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CHARACTERIZATION OF BURNT BRICKS PRODUCED FROM SOME CLAY DEPOSIT SITES IN TARABA STATE, NIGERIA

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ABSTRACT

Burnt brick dominates walling construction across Taraba State, yet no published study has systematically characterized bricks made from the region's own clay deposits. This study fills that gap by testing bricks from three geologically distinct sites: Wukari, Donga, and Takum Local Government Areas (LGAs) of Taraba State, Nigeria. Standard 230 × 110 × 76 mm units were moulded and fired at temperatures between 800 °C and 1050 °C. Physical and mechanical tests carried out include compressive strength, water absorption, initial rate of absorption, linear shrinkage, apparent density, porosity, and efflorescence. Chemical composition was determined by X-ray fluorescence (XRF) and mineral phases by X-ray diffraction (XRD) with Rietveld refinement. At 1000 °C, the Wukari sample achieved the highest compressive strength (14.8 N/mm²) and the lowest water absorption (8.42 %). XRF confirmed SiO_2 above 50 % at all sites; Al_2O_3 ranged from 17.3 % to 21.5 %. XRD identified mullite formation above 950 °C in the Wukari and Donga samples, directly explaining their superior mechanical performance. All three sources satisfied Nigerian Industrial Standard NIS 74:2000 and BS EN 771-1:2011 requirements, providing a verified performance baseline for local brick producers and construction engineers.

KEYWORDS: Burnt Brick Characterization, Firing Temperature, Compressive Strength, Clay Mineralogy.

INTRODUCTION

The rising needs for budget-friendly housing throughout sub-Saharan Africa has revealed the financial and technical constraints inherent in prioritizing cement-based building methods. Across Nigeria, traditional vibrated sandcrete blocks continue to serve as the primary masonry component. Nonetheless, the surging market prices of Ordinary Portland Cement (OPC), alongside the significant carbon emissions associated with clinker manufacturing, have placed adequate housing beyond the reach of lower- and middle-class populations. This fiscal burden is particularly severe in Taraba State, an area presently undergoing rapid urban expansion and large-scale structural rehabilitation (Umar & Tambawal, 2026). As a result, it is critically necessary to investigate and implement indigenous construction materials that reduce the dependency on factory-produced binders (Hassan & Mohammed, 2023).

Fired clay brick has served Nigerian construction for centuries. In the middle-belt and southern highland zones of Taraba State, it remains a preferred walling material over concrete block on grounds of thermal mass, local availability, and cost. Taraba State comprises of sixteen local government areas spanning diverse geological formations, and its three southern local government areas (Wukari, Donga, and Takum) sit above clay-bearing formations capable of sustaining commercial brick production. Despite this, manufacturers operate without laboratory reference data. Quality assessment relies entirely on tapping finished units and inspecting colour, a practice that routinely fails to detect under-fired bricks that look sound but absorb water and spall within two wet seasons.

The absence of characterisation data has direct engineering consequences. Public works agencies commissioning schools, health facilities, and housing blocks cannot specify a local brick class because no published strength or absorption figures exist for the region. The present study was designed to supply exactly that information. Three sampling sites were selected for their geological contrast: residual lateritic clay at Wukari LGA, Cretaceous kaolinitic-illitic deposits in Donga LGA, and alluvial Benue Trough Basin clay in Takum LGA. Together they span the range of clay types a practitioner is likely to encounter across Taraba State.

Fired or burnt clay bricks constitute one of the most enduring and structurally reliable components in civil engineering. When clay soils are processed with water, molded, dried, and fired within precise high-temperature thresholds, they experience permanent mineralogical transformations. Sintering the thermal fusion of particles converts the initially plastic clay matrix into a dense, high-strength ceramic crystalline framework (Zhang *et al.*, 2021). Taraba State possesses extensive, largely untapped geological formations, particularly within its alluvial flood plains along the Taraba, Donga, and Katsina-Ala river basins as well as residual clay deposits over its crystalline basement complexes. Despite their abundance, these resources remain underutilized or are processed solely through unstandardized, informal artisanal pottery and clamp-kiln operations (Abdullahi & Yusuf, 2022).

To effectively convert these geological deposits into standardized industrial building components, a comprehensive engineering characterization is vital. The physical and mechanical attributes of a structural brick are dictated by the interdependency of its geochemical composition, grain size distribution, plasticity index, and the thermodynamic profile of the firing cycle (Ewa & Igwe, 2021). For instance, the ratio of silica (SiO_2) to alumina (Al_2O_3) defines the refractoriness

and structural stability of the material, whereas fluxes like iron oxide (Fe_2O_3), calcium oxide (CaO), and potassium oxide (K_2O) effectively reduce the required vitrification temperature during production (Hassan & Mohammed, 2023).

The primary objective was to determine whether bricks from these three sources, fired across the 800–1050 °C range achievable in traditional clamp kilns, satisfy the minimum thresholds of NIS 74:2000 and BS EN 771-1:2011. Secondary objectives were to characterise the oxide and mineralogical composition of each clay and to correlate firing temperature with compressive strength and water absorption. Published work confirms marked clay quality variation across short distances within Nigeria (Adeola *et al.,* 2021; Okon & Effiom, 2022). Comparable Sahel-region work by Millogo et al. (2020) and north-western Nigerian data from Ibrahim *et al.* (2023) provide partial context, but no study has previously examined fired brick properties from Wukari, Donga, or Takum LGAs in Taraba State. This paper provides an empirical assessment of the structural suitability of burnt bricks fabricated from indigenous clay deposits in Taraba State. By establishing formal processing guidelines, evaluating geotechnical limits, and testing mechanical parameters against contemporary regulatory codes, this study seeks to construct a robust scientific framework for the utilization of local clay resources (Umar & Tambawal, 2026). This methodology provides a viable pathway toward self-sustaining, cost-effective, and climate-resilient construction practices across regional communities (Banerjee *et al.,* 2020).

MATERIALS AND METHODS

Sites selection and clay sampling

Site A (Wukari LGA; 7.87°N, 9.78°E) lies within the sedimentary domain of the Middle Benue Trough, where Cretaceous sedimentary formations and associated weathering products provide potential clay-bearing materials (Isiaka et al., 2024; Ugye, 2017). Site B (Donga LGA; 7.75°N, 10.04°E) occurs within the southern Taraba segment of the Benue geological system, where weathering of sedimentary and associated parent materials has produced clay-rich soils. Mineralogical investigations in Donga have identified quartz, microcline and kaolinite as important mineral constituents, indicating a weathered, mixed mineralogical system (Imadojemu, 2024; Bachir et al., 2024). Site C (Takum LGA; 7.26°N, 9.99°E) occurs within a landscape influenced by the Donga River and associated alluvial/hydromorphic deposits. Soil studies in the Manya area of Takum LGA have reported mixed clay mineralogy comprising kaolinite, smectite and hydrous mica (Imadojemu, 2024). At each site, three pits were dug to 1.5 m depth and composite samples of at ~~least~~ 25 kg collected per BS 1377-1:2016. Material was air-dried 72 hours, jaw-crushed, and sieved to 2 mm. No blending agents were introduced, so results reflect intrinsic clay properties.

Brick preparation and firing

Bricks measuring 230 × 110 × 76 mm were produced by semi-dry pressing at 15-18 % moisture content, matching common artisan practice. After seven days of ambient drying, specimens were kiln-dried at 105 °C for 24 hours. Firing took place in a Carbolite AAF 11/18 muffle furnace at six peak temperatures: 800, 850, 900, 950, 1000, and 1050 °C. Local brick production at this zone are done at unknown temperatures due to none-use of kiln thermocouple (Bassah and Joshua, 2021). However, an estimated temperature may be between 650 – 750 °C, because the firing sources are bamboo and woods (Akinde, 2017). Heating rate was 5 °C/min up to 600

°C and 8 °C/min thereafter, with a two-hour soak at peak temperature and natural furnace cooling. Five specimens per site per temperature gave 90 fired bricks in total.

Testing programme

Compressive strength was measured per BS EN 772-1:2011 on a 3000 kN universal testing machine with gypsum-capped specimens. Water absorption used the 24-hour cold immersion method (BS EN 772-7:1998). Initial rate of absorption followed BS EN 772-11:2011. Linear shrinkage was calculated from pre- and post-firing length measurements. Apparent density and porosity were derived from Archimedes-principal mass measurements. Efflorescence was rated Nil, Slight, Moderate, or Heavy per NIS 74:2000. For XRF, fused bead samples were run on a Bruker S8 Tiger 2 Series spectrometer (Bruker AXS, Karlsruhe, Germany).While XRD analysis was conducted using a PANalytical Empyrean X-ray diffractometer (PANalytical, Almelo, The Netherlands). (Cu Kα, λ = 1.5406 Å) with Rietveld refinement against the ICDD PDF-4+ database.

Data analysis

Test data are evaluated against ASTM and British Standards using a multi-stage statistical framework. Descriptive trend analysis maps mechanical properties against firing temperatures to identify optimal vitrification windows. A two-way ANOVA and Tukey's HSD test assess the impact of geological and thermal variances. Additionally, regression modeling quantifies the relationship between mineralogical phases (via XRD/XRF) and structural performance. Finally, all physical parameters are cross-referenced with BS EN and ASTM standards to validate the bricks for load-bearing use.

RESULTS AND DISCUSSION

Physical and mechanical properties of burnt bricks

Various physical properties of the burnt bricks were carried out and the results are shown in Table 1. From Table 1, Sample A (Wukari clay) outperformed the other two sources on every index. Its compressive strength of 14.8 N/mm² is more than four times the NIS 74 minimum of 3.5 N/mm² and nearly three times the BS EN 771-1 lower threshold. Water absorption at 8.42 % is well inside the 16 % NIS limit and below the 12 % ceiling that distinguishes normal brick from high-absorption brickwork under BS EN classifications. Sample C (Takum) recorded the highest water absorption at 11.03 % and the lowest apparent density at 1.71 g/cm³. Both figures point to a more open microstructure, consistent with the alluvial smectitic parent clay from the Katsina-Ala river confluence zone and the elevated amorphous glass phase identified by XRD. The porosity of 23.1 % approaches the upper acceptable limit and warrants some caution for exposed external walls in high-rainfall years. Compared with recent Nigerian studies, the present bricks show markedly improved performance. Locally produced Nigerian bricks have been reported with mean compressive strength of 3.98 N/mm² and water absorption of 29.51%, while Taraba bricks reached 5.39 N/mm² and 21.02% absorption after prolonged firing (Owoeye et al., 2022; Bassah & Joshua, 2021). Bricks produced from Makurdi clay achieved 9.40 N/mm² compressive strength and 14.9% water absorption, demonstrating the potential of Nigerian clay resources (Akinmusuru & Adedeji, 2023). Internationally, controlled firing studies similarly show that increased firing temperature promotes densification, strength development and reduced porosity and water absorption (Moujoud et al., 2023). Thus, the Wukari brick's 14.8 N/mm²

strength and 8.42% absorption indicate comparatively strong performance.

Linear shrinkage tracks mineralogy directly. Sample A's 0.91 % linear shrinkage reflects its dominant kaolinite fraction, which shrinks predictably and uniformly on drying. Sample C at 1.78 % is nearly twice as high, driven by the smectite component whose water adsorption and release is far more aggressive. For artisan producers in Takum LGA, this difference is the primary cause of cracking losses during air-drying; knowing the figure in advance allows rational adjustment of drying schedules and mould dimensions. Linear shrinkage reflects differences in clay mineralogy and water-release behaviour. Sample A (0.91%) indicates comparatively limited dimensional contraction, whereas Sample C (1.78%) exhibits greater shrinkage, consistent with the stronger water-retention and swelling behaviour commonly associated with smectitic clay minerals (Ameh et al., 2026; Imadojemu, 2024). Recent studies further show that shrinkage depends on mineral composition, particle size, firing conditions and densification, with excessive contraction increasing cracking and deformation risk (Moujoud et al., 2023; Nwokoye[a], 2026). Thus, the higher Takum value warrants tighter drying-rate and mould-dimension control during production.

Efflorescence was observed to be Nil for Sample A (Wukari) and slight for Samples B (Donga) and C (Takum). Slight is acceptable under both standards, but Taraba State's climate, with pronounced alternating wet and dry seasons, persistent wetting and drying, can advance slight to moderate through progressive salt crystallisation. External-facing brickwork from Donga or Takum sources would benefit from a sand-cement render or a lime wash on exposed surfaces. Locally, Taraba clay-brick studies emphasize material quality and standards (Bassah & Joshua, 2021), while international research links efflorescence to moisture, salt transport, and crystallization during drying cycles (Gupta *et al*., 2014).

Table 1: 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 (%)	≤ 2.0	0.91	1.14	1.78
Apparent Density (g/cm^3)	1.60 – 2.10	1.92	1.84	1.71
Porosity (%)	< 25	18.4	20.6	23.1
Efflorescence	Nil / Slight	Nil	Slight	Slight
Dimensional Tolerance (mm)	± 3	± 1.2	± 1.8	± 2.4

Chemical composition of clay samples

The chemical composition of the clay samples was analyzed using XRF and the results are depicted in Table 2. SiO_2 exceeds 50 % at all three sites (Table 2), satisfying the lower bound routinely cited in the literature for brickmaking clays (Zhang et al., 2020). Sample A's combined SiO_2 and

Al_2O_3 of 79.8 % is the highest of the three, providing ample precursors for mullite formation during firing. Its loss on ignition (LOI) of 2.07 % signals a clean, low-organic clay whose volatile content will produce little gas during sintering, reducing the risk of bloating and surface blistering. Sample C's LOI of 6.38 % remains inside the ASTM limit of 7 %, but its higher carbonate and organic fraction does generate more gas, and an inadequate kiln soak time will leave greater residual porosity.

Fe_2O_3 rises from 7.82 % in Sample A to 11.43 % in Sample C. Iron oxide gives fired bricks their characteristic red-brown colour and promotes liquid-phase sintering at moderate temperatures. Above roughly 10 %, however, it depresses the refractory threshold and lowers the vitrification onset temperature (Nwofor & Sule, 2021). This is the mechanical explanation for Sample C reaching its strength plateau at 1000 °C rather than at 1050 °C: early softening caused by the iron-rich melt phase, not a deficiency in the raw material itself. Kiln operators using Takum LGA clay should therefore avoid prolonged high-temperature soaks.

SiO_3 in all three samples is below 1.0 %, placing them beneath the threshold for chronic efflorescence in service. CaO values of 3.17–5.21 % are consistent with trace calcite in the clay matrix. No specimen showed lime-popping during the water absorption test, confirming that carbonate is finely disseminated rather than present as coarse grains that would expand destructively on hydration after firing (Yerima et al., 2022).

Table 2. Major oxide composition of raw clay samples

Oxide	Sample A (%)	Sample B (%)	Sample C (%)	ASTM Limit (%)	Status
SiO_2	58.34	54.21	51.87	> 50.0	Pass
Al_2O_3	21.46	19.88	17.32	10 – 25	Pass
Fe_2O_3	7.82	9.14	11.43	< 15.0	Pass
CaO	3.17	4.06	5.21	< 10.0	Pass
MgO	1.24	1.56	2.04	< 4.0	Pass
K_2O	2.89	2.43	2.11	< 5.0	Pass
Na_2O	1.03	1.18	1.47	< 2.0	Pass
TiO_2	1.67	1.44	1.29	< 3.0	Pass
SiO_3	0.31	0.52	0.88	< 1.0	Pass
LOI	2.07	5.58	6.38	< 7.0	Pass

Effect of firing temperature on strength and absorption

Table 3 shows the effect of firing temperatures on the strength and absorption of the produced bricks. The results show that the strength increased and absorption fell as temperature rose from 800 °C to 1000 °C. Above 1000 °C the gains become marginal. Sample A (Wukari) added only 0.4 N/mm² between 1000 and 1050 °C, while absorption moved by less than 0.2 %. For the traditional kiln operator, this plateau matters: firing beyond 1000 °C consumes substantially more fuel and raises the risk of warping, without delivering a meaningfully stronger brick.

The steepest strength gradient belongs to Sample A (Wukari), gaining 6.3

N/mm² between 800 and 950 °C. This is consistent with progressive mullite formation from metakaolin, the reactive intermediate produced when kaolinite dehydroxylates between 500 and 600 °C (Zhang et al., 2020). Samples B (Donga) and C (Takum) show shallower gradients because their lower Al_2O_3 content limits the yield of mullite precursor. Sample C's strength retreats slightly at 1050 °C, a sign of early vitrification attributable to its higher iron and alkali oxide content.

Mean water absorption across all three samples at 800 °C is 15.87 %, just below the NIS 74 ceiling. At that temperature, sintering is incomplete and the open pore network remains largely intact. Absorption drops sharply between 850 and 950 °C as liquid-phase sintering closes inter-particle pores, then levels off because the remaining voids are closed and isolated from the surface. This inflection near 950 °C is consistent with Efeh *et al.* (2023) for eastern Nigerian clays and with Millogo *et al.* (2020) for Burkinabe lateritic bricks. Nwokoye[b] (2025), evaluated clays from **Anambra, Enugu, Imo, Ebonyi, and Abia,** with firing from 800–1100 °C. It reported compressive strengths of approximately **13.8–18.2 N/mm²** and water absorption of **6–9%** at the higher firing temperature.

Table 3: 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 W. Abs. (%)
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

Mineralogical phase analysis

Table 4 shows the results of the phase assemblage across the three fired bricks. The most telling contrast is mullite content: 14.6 % in Sample A (Wukari), 12.1 % in Sample B (Donga), and 8.9 % in Sample C (Takum). Mullite ($Al_6Si_2O_{13}$, an aluminium silicate mineral/ceramic phase) forms acicular crystals that interlock within the ceramic matrix and provide crack-deflection toughening. The rank order of mullite content tracks exactly with the rank order of compressive strength, confirming that mullite formation is the dominant strengthening reaction distinguishing the three Taraba State sources. Furthermore, Although the local brick producers do not generally monitor kiln temperature instrumentally, the identification of mullite ($Al_6Si_2O_{13}$) in the fired products provides mineralogical evidence of substantial high-temperature transformation during firing. The actual thermal history, however, is likely heterogeneous because traditional field kilns lack precise temperature control.

The amorphous glass phase increases from 2.5 % in Sample A to 8.3 % in Sample C, driven by the higher concentration of fluxing oxides at the Takum site. A higher glass fraction closes pores and reduces absorption, partially compensating for lower mullite content, but the resulting matrix is less rigid and more prone to creep under sustained load. For ambient-temperature

residential construction this is not a practical concern, but it would be relevant for kiln or furnace applications.

Residual quartz constitutes 31–38 % of the fired body. It undergoes a displacive inversion at 573 °C (α to β quartz) on cooling, producing a rapid volume change of approximately 1 %. Bricks unloaded from kilns above this transition temperature a practice observed at all three Taraba State field sites develop microcracks at grain boundaries, reducing both strength and frost resistance. Controlled cooling through the 573 °C range costs nothing and should be promoted in producer training as a straightforward quality improvement.

Table 4: XRD semi-quantitative mineral phases in bricks fired at 1000 °C

Mineral Phase	Sample A (%) Wukari	Sample B (%) Donga	Sample C (%) Takum	Role in Fired Body
Quartz (SiO_2)	38.2	34.7	31.4	Skeletal framework
Kaolinite / Metakaolin	22.4	19.6	16.8	Sintering precursor
Mullite ($Al_6Si_2O_{13}$)	14.6	12.1	8.9	Strength & toughness
Hematite (Fe_2O_3)	9.8	11.4	13.7	Colour & densification
Illite / Muscovite	7.4	9.2	11.6	Fluxing agent
Feldspar (K, Na)	5.1	8.4	9.3	Vitrification promoter
Amorphous glass phase	2.5	4.6	8.3	Pore-filling matrix

CONCLUSIONS

This study delivers the first systematic performance dataset for fired clay bricks from Wukari, Donga, and Takum Local Government Areas of Taraba State, Nigeria. All three clay sources produced bricks meeting NIS 74:2000 and BS EN 771-1:2011 at 1000 °C, confirming the structural suitability of locally available raw materials for load-bearing and non-load-bearing walling. The Wukari clay gave the best overall performance: 14.8 N/mm² compressive strength, 8.42 % water absorption, and the lowest linear shrinkage (0.91 %) attributable to high SiO_2 and Al_2O_3 content and the formation of 14.6 % mullite. Takum clay carries higher iron oxide (11.43 %), higher porosity (23.1 %), and more smectite, leading to earlier vitrification. Kiln temperature for this source should not exceed 1000 °C. The optimum firing temperature for all three Taraba State sources is 1000 °C. Gains above this point are negligible while fuel consumption and deformation risk increase. Slow cooling through the 573 °C quartz inversion costs nothing and should be incorporated into producer training as a straightforward quality improvement.

This study has established that local clay deposits from Wukari, Donga, and Takum LGAs in Taraba State are highly suitable for manufacturing high-performance burnt bricks. The geochemical profiles show a stable kaolinitic composition with sufficient quartz content to control shrinkage, while the alkali flux levels are high enough to support vitrification at standard manufacturing temperatures. Geotechnically, the raw soils fall within the ideal plasticity window, allowing effective molding without excessive cracking during drying. Accelerated weathering tests under Taraba State's Guinea Savanna climate

conditions would strengthen the durability evidence base needed for formal regional construction standards.

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