Characterization of Clay Deposits for Burnt Brick Production Obtained from Taraba State, Nigeria

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ABSTRACT

South of Taraba State in Nigeria harbours extensive alluvial and residual clay deposits associated with the Taraba, Donga, and Katsina-Ala river basins, but no systematic characterisation exists for brick production. This study characterised raw clay deposits from Wukari, Donga, and Takum Local Government Areas in Taraba State, Nigeria. Geotechnical properties, including Atterberg limits, linear shrinkage, specific gravity, and particle size distribution, were determined according to BS 1377:2016. Chemical composition and mineralogy were analysed using X-ray fluorescence and X-ray diffraction with Rietveld refinement. Standard bricks (230 × 110 × 76 mm) were fired between 800 and 1050 °C and evaluated for compressive strength, water absorption, initial rate of absorption, apparent density, porosity, linear shrinkage, and efflorescence. Wukari clay showed the most favourable properties, with a plasticity index of 20.9%, a specific gravity of 2.64, and a clay fraction of 38.4%. XRF indicated SiO_2 (58.34%) and Al_2O_3 (21.46%), while XRD confirmed 14.6% mullite at 1000°C. At this temperature, compressive strengths reached 14.8, 12.3, and 9.6 N/mm² for Wukari, Donga, and Takum, respectively, with water absorption of 8.42–11.03%, satisfying standard requirements for load-bearing burnt bricks.

Keywords: Clay characterization, burnt brick, XRF, XRD, particle size distribution, Taraba State,

INTRODUCTION

The fired-clay brick is one of the oldest, more robust, and most used construction materials in the world due to its superior mechanical properties, fire resistance, thermal insulation, durability, and low production costs [1-2]. Because of their lower embodied energy, transport costs, and their potential to be part of the principles of a 'circular economy,' there are many building materials that are becoming popular and are sustainable and locally sourced, compared to many other conventional building materials [3]. The engineering performance of fired-clay bricks is determined by both the intrinsic qualities of the raw clay and by the processes used in brick manufacture. The densification, vitrification, porosity, water absorption, dimensional stability, and compressive strength of the final fired product are influenced by the mineralogical composition, particle size distribution, plasticity, chemical composition, and firing temperature [4, 5].

The clay with high kaolinite content generally has good molding properties and can be made into a mechanically stable ceramic product; the excessive smectite content causes the clay brick to crack and shrink during drying and firing, and the clay brick is prone to dimensional change because of the high plastic viscosity of the clay body, which affects the quality of the clay brick. Likewise, mineralogical transformation of kaolinite to Meta kaolinite to mullite during firing leads to better bonding during firing of products and mechanical strength of the products; hence, mineralogical characterization is also a requirement of quality control of structural clay products [4, 5], British Standards Institution, BSI [6], and Standards Organisation of Nigeria-Nigerian Industrial Standard, SON-NIS [7].

Building using indigenous clay materials has gained significant momentum in recent years, driven by the rise in sustainable construction practices and the need for alternative building materials that are not energy-intensive. A number of studies have demonstrated that locally available clay resources are capable of yielding good quality bricks as structural units if the geotechnical, geochemical, and mineralogical properties of these clay resources are characterized and matched with appropriate firing procedures [2, 4, 8]. Therefore, it is important to perform detailed characterization of raw materials before brick manufacturing to optimize the brick production process, minimize manufacturing faults, utilize raw material, and comply with the national and international masonry standards [4, 9].

Variances in the geological origin of the clay, weathering history, sedimentary environment, and parent rock mineralogy have been reported to cause significant spatial variations in clay mineral composition from recent investigations throughout Africa and other developing regions [8-10]. The variation can also influence the processing characteristics and properties of fired bricks, indicating that properties of fired bricks derived from one deposit cannot be assumed to apply to another without investigation. This has highlighted the importance of localized characterization studies to obtain suitable clay resources for sustainable brick production and provide scientific evidence for quality control, industrial development, and standards. [2, 8, 10].

The presence of clay deposits in Nigeria has been found to be suitable for industrial uses such as ceramics and masonry, which have been confirmed in a number of studies carried out. Adeola et al. [11] and Dansarai et al. [12] studied the physicochemical and mineralogical properties of the Nigerian clays and found them to be quite variable depending on the geological context, and thus, site-specific evaluation is needed. Interestingly, Malu et al. [13] reported good clay properties of Ndia clay deposits in terms of silica and alumina content in Takum, Taraba State, and found that the clay was appropriate for ceramic application because of its high thermal stability. A lot of comparative details, however, are still lacking in terms of geotechnical, mineralogical, geochemical, and fired-brick performance of each of the major clay deposits of the southern Taraba State.

The area of southern Taraba State is one of the most promising clay-bearing areas of Nigeria with less investigation. Geologically it is a transitional zone between the Precambrian Basement Complex and the Lower Benue, and geologically the environment of formation of the clay is very complex; thus, the mineralogical and engineering properties of the clay are also variable. Wukari is characterized by a high proportion of highly weathered rocks in the basement with kaolinitic lateritic clays of relatively high silica and alumina content. In the Donga area, however, Cretaceous shale and mudstone underlie the area and produce illitic clays and mixed-layer clays, and the Takum area is underlain by Quaternary alluvial deposits of the Taraba and Katsina-Ala rivers that produce fine-grained sediments containing variable amounts of expandable clay minerals [8-11]. It is expected that these geological differences will have an impact on the properties of fired bricks, such as their plasticity, particle size distribution, shrinkage, composition of the oxides they contain, mineralogical changes during firing, and engineering behavior. Hence, it is necessary to have extensive scientific characterization of these deposits in order to assess their suitability for structural brick production for industrial use.

A number of studies have been conducted on clay deposits in different parts of Nigeria, but with few of them being contiguous in geographical extent and comprehensive in methods of investigation. The literature available on these deposits has been devoted so far mainly to the physicochemical characterization, mineralogical composition, and suitability of single deposits and has not yet established the relationships between the properties of the raw material and the firing temperatures as well as the engineering performance of the fired brick [3, 5, 7, 8]. The physicochemical properties and thermal stability of Ndia clay were determined to be suitable in the Takum Local Government Area, Taraba State, Nigeria [13], which makes it an industrial clay. It did not take into account geotechnical properties, particle size distribution, or mineralogical changes during firing, nor the physical and mechanical functioning of fired bricks, while only one deposit was studied. Hence, the engineering suitability of the main clay deposits of the Wukari, Donga, and Takum Local Government Areas is yet to be well understood.

This integrated characterization is one of the areas that require knowledge in both the research and industrial communities. The brick makers in the area are primarily using the empirical methods of production in which the lack of geotechnical, geochemical, mineralogical, and technological data leads to poor quality of the bricks, sub-optimal firing, and limited compliance with national and international specifications. Likewise, there is no scientific evidence that can back the government's and construction practitioners' claim of sustainable use of indigenous clay resources to provide affordable housing and infrastructure development. The situation is particularly dire in the southern part of the Taraba State, where there are huge quantities of clay sources that have not been exploited due to the growing demand for low-cost and environmentally friendly building materials. This was done by applying a common set of geotechnical tests, X-ray fluorescence (XRF) and X-ray diffraction (XRD), to the clay deposits in the Wukari, Donga, and Takum Local Government Areas, respectively, using the fired-brick performance evaluation. The study brings scientific insights on the correlation between physical properties of raw materials and the behavior of bricks during firing with engineering performance, which will help optimize the processing of raw materials in brick production, improve raw material quality control, and help develop local ceramic industries in Taraba State. Moreover, the findings contribute to the growing body of clay-related information for sustainable utilization of Nigerian clay resources and provide baseline information for brick classification and standardization in the region.

The study also considers the feasibility of clay deposits of Wukari, Donga, and Takum Local Government Areas of southern Taraba State, Nigeria, for use in the production of fired bricks for structures using geotechnical, geochemical, mineralogical, and engineering characterization. Specifically, this study involves the determination of the Atterberg limits, particle-size distribution, specific gravity, and linear shrinkage of the selected clay deposits to determine the geotechnical properties of the clay; chemical characterization of the clay deposits by XRF analysis and mineralogical characterization by XRD analysis; physical and mechanical properties of the produced bricks at different firing temperatures of 800 °C to 1050 °C; and compliance of the fired bricks with the specification for building bricks for structural masonry applications [14-15].

MATERIALS AND METHODS

Study area and sample collection

Clay samples were obtained from three active brick-making centers located in the major geologies of the southern part of Taraba State, Nigeria, namely Wukari (lateritic Precambrian basement), Donga (Cretaceous sedimentary sequence), and Takum (Quaternary alluvial deposits). Three pits (1.5 m depth) and, where applicable, composite samples (≥40 kg) were taken at 0.5 m intervals at each location according to BS 1377 1-4:2016 [15]. Samples were placed in polyethylene bags, air dried in the laboratory, disaggregated, and then sieved through a 2 mm mesh prior to analysis.

Geotechnical characterization

The geotechnical properties were determined according to the BS 1377-2:2022 [16]. The Casagrande cup method was used for determining the liquid limit and the thread-rolling method for the plastic limit, and the difference between the two was used to determine the plasticity index. The specific gravity was determined using the pycnometer method, particle size distribution by combined wet sieving and hydrometer analysis, and linear shrinkage after oven drying at 105 ± 5 °C. Determination of optimum moisture content (OMC) and maximum dry density (MDD) was done using standard proctor compaction tests in accordance with NIS [15].

Geochemical and mineralogical characterization

Major oxide composition was obtained by the fused-bead preparation with lithium tetraborate–metaborate flux and the wavelength-dispersive X-ray fluorescence (WD-XRF) measurement carried out by a Bruker spectrometer S8 TIGER. Loss on ignition (LOI) was measured at 1000 °C for 1 h. The Malvern Panalytical Empyrean X-ray diffractometer (CuKα radiation, λ = 1.5406 Å, 5–80° 2θ, 45 kV and 40 mA) was used to identify the mineralogical phases, and semi-quantitative phase analysis was performed by Rietveld refinement on the High Score Plus software and the ICDD PDF-4+ database [16].

Brick preparation and firing

The semi-dry pressed bricks were made with 15-18% moisture content, air-dried for 7 days, and then oven-dried at 105 °C for 24 h. Samples were heated in a Carbolite AAF 11/18 electric furnace at various temperatures of 800, 850, 900, 950, 1000, and 1050 °C, with heating rates of 5 °C min^{-1} up to 600 °C and 8 °C min^{-1} up to the peak temperature, followed by a soaking period of 2 h and furnace cooling. A total of 5 bricks were made with each of the 5 clay sources at each firing temperature (90 bricks total). Samples were fired at 1000°C and analyzed by XRD phase analysis [16].

Physical and mechanical characterization of fired bricks

The compressive strength was measured [17], while water absorption and initial rate of absorption (IRA) were also measured [18]. The apparent density and open porosity were calculated by means of the Archimedes immersion method. The linear shrinkage and dimensional tolerances were evaluated with a Vernier calliper after firing, while efflorescence was evaluated following the methods recommended by SON [7].

Statistical analysis

The data were analyzed using the IBM SPSS Statistics Version 29. The effects of clay source and firing temperature on brick properties were analyzed by two-way ANOVA, and mean separation was done using Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$. Pearson correlation analysis was performed to assess the correlations between geotechnical properties, oxide composition, mineralogical phases, and engineering performance.

RESULTS AND DISCUSSION

Geotechnical properties of raw clay deposits

The geotechnical properties of the clay deposits (Table 1) reveal that all three samples have plasticity properties suitable for the manufacture of fired brick with mineralogical composition and particle-size distribution giving different engineering behaviour.

The Wukari lateritic clay (Sample A) was found to have a plasticity index of 20.9% and a low linear shrinkage of 6.8%, which falls within the acceptable plasticity range required for the manufacture of structural brick. The relatively low shrinkage index is consistent with its kaolinite-dominated mineralogy and moderate sand content (27.4%), which both contribute to better dimensional stability during drying. Adeola et al. [11] reported similar behaviour for clays derived from the basement in southwestern Nigeria that exhibited moderate plasticity and low shrinkage associated with better mouldability and fewer drying defects, while Okon and Effiom [19] reported similar behaviour for the Cross River clay deposits, which exhibited moderate plasticity and low shrinkage associated with better mouldability and fewer drying defects. Similar results have been found for kaolinitic ceramic clays in Burkina Faso and China, where kaolinitic deposits have better dimensional stability and firing properties because of the small swelling potential [4, 20].

Table 1: Geotechnical properties of raw clay deposits from Wukari, Donga, and Takum LGAs

Property	**Sample A (Wukari)**	**Sample B (Donga)**	**Sample C (Takum)**	**Standard Limit**	**Status**
Liquid Limit (%)	42.3	47.8	54.1	35 – 65	All Pass
Plastic Limit (%)	21.4	24.6	28.7	15 – 30	All Pass
Plasticity Index (%)	20.9	23.2	25.4	10 – 25	A, B Pass C Borderline
Linear Shrinkage (%)	6.8	8.4	10.2	< 12	All Pass
Specific Gravity	2.64	2.61	2.57	2.5 – 2.8	All Pass
Optimum Moisture Content (%)	16.2	18.4	21.3	—	—
Max. Dry Density (Mg/m^3)	1.84	1.77	1.69	—	—
Clay Fraction (<0.002 mm, %)	38.4	43.1	49.6	25 – 50	All Pass
Silt Fraction (0.002–0.063 mm, %)	34.2	31.8	29.4	—	—
Sand Fraction (0.063–2.0 mm, %)	27.4	25.1	21.0	—	—
USCS Classification	CL	CI	CH	—	—

The Donga clay (Sample B) had a slightly higher plasticity index (23.2%), linear shrinkage (8.4%) and clay fraction (43.1%) and is likely to contain illitic minerals. While the liquid limit (47.8%) is higher than that of Sample A, it still falls within acceptable limits for brick production for structures. It is therefore scientifically valid to add about 15-20 per cent of river sand before moulding, as the effect of sand tempering will be to reduce the plasticity and shrinkage and increase the drying stability of the clay mix. The same has been reported for clay deposits in the Benue Trough region, which had controlled plasticity, low firing shrinkage and better ceramic brick performance due to the favourable sand and clay proportion [21-22]. Similar results have been documented for clay deposits in Benue State, where suitable particle size distribution and moderate plasticity resulted in good dimensional stability and reduced cracking during the firing and drying cycles [23].

The Takum alluvial clay (Sample C) had the highest plasticity index (25.4%), linear shrinkage (10.2%) and clay fraction (49.6%), suggesting a fine-grained material with a higher amount of expandable clay minerals such as smectite and illite. The relatively high optimum moisture content (21.3%) and lower maximum dry density (1.69 Mg m^{-3}) also indicate that the clay fabric is more compressible and expansive. However, all the geotechnical parameters measured were within the recommended limits for brick making, such as the maximum allowable linear shrinkage of about 12% reported for ceramic clays [5]. Alluvial clays were also observed to have similar behaviour [12], and smectite-containing clays were reported by Zhang et al. [24], who noted that higher plasticity improved workability but also increased the drying time to prevent cracking caused by shrinkage. As a result, the Takum clay can be used in the manufacture of fired bricks if moisture control, slower shade drying and appropriate tempering are applied prior to the firing process.

Therefore, the difference in the engineering behaviour which has been noted for the three clay deposits indicates the significant variation with geological source. Wukari clay in the basement revealed the most desirable plasticity and least shrinkage, while Takum clay from the alluvial area was close to the upper limit of plasticity due to its fine texture and high percentage of expansive clay minerals. The results are in agreement with other studies in Nigeria [1, 12, 15] and in other parts of the world [4, 7, 19], which have consistently revealed that the most important factors controlling the workability, drying behaviour and engineering suitability of clay materials for brick making are mineralogical composition and particle-size distribution. The results thus indicate that all three deposits are capable of brick production, but it is necessary to process them at the site to ensure a high quality of the manufactured brick and low production of defects.

The particle size distribution curves are shown in semi-logarithmic form in Figure 1, with the clay, silt and sand stone identified.

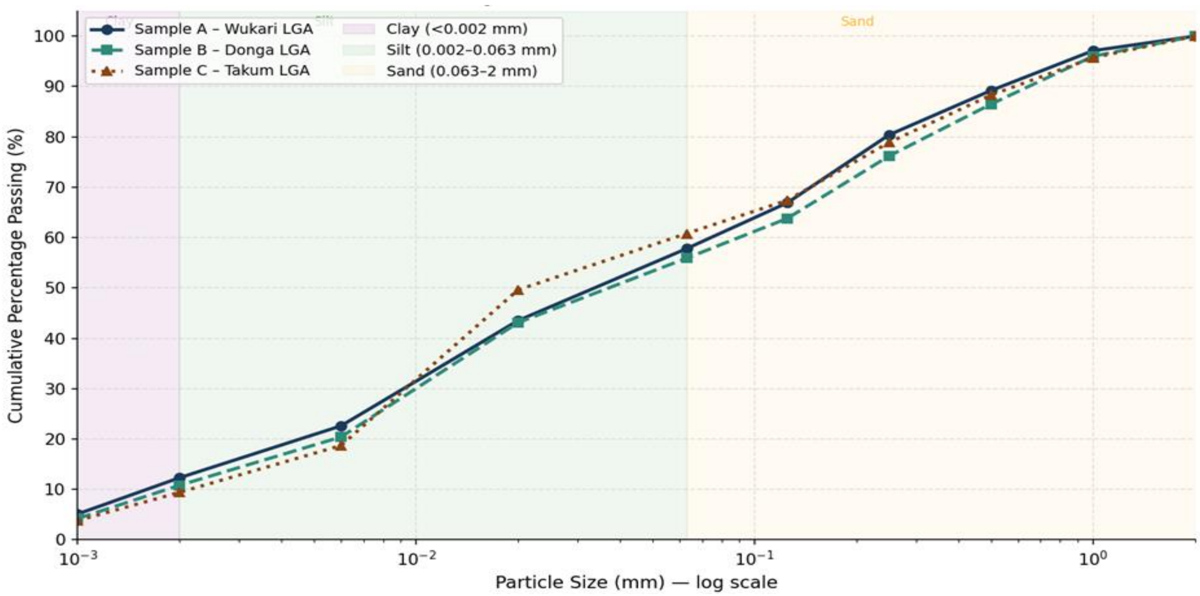

Figure 1: Particle size distribution curves of raw clay deposits of Wukari, Donga, and Takum LGAs, Southern Taraba State.

The three particle size distribution curves show the typical smooth S-shape gradation that would be expected for well-graded fine-grained soils that do not show any evidence of bimodal segregation and point to a relatively continuous distribution of clay, silt, and sand fractions. The Wukari clay (Sample A) is consistently coarser than the grading envelope in the silt and sand fractions, which is due to the presence of quartz-rich residual material inherited from the weathering of Precambrian basement rocks. This is in line with the mineralogical properties of basement-derived Nigerian clay reported by Yerima et al. [25] and Adeola et al. [11], which stated that the decrease in plasticity and shrinkage and increase in dimensional stability of the clay during drying and firing were as a result of the increase in quartz and sand content. The relatively coarse texture of the Wukari deposit is thus confirmed to account for the lower plasticity index and linear shrinkage values, which would indicate that the natural sand fraction would act as an internal temper that would minimize volumetric contraction and drying stresses. Increased coarse fractions with decreased shrinkage have also been found to be the case in lateritic clay materials from West

Africa and Cameroon, where quartz-rich clays have consistently shown better dimensional stability and less cracking susceptibility during brick production [19, 26].

The Takum clay, on the other hand, exhibits the highest difference in the clay-size fraction, having 49.6% of its particles below 0.002 mm, while the Wukari deposit has 38.4% below 0.002 mm. This finer particle distribution agrees with the majority of the smectite and illite clay minerals determined by XRD and correlates to the higher water demand, plasticity, and shrinkage behavior determined during the geotechnical analysis. Similar results have been reported all over Nigeria and other African countries for alluvial and floodplain clays, where an increase in the content of clay-sized particles leads to an increase in moisture absorption and workability capabilities but also presents a greater risk of drying shrinkage and cracking when the clay is employed without the proper tempering additives [12, 14, 15]. International research has also shown that the finer fractions of clays that contain expansive clay minerals are subject to shrinkage stresses during drying and require controlled drying schedules or the addition of coarse non-plastic materials to counteract this shrinkage [27].

The distinct differences in the particle size distribution between Wukari and Takum deposits, with the latter being finer than the former, consequently indicate the geological gradation in southern Taraba State from the older laterite derived from the basement to the younger alluvial deposits. This is a systematic textural variation as observed independently and confirms the mineralogical trends observed using XRD and illustrates the significant relationship between geological origin, particle-size distribution, mineral composition, and engineering behavior. Hence, the present results corroborate earlier suggestions that the use of particle-size distribution should not be considered alone but combined with the mineralogical and geochemical studies to ensure a more accurate prediction of brick-forming behavior, raw material processing optimization, and reduction of production defects within structural fired-clay bricks [4, 19, 27].

All three types of clays met minimum requirements at the optimal firing temperature of 1000 °C [7] (Table 2).

The Wukari clay (Sample A) had the best overall engineering performance, with bricks having the highest compressive strength of 14.8 N/mm^2, the lowest water absorption rate of 8.42%, and an initial rate of absorption (IRA) of 1.34 $kg/m^2 \cdot min$, which is optimum for mortar bonding as recommended [6].

Table 2: Physical and mechanical properties of burnt bricks fired at 1000°C

Property	**Standard Limit**	**Sample A (Wukari)**	**Sample B (Donga)**	**Sample C (Takum)**
Compressive Strength (N/mm^2)	≥ 3.5 (NIS 74)	14.8	12.3	9.6
Water Absorption (%)	≤ 16.0 (NIS 74)	8.42	9.17	11.03
Initial Rate of Absorption ($kg/m^2 \cdot min$)	< 2.0 (BS EN 772-11)	1.34	1.67	1.89
Linear Shrinkage after Firing (%)	≤ 2.0	0.91	1.14	1.78
Apparent Density (g/cm^3)	1.60 – 2.10	1.92	1.84	1.71
Open Porosity (%)	< 25	18.4	20.6	23.1
Efflorescence Rating	Nil / Slight	Nil	Slight	Slight
Dimensional Deviation (mm)	± 3.0	± 1.2	± 1.8	± 2.4

The results show the good densification and the balanced connectivity of the pores during firing. A similar performance was observed for kaolinitic Nigerian clays by Adeola et al [11] and Okon & Effiom [19], who stated that good strength and dimensional stability were due to moderate plasticity and the presence of higher quartz content along with controlled vitrification. Similarly, Millogo et al. [28] found that clays from the laterite formed better mechanical properties due to their lower drying shrinkage, reducing the formation of microcracks and improving sintering efficiency.

The Takum clay (Sample C) showed the highest water absorption value (11.03%), the lowest apparent density (1.71 g/cm³), and the highest open porosity (23.1%); hence, it is relatively less compacted. While these are acceptable, it indicates that these bricks may not have the same durability margin compared to the Wukari and Donga bricks [6]. The higher porosity is also related to the finer particle size distribution and higher content of smectite and illite, as determined by XRD, which are known to cause shrinkage and slow firing rates to complete vitrification [4, 7]. Similar observations have been reported by others [26-27] who found that bricks made from lateritic and alluvial clays were more porous and less dense than those that satisfied the structural requirements but also contained expandable clay minerals.

The absence of efflorescence in Wukari bricks and the slight absence in Donga and Takum were within the acceptable limits of the standard and were rated as slight for both. This has been reported previously for locally fired clay bricks in Nigeria, with some samples showing slight efflorescence [30]. All the dimensional deviations of the bricks were within the tolerance range of 3 mm as specified [6], showing that the dimensional conformity and consistency of the bricks were good in the molding and processing. Similarly, burnt-clay bricks made locally in the Benue state have been reported to have similar dimensional conformity [31-32].

Chemical composition analysis using X-ray fluorescence

The XRF profiles of the three deposits are shown in Table 3 and Figure 2. At all three sites, the concentration of SiO_2 is above 50%, which is the lower limit reported in the literature [20] for the concentration of SiO_2 for ceramic-grade clay.

The total content of $SiO_2 + Al_2O_3$ was in the range of 79.80% in Wukari clay to 69.19% in Takum clay, which is higher than the minimum of 65% recommended to be suitable for ceramic raw materials and the formation of mullite during firing [33]. These values are similar to those obtained in ceramic-grade Nigerian clay [11, 12, 34], indicating that the three clay deposits have a favorable aluminosilicate composition for the production of structural brick. But the oxide composition is not sufficient to describe the fired properties; it is also affected by the mineralogical composition and firing conditions, which are interdependent and affect both densification and phase transformations.

The largest geochemical difference among all the deposits is the progressive increase in Fe_2O_3 content, from 7.82% (Wukari) to 11.43% (Takum).

Table 3. Major oxide composition of raw clay deposits: XRF analysis

Oxide	Sample A (%) Wukari	Sample B (%) Donga	Sample C (%) Takum	ASTM / BS Limit (%)	Status
SiO_2	58.34	54.21	51.87	> 50.0	All Pass
Al_2O_3	21.46	19.88	17.32	10 – 25	All Pass
Fe_2O_3	7.82	9.14	11.43	< 15.0	All Pass
CaO	3.17	4.06	5.21	< 10.0	All Pass
MgO	1.24	1.56	2.04	< 4.0	All Pass
K_2O	2.89	2.43	2.11	< 5.0	All Pass
Na_2O	1.03	1.18	1.47	< 2.0	All Pass
TiO_2	1.67	1.44	1.29	< 3.0	All Pass
SO_3	0.31	0.52	0.88	< 1.0	All Pass
LOI	2.07	5.58	6.38	< 7.0	All Pass
SiO_2 + Al_2O_3 (%)	79.80	74.09	69.19	> 65.0	All Pass

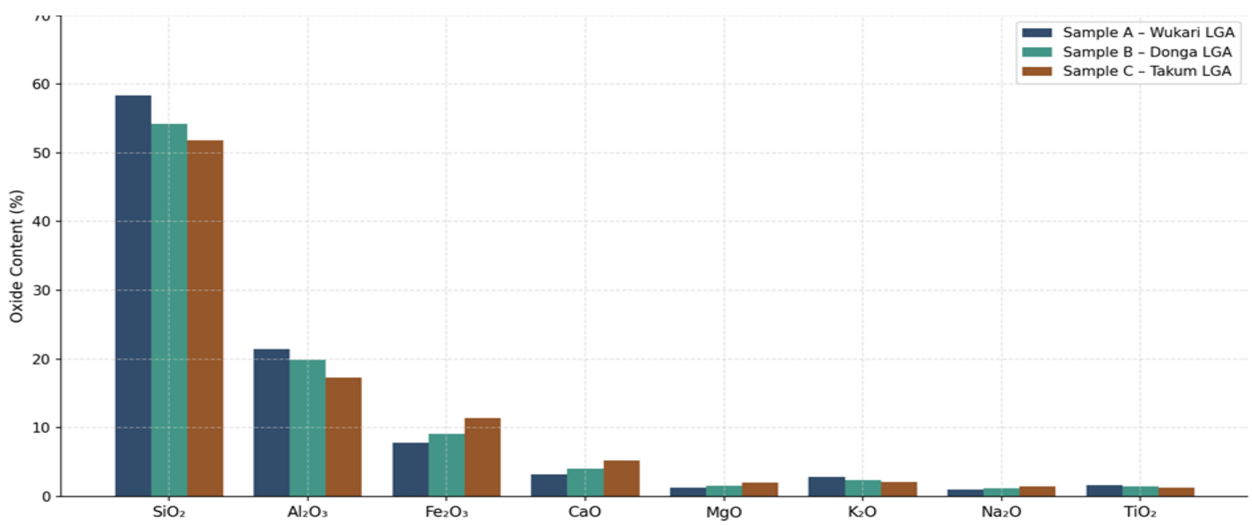

Figure 2: Major oxide composition of raw clay deposits of Wukari, Donga, and Takum LGAs, Taraba State, Nigeria

The phases containing iron may affect the behavior of the clay during firing as regards sintering and vitrification, and high firing temperatures accelerate the mineralogical changes and densification [35]. The minute decrease in compressive strength of Takum bricks when fired at 1050 °C, therefore, indicates that the firing process might have been close to or beyond the optimum firing range for the clay. This interpretation is in line with the studies conducted on Nigerian clays and locally manufactured clay-burnt bricks that indicate that mechanical properties of clay depend strongly on the firing conditions and that the strength is not necessarily proportional to the firing temperature and duration [36, 37]. Based on the observed strength response, therefore, it is hypothesized that about 1000 °C is the optimum firing temperature for the Takum clay for the firing conditions used in the present study.

The loss on ignition (LOI) value was higher in Takum (6.38%) compared to Wukari (2.07%) and shows that more of the volatiles have been lost from this sample during firing. LOI can be either the loss of organics, carbonates, or hydroxyl groups in the structure depending on the mineralogical composition. An increase in LOI may be associated with higher gas evolution upon firing, and in case gases are not well released, it may also be responsible for the occurrence of residual porosity and reduced density. The two hours soaking time used in this study would thus have been sufficient for further gas release and consolidation of the fired bodies. The relatively low SO_3 contents (below 1.0%) and medium CaO levels (3.17–5.21%) also suggest a low content of sulfate- and lime-bearing material that might lead to post-firing defects. Based on these chemical properties, coupled with the physical and mechanical characteristics observed, the three clay deposits are suitable for the manufacture of durable fired bricks [38, 36].

Effect of Firing Temperature on Compressive Strength and Water Absorption

Table 4, along with Figures 3 and 4, indicate the firing temperature and compressive strength and mean water absorption, respectively, in the range of firing temperatures 800 – 1050 °C.

The compressive strength of the samples increased and water absorption decreased with the rise in firing temperature from 800 to 1000 °C for all clay sources, which means that the samples became densified and closed the pores during firing. These changes correspond to the thermal transformation of clay minerals and the formation of a denser ceramic matrix with increased firing temperature [36, 39].

Table 4: Compressive strength and mean water absorption at six firing temperatures

Firing Temp. (°C)	**Strength A (N/mm²) Wukari**	**Strength B (N/mm²) Donga**	**Strength C (N/mm²) Takum**	**Mean Water Absorption (%)**
800	7.2	6.1	5.4	14.20
850	9.4	8.3	7.1	12.87
900	11.6	10.2	8.8	11.34
950	13.5	11.8	9.3	10.12
1000	14.8	12.3	9.6	9.57
1050	15.2	12.8	9.1	9.41

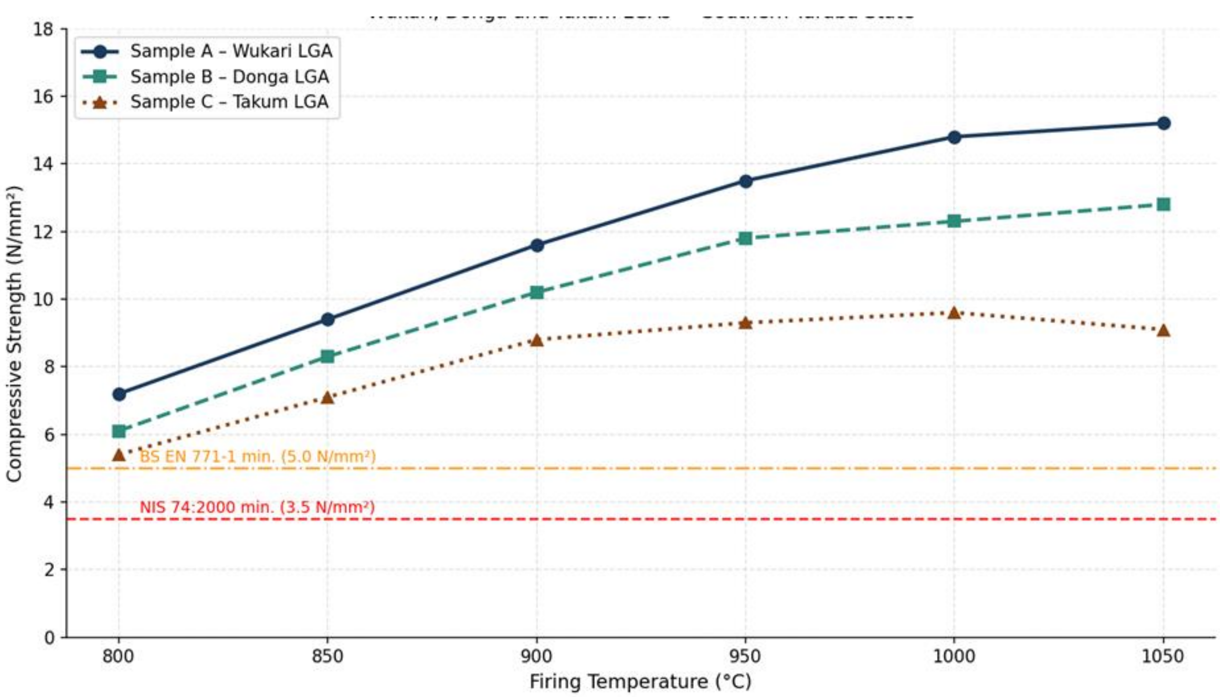

Figure 3; Compressive strength vs. firing temperature of clay deposits of Wukari, Donga and Takum LGAs, Southern Taraba State

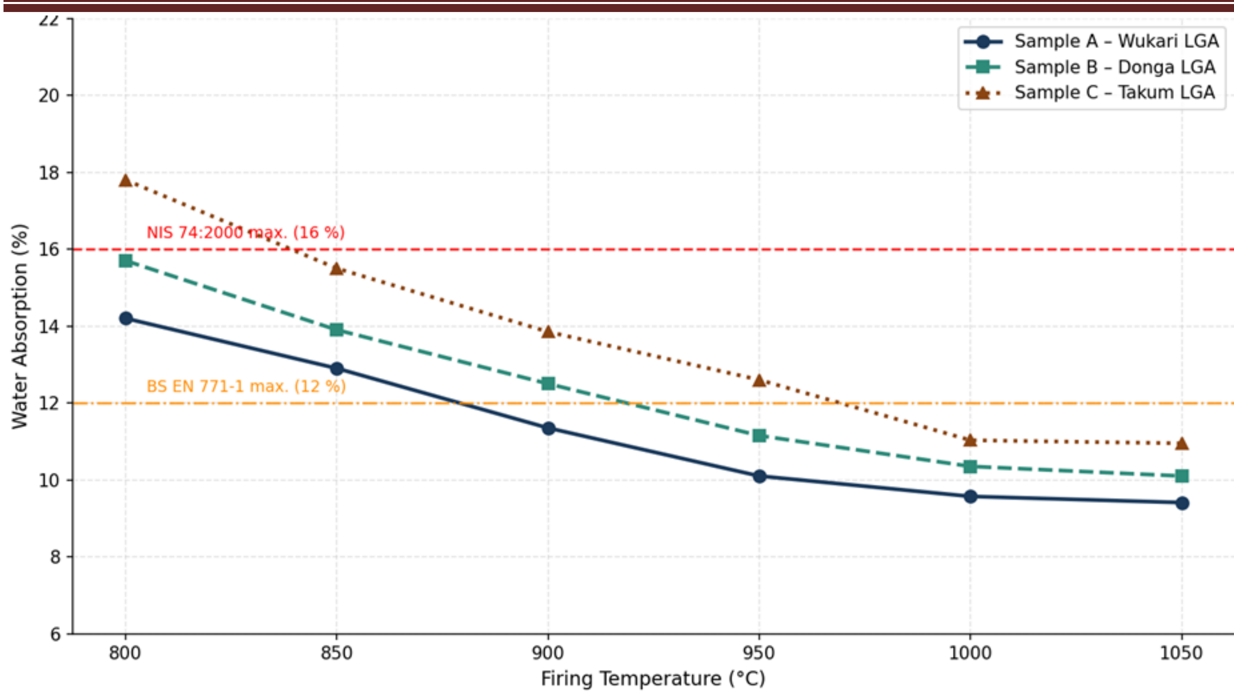

Figure 4: Water absorption vs. firing temperature of clay deposits of Wukari, Donga, and Takum LGAs, Southern Taraba State

The same dependence of brick properties on firing conditions has been published for the locally produced clay-burnt bricks in Taraba State, where the increase or decrease in firing duration resulted in significant differences in brick's compressive strength and water absorption properties [37]. The marginal strength increases obtained in the range of 1000-1050°C for the Wukari (0.4 N/mm²) and Donga (0.5 N/mm²) bricks suggest that no significant mechanical advantages were obtained after further heating under the test conditions. Hence, the practical maximum firing temperature for these two clay sources might be regarded as 1000 °C or less, taking into account the extra energy demand and risk of excessive shrinkage and/or deformation at higher firing temperatures.

The Takum bricks showed a slight decrease in compressive strength at 1050 °C as compared to the Wukari and Donga bricks. This response is due in part to the relatively elevated Fe_2O_3 content of the Takum clay, as the firing response is a result of the interaction of the chemical and mineralogical composition of the clay. The phases containing iron may affect the formation of the liquid phase, vitrification, densification, and development of mullite during firing [40, 41].

The water absorption of the fired bricks, at 14.20% at 800 °C, was also relatively high, approaching the applicable limit for the intended brick classification, which suggests that lower firing temperatures may not give adequate densification for consistent performance in structure. Thus, it seems that, under the conditions used in this work, the temperature of about 1000 °C seems to be adequate to give good strength development and further thermal exposure for the Takum clay. These differences in firing response can be further explained from the chemical composition determined by XRF analysis. The progressive increase of Fe_2O_3 from 7.82% in Wukari to 11.43% in Takum is a significant difference between the deposits of the site. Fe_2O_3, together with CaO, K_2O, and Na_2O, can take part in reactions in the liquid phase during firing and thus affect the sintering, vitrification, and densification.

However, the effect of these oxides is not independent, since the temperature at which liquid-phase formation becomes significant and relevant depends on the overall chemical and mineralogical composition of the clay [41]. The higher amount of Fe_2O_3 in Takum, therefore, is a plausible reason for the better vitrification response at high temperatures and should not be ignored as a factor to be considered for the mechanical behavior of locally produced fired bricks, the balance between compressive strength, water absorption, dimensional stability, and durability.

X-ray Diffraction is a type of mineralogical phase analysis.

Table 5 and Figure 5 indicate the phase assemblage that resulted after firing and the mechanical and physical test results.

The XRD results add to the mineralogical evidence of the differences observed in the engineering properties. Mullite ($Al_6Si_2O_{13}$) was found to be reduced from 14.6 to 12.1 and 8.9 percent for Wukari, Donga, and Takum, respectively; this is an important high-temperature aluminosilicate fired phase of the kaolinite materials.

The results of this trend agree generally with the Al_2O_3 distribution derived from XRF and with the differences in the compressive strength observed. The formation of mullite leads to the formation of a stable crystalline framework and is generally related to the improvement of mechanical and thermal properties of fired kaolinitic materials [35, 40]. Therefore, the higher mullite content in the Wukari is a plausible mineralogical reason for the comparatively high strength of the material, but the final mechanical properties are also dependent on other phases in the fired body, glass-phase content, residual quartz content, and porosity.

Table 5: XRD semi-quantitative mineral phase composition of bricks fired at 1000 °C

Mineral Phase	**Sample A (%) Wukari**	**Sample B (%) Donga**	**Sample C (%) Takum**	**Functional Role in Fired Body**
Quartz (SiO_2)	38.2	34.7	31.4	Skeletal load-bearing framework
Kaolinite / Metakaolin	22.4	19.6	16.8	Sintering precursor; reactive at > 900 °C
Mullite ($Al_6Si_2O_{13}$)	14.6	12.1	8.9	Primary strength and toughness phase
Hematite (Fe_2O_3)	9.8	11.4	13.7	Colour; liquid-phase sintering flux
Illite / Muscovite	7.4	9.2	11.6	Secondary flux; contributes to glass phase
Feldspar (K, Na)	5.1	8.4	9.3	Vitrification promoter above 900 °C
Amorphous glass phase	2.5	4.6	8.3	Pore-filling matrix; reduces absorption

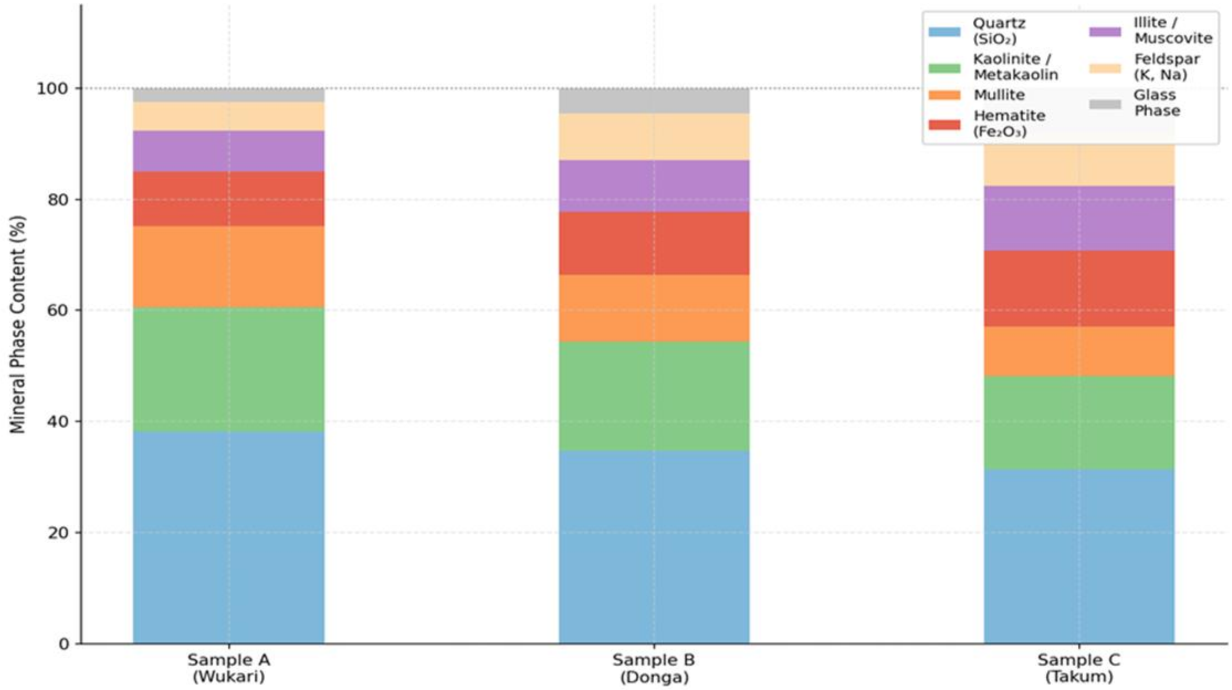

Figure 5: XRD semi-quantitative mineralogical phase composition of bricks fired at 1000°C of Wukari, Donga, and Takum LGAs, Southern Taraba State

The Nigerian Kankara kaolin has also been studied, and changes in mineralogical and microstructural composition occur during the firing process, with mullite formation at higher firing temperatures [35].

The amorphous glass phase, however, grew from 2.5% for Wukari to 8.3% for Takum, the opposite trend of the mullite. This rise was associated with the higher amount of Fe_2O_3 and other fluxing oxides in Takum. When firing occurs, the liquid formed due to the viscous behavior of the particles helps to bind and seal pores, which leads to densification. The amount of liquid phase formed, however, and the temperature at maximum densification are functions of the composition of the ceramic body [40]. Therefore, the higher amount of glass phase in Takum suggests that liquid-phase sintering and vitrification are more influential. This mineralogical feature offers a plausible explanation of the plateau of strength enhancement between 1000 and 1050 °C and of the slight decline at 1050 °C, where further heating for the duration would be unlikely to offer much benefit.

The relatively high quartz percentage of the fired bricks (31-38%) also affects the processing and the product quality. Although quartz gives a fairly stable crystalline phase in the fired body, the α–β transformation that occurs at about 573 °C is reversible, and a change in body volume can create thermal stresses during body heating and cooling. Therefore, the rate at which the kiln chamber is cooled and the uniformity of the cooling process may be a factor in the likelihood of microcracking, and the controlled cooling of the kiln is an important factor to consider in the operation of the kiln. The presence of alkali-bearing components that can engage in liquid-phase reactions at high temperatures may also have caused the firing behavior of the bricks from Donga and Takum to be affected by the presence of illite and muscovite, which also occurred in higher amounts in these bricks (7.4-11.6%). Similar quartz-, mica-, kaolinite-, and iron-bearing mineral assemblages have been reported in Nigerian and West African clay products that have been subjected to thermal treatment [18, 35].

The higher mullite content of Wukari in this study could, therefore, be correlated with the greater strength increase observed in this temperature range, while the relatively high content of the glass phase and Fe_2O_3 concentration of Takum indicate a stronger effect of liquid-phase sintering and vitrification. The differences show that the firing behavior of a clay body is not only influenced by the temperature applied to the clay but also the interplay between temperature and the transformation of mineral phases.

Two-way ANOVA analysis also indicated significant main effects of clay source ($p < 0.001$), firing temperature ($p < 0.001$), and the interaction between the two ($p < 0.001$), which further supports this interpretation. The significant interaction indicates that the effect of firing temperature was different for different clay sources, and therefore, the optimum firing temperature was not necessarily the same for all three deposits.

Combining the analytical results, it is evident that there is a direct correlation between feedstock chemistry, mineral-phase composition, firing reactions, and brick performance. The higher mullite content in Wukari is correlated with the higher degree of crystalline-phase development, whereas the higher Fe_2O_3 content and amorphous-phase content for Takum suggest that it contains more liquid-phase sintering and vitrification. On the industrial side, oxide profiles coupled with mineralogical data from XRD is a good basis for the selection of proper clay sources and the definition of the proper firing window. This study successfully accomplished the objective of evaluating and assessing the suitability of the clay deposits from the three local government areas of Wukari, Donga, and Takum in the southern part of Taraba State, Nigeria, for the production of structural fired brick through geotechnical, geochemical, mineralogical, and engineering characterization. The geotechnical evaluation revealed that the 3 clay deposits have suitable engineering properties for fired-brick production and that Atterberg limits, particle-size distribution, specific gravity, and linear shrinkage are in an acceptable range for fired-brick applications. The tested clay mineral deposits of Wukari, Takum, and Zazzau had the best combination of plasticity, shrinkage, and particle-size distribution for direct brick production, with the former deposit being the most suitable and the latter being more suitable for processing by adding sand to adjust the plasticity.

The geochemical and mineralogical characterization confirmed that the three deposits are ceramic-grade raw materials with good silica and alumina contents suitable for brick making. XRD analysis confirmed the presence of kaolinite as the main clay mineral before firing and the gradual formation of mullite during firing, which was reflected in the improvement in mechanical properties as observed. Iron oxide content was found to have a significant impact on the vitrification behavior, and these differences were related to the differences in firing response between the deposits.

The assessment of firing temperature showed that the engineering performance of the bricks increased gradually with the increase of the firing temperature up to 1000°C, and a further increment in firing temperature could not gain any additional advantage. Bricks that were fired at 1000°C showed the best compressive strength, low water absorption, moderate apparent density, low porosity, less efflorescence, and good dimensional stability. However, further heating beyond this temperature caused a slight drop in strength for the iron-rich Takum clay because of over-vitrification.

Thus, fired bricks from all three clay deposits were found to satisfy the criteria of Nigerian Industrial Standards (NIS) for burnt clay building bricks for structural masonry. The results show that the clay deposits examined are suitable local raw materials for producing good-quality fired bricks for building works. The results obtained will be helpful in choosing suitable clay sources, managing the firing conditions, and helping in maintaining the quality of the product. Besides supplying baseline information for regional clay-resource development, brick standardization, affordable housing, and development of indigenous ceramic industries in Nigeria.

CONCLUSION

The goal of the study was achieved by the integrated geotechnical, chemical, mineralogical, and engineering characterization of the clay deposits of Wukari, Donga, and Takum Local Government Areas of Taraba State. The geotechnical evaluation revealed that the three clay deposits were good for brick making with the exception of Takum, which needs new processing methods, including sand tempering or longer drying time, in order to prevent defects caused by shrinkage. All deposits had suitable ceramic oxide composition as confirmed by XRF analysis, with SiO_2 and Al_2O_3 being the major oxides present, and mullite and quartz (other mineral phases) were identified by XRD, which accounts for the firing behavior and engineering properties observed. In Wukari, the proportion of mullite was correlated with the compressive strength, while in Takum, the content of Fe_2O_3 and the amorphous phase were correlated with the vitrification response at high temperature.

Brick performance was strongly affected by firing temperature, and the optimum firing temperature for bricks made from all three clay sources was at 1000 °C, resulting in bricks that met the requirements for structural masonry units, with further heating to 1050 °C showing little additional gain and a slight loss of strength in the case of the Takum bricks. The study is therefore established that the use of appropriate firing and processing conditions makes Wukari, Donga, and Takum clays suitable local raw materials for the production of fired brick for structural applications. The results give scientific justification for raw material selection, optimization of firing temperature, quality monitoring, and sustainable development of indigenous fired-clay brick industries in Taraba State and Nigeria.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

1. The clay deposits from Wukari, Donga, and Takum Local Government Areas should be utilized as indigenous raw materials for structural fired-brick production. Wukari clay is suitable for direct use, whereas Donga and Takum clays should be subjected to appropriate sand tempering and controlled drying to improve workability and minimize shrinkage-related defects.
2. An optimum firing temperature of 1000 °C should be adopted for the production of structural fired bricks from the investigated clay deposits, as it provides the best balance between compressive strength, water absorption, dimensional stability, and energy efficiency.

3. Brick manufacturers should implement routine quality-control procedures, including determination of plasticity, particle-size distribution, linear shrinkage, compressive strength, water absorption, apparent density, and efflorescence, to ensure consistent compliance with national and international standards for structural masonry units.

4. Government agencies, the Standards Organizations in Nigeria and relevant stakeholders should develop a regional clay-resource database and quality classification system to support commercial exploitation of indigenous clay deposits, encourage investment in the ceramic industry, and promote affordable housing initiatives.

5. Future research should investigate the long-term durability, thermal insulation properties, weathering resistance, and environmental performance of bricks produced from these deposits under field conditions. Additional studies should also evaluate the incorporation of locally available agricultural and industrial by-products as sustainable additives for improving brick performance while reducing production costs and environmental impacts.

Declaration of Conflict

The authors declared that there was no conflict of interest.

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