Automotive Experiences
Vol. 4 No.2 (2021) pp. 68-82
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

# The Effects of Rice Husk Particles Size as A Reinforcement Component on Resin-Based Brake Pad Performance: From Literature Review on the Use of Agricultural Waste as A Reinforcement Material, Chemical Polymerization Reaction of Epoxy Resin, to Experiments

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https://doi.org/10.31603/ae.4815

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Published by Automotive Laboratory of Universitas Muhammadiyah Magelang collaboration with Association of Indonesian Vocational Educators (AIVE)

*Article Info*
*Submitted:* 07/03/2021
*Revised:* 18/03/2021
*Accepted:* 21/03/2021
*Online first:* 24/05/2021

## Abstract

This study aims to investigate the effect of rice husks' particle size on resin-based brake pad performance (i.e. compressive strength, puncture strength, mass loss, wear rate, friction coefficient, and heat resistance). Bisphenol A-epichlorohydrin and cycloaliphatic amine were mixed to form resin and used as the brake pad's base material. In the experiment, rice husk with a specific particle size (i.e., 250, 500, dan 1000 μm) was added to the resin. Rice husk has received considerable interest due to its lignin, cellulose, and silica content, making it suitable as friction material due to its ceramic-like behavior. The experimental results showed small rice husk particles improved compressive strength, puncture strength, and bulk density. This can be obtained from the analysis of the maximum compressive strength for the brake pad supported by particles with sizes of 250, 500, and 1000 um having values of 0.238; 0.173; and 0.144 MPa, respectively. In contrast, large particles formed coarse surfaces and pores, decreased mass loss rate, and improve friction properties (i.e. wear rate, friction coefficient). The friction coefficient values of the brake pad supported by particles with sizes of 250, 500, and 1000 μm were, respectively, 0.2075; 0.2070; and 0.3379. Particle size affected interpacking, interfacial bonding, pores number and size, thermal softening, mechanical properties, and friction properties of the brake pad. Comparison between the prepared resin-based and commercial brake pad was also done, confirming the utilization of agro-waste as a potential alternative for friction material in the brake pad.

**Keywords:** Rice husk; Brake pad; Resin; Epoxy; Particle size; Friction

## *Abstrak*

*Penelitian ini bertujuan untuk menyelidiki pengaruh ukuran partikel sekam padi terhadap kinerja kampas rem berbahan resin (yaitu kuat tekan, kuat tusuk, kehilangan massa, laju keausan, koefisien gesekan, dan ketahanan panas). Bisphenol A-epichlorohydrin dan cycloaliphatic amine dicampur untuk membentuk resin dan digunakan sebagai bahan dasar kampas rem. Pada percobaan ditambahkan sekam padi dengan ukuran partikel tertentu (250, 500, dan 1000 μm) ke dalam resin. Sekam padi cukup diminati karena kandungan lignin, selulosa, dan silika yang dimilikinya sehingga cocok sebagai material gesek karena sifatnya yang mirip keramik. Hasil percobaan menunjukkan partikel sekam padi yang kecil meningkatkan kuat tekan, kuat tusuk, dan densitas. Hal ini dapat diperoleh dari analisis kuat tekan maksimum kampas rem yang didukung oleh partikel berukuran 250, 500, dan 1000 μm dengan nilai 0,238; 0,173; dan 0,144 MPa. Sebaliknya, partikel besar membentuk permukaan dan pori-pori kasar, menurunkan laju kehilangan massa, dan memperbaiki sifat gesekan (yaitu laju keausan, koefisien* *gesekan). Nilai koefisien gesek kampas rem yang didukung oleh partikel berukuran 250, 500, dan 1000 µm berturut-turut adalah 0,2075; 0,2070; dan 0,3379. Ukuran partikel mempengaruhi interpacking, ikatan antar muka, jumlah dan ukuran pori, pelunakan termal, sifat mekanik, dan sifat gesekan dari kampas rem. Perbandingan antara kampas rem berbahan dasar resin dan komersial juga dilakukan, menegaskan pemanfaatan limbah pertanian sebagai alternatif potensial bahan gesekan pada kampas rem.*

*Kata-kata kunci: Sekam padi; Kanvas rem; Resin; Epoksi; Ukuran partikel; Gesekan*

## 1. Introduction

Aside from binders, fillers, and reinforcement agents, the friction material is an essential constituent in brake pads. Friction material has a significant role in brake pad properties such as improving fade resistance, controlling the friction coefficient, reducing porosity/noise, and increasing strength [1]. Asbestos as a friction material has dominated the industry for over 8 years before it was banned due to its carcinogenic and hazardous properties [2]. By taking the environment, aqua species, and human life into consideration, innovation in friction material formula has been developed.

In the past few years, researchers have been focusing on developing an environmentally friendly brake pad using biomass as a non-asbestos organic material (NAO). The utilization of biomass such as sawdust [3], palm kernel shell [4], periwinkle shell [5], cocoa beans [6], corn husk [2], and seashell [7] in brake pad has been studied. Embedded biomass has been proven to improve mechanical properties, friction coefficient, and brake pad's water absorption. In addition, agro-waste such as banana and rice husk has become an absolute advantage over synthetic reinforcement due to its high fiber content [8]. The addition of rice husk, especially in brake pad formula, has been proven to improve its friction behavior [9].

Rice husk has received considerable interest due to its lignin, cellulose, and silica content [10], [11]. The high silica and low lignin content made rice husk suitable as friction material due to its ceramic-like behavior [12]. Rice husk can be used as a filler element in a polymer resin to create natural organic-inorganic composite material [13]. The rice husk is also an abundant and inexpensive agricultural by-product that could reduce the composites' manufacturing cost [14]. The use of rice husk as filler may increase the composite stiffness [15]. However, it can decrease the composite strength and strain at failure significantly due to low interfacial bonding between the rice husk and the polymer resin [16].

Based on previous studies on the effect of particle size on the mechanical properties of materials [17]–[20], this study investigates the effect of rice husks' particle size on the brake pad's performance, which has not been well-reported. The rice husk was used as the friction material in a resin-based brake pad. Unlike other methods in preparing brake pads that needed high temperature and pressure, the fabrication of a resin-based brake pad is at room temperature without additional heat and pressure. The present brake pad used the involvement of the polymerization of epoxy resins under room temperature for binding rice husk particles in the construction of the brake pad. In short, epoxy resins may be reacted (cross-linked) with themselves in forming polyepoxy through co-reactants (such as polyfunctional amines, acids (and acid anhydrides), phenols, alcohols, and thiols (usually called mercaptans)).

The brake pad was fabricated using resin (made from bisphenol A-epichlorohydrin and cycloaliphatic amine) and rice husk with particular sizes (i.e. 250, 500, and 1000 µm). Mechanical properties were analyzed by conducting puncture strength and compressive tests. The friction tests were then conducted to provide heat resistance, mass loss, wear rate, and friction coefficient of the prepared brake pad. This study demonstrated the potential of rice husk as a friction material in the brake pad. This study also provided new information on how particle size affects the mechanical properties and the brake pad's friction properties. Those properties play an essential role in determining brake pad performance.

## 2. Current Studies in the Preparation of Brake Pads Using Agricultural Wastes

**Table 1** shows detailed current studies in the preparation of brake pads using agricultural wastes as reinforcement components. The table shows the type of agricultural waste, supporting components, and the results gained from the study. Significant results have been obtained from those studies which mean the agricultural waste has great potential to substitute inorganic material content for brake pads.

**Table 1.** Current studies in the preparation of brake pads using agricultural wastes **as a reinforcement component**

| Type of agricultural waste | Supporting components | Results | Ref |
|---|---|---|---|
| Sawdust (SD) | Slag waste, epoxy resin, silicon carbide, and graphite. | The addition of SD gave an impact on the wear rate and degradability of the brake pad. The high amount of SD has high ash content, low density, low compressive strength, and high degradability/wear rate. Large SD particle size attributed to increases in porosity and wear rate. | [3] |
| Palm kernel shell (PKS) | Epoxy resin, hardener, and cow bone | Increases in PKS's particle size attributed to low density, high impact strength, low hardness value, low water resistance, and low oil resistance. | [4] |
| Palm Ash | Epoxy resin, polychlorinated biphenyls (PCB), and metal filler | The higher percentage of palm ash resulted in the obtainment of the best mechanical and wear properties. | [21] |
| Periwinkle shell (PS) | Phenolic resin (phenol formaldenyde) | Decreases in PS's particle size attributed to high wear rate and high friction coefficient. | [22] |
| Bagasse (BGS) | Phenolic resin (phenol formaldehyde) | Decreases in BGS' particle size attributed to better particle distribution, high compressive strength, high density, high water resistant, high oil absorption, high flame resistant, and low wear rate. | [23] |
| Coconut shell (CCS) | Epoxy resin | Decreases in the amount of CCS correlated to high breaking strength, hardness, compressive strength, and impact strength. | [24] |
| Maize husk fiber (MHF) | Epoxy resin, hardener, maize husk, silica iron oxide, calcium carbonate, and powdered graphite | High amount of MHF correlated to high density, coefficient of friction, water absorption, and oil absorption. However, high amount of MHF decreased hardness, wear rate, tensile strength, compressive strength, and thermal conductivity. | [2] |
| Snail shell (SSH) | Phenolic resin, rubber seed husk, catalyst, and accelerator. | Increases in SSH's particle size contributed to high oil absorption, high water absorption, high wear rate, low compressive strength/hardness, and low density. | [25] |
| Banana peels (BPS) | Phenolic resin | Increases in the amount of BPS attributed to high compressive strength, high hardness value, high specific gravity, low wear rate, low water absorption, and low water absorption | [26] |
| Groundnut shell (GNS) | Phenolic resin | Increases in GNS attributed to high oil absorption, water absorption, density, and compressive strength. Large GNS particles improved the compressive strength. | [27] |
| Corn Husks (CHS) | Silicon carbide, graphite, resin, and steel dusk | The corn husk (100 μm) gave the finer distribution of the corn husk particle in the matrix. The corn husks resulted in the obtainment of the brake pads with better compressive strength, lower porosity, higher hardness, and lower rate of brake pad wear. | [28] |

| Type of agricultural waste | Supporting components | Results | Ref |
|---|---|---|---|
| Water Hyacinth *(Eichhornia crassipes)* | Phenolic resin | The brake pads with fiber from *Eichhornia crassipes* showed less acetone extraction value, had plateau formation, and good fiber bounding | [29] |
| Cashew nuts (CNS) | Epoxy resin, iron oxide, nano hematite Nano Talc, and Nano silicon oxide, which are milled from white sandstone. | CNS could make the brake pads to have high limit friction, good resistance to oil and water absorption, high tensile and compression properties, and good thermal stability. | [30] |
| *Miscanthus sp.* | Cashew, alumina, calcite, and phenolic resin | The addition of *Miscanthus sp.* on the brake pad affected the density and porosity, which was also a function of the mixture proportion of material, curing time, and curing temperature. | [31] |
| Seashell (The shells of sea snails) | Epoxy resin, graphite, and aluminum oxide | The brake pad made from seashells showed good mechanical and tribological properties, including good compressive strength, hardness, flexural, and impact strength. | [7] |
| Cow bone | Unsaturated polyester resin, methyl ethyl ketone peroxide (MEKP), polyvinyl acetate, 2% cobalt solution, and ethanol. | The brake pads reinforced with cow bones (sizes of 75 μm) gave a better tensile strength than other polyester matrices, while the sizes of 300 μm gave the optimal hardness result. The addition of cow bone also improved flexural strength. | [4] |
| Cow hooves | Graphite, aluminum oxide, barium sulfate, and epoxy resin. | The results showed that a sample composed of 15% pulverized cow hooves, 35% epoxy resin, and sample with 10% pulverized cow hooves, and 7% epoxy resin gave the optimum results when compared with commercially asbestos brake pads. The cow hooves brake pads gave good mechanical, tribological, and physical properties | [32] |
| Cocoa beans shells | Calcium carbonate, silica sand, anhydrous iron oxide, epoxy resin and graphite. | The brake pade with 60% of epoxy resin and 21% of cocoa beans shells gave the optimum performance compared to the asbestos–based brake pad in term of friction coefficient, tensile strength, compressive strength, and hardness. | [6] |
| Lemon peels | Epoxy resin, aluminium oxide, graphite, iron oxide, and calcium hydroxide | The brake pad with a density of 1.55–2.00 g/cm$^3$, hardness of 26–32 (barcol hardness), percentage wear loss of 13.45–19.14%, percentage water loss of 0.96 –1.38% and and oil absorption of 0.01– 0.02%, and wear of 13.45–19.14% was obtained when using lemon peels, which is better than commercial brake pads | [33] |
| Fly ash | Phenolic resin, rockwool, ceramic wool, zirconium silicate (zircon) and calcium hydroxide | The hard fibers in fly ash improved the tensile strength and hardness of the friction material. The friction test was in the range between 0.35 and 0.48, which better than barites based (without fly–ash) and asbestos based brake pads. | [34] |

## 3. Method

### 3.1. Brake pad production

Bisphenol A-epichlorohydrin and cycloaliphatic amine were used as the resin materials. Both materials were then mixed thoroughly with a 1:1 ratio. Rice husks (collected from Bandung, Indonesia) were saw-milled using the apparatus as reported in our previous studies [35], [36]. To obtain the specific size, the saw-milled rice husk particles were put into a sieve shaker (Niaga Kusuma Lestari, Indonesia) in accordance with ASTM D1921. The sieve pans with a specific mesh size of 18, 35, and 60 (that were put into the sieve shaker) were used to obtain rice husk particles with sizes of 250, 500, and 1000 µm, respectively.

To make the brake pad, 13 g of rice husks were added to 22 g of the resin mixture. After that, the prepared mixture was poured into a silicone mold (with a dimension of 4 x 3 x 1 cm) and dried in a room (at room temperature and pressure) for 2 days, avoiding sunlight exposure. For the characterizations, the prepared brake pad was sliced with a specific size.

### 3.2. Mechanical properties test

Compressive and puncture strength tests were conducted to determine the prepared brake pad's mechanical properties. For the compressive test, a Screw Stand Test Instrument (Model I ALX-J, China) equipped with a digital force gauge instrument (Model HP-500, Serial, No H5001909262) was used. The test was carried out by applying a constant displacement rate of 2.6 mm/min to the brake pad. The compressive force was simultaneously recorded, resulting in a curve displaying the texture profile. Compressive strength was then obtained from the maximum point of the compressive stress-strain curve.

Furthermore, the maximum force applied (in Newton (N) units) was used to assess the sample's hardness during the test. Shore Durometer instrument (Shore A Hardness, In size, China) was used to perform the puncture strength test. During the test, a probe was used to puncture the brake pad. The hardness was measured on a scale from 0 to 100.

Additionally, the bulk density of rice husk ($\rho$) was calculated using Eq. (1).

$$\rho = \frac{m}{V} \tag{1}$$

where $m$ is the mass of rice husk in the specimen and $V$ is the volume of the specimen.

### 3.3. Friction test

Prior to doing tests, the brake pad was polished to remove the resin layers on the surface of the brake pad. The friction test was conducted by sliding the brake pad against sandpaper (80 grit; Dae Sung CC-80Cw) with a mass load of 9 kg for 20 minutes at a speed of 25 cm/s. Every 2 minutes, the brake pad mass was recorded. The wear rate ($M$) was calculated using Eq. (2) [37].

$$M = \frac{(M_a - M_b)}{t\ x\ A} \tag{2}$$

where $M_a$ is the brake pad initial weight (g), $M_b$ is the brake pad final weight (g), $t$ is the testing time (s), and $A$ is the frictional cross-section area (mm²). The friction coefficient (µ) was the ratio of the friction force ($f$; Newton) to applied force ($N$; Newton) expressed in Eq. (3).

$$\mu = f/N \tag{3}$$

## 4. Results and Discussion

### 4.1. Proposal chemical polymerization reaction during the formation of resin-based brake pad

The concept in the preparation of resin-based brake pad is using the involvement of the polymerization of epoxy resins under room temperature for binding and compacting reinforcing components. Epoxy resins may be reacted (cross-linked) with themselves in forming polyepoxy through co-reactants.

Bisphenol A-epichlorohydrin (known as phenoxy resin) was used as the brake pad matrix material [38]. A two-step reaction sequence was involved. The first sequence is a reaction between bisphenol A and epichlorohydrin, producing bisepoxides (**Figure 1**). Bisepoxides were then reacted with a stoichiometric amount of sodium hydroxide to form bisphenol A diglycidyl ether (DGEBA), water, and sodium chloride. Bisphenol A improved strength, elongation, and ductibility of the epoxy matrix [39].

Thereafter, chain extension process of liquid epoxy resin (DGEBA) was taken place by reacting DGEBA with other bisphenol A molecules (**Figure 2**). This oligomerization process is exothermic and proceeds rapidly to near complextion, forming a higher molecular weight epoxy (as a long-chain polymer).

By curing with crosslinkers, the long-chain polymer of phenoxy resin (with high molecular weight) was transformed into an infusible and insoluble solid with three-dimensional thermoset networks. In this study, cycloaliphatic amine was used as a curing agent (**Figure 3**). The phenoxy resin chain structures were colored blue. The curing process involved cross linking by opening the oxirane ring, forming longer C-O bonds. The reaction forms the 3-dimensional structure since the curing agent molecules cross link the long polymer in its body (**Figure 4**). This process correlated to shrinkage and dimensional stability of cured epoxides. Cycloaliphatic amines were used as a curing agent for the resin-based brake pad since it can be used to cure the resin at low temperature/room temperature with good color and long pot-life. Furthermore, cycloaliphatic amine enchanced the electrical, mechanical, and thermal properties. It also has a good adhesive properties, which advantage the bonding between constituent such as rice husk particles in the resin matrix.

### 4.2. *Physical appearance of brake pad*

**Figure 5** shows the photograph image of the prepared brake pad. Resin-based brake pad reinforced with rice husk appeared brown, rough, and porous.

**Figure 6a-c** show the microscope images of rice husk particles with various sizes. When the rice husk particles were combined with the resin and packed into the brake pad, the packed material was obtained. The surface appearance of the prepared brake pad observed by microscope is presented in **Figure 6d-f**. According to the observation, the prepared brake pad with 1000-μm rice husk has bigger and numerous pores compared to other samples (see **Figure 6d**). The use of smaller rice husk particle size for the brake pad resulted in a smoother and fewer pores structures in the final product (**Figure 6e** and **Figure 6f**).

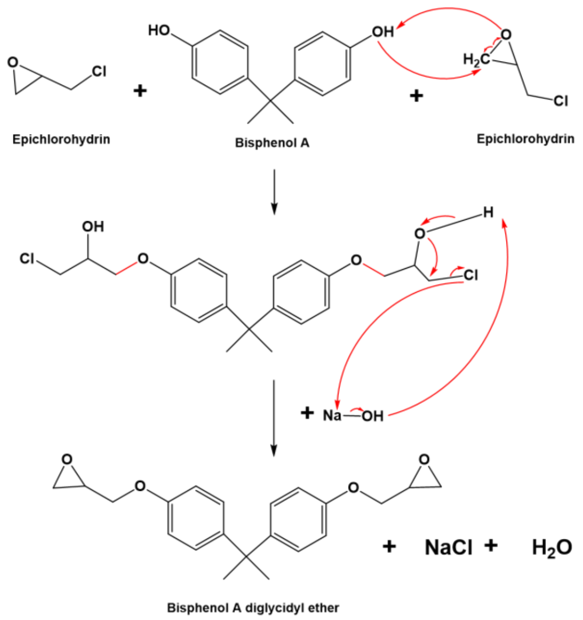


**Figure 1**. Synthesis of bisphenol A diglycidyl ether (DGBA)

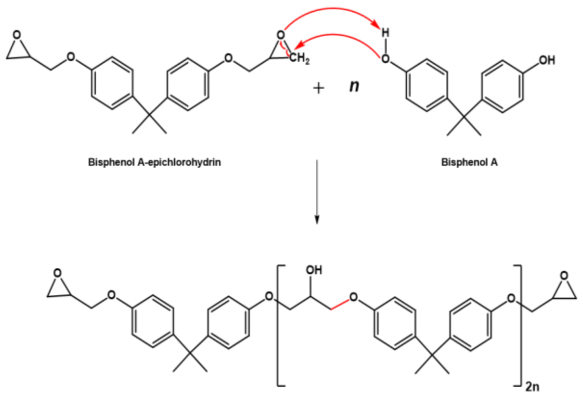


**Figure 2.** Polymerization process between DGEBA and other bisphenol A molecules

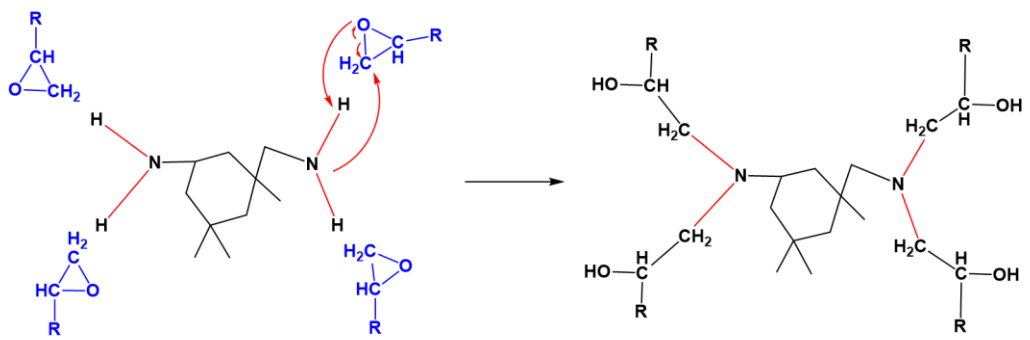

**Figure 3.** Curing process of bisphenol A derived epoxy resin by cycloaliphatic amine

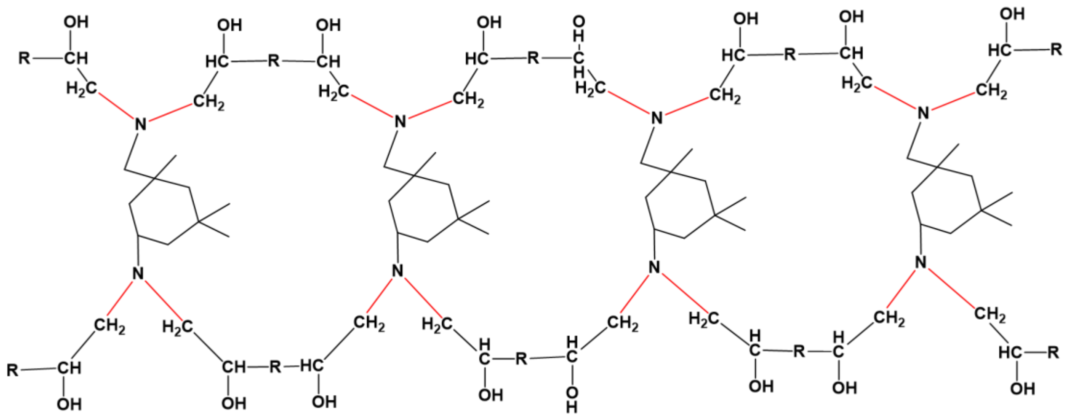

**Figure 4.** Bisphenol A derived resin with cycloaliphatic amine

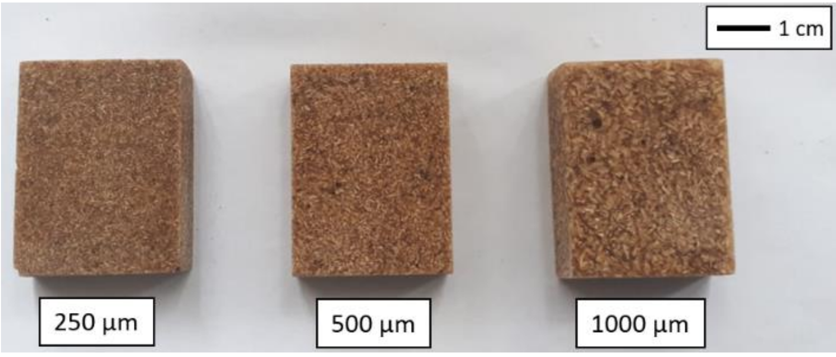


**Figure 5**. The photograph of prepared brake pad samples

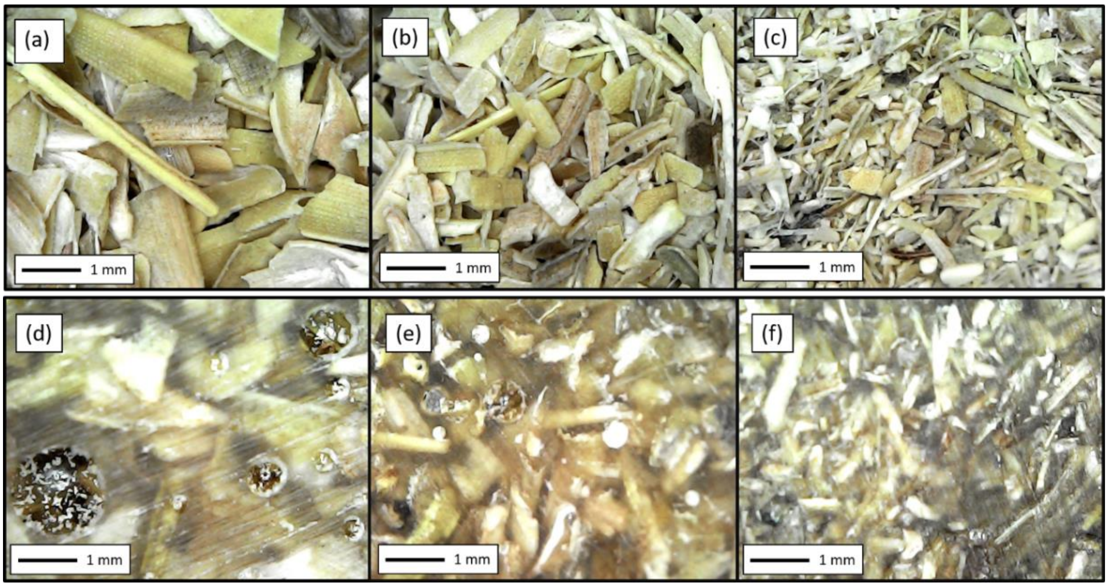


**Figure 6.** Microscope observation of (a-c) rice husk particles and (d-f) brake pad samples (particle size from left to right: 1000, 500, and 250 µm)

To support the analysis of the texture profile inside the brake pad, **Figure 7**, respectively, show the microscope images of the pores on the matrix of the prepared brake pad prepared with 1000-, 500-, and 250-µm rice husk particles. The porous structure was obtained. The largest pores were found on the brake pad prepared with 1000-µm rice husk particles (see **Figure 7c**; red circle). Then, when using 500-µm rice husk particles, the smaller pores were obtained (see **Figure 7b**; red circle). Moreover, the brake pad prepared with 250-µm rice husk particles has fewer pores.

When the larger particles of rice husks were used, it creates more spaces in the brake pad. The large particles reduce the bond area between resin-rice husk and rice husk-rice husk. The large pores on the brake pad increased the possibility of crack and reduced the performance of the brake pad.

On the contrary, the smaller rise husk particles increase the bond area between the resin-rice husk and the rice husk-rice husk. The small particles form a more homogeneous packing particle structure.

### *4.3. Mechanical properties*

The mechanical properties of the prepared brake pad were analyzed. The results of the compressive test and puncture strength test were shown in Table 2 and Figure 8a, respectively. The bulk modulus of three specimens with different rice husk particle sizes are also listed in Table 2. The values of the bulk modulus of all specimens were kept identic during the manufacturing process. The result shows the maximum variance of bulk modulus is less than 3%, which is considered small.

Higher compressive stress obtained from the compressive test indicates greater compressive resistance in the material. Figure 8b shows that the compressive strength of the brake pad increased with a decrease in particle size. The maximum compressive strength for the brake pad supported by particles with sizes of 250, 500, and 1000 μm were 0.238; 0.173; and 0.144 MPa, respectively. On the other hand, smaller numbers on the scale during the puncture strength test, suggesting a higher tolerance of indentation (see Table 2).

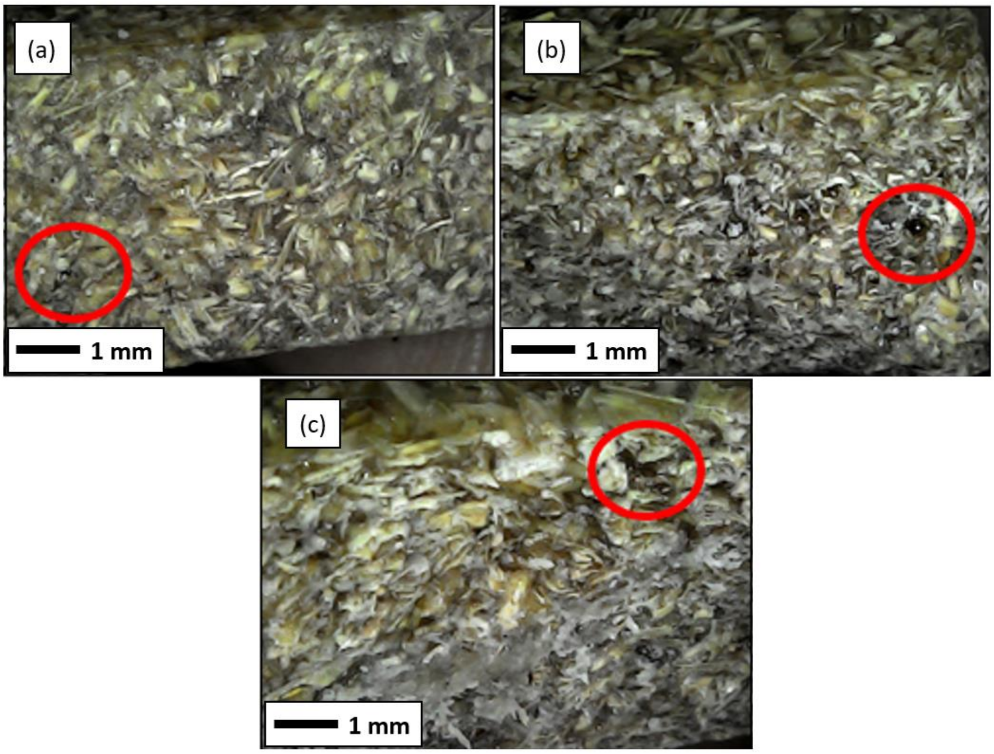


**Figure 7**. The microscope images of sliced brake pad prepared with rice husk with sizes of (a) 250, (b) 500, and (c) 1000 μm. Red circle is the appearance of large pores in the sample

**Table 2.** The puncture strength result and the bulk density

| Sample | Bulk density (g/cm³) of particles | Average size of pores (μm) | Durometer Shore A Hardness Scale of brake pad |
|---|---|---|---|
| 250 μm | 1.0958 | 93 | 84.43 |
| 500 μm | 1.0671 | 124 | 87.57 |
| 1000 μm | 1.0649 | 245 | 94.71 |

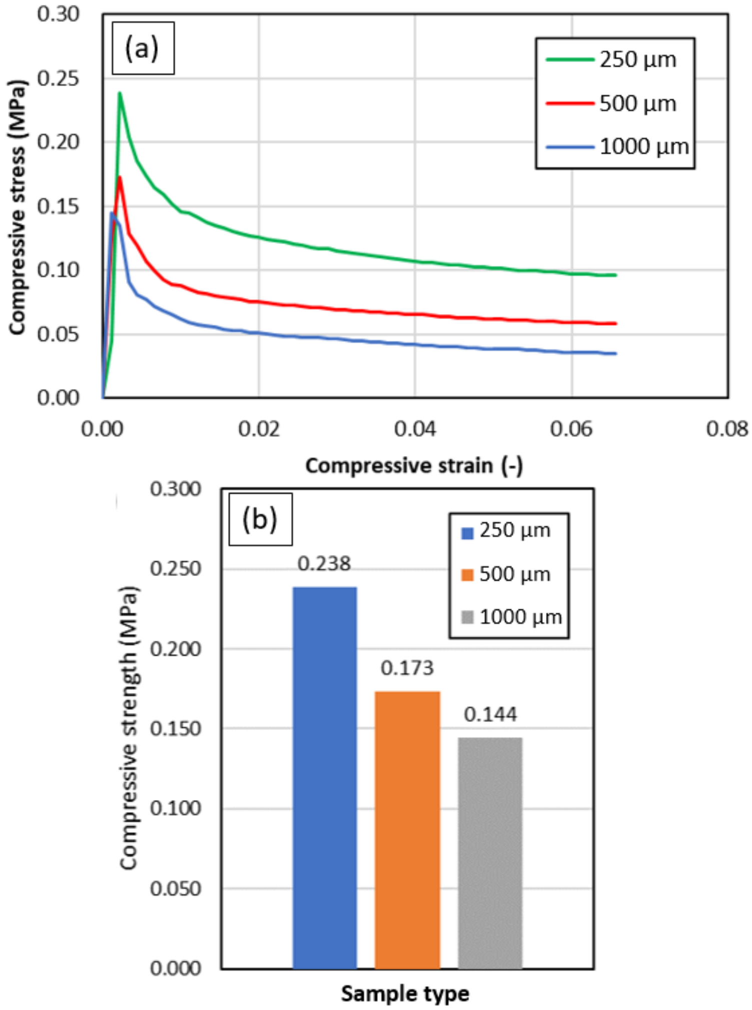


**Figure 8.** The compressive test result: (a) compressive stress-strain curves and (b) compressive strength

Since a specific particle size was used, the rice husk particles were uniformly distributed and developed a compact structure (see **Figure 7a**). The uniform dispersion of filler particles has influenced the mechanical properties/hardness of the brake pad [40]. Smaller particles have a larger surface area, which is advantageous for bonding ability with the resin. The inter-packing distances decreased as the particle size decreases due to several reasons: (1) proper distribution of rice husk particles inside the resin; and (2) proper bonding between the rice husk particles and the resin.

The particle size correlates with the size/number of pores in the material (**Table 2**). These pores are generated originally from trapped air during the mixing and solidifying processes of resin. Larger sizes of rice husk particles tended to trap more air during the mixing process compared with the smaller sizes. This is possibly the reason why more pores (cavities) were formed in the specimen with rice husk particles of 1000 µm (see **Figure 7c**). These pores increased the possibility of crack formation in the resin matrix due to stress concentration, making it more prone to fail under compressive load [41], [42].

In addition to the above results, comparing compressive strength and puncture strength, these parameters do not have proportional relations. This result can be classified as an unusual phenomenon comparing to common materials [43].

In the compressive test, the compressive load was held collectively by strengths of rice husk, resin, and their interface. While the rice husk strength is much higher than the resin, the interface is the weakest strength among them. To effectively bear the load, the stress in resin must be transferred into rice husk (having higher strength). However, low interfacial strength might cause the stress to not transfer well and even become a medium of crack initiation and propagation [44]. In the case of the specimen with large rice husk particles, the interfacial region appears dominant; and thus, the specimen failed under compressive load due to earlier crack propagation. In contrast, for small rice husk particles, the crack propagation is resisted by the appearance of a small interfacial region. This is the main reason why the specimen with small rice husk particles can bear compressive load effectively.

In the puncture strength test, different phenomena appeared. The probe with a diameter of 1 mm for the testing apparatus, which is identical to the large rice husk particle size, is pricked to both rice husk and resin of the specimen. The possibility of the probe tearing large rice husk particles directly is greater than that tearing the small rice husk particles. Considering the higher strength of rice husk particles comparing to resin and interfacial strength, the probe might require more force to tear the rice husk particles. This is the reason the shore hardness of specimens with large rice husk particles is higher than the small particles even though the different values are not significant. In designing particulate composites, the size of particles plays important roles to determine the mechanical behavior of the specimen including compressive and puncture strengths. When the particle size in the specimen is considerably large relatively to the probe diameter, the puncture test might not be beneficial to measure their hardness. This is in line with our previous studies [19] regarding the micromechanical properties of particles.

### 4.4. Friction properties

The mass changes of the prepared brake pads during the friction test were recorded (see **Figure 9**). During the friction test, the brake pad was forced to contact the sandpaper (as a model of brake drum/disc) and consequently conversing kinetic energy to thermal energy, producing heat and friction [45]. Debris also was produced during this process. A decrease in particle size of rice husk in the brake pad contributed to higher mass loss.

The mass loss rate, wear rate, and coefficient of the brake pad are shown in **Table 3**. In short, the friction coefficient values of the brake pad supported by particles with sizes of 250, 500, and 1000 μm were, respectively, 0.2075; 0.2070; and 0.3379.

Higher mass loss rate consequently replied to poor wear rate and low friction coefficient. Small particles have better particle distribution throughout the brake pad for friction resistance. However, small particles disadvantaged the brake pad's wear rate due to its large particle-matrix interfacial area. The large particle-matrix interfacial area increased the possibility of the small particles pulling out from the matrix. In contrast, larger particles were expected to be embedded within the matrix until they break down into smaller particles, decreasing the brake pad's wear rate [46]. Furthermore, small particles contributed to a higher density value [23], meaning more particles were lost due to abrasion (confirmed by high mass-loss rate).

Brake pad reinforced with large particles was showing better wear properties due to low-density value. However, it was producing a malleable and unstable structure when friction was applied. The heat produced during the friction test raised the temperature of the friction surface [47], which softens the resin. Furthermore, rice husk particles allowed thermal softening effects on the wear behavior. When thermal softening of the matrix material took place, the bonding effect of rice husk particles with matrix material (resin) lowered [46]. As a result, the structure conformed easily as expected from a porous and malleable material. Hardener constituent could be added into the brake pad formula to produce a stable structure.

In addition, interesting phenomena happen. The particle size affected the friction coefficient. The friction coefficient of brake pads with 250- and 500-μm rice husk particles were identical, while that with 1000-μm rice husk particles showed better performance. Smaller particles are easily released (dislocated) during the friction test. This makes the mass loss and friction coefficient lower compared to larger particles. Indeed, the more remained rice husk in the brake pad resulted in better performance since the main factor in the friction is the rice husk component itself.

**Figure 10** shows the comparison of prepared brake pads with conventional brake pads in terms of mass loss during friction tests. The prepared brake pad with 250-μm rice husk particles was used for the comparison. The mass loss was almost similar, informing that the rice husk is prospective for being used as the brake pad. The prepared brake pads were porous, making the mass loss not well-distributed.

Table 4 shows the comparison of the prepared brake pad and commercial pad in terms of the wear rate and the friction coefficient. In general, the prepared brake pads have a better wear rate compared to the conventional brake pad. Although the prepared brake pad has a lower friction coefficient value compared to the conventional brake pad, the difference is not so high (only 10 % lower).

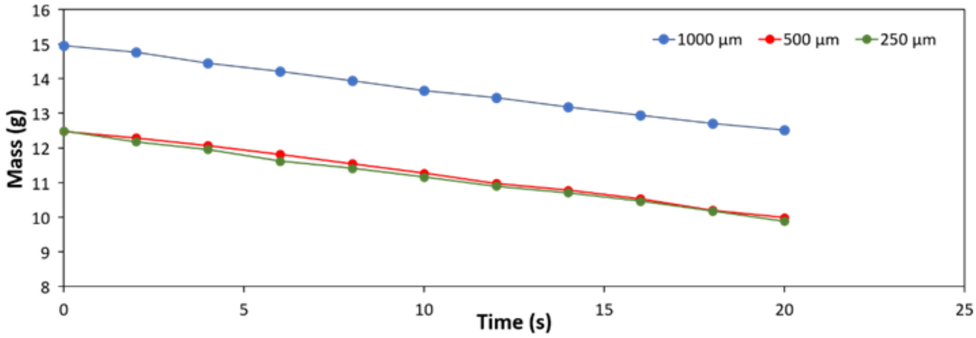


Figure 9. The mass loss of prepared brake pad (prepared with various rice husk sizes) as a function of time. The friction test's contact area size is 3.8 x 1 cm

Table 3. The mass loss, the wear rate, and the friction coefficient of prepared brake pads prepared with various rice husk particle sizes. $M_a$ and $M_b$ are the initial and final mass, respectively. $t$ is the friction time. $A$ is the friction test's contact area. $M$ is the wear rate

| Sample | $M_a$ (g) | $M_b$ (g) | Mass loss rate (g/min) | $t$ (s) | $A$ (mm²) | $M$ (g/s.mm²) (× 10⁻⁶) | Friction coefficient |
|---|---|---|---|---|---|---|---|
| 250 µm | 12.492 | 9.882 | 0.119±0.046 | 1200 | 3.8 | 5.72 | 0.2075 |
| 500 µm | 12.485 | 9.986 | 0.114±0.046 | 1200 | 3.9 | 5.34 | 0.2070 |
| 1000 µm | 14.952 | 12.512 | 0.111±0.041 | 1200 | 4.68 | 4.34 | 0.3379 |

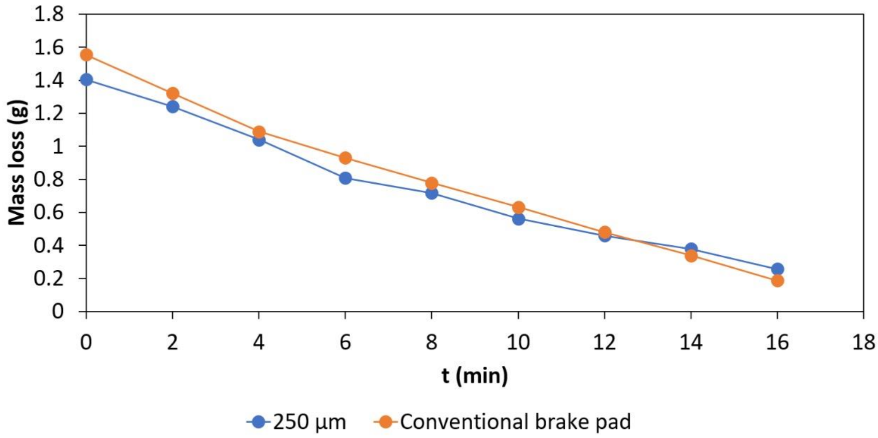


Figure 10. The mass loss of prepared brake pads with conventional brake pads. Friction test's contact area size of 2 x 0.4 cm

Table 4. The mass loss and the friction coefficient of prepared brake pads with conventional brake pads. $M_a$ and $M_b$ are the initial and final mass, respectively. $t$ is the friction time. $A$ is the friction test's contact area. $M$ is the wear rate

| Sample | $M_a$ (g) | $M_b$ (g) | Mass loss rate (g/min) | $t$ (s) | $A$ (mm²) | $M$ (× 10⁻⁶ g/s.mm²) | Friction coefficient |
|---|---|---|---|---|---|---|---|
| 250 µm | 1.405 | 0.258 | 0.063±0.069 | 60 | 81 | 1.48 | 0.1832 |
| Conventional brake pad | 1.555 | 0.187 | 0.076±0.067 | 60 | 85 | 1.68 | 0.2099 |

## 5. Conclusion

The effects of rice husk particle size on resin-based brake pad performance have been investigated. Particle size affected interpacking distances, interfacial bonding, and thermal softening of rice husk particle-resin matrix. Small particles improved the compressive strength of the brake pad. Decreases in particle size also resulted in fewer pores formation, less mass loss, better wear rate, high friction coefficient, and the brake pad's coarser surface. Comparison between the prepared resin-based and commercial brake pad was also done, confirming the utilization of agro-waste as a potential alternative for friction material in the brake pad.


## Acknowledgments

The authors acknowledged Universitas Pendidikan Indonesia.


## 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 approved the final manuscript.


### Funding

This study was supported by RISTEK BRIN (Grant in aid: 2021 Penelitian Terapan Unggulan Perguruan Tinggi - PTUPT).


### Availability of data and materials

All data are available from the authors.

### Competing interests

The authors declare no competing interest.

### Additional information

No additional information from the authors.

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