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Exploring the Mechanical Strength and Microstructure of Aluminium-Coconut Shell Ash Composites

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ABSTRACT

This study investigates the mechanical performance and micro-structural characteristics of a sustainable aluminium matrix composite reinforced with coconut shell ash (CSA), an underutilized agro-waste material. The novelty of this work lies in the systematic integration of CSA as a low-cost, eco-friendly reinforcement and the establishment of clear structure-property relationships across a wide composition range (2-12 wt.%). Coconut shell ash was produced via controlled thermal treatment, characterized using atomic absorption spectroscopy, and incorporated into molten aluminium through stir casting to ensure uniform dispersion. The results demonstrate a significant enhancement in mechanical properties with increasing CSA content, with tensile strength peaking at 65.8 N/mm² and hardness reaching 88.20 HR. Micro-structural analysis confirms homogeneous particle distribution and improved inter-facial bonding, which are responsible for the observed strengthening mechanisms. Unlike conventional ceramic reinforcements, CSA offers a lightweight and sustainable alternative while maintaining competitive performance.This work advances current knowledge by linking agro-waste-derived reinforcement characteristics to mechanical behavior in aluminium composites and demonstrates the viability of CSA as a functional engineering material. The findings provide a pathway for developing cost-effective, high-performance composites for structural applications in automotive, aerospace, and construction industries, while promoting circular economy and environmental sustainability.

1. Introduction

In recent years, there has been a growing demand for materials that possess enhanced mechanical properties, such as improved strength, hardness, wear resistance, and fracture toughness, for applications in industries like aerospace, automotive, and construction. Traditional materials, while functional, often lack the specific combination of properties needed for more specialized or high-performance applications. This has led to the development of composite materials, which combine different constituents to achieve superior performance compared to their individual components. Composites are generally classified into three main categories: polymer-matrix composites (PMCs), metal-matrix composites (MMCs), and ceramic-matrix composites (CMCs), depending on the type of matrix material used [1,2]. Among these, metal-matrix composites (MMCs) have garnered particular attention due to their versatility and potential for significant property enhancement.

MMCs are created by embedding reinforcing materials such as carbides, oxides, or nitrides into a metallic matrix, which can include magnesium, aluminum, copper, or iron. These reinforcements improve the mechanical and physical properties of the matrix, making MMCs ideal for applications that require enhanced strength, wear resistance, and thermal stability. Aluminum, in particular, has emerged as a popular matrix material for MMCs due to its lightweight, high corrosion resistance, and excellent

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thermal and electrical conductivity [3]. However, despite these inherent properties, pure aluminum lacks the strength and hardness required for certain high-performance applications, leading researchers to explore different reinforcement materials.

Agro-wastes, such as rice husk ash and coconut shell ash, have recently gained attention as environmentally friendly and cost-effective reinforcement materials for MMCs. These materials are rich in hard phases like SiO_2, Fe_3O_4, Al_2O_3, and Cr_2O_3, which can significantly enhance the mechanical properties of the composites in which they are incorporated [4]. For example, a study conducted by [5,6] demonstrated that rice husk ash, a byproduct of the rice milling industry, could be successfully utilized as a reinforcing agent in aluminum composites. The resulting materials exhibited improved hardness, tensile strength, and wear resistance, making them suitable for use in the automotive industry, particularly for components such as piston rings, cylinder liners, and connecting rods.

Similarly, coconut shell ash, another agro-waste material, offers great potential as a reinforcement in aluminum MMCs. Coconut shells, abundant in tropical and subtropical regions, are typically disposed of as waste, contributing to environmental pollution. However, when converted into ash through controlled incineration, coconut shells yield valuable compounds like silica, alumina, and iron oxides, which are known to improve the mechanical properties of metal composites. Coconut shell ash (CNSA) has been explored as a reinforcing material due to its high silica content, which enhances the hardness and tensile strength of aluminum composites. Studies have shown that CNSA can improve the wear resistance of aluminum alloys, extending the service life of components made from these materials
[7].

The incorporation of CNSA into aluminum matrices not only improves the mechanical properties of the resulting composites but also presents an environmentally sustainable alternative to synthetic reinforcement materials. By utilizing agro-waste like coconut shells, industries can reduce their reliance on non-renewable resources while simultaneously addressing the issue of waste disposal. This approach aligns with the principles of sustainable development, which emphasize the need for resource efficiency and environmental stewardship in industrial processes [8]. Several studies have reported the benefits of incorporating agro-waste-based reinforcements into metal matrices. For instance, [9] highlighted that the use of agro-waste-derived ash can reduce the overall cost of producing MMCs, making them more accessible for industries that require cost-effective solutions for high-performance materials. A recent study by [10] demonstrated that agro-waste, such as palm kernel shell ash, can serve as an effective reinforcement material in aluminum composites, enhancing mechanical properties such as tensile strength and hardness. The study found that the addition of palm kernel shell ash not only improved the wear resistance of the composite but also reduced its production cost, making it suitable for various industrial applications, including automotive and aerospace sectors. [11,12] explored the potential of rice husk ash as a reinforcement in magnesium-based metal-matrix composites (MMCs). Their findings showed that rice husk ash significantly enhanced the impact strength and corrosion resistance of magnesium alloys, while also contributing to weight reduction. This study emphasized that using agro-waste like rice husk ash promotes sustainability and environmental friendliness in material development, while also offering cost advantages over traditional synthetic reinforcements. [13,14] investigated the incorporation of sugarcane bagasse ash into copper-based metal-matrix composites. Their research indicated that bagasse ash improved the thermal stability and fatigue resistance of copper alloys. Additionally, they highlighted the economic benefits of using agro-waste, noting that it provides an affordable alternative to commercial ceramic reinforcements, contributing to the development of more sustainable and eco-friendly materials for high-performance industrial applications. Moreover, the natural abundance of these materials ensures a steady supply, further enhancing their appeal as reinforcement agents in MMC production.

In this study, coconut shell ash was utilized as a reinforcement in aluminum MMCs, with the aim of improving the mechanical properties of the composite material. The investigation focused on the effect of varying CNSA content (2%, 4%, 6%, 8%, and 12%) on the tensile strength and hardness of the aluminum matrix. By analyzing the mechanical behavior of the aluminum-CNSA composite, the study aims to provide insights into the potential applications of this innovative material in industries that require lightweight yet durable components. Furthermore, the study contributes to the growing body of literature on the use of agro-waste as a sustainable and cost-effective reinforcement material in MMCs, offering a viable alternative to traditional synthetic reinforcements. The results of this research could pave the way for the development of more environmentally friendly composite materials that meet the mechanical performance demands of various industries.

As the world continues to shift towards more sustainable and resource-efficient manufacturing practices, the development of composites that incorporate waste materials like coconut shell ash holds great promise. The combination of enhanced mechanical properties, reduced environmental impact, and cost-effectiveness makes aluminum-CNSA composites a compelling solution for the future of material science and engineering.

2. Materials and Methods

2.1 Materials

The materials used in this study include coconut shells (CNS) sourced from Ugwogo-Nike in Enugu-East Local Government Area of Enugu State, Nigeria, and pure aluminum obtained from Cutix Cable Ltd., Nnewi, Anambra State. The main equipment used for processing and testing were a heat treatment furnace, lathe machine, stainless steel crucible, tongs, galvanized steel pipes, steel rods, molding sand, a tensile testing machine, a Rockwell hardness testing machine, sieves, and other essential laboratory tools.

2.2 Methods

In the preparation and characterization of coconut shell ash (CSA), coconut shells were thoroughly washed with distilled water to remove adhering dirt and impurities, followed by oven drying at 105 °C for 24 h to eliminate moisture. The dried shells were subjected to controlled combustion in an electric muffle furnace at 600 ± 10 °C for 3 h to obtain coconut shell ash (CSA). The furnace heating rate was maintained at 10 °C/min to ensure uniform thermal decomposition. The resulting ash was allowed to cool naturally to room temperature inside the furnace to prevent thermal shock. The ash was then ground using a laboratory ball mill for 2 h at 300 rpm to obtain fine particles. Particle size classification was carried out using a standard sieve shaker equipped with ASTM sieves. Only particles within the size range of 75-106 µm were retained for composite fabrication to ensure uniform dispersion and minimize agglomeration. Oversized particles (>106 µm) were discarded, while finer particles (< 75 µm) were excluded to avoid excessive clustering and poor wettability. The chemical composition of the CSA was determined using atomic absorption spectrometry (AAS), focusing on key oxides and elements such as SiO_2, Al_2O_3, Fe_2O_3, and CaO, which are known to influence reinforcement behavior.

The fabrication of Aluminium-CSA composites was carried out. A commercially pure aluminium (≥ 99.5 % purity) was used as the matrix material. The aluminium ingots were charged into a graphite crucible and melted in an electric resistance furnace at a controlled temperature of 750 ± 10 °C, slightly above the melting point to ensure complete liquefaction and improved fluidity. To enhance wettability and reduce thermal gradients, the pre-weighed CSA particles (2, 4, 6, 8, 10, and 12 wt.%) were preheated separately at 300 °C for 1 h prior to their introduction into the molten aluminium. A two-step stir casting process was adopted to ensure homogeneous dispersion:

- The molten aluminium was first cooled to a semi-solid state (~600 °C), after which the preheated CSA particles were gradually introduced.
- The mixture was then reheated to 750 °C and mechanically stirred using a stainless steel impeller.

Stirring was carried out under the following controlled conditions:

- Stirring speed: 400 rpm
- Stirring duration: 10 minutes
- Impeller depth: 2/3 of melt height
- Stirring environment: Ambient atmosphere

To minimize oxidation, a small amount of flux using hexachloroethane tablets, was added to degas the melt and remove entrapped gases. Care was taken to introduce CSA particles slowly and uniformly to prevent agglomeration and settling. During casting and solidification, the homogeneous molten composite slurry was poured into pre-prepared sand moulds. The moulds were preheated to **200 °C** to reduce thermal shock and ensure uniform solidification. Casting was carried out at a pouring temperature of approximately **720 °C**. The castings were allowed to solidify under ambient conditions (25 ± 2 °C). After solidification, the samples were removed and visually inspected for surface defects such as shrinkage cavities, porosity, cracks, and inclusions. For sample preparation and machining, the cast specimens were machined using a precision lathe to obtain standardized dimensions for mechanical testing. Surface finishing was carried out using successive grades of emery papers (400-1200 grit) to ensure uniformity and remove surface irregularities.

2.3 Mechanical Testing

To evaluate the mechanical properties of the aluminum-CNSA composites, the prepared specimens were subjected to hardness and tensile strength tests. The hardness of the samples was determined using a Rockwell hardness testing machine. Each specimen was carefully positioned on the machine, and the hardness was measured using the hardness Rockwell B (HRB) scale to quantify the resistance of the material to indentation. Multiple measurements were taken from different areas of each sample to account for variations in hardness across the surface. The tensile strength of the composites was evaluated using a tensile testing machine. Specimens of pure aluminum and aluminum with 2 %, 4 %, 6 %, 8 %, 10 %, and 12 % CNSA reinforcement were tested to determine their tensile strength characteristics. Each specimen was clamped between two grips, and a uniaxial load was applied until failure occurred. The maximum tensile stress before fracture was recorded for each composite, providing insights into the impact of CNSA addition on the mechanical strength of aluminum.

These tests were conducted to determine the effect of CNSA reinforcement on the mechanical properties of aluminum, with a focus on understanding how increasing CNSA content influences tensile strength and hardness. All experimental data were analyzed to identify trends and correlations between CNSA percentage and the enhanced mechanical performance of the composites.

3. Results and Discussion

Carbonization of the coconut shell was performed in a controlled environment to convert the organic constituents into ash, ensuring a high content of carbon, silica (SiO_2), and alumina (Al_2O_3), which are beneficial for composite reinforcement [15]. The fine, black powder produced as ash enhances the mechanical properties of aluminum, such as tensile strength and hardness, as shown in previous studies [16, 17]. The results of the hardness test indicated that there was progressive increase in properties with increase in the percentage of coconut shell ash (CNSA) addition as shown in table 1.

Table 1: Hardness measurement and Aluminum coconut shell ash

Specimen	Hardness (HR)
0 volume % of CNSA	71.2
2 volume % of CNSA	73.5
4 volume % of CNSA	75.2
6 volume % of CNSA	80.0
8 volume % of CNSA	81.8
10 volume % of CNSA	83.4
12 volume % of CNSA	88.2

The hardness values for the aluminum-CNSA composites demonstrate a clear trend of increasing hardness with the addition of coconut shell ash (CNSA) reinforcement. Starting with a baseline hardness of 71.2 HR for pure aluminum, the hardness progressively increases as the CNSA content rises, reaching a maximum of 88.2 HR at 12 % CNSA. This steady increase can be attributed to the reinforcing effect of the hard particles present in the CNSA, such as silica (SiO_2) and alumina (Al_2O_3), which contribute to the composite's resistance to deformation. The observed increase in hardness at higher CNSA content (above 6 %) indicates improved particle-matrix interaction and a stronger interfacial bonding, allowing for better load transfer under applied stress. Similar findings have been reported by [18, 19], where agro-waste-based reinforcements improved the hardness of aluminum composites due to the presence of rigid particles within the matrix. The highest hardness value of 88.2 HR at 12 % CNSA demonstrates the potential of CNSA as an effective, low-cost reinforcement material for improving the wear resistance and durability of aluminum composites [20, 21]. This enhancement in hardness makes aluminum-CNSA composites suitable for applications requiring materials with high resistance to wear and surface indentation, such as in automotive and aerospace components. The results also align with the trend noted by [22, 23], who observed that agro-waste reinforcements can significantly improve the mechanical properties of metal-matrix composites (MMCs).

Table 2: Tensile strength (N/mm^2) and coconut shell ash (CNSA)

Specimen	Hardness (HR)
0 volume % of CNSA	28.60
2 volume % of CNSA	38.22
4 volume % of CNSA	38.74
6 volume % of CNSA	40.40
8 volume % of CNSA	46.67
10 volume % of CNSA	65.81
12 volume % of CNSA	62.28

The tensile strength values of Aluminum-Coconut Shell Ash (CNSA) composites reveal a distinct trend of improvement with increasing CNSA content, peaking at 10 % CNSA and then slightly decreasing at 12 %. The tensile strength of pure aluminum (0 % CNSA) begins at 28.60 MPa and increases steadily with the addition of CNSA, reaching a maximum of 65.81 MPa at 10 % CNSA. The significant enhancement in tensile strength at this level can be attributed to the uniform dispersion of hard CNSA particles within the aluminum matrix, which contributes to better load transfer during tensile testing [24]. The increase in tensile strength up to 10 % CNSA indicates improved interfacial bonding between the aluminum matrix and the reinforcing CNSA particles. The particles act as barriers to dislocation movement, which enhances the material's overall strength [7, 17, 25]. However, at 12 % CNSA, the tensile strength drops slightly to 62.28 MPa, which suggests that excessive CNSA content may result in agglomeration of the ash particles, leading to stress concentration sites that weaken the composite [7, 26]. Such particle clustering can cause a reduction in the material's ability to sustain applied loads.

Similar studies have shown that agro-waste-based reinforcements, such as rice husk ash and palm kernel shell ash, follow a similar pattern of improvement in mechanical properties with increased reinforcement content, up to an optimal level. Beyond this point, the properties tend to diminish due to particle agglomeration and porosity [27]. The optimal CNSA content for tensile strength enhancement in aluminum composites is around 10 %, after which the benefits start to decline. This reinforces the idea that careful optimization of reinforcement content is crucial for achieving desired mechanical properties in metal-matrix composites. The carbonized CNSA exhibits superior compatibility with molten aluminum, contributing to uniform dispersion when mixed, which was observed in the microstructural analysis of the composite. The presence of CNSA in varying percentages increased the hardness and tensile strength of the aluminum composites, indicating that carbonized CNSA particles form strong interfacial bonding with the aluminum matrix, enhancing load transfer during mechanical stress [28].

The chemical composition of the coconut shell ash, indicated that the ash has the following elements: zinc, magnesium, phosphorus, calcium, iron, nitrogen, potassium, silicon and lead with their various percentages as ash as shown in the table 3 below.

Table 3: Chemical Analysis Result

Sample identification	Element (%)									
	Zn	Mg	P	Ca	C	Fe	N	K	Si	Pb
Coconut shell	0.003	0.040	0.003	0.020	0.960	0.060	0.190	0.050	0.050	0.190

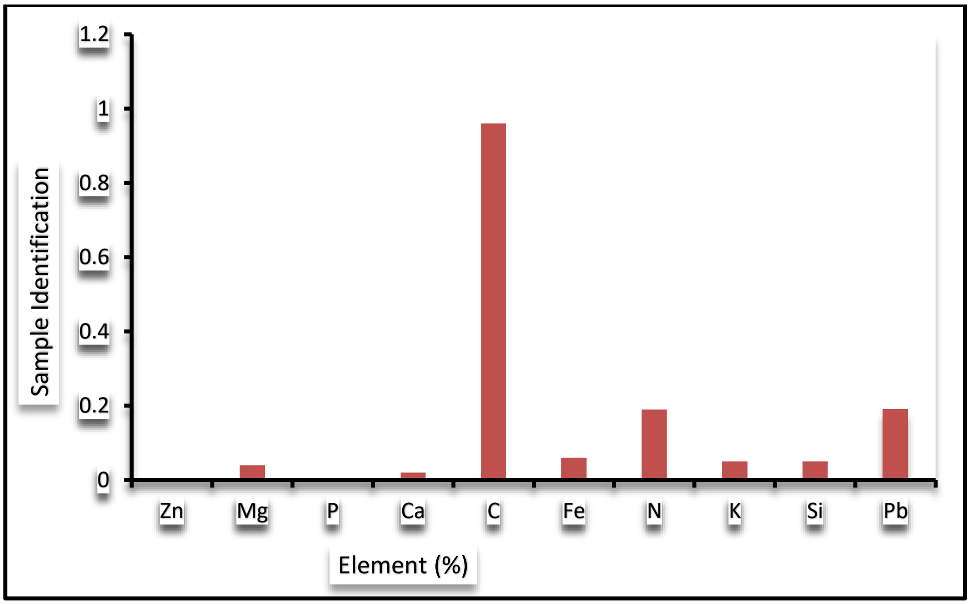

Figure. 1: Chemical Composition of Coconut Shell (%)

The chemical composition of coconut shell ash (CNSA) as shown in the provided Table 3, and Figure 1, highlights a predominant presence of carbon (C) at 0.96 %, followed by significant amounts of nitrogen (N), lead (Pb), and iron (Fe) at 0.19 %, 0.19 %, and 0.06 %, respectively. Calcium (Ca) also features prominently, though in two forms: elemental calcium at 0.02 % and Ca compounds (likely CaO) at around 1 %. Trace amounts of zinc (Zn), magnesium (Mg), potassium (K), phosphorus (P), and silicon (Si) are present as well. The high carbon content suggests that CNSA has considerable potential to act as a reinforcing phase in aluminum composites. Carbonaceous materials contribute to improved hardness and wear resistance, making CNSA-reinforced aluminum composites suitable for applications requiring durable, lightweight materials [7, 27, 29]. The nitrogen content might also contribute to increased hardness, as previous studies have suggested nitrogen's role in improving the mechanical properties of composites when combined with metal matrices [30,31].

The presence of calcium, particularly as CaO, is notable because calcium compounds can increase the thermal stability and corrosion resistance of the composite. This enhances the overall durability of the aluminum-CNSA matrix, making it more resistant to harsh environmental conditions [32, 33]. The detection of lead, however, may raise concerns due to its potential toxicity, but its relatively low content should not significantly impair the composite's properties. Iron and silicon content can contribute positively to tensile strength and wear resistance. The presence of these elements is beneficial as they help to improve the overall mechanical properties of the material, similar to ways other agro-waste-derived composites perform when integrated with metal matrices [34 35]. The chemical composition of CNSA shows that it has suitable characteristics for reinforcing aluminum composites, contributing to mechanical strength, wear resistance, and thermal stability.

Table 4: The Summary of Result of force (N), Elongation (mm) and tensile strength (N/mm^2) of Al, Al-CNSA

Breaking force (N)	Final length	Elongation (mm)	% Elongation	T.S. (N/mm^2)
1367	8.8	0.3	3.53	28.60
1827	8.8	0.3	3.53	38.22
1852	9.0	0.5	5.88	38.74
1931	9.0	0.5	5.88	40.40
2231	9.0	0.5	5.88	46.67
3337	12.1	3.6	8.50	65.81
1827	8.8	0.3	3.53	62.28

The above Table 4, presents the results of tensile strength (T.S.), elongation, and breaking force for aluminum (Al) and Aluminum-Coconut Shell Ash (CNSA) composites with varying percentages of CNSA reinforcement. A clear trend is observed as the addition of CNSA improves the tensile properties of the aluminum matrix composite (MMC). At 0 % CNSA (pure aluminum), the tensile strength is relatively low at 28.60 N/mm² with a breaking force of 1367 N and elongation of 0.3 mm (3.53 %). However, as the CNSA content increases, a significant improvement in tensile strength is observed. For example, at 2 % CNSA, the tensile strength increases to 38.22 N/mm², and at 6 % CNSA, it reaches 40.40 N/mm². The elongation also slightly increases, indicating better ductility compared to pure aluminum.

The peak tensile strength is observed at 10 % CNSA with a value of 65.81 N/mm² and a breaking force of 3337 N. This improvement can be attributed to the uniform dispersion of CNSA particles within the aluminum matrix, which enhances the material's ability to withstand tensile forces by providing improved load transfer across the matrix and reinforcing particles [36, 37]. Additionally, the increase in elongation to 8.50 % at 10 % CNSA demonstrates improved ductility, likely due to better particle-matrix bonding [7,17,34]. However, beyond 10 % CNSA, at 12 %, the tensile strength declines slightly to 62.28 N/mm². This reduction could be due to the agglomeration of CNSA particles, which creates localized stress concentrations and defects, leading to reduced strength [7, 16, 34]. The slight decrease in elongation at 12 % further supports the idea that excessive CNSA content can negatively affect the mechanical properties by reducing ductility. Nevertheless, the incorporation of CNSA significantly enhances the tensile strength and elongation of aluminum composites up to an optimal level of 10 %, after which the mechanical properties slightly decline due to particle agglomeration and reduced inter-facial bonding.

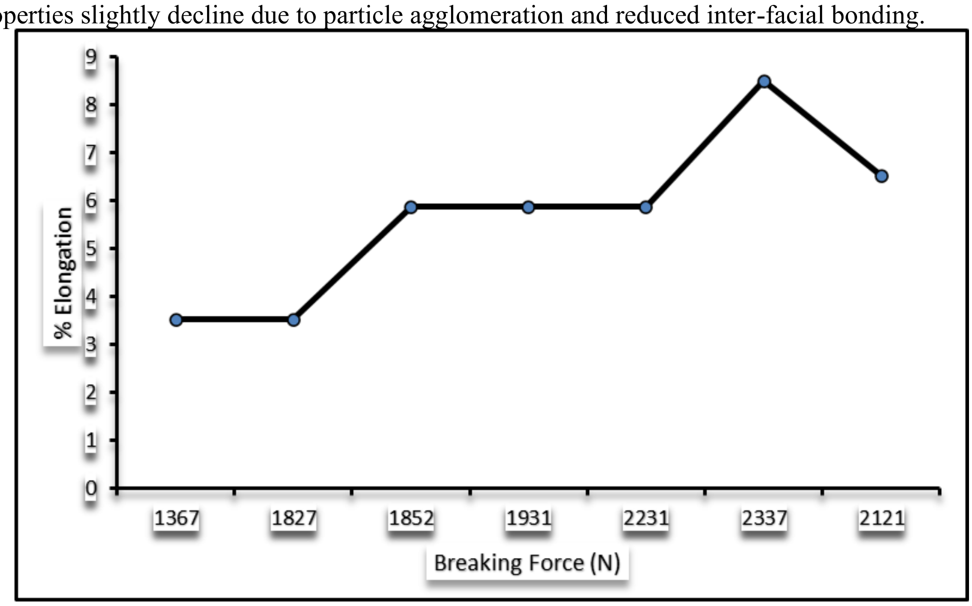

Figure 2: Effect of Breaking force on % Elongation

Figure 2 illustrates the relationship between breaking force and percentage elongation in aluminum-coconut shell ash (CNSA) metal matrix composites (MMCs). The graph reveals a direct correlation between increasing breaking force and elongation up to a critical point, followed by a decline, which offers insights into the behavior of the composite material under tensile stress. As seen in the graph, with an initial breaking force of 1367 N, the elongation is relatively low at 3.53 %. As the breaking force increases to 2231 N, the elongation rises steadily, reflecting the enhanced ductility of the composite up to this stage. This trend continues, with the peak elongation of 8.50 % observed at 3337 N. The increase in elongation alongside breaking force can be attributed to the reinforcing effect of CNSA, which disperses effectively within the aluminum matrix. This homogeneous dispersion strengthens the composite while allowing for better elongation under tensile loads [11, 38]. The coconut shell ash particles create load-bearing pathways within the composite, improving its ability to deform without fracturing.

However, as the breaking force reaches 2121 N, the percentage elongation declines slightly to around 6 %. This drop in elongation beyond the peak point suggests that excessive CNSA reinforcement may lead to particle agglomeration, which can reduce the overall ductility of the composite by creating stress concentrations and micro-cracks at the particle-matrix interface [37, 39]. These defects hinder the uniform distribution of stress and strain, thus limiting the material's capacity to elongate under higher loads. Moreover, the addition of CNSA improves the ductility and breaking force of aluminum-based composites up to an optimal point. Beyond this point, excessive reinforcement may cause agglomeration, reducing the material's ability to elongate further under tensile stress.

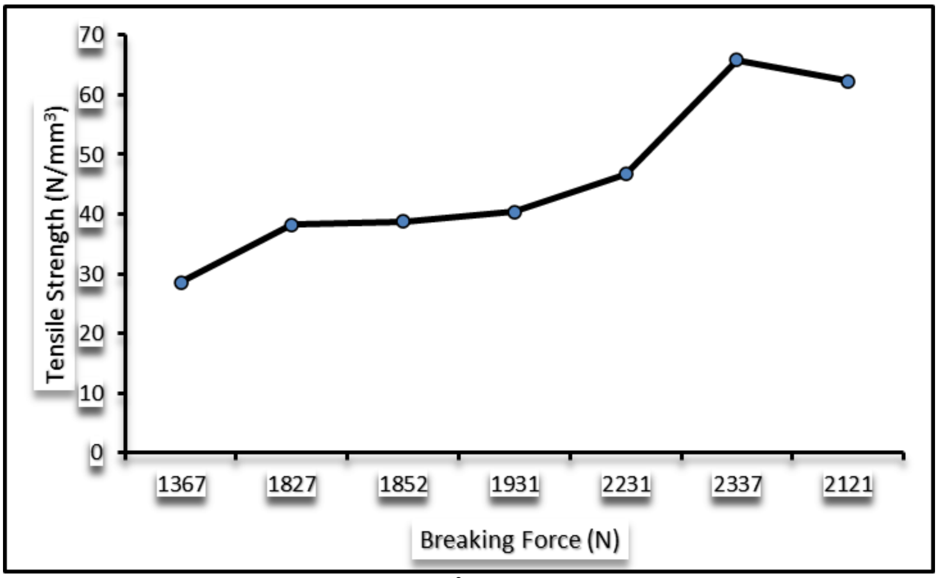

Figure 3: Effect of Breaking force on Tensile Strength (N/mm^2)

Figure 3 illustrates the effect of breaking force on the tensile strength of aluminum-coconut shell ash (CNSA) metal matrix composites (MMCs). The graph shows a progressive increase in tensile strength with increasing breaking force, reaching a peak at 65.81 N/mm² when the breaking force is 3337 N. Beyond this point, the tensile strength slightly decreases, indicating that the reinforcement of CNSA enhances the composite's mechanical properties up to a certain limit. The steady rise in tensile strength from 1367 N to 2231 N can be attributed to the uniform dispersion of CNSA within the aluminum matrix. The addition of coconut shell ash introduces hard phases such as silica (SiO_2), iron oxide (Fe_3O_4), and alumina (Al_2O_3), which serve as reinforcement particles within the aluminum structure [27, 40]. These phases improve the load-bearing capacity of the composite, allowing it to withstand greater tensile loads without failure. Additionally, the strong interfacial bonding between the matrix and the reinforcement contributes to better stress transfer during tensile loading, thereby increasing the tensile strength [11, 27].

However, at a breaking force of 2121 N, the tensile strength declines slightly to 62.28 N/mm². This drop can be explained by the possibility of particle agglomeration when higher volumes of CNSA are added, leading to stress concentration sites. These agglomerates act as points of weakness where micro-cracks can initiate, eventually reducing the overall strength of the composite [41]. This indicates that while CNSA reinforcement improves tensile strength, there is an optimal volume beyond which the mechanical properties may deteriorate. Importantly, the tensile strength of aluminum-CNSA composites improves significantly with increasing reinforcement up to an optimal point. Beyond this, excessive CNSA may lead to agglomeration and stress concentration, negatively affecting the material's strength.

4. Conclusion and Recommendation

This research on the production of aluminum-coconut shell ash (CNSA) metal matrix composites (MMCs) demonstrates the significant potential of using agro-waste materials as reinforcements in metal matrices to enhance mechanical properties. The incorporation of CNSA into aluminum resulted in improved tensile strength, hardness, and other mechanical characteristics, which make the resulting composites suitable for applications in industries that require lightweight materials with enhanced strength, such as the automotive and aerospace sectors.

From the tensile and hardness tests, it was evident that the addition of CNSA to aluminum significantly improved the mechanical performance of the MMCs. The tensile strength progressively increased with higher CNSA content, peaking at 10 % reinforcement, after which it slightly decreased. This trend can be explained by the uniform dispersion of CNSA particles within the aluminum matrix, which facilitated better load distribution and increased resistance to deformation. However, beyond 10 % CNSA content, particle agglomeration likely occurred, which caused stress concentration points and reduced the overall strength of the composite. This suggests that there is an optimal CNSA content for maximizing mechanical performance.

The hardness of the aluminum-CNSA composites also improved with increasing CNSA content. The presence of hard phases such as silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_3O_4) in the CNSA contributed to this enhancement, as these phases serve as hard particles that resist deformation under load. The highest hardness was observed at 12 % CNSA, indicating that CNSA reinforcement not only increases the strength but also the wear resistance of the composites. This finding aligns with previous studies that have shown the benefits of agro-waste-based reinforcements in improving the hardness of metal matrix composites [18, 27]. The analysis of the chemical composition of the CNSA revealed that elements such as calcium (Ca), iron (Fe), and silicon (Si) are present in significant quantities. These elements contribute to the improved mechanical properties observed in the composites, as they form hard reinforcing particles when integrated into the aluminum matrix. Moreover, the environmental benefit of utilizing agro-waste such as coconut shell ash in MMC production cannot be overstated, as it contributes to waste reduction and promotes sustainability in material engineering.

Based on the findings of this study, the following recommendations are proposed:
1. Optimization of CNSA Content: While the mechanical properties of the aluminum-CNSA MMCs improved with increasing CNSA content, the study identified an optimal reinforcement level at approximately 10 % CNSA. Beyond this point, the tensile strength begins to decline due to particle agglomeration. It is recommended that future studies explore surface treatments or particle dispersion techniques to prevent agglomeration and further optimize the mechanical performance of the composites at higher reinforcement levels.

2. Applications in High-Stress Environments: The improved hardness and tensile strength of the aluminum-CNSA composites suggest that they could be highly effective in applications that require high wear resistance and strength. These composites could be used in the production of automotive components such as engine parts, connecting rods, and pistons, as well as in aerospace applications where lightweight materials with high strength are essential.

3. Further Studies on Fatigue and Corrosion Resistance: While this study has focused on the tensile strength and hardness of the aluminum-CNSA composites, further investigations into other mechanical properties such as fatigue strength, impact resistance, and corrosion behavior are recommended. Understanding these properties is critical for determining the full potential of these composites in a wider range of industrial applications.

4. Environmental and Economic Impact Assessment: The use of agro-waste materials like CNSA offers not only mechanical benefits but also environmental advantages. Future studies should include a comprehensive environmental and economic impact assessment of producing aluminum-CNSA composites. This will help to quantify the sustainability benefits and cost savings associated with using agro-waste in material production, which could encourage broader adoption of these materials in industries.

5. Exploration of Other Agro-Waste Materials: In addition to coconut shell ash, other agro-waste materials such as rice husk ash, groundnut shell ash, and palm kernel shell ash have shown potential as reinforcements in MMCs. It is recommended that further research be conducted to explore the properties and performance of aluminum composites reinforced with other types of agro-waste to expand the application of these sustainable materials.

Furthermore, the production of aluminum-CNSA MMCs presents a viable and sustainable option for enhancing the mechanical properties of aluminum-based materials. The use of CNSA as a reinforcement not only improves tensile strength and hardness but also contributes to environmental sustainability by recycling agro-waste. With further optimization and exploration, aluminum-CNSA composites could play a critical role in advancing the performance of materials in various high-performance industries.

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