

CHARACTERIZATION AND EVALUATION OF SELECTED KAOLIN DEPOSITS IN KWARA STATE FOR FURNACE LINING APPLICATION

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Abstract

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This study evaluates the mineralogical, chemical, physical and thermal shrinkage characteristics of kaolin deposits in Kwara State, Nigeria. Sample were taken from Harmony, Kpandagari, Kutukpa, Share, and Gbaduwa site for suitability in furnace lining applications. The bulk density, porosity, moisture content, linear shrinkage and chemical composition investigations were performed using X-ray diffraction (XRD) and X-ray fluorescence (XRF) in accordance with ASTM standards. Results indicate that kaolinite and quartz are dominant in Kwara State with Harmony site having the highest feldspar content of between 30-35wt% and Gbaduwa with the lowest (25wt%). Gbaduwa also has the highest iron oxides concentration ($\leq 3\text{wt\%}$). Kaolin primarily consists of kaolinite, but often contains impurities such as quartz, iron oxides, and organic matter, which can affect its properties. The highest bulk density of 1.65 g/cm^3 was observed at Kutukpa site which is suitable for refractory linings. The lower apparent porosity of Harmony (137%) and Kutukpa (119%) contrasts with Kpandagari's high porosity (276%), which provides thermal shock resistance. The specific gravity values of Kpandagari correlate with quartz and kaolinite contents, while low water absorption of Kutukpa suggests minimal impurities. Share sites exhibit low shrinkage, ensuring stable high-temperature performance in demanding environments. The results demonstrate that locally sourced kaolin possesses thermal and structural characteristics comparable to commercial insulating materials, indicating its strong potential for application in industrial thermal insulation systems such as furnaces and kilns.

1. Introduction

Furnaces are critical components in high-temperature industrial processes, and their operational efficiency and durability largely depend on the performance of the refractory lining. Refractory materials play a critical role in high-temperature industrial applications, particularly in furnace lining, where thermal stability, corrosion resistance, and mechanical strength are essential (Ghosh *et al.* 2022). High-temperature industries such as metallurgy, ceramics, glass manufacturing and power generation, uses line furnaces,

kilns, and reactors to withstand extreme operating conditions without degrading. Among the commonly used refractory materials, kaolin ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) occupies a prominent position due to its high alumina and silica content, low cost, and wide availability (Stoianov *et al.* 2023; Shuaib- babata 2022). Advancements in refractory materials improve furnace performance, but challenges such as high-quality raw materials and environmental impact remain. Others are the high cost and import dependency associated with foreign refractory materials (Basu *et al.*, 2024; Kakroudi & Asl, 2011).

Nigeria is endowed with abundant kaolin deposits spread across several states, yet many of these resources remain underutilized. In particular, Kwara State has significant kaolin reserves, but there is limited systematic evaluation of their properties for specific industrial applications. Previous studies have emphasized the need for local raw material characterization to reduce dependence on imported refractory materials and to promote indigenous industrial growth (Oke *et al.*, 2016). However, the gap between resource availability and industrial utilization highlights the importance of detailed characterization of kaolin deposits in different regions. Several studies have highlighted the importance of systematic characterization of kaolin deposits to support local refractory industries and reduce import dependence (Adeniyi *et al.*, 2023; Mokwa *et al.*, 2019; Shuaib-Babata *et al.*, 2018a).

Research focuses on sustainable alternatives without compromising performance has become necessary. Kaolin, a naturally occurring clay with high alumina and silica content, is a popular raw material for refractory applications (Adeniyi *et al.*, 2023; Jacob *et al.*, 2025). The suitability of kaolin for refractory and furnace lining applications depends largely on its physicochemical, mineralogical, and thermal properties, which must meet the stringent requirements of strength, thermal stability, and resistance to slag attack (Injor *et al.*, 2025; Muhaba, 2025; Nnuka & Agbo, 2000; Ukwuoma *et al.*, 2018). However, its suitability for high-temperature applications like furnace linings in Nigeria remains underexplored. Few studies have systematically evaluated kaolin's physicochemical, mineralogical, and thermal properties.

The kaolin samples from Baruten Local Government Area showed high alumina (Al_2O_3) and silica (SiO_2) content, classifying them as alumino-silicate refractories with apparent porosity range of 19.4-25.6%, bulk density (1.83-1.90 g/cm³), cold crushing strength (38.7-56.1 N/mm²) and Refractoriness: >1300 °C (Shuaib-babata & Abdulrahaman, 2018). The kaolin was subjected to beneficiation processes to enhance its alumina content, improving its suitability for refractory applications (Oyewo *et al.*, 2025; Lamidi *et al.*, 2024; Mokwa *et al.*, 2019). Comparisons with international standards indicated that the local kaolin could effectively replace imported materials in certain applications (Azubuike, 2024; Shuaib-Babata *et al.*, 2018). The findings suggest that utilizing local kaolin deposits could bolster Nigeria's industrial capabilities and reduce reliance on imports for refractory materials (Olisa *et al.*, 2024; Shuaib-babata *et al.*, 2017). However, some kaolin samples may require further processing to remove impurities like iron and titanium oxides to meet specific industrial standards (Olisa *et al.*, 2024).

Recent years have witnessed intensified research and development endeavors aimed at augmenting the efficacy and adaptability of refractory ceramics to align with the evolving requisites of contemporary industries. This concerted effort has culminated in the emergence of novel materials characterized by heightened thermal conductivity and superior corrosion resistance. As industrial enterprises persist in pushing the boundaries of technological feasibility, the anticipated trajectory indicates a proliferation of applications for refractory ceramics, heralding innovative solutions poised to revolutionize diverse industrial processes. The need for sustainable practices is driving the industry to adopt energy-saving technologies and recycle refractory wastes become necessary.

Recent research and development have significantly enhanced the efficacy and adaptability of refractory ceramics, resulting in new materials with improved thermal conductivity and corrosion

resistance. As industries advance technologically, more applications for these ceramics are expected, offering innovative solutions to transform various processes. Additionally, there is a growing emphasis on sustainability, leading to the adoption of energy-saving technologies and the recycling of refractory wastes. The development of chrome-free refractories is also a response to environmental concerns, aiming to minimize harmful emissions during production (Ghosh & Tripathi, 2022; Majidian, *et al.*, 2022; Liu, *et al.*, 2024; Hongxia, 2010). Conversely, while domestic production is essential, challenges such as the initial investment in technology and the need for skilled labour can hinder rapid development. Balancing these factors is crucial for achieving a self-sufficient refractory industry. This study focuses on the characterization and evaluation of selected kaolin deposits in Kwara State for furnace lining applications. By assessing their chemical composition, mineralogical phases, thermal behaviour, and refractory properties, the study aims to determine their suitability as raw materials for refractory production. Such an investigation is critical for advancing sustainable industrial practices, reducing import reliance, and promoting value addition to Nigeria's mineral resources.

2. Materials and Method

2.1 MATERIAL COLLECTION AND SAMPLE PREPARATION

Samples were collected from Harmony with latitude and longitude of (8.5° N, 4.5° E), Kpandagari (8° 50' N latitude and 4° 50' E longitude), Kutukpa (8.6986° N, 4.6003° E), Share (8.8228° N, 4.9689° E) and Gbaduwa (8.38333° N, 4.38333° E) in Kwara state, Nigeria. The clay samples deposit sites were dug two meters deep into the earth using an iron digger as per ASTM D4220/D4220M-14 guidelines (Paranthaman and Azam, 2021). The Kaolin samples were washed, sieved, and oven-dried at 105°C to remove moisture. Subsequently, they were crushed and sieved to a uniform particle size to ensure consistency in testing. All the experiments for this work were carried out at the Laboratory of the Mechanical Engineering Department, Federal Polytechnic Ado Ekiti, Ekiti, Nigeria.

2.2 CHARACTERIZATION

2.2.1 Determination of Chemical Analysis

The chemical analysis of the raw clay samples was carried out using an X-ray fluorescence (XRF). The XRD was used to determine the crystalline phases, and XRF to assess the elemental composition, focusing on SiO_2 , Al_2O_3 , Fe_2O_3 , and TiO_2 concentrations, which are critical to refractory performance.

2.3 PHYSICAL TESTS:

2.3.1 Bulk Density

In evaluating the bulk density of kaolin samples which is crucial for determining the suitability of kaolin deposits for refractory applications, the samples were dried and weighed and the weighed samples were transferred into separate beakers and soaked with water. They were heated for 30 minutes to release the trapped air in the samples. The samples were cooled, and the weight of each sample was taken. Each sample were suspended in water inside the beaker, and the suspended weight was measured. The bulk density of each of the kaolin deposit samples was determined using the formula in Equation (1), with W_1 = Dried weight (g), W_2 = soaked weight of sample (g) and WD is the water density.

$$\text{Bulk Density (g/cm}^3) = \frac{W_1}{W_2 - WD} \quad (1)$$

2.3.2 Apparent Porosity

Porosity is a measure of volume of all pores present in a material. This was performed according to the standard test method in ASTM C20. With a weighing balance of 0.1g accuracy, and a water bath with temperature control, the initial dry sample (W_1) is immersed in water and boiled for 2 hours. After being removed from the water bath, it is weighed while suspended in water (W_2). Thereafter, excess water was removed from the sample surface and weighed in air (W_3). The apparent porosity is calculated using the formula in Equation (2):

$$\text{Apparent Porosity} = \frac{W_3 - W_1}{W_3 - W_2} \times 100 \quad (2)$$

2.3.3 Specific Gravity

This is represented by the ratio of the density of the material to the density of water. The powdered clay sample, passed through 100 sieve B.S.S, was introduced using a glass funnel into a previously weighed specific gravity bottle (W_p), and weighed, (W). The powder sample was covered with distilled water under vacuum, and the bottle was suspended in water of a known temperature for approximately 15 minutes to equilibrate, followed by weighing (W_2). The bottle was then washed, filled with distilled water, and allowed to equilibrate for another 15 minutes and weighed (W_1). The specific gravity was then calculated based on the following expression in Equation (3).

$$\text{Specific gravity} = \frac{W - W_1}{(W - W_p)(W_3 - W_1)} \quad (3)$$

2.3.4 Natural Moisture and Water absorption

The moisture content of the kaolin samples was determined to assess the amount of water present in the natural state of the material, which is a critical parameter in evaluating suitability for furnace lining applications. Excessive moisture in refractory materials can lead to steam spalling during service. A known mass of the wet sample (W_1) was weighed using a digital balance, and the sample was then placed in a drying oven maintained at $105^\circ\text{C} \pm 5^\circ\text{C}$ for a duration of 24 hours to ensure complete moisture removal. After drying, the sample was allowed to cool in a desiccator and then reweighed to obtain the dry mass (W_2). The moisture content (%) of each sample was calculated using the formula in Equation (4) in accordance with ASTM C566 standard. Equation (5) was used to calculate Water Absorption based on removing excess water from the sample surface and weighing it in air (W_3). This test is crucial for evaluating the sample's suitability for furnace lining applications, as excessive water absorption can affect the thermal and mechanical integrity of the refractory material.

$$\text{Moisture Content (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (4)$$

$$\text{Water Absorption (\%)} = \frac{W_3 - W_1}{W_1} \times 100 \quad (5)$$

2.4 THERMAL LINEAR SHRINKAGE TEST

A high-temperature furnace (BTI-35 Muffle Furnace, GMP Model) was used to process kaolin samples for shrinkage testing according to ASTM C367. The sample is shaped into a bar shape, dried at an ambient

temperature, and then measured using a vernier caliper (L_1). The sample was then placed in a preheated furnace, gradually heated to a predetermined temperature of 1000°C at a controlled heating rate. The sample was monitored at regular intervals to observe dimensional changes, or re-measured post-firing once the sample has cooled to room temperature. The final length (L_2) is measured after complete firing and cooling. The shrinkage is calculated using the formula in Eqn (6):

$$\text{Linear shrinkage (\%)} = \frac{L_2 - L_1}{L_1} \times 100 \quad (6)$$

3. Results and Discussion

3.1 CHEMICAL COMPOSITION AND MINERALOGICAL RESULTS:

The Harmony Site samples are dominantly kaolinite and quartz peaks with minor feldspar. High Al_2O_3 (30–35%) and low Fe_2O_3 (<2%) suggest excellent thermal resistance. The Kpandagari Site deposit exhibits moderate kaolinite, presence of muscovite and orthoclase. Fe_2O_3 levels (2–3%) indicate potential instability but can be improved with calcination. However, Kutukpa Site deposit recorded strong kaolinite peaks and minimal iron impurities (<1%). Ideal refractory candidate due to its purity and mineralogical profile. The share site clay is Kaolinite-rich with SiO_2 (52–57%) and Al_2O_3 (28–32%). Iron content (2–2.5%) remains within acceptable refractory thresholds but Gbaduwa Site deposit has weaker kaolinite intensity and Fe_2O_3 above 3% suggest the need for beneficiation, such as magnetic separation, to optimize for high-temperature applications. The chemical composition of the investigated Kwara State kaolin deposits (SiO_2 50–60%, Al_2O_3 25–35%, Fe_2O_3 ≤3%) closely matches those reported for other Nigerian and West African kaolin suitable for refractory applications. For example, Mokwa et al. (2019) revealed nearly identical ranges in their evaluation of Nigerian kaolin for furnace lining. Mineralogical analysis confirms kaolinite as the dominant phase, supported by similar findings in Baruten, Kwara state (Ganiyu et al., 2018).

Table 1: The percentage composition of the various constituents

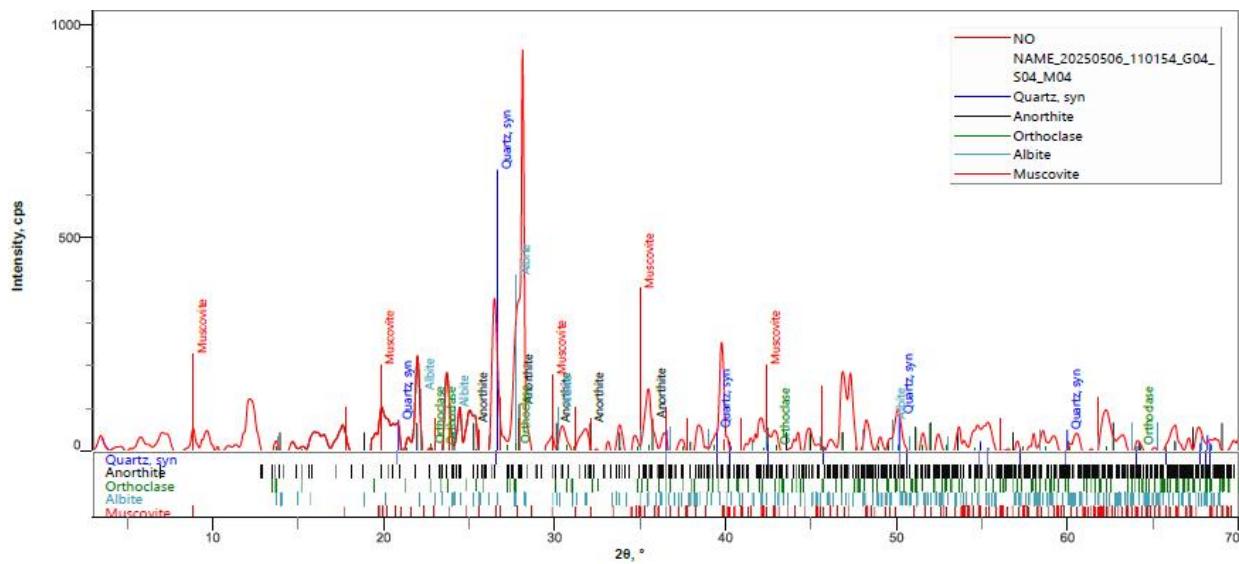
	Gbaduwa	Harmony	Kpandaragi	Share	Kutukpa
SiO_2	50-55%	55-60%	50-55%	52-57%	55-60%
Al_2O_3	25-28%	30-35%	25-30%	28-32%	30-33%
Fe_2O_3	3%	Trace	2-3%	2-2.5%	<1%
TiO_2	Trace	Trace	Trace	Trace	Trace

The presence of kaolinite, quartz, mullite, and other phases were evident as seen in the XRD patterns of Harmony site samples in Table 2 and Figure 1a revealed prominent peaks corresponding to kaolinite (<20> and <001> planes) and quartz, indicating the dominance of these phases. Minor peaks associated with feldspar minerals (orthoclase and albite) were also identified. These findings suggest a high kaolinite content, making the deposit suitable for refractory applications as kaolinite contributes significantly to

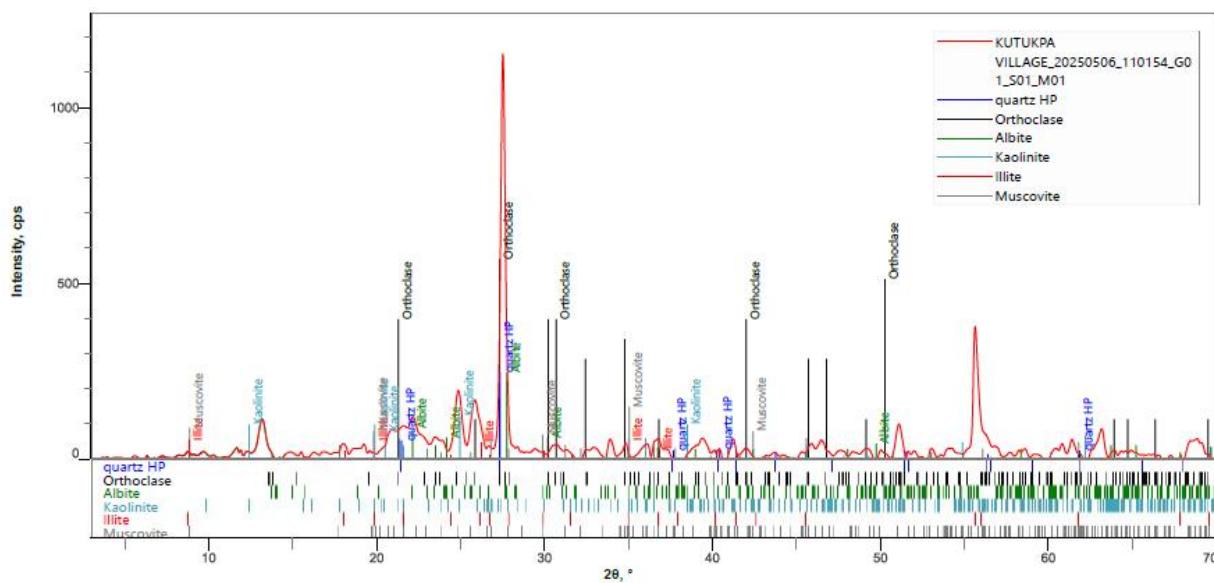
thermal stability and low thermal conductivity in furnace linings (Onosemudiana et al., 2024). From (Figure 1b), the Kutukpa sample shows that the kaolinite and quartz are the primary phases identified, with additional contributions from muscovite and orthoclase. The peak intensities of kaolinite are slightly lower compared to the Harmony site, indicating moderate kaolinite content. This composition is still viable for furnace lining but may require beneficiation to enhance kaolinite purity. The XRD profile of Kpandagari sample (Figure 1c) demonstrates strong kaolinite peaks, supplemented by quartz and minor feldspar phases. This mineralogical composition suggests high thermal shock resistance, a critical property for furnace linings. The sample from Share deposit (Figure 1d) shows that kaolinite and quartz dominate the mineralogical profile, with minor contributions from albite. The comparable kaolinite content of the Kutukpa site indicates potential thermal performance characteristics, reinforcing the suitability of the locally sourced kaolin for insulation applications. XRD results from Gbaduwa site (Figure 1e) show mineral phases which include kaolinite, quartz, and traces of muscovite. Compared to other sites, the kaolinite peak intensities are moderately weaker, indicating a lower kaolinite-to-quartz ratio. This suggests the need for beneficiation to improve thermal properties for specific furnace applications.

Table 2: XRD profile of mineralogical of various investigation sites

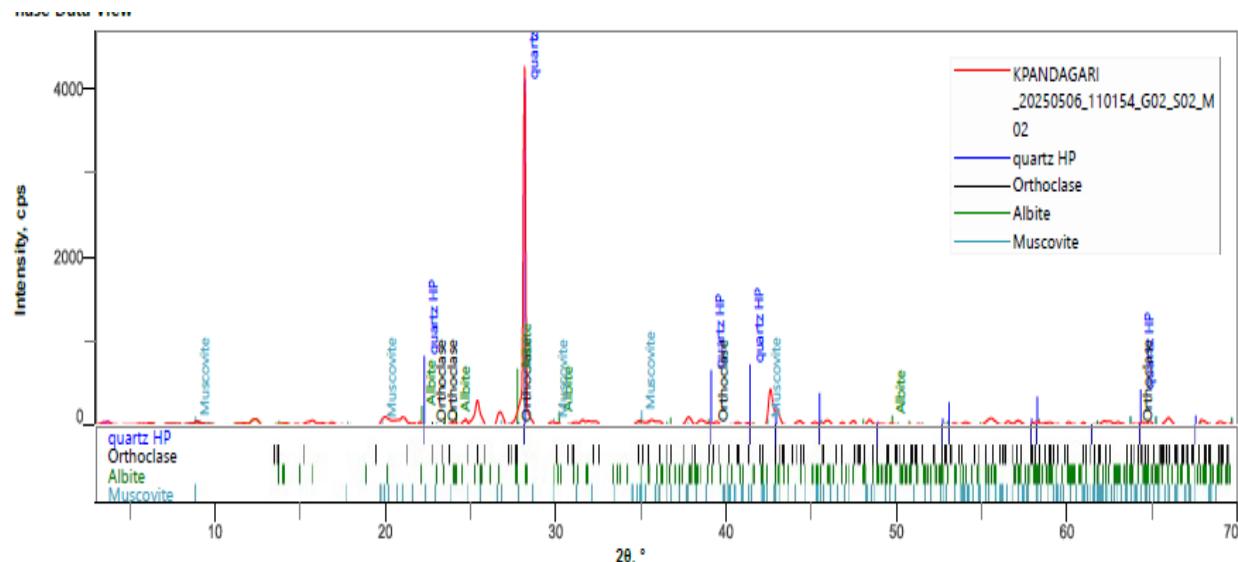
Phase name	Chemical Formula	Gbaduwa	Harmony	Kpandaragi	Share	Kutukpa
Kaolinite	$\text{Al}_2 \text{Si}_2\text{O}_5 (\text{O}\text{H})_4$	0.808	-	-	1.018	1.719
Quartz, syn	SiO_2	1.067	1.732	1.380	1.342	2.919
Anorthite	$\text{CaAl}_2 \text{Si}_2\text{O}_8$	-	1.940	-	-	-
Orthoclase	$\text{Al}_2\text{O}_3 \cdot \text{K}_2\text{O} \cdot 6\text{SiO}_2$	2.850	3.234	2.903	3.228	1.738
Albite	$\text{NaAlSi}_3\text{O}_8$	1.641	2.102	2.815	2.902	2.844
Illite	$2\text{K}_2\text{O} \cdot 3\text{MgO} \cdot \text{Al}_2\text{O}_3 \cdot 24$	3.145	-	-	2.825	3.552
Muscovite	$\text{H}_2\text{KAl}_3(\text{SiO}_4)_3$	3.078	2.898	3.106	2.203	3.268



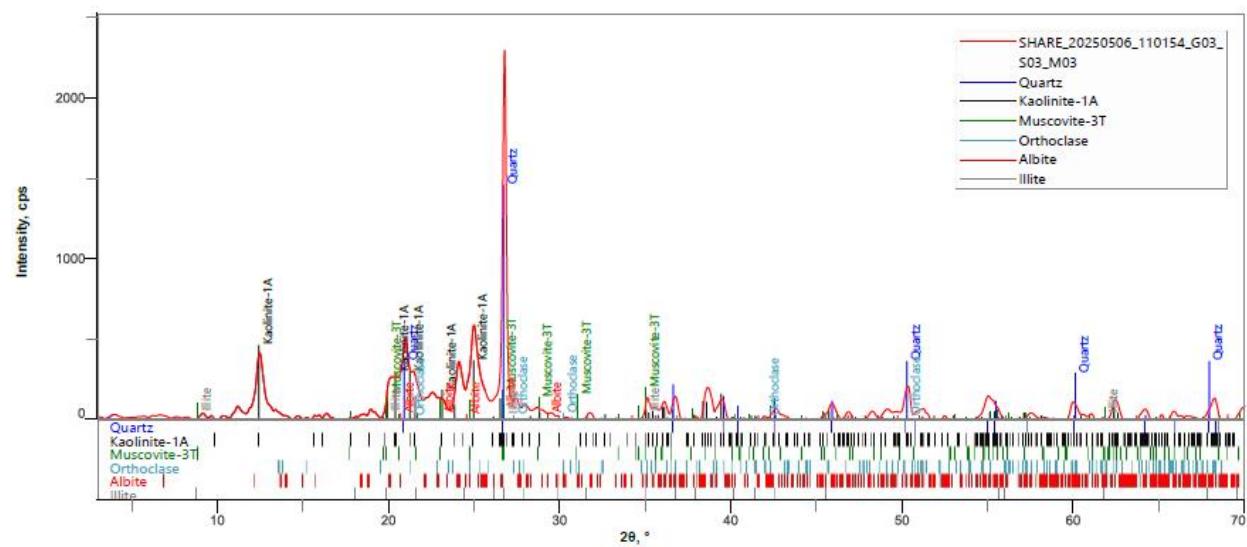
(a)



(b)



(c)



(d)

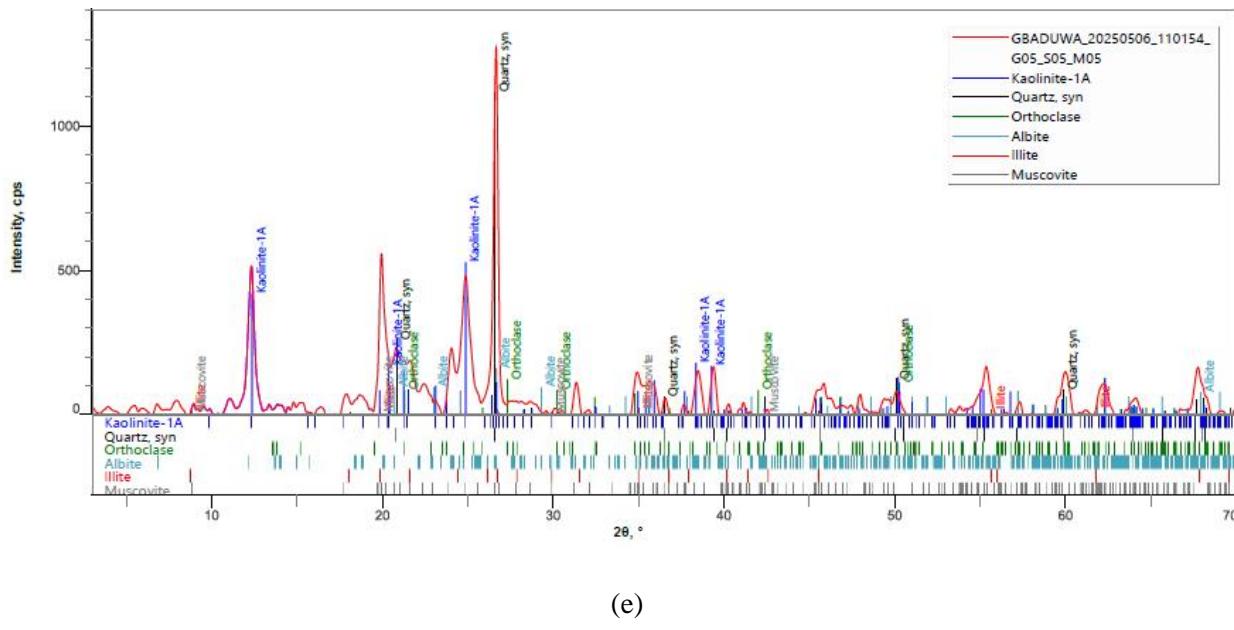


Figure 1: XRD pattern of Kaolin Samples of the deposit sites (a) Harmony site (b) Kutukpa site (c) Kpandagari site (d) Share site (e) Gbaduwa site

3.2 PHYSICAL PROPERTIES

Density

The chart in Figure 6 shows that bulk density ranges from 1.38 g/cm^3 (Kutukpa site) to 1.66 g/cm^3 (Share site). The Share site stands out with the highest bulk density, indicating a compact material suitable for dense and durable linings. Other site has 1.57 g/cm^3 (Harmony), 1.46 g/cm^3 (Kpadaragi) and 1.53 g/cm^3 (Gbaduwa) respectively, which were found to be in close comparison with the international acceptable range of $1.7\text{--}2.1 \text{ g/cm}^3$ (Mokwa et al., 2019). However, Kutukpa's lower bulk density may suggest higher porosity and reduced compactness, consistent with the high porosity values observed. Kpandaragi and Gbaduwa sites exhibit intermediate values of 1.57 to 1.60 g/cm^3 , reflecting a balance between insulation and structural strength.

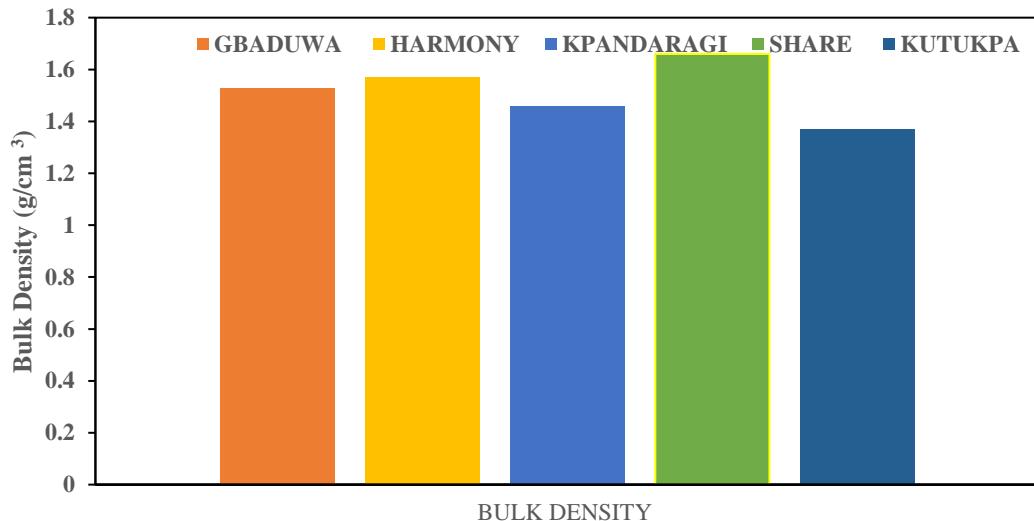


Figure 6: Bulk density variations of Kaolin deposits across all sites

Apparent porosity

Porosity varies significantly across the sites, with Kpandaragi showing the highest value (276%) and Kutukpa the lowest (137%). The elevated porosity at Kpandaragi supports thermal shock resistance but compromises slag penetration resistance, requiring surface treatments. Kutukpa's lower porosity indicates better impermeability, which is crucial for furnace linings. Kpandagari's porosity (276%) is high, suggesting a similar trade-off between insulation and permeability

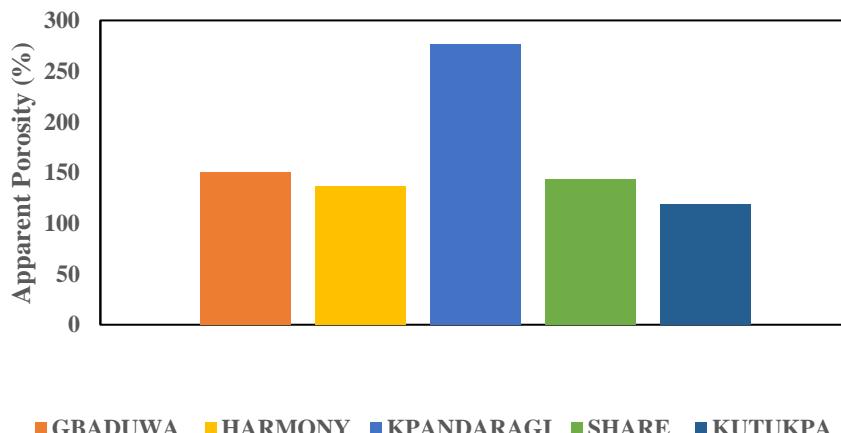


Figure 7: Apparent porosity variations of Kaolin deposits across all sites

Specific gravity

Specific gravity is relatively consistent across sites, ranging from 2.5 (Harmony, and Share) to 2.6 (Kpandagari, Gbaduwa, and Kutukpa). These values reflect the dominance of kaolinite and quartz

across all samples, as identified in the XRD results. The consistency suggests similar mineralogical contributions to the weight and thermal properties of the samples. The measured physical properties—bulk density, porosity, and specific gravity—align with standards for refractory-grade materials. These results are corroborated by Oladeji et al. (2019), who observed densities near 1.90g/cm^3 and porosities in the 19–26% range for local fireclays. Minimal shrinkage across the deposits further supports their suitability, as compared to Omifun kaolin blends reported by Adebisi et al. (2024).

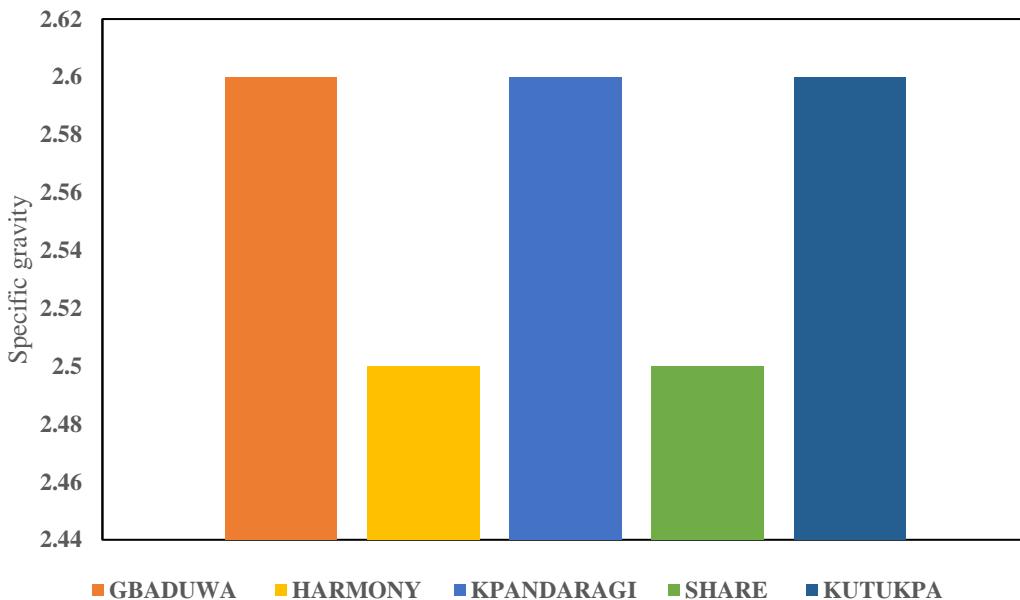


Figure 8: Specific gravity variations of Kaolin deposits across all sites

Natural Moisture and Water absorption

Water absorption exhibits wide variation, with Kutukpa ($\geq 20\%$), Gbaduwa (27%) and Kpandagari (44%) showing significantly higher values than Harmony (13%) and Share (30%). High water absorption in Share and Kpandagari can lead to increased vulnerability to thermal spalling, necessitating surface treatments or beneficiation. Kutukpa's low absorption aligns with its high bulk density and lower porosity, confirming its suitability for stable refractory applications.

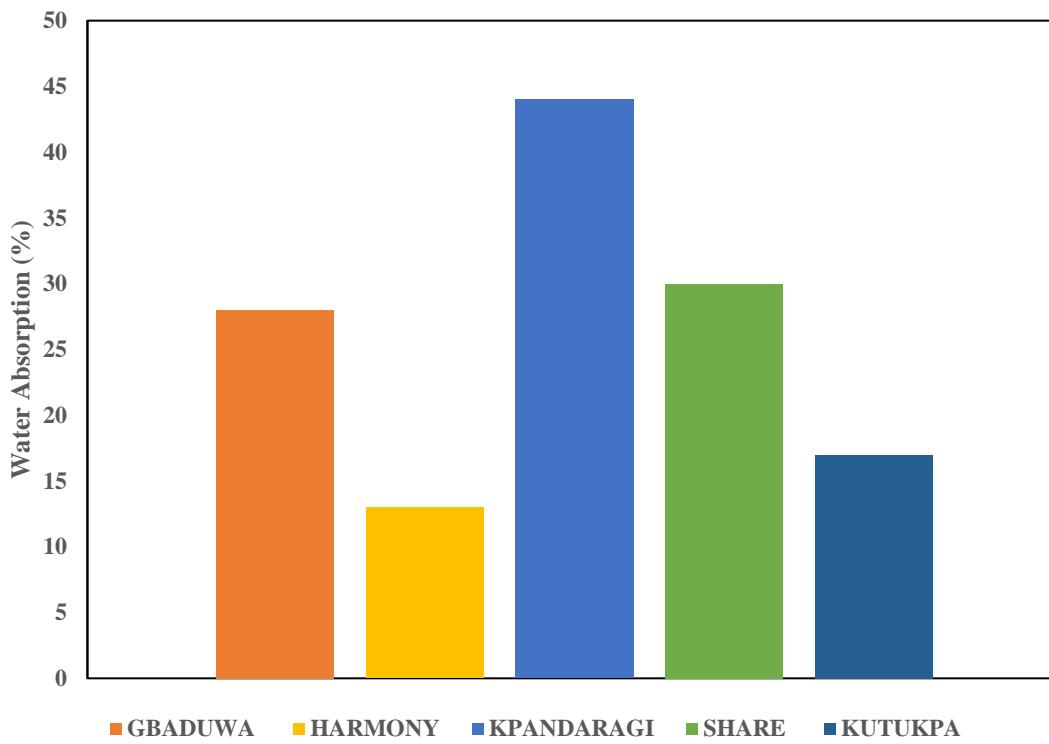


Figure 9: Water absorption variations of Kaolin deposits across all sites

The natural moisture content variations of Kaolin deposits across all sites in Figure 10 shows that the natural moisture content is lowest in Harmony (0.38%) and highest in Kpandagari (2.76%). The higher moisture content in Kpandagari may contribute to increased water absorption, reducing its thermal stability. The low moisture content in Harmony aligns with its low porosity and water absorption, enhancing its suitability for high-temperature applications.

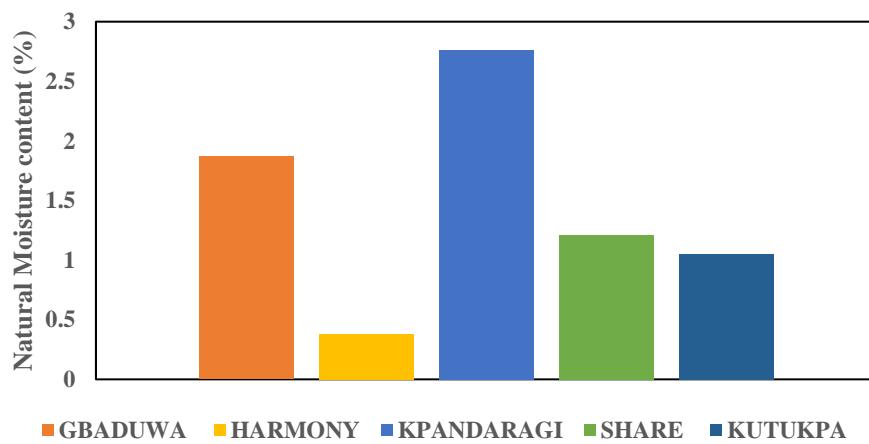


Figure 10: Natural moisture content variations of Kaolin deposits across all sites

3.3 LINEAR THERMAL SHRINKAGE

Shrinkage varies modestly, with the lowest values in Harmony and Kutukpa and the highest (6.3%) in Kpandagari. Minimal shrinkage is advantageous for maintaining dimensional stability during thermal cycling. Kpandagari's higher shrinkage may require additional processing to enhance its thermal performance. Furthermore, the specific gravity of 2.5 and low water absorption (13%) of Harmony site further reflect a predominantly kaolinite and quartz composition. In terms of refractoriness and thermal shock resistance, the evaluated deposits show comparable performance to international and local benchmarks, with kaolinitic composition and low iron content as key factors. After minimal beneficiation, these deposits exhibit properties making them viable substitutes for imported refractory materials, a finding consistent with Romero-Guerrero et al. (2018) and Omowumi (2000).

Overall, the Kwara State kaolin deposits display chemical, mineralogical, and physical properties comparable to globally recognized refractory clays. While minor variations arise from local geology, the main consideration remains adequate beneficiation to further reduce impurities. Aligning with national industrial goals, using these local resources can significantly advance Nigeria's self-sufficiency in furnace lining materials, as echoed in recent literature. Further studies may expand on mechanical strength or direct thermal shock testing, which some comparative works have explored but are not presented here.

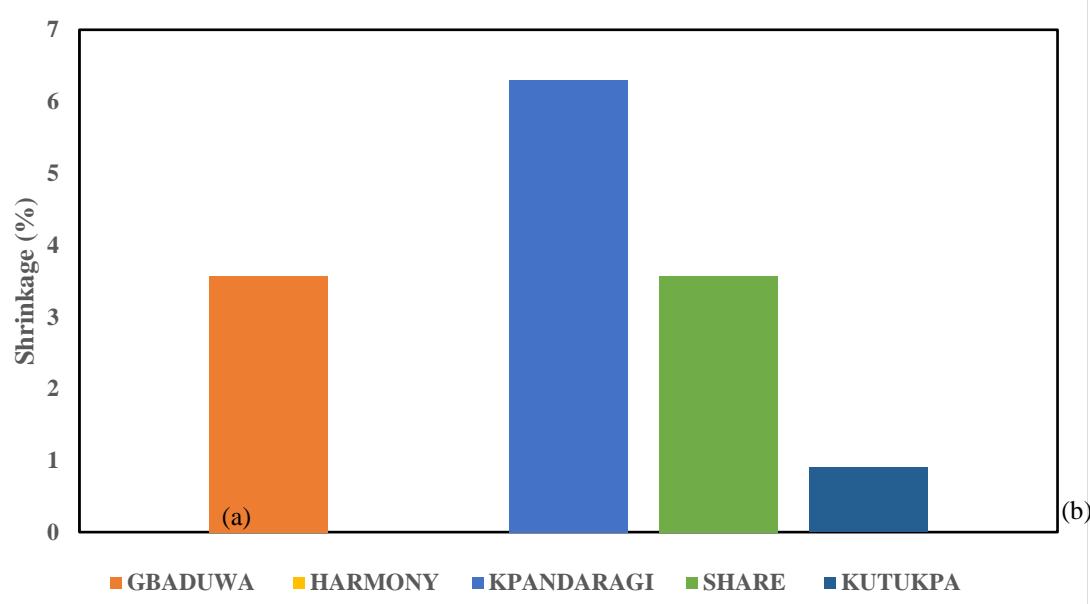


Figure 11: Shrinkage variation of Kaolin deposits across all sites

4. Conclusion

This study introduces the use of locally sourced kaolin deposits as a sustainable and cost-effective alternative for high-temperature insulation materials to replace imported processed kaolin. In this research emphasizes the compositional and thermal suitability of regional deposits, thereby promoting local resource

utilization and reducing production costs. The clay within Kwara state offer potential use as refractory lining application. The key findings were that Kaolin from Harmony and Kutukpa meet the mineralogical and chemical criteria for refractory furnace linings. Other sites may require beneficiation. Utilizing these local materials can significantly reduce Nigeria's dependence on imported refractories and promote sustainable material development. The specific findings from each site were presented below: In term of density, Kutukpa site has the highest bulk density of 1.65 g/cm³ followed by Share and Harmony site with 1.57 g/cm³, suitable for dense refractory linings with dense kaolinite structures has compared to Kpandagari site with lower bulk density of 1.46 g/cm³ and 1.40 g/cm³ from Gbaduwa indicating less compactness. Harmony site indicated Low apparent porosity for furnace linings, with moderate apparent porosity for Kutukpa and Share sites which gives structural strength and insulation capacity; however, Kpandagari Site has high apparent porosity of 276% for thermal shock resistance. Kpandagari Site indicates a specific gravity of 2.6 correlating with quartz content while Kutukpa Site provided specific gravity of 2.5. Low water absorption reflects minimal impurities in Kutukpa Site while Kpandagari site has water absorption of 44% suggesting the need for surface treatments. Share Site minimal shrinkage supports application in environments requiring stable high-temperature performance.

The Harmony and Kutukpa sites exhibit the most favorable physical properties for furnace linings, with low porosity, minimal shrinkage, and controlled water absorption. Share represents a balanced option, suitable for general refractory applications. Kpandagari and Gbaduwa require beneficiation to reduce water absorption and porosity for use in critical high-temperature environments.

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