Laboratory study of a lignocellulosic biomass as an alternative base material for brake pads

Abstract

This research work assesses the possibility of using sawdust as a base material for the production of light load brake pad by studying the physical, mechanical and microstructural properties of the developed sawdust-based pads. Different proportions of sawdust, slag waste dust, silicon carbide, epoxy resin, and graphite were used to form the polymeric matrix composites as eco-friendly brake pads. Compressive strength, hardness, wear, flame resistance, porosity, density and water absorption of the brake pads were investigated. Clustered particulates of sawdust were formed in the brake pad as the weight percentage of sawdust exceeded 40 owing to the low molecular weight and particle-to-particle cohesive ability of wood dust. The increase in the particle size of sawdust has an inverse relationship with the hardness value and the wear rate of the developed brake pad. Silicon carbide directly improves the hardness value, the wear rate and the strength of the brake pad. The compressive strength of the brake pad is impeded as the weight percentage of sawdust is increased. An optimum strength of about 126 kPa was achieved with the particle size of 100 μm. The total ash content of the brake pad has a direct correlation with the weight percentage of sawdust.

Keywords: Brake pad; sawdust; slag waste dust, silicon carbide; mechanical properties; physical properties; microstructure

1. Introduction

The rapid deceleration and immobility of mechanical devices or vehicles require friction composites with desirable properties such as low weight, low wear rate, moderate friction coefficient, high heat resistance, no vibration and unpleasant noise under different operating conditions [1] [2] [3]. Friction materials/composites are used in the development of brake pads. These composites are polymeric mixtures of different materials classified into four key classes which are binder resins, reinforcing fibers, space fillers and friction modifiers respectively [1] [4]. These materials are used to facilitate binding, provide reinforcement to withstand loading, enhance friction, to make up the volume (matrix) of the pad and to reduce cost [2]. Non-absestos organic (NOA) based brake pads are presently encouraged to eliminate

health issues (like asbestosis and mesothelioma) arising from the usage of asbestos brake pads.

Eco-friendly, inexpensive, readily available and non-toxic wastes have been deemed as suitable alternatives to carcinogenic asbestos fiber in brake pad production. Among the existing eco-friendly materials that have been used in the development of brake pads include waste corn stalk [1], chitin [5], palm kernel fibers (PKFs) [6], banana peels [7], palm slag [8], wood tannin extract [9], periwinkle shell particles [10], lapinus-aramid [11], and palm kernel shell (PKS) [12]. The granular nature and the low specific gravity of sawdust have made it suitable for the production of brake pad. Thus, the investigation of sawdust embedded polymeric mixture as a brake pad/composite for light load braking system is vital in order to widen the application areas of sawdust.

Sawdust (wood dust) is a lignocellulosic biomass material and a bulking agent (in the field of composite science) that is not easily deteriorated but rather remains stable/recalcitrant in the environment and it seldom produces odor during its long-term biodegradation process [13][14][15][16]. It is the unavoidable tiny-sized and powdery wood waste (byproduct) produced due to the sawing/cutting, grinding, drilling, sanding or other pulverizing actions of woods. The volumes and particle size of sawdust are greatly dependent on the thickness of the timber (to be sawn) and the average width of the saw kern or teeth [17][18][19]. Approximately 10-13% of the total volume of the wood log is reduced to sawdust in the milling/sawing operations of wood [18]. The percentage of hollocellulose in residual sawdust decreased while the extractives in it increased [13].

Literature has shown diverse application of sawdust in the production of charcoal briquettes, particle-board, and wood pulp, and to soak up liquid spills. For instance, Ahmed et al. [20] produced eco-friendly and thermal efficient normal and lightweight concretes with altered amounts of sawdust as replacement of sand. Alidadi et al. [21] examined tetracycline removal using sawdust modified with different agents. Chen et al. [22] showed that modified sawdust demonstrated excellent adsorption properties for contaminants such as resins and metallic particles under different adsorption conditions. Xu et al. [23] conducted oxidative degradation of the extraction residue from a sawdust with aqueous hydrogen peroxide (AHPO)/acetic anhydride (AAH) under mild conditions. It was reported that the molecular composition of macromolecular species in the sawdust was complicated. Krishna et al. [24] studied the effect of resin filler ratio on the physical and mechanical properties of epoxy resin

hybrid composites reinforced with fly ash and sawdust. It was revealed that the increase in the filler quantity to the mixture decreased the physical and mechanical properties of the hybrid composite owing to the reduced epoxy polymer content.

This paper focuses on the use of sawdust (wood dust) as a major constituent in the production of a polymeric composite or light load brake pad. Slag waste dust, silicon carbide, epoxy resin, and graphite were mixed at varying weight percentages with that of sawdust to produce the polymeric composite. The developed brake pads were subjected to hardness, wear rate, compressive strength, ash content, porosity, and density tests. The distribution of the constituents of the brake pad/composite was viewed under an optical microscope.

2. Materials and procedural methods

The materials employed for the production of the brake pad include sawdust, slag waste, epoxy resin, silicon carbide, and graphite. With a perspective of managing wood waste, sawdust was chosen as the base material for this research. Fig.1 shows samples of these materials. The sawdust, epoxy resin, slag waste dust, silicon carbide, and graphite were used as a filler, a binder, a reinforcing material (to produce mechanical strength), an abrasive material (to increase the coefficient of friction) and a lubricant (to stabilize the coefficient of friction) respectively. These components were weighed on a digital weighing balance for sample formulations and mixed together according to Table 1 to form brake pad composites. The percentage weights of sawdust (35 – 55 wt%) and silicon carbide (5 – 25 wt%) were varied while that of other additives (graphite, epoxy resin, and slag dust) were kept constant. In addition, the particle sizes of the sawdust were varied between 100 µm and 350 µm. The homogeneously mixed formulation was put inside cylindrical containers and compacted using a manually operated hydraulic press to obtain fifteen test samples (see Fig.2a). Afterward, the material composites were placed in a mild steel mold (see Fig.2b) shaped like a pathfinder jeep's brake pad and were subsequently compressed via a hydraulic press. The ejected brake pad (see Fig.2c) from the mold was covered for about 18 hours to allow slow curing process at room temperature (27°C). The brake pads were then sintered to ensure effective curing by putting them under a controlled temperature of about 150^{0}C for 3 hours in an oven.

Fig.1. Material samples (a) sieved sawdust (100µm), (b) Carbon black, (c) slag dust/waste

Table 1. Mixture formulation/proportion of the brake pad (wt%)

S/N	Ingredients	A	B	C	D	E
1	Sawdust	35	40	45	50	55
2	Graphite(carbon black)	10	10	10	10	10
3	Epoxy Resin	13	13	13	13	13
4	Slag Dust(steel dust)	17	17	17	17	17
5	Silicon Carbide	25	20	15	10	5
6	TOTAL	100	100	100	100	100

Fig.2. Composite samples and mold (a) test samples, (b) mild steel mold, (c) brake pad samples

2.1 Microstructure

The microstructural analyses of the brake pad samples were carried out by grinding the samples using 300, 400, and 600 grit papers respectively. Dry polishing was then carried out on the samples and the structures of the pads were viewed under an optical microscope.

2.2 Hardness

The resistance of the composites to indentation was carried out by employing Brinell hardness testing according to ASTM specifications. A 10 mm diameter (D) steel ball and 30000 N load (P) were used for the hardness test. The diameter of the indentation (d) on the brake pad sample was measured along two perpendicular directions, using an optical micrometer screw gauge. The mean value was taken and incorporated into equation 1 to obtain the Brinell hardness value (BHN).

$$\text{BH} = \frac{2P}{\pi D(D-\sqrt{D^2-d^2})} \qquad (1)$$

2.3 Wear rate

The wear rates for the samples were measured using a pin on disc machine by sliding it over a cast iron surface at applied loads of 10 and 20 N, sliding speeds of 125 and 250 rev/min, and sliding distances of 2000 and 4000 m. All tests were conducted at room temperature. The initial weight of the samples was measured using a single pan electronic weighing machine with an accuracy of 0.01g. During the test, the pin was pressed against the counterpart rotating against a cast iron disc (hardness 65 HRC) of the counter surface roughness of 0.3 µm by applying the loads. A friction detecting arm connected to a strain gauge held and loaded the pin samples vertically into the rotating hardened cast iron disc. After running through a fixed sliding distance, the samples were removed, cleaned with acetone, dried, and weighed to determine the weight loss due to wear. The differences in weight measured before and after tests give the wear of the samples. The formula used to convert the weight loss into wear rate is given as equation 2. Where ΔW is the weight difference of the sample before and after the test in mg, S is the total sliding distance in m.

$$\text{Wear rate} = \frac{\Delta W}{S} \qquad (2)$$

2.4 Compressive strength test

The compressive strength test was carried out by using the Tensometric Machine. The sample of diameter 29.40 mm was subjected to compressive force, loaded continuously until failure occurred. The load at which failure occurred was then recorded as the compressive strength of the sample.

2.5 Ash content test

About 1.20g ± 0.1g of the brake pad samples was weighed in a cooled crucible, oven dried by heating in a furnace at 550°C for 1 hour and reweighed. Subsequently, the samples were charred by heating in a hot plate. Thereafter, the charred samples were taken into the furnace and heated at 550°C for 1 hour then cooled in a desiccant and reweighed. This process of heating, cooling and reweighing was repeated until a constant weight was obtained. The ash content of the brake pad was computed by using equation 3. Where W_0 is the weight of the empty crucible, W_1 is the weight of the crucible and brake pad sample, and W_2 is the weight of the crucible and the residue after cooling.

$$\% \text{ ash} = \frac{w_2 - w_0}{w_1 - w_0} \times 100 \qquad (3)$$

2.6 Porosity

A sample with a diameter of 29.40 mm and a height of 15 mm was used for the porosity test. The specimens were weighed to the nearest mg and then soaked in oil and water container at 90°C-100°C for 8 hrs. The samples were left for 24hrs and then taken out from the oil container. Subsequently, the test samples were weighed to the nearest mg. The resulting porosity of the brake pad was estimated by using equation 4. Where D is the density of test oil and water, M_2 is the mass of test piece after absorbing oil and water (g), M_1 is the mass of test piece/brake pad (g) and V is the volume of test piece/brake pad (cm^3).

$$\text{Porosity } (\rho) = \frac{M_2 - M_1}{DV} \times 100\% \qquad (4)$$

2.7 Density test

The true density of the samples (brake pads) was determined by weighing the samples (mass) on a digital weighing machine and divided by measuring their volume by liquid displacement method. The density of the brake pad samples was determined via equation 5. Where, M is the mass of the test piece/brake pad (g) and V is the measuring volume of the test piece/brake pad (cm^3) by liquid displacement method.

$$\text{Density } (\rho) = \frac{M}{V} \times 1 \qquad (5)$$

3. Results and discussion

3.1 Microstructure

Fig.3 shows the optical micrographs of different compositions/formulations of the developed brake pads. The dark regions on the micrographs represent evenly dispersed graphite (carbon black) contents within the composite matrices. The brownish or lighter regions on the micrographs show the dispersion levels of the milled sawdust within the composite.

However, it is difficult to visually identify the other reinforcing components (slag/steel dust and silicon carbide) of the brake pad in Fig.3.

Homogeneous dispersion of sawdust within the composite is observed at weight percentages of 35 (formulation A) and 40 (formulation B) respectively. Agglomerations or brownish clusters of sawdust are revealed in Figs.3c-3e. This shows that clustering of sawdust within the matrices of the composites ensues as the percentage weight of sawdust is increased beyond 40 wt%. Thus, it could be inferred that as the wt% of sawdust is increased beyond 40, the milled particle sizes of the sawdust could fuse together owing to increased volume size and particle-to-particle cohesion/sticking. This particle-particle stickiness (cohesion property) of the sawdust powder can be attributed to the low molecular weight of the sawdust. The internal/cohesive force held up the sawdust particles to form lumps of varying sizes as the wt% of sawdust is increased (see Fig.3) during mixing. Mechanical interlocking (such as intermolecular and electrostatic forces), mobile/immobile liquid bridges and solid bridges [25] have been reported to cause inter-particle stickiness of this nature. Stasiak et al [26] reported that the flow index of sawdust was the characteristic for cohesive/easy flowing materials, and a strong correlation was affirmed to exist between cohesion and consolidation stress. Thus, inevitable cohesion-adhesion property exists between sawdust particles and this consequently results to agglomeration or sawdust lumping within the matrix of the developed brake pad (see Fig.3).

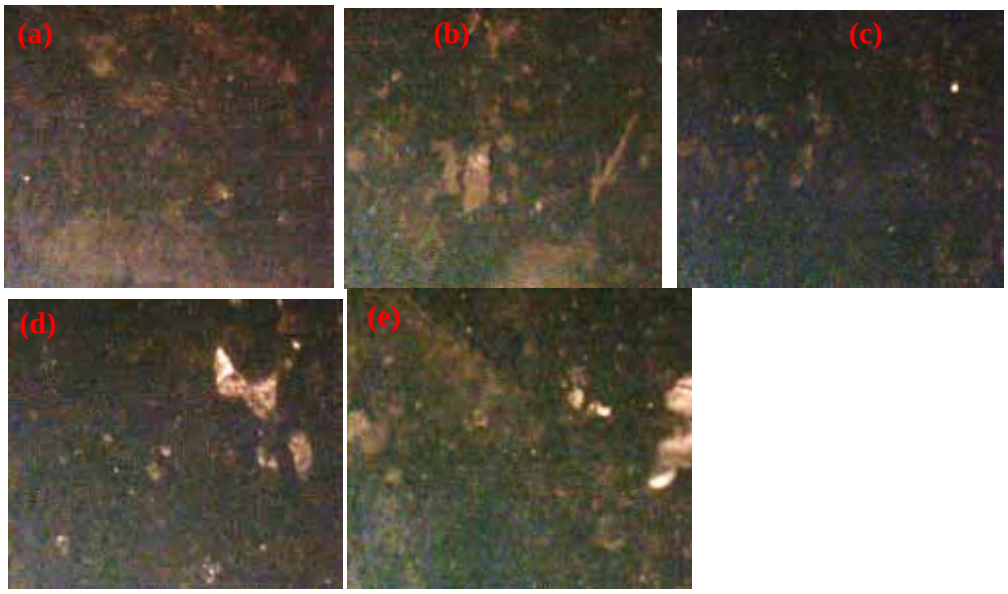


Fig.3. Optical micrographs of the brake pad produced at particle size (sawdust) of 200 µm (a) formulation "A", (b) formulation "B", (c) formulation "C", (d) formulation "D", (e) formulation "E"

The composition analysis of sawdust particles has been shown to consist of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O and MnO [19]. Xu et al. [27] reported that the molecular composition of macromolecular species in the sawdust is complicated. The compositional influence of the sawdust on the developed brake pad cannot be ascertained.

3.2 Hardness

Fig.4 reveals the effects of particle size, weight percentages of silicon carbide and sawdust on the hardness behavior of the developed brake pads. The results showed that the hardness values of the sawdust sieve grade of 100µm were higher than those of 200µm and 350µm. This implies that the lower the sieve size, the higher the hardness values. This observation agrees with the literature results [28][29][30] as the average grain size is affirmed to support grain-boundary strengthening and improved hardness value. Reduced grain sizes increase the grain boundaries within the matrix of the composite. Thus, the grain boundaries act as pinning points that impede dislocation propagation during the indentation process (hard test). As a result, an increase in particle sizes of sawdust from 100 µm to 350 µm has an inverse relationship with the hardness (see Fig.4a) irrespective of the formulation/compositions of the composite/brake pad. The emergence of the best hardness result at a particle size of 100 µm could as well be attributed to efficient bonding or interlocking of sawdust particle within the matrix of the composite.

The wt% of sawdust has an inverse relationship with the hardness value of the developed brake pad (see Fig.4b). This occurrence can be attributed to the increase in the volume fraction of sawdust present in the matrix of the developed composite. Agglomeration of sawdust has been revealed to ensue as the wt% of sawdust increases (see Fig.3) and this occurrence can be adjudged to impede bonding and eventually the resistance of the composite to indentation as revealed in Fig.4b. On the other hand, increase in the wt% of silicon carbide has a linear effect on the hardness of the brake pad as shown in Fig.4c. Silicon carbide is generally known to have properties such as high hardness, wear resistance and strength. The increase in the composition of silicon carbide is expected to improve the hardness values of the developed brake pad and this is validated in Fig.4c.

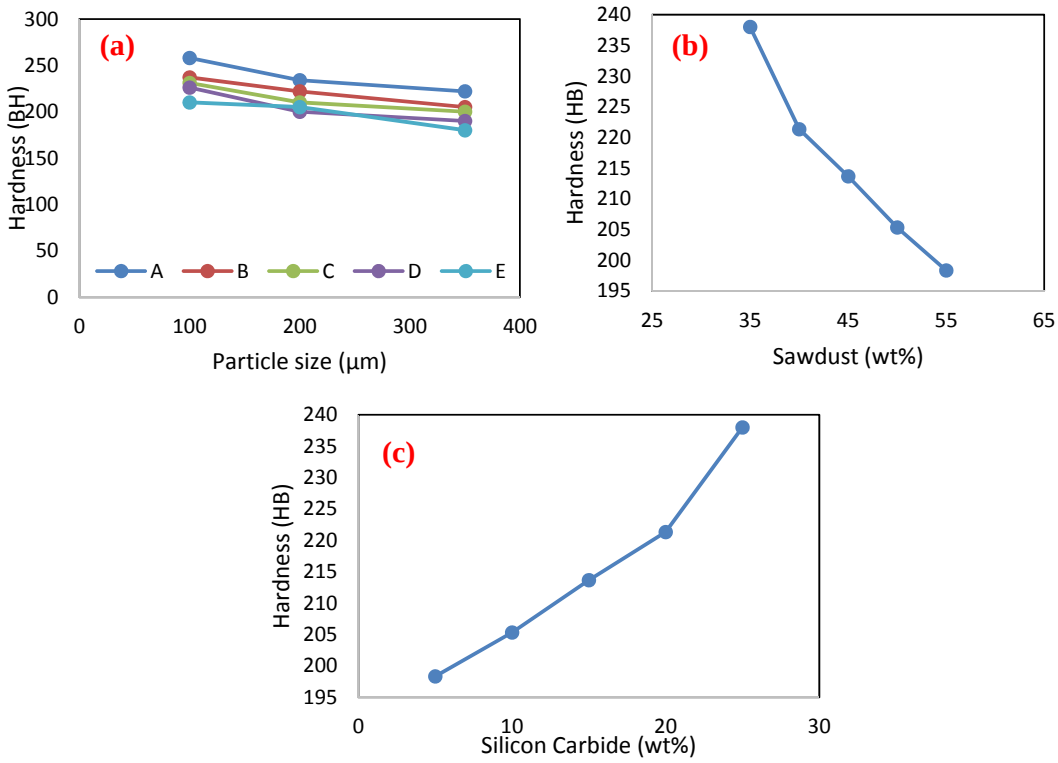


Fig.4. Hardness results as a function of (a) particle size, (b) wt% of sawdust, (c) wt% of silicon carbide

3.3 Wear Rate

The mechanical abrasion resistance of sawdust is expected to be low owing to its degradable nature. The wear rate test results indicated that the wear rate for 100µm sieve size is lower than that of 200 µm and 350 µm sieve sizes which is a good result for the properties of the brake pads. Increase in particle size directly increases the wear rate of the developed brake pads as revealed in Fig.5. However, the applied load has a dominant impact on wear rate while the rotational speed on the brake pad (during the wear test) has a slight impact on the wear rate. Wear rate increased from 2.215 g/km to about 3.905 g/km as the load is increased from 1 kg to 2 kg under the same conditions (exposure time of 30 min and the rotational speed of 125 rev/min).

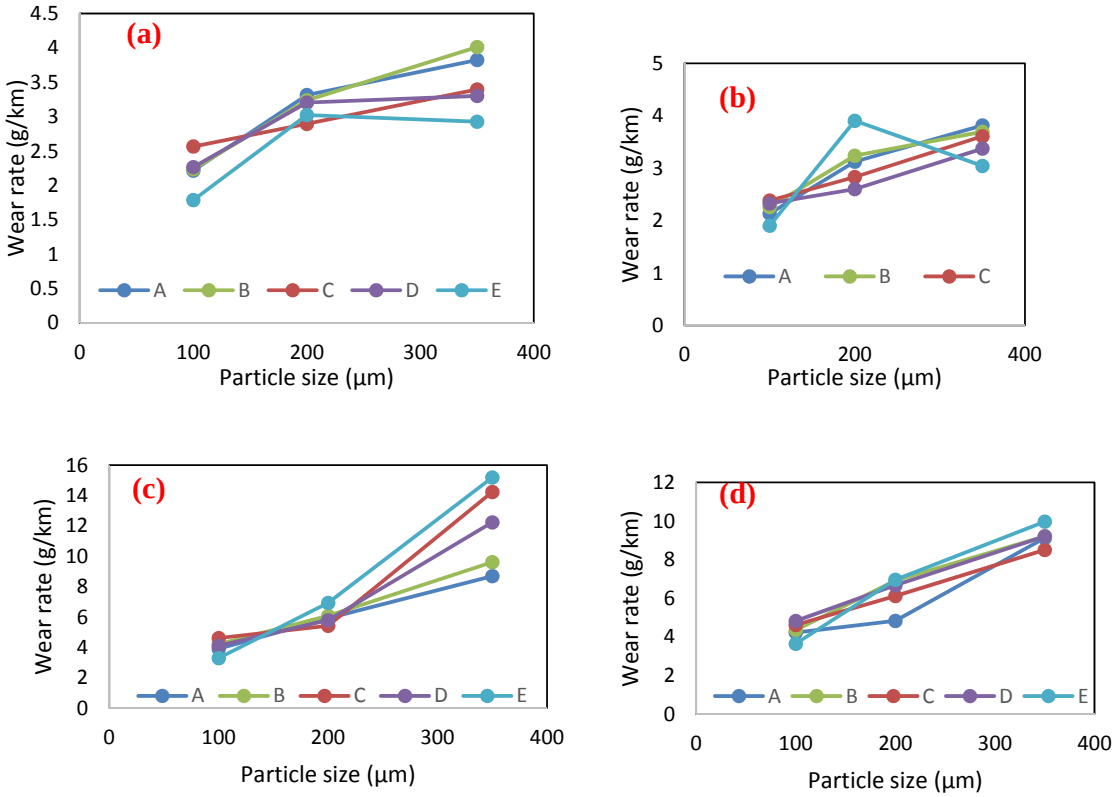


Fig.5. Wear rate at 30 min and at different loads and rev/min (a) 1 kg and 125 rev/min, (b) 1 kg and 250 rev/min, (c) 2 kg and 125 rev/min, (d) 2 kg and 250 rev/min

Fig.6a shows that increase in the wt% of sawdust has a negative impact on the wear rate of the brake pad. Increase in the wt% of sawdust directly increases the degradability of the brake pad due to the easy degradable nature of sawdust. The wt% of silicon carbide and the wear rate of the pad are directly related as shown in Fig.6b. Silicon carbide has high wear, hardness, and thermal shock resistance, and this is adjudged to have influenced the wear rate of the developed brake pad in Fig.6b. The low thermal expansion and high thermal conductivity of silicon carbide are viewed to be beneficial to the observed wear rate. Rigidity at elevated temperature (due to friction and abrasion effect on the brake pad) is expected to be attained during the wear test as a result of the presence of silicon carbide in the matrix of the brake pad. This is beneficial to the wear resistance of developed brake pad.

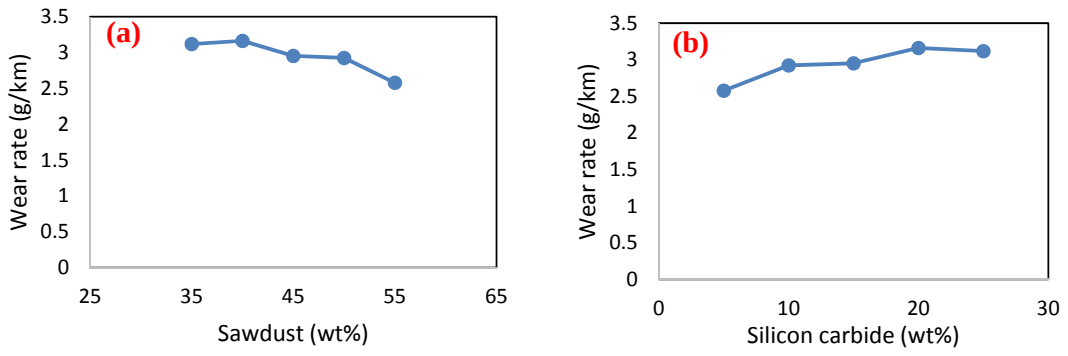


Fig.6. Effects of weight percentages on wear rate (a) sawdust, (b) silicon carbide

3.4 Compressive strength

Fig.7a reveals that an increase in the particle size of the sawdust negatively impacts the resistance of the developed brake pads to compressive loading. The particle size of 100 µm produced the optimum compressive strength of about 126 kPa as compared to that 200 µm and 350 µm particle sizes. A progressive increase in the amount of sawdust in the composite has been reported to cause an increase in the interfacial area with worsening interfacial bonding within the composite's matrix [31]. As a result, a drop in strength ensue owing to the agglomeration of sawdust (in the composite). In fact, the agglomeration of filler such as sawdust was revealed to promote improper curing of composite and this caused a decline in the tensile strength of such composite. Equally, fillers such as sawdust constitute defects (due to agglomeration) in composites at higher mass fraction owing to the lack/insufficient of resin required to wet their surfaces. This consequently results in weakened composite adhesion, inept stress transfer and affected tensile/compressive behavior [31]. Consequently, increase in the wt% of sawdust directly impedes the compressive strength of the brake pad (see Fig.7b) while increment in the wt% of silicon carbide improves the compressive strength of the brake pads (see Fig.7c) owing to the increase in the volume fraction of silicon carbide. Silicon carbide is known to exhibit high strength at both room and high temperatures. This unique attribute of silicon carbide is adjudged to have improved the compressive strength of the developed composite as the wt% of silicon carbide was increased.

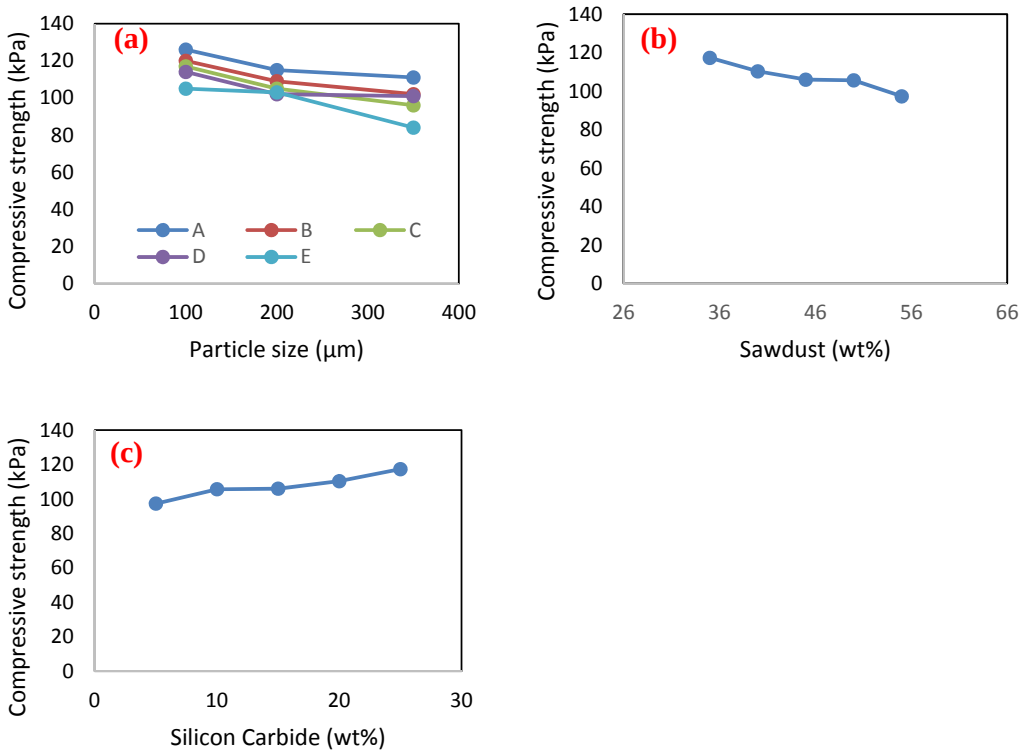


Fig.7. Correlation of compressive strength with (a) particle size, (b) wt% of sawdust, (c) wt% of silicon carbide

3.5 Ash Content

The results of the ash content revealed that 100 µm sieve grades of the brake pad had slightly lowered ash content values as compared to the other grade sizes. The ash content of the brake pad is revealed to increase with the particle size (Fig.8a) and the wt% of the sawdust (Fig.8b). The thermal combustion ability of biomasses such as sawdust largely increases the intrinsic total ash content of the biomasses. This occurrence is affirmed in Fig.8b. The total ash content of the developed brake pad has a direct correlation with the wt% of sawdust. On the other hand, increase in the wt% of silicon carbide reduces the ash content of the brake pad (see Fig.8c) due to the thermal properties of silicon carbide. Silicon carbide exhibits high melting temperature and low thermal conductivity. These properties indicate that the total ash content associated with silicon carbide will be lowered during the ash content test.

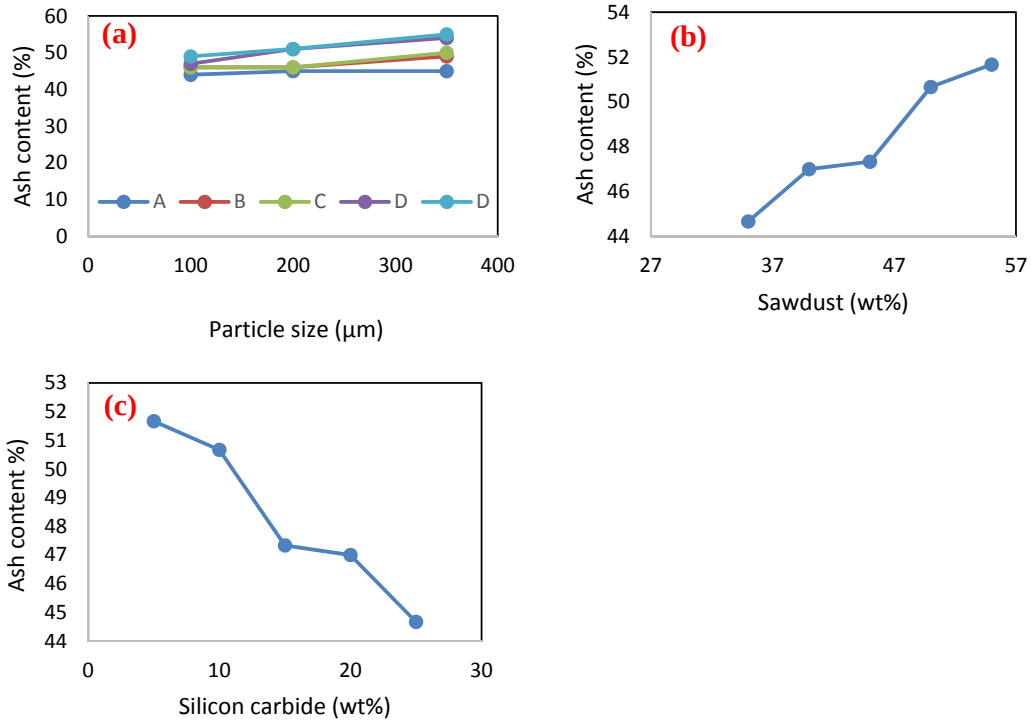
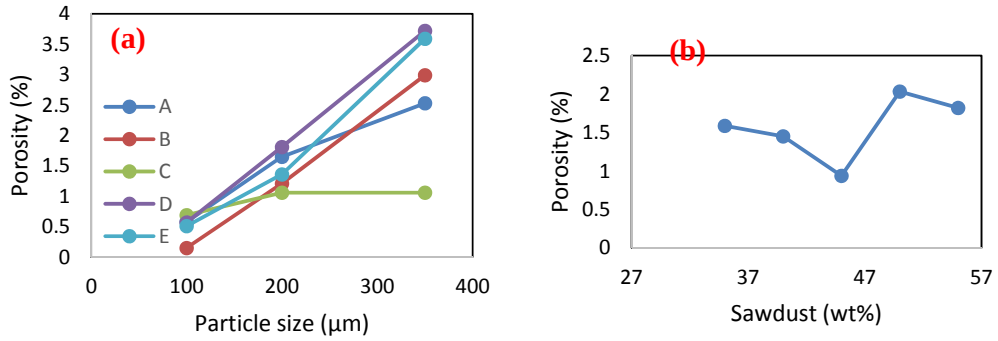


Fig.8. Relationship between ash content and (a) particle size, (b) wt% of sawdust, (c) wt% of silicon carbide

3.6 Porosity Test

The porosity of the brake pad increases with an increase in the grade sizes or particle sizes of the brake pad as shown in Fig.9a. The erratic behavior of the porosity values in the brake pad is difficult to analyze as both the wt% of silicon carbide and sawdust are increased.



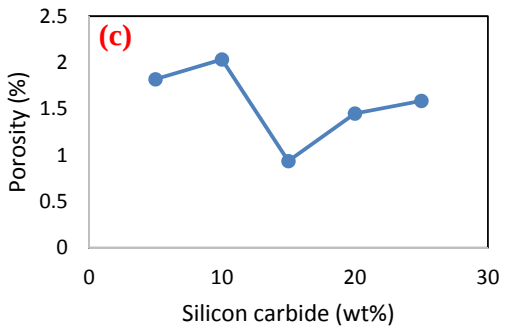
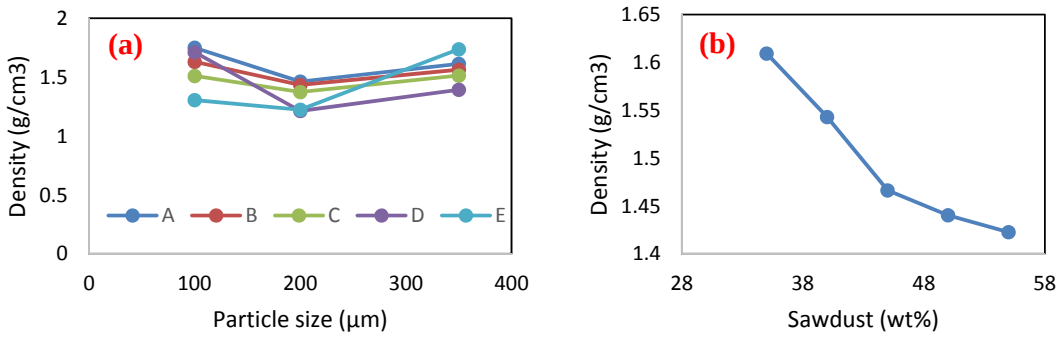


Fig.9. Relationship between porosity of brake pad and (a) particle size, (b) wt% of sawdust, (c) wt% of silicon carbide

3.7 Density Test

Although the density of the produced brake pads is low compared with similar ones produced from asbestos fibre, the density of the 100 µm sieve grade is slightly more than that of 200 µm and 350 µm sieve grades (see Fig.10a). Increase in wt% of the sawdust has a declining effect on the density of the brake pad (see Fig.10b) while an increase in the wt% of silicon carbide directly increases the density of the brake pads (see Fig.10c).

The increase in the density of the sawdust due to increase the wt% of sawdust can be attributed to the dimension of particles, their shape, and homogeneity [26]. Likewise, denser packing of wet sawdust in the matrix of the composite owing to the lubricating action of resin could have caused the slight increase in density (see Fig. 10). This agrees with the works of Stasiak et al. [26] as particle distribution and higher value of the density of sawdust was noted in sawdust with higher moisture.



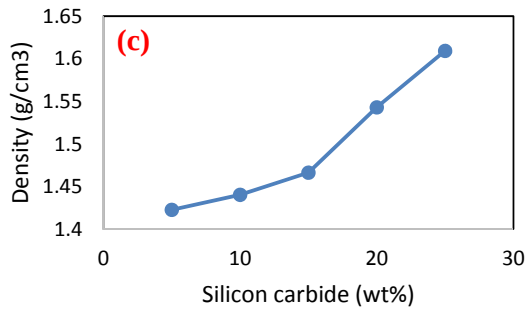


Fig.10. Relationship between density of brake pad and (a) particle size, (b) wt% of sawdust, (c) wt% of silicon carbide

3.8 Comparison of sawdust based brake pads with other organic based brake pads

Table 2 is adapted from the work of Ishola et al. [12] as a detailed tabular comparison of brake pads was provided. The comparisons of physical, mechanical and microstructural properties of the developed brake pad with other existing brake pads available in the literature are shown in Table 2.

The developed brake pad has the highest charred ash content (46%) as compared to other brake pads. This implies that the brake pad will be suitable for light load braking system in order to prevent burn out under continuous severe actions. On the other hand, the developed brake pad compares satisfactorily well with other brake pads in Table 2

Table 2: Comparison of the developed brake pads with other brake pads

Type of brake pads	**Grain size** (µm)	**Specific gravity (g/cm^3)**	**Brinell hardness** (BHN)	**Compressive strength (N/mm^2)**	**Wear rate** (%) mg/m	**Water absorption rate** (%)	**Ash content (%)**
Sawdust based BP	100	1.751	258	126	2.215	0.58	Charred ash 40%
	200	1.463	234	115	3.315	1.65	Charred ash 45%
	350	1.614	222	111	3.825	2.53	Charred ash 46%
	100	1.51	269	131	1.684	0.11	Charred ash 40%
PKS based BP [12]	200	1.46	245	125	2.497	1.00	Charred ash 42%

	350	1.61	233	121	2.825	2.42	Charred ash 43%
PKS based BP [7]	-	1.65	92.0	103.5	4.40	5.03	Charred ash 46%
Bagasse based BP [32]	-	1.43	100.50	105.60	4.20	3.48	Charred ash 34%
Palm kernel fibre based BP [6]	-	1.7-2.1	5.6-21h	-	3.62-9.21	1.02-1.04	-
Cow hooves and bagasse based BP [33]	-	-	97.34	107.02	3.80	3.00	Charred ash 41%
Banana peels based BP [7]	-	1.20	71.6	61.20	4.67	3.0	Charred ash 12%
Commercial (asbestos based) BP [34]	-	1.89	101	110	3.8	0.90	Charred ash 9%

Note: BP- Brake pad

4. CONCLUSION

An eco-friendly brake pad was successfully produced with readily available materials such as sawdust, as a base material, and other additives such as graphite, epoxy resin, slag dust, and silicon carbide. The overall performance of the newly produced brake pad shows that the developed brake pad is suitable for the light load braking system. The following conclusions were drawn from this research work:

1. Agglomeration or clustering of sawdust within the matrices of the developed brake pad ensues as the percentage weight of sawdust is increased beyond 40 wt%. The increased volume size, particle-to-particle cohesion and low molecular weight of sawdust have been attributed to promoting the observed defect or wood dust agglomeration.
2. An increase in the particle size of sawdust from 100 µm to 350 µm has an inverse relationship with the hardness value of the developed brake pad while an increase in the wt% of silicon carbide linearly improves the hardness of the brake pad.
3. An increase in particle size (100 -350 µm) of sawdust directly increases the wear rate of the developed brake pads. Increase in the wt% of sawdust directly increases the degradability/wear rate of the brake pad due to the easy degradable nature of sawdust. The presence of increased wt% of silicon carbide in the matrix of the brake pad improves wear resistance.

4. The particle size of 100 μm produced the optimum compressive strength of about 126 kPa as compared to that 200 μm and 350 μm particle sizes. An increase in the wt% of sawdust directly impedes the compressive strength of the brake pad while increment in the wt% of silicon carbide improves the compressive strength of the brake pads.
5. The total ash content of the developed brake pad has a direct correlation with the wt% of sawdust. The ash content of the brake pad increases with the particle size and the wt% of the sawdust.
6. The porosity of the brake pad increases with an increase in the particle sizes of the brake pad.
7. Increase in wt% of the sawdust has a declining effect on the density of the brake while an increase in the wt% of silicon carbide directly increases the density of the brake pads.
8. A lignocellulosic biomass such as wood dust/sawdust has proven to be a suitable alternative base material for the development of brake pads owing to the relative compressive strength of the developed pads with fine particles. The brake pads have high susceptibility to burn out due to its high ash content and this confines its suitability to only light load braking systems.

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