The Potentials of Kyanite Particles and Coconut Shell Ash as Strengthener in Aluminum Alloy Composite for Automobile Brake Disc

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Abstract

The use of waste materials to produce engineering components is currently attracting so much interest due to their low cost, availability and environmental impact. In this study, coconut shell ash (CSA) and kyanite particles (KP) produced from coconut shells and kyanite mineral respectively were characterized. X-ray Florence (XRF), X-ray diffractometer (XRD) and scanning electron microscope (SEM) were used to analyze the oxide compositions, crystalline phases and microstructures of CSA and KP. The XRF analysis revealed major oxides in CSA and KP as SiO₂ and Fe₂O₃; and Al₂O₃ and SiO₂ respectively. The XRD analysis revealed the presence of Quartz, Hematite, Andradite and Gaultite phases at major peaks in diffractogram of CSA; and Quartz and Beryl phases at major peaks in the diffractogram of KP. The crystallite sizes of the quartz phases in CSA and KP at diffraction angle of 26.72° and 20.91° were determined as 638.28 Å and 789.38 Å respectively. From the SEM image of CSA, it was observed that particles of different sizes are present in the microstructure of CSA. The average size of the particles in the microstructure of CSA is 26.24 µm. A similar result was observed in the SEM image of KP and average size of the particles is 3.074 µm. Also, the energy dispersive X-ray (EDX) spectrums of CSA and KP revealed the presence of many elements with calcium as the major element in CSA and Aluminium as major element in KP. The presence of the crystalline phases in CSA (SiO₂, Al₂O₃, andradite, gaultite and hematite) and KP (SiO₂ and Al₂O₃) will make them good strengthening materials for the production of Aluminium based composites that can be used in applications where a good combination of strength and wear characteristics is a basic requirement like brake disc.
Keywords
Kyanite Particles, Coconut Shell Ash, Oxide Compounds, Crystalline Phases, Density and Strengtheners

1. Introduction

Waste materials (metal scraps, plastic and crop) are materials that are discarded as refuse. They are mostly generated from food and crop processing either as solid or liquid waste [1] [2] [3]. In developing countries, proper management of wastes remains a big challenge. Wastes are burned in the open with resultant environmental pollution due to emission of gases [4] [5] [6] [7].

In Nigeria, wastes are generated daily in the cities due to diverse human activities, yet only few states provide dumpsites. These wastes include: cartons, papers, animals bones, plastics, aluminium plates, nylon bags, ceramics, vegetable stems, electronics, computers, photocopiers, aluminium cans, etc. Nigeria is the biggest contributors to solid waste in Africa with an estimated 32 million tons per year [8] [9] [10] [11] [12].

Coconut shell wastes are produced in large quantity in most tropical countries worldwide as Coconut forms a regular part of the human diets and other uses: food, drinks, oil, decorations, charcoal, cosmetics, etc. In Kumasi, Ghana, 91% of the 4.5 tonnes of coconut wastes produced monthly are abandoned as refuse [13] [14] [15]. In Nigeria, coconut is produced in a large quantity; and in 2017, Nigeria was ranked 18th in the world with a production capacity of 288,615 tonnes behind Ghana that produced 366,183 tonnes [16].

Some studies recommended the use of coconut shell ash (CSA) as reinforcing material in place of silicon carbide (SiC) and aluminium oxide (Al₂O₃) because it is cheap, light, and contains oxides such as silicon oxide (SiO₂), Al₂O₃, magnesium oxide (MgO), iron oxide (FeO), etc. that have been used to strengthen metal matrix composites [13] [14]. Also, studies on the physical and chemical characteristics of the rice husk, palm kernel shell, coconut shell, wood sawdust, palm oil fibre, fly ash, and groundnut shell showed similar oxide compositions. The apparent density, total ash content, moisture content, particle size distribution and average particle size distribution were found to fall within the range recommended by ASTM [17] [18] [19].

Coconut shell ash was reported to be good filler in concrete mix as it contained carbon, silicon dioxide, potassium oxide, etc. [18] [19]. The apparent densities and particle sizes of carbonized and uncarbonized coconut shell were found to decrease with increase in milling time. The average particle sizes were reported as 50.01 nm (uncarbonized) and 14.29 nm (carbonized) for the milling time of 70 hours. Reduction in the volatiles content of the shell enhanced hardness [20] [21] [22].

Kyanite, on the other hand, is a mineral resource that exists in commercial
quantity in Niger and Kaduna [23]. It is mostly found in aluminium-rich metamorphic pegmatites and has a chemical formula Al₂O₃·SiO₂. It is used to produce heat resistant ceramics, abrasives, plumbing fixtures and high-temperature furnaces because of its high, hardness and decomposition temperature of 4 - 7 HV and 1380˚C [24] [25] [26] [27] [28].

A study on the Geochemistry and Mineralogy of Kyanite revealed that Al₂O₃ and SiO₂ constitute 92%. This confirms the suitability of Kyanite for use as reinforcing material [29].

The purpose of this study is to explore the potentials of kyanite particles and coconut shell ash as strengtheners in AMC as alternatives to Al₂O₃ and SiC in view of the fact that they contained SiO₂, Al₂O₃, MgO, FeO, etc.

2. Experimental Methodology

2.1. Production of the Coconut Shell Ash

The coconut shells were sourced, cleaned and dried for 2 days, and crushed into smaller particles using a crusher. The crushed particles (Figure 1(a)) was sieved to fine powder using a 300 mesh screen of size 53 µm. 10 g of the shell powder was weighed and placed in a small graphite crucible. The crucible was placed in an electric resistance furnace and fired at 1200˚C for 6 hours to form CSA. The ash, shown in Figure 1(b), was again sieved to size 53 µm using a 300 mesh screen.

2.2. Production of Kyanite Particles

The Kyanite mineral (Figure 2(a)) was sourced and pulverized to form kyanite particles (KP) in the Material Processing Laboratory. The KP was sieved by passing it through a 300 mesh screen of size 53 µm and is as shown in Figure 2(b).

2.3. Characterization of CSA and KP

2.3.1. Density

First, the Pycnometer bottle (Figure 3) was washed using distilled water and allowed to dry. Then the following weights: dry empty bottle (Wₒ); bottle with

![Figure 1](image1.png)  
Figure 1. (a) Crushed coconut shell powder and (b) Coconut shell ash.
Figure 2. (a) Kyanite material; (b) Kyanite particles.

Figure 3. Pycnometer bottle for density test.

 CSA (W2); bottle with CSA and water (W3); and bottle with water (W4) were determined. This procedure was repeated for KP.

Then Equation (1) was used to evaluate the density of CSA and KP [30]:

\[
\rho = \frac{W_2 - W_1}{(W_4 - W_2) - (W_3 - W_2)} \times \text{density of water}
\]  

\[
\rho_{\text{CSA}} = \frac{51.316 - 37.648}{(87.135 - 37.648) - (95.862 - 51.316)} \times 1.0 = 2.7662 \text{ g/cm}^3
\]

\[
\rho_{\text{KP}} = \frac{45.342 - 37.604}{(87.137 - 37.604) - (92.499 - 45.342)} \times 1.0 = 3.2567 \text{ g/cm}^3
\]

2.3.2. Thermal Conductivity

10 g each of CSA was ground to very fine powder and liquid binder were added; then homogenized gently using a small mortar and pestle until the CSA turned to powder form. The prepared CSA was compacted to cylindrical specimens using a hydraulic press and specimen (Figure 4) was placed in Searle’s apparatus to measure the thermal conductivity. This procedure was repeated for the KP.

Equation (2) was used to evaluate the thermal conductivity of CSA and KP.

\[
K = \frac{QL}{A(T_2 - T_1)}
\]  

where: \( Q = \) heat (w); \( L = \) length or thickness of the specimen (m); \( A = \) cross-sectional area of the specimen; \( T_2 - T_1 = \) temperature gradient (K).
2.3.3. Oxide Compounds

The XRF was used to determine the Oxide compounds present in the CSA and KP. 10 g of CSA was placed in agate mortar and 1 g of stearic acid (binder) was added and the mixture thoroughly homogenized. The homogenized CSA was placed in a hardened steel disc and pressed into a pellet using hydraulic pressure press. Minipal 4 EDXRF at National Geoscience Research Laboratory was used to analyze the pellets. This procedure was repeated for the prepared specimen of KP.

2.3.4. Crystalline Phases

Empyrean XRD Spectrometer was used to determine the crystalline phases present in CSA and KP. 10 g of CSA was placed in a specimen holder and pressed. The specimen was placed in the spectrometer and the test parameters (diffraction angles) inputted through a computer system connected to the spectrometer. The measurement conditions were copper target operated at 40 keV and 30 mA, with a continuous scan mode in the range of 2° to 80° and drive axis of Theta-2-Theta. This procedure was repeated for 10 g of KP. The results are presented in Figure 5 and Figure 6 respectively.

The size of crystallite at the major peaks in the XRD profiles of CSA and KP was determined using Scherrer’s equation shown below:

\[ D = \frac{0.9\lambda}{\beta \cos \theta} \]  

where \( D \) = particle size; \( \lambda \) = wavelength of CuKa1 radiation = 1.5406 \( \text{Å} \); \( d \) = full width at half maximum intensity of the peak (in radians); \( \theta \) = half diffraction angle; \( \beta \) = constant = 0.9

The size of the crystallite particle at 2\( \theta \) of 21.7194° for CSA was determined as thus:

\[ D = \frac{0.9 \times 1.5406}{2.233 \times 10^{-3} \cos 13.3597} = 638.28 \text{Å} \]

2.3.5. Crystal Structure Analysis

5 g of CSA was used for the analysis. A double sided adhesive pad was attached
Figure 5. XRD profile of CSA.

Figure 6. XRD profile for KP.

to a bare specimen stub. Then the specimen was collected on the tip of a toothpick and the coated tip brushed against the expose adhesive of the specimen stub. The particles were pressed firmly against the adhesive pad. The stub containing the specimen was griped in place using a tweezer and then taped forcibly on the side of a table or bench to remove loose particles from the specimen stub. The specimen was placed in the Phenom SEM, and the specimen was transferred automatically to the optical imaging position. The optical camera was activated and the image was displayed in the main viewing window of the image screen. The brightness and magnification of the optical image were adjusted. The SEM image of CSA is shown in Figure 5. The procedure was repeated using 10 g of KP and SEM image is presented in Figure 6.

3. Results and Discussion

3.1. Density of CSA ($\rho_{CSA}$) and KP ($\rho_{KP}$)

The densities of CSA and KP are presented in Table 1.
Table 1. Density of CSA and KP.

|         | CSA (g·cm⁻³) | KP (g·cm⁻³) |
|---------|--------------|-------------|
| ρ       | 2.77         | 3.26        |

The results showed that CSA and KP are light materials. The density of the kyanite particle is higher than that of coconut shell ash. This perhaps is due to the high concentrations of Al₂O₃ and SiO₂ in kyanite particles compare to that in coconut shell ash. These densities fall within the range of densities of some ashes (fly ash, rice husk ash, groundnut shell ash, silica, etc.): 1.8 to 3.5 g·cm⁻³.

3.2. Thermal Conductivity of CSA and KP

Thermal conductivity (TC_{CSA}) of CSA and KP (TC_{KP}) are shown in Table 2.

The thermal conductivity of KP is higher than that coconut shell ash. This is attributed to the high concentration of aluminium in KP. This is in agreement with thermal conductivities of the ashes of most crop wastes which are generally low [18] [19].

3.3. Oxide Compounds Present in CSA and KP

The oxide compounds present in CSA and KP were obtained through XRF analysis and the results are presented in Table 3.

From Table 3, the major oxides present in CSA and KP are SiO₂, Al₂O₃, Fe₂O₃, and CaO. SiO₂ is major in CSA while Al₂O₃ is major oxide in KP. The higher concentrations of Al₂O₃ and SiO₂ particles in kyanite particles confirm the fact that is a compound of aluminium silicate [24] [25] [26] [27]. The oxides of CSA are similar to that presented by [17].

3.4. Crystalline Phases Present in CSA and KP

The different crystal phases present in CSA and KP are shown in Figure 5 and Figure 6.

Figure 5 showed the intensity of the different crystalline phases present in CSA. The crystalline phases are Quartz-Gautite, Quartz-Andradite, Hematite, Quartz, and Quartz-Andradite at respective diffraction angles (2θ) of 26.62°, 49.20°, 55.0°, 59.06° and 69.01°. The respective inter-planar spacing is 3.34, 2.69, 3.01 and 6.38 Å. The standard reference codes that matched the phases in the CSA are presented in Table 4. The amounts (in percent) of Quartz, Hematite, Andradite and Gautite are 61.6%, 1%, 18.2% and 19.2% respectively; revealed quartz to be the major Phase.

Figure 6 presents the intensity of the different crystalline phases in KP. The peaks indicated quartz and beryl when matched with standard codes. At diffraction angles (2θ) of 26.62° and 31.03°, the peaks are Quartz and Beryl at respective inter-planar spacing is 3.34 and 7.98 Å. The amount of quartz and beryl in KP are 64% and 36% respectively. The standard reference codes that matched the crystalline phases in KP are as shown in Table 5.
Table 2. Thermal conductivity of CSA and KP.

| Compound | CSA (Wm−1·k−1) | KP (Wm−1·k−1) |
|----------|----------------|---------------|
|          | 0.891          | 1.111         |

Table 3. Oxide compounds of CSA and KP (%).

| Compound | CSA (%) | KP (%) |
|----------|---------|--------|
| SiO2     | 25.14   | 47.10  |
| TiO2     | 2.38    | 01.15  |
| Al2O3    | 10.23   | 48.60  |
| Fe2O3    | 23.17   | 0.496  |
| SO3      | 5.90    | -      |
| CaO      | 18.20   | 0.14   |
| MgO      | 2.80    | 0.013  |
| Na2O     | 5.69    | 0.105  |
| K2O      | 3.10    | 0.13   |
| Cl       | 1.20    | -      |
| MnO      | 0.20    | 0.02   |
| V2O5     | 0.048   | 0.028  |
| Cr2O3    | 0.068   | <0.001 |
| CuO      | 0.476   | 0.03   |
| ZnO      | 0.476   | 0.006  |
| SrO      | 0.28    | 0.04   |
| BaO      | 0.65    | -      |
| L.O.I    | -       | 2.14   |

Table 4. Reference codes of standards that matched the crystal phases in CSA.

| Ref. Code | Score | Compound name | Chem. Formula |
|-----------|-------|---------------|---------------|
| 96-901-0146 | 72   | Quartz | Si6O6 |
| 96-900-9783 | 42   | Hematite | Fe2 O3 |
| 96-900-1254 | 29   | Andradite | Ca12 Fe7.54Si12O48 |
| 96-900-4338 | 18   | Gaultite | Zn33Si56 Na32O192H64 |

Table 5. Standard reference codes that matched the phases in KP.

| Ref. Code | Score | Compound name | Chem. Formula |
|-----------|-------|---------------|---------------|
| 96-900-9667 | 65   | Quartz | Si3O6 |
| 96-900-1555 | 72   | Beryl | Si3Be3Al33Fe18O36.41Na8.25H12.52 |

The presence of Quartz and Beryl will make KP suitable for use as a strengthening material for the production of metal composites.
The sizes of crystallites at the major peaks of the XRD profile of CSA and KP were determined using Scherrer’s equation shown below:

\[ D = \frac{0.9\lambda}{\beta \cos \theta} \]  

(4)

where \( D \) = particle size; \( \lambda \) = wavelength of CuKa1 radiation = 1.54060 Å; \( \beta \) = full width at half maximum intensity of the peak (in radians); \( \theta \) = half diffraction angle.

The size of the crystallite at \( 2\theta \) of 20.9134˚ and \( \beta = 0.1023^\circ \) was determined as follows:

\[ D = \frac{0.9 \times 1.5406}{1.7862 \times 10^{-3} \cos 0.4567} = 789.377 \text{ Å} \]

3.5. Microstructures of CSA and KP

The microstructures and energy dispersive spectrographs of the CSA and KP determined through SEM and Energy dispersive X-ray analysis respectively are presented in Figure 7 and Figure 8.
The SEM image of CSA presented in Figure 7 above revealed the presence of particles of different sizes. The microstructure of the produced CSA is not uniform. This perhaps is due to the presence of the crystalline phases (quartz, andradite, gaultite and hematite) in the ash. Also, the EDX spectrograph of the CSA revealed the presence of the following elements: calcium (Ca), phosphorus (P), silicon (Si), carbon (C), oxygen (O), iron (Fe), potassium (K), aluminum (Al), magnesium (Mg), silver (Ag), sodium (Na), sulphur (S), chlorine (Cl) and titanium (Ti); with Ca having the highest intensity. The presence of these elements showed that CSA has no radioactive and as such it is not toxic.

Like the SEM image of CSA, the SEM image of KP presented in Figure 8 above showed non-uniform microstructure. Particles of different sizes are observed to be present in the microstructure of KP. Perhaps, this is due to the presence of the crystalline particles (quartz and beryl) in KP. Also, the EDX spectrograph revealed the presence of the following elements: Al, Si, C, O, Mg, Ag, Nb, K, Ti, Ca, Cl, S, Na, P and Fe; with Al having the highest intensity.

3.6. Particle Sizes of CSA and KP

Imaging particle sizes of CSA and KP obtained from SEM images of CSA and KP (Figure 7 and Figure 8) are presented in Figure 9 and Figure 10. Tomography

![Figure 9. Particle size of CSA.](image1.jpg)

![Figure 10. Particle size of KP.](image2.jpg)
in Figure 9 and Figure 10 showed that the average particles sizes of CSA and KP are 26.42 µm and 3.074 µm respectively.

4. Conclusions

The following conclusions were made based on the production and characterization of coconut shell ash and kyanite particles.

1) The densities of CSA and KP showed CSA and KP are light materials.

2) The XRF analysis revealed SiO$_2$, Al$_2$O$_3$ and Fe$_2$O$_3$ as major oxides in CSA while SiO$_2$ and Al$_2$O$_3$ as major oxides in kyanite particles. The presence of these hard particles will make CSA and KP suitable for use as reinforcements for the production of Al composites.

3) The XRD analysis revealed Quartz, Hematite, Andradite and Gaultite as crystalline phases in CSA; and Quartz and Beryl as crystalline phases in KP. The quantity of the phases in CSA are Quartz (61.6%), Andradite (18.2%), Gaultite (19.2%) and Hematite (1%) while in KP Quartz and Beryl are 64% and 36% respectively.

4) The crystallite size quartz at 2θ of 26.7194˚C in XRD profile of CSA is 638.28 Å; while that quartz at 2θ of 20.9134˚C in the XRD profile of KP is 789.38 Å

5) The average particle sizes in the microstructures of CSA and KP are 26.42 µm and 3.074 µm. These will enhance strengthening when used as reinforcing material. No radioactive element was revealed by the EDX of CSA and KP.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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