

Development of Ecofriendly Automobile Brake Pad Using Different Grade Sizes of Palm Kernel Shell Powder

Abstract:

Serious health repercussions/risks such as asbestosis and mesothelioma have engendered automakers to earnestly consider the use of non-asbestos organic (NAO) brake pads in contemporary manufacturing. On this account, sustainable agro waste with higher heating value compared to other lignocellulosic biomass is considered as a better alternative to asbestos. As a result, palm kernel shell (PKS) is chosen and employed as a friction lining material for the designed NAO-based brake pad. The friction material was based on a simple formulation with five ingredients; PKS as base material while phenolic resin, steel slag, iron waste and carbon black were other additives. Mixtures of these constituents were obtained at varying compositions by using PKS of grade sizes 100 μm , 200 μm and 350 μm respectively. A mild steel mould shaped like that of a Pathfinder Jeep's brake pad was fabricated for compacting the formed composite. The produced samples were subjected to tests such as hardness, compressive strength, wear, flame resistance, porosity, density and water absorption tests. The results affirm that grain size has substantial effects on compressive strength, hardness, porosity, ash content and wear rate of the brake pad. 100 μm grain sizes of PKS produced the optimum brake pad. Thus, the results show that PKS can be efficiently used for asbestos replacement in brake pad production.

Keywords: Palm kernel shell; Brake pad; Phenolic resin; Hardness; Wear rate

1. Introduction

One of the indispensable components of a braking system is the brake pad. Brake pads are essential for smooth retardation or speed control and eventual stoppage of a vehicle on the application of pressure to the vehicle's brake pedal. In reality, brake pads facilitate the conversion of kinetic energy of a vehicle to thermal energy by friction [1]; and the effectiveness of brakes and performance of brake pads are exclusively dependent on the frictional material used in the production of the brake pads [2, 3]. However, contemporary brake pads are known to be polymer matrix composites due to the presence of several macroscopic and microscopic constituents in them [4-6]. The blend of these constituents to form a suitable formulation is carried out in order to obtain brake pads with good synergetic attributes such as

prolonged life, improved wear rate, water resistance and increased strength at a wide range of operating conditions [3]. Thus, frictional material selection and development are still ongoing areas of research in improving brake pad. As a result, this work focuses on the use of palm kernel shell (PKS) in developing brake pads as well as its grain/particle size effect on mechanical properties and wear rate.

Although, there are existing frictional materials that have been employed in developing brake pads; but works on the formulation and development of brake pads are continuous/unending owing to customers' demands, different braking requirements for vehicles and applications. However, copper based brake pads are not encouraged due to the deleterious impact of copper on aquatic life. Likewise, asbestos fibers embedded in a polymeric matrix with other constituents to form brake pads are to be avoided due to the carcinogenic nature of asbestos [7]. Asbestos based brake pads could cause health risks such as asbestosis and mesothelioma in human. As a result, non-asbestos heterogeneous frictional materials are being explored for the production of brake pads.

Considering environmental acceptability, commercial viability, sustainability, and cost, agricultural residual or wastes have emerged as alternative materials for the production of brake pad. For instance, K. K. Ikpambese et al. [8] studied the use of palm kernel fibers (PKFs) in the production of asbestos-free brake pads. Their results revealed that PKF can be effectively utilized as a replacement for asbestos in brake pad production. Likewise, U. D. Idris et al. [7] utilized banana peels in manufacturing eco-friendly asbestos-free brake pad. Compressive strength, hardness and specific gravity of produced brake pads were affirmed to increase with an increase in wt% resin. Also, Palm slag was utilized as fillers in developing asbestos-free brake pads by C. M. Ruzaidi et al. [9]. However, it was revealed that processing compression load or compactness of the palm slag brake pad compound/composite influenced the wear and mechanical properties of the developed brake pads. M.C. Lagel et al. [10] developed greener brake pads made from wood tannin extract and it was affirmed that the developed brake pad was more efficient during an emergency braking than those of commercial brake pads. Other frictional filler materials have been utilized in the formulation of brake pads. Periwinkle shell particles and lapinus-aramid have been successfully employed by D.S. Yawas et al. [11] and T. Singh and A. Patnaik [12] in developing eco-friendly brake pads.

61 In the selection of appropriate frictional material for the development of brake pad, moisture or water
62 retention ability and heating value are critical considerations. On this account, palm kernel shell (PKS),
63 otherwise known as shell fraction of palm nut/fruit is chosen due to its low water retention ability and
64 high heating value compared to other lignocellulosic biomasses or fibers. It has low moisture content of
65 about 11-13% (that is >80% dry matter) compared to other biomass residues [13]. In fact, PKS generates
66 low ash quantity and the presence of low K and Cl content in it facilitates less ash agglomeration [14].
67 Thus, the danger of outgassing or decomposition of the base material at high temperature is expected to be
68 considerably reduced in PKS based brake pad compared to other organic biomass-based brake pads. As a
69 result, five constituents such as PKS, phenolic resin, steel slag, iron waste and carbon black are employed
70 in the development of a PKS based brake pad. The grain/particle sizes of PKS are altered in order to
71 identify the role of grain sizes on the mechanical properties and wear behavior of the developed brake
72 pads. Hardness, compressive strength, wear rate, flame resistance, porosity, density, and water absorption
73 tests are employed in characterizing the PKS based brake pads.

74

75 **2. Materials and Method**

76 The materials used for the formulation of the non-asbestos organic based brake pad are palm kernel shell
77 powder (PKS), phenolic resin, steel slag, iron waste and carbon black. Figure 1 shows the representations
78 of these materials. About 30kg of PKS was obtained, ground and utilized for the entire research work. 5
79 liters of phenolic resin were purchased and employed as an unsaturated polyester binder for the mixture.
80 Steel slag and iron waste obtained from the production of pig iron were employed as reinforcement
81 fractions/constituents in order to offer additional necessary wear resistance, thermal stability, mechanical
82 strength, rigidity and integrity at high temperature to the resultant composite material. However, the
83 obtained iron waste from the blast furnace, although waste, possesses characteristics similar to that of
84 calcium carbonate; this was included to serve as filler material for the composite matrix. Equally, carbon
85 black was used as a major constituent of the composite material because of its good lubrication properties.
86 Ground fine charcoal was utilized as carbon black for the research.

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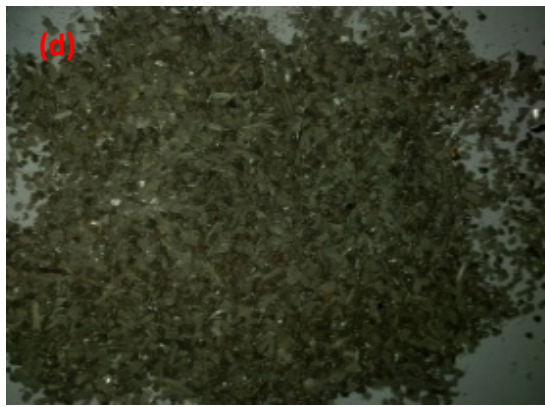
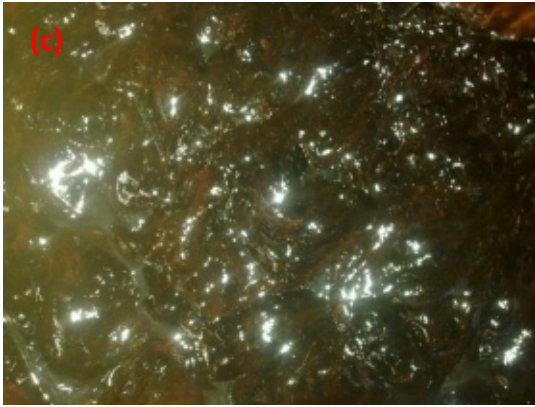
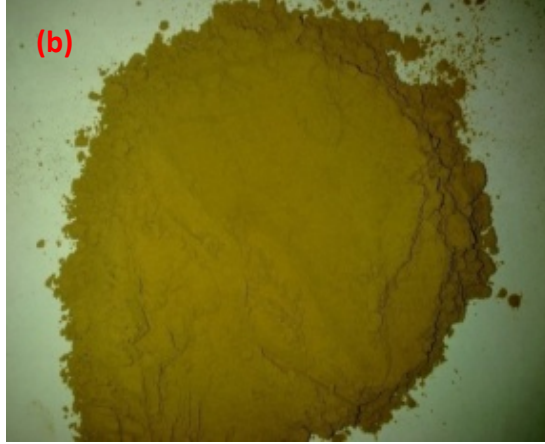


Fig. 1: (a) Raw palm kernel shell (PKS), (b) Grounded palm kernel shell (PKS), (c) Phenolic resin, (d) Steel slag, (e) Grounded iron waste

The friction materials were crushed and blended using a crushing machine of model BYCYEUR CLERO puissance type 101 having ABB electric motor power of 1.5/1.7KW and engine mill of model FLENDER HIMMEL ZF30-G80M4 having an electric motor capacity of 0.75KW respectively. Thus, each of the blended friction materials was sieved into three different particle sizes using sieve sizes of 100 μ m, 200

98 μm , and $350\ \mu\text{m}$ respectively. The formulation of the brake pad composite was conducted in ratios and
 99 the weight percentages (for the mixture) employed for the experiment are shown in Table 1. 15% of
 100 phenolic resin, 5% of carbon black and 15% of steel slag were made constant for the entire formulations
 101 while other ingredients' weight percentages were varied. However, the proportion of the base material
 102 (PKS) was based on the particle sizes of $100\mu\text{m}$, $250\mu\text{m}$, and $350\mu\text{m}$. Consequently, five (5) sets of the
 103 experiment (according to Table 1) were conducted with each of the particle sizes.

104 **Table 1: Mixing proportion of the constituent**

S/N	MATERIAL	SAMPLE (%weight)				
		A	B	C	D	E
1	Palm kernel shell powder	40	45	50	55	60
2	Steel slag	15	15	15	15	15
3	Carbon black	5	5	5	5	5
4	Iron waste	25	20	15	10	5
5	Phenolic resin	15	15	15	15	15

105
 106 Based on Table 1, each recipe was mixed or blended for about 10 minutes until a homogeneous mixture
 107 was formed. Immediately after mixing, the mixed composite samples were cast into cylindrical chambers
 108 of 29.44mm diameter and ejected for curing as shown in Fig. 2. The cured samples then went through
 109 several testing to confirm the integrity of the composite. Afterward, the mixed composite was poured into
 110 the fabricated mould cavity shaped like a Pathfinder's brake pad. The composite in the mould was then
 111 compacted and rammed on a backing plate made of steel until the designed shape was formed. The
 112 resultant samples were sintered at 150°C for about 10 minutes inside an electric furnace where curing
 113 process was initiated. The sintered samples were hot pressed immediately after removal from the furnace
 114 by using a hydraulic press for about 30 to 45 seconds in order to induce satisfactory compactness in the
 115 composite matrix at the attained temperature level. Consequently, the formed brake pads are removed and
 116 the edges are trimmed to the desired shape before they are allowed to cool naturally for about 3 days. The
 117 finishing (grinding) of the brake pads was carried out to a standard thickness of 16mm and all resinous
 118 layers were removed using emery cloth made of silicon carbide. The brake pad was then reheated at a
 119 temperature between $20\text{-}50^{\circ}\text{C}$ for about ten (10) minutes to remove the possible residual stresses induced

120 during the finishing process. Thus, this procedure described above was repeated for all the experimental
121 sets. Samples of the produced PKS brake pads are shown in Fig. 3.

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123

124 **Fig. 2: Cast composite test samples**

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126

127 **Fig. 3: Samples of the developed PKS brake pads**

128 Chemical compositional analysis of the constituent elements of the formulation and that of the brake pad
129 was carried out. The microstructure analysis of the brake pad samples was carried out by grinding the
130 samples using 300, 400, and 600 grit papers respectively. Dry polishing was then carried out on these
131 samples and the internal structures were viewed under a metallurgical microscope. Mechanical properties
132 such as hardness and compressive strength of the brake pads were determined. 10mm diameter steel ball
133 indenter with a load of 3000kg was utilized in assessing the Brinell hardness values of the brake pad
134 samples whereas a hydraulic compressive strength tester was utilized to determine the compressive
135 strength of the formed brake pad samples at failure.

The wear rates for the samples were measured using a pin on disc machine by sliding it over a cast iron surface at loads of 10N and 20N, sliding speed of 125rev/min and 250rev/min, and sliding distance of 2000m and 4000m. 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 μ m by applying the load. A friction detecting arm connected to a strain gauge hold and presses 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. In addition, this research focuses on the development of laboratory PKS brake pads and as such, the service life of the developed brake pad is not studied. However, the life of brake pad is dependent on operating temperature and intrinsic wears. The wear rate of PKS brake pad is studied while the operating temperature of the developed PKS brake pads is not examined based on the fact that an approximate brake pad structure has the capability of evenly distributing frictional energy/heat around the brake pad and rotor surfaces. Thus, induced peak temperature within the brake pad is adjudged to be lowered during braking condition. Based on this, correlation of mechanical properties with respect to temperature was not undertaken in this research.

The characterization of the brake pads' porosity was ascertained by employing in-water weight gain approach. The specimens (brake pad samples) were weighed to the nearest milligram and then soaked in water container at 90-100°C. The samples were left for 24hrs and then removed from the water container. The test samples were reweighed in order to determine weight gain and consequently the porosity of the brake pad. Likewise, characterization of the ash content of the brake pads was carried out by subjecting a known sample of the brake pad to oven drying in a furnace at 550°C for 1 hour. Consequently, the samples were charred and they were cooled in a desiccator and weighed. Heating, cooling and reweighing processes were repeated until a constant weight is obtained.

3. Result and Discussion

3.1 Elemental analysis

Table 2 shows the elemental compositions of the individual ingredient/constituent employed in the formation of PKS based brake pads. Some of the observed elements are also found in asbestos and this suggests that PKS can also be used in the development of brake pads. Similarly, Table 3 shows the elemental compositions of the developed brake pad. Magnesium (Mg), carbon (C), iron (Fe) and aluminum (Al) are the major compositions of the brake pad. The addition of Mg is noted to improve the quality of brake pad [6]. Thus, the increased magnesium content in the developed brake pad is considered to be beneficial. Likewise, wear and heat resistance, and material stability are envisaged to be contributing features of magnesium in brake pads especially when magnesium oxide is formed within the composite matrix of the brake pads. As a result, the compositions of the developed brake pads are desirable features in brake pads.

Table 2: Chemical composition test analysis of constituents

Constituents	Ca%	Cr%	Cu%	Fe%	K%	Mn%	Ni%	Zn%
Carbon black	12	3	2	8	ND	ND	ND	5
Iron waste	36.92	ND	ND	3	ND	ND	ND	ND
PKS Powder	15	4	22	30	10	4	2	4
Steel slag	7	5	ND	58.68	ND	1	2	35

Note: ND means element not detectable, it falls below the detection limit of the material

Table 3: Chemical analysis of the newly formulated laboratory brake pad

Al	Ba	C	Ca	Cr	Cu	Fe	K	Mg	Mn	Ns	Ni	O	Si	Zn
5.38	3.64	20.89	3.40	0.046	0.025	10.54	0.71	53.6	0.02	0.18	0.045	1.02	0.35	0.069

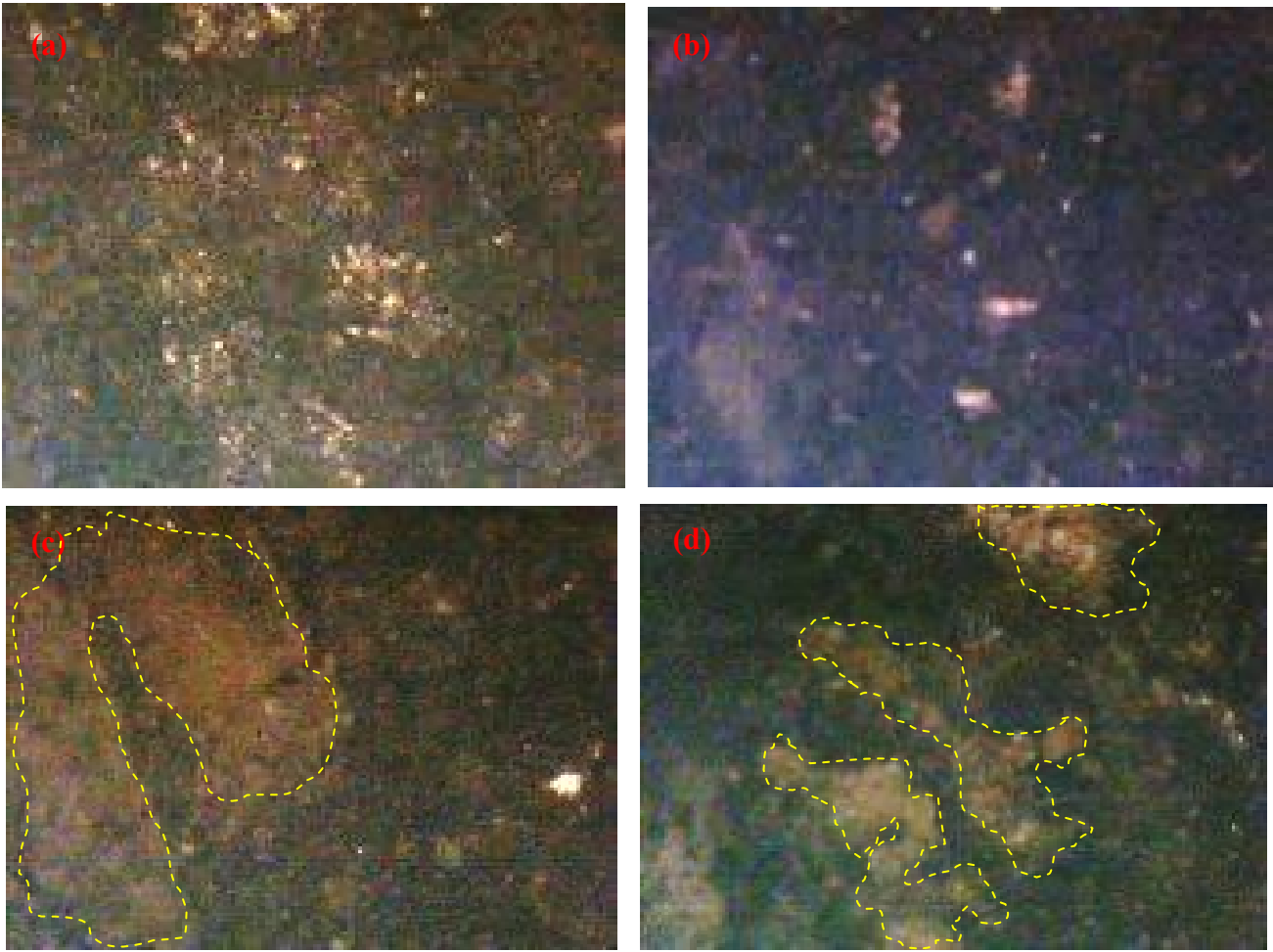
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3.2 Microstructure examination

The microstructures of different formulations of the brake pad composite based on Table 1 for a 100µm grain size of PKS are investigated. The microstructural examinations of the produced brake pads are shown in Fig.4. The microstructural assessment shows color patches which indicate the presence of

183 different additives or constituents. The brownish region on the micrographs indicates the palm kernel
184 shell (PKS). Fig. 4a and Fig. 4b show agglomerates of tiny brownish spots which represent PKS
185 reinforcement while Fig. 4c, 4d, and 4e show conspicuous brownish areas or PKS-regions which are
186 enclosed with yellow dotted lines. The black spots in Fig. 4 represent the carbon black constituent used as
187 a lubricant for the brake pad composite matrices whereas the black regions indicate regions with a
188 combination of phenolic resin and carbon black. Similarly, the whitish regions and spots in Fig.4 indicate
189 iron waste rich region because the utilized iron waste for the brake pad had coloration similar to that of
190 calcium carbonate. Also, no crack or defect is observed on the macrographs of the brake pad composites.

191



193



Fig. 4: Optical micrographs of the cross-sectional area of the PKS reinforced phenolic resin composites with 100 μ m grain sizes (a) formulation “A” (b) formulation “B” (c) formulation “C” (d) formulation “D” (e) formulation “E”

3.3 Influence of particle size on physical and mechanical properties

3.3.1 Wear rate

Fig.5 shows the variations of wear rate with particle sizes (sieve grade sizes) of the developed brake pads. It was observed that wear rate increased as the grade sizes of PKS increases from 100 μ m to 350 μ m for the same and different compositional weight percentages. In Fig.4a-d, the formulation/composite “E” with 60% weight percentage of palm kernel shell (PKS) showed that the least/lowest wear rate is obtained at grade size of 100 μ m. The wear rates of 100 μ m based samples A (2.11g/km), B (2.13g/km), C (2.461g/km), D (2.16g/km) and E (1.681g/km) at 125rev/min displayed less wear rate compared to commercial brake pad (3.8g/km) [8]. Also, wear rate decreased with increasing amount of reinforcing constituent (PKS) in Fig.5. This corroborates the work of S. N. Nagesh et al. [2] which affirms that friction material wear increases with decreasing quantity of reinforcing fiber. Although, wear rate differed for different formulations/composites (A, B, C, D, and E); but this could be attributed to the variations in weight percentages of the brake pads’ constituents. In the same manner, as the speed increased from 125-250rev/min, the wear rate of the brake pads was observed to increase. This occurrence is attributed to the likelihood of achieving increased contact pressure at the surface of the brake pad as the speed is raised.

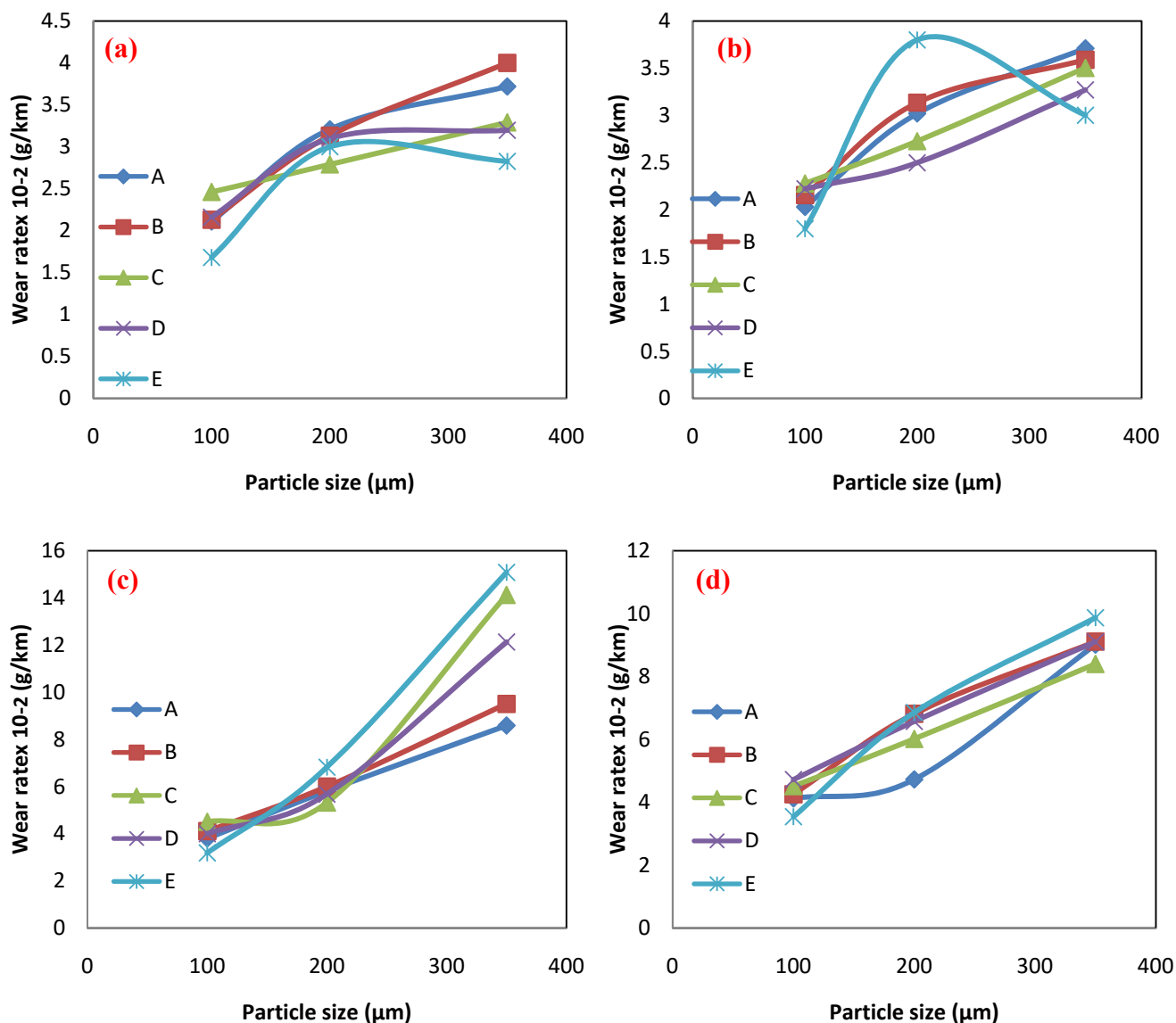


Fig. 5: Wear rate of samples compared with sieve grade sizes (a) at 30min, 1kg and 125rev/min (b) at 30min, 1kg and 250rev/min (c) at 30min, 2kg and 125rev/min (d) at 30min, 2kg and 250rev/min

3.3.2 Hardness

The results obtained from the assessment of hardness of the brake pads are shown in Fig.6. Maximum hardness values are obtained at 100μm grade size. However, as the grade size increases the hardness values of the brake pads are observed to reduce. This is in agreement with the Hall-Petch relationship on hardness.

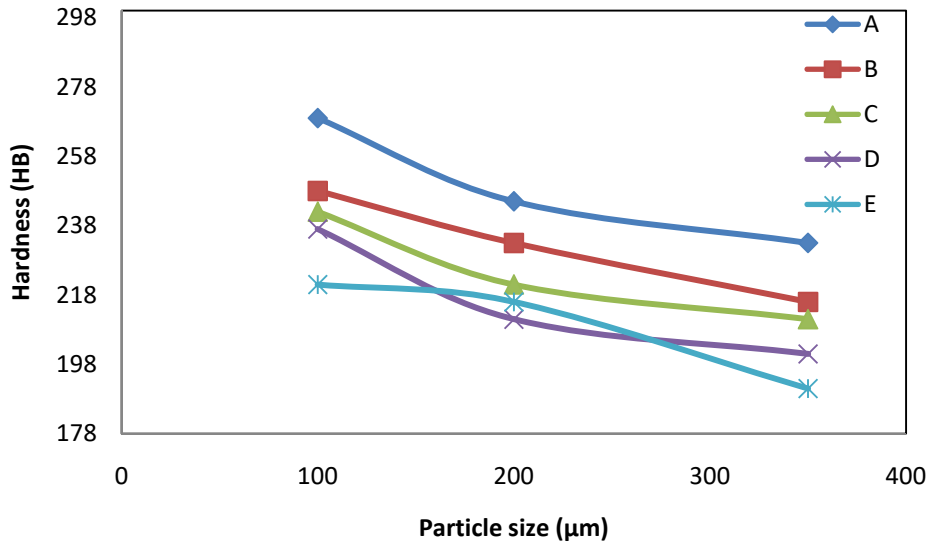


Fig.6: Variation in the hardness of samples compared with sieve grade sizes

3.3.3 Compressive strength

The compressive strength of brake pads was observed to be indirectly related to the particle size of PKS as revealed in Fig.7. Brake pads produced with 100μm particle-sized PKS gave the best compressive strengths irrespective of the weight percentages of other additives utilized in manufacturing the brake pads. This corroborates the results of D. S. Yawas et al. [11] where the periwinkle shell was used as the frictional filler material. It was affirmed in their work that compressive strength of the developed brake pads increased with decreasing periwinkle shell particle. However, formulation “A” which had 45wt% of PKS compared to 60wt% of PKS exhibited better compressive strength. A maximum compressive strength of 131kpi was attained.

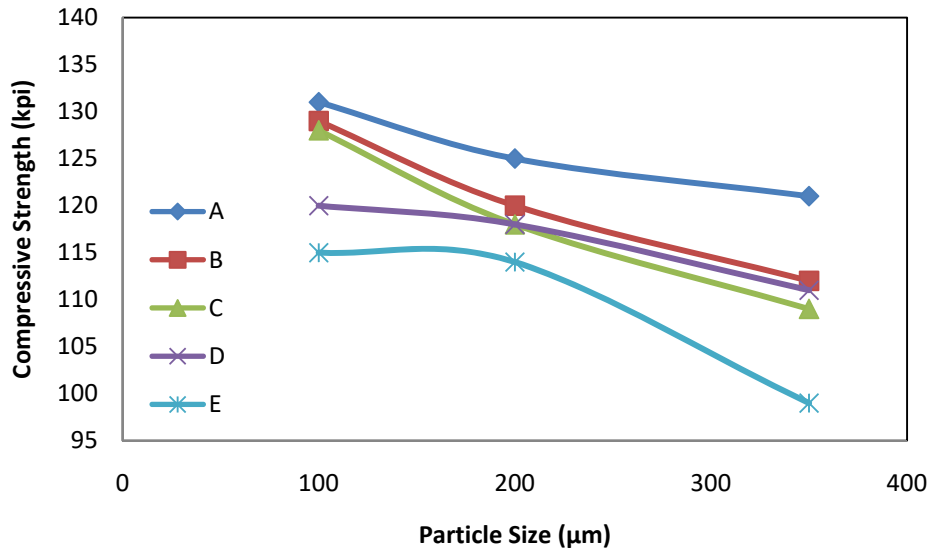


Fig. 7: Compressive strength of sample

3.3.4 Ash content

Fig.8 shows the correlation between grain sizes and ash contents for the developed PKS brake pads. The 100μm grade size yielded the best ash content (that is lowest ash content) compared to other grade sizes of 200 μm and 350 μm. Brake pad formulation having PKS with the largest composition of 60%wt (formulation “E” shown in Fig.8) produced the highest percentage of ash content. However, at 40%wt compositions of PKS (formulation “A”), the ash contents produced with 100 μm, 200 μm, and 350 μm are 40%, 42% and 43% respectively. Thus, it can be concluded that the percentage ash content of the developed PKS brake pad increases with increasing %wt of the PKS.

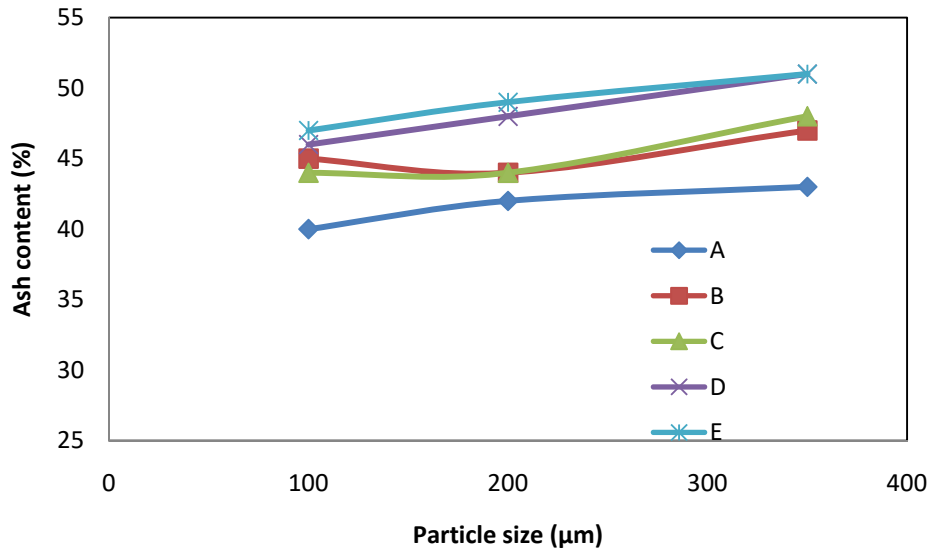


Fig. 8: Ash content of samples

3.3.5 Porosity

Fig.9 shows the relationship between porosity, grain size, and formulations of the newly developed PKS brake pads. The porosity of the developed PKS brake pad is observed to increase with increasing grain size irrespective of the ratio of weight percentage of the other constituents of the brake pad. As a result, 100μm grade size of the PKS produced the least porosity or water absorption capacity. With increasing grain size and at the least %wt composition of PKS, porosities of water after 24hrs were observed to be 0.47%, 1.54%, and 2.42%, respectively.

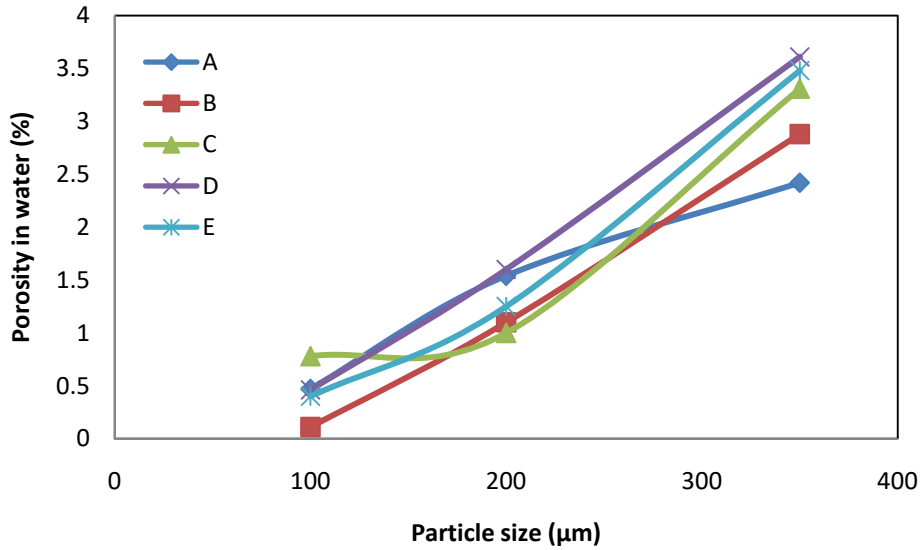


Fig. 9: Porosity of samples with particle size

3.3.6 Density

The densities of the brake pad samples are shown in Fig.10. At 60%wt and 55%wt of PKS, the relationship between density and grain size shows a parabolic trend whereas at 40-50%wt of PKS, a slightly close trend is observed between the density of the brake pad and grain size. Thus, owing to the irregularities in trend pattern, a nonlinear relationship is said to exist between grain size and density.

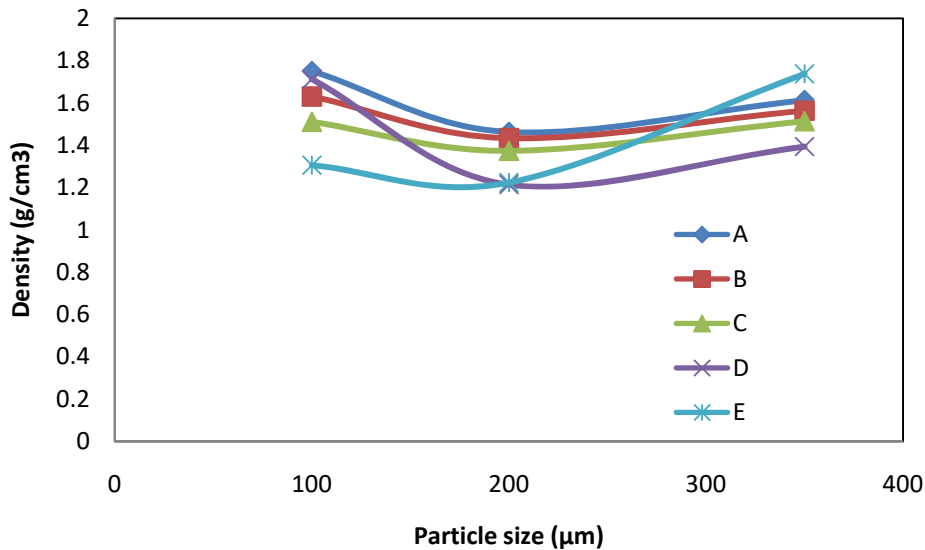


Fig. 10: Density of samples

3.4 Influence of weight percentage of PKS on physical and mechanical properties

Fig. 11 shows the effect of weight percentages of PKS on porosity, wear rate, hardness, compressive strength and ash content respectively. The influences of the wt% of PKS on porosity and wear rate of the developed brake show erratic behaviors as revealed in Fig. 11a and Fig. 11b respectively. This occurrence could be attributed to agglomeration or improper distribution of PKS within the composite matrix. At grain or particle sizes of 100 μ m and 200 μ m, the porosity levels of the brake pads are less than 1.6% and the irregularities in the obtained curves or trends make the determination of the effect of wt% of PKS on porosity to be difficult. However, progressive increase in porosity with wt% of PKS is observed as the particle size is increased to 350 μ m. With the same particle size and as 55wt% of PKS is exceeded, a slight decline in porosity is attained. Thus, it can be inferred that porosity is significantly influenced by wt% of PKS at high particle sizes such as 350 μ m. On the other hand, the effect of wt% of PKS on wear rate cannot be explicitly expressed due to uneven trends in Fig. 11b.

Fig. 11c and 11d show a slight and progressive decline in the hardness and compressive strength values of the brake pad as the wt% of PKS is increased. The hardness values declined from 269HB to 221HB when the wt% of PKS was increased from 40% to 60% for brake pads developed with 100 μ m grain size. Similarly, drop in strength from 131N/mm² to 115N/mm² was achieved as the wt% of PKS was increased from 40% to 60% for brake pads (100 μ m grain size).

However, in the developed PKS based brake pads, a linear relationship is observed to exist between the charred ash content and the wt% of PKS, irrespective of the grain or particle size of the PKS as shown in Fig. 11e. As the wt% of PKS is varied from 40 to 60wt%, the charred ash content of the developed brake pad also increased from 40% to 47% in a 100 μ m grain sized brake pad. As a result, it could be inferred that increase in the amounts of combustible constituent and carbon content of the PKS (biomass) are directly associated with an increase in wt% of PKS. Consequently, this leads to increase in ash content as the wt% of PKS is increased.

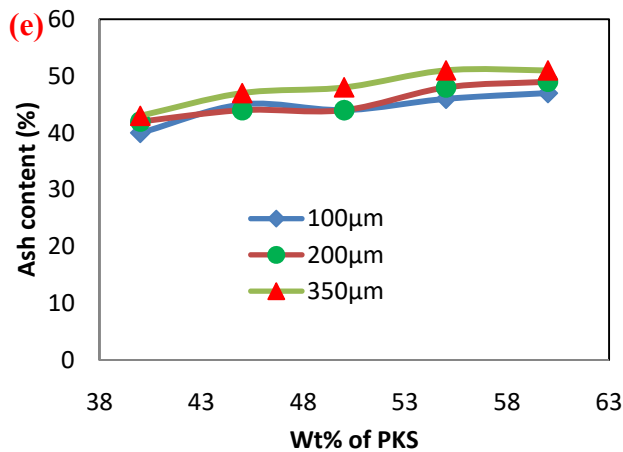
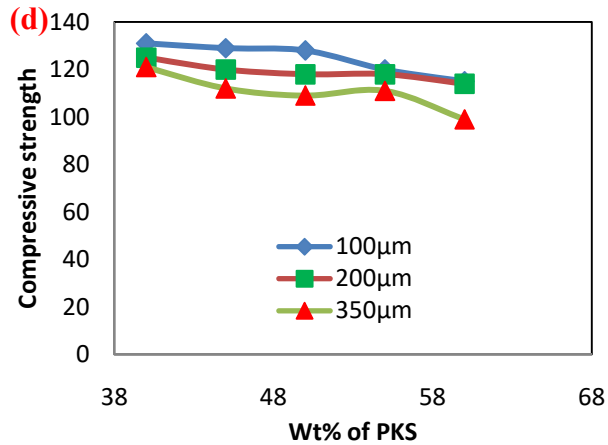
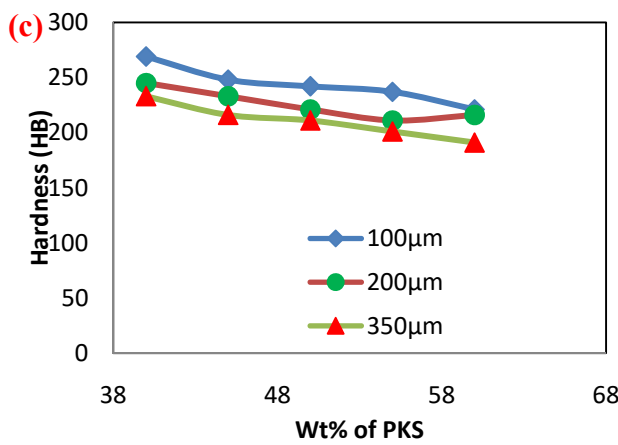
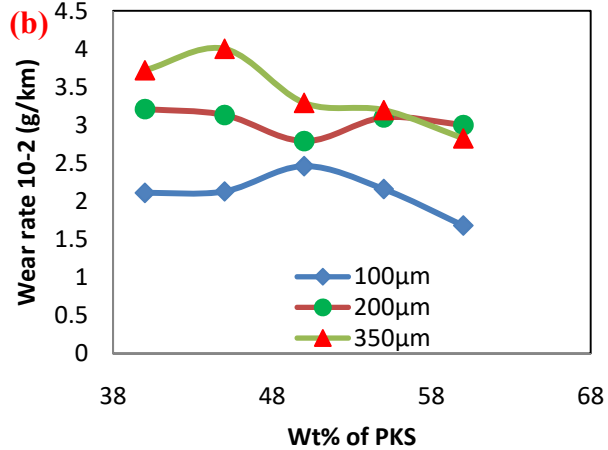
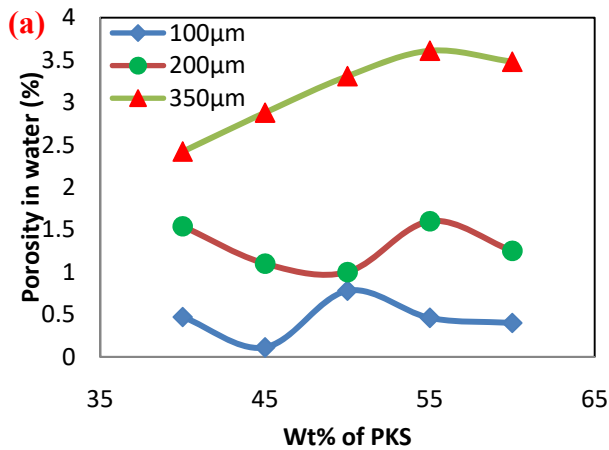
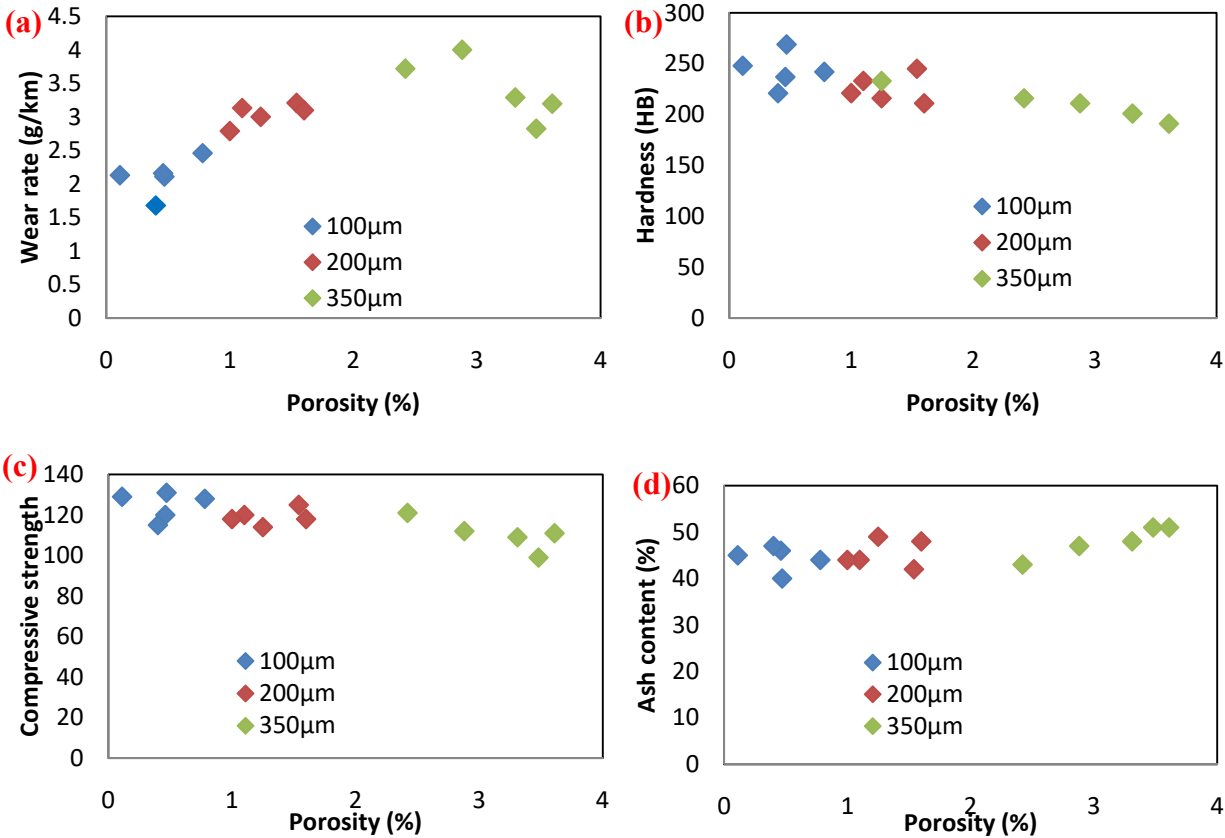


Fig. 11: The influence of wt% of PKS on (a) porosity, (b) wear rate, (c) hardness, (d) compressive strength, (e) ash content

302 **3.5 Influence of porosity on physical and mechanical properties**

303 Likewise, Fig. 12 shows the influences of porosity on wear rate, hardness, compressive strength and ash
304 content. Porosity has a direct influence on the wear rate of the developed PKS brake pad as revealed in
305 Fig. 12a. The hardness and compressive strength of the brake pad show inverse relationship with porosity
306 as shown in Fig. 12b and Fig. 12c. Reduced porosities (at 100 μm particle sizes) produced relatively the
307 optimum hardness and compressive strength values in all examined brake pads. On the contrary, the
308 porosity of the developed brake pad shows no significant effect on the charred ash content obtained from
309 the brake pad samples as depicted in Fig. 12d.



312 **Fig. 12: The influence of porosity on (a) wear rate, (b) hardness, (c) compressive strength, (d) ash**
313 **content**

314 **3.6 Appraisal of the developed PKS brake pad with other brake pads available in literature**

315 Comparison of the physical and mechanical properties of the developed PKS brake pad with existing
316 brake pads in literature is shown in Table 4. The wear rate of the newly developed PKS brake pad shows

improved wear rate, compressive strength, and hardness compared to commercial brake pad and other laboratory developed brake pads. In addition, the constituents of the developed PKS brake pads do not have aggressive influence on the environment and human health as compared to asbestos based brake pad. As a matter of fact, the eco-friendly nature of PKS has tremendously encouraged its usage in many areas such as asphalt stabilization in road and construction works, and so on. However, steel slag with less percentage composition of vanadium is encouraged for the development of brake pads in order to prevent the formation of toxic pentavalent oxide form of vanadium (V_2O_5) in the environment. In addition, one of the main issues on brake pad is the unpleasant noise obtained during braking action. However, non-metallic based brake pads are known to be quiet (produce lesser noise) during braking action. Thus, PKS brake pad is adjudged to be gentle or quieter on rotors and produced less unpleasant noise during braking action owing to its organic nature (base material). As a result, the anticipated noise problem of metallic pads can be reduced with PKS brake pads. However, wear induced noise could be possible with PKS brake pad but this would require real time validation on a braking system beyond the laboratory test.

Table 4: Comparing properties of PKS based brake pads with existing literature data

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 (%)
PKS based BP	100	1.51	269	131	1.684	0.11	Charred ash 40%
	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 [15]	-	1.43	100.50	105.60	4.20	3.48	Charred ash 34%
Palm kernel fibre based BP [8]	-	1.7-2.1	5.6-21h	-	3.62- 9.21	1.02-1.04	-
Cow hooves and bagasse based BP [16]	-	-	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 [17]	-	1.89	101	110	3.8	0.90	Charred ash 9%

Note: BP- Brake pad

4. Conclusion

Non-asbestos organic (NAO) based PKS brake pad was successfully developed via compressive moulding by varying the particle sizes of PKS. From the observed results, the following conclusions can be drawn:

- (i) The microstructure of the developed brake pad shows heterogeneously dispersed constituents within the composite matrix of the brake pad. However, magnesium, carbon, iron, and aluminum are the dominant compositions of the developed brake pad. The matrix of the developed brake pad has magnesium has the most dominant element followed by carbon, iron, and aluminum respectively.
- (ii) Particle size increase (from 100 μ m to 350 μ m) of the PKS based brake pad exhibits an inverse relationship with wear rates, hardness, and compressive strength. However, a direct increase in particle size leads to increase in porosity of the brake pad. Brake pad with the optimum properties is obtained with a 100 μ m particle size of PKS. Also, the developed brake pad relatively exhibited improved properties when compared with other brake pads available in the literature.

- (iii) The wt% of PKS shows direct influence on the amount of charred ash content whereas somewhat declines in hardness and compressive strength are associated with an increase in wt% of PKS from 40% to 60%. However, the influences of increase in wt% of PKS on wear and porosity are somewhat erratic and unclear.
- (iv) The porosity of the developed brake pad linearly affects wear rate at varied speeds. Also, increase in porosity impairs the resultant hardness values of the brake pad. However, porosity shows insignificant influence on charred ash content and slight declining effect on the compressive strength of the developed brake pads.
- (v) The obtained result indicates that palm kernel shell (PKS) can be effectively used as a substitute for asbestos in the development of brake pad.

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