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# Suitability Assessment of Okelele Ilorin Clay Mineral as a Raw Material for Sustainable Cement Production

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## ABSTRACT

Integrating the Sustainable Development Goals (SDGs)—particularly those related to innovation and infrastructure, responsible consumption, and climate action—into industrial practices is crucial, as the rising demand for cement depletes natural resources and poses significant environmental and social challenges. This article delves into the intricate relationship between the escalating demand for cement and the depletion of essential resources, while emphasizing the crucial need to align industry practices with the overarching principles of sustainable development as outlined by the SDGs. This article aims to shed light on the path towards a more sustainable and responsible approach to cement production. The objective of this study is to evaluate a clay mineral from Okelele, Ilorin, Kwara State, Nigeria, for its potential use as a raw material in cement production. The mineralogical and chemical compositions of the clay were analyzed using modern characterization techniques, including XRF, XRD, SEM/EDX, and DTA-TG. Cement was produced using the clay mineral and the limestone as raw materials with gypsum as admixture. Raw mix was prepared from clay and limestone to produce cement clinker. Sample A consisted of 70% limestone and 30% clay, sample B contained 75% limestone and 25% clay, while sample C was composed of 80% limestone and 20% clay. The cement produced from raw mixes A, B, and C was used to produce mortar specimens. The compressive strength of mortar samples A, B, and C was tested after curing periods of 7 and 28 days. XRF results indicated that the clay mineral contained silica ($SiO_2$) and alumina ($Al_2O_3$) as the major chemical constituents, with percentages of 70.226% and 20.815%, respectively—values typical of kaolinitic clay. Consistent with the XRF results, XRD analysis indicated that quartz and kaolinite were relatively abundant in the clay sample. EDX result shows a high proportion of silicon (48.74%) and aluminum (12.78%) in the clay. DTA-TG analysis of the raw mixes (samples A, B, and C) prepared from the clay and limestone showed an endothermic peak at 870°C and an exothermic peak at 1200°C. Sample B exhibited the highest compressive strength, with a value of 21.7 N/mm², compared to samples A and C. This compressive strength is in reasonable agreement with the minimum requirements of the British Standard. These results indicate that the clay mineral can be considered a suitable alumino-silicate raw material for cement production, and its composition is consistent with that of typical kaolin clay. The clay meets the minimum quality standards required for its use as a raw material in cement production.

## 1. INTRODUCTION

Ilorin possesses a variety of mineral resources, including clay minerals. Local clay minerals are mined from surrounding sources to produce pottery and ceramics. The potential uses of clay minerals are determined by their structural, physical, chemical, and other intrinsic properties [1]. The physical and chemical features of clay minerals influence their industrial applicability and appropriateness. Beneficiation processes are required before they may be used. Clay minerals are widely employed in a variety of industries, including oil absorption, iron casting, animal feeds, ceramics, medicines, drilling fluids, waste water treatment, food preparation, cosmetics, cements, and others [2]. Engineering applications encompass a broad range of uses for clay materials. Earth dams are rendered impervious to water by incorporating appropriate clay elements into porous soil. Similarly, the addition of clay can help mitigate water loss in canals. Furthermore, clay plays a crucial role as a fundamental component in the manufacturing of Portland cement. Clay minerals are crucial raw materials for the cement industry and several ancillary applications. The current study investigates the potential use of clay minerals in the construction sector. These minerals can be used as raw materials for producing white cement clinker and as an artificial pozzolanic addition for concrete, particularly in the form of metakaolin [1]. Clay is a crucial constituent in the contemporary material universe [3]. Clay is a type of material that is mostly composed of loose, earthy particles with a grain size smaller than 4 micrometers (μm) [3]. Feldspar-rich rocks gradually accumulate over long periods to form clay deposits [4]. Minerals, including those in clay, are naturally occurring substances distinguished by their specific chemical compositions and crystalline structures [4]. Clay minerals possess a layered structure and consist primarily of tetrahedrally structured silicate and octahedrally arranged aluminate groups [5]. The three primary categories of clay minerals are kaolinite, illite, and montmorillonite, also known as smectites. Clay minerals are composed of phyllosilicates, which consist of a layer of silicon tetrahedra and layers of aluminum, iron, and magnesium octahedra [4]. Cement is a binding material created by combining various raw materials, including lime, silica, alumina, and iron, which are then subjected to high temperatures [6]. The final product primarily consists of calcium silicates, with smaller amounts of calcium aluminates. When mixed with water, a chemical reaction known as hydration occurs, causing the cement to harden. Hydraulic cements, like Portland cement, can set and harden even underwater due to their strong affinity for water. Portland cement, the most commonly used type of hydraulic cement, is widely used in Nigeria and globally. It is typically produced either as an inter-ground blend or by blending the raw components at the concrete mixing plant [7].

Both naturally occurring minerals and manufactured products are frequently utilized in the production of cement. The materials used in cement manufacture are mineral compounds that consist of the essential components of cement: lime (Calcium oxide, CaO), silica (Silicon oxide, $SiO_2$), alumina (Aluminum oxide, $Al_2O_3$), and iron oxide ($Fe_2O_3$). The required proportions of these raw material components are seldom obtained in a single raw material. Therefore, it is crucial to select a balanced mixture of a high lime component and a component that is lower in lime but contains higher amounts of silica, alumina, and iron oxide. The primary components consist of limestone and either clay or limestone and marl [6].

Cement is the primary material used for building and construction. The primary steps in the cement production process include grinding raw materials (limestone and clay), combining the resulting raw meal, calcining the raw meal, chilling the clinker formed from the calcination process, blending the clinker with gypsum, and grinding them together [8]. The raw materials used for cement manufacture consist of four components: lime (calcareous), silica (siliceous), alumina (argillaceous), and iron (ferriferous) [8].

The chemistry involved in the manufacturing procedure of cement begins with the disintegration of clay minerals into $SiO_2$ and $Al_2O_3$, as well as calcium carbonate ($CaCO_3$), at a temperature of 840℃. This breakdown results in the release of carbon (IV) dioxide and the formation of calcium oxide (CaO). Calcination refers to the decomposition of calcium carbonate into calcium oxide and carbon dioxide [8]. Next, a clinking process occurs where calcium oxide (CaO) reacts with silica, alumina, and ferrous oxide at extremely high temperatures (1200-1450℃). This reaction produces tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium alumino ferrite, which make up the composition of a clinker. Subsequently, the clinker is pulverized in conjunction with gypsum and additional admixtures to generate cement. The quality of cement production is mostly determined by the quality of the raw feed, which may be checked and managed [8].

The ongoing exhaustion of raw materials for cement manufacturing, resulting from a rise in the demand for cement in construction and building applications, necessitates the exploration of commercially abundant and sustainable natural resources as alternative raw materials. The necessity to assess the Okele clay mineral in Ilorin, Kwara State, as an indigenous resources for long-lasting cement manufacturing has been stimulated.

This study primarily aimed to conduct a comprehensive mineralogical and chemical characterization of the investigated clay mineral. Modern characterization techniques, including X-ray Fluorescence (XRF), X-ray Diffraction (XRD), Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM/EDX), and Differential Thermal Analysis-Thermogravimetric Analysis (DTA-TG), were employed to analyze the mineral composition and structural properties of the clay. XRF was used to identify the chemical composition, while XRD facilitated the identification of the mineral phases present in the clay. SEM/EDX provided insight into the microstructure and elemental composition, while DTA-TG helped in understanding the thermal behavior and stability of the clay material.

Another key objective was to utilize the clay mineral in combination with limestone as raw materials for the production of cement. The specific aim was to investigate the potential of the selected clay mineral as a sustainable raw material in cement manufacturing. Cement was produced by blending the clay mineral with limestone and adding gypsum as an admixture to regulate the setting time of the cement. A raw mix was carefully prepared using appropriate proportions of clay and limestone, which was then subjected to high-temperature firing to produce cement clinker. Following the production of cement clinker, it was essential to assess the properties of the resulting cement. This included evaluating the physicochemical properties, such as setting time, compressive strength, and mineral composition, to determine the performance of the cement when used in construction.

This research is guided by the central question: "*Can the Okelele clay mineral from Ilorin, upon thorough characterization and processing, serve as an effective alternative raw material for sustainable cement production?*" The practical application of this study focuses on leveraging locally abundant clay resources to develop more sustainable cement manufacturing processes. By partially replacing traditional raw materials like limestone with clay minerals, the research aims to reduce raw material depletion, lower carbon emissions, and support the goals of environmental sustainability in line with the Sustainable Development Goals (SDGs).

## 2. MATERIALS AND METHODS

### 2.1 Materials

Clay minerals were obtained from the Okelele deposit in Ilorin, Kwara State of Nigeria. Fine powder of calcium carbonate (industrial grade) as well as gypsum was purchased from Integrated Research Laboratory, Aleniboro village, Ilorin, Kwara State.

### 2.2 Methods

2.2.1 Clay mineral sample collection

Clay mineral samples were collected by the method described by Damilola et al. [9]. A hand auger was used to drill to the basement complex of the clay mineral deposit in Okelele, Ilorin, Kwara State, Nigeria. Both surface and subsurface clay minerals were collected at four different cardinal points with an equidistance of 400m away from one another on the study site.

The clay samples were collected from the Okelele area in Ilorin, Kwara State, Nigeria. Sampling points were selected based on preliminary geological surveys that identified representative and homogeneous exposures of the clay deposit. Areas with minimal surface contamination, visible impurities, or human disturbances were prioritized. To obtain samples that accurately reflect the in-situ properties of the clay, the material was collected at depths ranging from 0.5 to 1.0 meters below the surface. This depth was chosen to minimize the influence of surface weathering, organic matter accumulation, and anthropogenic activities, thereby ensuring the integrity and consistency of the clay's mineralogical and chemical characteristics. Multiple samples from different points were combined to form a composite sample, ensuring a more comprehensive representation of the deposit. The collected samples were air-dried, pulverized, and sieved before being subjected to further characterization and testing.

2.2.2 Clay mineral sample preparation

The clay mineral sample was prepared as described by DamilolaKayode et al. [10]. The clay mineral sample from the study site was mixed to obtain uniform samples of the clay Mineral. The non-clay mineral samples were separated from the Clay mineral sample by hand picking. The clay mineral was then dried at ambient temperature for 5 days. The clay Mineral samples were crushed and milled using pestle and Mortar prior to the analysis. The milled clay mineral sample was sieved using an ASTM-E11 Sieve. The clay mineral sample of size less than W0.6 mesh was obtained.

2.2.3 Moisture content determination

The aluminum dishes were washed and then dried in an oven and a desiccator to chill. Every dish was measured for weight. A sterile metal dish was used to weigh 5.0 g of the ground clay mineral sample. The dish's weight and the weight of the clay mineral sample in its undried state were measured. The sample was placed in an oven set at a temperature of 80℃ for 2 hours, followed by a temperature of 105℃ for 3 hours. The item was extracted and subsequently cooled inside a desiccator. Subsequently, the weight was determined utilizing a scale balance. The item was returned to the oven for an additional hour and subsequently weighed again. The process persisted until a stable weight was achieved. The disparity in mass between the starting mass and the ultimate stable mass signifies the moisture content [11].

2.2.4 Particle size distribution

The particle size examination of the clay mineral sample was done using the approach given by Gavlak et al. [12]. A hydrometer of standard specifications, specifically ASTM NO1.152H-Type, equipped with a buoyancy scale measured in grams per liter (gl-1), was utilized. The proportions of clay, sand, silt, and gravel were calculated by measuring the values from the graph of the grain size curve D versus the adjusted percentage finer on the semi-logarithmic chart.

2.2.5 Clay mineral characterization

The clay mineral was subjected to an extensive examination utilizing advanced characterization techniques. X-ray fluorescence (XRF) was used to determine the elemental composition, typically with 40–50 kV and 10–40 mA for voltage and current, respectively, with 300–600 seconds of exposure time for optimal results. X-ray diffraction (XRD) was used to identify the mineral phases in the Okelele Ilorin Clay, typically CuKα (wavelength λ = 1.5406 Å) with 5° to 70° scan range, step size of 0.02°, and 1°/min scan speed. The surface morphology of the clay mineral was examined through a scanning electron microscope (SEM) with accelerating voltage 20 kV, working distance 10 mm and detector range set between 5 – 20 keV while the magnification was taken at 10 µm, and the spatial distribution of various components was determined using energy dispersive x-ray emission (EDX) technique. Additionally, the thermal behavior of the clay mineral and raw mix was investigated using differential thermal analysis-thermogravimetric analysis (DTA-TG) with a heating rate of 10°C/min and a temperature range of 25℃ to 1000℃.

2.2.6 Raw mix design and proportioning

The blending of limestone and the clay mineral sample was carried out as described by Fredrick and Thomas [7]. The blending range of ordinary Portland cement is 70 – 80 % calcium carbonate and 20 – 30% clay mineral [13]. Three samples of raw mix were obtained for this research purpose. Limestone was blended with a clay mineral sample to obtain a single homogeneous material called the raw mix. A hand trowel was used to mix the raw material together. Table 1 summarizes the feed composition for the raw mix.

The selection of the mixing ratio between the Okelele Ilorin clay mineral and limestone was based on achieving the ideal chemical composition for clinker production, specifically targeting the required ratios of lime saturation factor (LSF), silica modulus (SM), and alumina modulus (AM). These ratios ensure the formation of the primary clinker phases—alite ($C_3S$), belite ($C_2S$), aluminate ($C_3A$), and ferrite ($C_4AF$)—which are essential for producing high-quality Portland cement. The raw mix was proportioned to achieve an LSF of approximately 0.92–0.98, SM between 2.0–2.6, and AM in the range of 1.3–1.6, in accordance with the standard cement chemistry guidelines [13]. The chemical composition of the raw materials, determined through XRF analysis, guided the mix calculation using the Bogue formula.

**Table 1.** Summary of raw mix composition

| Raw Mix Samples | Composition of $CaCO_3$ (%) | Composition of Clay Mineral (%) | Weight of $CaCO_3$ (g) | Weight of Clay Mineral (g) | Total Feed (g) |
|---|---|---|---|---|---|
| A | 70 | 30 | 1050 | 450 | 1500 |
| B | 75 | 25 | 1125 | 375 | 1500 |
| C | 80 | 20 | 1200 | 300 | 1500 |

2.2.7 High-temperature calcination parameters of the blended material (Raw mix)

The composite substance (sample A) was subjected to high temperatures in a furnace, reaching a sintering temperature of around 1300℃ for 1 hour, resulting in the formation of cement clinker. The clinker was permitted to cool at ambient temperature. The process was replicated for samples B and C.

The calcination process was carried out in a muffle furnace under controlled conditions to mimic industrial clinkerization. The raw mix was initially heated to 900℃ at a ramp rate of 10℃/min to remove chemically bound water and initiate decomposition of carbonates. It was subsequently raised to the sintering temperature of 1,300℃, held for 1 hour to ensure complete formation of clinker phases, and then cooled gradually to room temperature.

Key parameters for the calcination process included:

- Pre-heating temperature: 900℃
- Sintering temperature: 1,300℃
- Holding time at peak temperature: 60 minutes
- Heating rate: 10℃ per minute
- Cooling rate: Natural furnace cooling to minimize thermal shock

These conditions were chosen based on established laboratory protocols for cement clinker synthesis [14] and were optimized to ensure phase development and uniform sintering of the raw mix.

2.2.8 Grinding of the clinker

The clinker obtained and 5% of gypsum were ground together using pestle and mortar to produce the cement. The cement produced was sieved to a fine powder of about 90µm using ASTM-E11 Pre-sieve W0.2 mesh. The fine powder obtained is the cement product. This was repeated for samples B and C.

2.2.9 Cement testing

The quality of the generated cement was assessed through analysis. The cement produced underwent several tests, including normal consistency to assess its consistency, setting time to determine the time it takes to harden, soundness to evaluate how well it holds up during volume changes, and compressive toughness to measure its ability to withstand pressure. The testing procedures utilized in this study were derived from the British standard for testing cement in a laboratory setting (BS EN 196-6: 2018 Standards of Testing Cement).

## 3. RESULTS AND DISCUSSION

The result of the percentage moisture content and particle size distribution is shown in Table 2.

The percentage moisture content of the clay mineral sample under evaluation is 11.20%. The result clearly indicated that the clay mineral is characterized by low moisture content compared with the Ire-Ekiti clay mineral deposit. The percentage moisture content of the Ire-Ekiti clay mineral deposit is 15.28% [9]. The difference in the percentage moisture content between the Okelele clay mineral deposit, Ilorin, and Ire Ekiti clay mineral deposit could be as a result of geographical location and geological conditions [10]. The clay mineral under investigation shows a higher percentage of clay composition (57%) and sand composition of 23%. This indicated that the clay mineral is clayed sand, as suggested by Ochieng [5].

**Table 2.** Percentage moisture content and size distribution of the clay mineral under investigation

| **Moisture Content (%)** | **Particle Size Distribution (%)** | | | |
|---|---|---|---|---|
| | Clay | Sand | Silt | Gravel |
| **11.20** | 57 | 23 | 17 | 3 |

### 3.1 Clay mineral sample characterization

The clay mineral sample was characterized to determine its suitability as a cement raw material for cement production. The chemical composition (see Table 3), mineralogical composition, surface morphology, elemental distribution (see Table 4), as well as thermogravimetric analysis of the clay mineral sample were determined /carried out.

**Table 3.** Chemical composition of the clay mineral under investigation

| **Chemical Compounds** | **Composition (wt %)** |
|---|---|
| $SiO_2$ | 70.226 |
| $Al_2O_3$ | 20.815 |
| $Fe_2O_3$ | 2.1810 |
| $V_2O_5$ | 0.162 |
| $C_2O_3$ | 0.056 |
| MnO | 0.043 |
| $CO_3O_4$ | 0.020 |
| NiO | 0.005 |
| CvO | 0.042 |
| $Nb_2O_3$ | 0.027 |
| $MoO_3$ | 0.001 |
| $P_2O_5$ | 0.102 |
| $SO_3$ | 0.613 |
| CaO | 0.356 |
| $K_2O$ | 0.777 |
| BaO | 0.192 |
| $Ta_2O_5$ | 0.024 |
| ZnO | 0.012 |
| $Ag_2O$ | 0.029 |

**Table 4.** Elemental composition of the clay mineral under study

| **Elements** | **Concentration (%)** |
|---|---|
| O | 50.066 |
| Al | 11.017 |
| Si | 32.827 |
| P | 0.045 |
| S | 0.245 |
| Cl | 0.588 |
| K | 0.645 |
| Ca | 0.254 |
| Ti | 1.754 |
| V | 0.091 |
| Cr | 0.038 |
| Ma | 0.033 |
| Fe | 1.965 |
| Co | 0.015 |
| Ni | 0.004 |
| Cu | 0.034 |
| Zn | 0.010 |
| Zr | 0.129 |
| Nb | 0.022 |
| Mo | 0.001 |
| Ag | 0.027 |
| Ba | 0.172 |
| Ta | 0.019 |

3.1.1 Chemical composition

The result of the chemical composition of the clay mineral and the elemental compositions are shown in Tables 3 and 4, respectively. From the result in Table 3, it is shown that silica ($SiO_2$) and alumina ($Al_2O_3$) are the major chemical composition of the clay mineral sample, with percentage composition of 70.226 and 20.813% respectively. For a clay mineral to be suitable for cement production, the percentage composition of silica ($SiO_2$) and alumina ($Al_2O_3$) should be in the range of 70-75% and 18-22%, respectively [4]. This indicated that the clay mineral sample under investigation could serve as a suitable raw material for cement production. According to the international cement standard, the maximum concentration of MgO for clay minerals to be suitable for cement production should be less than 5%. The clay material under evaluation has no MgO at all, which further attests to its suitability for cement production.

The higher percentage of silica ($SiO_2$) and Alumina ($Al_2O_3$) in the clay mineral under investigation also indicated higher kaolinite content of the material as suggested by DamilolaKayode et al. [10]. This indicated that the clay mineral under investigation is kaolin clay. From technical literature, it has been indicated that kaolin clay consists mainly of kaolinite mineral, which is characterized by a higher percentage of silica ($SiO_2$) and Alumina ($Al_2O_3$) compared to other chemical compositions [14-16].

The result of the elemental constituents of the clay mineral sample, shown in Table 4, indicated that Aluminum, Silicon, and Oxygen are the major elemental constituents of the clay material. The higher percentage of Aluminum (11%) and silicon (32%) in the clay mineral sample further confirmed the alumino-silicate nature of the clay mineral under evaluation as typical kaolin clay. The presence of a high percentage of oxygen (50.066%) in the clay mineral sample could indicate that the elements were present in their oxide form.

The exchangeable ions, such as Ca, Na, Fe, Cu, Zn, and K, which are present in significant amounts as shown in Table 4 in the clay mineral, indicate an absorbent property of the clay mineral under investigation. This suggested that the clay mineral could be used for the remediation of metals and non-metals from their contaminated medium by an ion exchange mechanism [9, 15].

**3.2 Mineralogical composition of the clay mineral**

The result of the mineralogical composition (phase identification) of the clay mineral under evaluation is presented in Table 5 and Figure 1. The mineralogical composition (phases) present is quartz, allophone, kaolinite, chlorite, garnet, anatase, and muscovite. The main minerals are quartz, allophone, and kaolinite. The allophone and kaolinite belong to the group of clay called kaolin clay. This further agrees with the result of the chemical composition of the clay mineral, which suggests that the clay is typical kaolinite clay.

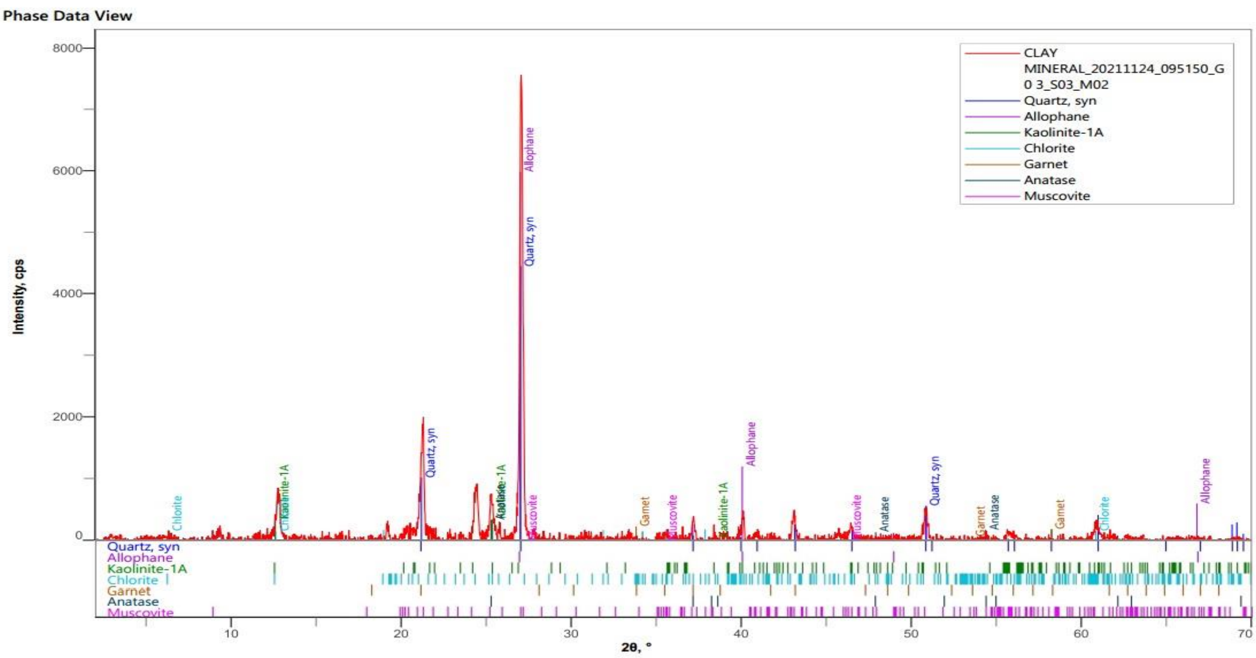



**Figure 1.** XRD was generated for the clay mineral sample

**Table 5.** XRD qualitative analysis of the clay mineral sample

| Phase Name | Formula |
|---|---|
| Kaolinite | $Al_2Si_2O_5(OH)_4$ |
| Quartz | $SiO_2$ |
| Garnet | 3(Ca,Fe,Mg)O.(Al,F) |
| Muscovite | $KAl_2(Si_3Al)O_{10}(OH)_2$ |
| Chlorite | $(Mg,Fe)_3(Al,Si)_3O_{10}$ |
| Anatase | $TiO_2$ |
| Allophane | $Al_2O_3.SiO_2.3H_2O$ |

### 3.3 Surface morphology of the clay mineral sample

The Microspores structure, size of the pores on the surface of the clay mineral sample, and the pore diameter are presented in the SEM Micrograph shown in Figure 2, and its EDX chemical analysis is presented in Table 6.

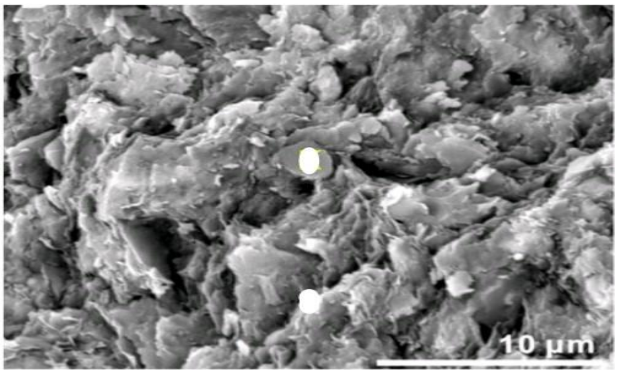



**Figure 2.** SEM surface morphology of the clay mineral under investigation

The SEM image in Figure 2 indicates that the clay mineral sample has platy grains, rounded edges, and a centered, dense, compacted texture with a pore diameter of 10 micrometers.

### 3.4 EDX of the clay mineral sample

The EDX data were displayed in Table 6. The EDX analysis also revealed the presence of significant exchangeable cations, including iron (Fe), calcium (Ca), and sodium (Na). The elevated proportions of Si (48.74%) and Al (12.78%) in relation to other elements indicate that the clay mineral being studied is predominantly kaolin. This finding corroborates the results obtained from XRD and XRF analysis, as proposed by Awokunmi and Asaolu [15].

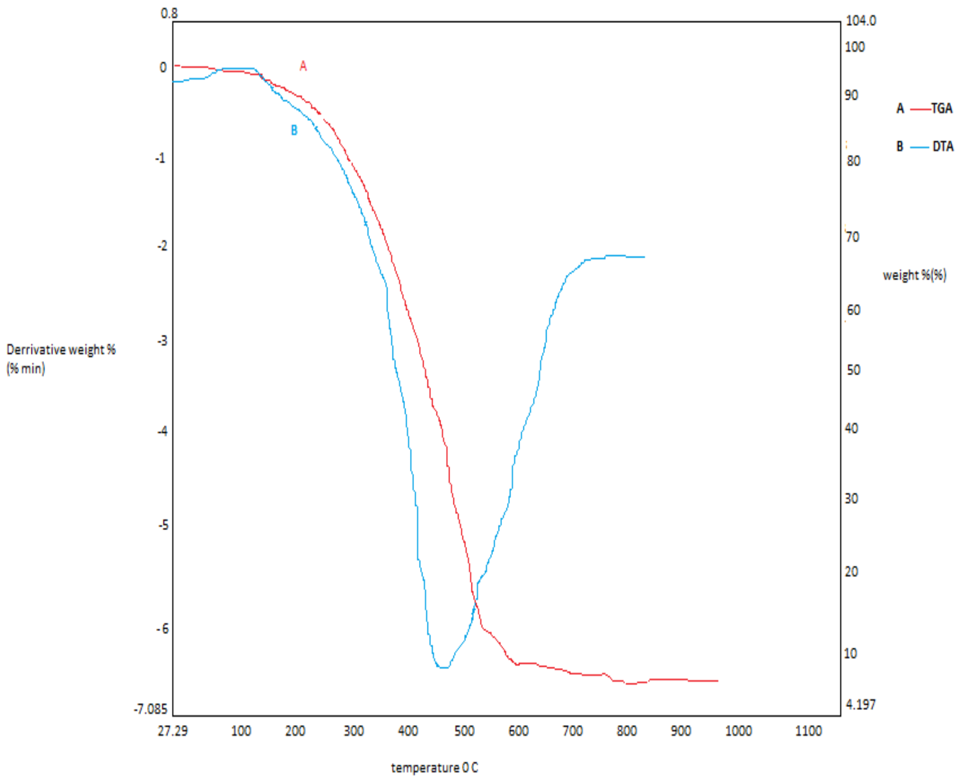
**Table 6.** EDX chemical analysis of the clay minerals

| Element Number | Element Symbol | Element Name | Atomic Conc. | Weight Conc. |
|---|---|---|---|---|
| 14 | Si | Silicon | 57.65 | 48.74 |
| 13 | Al | Aluminum | 15.74 | 12.78 |
| 26 | Fe | Iron | 6.94 | 11.67 |
| 22 | Ti | Titanium | 5.06 | 7.29 |
| 19 | K | Potassium | 4.86 | 5.72 |
| 47 | Ag | Silver | 1.00 | 3.24 |
| 39 | Y | Yttrium | 1.18 | 3.16 |
| 41 | Nb | Niobium | 0.57 | 1.60 |
| 20 | Ca | Calcium | 1.26 | 1.53 |
| 17 | Cl | Chlorine | 1.38 | 1.47 |
| 16 | S | Sulfur | 1.43 | 1.38 |
| 6 | C | Carbon | 1.57 | 0.57 |
| 11 | Na | Sodium | 0.54 | 0.37 |
| 12 | Mg | Magnesium | 0.00 | 0.00 |
| 7 | N | Nitrogen | 0.37 | 0.16 |
| 15 | P | phosphorus | 0.00 | 0.00 |

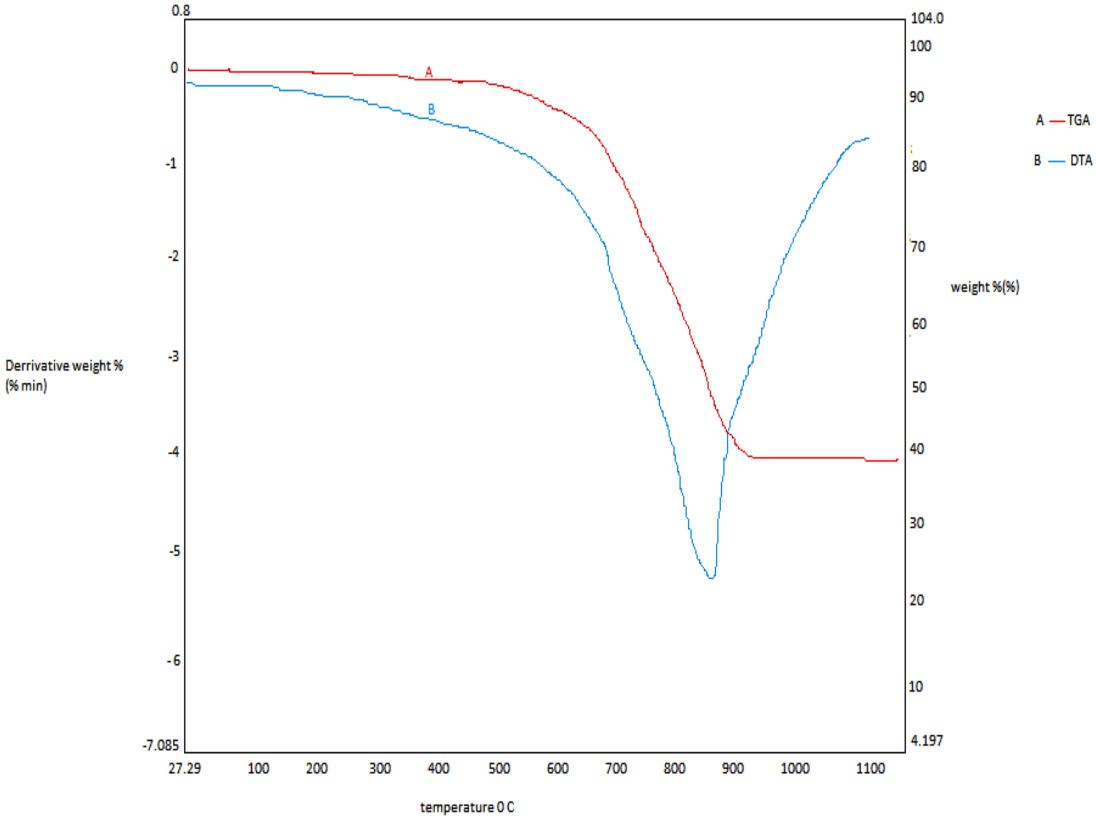
### 3.5 Thermogravimetric analysis

The thermal degradation behavior of the clay mineral, calcium carbonate, and the raw mix for samples A, B, and C was studied by DTA-TG, and the results are presented in Figure 3(a)-(e).

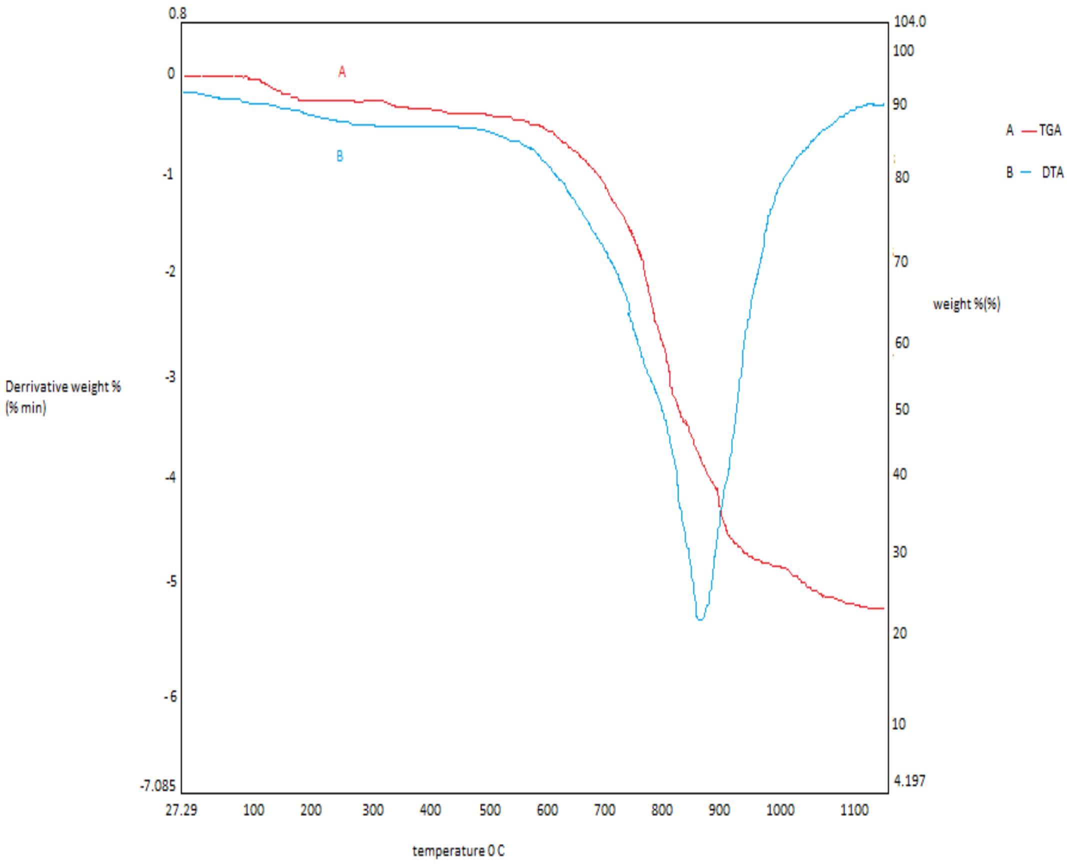
The DTA–TG curve for the clay mineral under investigation is shown in Figure 3(a). From Figure 3(a), the result shows that, at a temperature of about 230.02°C, 96.5% of the weight was still retained, showing a drying process which resulted in low moisture content. The dehydroxylation endotherm at about 375.16°C is associated with a weight loss of 4.635%. This is as a result of the removal of OH groups and conversion of kaolin to meta-kaolin as suggested by Yassin et al. [4]. The recrystallization exotherm was noted at 887.28°C. At a temperature of about 650°C, the weight of the clay material begins to be relatively stable due to the complete removal of the OH group from the clay mineral.



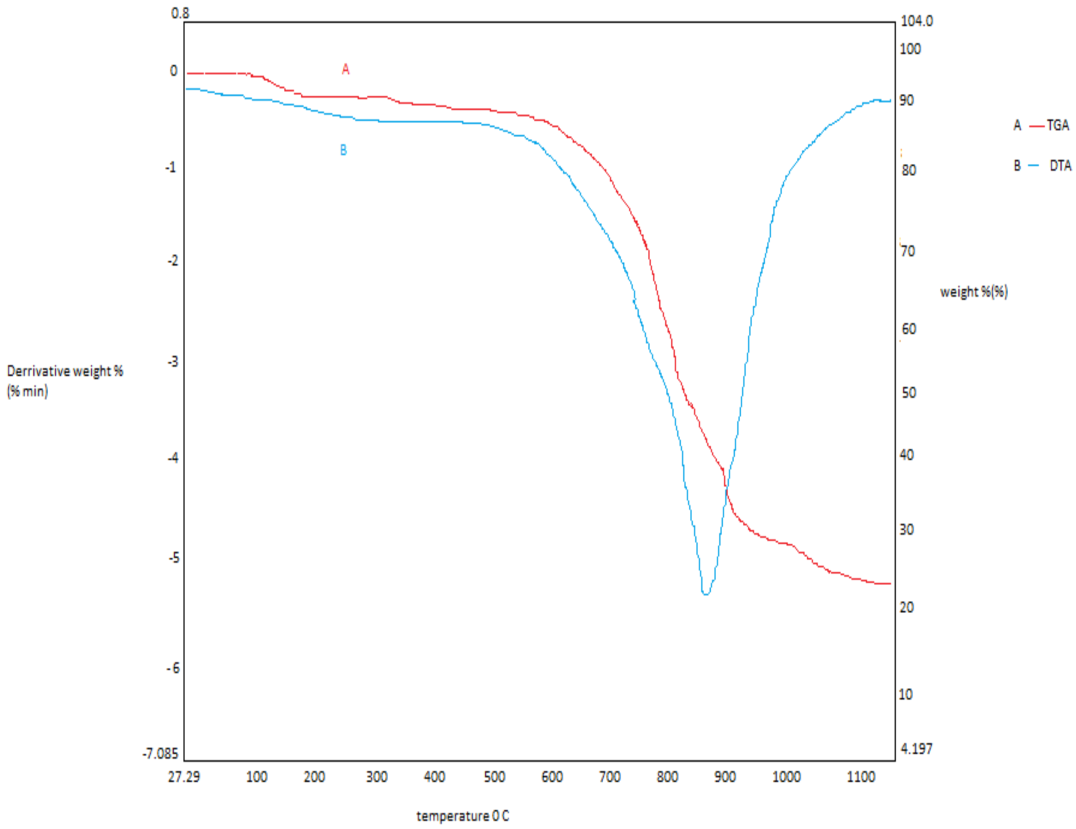

(a) DTA-TG analysis of the clay mineral



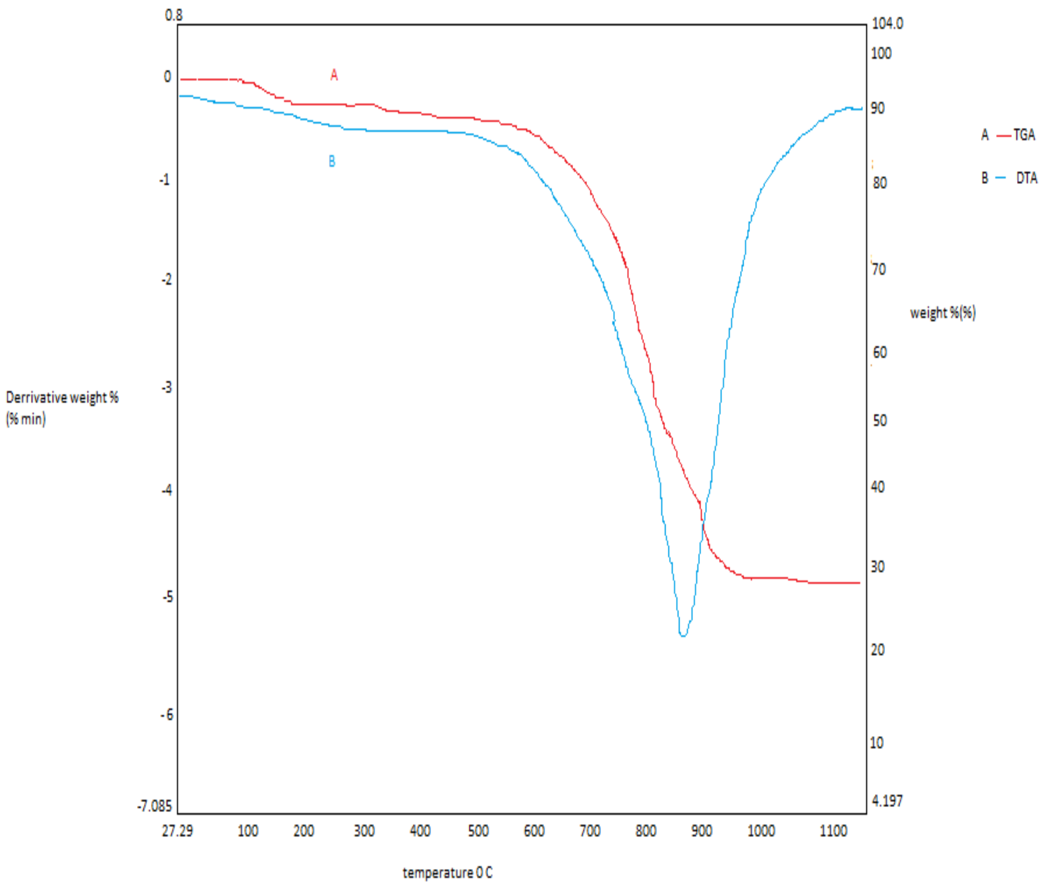

(b) DTA-TG analysis of the calcium carbonate (Limestone)




(c) DTA-TG analysis of the raw mix (Sample A)




(d) DTA-TG analysis of the raw mix (Sample B)




(e) DTA-TG analysis of the raw mix (Sample C)

**Figure 3.** DTA-TG curve

The result of DTA-TG analysis for limestone (calcium carbonate) is shown in Figure 3(b). At a temperature range of about 0-450°C, the weight of the limestone is relatively stable, which is an indication of little or low moisture in the material. The decomposition endotherm is about 870°C, with a weight loss of about 40%. This is associated with the decomposition of $CaCO_3$ into CaO and $CO_2$. The exotherm temperature is about 1100°C. This is a result of the transformation of limestone into CaO [16]. At a temperature of 890°C, the weight of the material begins to be relatively stable due to the complete removal of $CO_2$ from the limestone [16].

The DTA-TG analytical curves for the raw mixtures of samples A, B, and C are shown in Figures 3(c), 3(d), and 3(e), sequentially. Throughout the sintering procedure of the raw mix for samples A, B, and C, both endothermic and exothermic processes occur to generate clinker [16]. The endothermic peak, observed at around 870°C, is indicative of the disintegration of limestone into calcium oxide (CaO) and carbon dioxide ($CO_2$). This peak is consistent across samples A, B, and C. The exothermic peak observed at 1200°C, when analyzing the raw mix of samples A, B, and C, is caused by a solid-state reaction. This reaction involves the gradual synthesis of tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium alumino ferrite, as described by Luo et al. [16]. The analysis indicates that the breakdown of limestone and the fusion of the liquid phase, along with the formation of tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium alumino ferrite in the raw mixture of samples A, B, and C, are identical. Changes in the composition of the raw mix can only impact the strength of the cement generated from that mix [16-18].

### 3.6 Normal consistency of the cement produced

The normal consistencies of the cements produced are 37%, 35%, and 30% for samples A, B, and C, respectively. The Normal consistency for cement according to the British standard is between 25%-35%. Samples B and C of the cement produced fall within this range, which indicates moderate silica composition in the cements. Sample A of the cement produced has 37% as its normal consistency, which was a little bit higher compared to the British Standard; this could be a result of excessive composition of silica in the cement [19, 20].

### 3.7 Setting time

The cement developed has an initial setting time of 112 minutes. According to the British standard, the suggested initial setting time should be a minimum of 45 minutes. This aligns with the initial setting time of the cement manufactured. The cement developed has a final setting time of 262 minutes. The maximum acceptable duration should not exceed 10 hours (600 minutes) as specified by the British Standard [17, 21-24]. The final setting time of the Cement produced conforms to the specified standard.

### 3.8 Soundness of the cements produced

The standard value of the soundness of cement should not exceed 10 mm [17, 25, 26]. The soundness of the cement produced ranges between 0-1 mm, which is in good agreement with the standard value. This could suggest that the cement produced is of good quality.

### 3.9 Strength of the cements produced

The summary of the results of compressive strength of samples A, B, and C of cement produced and control cement is presented in Table 7.

The compressive strengths obtained for the cements produced for 7 days curing period are 13.1, 14.3, and 13.5 $N/mm^2$ for samples A, B, and C, respectively. The result for Sample B is close to the compressive strength of the control cement (OPC), which is 16.6 $N/mm^2$. The different experience in the compressive strength of the cement produced could be a result of compaction of the mortars, quality of raw material, and strength of the aggregate, as suggested by the following authors [18, 27, 28].

**Table 7.** Summary of results of compressive strength of samples A, B, and C of cement produced & control cement

| Period (Days) | Sample A ($N/mm^2$) | Sample B ($N/mm^2$) | Sample C ($N/mm^2$) | Control (OPC) ($N/mm^2$) |
|---|---|---|---|---|
| 7 | 13.1 | 14.3 | 13.5 | 16.6 |
| 28 | 18.3 | 21.8 | 19.8 | 23.7 |

The results obtained for 28 days curing for the cements produced are 18.3, 21.8, and 19.8 $N/mm^2$ for samples A, B, and C, respectively. For the control, the result is 23.7 $N/mn^2$. The results obtained are different from the control but are within the minimum values for the British standard (16-21 $N/mn^2$). Sample B gave the best compressive strength of value 21.8 $N/mm^2$, followed by sample C (19.8 $N/mn^2$), and sample A has the least compressive strength value of 18.3 $N/mm^2$. The high compressive strength of Sample B could be a result of the raw mix ratio of 3:1 of limestone and the clay mineral under investigation. Sample B gave the best result of the cements produced.

The high alumina ratio (AR) reduces the early strength of the cement produced [19, 28-30]. The strength of samples A (13.1 $N/mm^2$) and C (13.5 $N/mm^2$) at 7 days curing period differed from the strength of the control cement (16.6 $N/mm^2$). The effect of high AR is also felt on the strength of sample B (14.3 $N/mm^2$) at 7 days curing period. This reduction in the early strength of the cements produced (samples A, B, and C) compared with the strength of the control cement (OPC) is a result of the high alumina ratio N [31, 32]. The high AR could be easily controlled by adding an appropriate amount of iron oxide to the raw mix [33-35].

## 4. CONCLUSIONS

Okelele Clay Mineral in Ilorin, Kwara State, Nigeria, was studied for its potential application as raw material for cement production. The mineralogical evaluation, as well as the chemical composition of the clay mineral sample, was carried out using modern characterization techniques: XRF, XRD, SEM/EDX, and DTA-TG. These techniques employed to characterize the clay mineral sample show consistency with one another in the results obtained. The results of the research indicated that the clay mineral can be considered as a good alumina-silicate raw material for cement production due to its high content of quartz and kaolinite. This further suggested that the clay mineral is typical kaolin clay.

The clay mineral sample under investigation meets the minimum quality standard required for clay minerals to serve as raw material for cement production. It can therefore be used for the production of cement. The presence of exchangeable ions such as Ca, Na, Fe, Cu, Zn, and K, which are present in significant amounts in the clay mineral under investigation, suggests that the clay mineral could be used as an absorbent for remediation of contaminants in wastewater.

Cement was produced using the clay mineral under evaluation to further investigate its potential for cement production. Different ratios of the raw mix of limestone and clay mineral (70:30), (75:25), and (80:20) were used to determine the best raw mix for the production of the cement.

The following tests were conducted on the cement produced: normal consistency, setting time, soundness, and compressive strength. The results of normal consistency, setting time, and soundness of the cements produced for all the raw mixes fall within the standard requirements. The raw mix (75:25) gave the best result in terms of compressive strength (21.9 $N/MM^2$) at 28 days curing period. This value is in agreement with the minimum British Standard for compressive strength of cement.

### 4.1 Contribution to sustainable cement production

This research contributes significantly to sustainable cement production by exploring the use of locally sourced Okelele Ilorin clay mineral as a viable alternative raw material. By partially substituting conventional resources with abundant and underutilized clay, the study promotes resource conservation, reduces dependence on non-renewable materials, and minimizes the environmental footprint associated with cement manufacturing. The practical significance of the research for sustainable cement production includes the potential of utilizing locally available clay minerals to reduce dependence on conventional raw materials, thereby lowering energy consumption, carbon emissions, and production costs in line with sustainable development goals. Furthermore, the integration of this alternative material aligns with the objectives of Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production (SDG 12) and climate action (SDG 13). The findings provide a scientific basis for the development of more eco-friendly and economically viable cement formulations, thereby contributing to the advancement of sustainable construction practices.

### 4.2 Recommendations

Having carried out the evaluation of Okelele clay mineral as a potential cement raw material, it is therefore recommended that:

i. The deficiency of Iron oxide ($Fe_2O_3$) in the clay mineral should be corrected by adding an adequate proportion of iron oxide ($Fe_2O_3$) to the clay mineral in order to decrease the alumina ratio (AR) to the required standard.
ii. The clay mineral indicated properties that show its potential as an adsorbent for the remediation of contaminants in wastewater. Further research should be conducted on this effect in order to establish it.

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