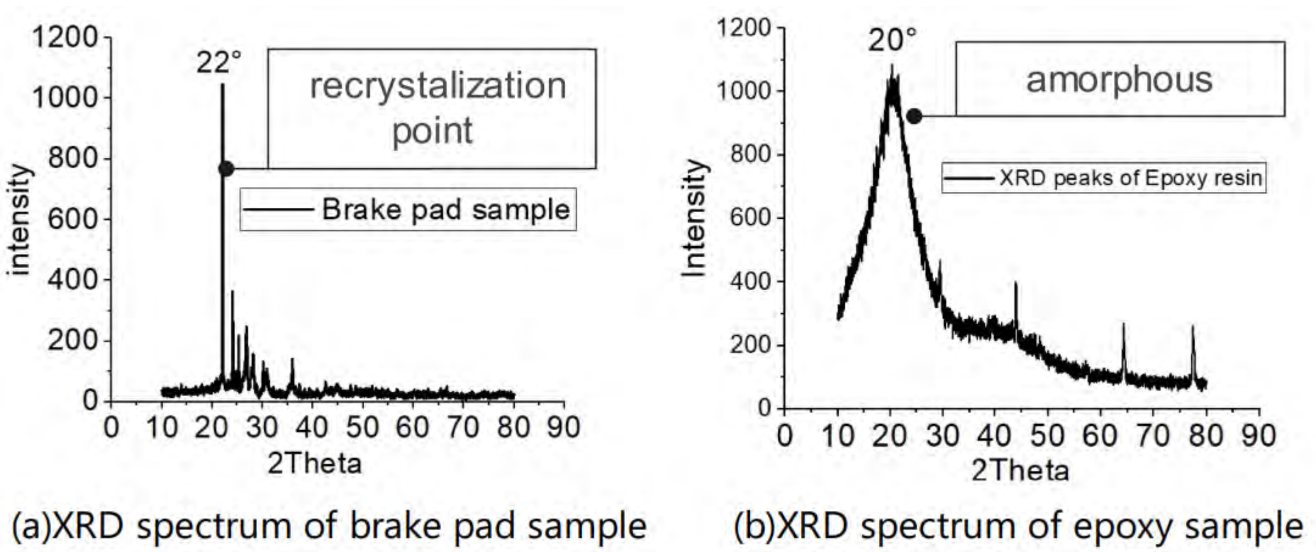

Fig 7. Recrystalization point of the optimal composite

Methyl-Ethyl-Ketone Peroxide (MEKP)
Noise, Vibration, and Harshness (NVH)
Optical Emission Spectrometer (OES)
Particulate Matter (PM)
Polypropylene (PP)
Polystyrene (PS)
Polyvinyl Chloride (PVC or vinyl)
Scanning Electron Microscopy (SEM)

6 Author Contributions

Conceptualisation, W.M.Y., B.S., L.S. and G.A.; Methodology, W.M.Y., B.S. and G.A.; Software, W.M.Y. and B.S.; Validation, W.M.Y., B.S., G.A. and M.W.; Formal analysis, W.M.Y., B.S. and G.A.; Investigation, W.M.Y., B.S., G.A. and Y.D.; Resources, B.S., G.A. and Y.D.; Writing—original draft preparation, W.M.Y., B.S. and G.A.; Writing—review and editing, M.W., B.S. and Y.D.; Visualisation, B.S., G.A., M.W., L.S. and Y.D.; Supervision, B.S., G.A., and M.W.; Project administration, B.S., L.S. and G.A.. All authors have read and agreed to the published version of the manuscript.

7 Data Availability Statement

All the required data are available within the article.

8 Conflicts of Interest

The authors declare no conflict of interest.

References

1) Naidu M, Bhosale A, Munde Y, Salunkhe S, Hussein HMA. Wear and Friction Analysis of Brake Pad Material Using Natural Hemp Fibers. *Polymers*. 2023 Jan;15(1). https://doi.org/10.3390/polym15010188.
2) Giechaskiel B, Grigoratos T, Dilara P, Karageorgiou T, Ntziachristos L, Samaras Z. Light-duty vehicle brake emission factors. *Atmosphere*. 2024;15(1):97. https://doi.org/10.3390/atmos15010097.
3) Hamatschek C, Augsburg K, Schobel D, Gramstat S, Stich A, Gulden F, et al. Comparative Study on the Friction Behaviour and the Particle Formation Process between a Laser Cladded Brake Disc and a Conventional Grey Cast Iron Disc. *Metals*. 2023 Feb;13(2). https://doi.org/10.3390/met13020300.
4) Khanpour E, Partovinia A, Mallaki H. Improving thermal stability and frictional performance of brake pad: A study on interactive effects of compression and gas release. *Results Eng*. 2025 Dec;28:107820. https://doi.org/10.1016/J.RINENG.2025.107820.
5) Gore M, Bhosale A, Naidu M, Čep R, Salunkhe S, Nasr EA. Experimental study on polymer friction composite with natural friction modifiers for brake pads. *PLoS One*. 2025 Sep;20(9):e0328987. https://doi.org/10.1371/journal.pone.0328987.
6) Haniel BB, Anggoro PW. Optimization of Characteristics Polymer Composite Reinforced Kenaf and Jute Fiber Using Taguchi-Response Surface Methodology Approach. *J Nat Fibers*. 2023 Nov;20(2):2204453. https://doi.org/10.1080/15440478.2023.2204453.
7) Storch L, Hamatschek C, Hesse D, Feist F, Bachmann T, Eichler P, et al. Comprehensive Analysis of Current Primary Measures to Mitigate Brake Wear Particle Emissions from Light-Duty Vehicles. *Atmosphere*. 2023 Apr;14(4):712. https://doi.org/10.3390/atmos14040712.
8) Irawan AP, Fitriyana DF, Tezara C, Siregar JP, Laksmidewi D, Baskara GD, et al. Overview of the Important Factors Influencing the Performance of Eco-Friendly Brake Pads. *Polymers*. 2022 Mar;14(6). https://doi.org/10.3390/polym14061180.
9) Zheng K, Min Z, Zhang F, Ren Z, Lin Y. High Heat-fade Resistance, Metal-free Resin-based Brake Pads: A Step towards Replacing Copper by Using Andalusite. *Chin J Mech Eng (Engl Ed)*. 2025 Dec;38(1). https://doi.org/10.1186/s10033-025-01310-x.
10) Ammar Z, Adly M, Abdalakrim SYH, Mehanny S. Incorporating date palm fibers for sustainable friction composites in vehicle brakes. *Sci Rep*. 2024 Oct;14(1):23204. https://doi.org/10.1038/s41598-024-73275-1.
11) Geremew A, Winne PD, Demissie TA, Backer HD. Characterization of Wheat Straw Fiber Grown Around Jimma Zone, ETHIOPIA. *J Nat Fibers*. 2023;20(1). https://doi.org/10.1080/15440478.2022.2134268.
12) Yilma WM, Singh B, Asrat G, Hossain N. Taguchi Method Optimization of Water Absorption Behavior by Wheat Straw-Basalt Hybrid Brake Pad Composite. *J Compos Sci*. 2023 Feb;7(2):62. https://doi.org/10.3390/jcs7020062.
13) Kumar N, Kumar S, Grewal JS, Mehta V, Ali S. Comparative study of Abaca fiber and Kevlar fibers based brake friction composites. *Polym Compos*. 2022 Feb;43(2):730–740. https://doi.org/10.1002/pc.26405.
14) Manjulaiah H, Dhanraj S, Yogesha B, Lamani LN, Madhu P, Sanjay MR, et al. A novel study on the development of sisal-jute fiber epoxy filler–based composites for brake pad application. *Biomass Convers Biorefin*. 2024;14(19):23411–23423. https://doi.org/10.1007/s13399-023-04219-4.
15) Jiyas N, Akshay SD, Ardra SJ, Sekhar AMR, Jayakrishnan M, Sasidharan I, et al. Harnessing molluscan shell waste for sustainable tribology by integrating biogenic fillers in eco-friendly brake pad development. *Sci Rep*. 2025 Jul;15(1):21804. https://doi.org/10.1038/s41598-025-06775-3.
16) Dirisu JO, Okokpujie IP, Apiafi PB, Oyedepo SO, Tartibu LK, Omotosho OA, et al. Development of eco-friendly brake pads using industrial and agro-waste materials. *J Eng Appl Sci*. 2024 Dec;71(1). https://doi.org/10.1186/s44147-023-00345-y.
17) Nwankwo E, Onyenanu I, Nwobi-Okoye C. Sustainable Brake Pad Composites: RSM-Based Optimization of African Oil Bean and Palm Fiber for Enhanced Performance. *NJSTR*. 2025 Nov;7(4):87–107. https://doi.org/10.37933/nipes/7.4.2025.1440.