Waste Glass Powder as a Sustainable Abrasive Material for Composite Brake Block

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Keywords:

Abrasive
Glass powder
Composite friction
Tribology properties
Thermal behaviour

ABSTRACT

In this paper, waste glass powder (GP) is selected as a sustainable abrasive to replace pure silica minerals. XRF analysis to determine the content of glass waste. Composite specimens have volume fraction ratios of 0%, 2%, and 4% GP evaluated with TGA, Pin on Disc friction test, and Hardness Rockwell type R. Scanning electron micrograph (SEM) observe the formation of abrasion and surface wear of the specimen. The results of the X-ray fluorescence (XRF) glass powder waste obtained that the main content of silicon dioxide (SiO₂) was 65.58%. Thermogravimetry (TG) showed that the thermal resistance of the composite from the addition of glass powder increased. Glass powder as an abrasive shown that increase the coefficient of friction brake friction materials. The presence of glass powder increases the hardness of the composite, and the coefficient of wear rate of the composite decreases.

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Received: 26 February 2021

Revised: 11 April 2021

Accepted: 30 June 2021

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1. INTRODUCTION

The brake block is part of the train wheel braking system. In general, rail brake block materials are classified as cast iron, sintered, and composite brake blocks [1]. Indonesian railways have used brake blocks made of cast iron. Cast iron brake blocks have the disadvantage of rapid wear and, therefore, frequent replacement. In addition, cast iron brake blocks are heavy, requiring high replacement costs. Although sintered brakes are available, sintered brake blocks are more expensive and require high technology to manufacture. Therefore, composite brakes are an alternative to cast iron brake materials. Composite brakes to be used instead of cast iron

brake blocks, a review of the availability of raw materials is required.

The abrasive plays a vital role in determining braking distance, wear rate, and increased friction. Therefore, the selection of abrasive material is significant to achieve proper braking performance and properties. Materials containing silicon (Si), such as zircon (ZrSiO₄), quartz, and silicon carbide (SiC), have been widely used as abrasives for the manufacture of composite friction brakes [2]. The natural mineral silicon (Si) is obtained by mining quartz sand [3]. Long-term mining of natural quartz sand as a silicon source will ultimately lead to the depletion of this limited resource. Hence the

availability of raw materials, cost, and friction performance; is also considered when choosing an abrasive for making composite friction brakes. While Glass is an industrial product with high silica content, X-ray fluorescence (XRF) analysis shows that Glass has the main content of Silica 59,245% (SiO₂) [4]. Glass is brittle and breaks easily when not in use; it is discarded as waste glass. Inorganic waste glass, which takes millions of years to decompose in the soil [5]. The process of recycling waste glass is high energy and expensive [6]. However, if the abundant broken Glass is not recycled, it will also impact environmental damage. Therefore, the high silica content in used glass powder can replace pure silica as a continuous abrasive in composite brake blocks.

In this research, the remaining Glass from the waste is powdered as an abrasive for composite block brakes. Tribological and thermal analyzes were evaluated and discussed to determine the characteristics of friction composites against thermal stability, friction coefficient, and disc surface temperature under various conditions of contact pressure and sliding speed. The coefficient of wear rates of the specimen are compared, and the friction composite contact surface wear is investigated to determine the wear mechanism. XRF examines glass powders to ensure that glass waste content. Three compositions of the volume fraction of glass powder as friction material 0%, 2%, and 4% have been prepared in this study.

2. EXPERIMENTAL

2.1 Material preparation

The soda-lime glass waste is purified by first pounding it with a mortar and pestle, then a ball mill grinder until smooth and then filtered through the filter net No. 200 was then calcined at 500°C for 3 hours to remove impurities. The materials required for the friction composite in a volume fraction consist of 25% phenolic resin as a binder, equal parts kenaf, and 12% glass fiber as reinforcement. The basic material consists of 5% acrylonitrile-butadiene rubber (NBR), 5% molybdenum disulfide (MoS₂), 10% graphite, 10% cashew dust which functions to improve friction performance. The powder waste abrasive to increase the friction coefficient was varied and

varied to reduce calcium carbonate (CaCO₃) as a compensator. Table 1 presents the wide variations in the volume fraction of each specimen.

Table 1. The volume fraction of the specimen composition.

Element	Glass powder composition [%]		
	Non GP	GP 2	GP 4
Basic materials	67	67	67
CaCO ₃	33	31	29
Glass powder	0	2	4

2.2 Spesimen preparation

The constituent materials are weighed according to the three specimen compositions described in Table 1. The preparation of the specimens includes; the composition weighing process, the next mixing process is the cold moulding process and the hot moulding process [7]. First, the ingredients were mixed for eight minutes using an electric mixer on a gradual speed setting to produce a homogeneous mixture. The filler and the matrix were added and stirred gradually with variants of five levels of speed for one minute each. Finally, the kenaf and fiberglass were added and stirred at a constant medium speed for three minutes. The specimens were then pre-formed by pouring the mixture into moulds and applying constant pressure of 40 MPa for 10 minutes. Phenolic resin functions as a binder having an exothermic reaction at a temperature of 130 -200 C [8]. The process of hot molding followed by post-curing refers to previous research [9]. Hot molding is performed to improve specimen bonding. Hot specimen printing takes place at 150°C for 10 minutes at a pressure of 40 MPa. The hot moulding process on the phenolic resin matrix gives the effect of the formation of NH₃ gas. The gas formed can be trapped in the mould, causing porosity as the main cause of cracking [10]. During the hot moulding process, gas is released six times with a holding time of every 10 seconds. Then pressed again for 9 minutes to complete the pressing time. Heat treatment or post-curing can increase the storage modulus of phenolic resin compounds optimally, which can be achieved by increasing the curing time. Post-curing to improve the mechanical and frictional properties of composites. [9]. The post-curing procedure includes heating at 30°C to 140°C for one hour then at 140°C to 180°C for 6 hours, followed by cooling from 180°C to 30°C in 30 minutes.

2.3 Friction test

The tribological properties of the composite were tested under dry conditions. The actuator presses the specimen horizontally on the surface of the rotating disk, as shown in Figure 1. The normal force is determined from the air pressure acting on the pressure gauge. DIN X 153 CrMoV 12 steel with a hardness of 54 RC and roughness of about 0.43-1.37 μm was used as the disc material. Friction testing is initiated by rubbing the specimen against the disc surface at a contact pressure of 2.5 MPa and a shear speed at 5m/s until the contact surface is completely worn. Next, clean the surface of the disc with 800-2000 grit abrasive paper. Friction test with parameter settings, as shown in Table 2. The friction force is obtained from the response of the load cell, which receives pressure from the lever arm when the pin opposes the rotation of the disc. The friction forces were recorded using a load cell and data acquisition system (Advantech USB-4716). In addition, the surface temperature of the disc is read using a non-contact infrared sensor and recorded using a data acquisition system. Friction force and disk temperature data were collected with 1 data every second. Three specimens were used for friction testing, and each sample was tested three times.

Fig. 1. Schematic pin-on-disc friction testing machine.

The coefficient of friction is obtained by dividing the frictional force (F_f) by the normal force (F_N). Then, the coefficient of friction is calculated using equation [1].

$$\text{Coefficient of friction} = \frac{F_f}{F_N} \quad (1)$$

Table 2. The variable parameters of the friction test.

Variation of parameter	Testing parameter
Contact Pressure (MPa)	0.25 ; 0.5 ; 0.75 ; 1 Sliding speed at 3 m/s and 12 m/s
Sliding Speed (m/s)	3 ; 6 ; 9 ; 12 Contact pressure at 0.25 MPa and 1 MPa

Wear tests are performed to measure specific wear rates with a pin-on-disk tribometer tester. The sliding speed and contact pressure are set at 12 m/s and 1 MPa. The wear test is carried out within a sliding distance of 6000 m for each friction. The Archard wear equation is intended for adhesive wear and represents abrasive wear [11]. Archard's theory states the relationship between abrasive wear rate, material properties, load, and sliding distance. The wear volume rate is expressed in terms of the specific wear rate, calculated as:

$$k = \frac{\Delta V \cdot H}{F_N \cdot S} \quad (2)$$

Where k : spesific wear rate ($\text{m}^3/\text{N.m}$), ΔV : wear volume (mm), H : hardness of the specimen (HR), F_N : Normal force (N), and S : sliding distance (m). The volume loss was obtained by the weight reduction method, where the mass before and after rubbing was divided by the specimen's density. The weight of the specimen before and after friction was measured with a digital scale with an accuracy of 1/1000.

The hardness of the composite specimens was tested using a Rockwell hardness tester with a type R indenter. Hardness testing was based on ASTM D 785 standards. Three specimens were prepared for each variation in the volume fraction of glass powder-at least five traces of indentation per specimen. The distance between the indent points is set at 20 mm to eliminate the effect of adjacent indents. Finally, the microstructure of the worn specimen surface is examined by scanning electron microscopy.

3. RESULT AND DISCUSSION

3.1 X-ray fluorescence

The elemental composition of the GP was determined via XRF analysis. The chemical composition concentrations by percentage [%]

are presented in Figure 2. SiO_2 was the central element in the glass powder, followed by CaO , MgO , and Al_2O_3 , as these elements give soda-lime glass its characteristics. An XRF analysis of the glass waste showed the main composition of 65.58% (SiO_2), 21.34% (CaO), 4.34% (MgO), ZrO_2 , Al_2O_3 , and other trace elements; in that order. The results of XRF characterization showed that the glass powder waste contained a high silica oxide content of 65.58%. The presence of silica in glass powder waste can be used as an abrasive.

Fig. 2. XRF-analysis of Glass Powder

3.2 Thermal behavior

The thermal decomposition behavior of brake block composites prepared in atmospheric air was investigated by thermogravimetric analysis (TGA). The study aimed to estimate the stability of brake block composites against increasing temperatures.

The results of the composite thermogravimetric analysis are as shown in Figure 3. It can be seen that weight loss indicates that the decomposition occurs gradually. The weight reduction process begins with the evaporation of the volatile material at a specific temperature; first stage decomposition level, and second stage decomposition rate; Furthermore, the third stage of decomposition occurs quickly. The initial temperature at which the material is initially reduced to mass is known as the initial temperature (T_{onset}). The temperature of maximum mass loss of the decomposition is known as peak temperature (T_{peak}), shown in Table 3.

Fig. 3. TGA and DTG analysis of specimen different composition.

Table 3. Temperature degradation and weight loss.

Sample code	T_{onset} (°C)	$T_{\text{peak 1}}$ (°C)	$T_{\text{peak 2}}$ (°C)	Wt (%)
				at 800 °C
Non GP	273.4	423.4	761.4	39.04
GP 2	273.4	423.4	775.25	40.2
GP 4	273.4	423.4	773.4	40.33

The preheating temperature is started from 30°C to 1000°C. The initial mass weight decreases at temperatures between 100° C due to water evaporation. The weight loss of all specimens at an initial temperature (T_{onset}) of approximately 300°C and continued up to 750°C, where each composite undergoes a different and gradual percentage weight loss (wt.%). The initial weight loss is due to the degradation of the phenolic resin. Meanwhile, the second stage of weight loss occurs at a temperature of about 600°C due to the decomposition of CaCO_3 . This weight loss demonstrates the similarity of other researchers stating that phenolic formaldehyde resin is a known polymer with maximum reaction rates occurring between 300° C and 600° C [12]. Ghosh et al. [10] stated that phenolic resin is thermally stable up to 300° C, after which it breaks down continuously and more than 350° C, will be severely damaged. The thermal decomposition of CaCO_3 has been investigated, respectively, from 675 to 800° C at 25 ° C intervals. The results show that it starts at a slow rate and quickly decomposes at more than 750° C. It is proven that the thermal decomposition of calcite starts at a slow rate of about 700°C [13].

Differential thermogravimetric (DTG) curves show peaks of degradation in all composites were similar, as shown in Figure 3. Glass powder 2%

and 4% showed a decrease in the composite's thermal stability, below the thermal stability of the composite with 0% glass powder. This is due to glass powder constituents other than silica, which affects the composite's thermal stability. XRF analysis of glass powder shows that glass powder contains other ingredients besides silica. It gives the characteristics of soda-lime glass compared to other glasses [14]. The soda-lime glass element affects the thermal stability of the composite. Thermogravimetric curves from other studies on the thermal behavior of soda-lime glass powders' showed a reduction in glass powder weight of about 5% starting from 235.6° C. The exothermic peak occurring at 425° C was recognized as the peak of phenolic resin decomposition [15]. The second peak at 760° C is indicated as the peak of carbonate decomposition [13]. Temperatures above 800° C indicate a reduction in the final weight for composites with a volume fraction of glass powder having a lower weight loss than for non-glass powder composites. This indicates that the presence of glass powder increases the thermal resistance of the composite. Composites with a glass powder volume fraction of 4% have the highest weight, while the lowest weight is found in composites with non-glass. Therefore, the presence of glass powder in friction composites increases the thermal stability of the composites.

3.3 Effect of contact pressure on coefficient of friction disc temperature.

Figure 4 shows the relationship between variations in contact pressure at constant sliding speed on the coefficient of friction and disc temperature. The slope of the line indicates an upward trend in the coefficient of friction. The coefficient of friction is determined from the frictional force on the contact surface, divided by the normal force. The normal force is a function of the contact pressure with the area of the specimen. Figure 4a shows the low friction coefficient at a sliding speed of 3 m/s. An increase in contact pressure does not provide an increase in the coefficient of friction. The friction of the metal disc with the composite material at low shear velocities is insufficient to erode the composite surface. The composite surface is slightly worn and does not form a large contact area. The small contact surface provides a low friction force so that the resulting friction coefficient is also low. The disk temperature growth due to friction at low speed increases slightly, as shown in Figure 4a.

Fig. 4 The coefficient of friction and disc temperature at various pressures with (a) low sliding speed (3m/s) and (b) high sliding speed (12m/s).

Figure 4b shows the coefficient of friction and the disc temperature concerning the increase in contact pressure at a high sliding speed of 12m/s. High sliding speed shows the friction coefficient increases at a contact pressure of 0.25 MPa to 0.5 MPa, then stabilizes at a contact pressure of 0.75 MPa and decreases at 1 MPa. The combination of increasing braking force at high sliding speeds results in rough deformation of the material, leading to debris formation. Some debris is blown out, and others are embedded in the contact surface. The debris undergoes compaction increasing the actual contact area [16].

The increase in the contact area increases the friction force, increasing the coefficient of friction. The disc temperature at a high sliding speed (12 m/s) increases with increasing contact pressure.

Furthermore, high heat affects the coefficient of friction decreases occurring at a contact pressure of 1 MPa. Shown that the high temperature of friction decreases the interfacial shear strength, a phenomenon called fading [17]. Fading is generally considered to be the main reason

behind the decrease in friction coefficient. The high heat growth at a pressure of 1 MPa and the high speed of the matrix material structure and accelerate the oxidation of the friction material [18], suggest that decomposition in the matrix leads to deformation at the actual contact surface, reducing the friction coefficient.

3.4 Effect of sliding speed on the friction of coefficient and disc temperature

Figure 5 shows the relationship between the shear velocity and the coefficient of friction at 0.25 MPa and 1 MPa. Figure 5a shows the coefficient of friction at low contact pressure (0.25MPa), almost unchanged and decreasing with increasing shear speed. Figure 5b shows the coefficient of friction at high pressure (1MPa), showing an increase in friction with increasing sliding speed. The coefficient of friction (μ) of all composites increased significantly at the shear velocities of 9 and 12 m/s—the temperature of the disc increases as the sliding speed increases. This is because the friction between the brake material and the disc generates heat. Figure 5 shows that the highest disc temperature due to friction is generated in the friction disc and the GP-4 specimen, followed by the Non-GP specimen and the lowest in the GP2 specimen. Facts show that the presence of glass powder increases the coefficient of friction, but the volume fraction of 4% GP generates higher heat, thereby lowering the coefficient of friction. The decrease in the coefficient of friction at high temperatures can be attributed to the increase in heat to the transition temperature of the polymer as a binder. The polymer transition temperature provides relaxation of the molecular chains, which decreases the bond strength of the matrix [19]. So the high heat causes fading, which reduces the shear strength between the contact surfaces.

Fig. 5 The coefficient of friction and disc temperature at various sliding speed with (a) low pressure (0.25MPa) and (b) high pressure (1MPa).

3.5 Effect of glass powder on the specific wear rate composite and hardness

Figure 6 shows the hardness of the composite specimen and the content of glass powder. The lowest hardness is seen in Non-GP composites, then GP 2 and GP 4 composites have the highest hardness. The specimen-specific wear rate of various specimens with glass powder, indicating that Non-GP has the highest wear rate, followed by GP 2, which is slightly lower, GP 4 has a much lower specific wear rate. Figure 6 shows the presence of glass powder which shows an increase in hardness and a decrease in the specific wear rate. The wear and hardness behavior of Figure 6 is linear with the classical Archard theory that the specific wear rate is related to the mechanical performance, structure, and adhesion performance of the material interface.

Fig. 6. Micrographs of worn surfaces of friction materials sliding speed at 12 m/s and contact pressure 1 MPa.

Wear is defined as an increase in material loss caused by the movement of an object and a substance in contact [20]. Shear on a rough contact surface produces wear particles, as a ratio between the wear volume and the deformation volume. During the sliding process, wear is determined by the extent to which the material resists the abrasion process, and the hardness of the material determines the abrasion process.

Theoretically, the Archard model shows that the wear value will decrease along with the material's greater hardness. So the presence of glass powder as an abrasive gives a different hardness. Polymer-based composite materials with low transition temperatures tend to experience adhesive wear [21]. When two materials come close to each other across a transition boundary, they will form a molecular bond. Some plastic deformation will occur when the frictional force exceeds the material's shear strength [22]. The plastic deformation of the soft material forms the bonds of the larger particles first. It then decomposes into several smaller particles so that the initial wear of the adhesive turns into abrasive. The higher the specimen hardness, the lower the abrasion wear and then the lower the wear volume. The lower the wear rate, the more friction material has a longer life in its application [23].

3.6 Worn surface of friction material

Figure 7 shows the severe wear occurring on the Non GP friction composites. Non GP composite surface showing grooves, ploughing and cracks indicating separation of material parts.

Fig. 7. Micrographs of of Non GP showing groove, plowing, and cracks.

During rubbing, the rough surface of the metal disk rubs against the surface of the composite specimen. The fact that the disc roughness penetrates soft material is called ploughing [24]. Its surface was torn, accompanied by debris that had appeared on the surface; this indicates that Non-GP composites have poor wear resistance. The normal force of the Non-GP composite specimen presses the surface of the rotating metal disk.

The two materials that are close together form a bonded surface and increase the shear strength. When friction continues and pressure increases, it generates heat [25]. The increase in heat to the transition temperature of the matrix causes plastic deformation of the composites. When the increased friction force exceeds the material's shear strength, causing the soft material to be pulled out, it transfers to the hard material, leaving a plough on the surface of the specimen. Ploughing of the material surface was identified as adhesion wear. Crack growth and release of wear particles caused by repeated loading [26]. Fatigue wear is closely related to the mechanical properties of the material. One way to increase friction materials' fatigue resistance is by adding friction-resistant materials [27].

Fig. 8. Worn surfaces showing plateau of GP 2 spesimen.

Figure 8 shows the friction area of the GP-2 composite specimen, which indicates a plateau. Continued friction and stress causes the matrix to wear out and results in debris. The contents of hard materials such as fibres and abrasive materials are exposed to form plateaus [28].

The presence of powdered glass increases the surface hardness of the specimen. The glass powder becomes the leading load carrier when the matrix wears out. Small cracks indicate increased bearing capacity on the contact surface to withstand frictional forces. Figure 8 shows that the GP 2 composite experienced improvement with small surface ploughing and cracks on the wear surface compared to the Non-GP composite.

Fig. 9. Micrographs of worn surfaces of GP 4 specimen.

Figure 9 shows the surface wear of the GP 4 specimen, and it can be seen that a reduction in cracks and plateaus are formed spread across the wear surface. The primary contact plateau by the hard material constituent of the friction composites [29]. The combination of contact pressure and frictional heat and wear debris accumulating around the primary plateau can form a new plateau that increase the actual contact area [21,30]. The formation of a plateau spreading over the contact surface indicates an increase in the contact surface area. The presented of glass powder as abrasive provides the effect of increasing mechanical strength on the friction surface. The mechanical strength of the composites is increased, thereby reducing the wear rate of the composites [31].

4. CONCLUSION

A systematic study was carried out to investigate glass powder waste's potential as a sustainable abrasive for composite brake blocks. Glass powder has a high silica dioxide content; it provides an opportunity as a sustainable abrasive, replaces pure silica, and reduces the environmental impact of glass waste. Thermal

behavior and tribological characteristics of composite brake blocks to determine the performance of glass powder as an abrasive.

- XRF analysis of the elemental composition of glass waste shows glass powder has a high silica dioxide content.
- The thermal stability of composites with glass powder increase with increasing content of glass powder (GP)
- Glass powder-modified abrasive composite brake blocks had an increased coefficient of friction and higher wear resistance than Non-GP brake blocks
- The coefficient of friction GP 2 increases compared to the coefficient of friction GP 4. The highest friction temperature is seen in the GP 4 composite, which has a range of fading properties.
- Glass powder (GP) as an abrasive is proven to increase the brake friction material's friction coefficient. The presence of glass powder increases the hardness and decreases the composite's specific wear rate.

Acknowledgement

The authors wish to thank the Ministry of Research and Technology (National Agency for Research and Innovation) Republic of Indonesia for supporting and funding research through the Research Grant No. 112/UNS27.21/HK/2020.

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