Morphology and Physico-Mechanical Properties of Resin-bonded Palm Kernel Shell and Coconut Shell Grain-based Sandpaper Composites

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ABSTRACT: Due to the challenges associated with using crude oil-derived phenolic- or thermoplastics-based materials, agro-based composites have been used as alternative abrasive grains for abrasive tool manufacturing. This paper examines the morphology and physico-mechanical properties of resin-bonded palm kernel shell (PKS) and coconut shell (CNS) grain-based sandpaper composites and their wear performance. The PKS and CNS were collected, pulverised and screened into 250 and 500 µm grainsizes and mixed at ratios of 1:1, 1:2 and 2:1, respectively. Methyl-ethyl-ketone-peroxide and cobalt naphthalene of 1.5 wt. % each were utilised as hardener and catalyst, respectively for proper bonding of the aggregates with unsaturated polyester resin of compositions 12, 15, 18, 21 and 24 wt. %, respectively. To produce the sandpaper samples, the aggregates were compacted at a pressure of 15 MPa and the samples were cured and their morphology, mechanical, and wear properties were investigated.The shatter index, hardness, and compressive strength varied from 66.36% to 95.76%, 6.52 to 11.3 HRB, and 4.41 to 7.24 MPa, respectively. The wear resistance varied from 0.94 to 1.54 mg/m at 50 ^{o}C, and 1.02 to 2.09 mg/m at 150 ^{o}C. The properties of the aggregates made from PKS and CNS were found to have much influence on the performance parameters of sandpaper composites.

KEYWORDS: Agro-residues, Agro-based abrasive, Bio-composite, Sandpaper composites, Performance indices.

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I. INTRODUCTION

Numerous techniques for using alternative and renewable materials from agro forestry as an alternative and renewable class of low-cost bio-composites have been developed to address the environmental challenges and rising costs associated with the use of crude oil-derived phenolic-or thermoplastics-based materials (Ajimotokan and Samuel, 2020; Sauget, Zhou, and Pizzi, 2014; Zhang, Luo, Pizzi, Du, and Deng, 2015). Grain from organic or recycled resources is embedded in other inexpensive engineering materials to make a bio-composite through one of the most advanced, inventive, and adaptive materials engineering approaches (Jaya et al., 2016). A renewable alternative to expensive bio-composite materials is frequently made using the grains from agro-residues (Ajimotokan and Samuel, 2020; Samuel, 2019).

Agro-residues, also known as agricultural or crop residues, are produced commercially from post-harvest agrarian activities and can be used as a substitute feedstock to produce natural abrasives as an alternative to synthetic abrasives derived from crude oil (Iyasara et al., 2014; Sadh, Duhan and Duhan, 2018). They are widely distributed in tropical regions, especially in Africa, Asia, and the Americas (Sadh, Duhan and Duhan, 2018; Ajimotokan, Ehindero, et al., 2019). These agro-residues, such as the shells from oil palm, coconut, palm kernel, periwinkle, and other solid crop residues, have become increasingly popular in engineering and environmental applications due to their comparative economic advantages as well as environmental advantages (Ajimotokan and Samuel, 2020; Aku, Yawas, Madakson, and Amaren, 2012).

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A sandpaper is a durable single layer of abrasive grain protected by a flexible backing material, which is a type of paper or cloth with abrasives attached to its surface (Obot,

Yawas, and Aku 2016). The abrasives used to make these sandpapers are treated, pulverised, and sieved into the desired grain sizes, known as grits (Maksoud and Atia, 2004). Sandpaper is used to smooth, shape, or polish the surfaces of less-hard materials, especially those made of wood, metal, and materials linked to those materials (Harraz, 2016; Ibrahim et al., 2019). They possess distinctive qualities that include purity, homogeneity, grain shape, size, brittleness, toughness, hardness, and fracturability, making them appropriate as friction materials (Odior and Oyawale 2010). According to Kalácska (2013), the abrasives used to make sandpapers can either be natural (i.e., found or derived from nature) or synthetic. The most frequently used synthetic abrasive materials are silicon carbide, aluminium oxide, and cubic boron nitride, which are primarily based on crude oil (Zhong and Venkatesh, 2009; Samuel, 2019).

Studies on a variety of performance parameters, such as grain, mesh, or particle sizes, mixing ratios, compaction pressures, and binder weight percentage, among others, that set agro-residues apart as substitute abrasives for making abrasive tools have been carried out. Sa'ad et al. (2021) investigated the mechanical properties of palm kernel shell (PKS) and coconut shell (CNS) grain-based abrasive sandpapers. The authors found that an increase in the weight percent of unsaturated polyester resin present in the composition at a range of 7.8% to 22.2% for 250 µm grain size resulted in an increase in the hardness values of the produced sandpaper of about 20% and 25% for PKS and CNS, respectively. Similar increases in PKS and CNS were observed at grain sizes of 420 µm, with 29.23% and 32.44%, respectively. Ibrahim et al. (2019) evaluated the physico-mechanical characteristics of PKS and CNS grain-based sandpapers for wood surface finishing. It was discovered that PKS and CNS sandpaper samples made with 250 µm grain sizes had superior mechanical properties to those made with 420 µm grain sizes. The hardness and wear characteristics of the produced sandpapers were enhanced by increasing the weight percent of the resin component. In their study, Obot, Yawas, and Aku (2016) examined the physico-mechanical characteristics of PKS and periwinkle shell grain-based sandpapers. They discovered that the periwinkle sandpaper samples compared favourably to commercially available garnet sandpapers and had superior physico-mechanical characteristics, a higher coefficient of friction, and wear resistance. Another study by Fono-Tamo and Koya (2019) evaluated the thermo-physical properties and elemental composition of pulverised samples of PKS abrasives for sustainable waste diversification. The authors found that the PKS abrasives were appropriate for brake pad linings and frictional filler materials.

However, despite these studies on the production of abrasive grains from various agro-residues and the various organic and inorganic binders that can be used to bind these grains, there are still knowledge gaps regarding the microstructure evolution, mechanical and tribological properties, among others, on pertinent performance characteristics of abrasive tool composites. As a result, it is imperative to evaluate the properties of various agro-residues and their aggregates as alternatives materials. Thus, this study examines the morphology and physico-mechanical properties of resin-bonded palm kernel shell and coconut shell grain-based sandpaper composites and their wear performance.

II. METHODOLOGY

Agro-residues of palm kernel shell (PKS) and coconut shell (CNS), obtained from Ila Orangun town in Ila Orangun, Osun state and Oja-oba in Ilorin, Kwara state; as well as the unsaturated polyester resin, methyl-ethyl ketone peroxide (MEKP) and cobalt naphthalene (CN), obtained from Ojota, Lagos State, were employed in this study. The PKS and CNS were pulverised and screened into 250 and 500 µm grain sizes and aggregated at mixing ratios of 1:1, 1:2, and 2:1, respectively. These aggregates were bonded with unsaturated polyester resin at the different compositions of 12, 15, 18, 21, and 24 wt. %; and 1.5 wt. % each of MEKP and CN added as hardener and catalyst, respectively. The aggregates were compressed at a compaction pressure of 15 MPa for a three-minute holding time and cured in a well-ventilated environment for 14 days to produce the sandpaper samples. Their morphology, mechanical, and wear properties were then investigated.

A. Material Preparation

The raw samples of the selected PKS and CNS were rinsed and screened to remove any dirt or debris before being oven dried for four hours at100^{o}C to reduce the moisture content. These were subsequently pulverised with a 3.73 kW hammer mill and sieved into 250 and 500 µm grain sizes in accordance with the ASTM E11-20 (2020) standard method, classified as FEPA abrasive grits P30 and P36, respectively (Federation of European Producers of Abrasives, 2020). Figure 1 shows the raw samples of CNS and PKS.

Figure 1: Raw samples of (a) Coconut shells and (b) Palm kernel shells

B. Formulation and Production of Sandpaper Samples

The pulverised fine grains of PKS and CNS abrasives were weighed using an electronic scale (Model MP5000, 0.001 g resolution) before being mixed in ratios of 1:1, 1:2, and 2:1 of PKS to CNS, at weight percent compositions of 85, 82, 79, 76, and 73 wt.% of PKS/CNS aggregates, respectively (see Table 1). Using a manual stirrer, the aggregated abrasive grains were mixed with the solution of the binding agent (consisting of methyl-ethyl ketone peroxide as hardener, cobalt

Table 1: Weight percentage composition of PKS/CNS/ unsaturated polyester resin composite

Mixing ratio	PKS/CNS	UPR	MEKP	CN	Total (%)
1:1 of PKS/CNS	85	12	1.5	1.5	100
	82	15	1.5	1.5	100
	79	18	1.5	1.5	100
	76	21	1.5	1.5	100
	73	24	1.5	1.5	100
1:2 of PKS/CNS	85	12	1.5	1.5	100
	82	15	1.5	1.5	100
	79	18	1.5	1.5	100
	76	21	1.5	1.5	100
	73	24	1.5	1.5	100
2:1 of PKS/CNS	85	12	1.5	1.5	100
	82	15	1.5	1.5	100
	79	18	1.5	1.5	100
	76	21	1.5	1.5	100
	73	24	1.5	1.5	100

*MEKP denotes Methyl ethyl ketone peroxide, UPR denotes Unsaturated polyester resin and CN denotes Cobalt naphthenate

naphthalene as catalyst, and unsaturated polyester resin as binder). In the abrasive composite samples, the binder was 12, 15, 18, 21, and 24 wt.% with 1.5 wt.% each of hardener and catalyst. After mixing the aggregated abrasive grains and binding agent solution, the mixture was pour to a prepared mould. The mould was then compacted at room temperature under a constant 15 MPa pressure for a three-minute holding time, and the samples were then kept in an area with good ventilation for a 14-day curing period. Figure 2 shows sandpaper samples made from 250 and 500 µm grains with PKS to CNS mixing ratios of 1:1, 1:2, and 2:1.

Figure 2: Abrasive samples of (a) 250 µm grain sizes and (b) 500 µm grain sizes

C. Performance Characterisation of the Produced Sandpaper

The morphology, mechanical and wear properties in relation to microstructure, shatter index, hardness, compressive strength, and wear resistance of the produced resin-bonded palm kernel shell and coconut shell grain-based sandpaper compositeswere investigated.

1) Microstructural evaluation

The produced sandpaper samples were examined using optical microscope (Model: NJF-120A) at M50 and M250 magnification, and the built-in camera was used to capture the microstructural details. Due to the particle nature of the produced samples used for the microstructure analysis, polishing was not necessary. The optical microstructural analysis was carried out to assess the uniformity of particle distribution in the sandpaper as well as to better understand and confirm the physico-mechanical and tribological behaviours of the abrasive sandpaper.

2) Shatter index test

To determine the storage life of the produced sandpapers, the standard test method ASTM D440-07(2019)e1 (2019) was used to conduct a shatter index test, also known as a durability test. The procedure entailed putting the initial known weight of the sandpaper sample through four gravitational falls onto a cast iron floor plate from a constant height of 2 m (Ajimotokan *et al.*, 2019). The shatter index, a ratio of the retained sample weight after the four gravitational falls to the original weight before the falls (Ajimotokan, Ibitoye, *et al.*, 2019a; Ajimotokan, Ibitoye,*et al.*, 2019b; Kpalo *et al.*, 2020),was computed using Eq. 1 (Ajimotokan, Ibitoye,*et al.*, 2019b):

$$Shatter\ index = \frac{W_{RS}}{W_o} \times 100 \quad (1)$$

where, W_{RS} denotes the retained sample weight after four falls and W_o is the initial sample weight before falls.

3) Hardness test

The produced sandpapers were tested for hardness in accordance with standard test method ASTM E18-20 (2020). With a Rockwell hardness tester, the hardness of the sandpaper samples was assessed using a 1.56 mm steel ball indenter, 10 kg minor load, 100 kg major load, and a 101.2 HRB standard block of hardness value at a predetermined dwell time on the "B" scale (38,506). The sample's hardness value is determined by subtracting the baseline measurement from the final depth reading after accounting for the hardness value. As a result, the difference between the baseline and ultimate depth reading was used to determine the sandpaper's hardness.

4) Compressive strength test

A compressive strength test was carried out using the standard test method ASTM D2166-85 (2008) to determine the maximum load that the produced sandpawers can withstand before cracking and breaking apart. A universal strength tester with a 100 kN capacity was used to measure the compressive strength of the sandpaper samples (Model: Testometric FS5080). In between the machine's plates, each test sample was placed, and the machine was then loaded equally until the sample failed.

5) Wear rate test

To assess how the produced sandpapers wear under heat-producing friction during service circumstances, the wear rate test was conducted using the standard test method ASTM G99-17 (2017). By sliding each sample over a cast-iron surface at different weights of 40, 80, and 120 g, a sliding speed of 2.4 m/s, and a 20-minute holding time at temperatures of 500ºC and 1500ºC, the wear rate of each sample was assessed using a pin-on-disk machine (manufactured by Saini Science Industries, Ambala, India). The initial sample weight was determined prior to running the sample through a fixed sliding distance, and the sample was removed, cleaned, and dried after running through the fixed sliding distance. The weight loss resulting from abrasive wear was then determined using the sample's ultimate weight. The weight loss can be converted to a wear rate using Eq. 2 (Bashar, Peter and Joseph, 2012; Edokpia *et al.*, 2016):

$$Wear\ rate = \frac{\Delta W}{s} = \frac{W_i - W_f}{s} \quad (2)$$

where Δw is the change in weight (i.e., weight loss)of the sample before and after the wear rate test (in g), s is the total sliding distance, W_i is the initial weight of the sample before the wear rate test and W_f is the final weight of the sample after the wear rate test.

III. RESULTS AND DISCUSSION

A. Microstructural Evaluation of Developed Sandpaper

Figures 3 and 4 show the 50X and 250X magnified optical images of the manufactured abrasive sandpaper for grain sizes of 250 and 500 µm, respectively. The grains are closely packed in Figure 3, resulting in relatively strong interfacial bonding between the grain matrix and the binder. The finer grain sizes produce a higher surface area per volume of binder, resulting in a closer and stronger bond. The grains also maintained good alignment with minimal distortion with the resin matrix, providing high resistance to wear due to grain pull-off effects (Obot, Yawas, and Aku 2017). Larger pores, poor grain alignment, uneven protrusion, and poor abrasive distribution and orientation were noted in Figure 4, which might result in surface defects, residual stress, sandpaper deterioration, and early abrasive grain chipping (Aurich *et al.*, 2013; Li and Axinte, 2016). Also, due to the ease with which grain pulls off when applied at high temperatures, this may result in an increase in wear rates.

B. Shatter Index

The effects of grain size, mixing ratio, and resin weight percentage on the shatter index of the produced sandpapers are depicted in Figure 5. The created sandpapers' shatter indices ranged from 66.36% to 95.76%. The maximum shatter index was found in the sandpaper produced from 250 µm grains with a 2:1 ratio of PKS to CNS and 24 wt.% resin, while the lowest shatter index was found in the sandpaper made from 500 µm grains with a 1:2 ratio of PKS to CNS and 12 wt.% resin. The shatter index of manufactured sandpapers in the various investigated aggregates rose with a rise in resin weight percentage and fell with a rise in grain size. The proximity of the more refined grain packing and the increasing impacts of the resin's binding on the grains on the grains may account for the rise in shatter index with an increase in resin weight percentage. Additionally, these findings revealed that sandpaper samples with higher PKS content in their aggregates had better shatter indices than those with higher CNS content, indicating that the drop in shatter index with increasing grain size may be brought on by the sandpaper composite becoming more brittle as grain size increases (Obot, Yawas, and Aku 2017). Additionally, it was discovered that when compared to samples of sandpaper with higher CNS concentrations, those with higher aggregate PKS content had better shatter indices. As a result, sandpapers with finer grain sizes and a larger mix of resin and PKS would be more long-lasting and durable when in use.

C. Hardness Values

The effects of grain size, mixing proportion, and resin weight percentage on the Rockwell hardness values of the manufactured sandpapers are shown in Figure 6. The produced sandpapers ranged in hardness from 6.52 to 11.3 HRB. The highest hardness value of 11.3 HRB was found in the sandpaper created from 250 µm grains with a 2:1 ratio of PKS to CNS and 24 wt. % resin, while the lowest hardness value of 6.52 HRB was found in the sandpaper made from 500 µm grains with a 1:2 ratio of PKS to CNS and 12 wt.% resin. In the various aggregates under investigation, the hardness value increased with a rise in resin weight percentage and reduced with a rise in grain size. Increased grain size may cause brittleness and lower hardness, which would explain why hardness decreases as grain size increases (Yawas, Aku and Amaren, 2016).

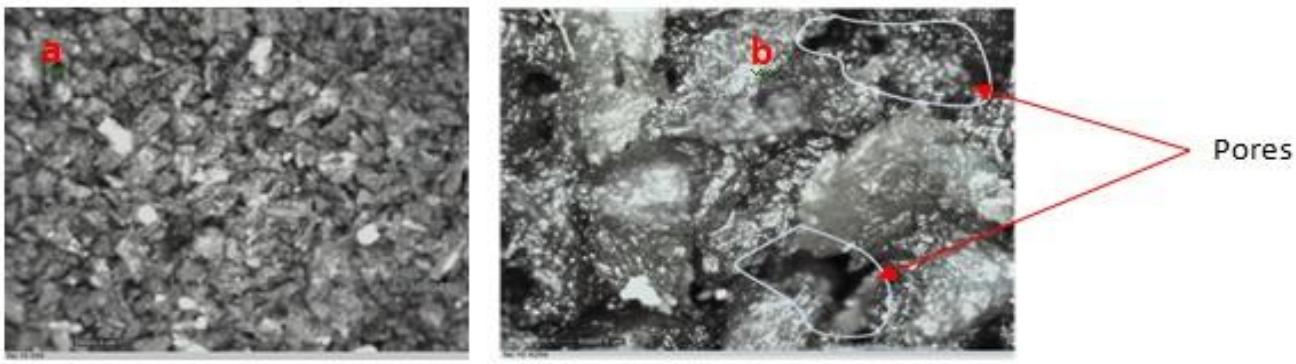

Figure 3: Optical micrograph of the abrasive sandpaper for 250 µm grain size: Magnification (a) 50X and (b) 250X.

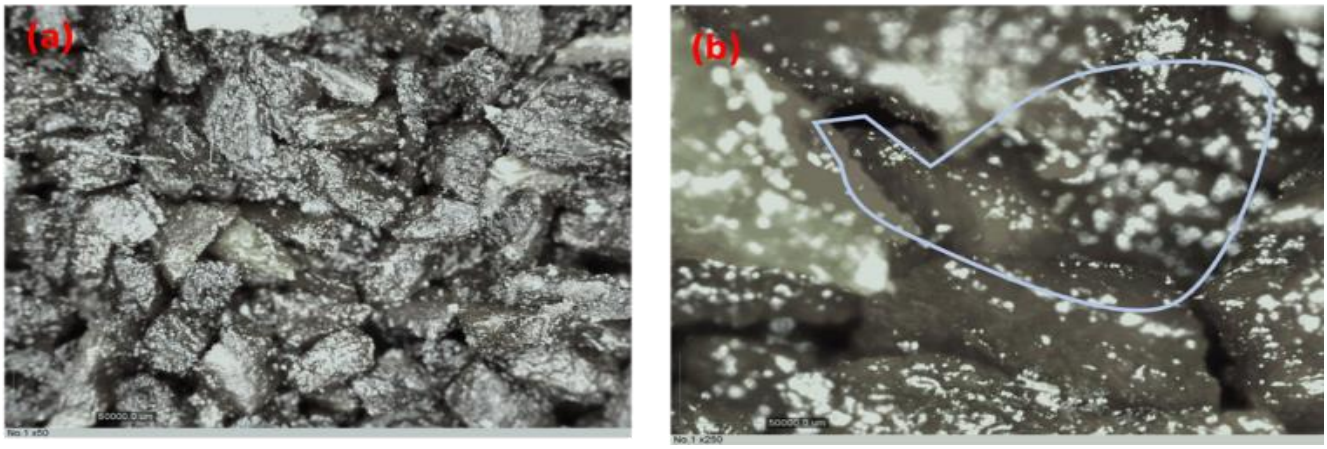

Figure 4: Optical micrograph of the abrasive sandpaper for 500 µm particle size: Magnification (a) 50X and (b) 250X.

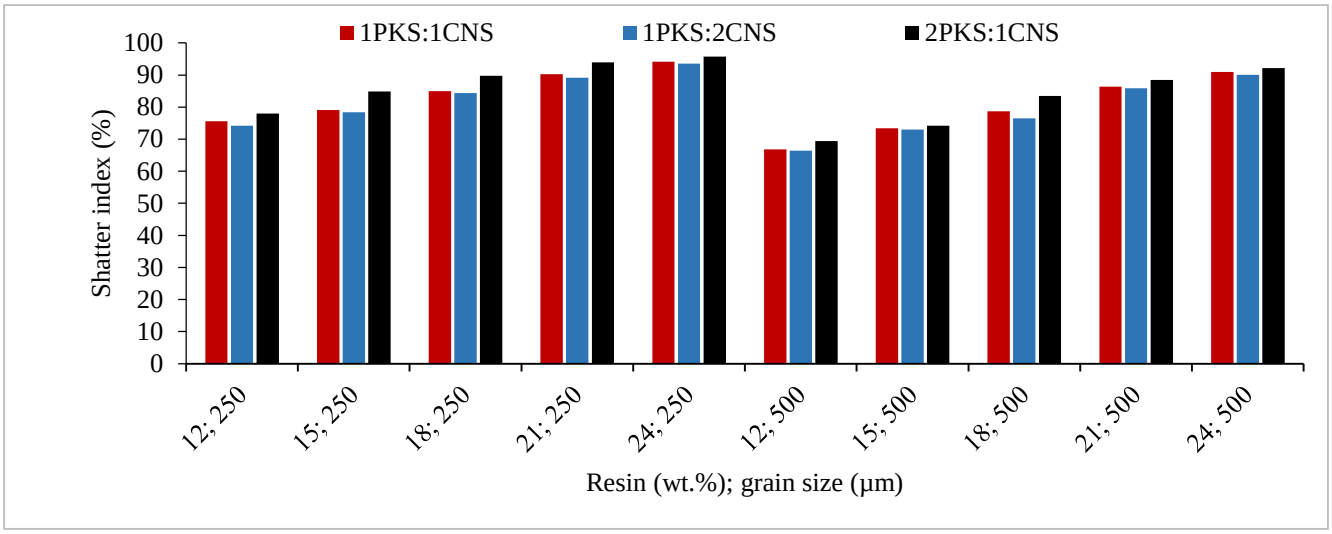

Figure 5: The variation effects of grain size, mixing ratio and resin weight percent on shatter index.

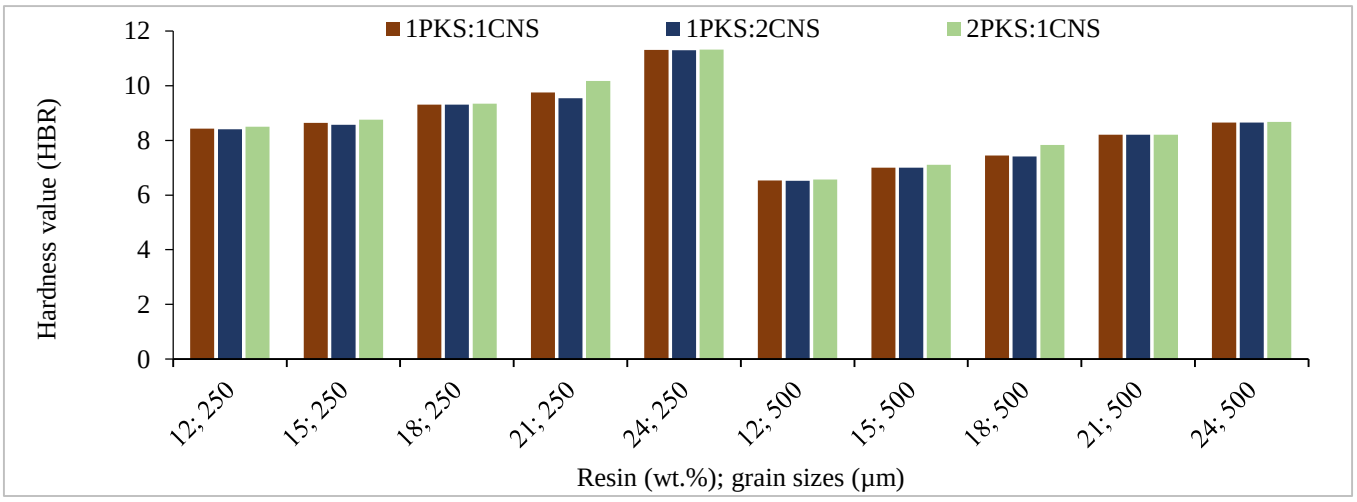

Figure 6: The variation effects of grain size, mixing ratio and resin weight percent on the hardness.

The interfacial and intermolecular bonding properties of the unsaturated polyester resin, which keep the PKS and CNS grains together in the aggregates and contribute to the hardness of the parent composite material, can be blamed for the rise in hardness with increasing resin content weight percentage. As a result, the hardness of the sandpapers increased with increasing resin content in the aggregates under study while decreasing with increasing grain size. These findings were consistent with those reported by Obot, Yawas, and Aku (2016) and Ibrahim et al. (2019) that investigated the hardness of sandpapers developed from composite using agro-residues and resin.

D. Compressive Strength

The effects of grain size, mixing ratio, and resin weight percentage on the compressive strength of the made-to-order sandpapers are depicted in Figure 7. The produced sandpapers had compressive strengths ranging from 4.41 to 7.24 MPa. The sandpaper made from 500 µm grains with a 1:2 ratio of PKS to CNS and 24 wt. % resin exhibited the highest compressive strength of 7.24 MPa, while that of the 250 µm grains with a 2:1 ratio of PKS to CNS and 12 wt. % resin exhibited the minimum strength of 4.41 MPa. It can be observed that the compressive strength increased with an increase in grain size and an increase in the weight percent of the resin content. The increase in grain sizes results in an increase in compressive strength, thereby making the composites more brittle (Obot, Yawas, and Aku 2017). The increase in compressive strength with an increase in weight per cent of the resin content may be due to the stronger interfacial and intermolecular bonds within the sandpaper composite grains, which gives an improved resistance against failure from the compressive force. Sandpapers with higher CNS content exhibited better resistance to a compressive force, which might be due to the high lignin content of the CNS acting as a solidifying agent for the cellulose molecules within the sandpaper composite (Ibrahim *et al.*, 2019). These findings compared favourably with those reported by Obot, Yawas, and Aku (2016) and Ibrahim et al. (2019) that investigated the compressive strengthof sandpapers developed from composite using agro-residues and resin.

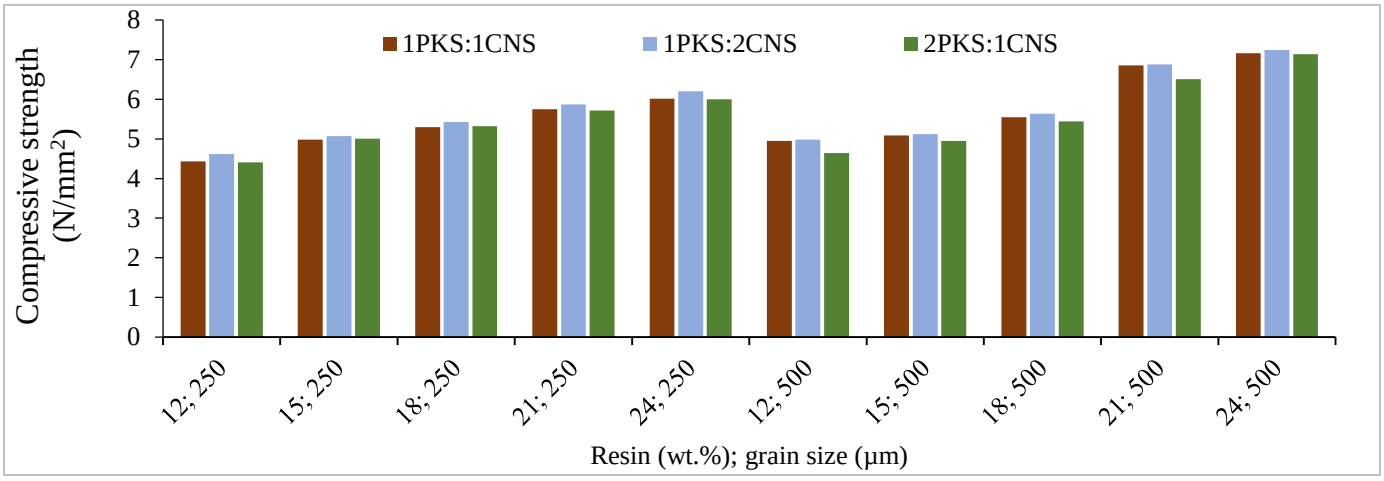

Figure 7: The variation effects of grain size, mixing ratio and resin weight percent on compressive strength.

E. Wear Rate

Figures 8 and 9 depict the effects of grain size, mixing ratio, and resin weight percent on the wear rate of the produced sandpapers at 50ºC and 150ºC, respectively. The produced sandpapers varied in wear resistance from 0.94 to 1.54 mg/m at 50ºC, and 1.02 to 2.09 mg/m at 150ºC. Figure 8 depicted that the wear rate of the produced sandpapers made from 500 µm grains with a 2:1 ratio of PKS to CNS and 12 wt.% resin content under a 120 g at 50ºC load exhibited the highest wear rate of 1.54 mg/m, while that of the 250 µm grains with 24 wt.% resin content under a 40 g load exhibited the least wear rate of 0.94 mg/m. Figure 9 depicted that the wear rate of the sandpapers made from 500 µm grains with a 2:1 ratio of PKS to CNS and 12 wt.% resin content under a 120 g load at 150^0C exhibited the highest wear rate of 2.09 mg/m, while that of the 250 µm grains with 24 wt.% resin content under a 40 g load exhibited the least wear rate of 1.02 mg/m. It can be observed that the wear rate increased with an increase in load, temperature, and grain size because, at elevated temperatures, the binding effects of the resin in the composite have weakened. As the load was increased, the heat generated due to frictional force between the sliding surfaces of the materials increased, and consequently, the removal rate of surface materials. These findings compared favourably with those reported by Obot, Yawas, and Aku (2016);Ibrahim *et al.* (2019); and Borisade, Oyelaran, and Abioye (2021) that investigated the wear rate of sandpapers developed from composites using agro-residues and resin. Therefore, the wear rate increases with a decrease in weight per cent of the resin content and increases with an increase in load, temperature, and grain size. Consequently, the life span of sandpaper employed at a high temperature is shorter compared to those used at a low temperature.

IV. CONCLUSION

This study investigated the morphology, mechanical properties and wears performance of resin-bonded palm kernel and coconut shell grain-based sandpaper composites. The grain-based sandpaper's microstructure, shatter index, hardness, compressive strength, and wear rate were all evaluated. Variations in process parameters had a significant impact on the sandpaper composites, their investigated qualities and wear rate. As the resin content in the sandpaper composites increased, their shatter index, hardness values, and compressive strength increased, while the wear rate decreased. With a rise in temperature and a rise in load, the wear rate increased. This suggests that at higher temperatures and with more load, the rate of material removal was faster. The wear rate, on the other hand, decreased as the weight percent of resin in the composites increased and increased as the weight percent

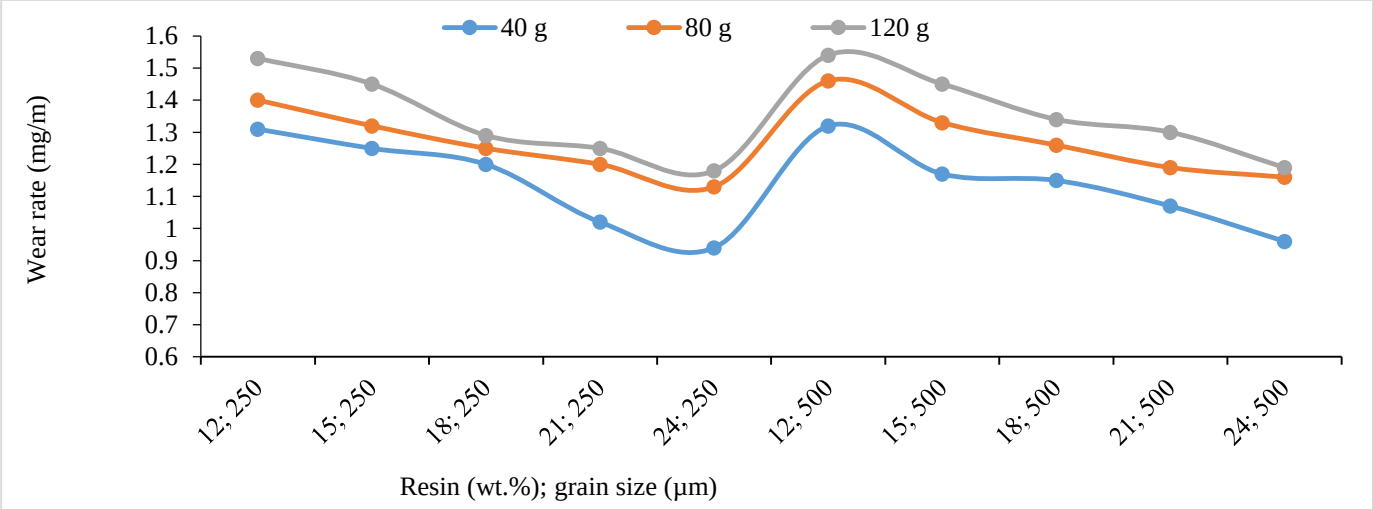

Figure 8: The variation effects of grain size and resin weight percent on wear rate at 50 ^{0}C.

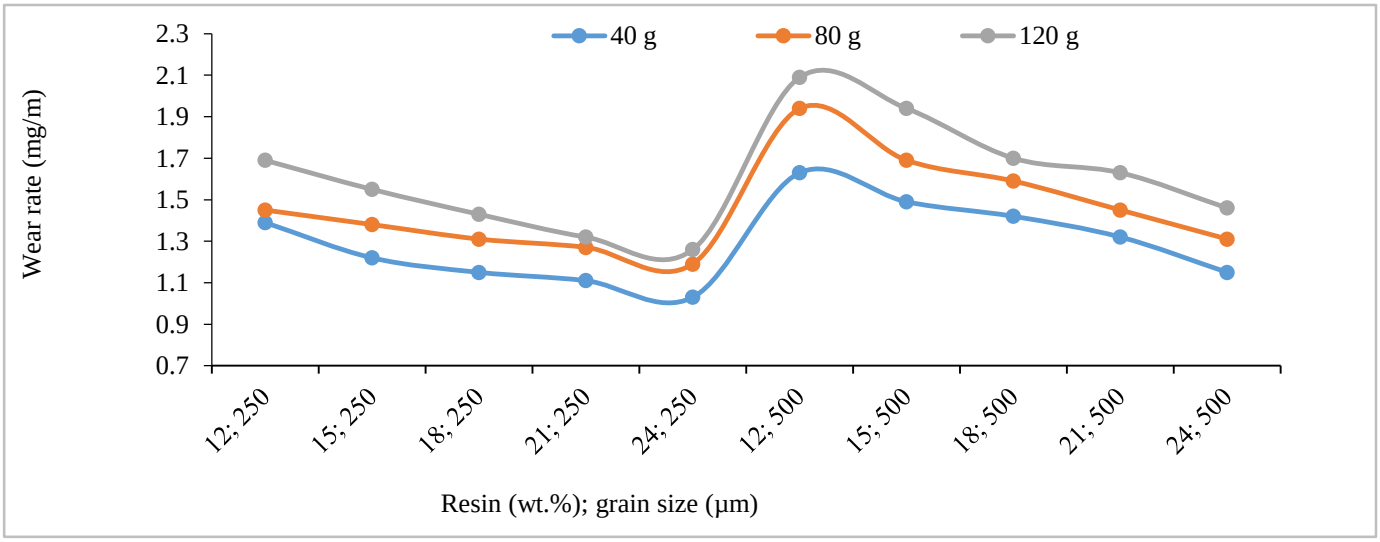

Figure 9: The variation effects of grain size and resin weight percent on wear rate at 150 ^{0}C.

of resin in the composites decreased. Hardness and wear rate decreased as grain size increased, while water resistance rate and compressive strength increased as grain size decreased.

AUTHOR CONTRIBUTIONS

H. A. Ajimotokan: Visualisation, Supervision, and Writing - Reviewing and Editing. **A. A. Samuel:** Conceptualisation, Development and Characterisation, and Writing - Draft Preparation and Final Editing. **T. K. Ajiboye:** Writing - Reviewing and Editing. **T. S. Ogedengbe:** Writing - Reviewing and Editing and Writing - Draft Preparation and Final Editing. **I. O. Alabi:** Writing - Reviewing and Editing and Writing - Draft Preparation and Final Editing.

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