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Research Paper

Fabrication and Characterization of Asbestos Free Brake Pads Composite using Elaeocarpus Ganitrus as Reinforcement

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Abstract

To minimize the potential health hazards, there is a conscious avoidance of using asbestos fiber due to its recognize carcinogenic nature. This research aimed to produce a brake pad composite using elaeocarpus ganitrus seed powder to replace asbestos. The composition of elaeocarpus ganitrus seed powder was varying volume fraction from 8 wt% to 12 wt% with an interval of 2 wt%. The properties of brake pads, including their morphology, physical characteristics, mechanical performance, and wear behavior, were thoroughly investigated and analyzed. The experimental results indicated a positive correlation between the addition of 12 wt% ealeocarpus ganitrus and the observed increase in density and hardness of the produced samples. Moreover, the wear resistance increased with the percentage of elaeocarpus ganitrus increased. The samples containing 12 wt% in elaeocarpus ganitrus seed powder gave better properties compared with other sample composites. The research finding suggests that elaeocarpus ganitrus particles can be a viable alternative to asbestos in the manufacturing of brake pads.

Keywords: Elaeocarpus ganitrus; Mechanical; Morphology; Physical; Wear properties

1. Introduction

An acceleration in the automotive industry has increased in the modern era. The utilization of the disk brake system is fundamental for ensuring safe deceleration and retardation in the wheel. This setup comprises three key elements: the brake pad, rotor, and caliper, which work together to achieve efficient braking performance [1], [2]. The braking system holds immense importance as one of the fundamental safety components in modern passenger cars, as it plays a critical role in stopping or reducing the speed of vehicles [3]. The friction mechanism in the braking system transforms mechanical energy into the thermal energy of the vehicle. The heat generated during the transformation process is dissipated into the air through the braking system [4]. The brake linings are the most crucial and indispensable component of the brake system. It is vital to ensure that the heat generated from the friction lining does not surpass the temperature threshold for the safe and optimal operation of the brake lining. The substantial heat generated by the brake composite can lead to thermo-mechanical changes in the brake lining material. The distortion of the brake composite surface leads to "lining wear," which can adversely affect the performance of the braking system.

The brake pad comprises materials that are abrasive, filler, friction modifier, reinforcement, and binder [5]. The brake pad is composed of composite materials with numerous constituents, often exceeding 10, which are compressed into a solid mass with a porosity ranging from 5% to 10% through hot-pressing. The composition of these composite friction materials varies significantly, but they can generally be categorized into binders, fibers, frictional additives (including lubricants and abrasives), and fillers [6].

Typically, the brake pad is composed of a polymeric matrix with embedded asbestos fibers, complemented by various additional ingredients [7]–[11]. Brake pad materials should exhibit dependable wear and friction characteristics, as well as stability, across different conditions of speed, weight, temperature, and endurance [12]. In manufacturing composite for brake materials, various materials including metallic, semi-metallic, organic, polymer, and asbestos have been utilized. Historically, asbestos was popular due to its effective heat dissipation capabilities. However, the use of asbestos in brake pad materials has been found to cause numerous harmful health conditions in humans such as asthma and lung cancer, as well as air pollution [13], [14]. The primary concern of researchers is finding a substitute material that can offer comparable mechanical properties to asbestos. Asbestos brake pads have been an environmental and health concern for a long time because the initial generation of composite materials relied heavily on asbestos reinforcement, even before its hazardous effects were known [8], [15], [16]. Currently, there is a decreasing trend in the use of copper in friction materials, and it is anticipated to be banned by 2025 in developed nations. This reduction is primarily due to the harmful effects of copper on aquatic life [17].

A number of current approaches suggest utilizing brake pads made of organic, semi-metallic, or metallic materials that are asbestos-free and copper-free [5], [18], [19]. Recently, researchers have made progress in developing brake pads that use alternative materials like agricultural waste [20], coconut shells [21], maize husks [22], palm kernels [23], and banana peels [8]. Abutu, et al. Developed a brake pad by using coconut shells for the manufacturing of brake pads. Additional ingredients such as epoxy resin, silica, catalyst, and accelerator with the coconut shells. However, only the weight of the epoxy resin was adjusted while keeping the proportions of the other ingredients constant. The findings of the study indicated that as the percentage of coconut shell content increased, the strength, hardness, and compressive strength of the composite material decreased [21]. Amaren et al. conducted a study where brake pads were produced using periwinkle shells and a phenolic resin binder. The authors examined the effects of temperature variation, particle sizes of periwinkle shells, applied load, and sliding velocity on the wear resistance of the composite material. The results indicated that an increase in these factors leads to an increase in the wear rate. The authors also noted that the best wear resistance was observed with periwinkle shells sized at 125 μm [24].

Furthermore, Tang et al. [25] incorporated expanded graphite (EG) into non-asbestos organic composite brake material. This improvement was attributed to the local flexible internal stress caused by graphite expansion during high braking temperatures, which partially offset crack expansion, leading to a significant reduction in delamination wear and improved braking performance. The authors observed that EG enhanced the physical properties, wear resistance, and braking performance of the specimens. Kun et al. [26] confirmed that incorporating basalt fiber (BF) into braking material improves its mechanical and thermal properties while enhancing frictional stability. Basalt fiber is considered a pollution-free green material for the 21st century. Jyotishkumar et al. [27] confirmed that NFRP (Non-Ferrous Reinforced Plastics) are replacing conventional materials due to their numerous advantages, including higher strength, lightweight, nonconductive nature, maintenance-free properties, and corrosion resistance, among others.

Therefore, the primary aim of this study is to examine the potential of utilizing elaeocarpus genitrus seed (EGS) powder as a replacement material to offset the properties that are compromised when asbestos is substituted. Moreover, the selection of other ingredients was carefully made to maximize the effectiveness of the composite in the absence of asbestos. The choice of elaeocarpus ganitrus seed powder as a reinforcement material in the fabrication of brake friction materials was based on its high hardness and density [28]. These properties make it well-suited for enhancing the performance and durability of brake pads. In order to optimize the brake lining characteristics, the elaeocarpus ganitrus seed contents were varied at different volume percentages of 8%, 10%, and 12% in relation to the total weight of the matrix composites. The effects of these variations were thoroughly analyzed and assessed to determine the optimal elaeocarpus ganitrus seed content that results in the desired brake lining characteristics. Experimental evaluations were carried out to analyze the density, hardness, wear rate, and surface morphology of the samples. The results of these experiments revealed that the optimize percentage of elaeocarpus ganitrus seed demostrated reduce wear specific, improve the density and hardness be well suited for making brake pad material.

2. Methods

2.1. Materials

The elaeocarpus ganitrus seeds were collected from the farm of elaeocarpus ganitrus in Kebumen, Central Jawa, Indonesia. Drying of the elaeocarpus ganitrus seed was done via sunlight as seen in **Figure 1a**. To convert the elaeocarpus ganitrus seed into a powder form, it was essential to grind it after drying in the sun. The milling process was conducted at a speed of 250 revolutions per minute. ASTM E11 standard was followed to conduct a particle size analysis of the 100 g sample. The particle was placed into a series of sieves arranged in descending order of fineness. The sample was then subjected to shaking to separate and classify the particles based on their size distribution according to the ASTM E11 standard procedure. The Elaeocarpus ganitrus seed powder obtained had a particle size of 120 μm, a density of 0.887 g/cm^3, and a weight range 20 to 34 mg, as indicated in **Figure 1b**. The brake friction material comprised polymers, namely styrene butadiene rubber (SBR-1712) from CV Darat (Indonesia), and bakelite, with densities of 0.924 g/cm^3 and 1.3 g/cm^3, respectively, serving as the matrix. The curing agents for SBR included sulfur, stearic acid, and zinc oxide. Additionally, the brake pads were reinforced with elaeocarpus ganitrus seeds, while fillers consisted of magnesium oxide (MgO), calcium carbonate ($CaCO_3$), and metal powders (brass oxide, bronze oxide, and stainless steel). The volume fractions of the brake pad samples are provided in **Table 1**.

Figure 1. Photograph of Elaeocarpus Ganitrus (a) seed and (b) seed powder

Table 1. Volume fraction of raw materials in the sample

No.	Material	Wt% (X)	Wt (X)	Wt% (Y)	Wt (Y)	Wt% (Z)	Wt (Z)
1	EGS powders	0.8	0.50 g	0.10	0.63 g	0.12	0.72 g
2	SBR-1502	0.24	1.57 g	0.24	1.57 g	0.24	1.57 g
3	Bakelite	0.18	1.6 g	0.18	1.6 g	0.18	1.6 g
4	Stearic Acid	0.04	0.27 g	0.04	0.27 g	0.04	0.27 g
5	Calcium Carbonate	0.08	1.53 g	0.08	1.53 g	0.08	1.53 g
6	Magnesium Oxide	0.03	0.41 g	0.03	0.41 g	0.03	0.41 g
7	Sulfur	0.02	0.29 g	0.02	0.29 g	0.02	0.29 g
8	Zinc Oxide	0.05	0.14 g	0.05	0.14 g	0.05	0.14 g
9	Bronze Oxide	0.08	4.2 g	0.08	4.2 g	0.08	4.2 g
10	Brass Oxide	0.08	4.7 g	0.08	4.7 g	0.08	4.7 g
11	Stainless Steel	0.08	4.2 g	0.08	4.2 g	0.08	4.2 g

2.2. Fabrication

The method used for producing the brake friction material involved the isostatic pressing technique (see **Figure 2**). To determine the volume fraction of each component, the measurements were taken using a beaker glass prior to the mixing process. The calculation was based on the total volume of mixing or mold volume which was 67.44 ml. The procedure for producing the material involved several steps. Firstly, the proportions of elaeocarpus ganitrus seed powders and MgO varied within the range of 8-12% and 3%, respectively. After determining the volume fraction of the remaining components, the mixing process was carried out until achieving homogeneity. The mixing procedure involved adding the metal fibers initially, followed by the pulpy materials, and finally the powdery materials. The entire mixing schedule lasted for a duration of 10 minutes. Subsequently, the mixture underwent hot isostatic pressing at a temperature of 190 °C and a pressure of 490 kgf/cm^2 for a duration of 3 hours. Following the pressing, the specimen was subjected to post-curing at a temperature of 200 °C for 4 hours.

2.3. Material Characterization and Test Performance

To determine the chemical compositions of all specimens, energy dispersive X-ray (EDX) spectroscopy was employed. Additionally, scanning electron microscopy (SU3500) with an accelerating voltage of 15 kV was utilized to characterize the phases present in the specimens. In this research, the contents of elaeocarpus ganitrus seed powders were considered independent variables, while wear resistance and density were treated as dependent variables. The temperature, duration of pressing, and pressure were kept constant as controlled variables. The relationship between the contents of elaeocarpus ganitrus seed powders and the mechanical properties of brake friction materials was analyzed, and conclusions were drawn based on the findings.

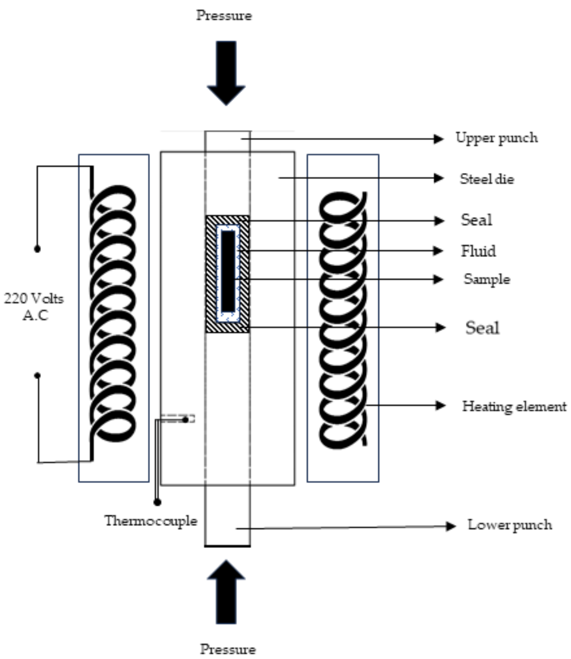

Figure 2. Schematic process of the Isostatic Pressing

To assess the wear resistance of the brake friction materials, a wear testing machine, specifically the Ogoshi high-speed universal wear testing machine, was utilized. The specimens used for testing were rectangular with dimensions of 3x1.5 cm^2. A test load (P_0) of 6.36 Kg was applied to the specimens for (t) 60 seconds. The test was conducted using a disc with a thickness (B) of 3 mm and a radius (r) of 15 mm, which rotated a total distance (l_0) of 36 m during the test. The length of the grid (b_0) was determined by observing the specimens under an optical microscope (Olympus, model PME3) with a magnification of 50x. The specific wear resistance (W_s) was then calculated using a prescribed Eq (1).

$$W_s = \frac{Bb_0^3}{8rP_0l_0} \tag{1}$$

The hardness of the specimen was assessed using the Vickers microhardness test method, as outlined in ASTM E92-82. The density of the specimen was determined using Archimedes' principle [29], the method employed to determine the volume and density of an irregularly shaped object involved measuring its mass in air and then measuring its mass when submerged in water.

3. Results and Discussion

The properties of the various brake friction constituents, including hardness, density, and specific wear, are listed in **Table 2**. These properties are influenced by both the ingredients used and the volume fraction of the constituents. It is evident that an increase in the volume fraction of elaeocarpus ganitrus seeds results in higher density and hardness values.

Table 2. Physical and mechanical properties of the developed composites

Properties	Unit	X	Y	Z
Density	g/cm³	2.47	2.773	3.0447
Hardness	VHN	43.592	68.773	70.276
Specific Wear	mm²/kg	0.22784	0.20743	0.1576

Elaeocarpus ganitrus is a fruit that grows in the high-altitude forests of South Asia, particularly in Indonesia. It is considered an inconspicuous fruit and is highly regarded in the local communities as an indestructible and everlasting prayer bead, also known as rudraksha. The fruit of the elaeocarpus ganitrus plant is notable for its iridescent blue color, which has been a subject of study and fascination [30]. The height of the elaeocarpus ganitrus tree is known to reach impressive heights which have been reported to reach up to 200 feet [31], [32]. The hardness value of the material was measured to be 0.4 ± 0.6 GPa, while the modulus value was determined to be 8 ± 1 GPa [33]. EGS is categorized as a composite material due to its composition of carbon, hydrogen, oxygen, and trace elements. The percentage composition of these gaseous elements was determined using both a C-H-N Analyzer and Gas Chromatography. EGS consists of 50.031% carbon, 0.95% nitrogen, 17.897% hydrogen, and 30.53% oxygen [28]. Moreover, it increases the hardness and imparts good recovery behavior to friction material. Furthermore, the incorporation of Elaeocarpus ganitrus seed powder into the friction material not only increases its hardness but also improves its recovery behavior.

3.1. *Tribological Behavior*

Maintaining a stable friction coefficient across different sliding speeds and pressures is essential for drives to anticipate and predict the frictional behavior during braking. In line with existing literature, the findings of this study demonstrate a consistent trend of decreasing friction values with higher speeds and pressures for all the examined composites. The decrease in the coefficient of friction can be attributed to multiple factors. Firstly, under higher pressure, there is an increase in the real contact area between the surfaces, which can lead to a reduction in friction. Secondly, higher speeds can result in increased frictional heating, causing changes in the material properties and contributing to the decrease in the coefficient of friction. Additionally, thermal and mechanical overloading can lead to the breakage of asperities on the surface, exposing plateaus and causing sudden variations in friction values. These factors collectively contribute to the observed decrease in the coefficient of friction [34], [35].

The friction coefficient observed in the tested composites ranges from 0.34 to 0.5, which aligns with the standard range commonly observed in industrial applications [36], [37]. It is desirable to have minimal undulations or fluctuations in the friction value to ensure stable and predictable friction behavior [38]. In X sample composites the wear specific is highest than other samples. Moreover, as inferred from **Figure 3b**, the specific wear value is expected to consistently decrease with an increase in the volume fraction of elaeocarpus ganitrus in the composite material. This behavior can be attributed to the presence of organic materials such as bakelite, rubber, and elaeocarpus ganitrus seed in the braking surface. These organic components can undergo thermal decomposition during braking, leading to the formation of carbon (C) phases.

The presence of carbon phases as shown in **Figure 6b** can contribute to increased wear resistance in the composite material, resulting in the observed decrease in specific wear values with higher volume fractions of elaeocarpus ganitrus, affecting its hardness and wear specific, but to reduce flunctuation by thermal or pressure, the need of lubricant becomes crucial. Hydrodynamic lubricant films or elastohydrodynamic (EHL) films play a crucial role in reducing wear rates by providing a separating layer between sliding surfaces. These lubricant films form under conditions of high pressure and sliding speed, effectively reducing the contact stresses between the surfaces. As a result, wear rates are lowered due to the reduced direct contact and minimized frictional forces. Polymers, with their lower elastic modulus values compared to metals, exhibit favorable characteristics for maintaining EHL conditions at lower sliding speeds and higher normal loads. This enables them to effectively reduce wear and provide lubrication in a wide range of applications [6].

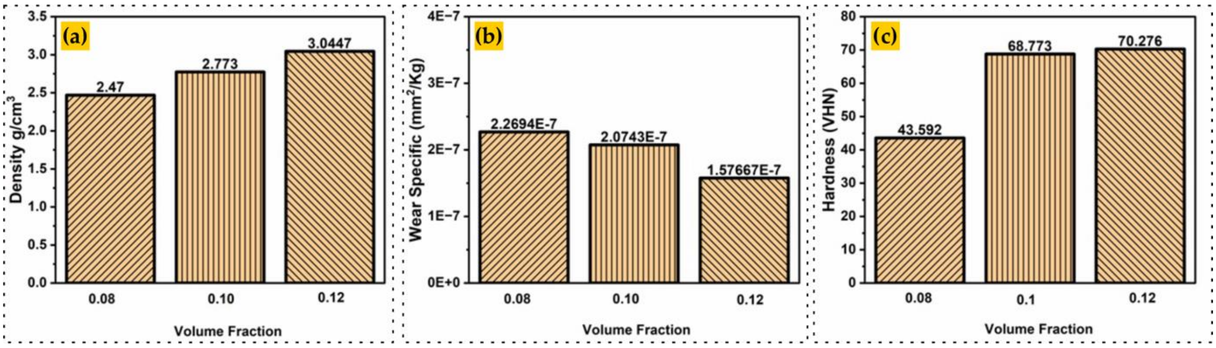

Figure 3. Mechanical and phisycal properties of brake friction materials: (a) density; (b) wear specific; and (c) hardness

However, carbon-based materials, such as graphite, exhibit exceptional lubricity owing to their unique structural properties. Graphite has weak interlayer bonding, allowing for easy shearing along the basal plane. This property enables the graphite layers to slide over one another, resulting in effective lubrication. Graphite's lubricating properties are particularly notable at temperatures below 400 °C. At such temperatures, the interlayer forces remain relatively weak, facilitating smooth sliding and reducing friction between surfaces. The presence of carbon-like graphite can significantly enhance the lubrication performance in various applications. Based on the available literature, the incorporation of elaeocarpus ganitrus has been found to contribute to consistent friction performance.

The utilization of elaeocarpus ganitrus as an ingredient in friction materials has demonstrated reliable and predictable friction characteristics. The presence of elaeocarpus ganitrus in the composite formulation helps maintain a stable and consistent friction response, which is crucial for effective braking performance. The consistent friction behavior provided by elaeocarpus ganitrus further supports its potential as a valuable component in friction materials. This is due to the fact that materials with high thermal stability can maintain their properties over a longer period of time, thereby delaying degradation and contributing to the effectiveness of the braking cycle. Another contributing factor to the stabilized friction characteristics observed in the presence of elaeocarpus ganitrus could be attributed to its elastic nature within the friction materials. The inclusion of elaeocarpus ganitrus seeds in the composite formulation introduces an element that exhibits elastic deformation during frictional contact. This elastic behavior helps in stabilizing the primary contact area between the braking surfaces [39]. As a result, the elastic deformation of the friction ganitrus seed assists in maintaining a consistent and stable contact between the brake pad and the rotor, leading to more predictable and stabilized friction characteristics. The elastic properties of the elaeocarpus ganitrus seed play a vital role in contributing to the overall performance and stability of the friction materials in braking applications.

The wear of composites is a multifaceted phenomenon that involves various mechanisms, many of which are thermally activated. The interaction between the composite materials and the contacting surfaces leads to wear processes that are influenced by temperature. Thermal activation plays a crucial role in initiating and facilitating wear mechanisms such as adhesive wear, abrasive wear, and tribochemical reactions. At elevated temperatures generated during braking, the composite materials undergo thermal changes that can affect their mechanical properties, surface interactions, and wear behavior. These thermal effects can lead to the degradation of the composite matrix, the formation of oxides or glazes on the surface, and changes in the frictional and lubrication properties [40]. The wear resistance was found varied in the range of specific wear between 1.5766 x 10^{-7} mm^2/Kg to 2.2694 x 10^{-7} mm^2/Kg (**Figure 3b**). The wear resistance of brake friction materials exhibits an inverse relationship with the content of elaeocarpus ganitrus seed powders. Specifically, the brake friction materials containing a lower content of elaeocarpus ganitrus seed powders (8%) demonstrate the smallest wear resistance, while those with a higher content (12%) exhibit the largest wear resistance. Generally, an increase in the content of elaeocarpus ganitrus seed powders in brake friction materials leads to an increase in wear resistance. In other words, higher concentrations of elaeocarpus ganitrus seed powders result in improved resistance to wear. In sample X composites have highest specific wear rate revealing that increases friction. Increasing friction during braking leads to the generation of third body asperities, which are small particles that are chipped off from the friction material at a microscopic level. These asperities can cause ploughing on the mating surface, resulting in wear of the rotor. Additionally, the ploughing action produces iron oxide as a result of tribo-oxidation from the mating surface, further contributing to abrasive wear.

The presence of iron oxide can be confirmed through elemental mapping techniques (see Figure 6d). It is worth noting that the hardness of the materials cannot be directly correlated with wear resistance, as wear is a complex phenomenon influenced by multiple factors [41]. But sample Y and Z were visualized differently, where its hardness is more in line with decrease of specific wear rate (see Figure 3c). Sample Z composites exhibited superior wear resistance compared to the other composites, and this can be attributed to the increased content of ganitrus seed. Another significant observation is the reduced wear of the disc, which contributes to decreased noise, vibration, and judder during braking. The wear resistance trend observed among the composites is as follows, from highest to lowest: sample Z, sample Y, and sample X.

3.2. *Worn Surface Characterizations*

Scanning electron microscopy (SEM) analysis was conducted to examine the worn surface characteristics of the tested friction composites and to understand their tribological properties. The formation of plateaus on the worn surfaces was identified as a critical factor influencing the tribological behavior of the composites. The formation of these plateaus was found to be dependent on both the working environment and the performance of the ingredients during braking. The primary plateaus observed on the worn surfaces are formed due to the presence of elaeocarpus ganitrus seed particles acting as reinforcement in the composite. These plateaus play a crucial role in preventing the movement of fine wear particles at the interface. Additionally, loose fine wear particles, mainly consisting of fillers such as metal powder, combine with a decrease in the volume fraction of elaeocarpus ganitrus seed, forming a back transfer layer. The formation of these primary plateaus enhances the load-bearing capacity and contributes to the overall friction performance of the composites.

Therefore, it is recommended to prioritize the formation of primary plateaus while minimizing the occurrence of secondary plateaus [40], [42]. SEM analysis of the X sample composite (shown in Figure 4) reveals the presence of numerous back transfer patches accompanied by a higher density of nucleated primary plateaus. However, this composite also exhibits pits on its surface and a greater amount of wear debris. These observations suggest that there is debonding of materials within the composite, which contributes to an increased wear rate. The presence of pits and wear debris indicates the detachment and removal of material during the tribological testing, which can negatively impact the overall wear resistance of the composite. In the SEM analysis, it is observed that in the Y sample composite (see Figure 4b), the back transfer is slightly lower compared to the X sample composite. Additionally, the Y sample composite

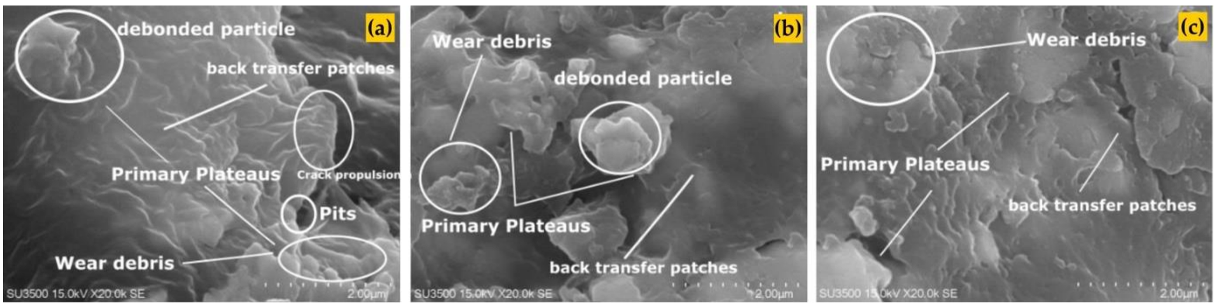

Figure 4. Worn surface characterization of Ogoshi wear tested friction composites: (a) sample X composites; (b) sample Y composites; and (c) sample Z composites

exhibits fewer primary plateaus and loose wear debris, which can be attributed to the lower content of elaeocarpus ganitrus seed and other ingredients. The pits observed on the surface of the Y sample composite are also smaller in size compared to the X sample composite. On the other hand, the Z sample composite shows a nominal level of wear compared to both the X and Y composites. SEM analysis reveals the presence of more primary plateaus and several back transfer layers in the Z sample composite. Furthermore, the Z sample composite exhibits less wear debris in comparison to the X and Y composites. Overall, the SEM analysis indicates that the variation in the content of elaeocarpus ganitrus seed and other ingredients affects the formation of primary plateaus, back transfer layers, pits, and wear debris on the surface of the composites. The Z sample composite shows the most favorable characteristics, with a higher number of primary plateaus and minimal wear debris, indicating better wear resistance compared to the X and Y composites.

3.3. Chemical and Elemental Mapping

The combination of SEM imaging with energy dispersive X-ray spectroscopy mapping provides valuable insights into the morphology and distribution of various constituents within brake friction materials. In the EDX image shown in **Figure 5**, it can be observed that organic materials such as elaeocarpus ganitrus seeds powder, rubber, and bakelite undergo thermal oxidation and carbonization, resulting in the formation of carbon (C). As the content of elaeocarpus ganitrus seed increases in the composite, the quantity of carbon also increases. According to the literature, the presence of carbon enhances the hardness of composite materials. This occurs because of the interlocking between rough surfaces when the friction film is not formed on the carbon's surface [43]. Hence, the EDX spectra showed sharp peaks for carbon phases (**Figure 5**), which aligns with the literature indicating that the friction film with carbon phase has a definite impact on solid lubrication [44]. The large bright areas in the SEM image correspond to metallic particles, such as bronze or brass, while the rubber components appear black. In SEM image shown constituents with smaller atomic weights appear darker in color. The uniformity in size and distribution of elements plays a role in determining the hardness and roughness of the specimens. **Figure 5** also presents the results of EDX analysis, which involves taking spectra from specific areas of the specimens and determining the elemental composition. In this analysis, the C phases appear to be the most dominant in the EDX spectra, further highlighting the presence and contribution of carbonized materials in the brake friction composites.

The properties of the composites produced are depicted in **Figure 3**, including their mechanical and physical characteristics. In **Figure 3a**, the density values are illustrated, with the highest density of 3.0447 g/cm^3 observed in sample Z, which consists of 12% elaeocarpus ganitrus seed powders. Conversely, the lowest density of 2.47 g/cm^3 is found in sample X, which contains 8% elaeocarpus ganitrus seed powders. It is evident that an increase in the content of elaeocarpus ganitrus seed powders leads to an increase in the density of the specimens. According to the literature, there is a relationship between density and porosity in composite materials. When the density is high, the porosity tends to be low, resulting in higher hardness values. Increased interconnected porosity contributes to enhanced hardness and overall mechanical properties. Additionally, this interconnected porosity offers benefits such as reduced wear rate, decreased friction, and increased corrosion resistance, especially in moderately aggressive environments [6].

Sample X, which contains the lowest content of elaeocarpus ganitrus seed powders (8%), exhibited a soft texture and the lowest hardness number, as shown in **Figure 3c**. The addition of elaeocarpus ganitrus seed powders has a direct impact on the hardness of the composites. The Micro Vickers hardness values obtained ranged from 43.59 VHN to 70.276 VHN, which, according to the literature, may correspond to automotive specifications [45]. It is worth noting that multiple hardness tests were conducted on each sample, resulting in varying hardness numbers. This indicates that the distribution of phases within the composite materials is sporadic despite these variations, this study is considered novel and the obtained results serve as a motivation for further exploration of the utilization of elaeocarpus ganitrus seed powders in this context.

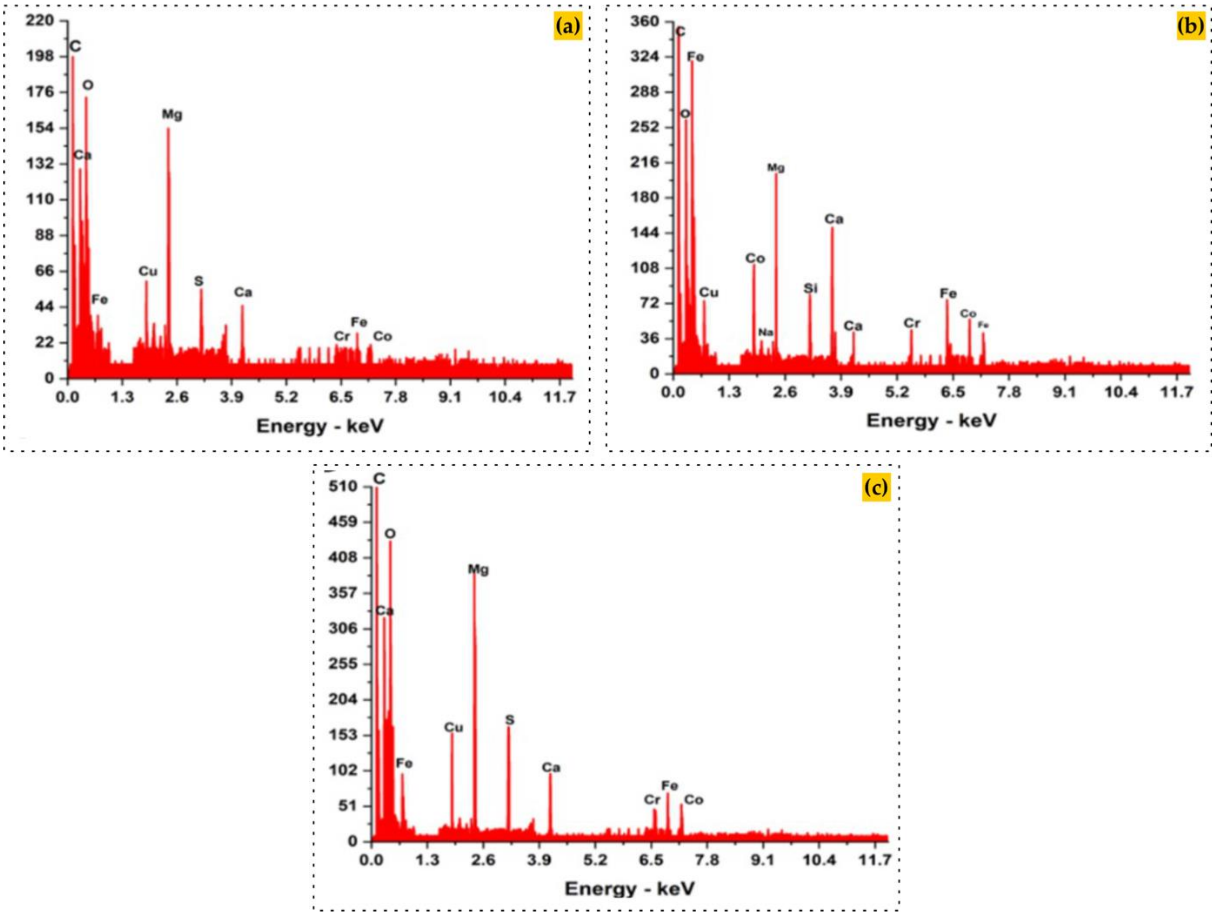

Figure 5. EDX spectra of composite specimen surface: (a) X sample composite; (b) Y sample composite; and (c) Z sample composite

Figure 6 provides evidence of the presence of elaeocarpus ganitrus seed in the composites. The elemental mapping reveals the presence of carbon ('C') in various regions, while the presence of oxygen ('O') confirms the presence of ganitrus seed. Specifically, **Figure 6b** and **Figure 6c** highlight the distribution of these elements. The iron ('Fe') mapping in **Figure 6d** indicates a higher concentration of iron particles in the secondary plateaus region, which contributes to increased wear on the mating surface. The mapping of oxygen ('O') confirms the back transfer of the mating surface, where oxidation occurs and ferric oxide is formed. Sample Z composites exhibit well-formed plateaus, as shown in **Figure 6**, which can be attributed to the higher volume fraction of ganitrus seed. The elemental maps in **Figure 6** provide further confirmation of the presence of ganitrus seed. The presence of wear debris on the mating surface is confirmed by the iron ('Fe') mapping, with **Figure 6d** showing less back transfer, indicating that this composite is more rotor-friendly compared to the other two samples.

4. Conclusion

Through extensive investigation into the influence of different volume fractions of elaeocarpus ganitrus seed powder on the properties of styrene butadiene rubber composites used for brake pad materials, it has been established that incorporating elaeocarpus ganitrus leads to significant improvements in the physical, mechanical, and brake performance characteristics of the composites. These improvements include enhanced hardness, increased density, and reduced fade, all of which contribute to improved wear resistance. The addition of the weight fraction of elaeocarpus ganitrus seeds affects the average density value in the composite sample. The average high density value is 3.0447 g/cm^3, influenced by the addition of 12% of the weight fraction of elaeocarpus ganitrus seed powder. The use of elaeocarpus ganitrus seed powder reinforcement has the effect of producing a high density value, which is 3.0447 g/cm^3, exceeding the specifications for railroad brakes, which is 2.4 g/cm^3 [46]. We suggest for fur-

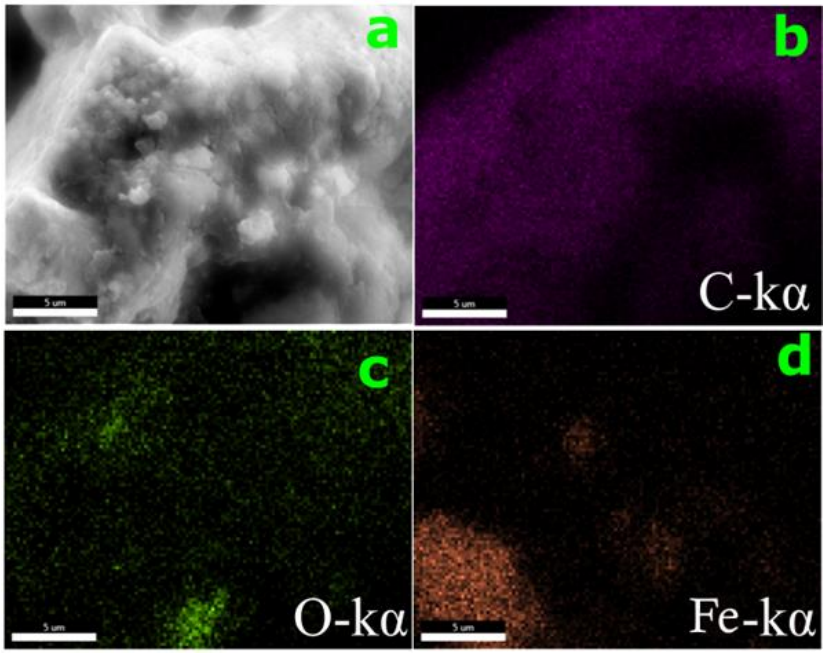

Figure 6. Worn surface of the Z sample composites: (a) electron image; with elemental mapping of (b) C; (O); and (d) Fe

ther study had higher density in range 5.1 g/cm^3 – 7.2 g/cm^3 [47], [48].

Furthermore, the incorporation of elaeocarpus ganitrus seed powder in the composites resulted in the highest average hardness value of 70.275 VHN. This increase in hardness was directly influenced by the weight fraction of elaeocarpus ganitrus seed powder, particularly with the addition of 12% weight fraction. There is a relationship between the hardness value and the density value in the sample. The increase in density value is proportional to the increase in hardness value. This is because the density value affects porosity so that if the density is high, the porosity will be low and the hardness value will be higher. While, the specific wear value on the variation of sample 1 with the smallest specific wear value is 1.57667×10^{-7} mm^2/kg in the addition of the highest weight fraction of elaeocarpus ganitrus seed powder which is 12%. The relationship between specific wear value and hardness shows that materials with high hardness values will be more difficult to experience abrasion. Samples with lower specific wear values exhibit higher resistance to abrasion due to their higher hardness values. The results of these experiments revealed that the optimized percentage of elaeocarpus ganitrus seed demonstrated excellent suitability for the fabrication of brake pad composite material.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and apporved the final manuscrips.

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All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

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