Journal of Engineering Research Innovation and Scientific Development
2(3): 9-17 2024, https://doi.org/10.61448/jerisd23242
Print ISSN 2971-6594 Online ISSN 2971-6608
www.jerisddelsu.com

Comparative Analysis of Palm Kernel Shell Powder and Ash as Reinforcements on the Mechanical Properties of Aluminium Alloy Matrix Composites

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Article History

Received: 13-08-24
Revised: 05-09-24
Accepted: 16-10-24
Published: 25-10-24

ABSTRACT

The present study examines comparative analysis of palm kernel shell powder (PKSP) and ash (PKA) as reinforcements on the mechanical properties of Aluminium alloy matrix composites. The produced composites have various percentage weights of PKSA and PKSP (3 wt.%, 6 wt.%, 9 wt.%, and 12 wt.%), and their impacts on hardness, tensile strength, material stiffness, impact strength, and compressive strength were assessed. All the mechanical property tests were conducted following appropriate ASTM standard specifications. The findings showed that both reinforcement materials considerably enhanced the mechanical properties of the aluminium alloy, while PKSA demonstrated better performance than PKSP. The maximum mechanical effectiveness was achieved at 3 wt.% concentration for both reinforcements. Notably, PKSA-reinforced composites exhibited superior tensile strength and hardness (164.61 MPa and 156.32 HRB respectively) compared to PKSP-reinforced composites with 131.16 MPa and 142.11 HRB respectively. The unreinforced aluminium alloy has tensile strength and hardness value of 116.31 MPa and 124.85 HRB respectively. Hence, the percentage improvement of 41.5% and 12.8% were recorded by PKSA and PKSP respectively in tensile strength and 25.2% and 13.8% respectively in hardness. However, tensile strain was negatively affected by the addition of PKSA and PKSP to the aluminium alloy matrix but for the composite containing 9%PKSP that recorded 9.98% improvement. Microstructural analysis revealed homogeneous dispersion of reinforcements and improved interfacial bonding between the matrix and reinforcements. The results demonstrated the prospect of utilizing natural and eco-friendly reinforcements such as PKSA to enhance the effectiveness of Aluminium alloy composites for application in the automotive and aerospace industries.

Keywords: Aluminium alloy matrix composites; Palm kernel shell powder; Palm kernel shell ash; Mechanical properties; Reinforcements

1. Introduction

The incread need for materials with improved mechanical properties has prompted huge cognizance in metal matrix composites (MMCs). In automotive and aerospace industries, there is great importance in the use of materials with better strength, less weight, and economical energy requirements (Edozinuno et al., 2021a). Ultimately, metal matrix composites derived from aluminium are frequently utilized due to their excellent strength/weight ratios as well as dominant mechanical properties (Oyedejiet al., 2021).Sequel to these attributes, aluminium alloys are greatly efficient for utilization in aerospace and automotive industries, in which there are ultimate concerns in efficiency, performance, and weight of the material (Oladele and Okoro, 2016). Ibhadode et al. (2018) opined that the efficiency of fuels can be enhanced by utilizing materials that are lightweight in internal combustion engines.Metal matrix composites have substantial industrial significance over traditional metallic alloys as a result of diverse properties inherent in reinforcements (Singh et al., 2019).Aluminium matrix composites (AMCs) are the most widely investigated materials among the metal matrix composites due to their ease of production as well as their ability to be synthesized by incorporating reinforcements from non-metals into aluminium and its alloys, creating binary phases (Manohar et al., 2019). The production and categorization of reinforced composite materials have attracted extensive global concern as a result of their higher workability, accessibility, eco-friendliness and profitability (Sanjay et al., 2016).Natural fibres and particulates obtained from organic matter are efficacious materials that could be employed as replacements for synthetic materials and some industrial wastes that are costly and constitute environmental pollution (Edoziuno et al., 2021b). The several reinforcements applied to improve the mechanical properties of aluminium matrix composites (AMCs) are grouped into synthetic/ceramic particulates and agricultural and industrial waste products (Bodunrin et al., 2015). Currently, the focus on the utilization of natural and waste products as reinforcement materials in MMCs has risen, owing to environmental challenges and sustainability. These materials are renewable, recyclable, biodegradable, and readily available since they are natural, agricultural, and industrial by-products, unlike the synthetic and fibre reinforcing materials (Monteiro et al., 2010). The integration of relatively cheap and renewable material filler particles like palm kernel shell, corncob, coconut shell, charcoal, and periwinkle shell in their unprocessed and processed forms has been found to reduce the overall cost of AA6063 and its products (Zamri & Shamsul, 2011; Edoziuno et al., 2021b; Odoni et al., 2020). Palm kernel shells are wastes generated from the manufacture of palm oil and are easily available in West Africa and Southeast Asia.In the reinforcement of metal matrix composites, the palm kernel shells can be refined into powder or ash.The two forms provide distinct characteristics, which can impact the mechanical efficiency of the composites. PKS ash is usually obtained by charring palm kernel shells, which provides better hardness because of its greater amount of silica content, while PKS powder offers a natural reinforcement with a high amount of carbon (Oladele & Okoro, 2016). This research aims to conduct a comparative analysis of the impacts of palm kernel shell powder and palm kernel shell ash as reinforcements on the mechanical properties of aluminium alloy matrix composites. By altering the percentage composition of PKS powder and ash, the study will examine crucial mechanical properties like tensile strength, hardness, and impact strength. Comprehending how these two kindsof PKS influence the composite's characteristics will offer significant awarenessinto the development of cheap, eco-friendly materials with enhanced mechanical effectiveness.

The findings of this research will not only assist to the growth of aluminium matrix composites but also foster the environmentally friendly resource use of agricultural waste, hence minimizing the environmental effect of palm oil production.

2. Materials and Methods

2.1 Materials

In this research, the key materials employed were the aluminium magnesium-silicon alloy AA6061 and palm kernel shell (PKS). The alloy ingot was purchased from Nigalex Company in Ikeja, Nigeria. The fresh palm kernel shells (PKS) were procured from an oil palm processing mill in Akwukwu-Igbo, Nigeria. The obtained samples entail a combination of shells from Dura and Pisifera species, since these varieties are mainly not segregated in the course of processing. The matrix material employed was AA6061 alloy, with the chemical composition shown in Table 1. The particles of palm kernel shell obtained locally were integrated as composite enhancement for the fabrication of the metal matrix composite.

Table 1: Chemical composition of the AA6061 aluminium matrix alloy

Element	Al	Mg	Si	Cu	Fe	Cr	Zn	Ti	Mn
% Composition	97.62	0.80	0.60	0.28	0.22	0.20	0.13	0.08	0.07

2.2 Collection and processing of palm kernel shells

The gathered palm kernel shells were washed with tepid water and sun-dried for two weeks in order to remove the moisture content and evaporate volatile organic compounds. A part of the shells was then ground into fine powder at the Akwukwu-Igbo market with the aid of a standard grain grinding machine. The resultant PKS powder underwent sieving using a 250 µm mesh sieve to ascertain a homogenous particle size. The second portion left was subjected to controlled combustion by heating to a temperature of 950 oC for 3 hours until fully charred. The burned shells were then ground into fine ash and also sieved using the same mesh sieve, ensuring that only the fine particles were utilized in the process of reinforcement. Therefore, the PKS particles retrieved underneath the 250 µm sieve were used in the study. This approach facilitates a better homogenous distribution within the aluminium matrix, improving the mechanical properties of the composite.

2.3 Fabrication of composites

In this study, hybrid aluminium matrix composites were moulded using the stir casting method at JAMO Global Ventures in Warri, Nigeria. The stir casting method entails melting the metal matrix alloy together with the reinforcement and continuously stirred to enable proper penetrability and uniform distribution of the reinforcement within the molten metal, accompanied by instant pouring into a mould for solidification (Edoziuno et al., 2021a).The composites were produced by varying the percentage weight of the reinforcing material (palm kernel shell powder) from 3% to 12%, with intervals of 3%.

Prior to the casting, the AA6061 alloy ingot was mechanically cut to align with the various weights of the palm kernel shell powder (PKSP), ensuring that it fits into a stainless steel pot for charging into the furnace as an ingot. The aluminium alloy ingots were situated in a preheated stainless steel melting pot within an electric resistance furnace, which was heated to about 700 °C for 3 hours. In order to enhance wettability and constant temperature, the PKS powder and ash were preheated to 50 °C in an oven for a period of 3 hours before being mixed to the molten matrix. The temperature was previously raised to 750 °C to completely melt the alloy and subsequently reduced to 600 °C to maintain a semi-solid state. The preheated PKS powder or ash (at different weight percentages of 3%, 6%, 9%, and 12%) was slowly added to the molten alloy and simultaneously stirred continuously with a steel rod. This enables uniform distribution of the reinforcements in the molten aluminium. After meticulous mixing, the composite slurry was reheated to 750 °C, enabling full incorporation of the reinforcements, and then poured into preheated cylindrical steel moulds (240 mm length, 14 mm diameter) for casting. The composite obtained from the casting process was allowed to cool and solidify before being recovered from the moulds. The composition of the AA6061 alloy and details of the samples are provided in Table 2.

Table2: Aluminium 6061 alloy and its weight fractions of PKSP and PKSA

Sample Number	Sample Compositions (with and without PKSP)	Sample Compositions (with and without PKSA)
1.	AA6061	AA6061
2.	Aa6061 + 3 wt.% PSKP	AA6061 + 3 wt.% PSKA
3.	AA6061 + 6 wt.% PSKP	AA6061 + 6 wt.% PSKA
4.	AA6061 + 9 wt.% PSKP	AA6061 + 9 wt.% PSKA
5.	AA6061 + 12 wt.% PSKP	AA6061 + 12 wt.% PSKA

2.4 Mechanical Evaluation of Samples

The produced composite samples, in conjunction with the control sample, were subjected to various mechanical tests such as tensile, hardness, and impact tests utilizing different machines and then metallographic analysis of the fractured surfaces.

2.4.1 Tensile Test

The tensile test was carried out utilizing the 3345-INSTRON Universal Testing Machine with a load frame of 100KN. It ensures the configuration of the specimen with wedge grips at either end, with many strain gauge extensometers, and alongside Merlin software that was incorporated into the machine for collection and analysis of data. For each composition, three samples underwent tests, and a mean value was taken as the representative outcome.

2.4.2 Hardness test

The hardness of the samples was examined using a Hardrocker TM 150-a Rockwell hardness tester at the Department of Materials and Metallurgical Engineering, Federal University of Technology, Akure, Nigeria. The test was performed on the samples with the aid of the machine, and the material resistance to indentation was determined by examining the indentation depth. Also, for the various compositions, three samples were tested, and a mean value was considered as the representative result.

2.4.3 Impact test

The composites produced were fabricated into specimens for the impact test, with a centralized notch. The specimens were tested using a FIT-300EN impact testing machine, where a sudden load was employed to break the samples. The test was conducted on three samples for each composition, and the mean value was evaluated.

2.5 Metallographic Examination

The metallographic evaluation was performed at the metallurgical laboratory of Delta State University, Oleh campus, Nigeria. The specimens to be tested were machined from the samples and placed on Bakelite thermosetting powder. The specimens were grounded using emery papers of different grades (120, 240, 340, 400, and 600) in order to polish the surfaces. The surfaces were further polished using velvet cloth and finally etched before the metallographic examination.

3.0 Results and Discussions

3.1 Tensile test

The tensile test is vital in determining the mechanical properties of reinforced aluminium alloy matrix composites. The material tensile strength gives an understanding of the ability to withstand stress without failure; hence, it is an important parameter in evaluating the performance of reinforcements. The results from Figure 1 show that PKSA has better reinforcement effectiveness than PKSP in improving the ultimate tensile strength of the reinforced composites. The maximum UTS is attained with 9 wt.% PKSA, with a corresponding tensile strength of 164.61MPa, indicating a substantial increase of 41.5% in relation to the control sample, which has a tensile strength of 116.31MPa. However, PKSP indicates enhancement in properties at lesser percentage weights but demonstrates decreased effectiveness at greater weight percentages, possibly due to weak matrix bonding and coalescence of particles (Nwaobakata & Agunwamba, 2014).

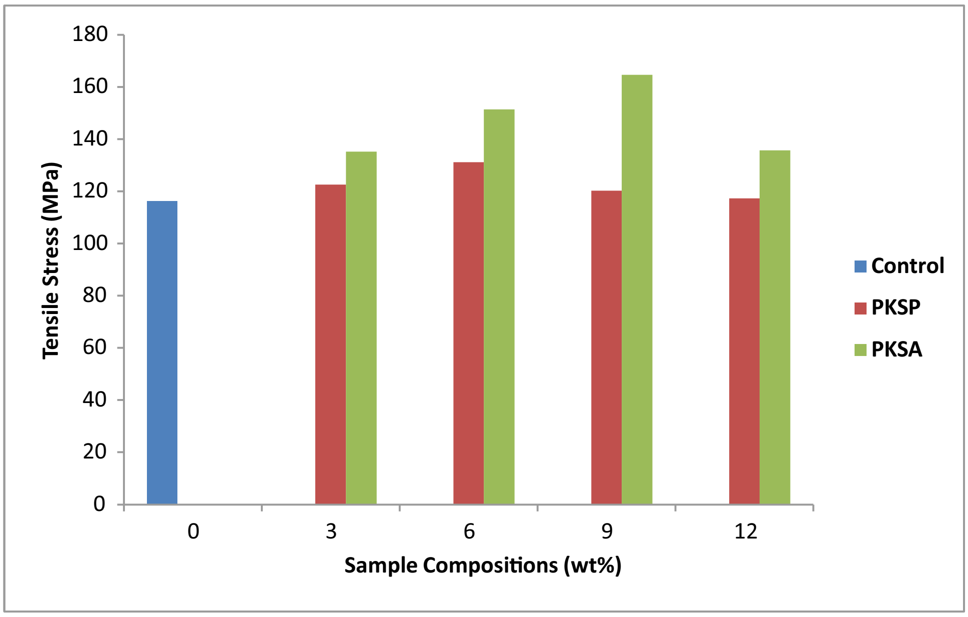

Figure 1: Variation in tensile stress between the prepared composites and the control sample

As indicated in Figure 2, the control sample exhibits a tensile strain of 0.415, offering a basis for the comparison of the composites ductility. A minimum tensile stain of 0.298 is obtained at 6 wt.% PKSA, showing a decrease in ductility as a result of the more rigid PKSA particles, which improves reinforcement but reduces resilience. Conversely, the tensile strain unpredictably increases to 0.461, exceeding the control at 9 wt.% PKSP. This deviation could be due to particle coalescence and weak matrix adhesion, resulting in increased flaws and more extension prior to failure, indicating that additional PKSP particles could not steadily enhance the mechanical properties (Olumuyiwa et al., 2012).

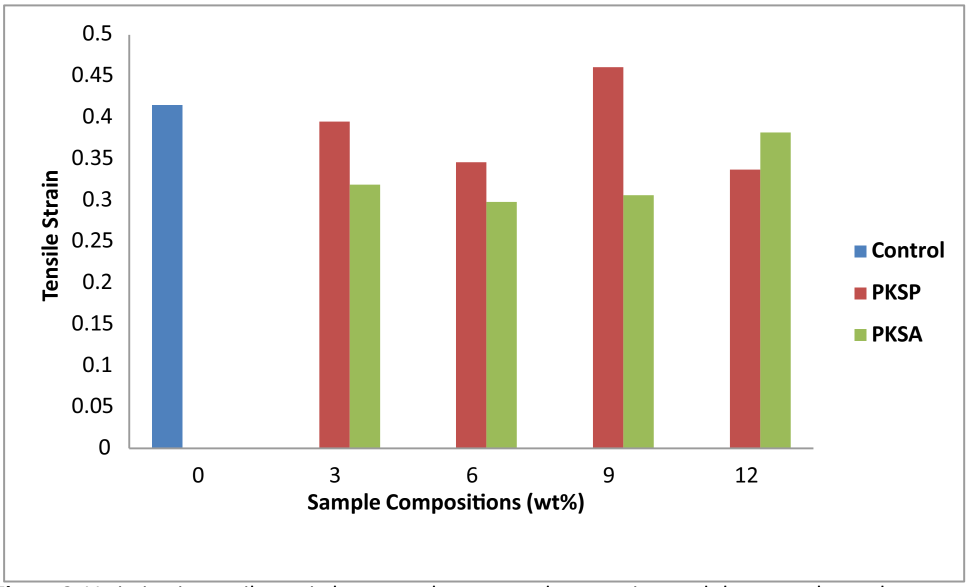

Figure 2: Variation in tensile strain between the prepared composites and the control sample

As indicated in Figure 3, the control sample demonstrated a modulus of 1148.5 MPa. The findings also show that PKSA is more efficient than PKSP in improving the modulus of elasticity of the reinforced composites. An optimum stiffness with a modulus of 3571.32 MPa is attained with 6 wt.% PKSA, showing great effectiveness with respect to the control. Nevertheless, the performance of both PKSA and PKSP reduces at increased weight percentages, specifically at 9 wt.% and 12 wt.%.

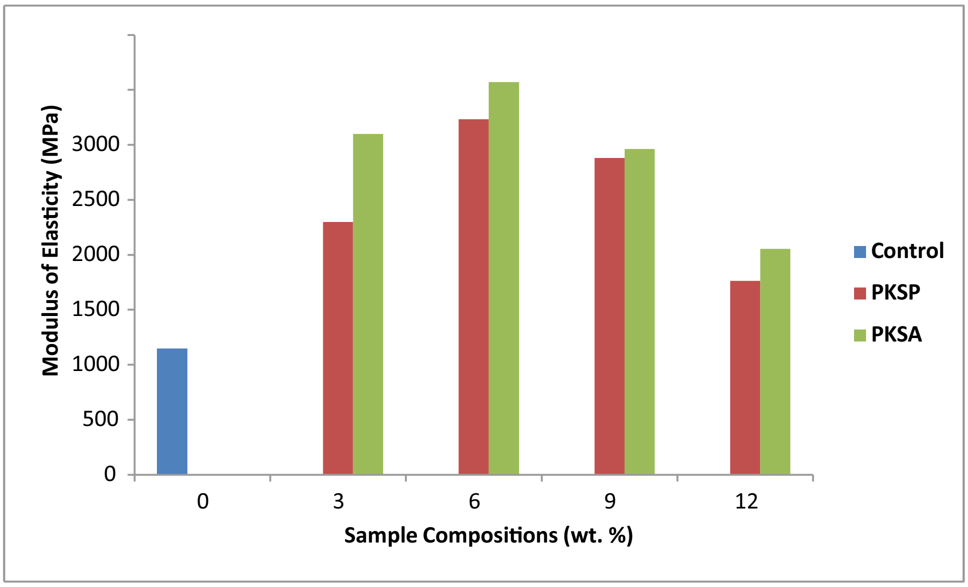

Figure 3: Variation of Modulus of Elasticity between the prepared composites and the control sample

3.2 Hardness test

Figure 4 demonstrates that the control sample has a hardness of 124.85 HRC, and this serves as a reference point for the comparison of the effect of the reinforcement on the hardness of the composites. The results also demonstrate that PKSA offers better efficiency in the reinforcement of aluminium alloy matrix composites. At 6 wt% PKSA, a maximum hardness value of 156.32 HRC is reached, suggesting a notable improvement against the control value of 124.85 HRC. Additionally, the performance of both reinforcements reduces at higher concentration weight percentages, especially at 9 wt.% and 12 wt.%. This could be as a result of agglomeration of particles and ineffective bonding within the composites that adversely impacts the hardness and general mechanical properties of the composites (Nwaobakata & Agunwamba, 2014).

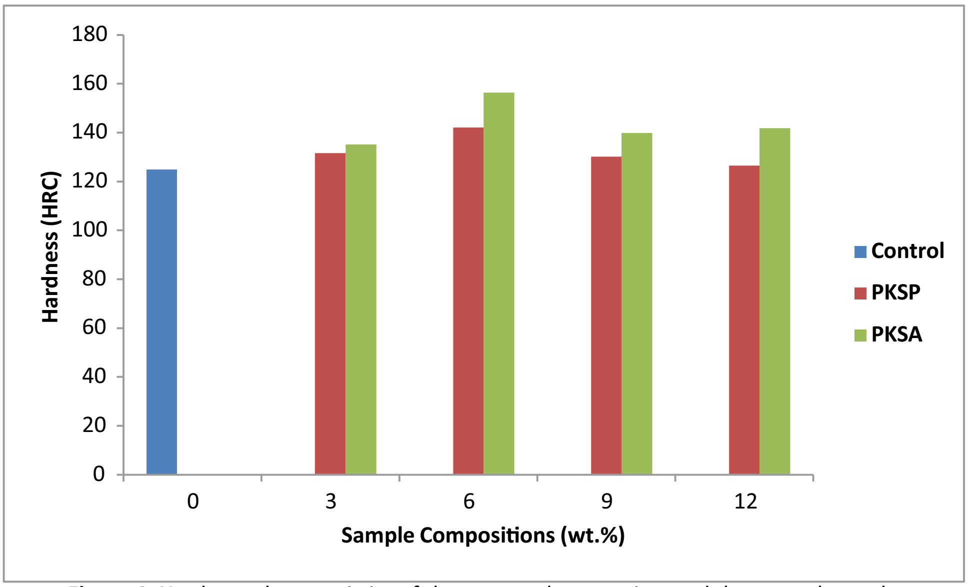

Figure 4: Hardness characteristics of the prepared composites and the control sample

3.3 Impact test

The impact strength is a crucial property to be considered in areas where equipment experiences sudden load or stress. It can be deduced from Figure 5 that PKSA indicates a better reinforcement in comparison with PKSP in the improvement of impact resistance of aluminium alloy matrix composites. A maximum impact strength of 13.1 J is achieved with 3 wt.% PKSA, indicating a significant performance against the value of the control sample, which is 11.2 J. Nevertheless, at higher weight percentages, typically at 9 wt.% and 12 wt.%, the effectiveness of both reinforcements decrease. These findings align with previous studies, which highlight the importance of optimization of the amount of reinforcement in order to attain optimum mechanical properties in composite materials (Edoziuno et al., 2021a; Oladele & Okoro, 2016; McDaniels, 1985).

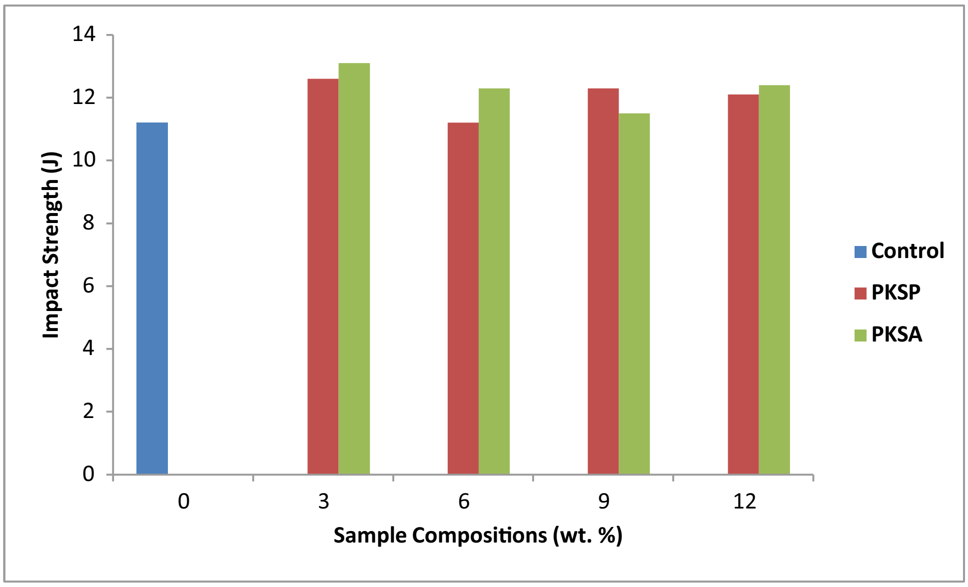

Figure 5: Variation of Impact Strength between the Prepared Composites and the Control Sample

Figure 6 reveals that the compressive strengths of reinforced materials improved; however, PKSA exhibits better performance than PKSP. At 3 wt.% PKSA, a maximum compressive strength of 165.1 MPa is obtained, denoting a remarkable improvement with respect to the control sample with a compressive strength of 128.3 MPa. However, for both reinforcements, there is a decrease in their performances at increased percentage weights, basically at 6 wt% and 9 wt%.

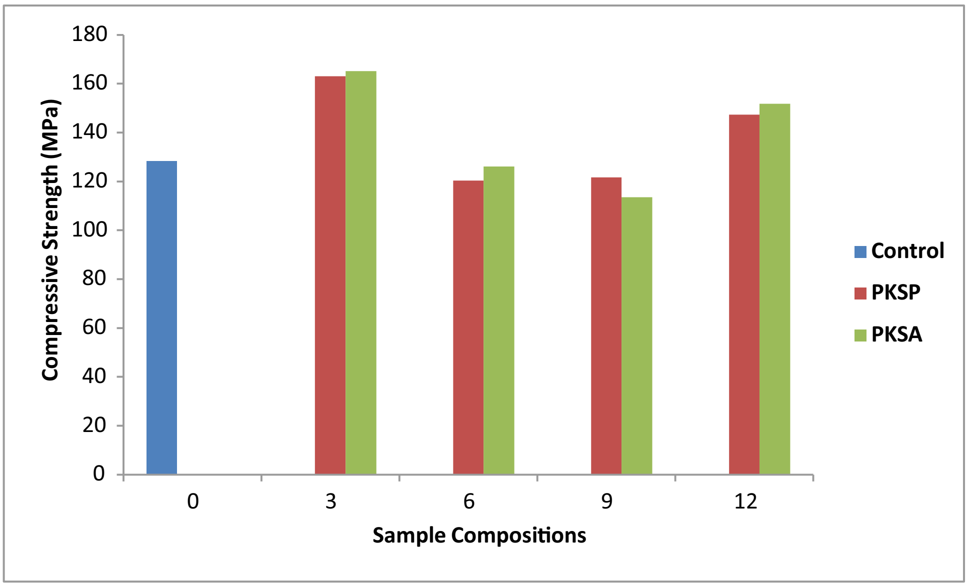

Figure 6: Variation of Compressive Strength between the Prepared Composites and the Control Sample

As depicted in Figure 7, the control sample indicates a compressive strain of 32.7%, while those of PKSA and PKSP show considerable improvement on ductility. A maximum compressive strain of 37.1% is attained at 3 wt.% PKSA, evidently more than the value of the control sample. However, with higher weight percentages of the reinforcement materials, particularly at 9 wt.%, the ductility decreased for both PKSA and PKSP.

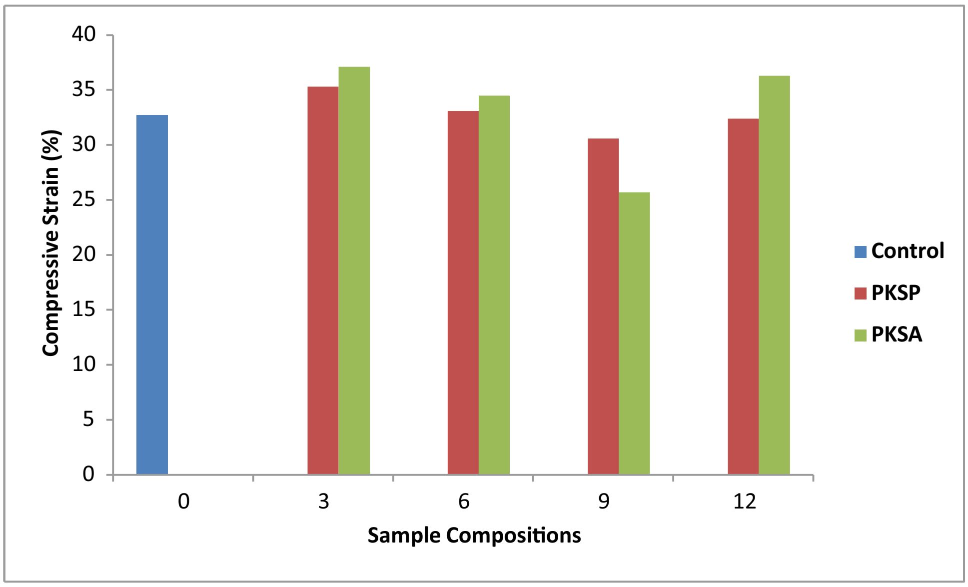

Figure 7: Variation of Compressive Strain between the Prepared Composites and the Control Sample

3.4 Ranking and Selection of Composite with best combination of Properties using Weight Method

In order to select the composite with best combination of properties, weight was assigned to each of the measured properties. The sample possessing the highest magnitude of the measured property is assigned the highest value of 9 and continued in descending order to the sample with the least magnitude assigned weight value of 1. However, if two samples have the value for a particular property, both are assigned the same weight and the next weight value is skipped for the following sample. Tables 3 presents the assigned weights, total weight and rank of each composite and the control sample.

Table 3: Weight and ranking of PKSP composites and the control sample

Sample	Assignedweight to measured properties								
	Tensile strength	Tensile Strain	Modulus of Elasticity	Hardness	Impact Strength	Compressive Strength	Compressive Strain	Total weight	Rank
Control	1	8	1	1	2	4	4	21	9th
PKSA 3	6	3	7	5	9	9	9	48	1st
PKSA6	8	1	9	9	6	5	6	44	2nd
PKSA9	9	2	6	6	3	1	1	28	6th
PKSA12	7	6	3	7	7	7	8	43	3rd
PKSP 3	4	7	4	4	8	8	7	42	4th
PKSP 6	5	5	8	8	2	2	5	35	5th
PKSP 9	3	9	5	3	6	3	2	31	7th
PKSP 12	2	4	2	2	4	6	3	23	8th

Critical inspection of Tables 3 reveals that samples reinforced with 3% PKSA particles displayed the highest weight and thus ranked first. The control sample has the least total weighted value and thus ranked ninth, which is the least rank is an indication that the addition of both PKSA and PKSP enhanced the mechanical properties of the investigated aluminium alloy. Table 3 shows that mechanical property improvement increased with decrease in the amount of additives added, but for sample containing 12 wt% PKSA. Overall, composites reinforced with PKSA showed better enhancement of mechanical properties compared to those reinforced with PKSP. However, it is worthy to note that for this ranking all the properties were assumed to be of equal importance. But in real life, some applications may have preference for some properties over others, which may require higher weight assigned to those preferred properties, which invariably may affect the ranking.

3.5 Metallographic Test Results

The metallographic evaluation of the reinforced aluminium alloy matrix composites gives a discerning understanding of the metallographic features of the materials. The surface examination of the samples was carried out using an optical microscope, indicating discrete geometric configurations. Figures 8-12 show the micrographs obtained with the aid of the computerized microscope. As illustrated in Figure 8, the microstructure of the control sample indicates homogenous grain boundary features, hence constituting a reference for the comparison of the effect of PKSP and PKSA reinforcements on the aluminium alloy matrix composites. Also, Figures 9-12 showcase the micrographs of the samples reinforced with PKSP and PKSA, and it can be observed that there is remarkable modification in the microstructure due to the addition of reinforcements. The particles of both reinforcements are dispersed extensively in the alloy matrix; however, the weight percentages are functions of the degree of dispersion. Additionally, it is also evident from Figures 9-12 that the PKSP reinforced composites have larger and irregular particles on their microstructure than the PKSA composites, which are more refined and evenly distributed. The better refined and evenly dispersed PKSA particles in the aluminium matrix improve the mechanical properties such as hardness, material stiffness, and toughness (Bharanidaran, 2021).

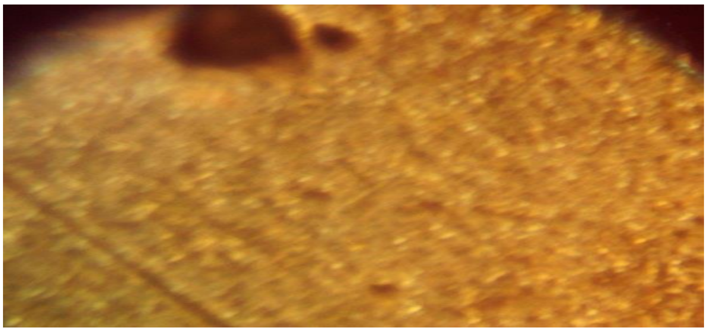

Figure 8: Micrograph of control sample x400

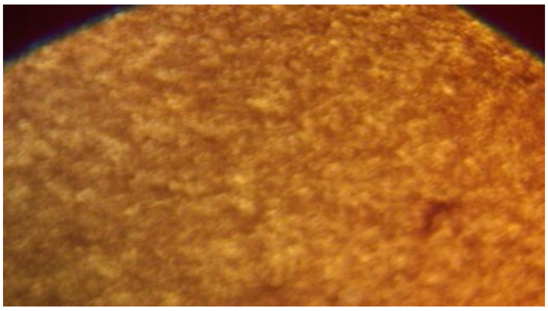

Figure 9a: Micrograph of sample with PKSP at 3%

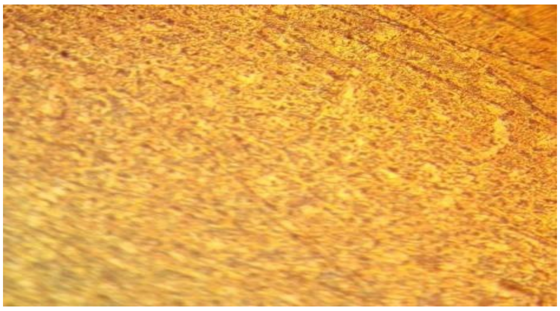

Figure 9b: Micrograph of sample with PKSA at 3%

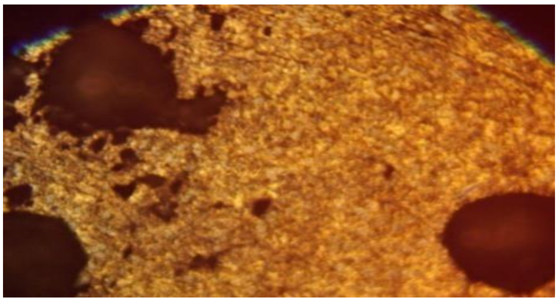

Figure 10a: Micrograph of sample with PKSP at 6%

Figure 10b: Micrograph of sample with PKSA at 6%

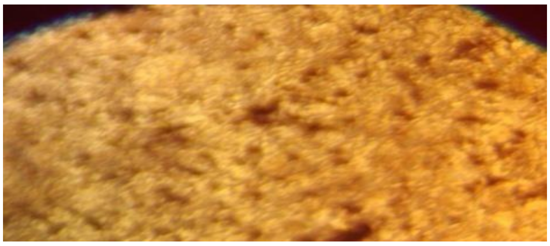

Figure 11a: Micrograph of sample with PKSP at 9%

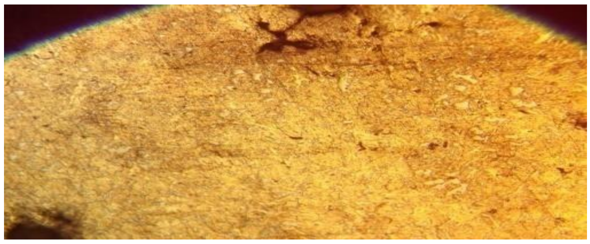

Figure 11b: Micrograph of sample with PKSA at 9%

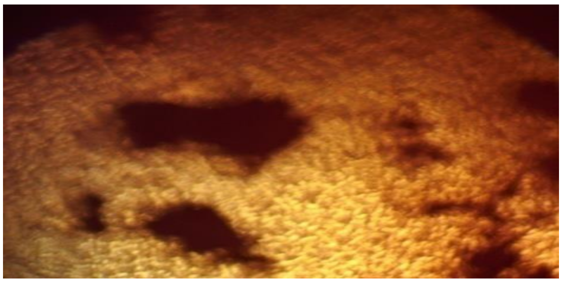

Figure 12a: Micrograph of sample with PKSP at 12%

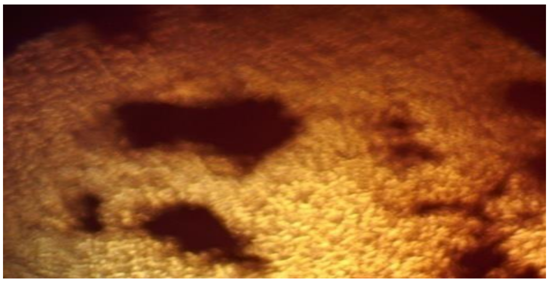

Figure 12b: Micrograph of sample with PKSA at 12%

4.0 Conclusion

The findings of the study have shown that both PKSP and PKSA particles have substantial effects on the mechanical properties of the aluminium alloy. Nevertheless, PKSA exhibited better efficiency than PKSP in improving the tensile strength, hardness, impact strength, and stiffness of the material. The most remarkable performances were achieved at lower concentrations of the reinforcement contents, notably at 3wt%, while greater concentrations constituted coalescence of particles and decreased effectiveness. Generally, PKSA particles appeared to have better performance in reinforcement. These indicate that the addition of these identified eco-friendly materials has potential applications in automotive and aerospace industries. Future studies could investigate the optimization of the dispersed particles and other eco-friendly reinforcements for better effectiveness.

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Acknowledgement

Authors wish to appreciate the Tertiary Education Trust Fund (TETFund) for its financial assistance in the course of this research. The authors equally extend gratitude to JAMO Global services, Warri, Delta State for her technical assistance during the casting and machining operations.

Declaration of competing interest

There is no conflict of interest regarding this paper.

Data availability statement

All data underlying the results are available in the article with related references.