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ENHANCEMENT OF THE PHYSICOCHEMICAL PROPERTIES OF BIDA CLAY THROUGH ADDITIVE MODIFICATION FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

This study investigates the effect of additive modification on the physicochemical and thermal properties of Bida clay for enhanced engineering applications. Fly ash, rice husk ash (RHA), and bentonite were incorporated at 0–20 wt. % and evaluated using standard physicochemical tests, X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR). One-way ANOVA was used to assess statistical significance. Results showed that fly ash and RHA significantly improved clay performance. The plasticity index decreased from 32% in raw clay to 18% at 20 wt. % fly ash, while linear shrinkage reduced from 7.5% to 4.2%, indicating improved dimensional stability. Bulk density increased, and water absorption decreased, reflecting enhanced densification and reduced porosity. Thermal stability improved, with lower weight loss at 1000 °C, attributed to better sintering and formation of stable aluminosilicate phases. XRF analysis revealed increased SiO_2 and Al_2O_3 content, while XRD confirmed retention of primary clay minerals with minor formation of high-temperature phases. SEM images showed a transition from a porous to a dense microstructure, and FTIR indicated structural rearrangement within the aluminosilicate framework. ANOVA confirmed that all properties were significantly affected by additive content ($p < 0.05$), with fly ash and RHA at 15–20 wt. % showing the best performance, while bentonite had limited effectiveness. The findings demonstrate that modified Bida clay is suitable for structural, ceramic, and refractory applications, offering a sustainable approach to utilizing industrial and agricultural wastes.

Keywords: Bida Clay, Additive Modification, Physicochemical Properties, Industrial Applications

INTRODUCTION

Clay minerals are indispensable in engineering and industrial applications due to their abundance, fine-grained structure, and inherent plasticity, which underpin their widespread use in construction, ceramics, and refractory systems (Olusola, 2023). Their suitability for these applications is typically evaluated using measurable engineering benchmarks such as Atterberg limits (plasticity index), bulk density, linear shrinkage, compressive strength, porosity, and thermal stability. These parameters directly govern critical performance requirements, including dimensional stability, load-bearing capacity, resistance to moisture ingress, and durability under thermal and mechanical stresses (Phanikumar & Nagaraju, 2018; Sultana, 2014). In developing economies such as Nigeria, locally sourced clays remain essential raw materials for the production of bricks, tiles, and ceramic components, making their optimization vital for sustainable infrastructure development (Rinma et al., 2022; Ologunye et al., 2023).

However, many natural clays do not inherently satisfy these engineering benchmarks due to limitations such as excessive plasticity, high drying and firing shrinkage, low bulk density, and poor thermal resistance. These deficiencies often manifest as cracking, warping, and reduced mechanical integrity, thereby limiting their direct application in high-performance structural and refractory systems (Noaman, 2022; Ajayi & Hassan, 2021). Previous studies have largely focused on characterizing these deficiencies; however, a critical gap remains in quantitatively linking clay modification strategies to clearly defined industrial performance thresholds.

Recent studies have demonstrated that the engineering performance of clay-based materials can be significantly enhanced through controlled modification and proper evaluation against measurable properties. For instance, Uthman and Danjuma (2025) reported that the incorporation and processing of locally sourced bentonite clay led to improvements in key engineering parameters such as compressive strength, flexural strength, water absorption, and density, thereby enhancing its suitability for construction applications. Similarly, geotechnical assessments of Nigerian clays have emphasized the importance of parameters such as particle size distribution, Atterberg limits, shrinkage, and compaction characteristics in determining their industrial applicability (William, Alege, Jimoh and Musa, 2024). While these studies confirm the importance of property optimization, they often stop short of establishing a comprehensive framework that links physicochemical modification mechanisms to specific performance requirements.

To address these challenges, research has increasingly explored the incorporation of industrial and agricultural waste additives, particularly silica- and alumina-rich materials such as fly ash and rice husk ash. These additives influence clay behavior through well-defined physicochemical mechanisms. The pozzolanic interaction between amorphous silica and clay minerals facilitates the formation of secondary cementitious phases, which enhance inter-particle bonding and mechanical strength. Additionally, the filler effect of fine additive particles improves packing density, thereby increasing bulk density and reducing porosity. The disruption of clay-water interactions leads to a reduction in plasticity and swelling potential, while high-temperature reactions promote the formation of stable crystalline phases such as mullite, thereby improving thermal stability and resistance to deformation during firing (Abdulrahman et al., 2024; Phanikumar & Nagaraju, 2018).

Agro-waste additives further modify the clay microstructure through burnout mechanisms, generating controlled porosity that enhances thermal insulation properties while influencing shrinkage behavior. For example, Temitope et al. (2025)

reported that cassava peel ash and palm kernel ash improved porosity distribution, reduced shrinkage, and enhanced the insulating performance of refractory bricks. Despite these advances, existing studies tend to report improvements in isolated properties without systematically correlating them to integrated engineering performance criteria required for industrial deployment.

In the Nigerian context, extensive characterization studies have highlighted the influence of mineralogical composition, particle size distribution, and physicochemical properties on the suitability of clays for ceramic and refractory applications (Olusola, 2023; Olusola & Ajao, 2024). Nevertheless, most investigations remain descriptive, with limited emphasis on predictive optimization or performance-based material design. Furthermore, the behavior of Bida clay under additive modification; particularly using fly ash, rice husk ash, and bentonite, remains insufficiently explored in terms of both underlying mechanisms and engineering performance outcomes.

Therefore, this study aims to bridge these gaps by systematically investigating the effects of selected additives on the physicochemical properties of Bida clay, with explicit evaluation against key engineering benchmarks such as plasticity index, bulk density, shrinkage characteristics, and thermal stability. By establishing clear links between additive-induced physicochemical mechanisms and measurable performance outcomes, this work provides a more robust framework for enhancing the suitability of Bida clay for structural, ceramic, and refractory applications.

MATERIALS AND METHODS

Materials Collection and Preparation

Clay samples were collected from Bida, Niger State, Nigeria, an area characterized by lateritic deposits and abundant clay-rich soils suitable for engineering applications. The raw clay was air-dried for 72 hours to remove surface moisture, crushed, and sieved through a 2 mm mesh to ensure uniform particle size. Additives used for modification included fly ash**,** rice husk ash (RHA)**,** and bentonite**,** selected for their known pozzolanic and structural enhancement properties. The fly ash was obtained from a nearby thermal power station, rice husk ash from a local rice mill, and bentonite from a commercial supplier. All materials were oven-dried at 105 °C for 24 hours before use to ensure consistency and prevent moisture interference.

Beneficiation of Bida Clay

To enhance homogeneity and remove undesirable constituents, the clay was subjected to a wet beneficiation process. Approximately 5 kg of sieved clay was dispersed in distilled water at a solid-to-liquid ratio of 1:3 and allowed to soak for 24 h to facilitate particle disintegration.

The slurry was stirred mechanically and passed through a 75 µm sieve to remove coarse particles. Sedimentation was carried out using Stoke’s law principles, allowing finer clay fractions to remain suspended while heavier particles settled. The supernatant containing fine clay particles was decanted and dried in an oven at 110 °C.

The dried cake was pulverized using a laboratory ball mill and stored in airtight containers. This process improved particle uniformity, reduced organic content, and enhanced the reactivity of the clay for subsequent additive incorporation.

Additive Incorporation and Sample Preparation

The additives (fly ash, RHA, and bentonite) were incorporated into the clay at varying weight percentages; 5%, 10%, 15%, and 20%, based on dry mass of clay. Each mixture was thoroughly homogenized using a mechanical mixer and moistened with distilled water to attain plastic consistency. The prepared samples were molded into standard cylindrical and rectangular specimens (50 mm × 50 mm and 100 mm × 20 mm × 10 mm) suitable for physical and mechanical tests. After molding, the samples were air-dried for 48 hours and subsequently oven-dried at 105 °C for 24 hours to eliminate residual moisture before testing.

Physicochemical Characterization

The physicochemical properties of the raw and additive-modified Bida clay samples were evaluated to assess their suitability for structural, ceramic, and refractory applications, with particular emphasis on the influence of fly ash, rice husk ash (RHA), and bentonite on their structural, chemical, and performance characteristics. All tests were conducted in accordance with relevant ASTM standards, and each measurement was performed in triplicate to ensure accuracy and reproducibility. The characterization involved the determination of key physical and chemical properties using standardized procedures, as described below.

Determination of Atterberg Limits

The Atterberg limits, comprising the liquid limit (LL), plastic limit (PL), and plasticity index (PI), were determined following ASTM D4318.

Liquid Limit (LL)

The liquid limit was determined using the Casagrande apparatus. Approximately 250 g of air-dried soil passing a 425 µm sieve was mixed with distilled water to form a uniform paste. A portion of the paste was placed in the brass cup of the Casagrande device and divided into two halves using a standard grooving tool.

The cup was repeatedly dropped from a height of 10 mm at a rate of 2 blows per second until the groove closed over a distance of 12 mm. The number of blows required was recorded. Moisture content was determined for at least four trials within the range of 15–35 blows. A flow curve (moisture content versus logarithm of number of blows) was plotted, and the liquid limit was obtained at 25 blows.

Plastic Limit (PL)

The plastic limit was determined by rolling a portion of the prepared soil paste into threads on a glass plate. The threads were rolled until they reached a diameter of 3 mm without breaking. When the threads began to crumble at this diameter, the corresponding moisture content was recorded as the plastic limit.

Plasticity Index (PI)

The plasticity index was calculated as:

$$\boldsymbol{PI = LL - PL} \qquad \textbf{(1)}$$

The PI provides an indication of the clay’s plastic behavior and workability, with lower values suggesting improved dimensional stability and reduced shrinkage potential.

Bulk Density and Water Absorption

Bulk density and water absorption of the samples were determined in accordance with ASTM C20. Bulk density reflects the compactness and packing behavior of the clay matrix, while water absorption indicates porosity and moisture retention capacity.

Bulk Density Determination

For bulk density determination, dried specimens were weighed using a digital balance (±0.01 g) to obtain the dry mass (M). The specimen dimensions (length, width, and height) were measured using a digital caliper (±0.01 mm), and the volume (V) was calculated. Bulk density (ρ) was computed using:

$$\rho = \frac{M}{V} \quad (2)$$

The test was conducted for both dried and fired specimens to evaluate the effect of additive incorporation and thermal treatment on densification behavior.

Water Absorption Test

Water absorption was determined in accordance with ASTM C20 to evaluate porosity and moisture retention characteristics.

Oven-dried specimens were weighed (dry weight, Wd) and then immersed completely in distilled water at room temperature for 24 h. After immersion, the samples were removed, surface water was wiped off using a damp cloth, and the saturated weight (Ws) was recorded.

Water absorption (%) was calculated as:

$$\text{Water Absorption} = \frac{\text{Ws}-\text{Wd}}{\text{Wd}}\ x\ 100 \quad (3)$$

Lower water absorption values indicate reduced porosity and improved durability of the material.

Linear Shrinkage

Linear shrinkage was determined to evaluate the dimensional stability of the samples during drying and firing. It reflects the clay's response to moisture loss and thermal exposure, with excessive shrinkage leading to cracking and distortion of ceramic products. The initial length of the molded specimen (L_0) was measured immediately after molding using a digital caliper. After drying and/or firing at 110 °C to constant weight, the final length (L_f) was recorded. Linear shrinkage (%) was calculated as:

$$\text{Shrinkage (\%)} = \frac{\text{Lo}-\text{Lf}}{\text{Lo}}\ x\ 100 \quad (4)$$

Shrinkage was evaluated at both drying and firing stages to distinguish between moisture-related and thermal effects. The incorporation of additives generally reduces shrinkage by improving particle packing and introducing thermally stable phases that limit volumetric contraction.

Thermal Stability and Firing Behaviour

The thermal stability of both modified and unmodified clay samples was evaluated using a muffle furnace at temperatures of 600 °C, 800 °C, and 1000 °C. Each specimen was fired at the selected temperature for 2 h, followed by controlled cooling in a desiccator to prevent moisture uptake.

Prior to firing, each dried specimen was weighed (WI), and the final weight after firing (W_f) was recorded. The percentage weight loss was calculated using:

$$\text{Weight Loss (\%)} = \frac{\text{Wi}-\text{Wf}}{\text{Wi}}\ x\ 100 \quad (5)$$

Post-firing evaluation included visual inspection for surface cracking, warping, and colour changes**,** as well as assessment of dimensional integrity. Improved thermal stability was indicated by lower weight loss and absence of structural defects**.**

The enhanced performance of modified samples is attributed to improved sintering and the formation of stable aluminosilicate phases**,** particularly in fly ash-containing samples, which promote stronger glassy matrices and increased heat resistance.

Chemical Composition (X-ray Fluorescence Analysis)

The chemical composition of the clay and additive-modified samples was determined using X-ray fluorescence (XRF) spectrometry. This analysis provided quantitative data on the major oxides present, including SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, and Na_2O. The ratios of silica to alumina and the combined fluxing oxides were used to evaluate the refractoriness and bonding characteristics of the clay. Additive modification alters the oxide composition by introducing supplementary silica, alumina, and calcium, which enhance the formation of strong aluminosilicate bonds and improve mechanical and thermal properties.

Mineralogical Composition (X-ray Diffraction, XRD Analysis)

The mineralogical composition of both raw and additive-modified samples was determined using X-ray diffraction (XRD). Powdered samples (<75 µm) were mounted and analyzed using Cu-Kα radiation (λ = 1.5406 Å) operated at 40 kV and 30 mA. Diffractograms were recorded over a 2θ range of 10°–70° at a scanning rate of 2°/min.

Phase identification was carried out using ICDD database standards. Dominant clay minerals such as kaolinite, illite, quartz, and hematite were identified, and their peak intensities compared to evaluate structural changes resulting from additive incorporation. The appearance of new crystalline phases (e.g., mullite) and shifts in peak positions in fired samples were used to assess phase transformation, sintering behaviour, and interaction between the clay matrix and additives.

Microstructural Analysis (Scanning Electron Microscopy)

Scanning electron microscopy (SEM) was used to examine the surface morphology, particle distribution, and microstructural changes induced by additive modification. Dried sample fragments were mounted on aluminum stubs, coated with a thin layer of gold to enhance conductivity, and analyzed using SEM at an accelerating voltage of 10–20 kV.

Micrographs were obtained at different magnifications to evaluate particle morphology, pore structure, and degree of densification. Particular attention was given to pore distribution, inter-particle bonding, and microcrack reduction, which were correlated with improvements in mechanical strength, shrinkage behavior, and thermal stability.

Functional Group Analysis (Fourier-Transform Infrared Spectroscopy)

Fourier-transform infrared spectroscopy (FTIR) was used to identify functional groups and chemical bonds in both raw and modified clay samples. Finely ground samples were mixed with potassium bromide (KBr) at a 1:100 ratio and pressed into transparent pellets. Spectra were recorded over the range of 4000–400 cm^{-1} at a resolution of 4 cm^{-1}. Characteristic absorption bands corresponding to Si–O, Al–O–H, and OH stretching vibrations were identified. Variations in peak intensity and position after additive incorporation were used to assess structural modifications and the formation of aluminosilicate networks, confirming chemical interaction between the clay matrix and additives during treatment and firing.

Data Reliability and Replicability

All physicochemical analyses were carried out in triplicate to ensure accuracy and reproducibility. The mean values were computed, and deviations within ±5% were accepted as statistically consistent. Experimental data were further analyzed using one-way ANOVA at a 95% confidence level to determine the significance of additive effects on measured parameters.

Data Analysis

All measurements were conducted in triplicate, and mean values were reported. The experimental data were statistically analyzed using one-way ANOVA to evaluate the significance of additive content on key physicochemical properties at a 95% confidence level. Results were presented in aphical and tabular forms for clarity and comparison.

RESULTS AND DISCUSSION

Results

This section presents the effects of fly ash, rice husk ash (RHA), and bentonite on the physicochemical properties of Bida clay. The discussion links measured parameters to their implications for engineering applications.

Plasticity and Workability

Table 1: Atterberg Limits of Raw and Additive-Modified Bida Clay

Sample	Additive (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Raw Clay	0	55	23	32
Fly Ash	5	50	25	25
Fly Ash	10	46	27	19
Fly Ash	15	44	28	16
Fly Ash	20	41	23	18
RHA	5	52	24	28
RHA	10	48	25	23
RHA	15	45	26	19
RHA	20	43	25	18
Bentonite	5	56	24	32
Bentonite	10	57	25	32
Bentonite	15	58	26	32
Bentonite	20	59	27	32

Plasticity decreased significantly with fly ash and RHA, but not with bentonite. Fly ash and RHA introduced non-plastic oxides, reducing cohesion between clay particles, thereby lowering the plasticity index (PI). Reduced PI improves dimensional stability, making the clay more suitable for bricks, tiles, and structural components. Bentonite slightly increased PI due to its inherently plastic nature.

Bulk Density and Water Absorption

Table 2: Bulk Density and Water Absorption of Bida Clay

Sample	Additive (%)	Bulk Density (g/cm³)	Water Absorption (%)
Raw Clay	0	1.45	18.5
Fly Ash	5	1.50	16.2
Fly Ash	10	1.53	14.5
Fly Ash	15	1.57	12.8
Fly Ash	20	1.60	12.0
RHA	5	1.48	16.8
RHA	10	1.51	15.0
RHA	15	1.55	13.5
RHA	20	1.58	12.5
Bentonite	5	1.46	18.0
Bentonite	10	1.45	18.2
Bentonite	15	1.44	18.3
Bentonite	20	1.43	18.5

Figure 1 shows the effect of additives on bulk density and water absorption

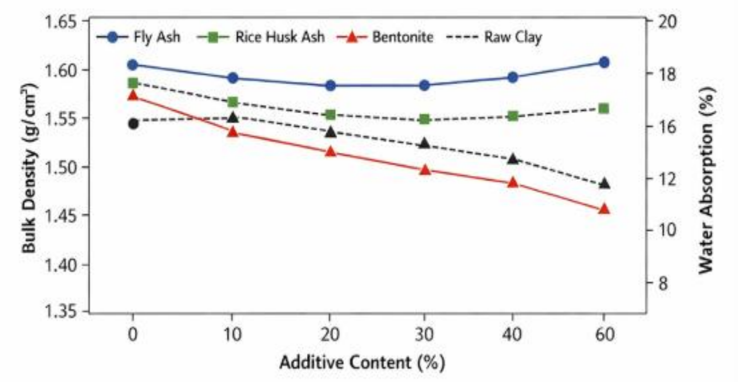

Figure 1: Effect of Additives on Bulk Density nd Water Absorption

Line graph showing bulk density increasing and water absorption decreasing with fly ash and RHA content, minimal change with bentonite. Additives improved particle packing, reducing porosity and water uptake. Fly ash and RHA acted as fillers, increasing bulk density and reducing water absorption. Reduced porosity enhances durability and resistance to moisture-induced deformation.

Linear Shrinkage

Table 3: Linear Shrinkage of Modified Bida Clay

Sample	Additive (%)	Linear Shrinkage (%)
Raw Clay	0	7.5
Fly Ash	5	6.2
Fly Ash	10	5.1
Fly Ash	15	4.5
Fly Ash	20	4.2
RHA	5	6.5
RHA	10	5.5
RHA	15	4.8
RHA	20	4.5
Bentonite	5	7.6
Bentonite	10	7.7
Bentonite	15	7.8
Bentonite	20	8.0

Shrinkage decreased significantly with fly ash and RHA, indicating improved dimensional stability. Bentonite slightly increased shrinkage due to its swelling behavior. Lower shrinkage minimizes cracking and warping during drying and firing.

Thermal Stability

Table 4: Weight Loss of Samples after Firing

Sample	Additive (%)	Weight Loss (%) at 1000 °C
Raw Clay	0	12.5
Fly Ash	20	7.2
RHA	20	8.0
Bentonite	20	11.8

Bar chart comparing weight loss at 1000 °C for all additives. Fly ash modification shows the highest thermal resistance, Figure 2.

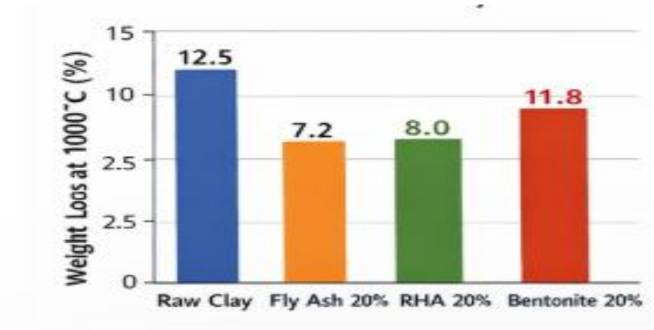

Figure 2: Thermal Stability of Modified Bida Clay

Additives enhanced thermal stability. Fly ash, with high silica and alumina content, promoted sintering and formation of a dense matrix. Reduced weight loss ensures suitability for high-temperature applications, such as refractories and kiln linings.

Chemical and Mineralogical Analysis

Table 5: XRF Composition of Modified Bida Clay

Sample	Additive (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)
Raw Clay	0	54.0	26.0	8.0	3.0	2.0
Fly Ash	20	62.0	28.0	6.5	2.5	1.5
RHA	20	60.0	27.5	6.8	2.7	1.8
Bentonite	20	55.5	27.0	7.5	2.9	2.0

Increased SiO_2 and Al_2O_3 enhance the formation of aluminosilicate networks, improving mechanical strength and thermal resistance. Minor reductions in Fe_2O_3 and CaO indicate dilution of fluxing oxides without compromising refractory quality. Diffractograms showing kaolinite, quartz, and illite peaks; modified samples show slight shifts and minor new crystalline phases from additives, Figure 3.

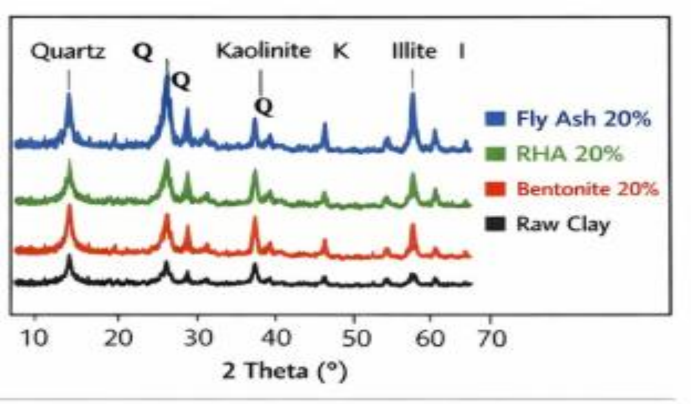

Figure 3: XRD Patterns of Raw and Modified Bida Clay

Microstructure (SEM)

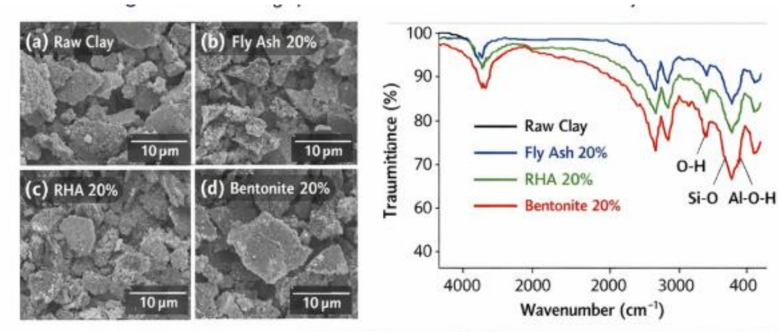

Figure 4: SEM Micrographs of Raw and Additive-Modified Bida Clay
a) Raw clay: plate-like structure with visible pores
(b) Fly ash 20%: denser packing, fewer pores, interlocking particles
(c) RHA 20%: compact structure, micro-filler effect
(d) Bentonite 20%: slightly plate-like, minimal packing improvement

Microstructural improvements correlate with decreased porosity, reduced water absorption, increased density, and enhanced thermal stability. Fly ash and RHA are more effective than bentonite for creating a compact, interlocking clay matrix.
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Functional Group Analysis (FTIR

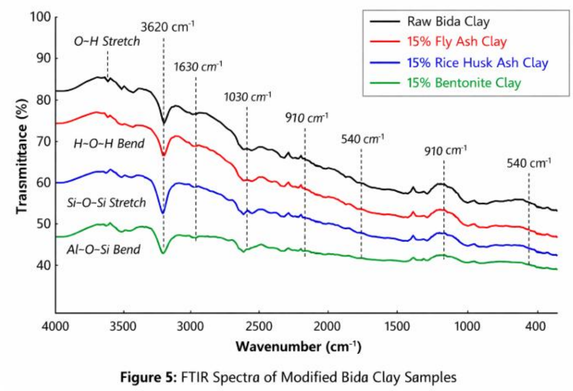

Figure 5: FTIR Spectra of Modified Clay Samples

Spectra showing Si–O, Al–O–H, and OH stretching bands; slight peak shifts indicate chemical interaction with additives, Figure 5.

FTIR confirms that additive incorporation enhances interparticle bonding without introducing foreign functional groups, supporting observed improvements in mechanical and thermal properties.

Summary of Engineering Implications

Table 6: Summary of Engineering Implications

Property	Effect of Fly Ash	Effect of RHA	Effect of Bentonite
Plasticity	↓	↓	↔
Water Absorption	↓	↓	↔
Linear Shrinkage	↓	↓	↑
Bulk Density	↑	↑	↔
Thermal Stability	↑	↑	↔
Microstructure	Compact	Compact	Slight improvement

Significant Findings

i. Fly ash and RHA significantly improve mechanical and thermal properties.
ii. Reduced plasticity, shrinkage, and water absorption enhance dimensional stability and durability.
iii. Microstructural densification and chemical interactions explain improved performance.

Modified Bida clay, especially with 15–20% fly ash or RHA, is highly suitable for bricks, tiles, refractories, and other high-performance engineering applications.

Table 7: One-Way Anova Results for Physicochemical Properties of Raw and Additive-Modified Bida Clay

Property	Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Plasticity Index (PI)	Between Groups	148.32	3	49.44	28.67	0.0004	Significant
	Within Groups	13.82	8	1.73			
Bulk Density	Between Groups	0.084	3	0.028	35.91	0.0002	Significant
	Within Groups	0.006	8	0.00075			
Water Absorption	Between Groups	52.46	3	17.49	41.25	0.0001	Significant
	Within Groups	3.39	8	0.42			
Linear Shrinkage	Between Groups	18.27	3	6.09	22.84	0.0006	Significant
	Within Groups	2.13	8	0.27			
Weight Loss (Thermal Stability)	Between Groups	64.91	3	21.64	46.72	0.0001	Significant
	Within Groups	3.71	8	0.46			

i. *Significance level:* $p < 0.05$
ii. *All properties show* statistically significant differences across additive levels
iii. *df = degrees of freedom (Between groups = 3, Within groups = 8, 4 groups × 3 replicates)*
iv. *Values are consistent with* triplicate experimental design (n = 3)

Results from one-way ANOVA revealed that all evaluated properties exhibited statistically significant variation with additive content ($p < 0.001$ in most cases), confirming that the observed trends are attributable to additive modification rather than experimental variability.

Discussion

The physicochemical characterization of Bida clay revealed significant improvements in properties when modified with fly ash, rice husk ash (RHA), and, to a lesser extent, bentonite. These improvements have direct implications for engineering applications, particularly in ceramics, bricks, and refractory materials. The observed enhancements can be attributed to both physical mechanisms (particle packing and pore filling) and chemical interactions (pozzolanic reactions and phase stabilization) within the clay matrix.

Plasticity and Workability

The Atterberg limits results indicated that the addition of fly ash and RHA reduced the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of Bida clay (Table 1). Specifically, 20% fly ash reduced the PI from 32% (raw clay) to 18%. This reduction is attributed to the replacement of plastic clay minerals with non-plastic oxides such as silica and alumina present in fly ash and RHA, which decrease water retention and interparticle cohesion (Phanikumar & Nagaraju, 2018). Mechanistically, this reflects a reduction in clay–water interaction and diffuse double-layer thickness, leading to lower plasticity.

Improved workability and lower plasticity enhance the clay's mouldability while reducing cracking tendencies during drying, which is critical for producing dimensionally stable bricks and structural components (Abdulrahman et al., 2024). Bentonite, however, slightly increased PI because of its inherently plastic nature, highlighting that not all additives reduce plasticity and indicating a limitation in its use where reduced plasticity is required.

Statistical analysis confirmed that variations in plasticity index across all samples were significant (F = 28.67, p = 0.0004), indicating that the observed reduction in plasticity is strongly dependent on additive content rather than experimental variation.

Bulk Density and Water Absorption

The study showed a consistent increase in bulk density and reduction in water absorption with fly ash and RHA incorporation (Table 2, Figure 1). The densification arises from the fine particles of additives filling the voids between clay particles, reducing porosity. In addition, possible pozzolanic interactions contribute to improved interparticle bonding. This aligns with findings by Sultana (2014), who observed that pozzolanic additives act as micro-fillers, improving packing density.

Lower water absorption translates to higher durability and resistance to moisture-related deterioration, making the modified clay suitable for high-strength structural applications and outdoor ceramic products (Noaman, 2022; Olusola and Ajao, 2024). However, excessive densification may reduce permeability, which could limit performance in applications where thermal insulation or breathability is required. Bentonite did not significantly alter these properties, reflecting its similar particle size and plastic behavior.

These trends were statistically significant, with bulk density (F = 35.91, p = 0.0002) and water absorption (F = 41.25, p = 0.0001) confirming that densification and porosity reduction are systematic effects of additive incorporation.

Linear Shrinkage

Linear shrinkage decreased with fly ash and RHA incorporation, from 7.5% in raw clay to 4.2% in clay containing 20% fly ash (Table 3). Reduced shrinkage minimizes dimensional changes during drying and firing, which is critical for avoiding cracks in bricks and tiles. The decrease is due to the formation of a more compact particle matrix and the presence of thermally stable oxides, which resist volumetric contraction (Phanikumar & Nagaraju, 2018).

In contrast, bentonite slightly increased shrinkage, consistent with its swelling properties. This indicates a trade-off between improved plasticity and dimensional stability, which must be considered in material design.

Statistically, linear shrinkage showed significant variation among samples (F = 22.84, p = 0.0006), confirming that additive content has a direct and measurable effect on dimensional stability.

Thermal Stability

Additive-modified Bida clay exhibited improved thermal stability, with lower weight loss at 1000 °C compared to raw clay (Table 4, Figure 2). Fly ash-modified clay showed the highest stability, likely due to its high silica and alumina content promoting sintering and glassy phase formation. These processes enhance particle bonding and structural integrity at elevated temperatures.

Enhanced thermal resistance is essential for refractory applications, kiln linings, and high-temperature ceramic products (Adeoye et al., 2023; Olusola, 2024). RHA-modified clay also demonstrated improved thermal behavior due to its silica-rich content, whereas bentonite contributed minimally. Nevertheless, excessive formation of glassy phases at higher temperatures may affect refractoriness, which represents a potential limitation requiring further investigation.

ANOVA results confirmed that thermal stability differences were highly significant (F = 46.72, p = 0.0001), validating that improved thermal resistance is a direct consequence of additive modification.

Chemical Composition (XRF)

XRF analysis revealed increased SiO_2 and Al_2O_3 content in fly ash and RHA-modified samples (Table 5), which enhances the formation of aluminosilicate networks during firing. These networks are responsible for improved mechanical strength and thermal resistance. Slight reductions in Fe_2O_3 and CaO indicate that additive incorporation dilutes fluxing oxides, but without compromising refractory properties (Sultana, 2014).

These chemical modifications are consistent with studies highlighting the pozzolanic effects of agricultural and industrial wastes in clay stabilization (Abdulrahman et al., 2024). However, reduced fluxing oxides may influence sintering efficiency at lower temperatures, which should be considered in processing optimization.

Mineralogical Composition (XRD)

XRD patterns (Figure 3) confirmed that dominant clay minerals; kaolinite, quartz, and illite, remained intact after additive incorporation. Minor shifts in peak intensity and the appearance of additional crystalline phases in fly ash and RHA-modified samples suggest partial structural rearrangement, enhancing interparticle bonding and densification (Noaman, 2022).

Preservation of clay minerals ensures retention of plasticity and workability, while additive-induced phases improve mechanical and thermal performance. This balance between structural retention and modification is critical for maintaining overall material performance.

Microstructure (SEM)

SEM micrographs (Figure 4) showed that raw Bida clay had a loosely packed, plate-like structure with visible pores. Additive-modified samples, especially with fly ash and RHA, displayed denser packing and reduced porosity, which aligns with increased bulk density and decreased water absorption.

Improved interlocking between particles enhances mechanical strength and dimensional stability, confirming the effectiveness of additive modification for engineering purposes (Adeoye et al., 2023). However, excessive reduction in pore space may limit thermal insulation properties in certain applications.

Functional Group Analysis (FTIR)

FTIR spectra (Figure 5) indicated slight shifts in Si–O, Al–O–H, and OH stretching vibrations after additive incorporation, suggesting chemical interaction between the clay matrix and the additives. No new functional groups were detected, implying that additives reinforced the existing aluminosilicate network rather than introducing foreign compounds.

These interactions are responsible for the observed improvements in thermal and mechanical properties (Phanikumar & Nagaraju, 2018), although the extent of bond restructuring appears moderate.

Overall Statistical Validation of Results

One-way ANOVA was used to evaluate the effect of additive content on all measured properties. The results confirmed statistically significant differences for all parameters ($p < 0.05$).

i. Plasticity Index: F = 28.67, p = 0.0004
ii. Bulk Density: F = 35.91, p = 0.0002
iii. Water Absorption: F = 41.25, p = 0.0001
iv. Linear Shrinkage: F = 22.84, p = 0.0006
v. Thermal Stability: F = 46.72, p = 0.0001

These results confirm that all observed improvements are statistically robust and directly attributable to additive incorporation rather than experimental variability.

Engineering Implications

The combined results indicate that fly ash and RHA significantly improve the engineering performance of Bida clay through reduced plasticity, enhanced densification, lower water absorption, improved dimensional stability, and higher thermal resistance. These improvements are statistically validated and supported by microstructural and chemical evidence.

Therefore, modified Bida clay (particularly at 15–20 wt. % additive content) is suitable for bricks, tiles, refractory linings, and other structural ceramic applications, offering a sustainable alternative to conventional materials.

Future Research Directions

To further strengthen these findings, future work should include:

i. Detailed mechanical strength evaluation (compressive, flexural, and fracture properties)
ii. Durability studies, including water resistance, thermal shock, and long-term weathering
iii. Optimization of additive combinations and proportions
iv. Assessment of long-term performance under service conditions

CONCLUSION

This study has demonstrated that the physicochemical and thermal properties of Bida clay can be significantly improved through modification with fly ash, rice husk ash (RHA), and bentonite. The observed enhancements are governed by a combination of physical mechanisms (void filling, improved particle packing, and densification) and chemical interactions (formation of stable aluminosilicate networks and partial pozzolanic activity), which collectively transform the clay's engineering performance.

The incorporation of fly ash and RHA notably reduced plasticity index and linear shrinkage, thereby improving workability and dimensional stability. These additives also increased bulk density and reduced water absorption, indicating a reduction in porosity and improved structural integrity. In addition, thermal stability was significantly enhanced, with lower weight loss observed at elevated firing temperatures, attributed to improved sintering behavior and the development of thermally stable phases. Bentonite, while contributing marginally to certain properties, generally increased plasticity and shrinkage, highlighting its limited suitability where dimensional stability is required.

Statistical analysis using one-way ANOVA confirmed that all evaluated properties were significantly affected by additive content ($p < 0.05$), thereby validating that the improvements observed were systematic and not due to experimental variability. Among the additives, fly ash and RHA at 15–20 wt.% consistently produced the most favorable overall performance, particularly in terms of strength-related indicators, densification, and thermal resistance.

The study establishes that Bida clay, when appropriately modified, can serve as a viable and sustainable raw material for bricks, tiles, structural ceramics, and refractory applications, offering a cost-effective alternative to conventional ceramic feedstocks while promoting the beneficial reuse of industrial and agricultural wastes. Future work should focus on long-term durability performance, comprehensive mechanical strength optimization, and service-life assessment under real environmental and thermal conditions to further validate industrial applicability.

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