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Advances in the Development, Processing, and Application of Locally Sourced Clay-based Refractory Materials for Furnace Application in Nigeria

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Abstract

Refractories are ceramic materials that are used in high-temperature applications, often above 1100ºC. These materials find applications in reactors, kilns, ovens, and furnace linings. The need for refractory materials is consistently increasing to accommodate the ongoing development of different industries and factories. Local clays are currently under investigation to address the insufficient supply of refractory materials. Although the geo-morphology of the various locations where deposits of clay are found has been examined, comparatively little work has been done to fully evaluate these deposits to ascertain their suitability for use. This paper includes a review of the refractories produced from locally sourced clay deposits in Nigeria, followed by an evaluation of their usability for furnace lining. Generally, most of the findings reiterate the fact that the local clay has excellent properties for refractories; however, the local manufacturing of refractories in Nigeria has been very low, hence the nation still depends largely on imported refractories. Adequate funding for the local manufacturing of refractories would be needed to access and explore about 8 billion tonnes of clay deposits across Nigeria, thereby reducing imports and maximizing local production.

Keywords: *Refractories, Local clay, Furnace lining, Physical properties, Chemical properties.*

1. Introduction

Nigeria's urgent needs and the accessibility of its vast resources necessitate those local resources to be used more effectively, through scientific awareness and cutting-edge innovations, to satisfy the demands of the manufacturing industries. Industrial advancement in Nigeria has produced an understanding and has also improved the living conditions of both the metropolitan and rural inhabitants, thereby resulting in the perpetual utilization of advanced manufacturing equipment. Nigeria is a developing nation with numerous businesses that heavily rely on refractory materials. Clay is one of the numerous mineral resources that are available in Nigeria. The presence and the significance of clay are understood since prehistoric periods, when it was employed for simple tasks, such as making bricks, earthenware, mud-house buildings, and other structures [1]. Even though several regions of the country have substantial clay deposits, there has been practically minimal local production of refractory materials [2], [3].

Nigeria must preserve its steel and iron manufacturing industries, while establishing new ones, if it is to continue its rapid industrial growth. The refractory bricks used in these industries are made from kaolin or other clays that are now imported [4]. The petrochemical, metallurgical, and related industries in Nigeria are challenged by foreign

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exchange scarcity, infrastructure decay, high production costs, obsolete technology, policy inconsistencies, inadequate raw material characterization, and often weak investment support. This has made it imperative that local raw materials be sourced to enhance productivity.

Locally sourced materials hold significant potential for the fostering of sustainable development, importantly, in developing countries, like Nigeria, and especially in sectors such as construction, manufacturing, and metallurgy. The utilization of indigenous resources reduces dependence on costly imports, lowers production costs, and enhances local industries' capacity to embrace innovation and growth [5]. In Nigeria, between 7 and 8 billion tonnes of deposits of natural materials, such as clay, limestone, and laterite, offer viable alternatives to produce materials, such as refractory bricks, cement, and ceramics.

In Nigeria, the use of locally sourced refractory materials in furnaces remains limited when compared to the imported alternatives; this is due to several challenges. Foremost, the inadequate characterization and standardization of indigenous clays make many industries uncertain about their suitability and sustainability for high-temperature applications [4]. Many deposits remain unprocessed or lack the beneficiation to remove impurities, thereby resulting in inconsistent quality and performance when subjected to the rigorous thermal, chemical, and mechanical demands of furnaces [6]. In addition, most industrial operators perceive imported refractories as more reliable, given their certification, uniformity, and proven track record in the global markets. The absence of advanced processing technology, poor collaboration between research and industry, and the insufficient investment in pilot-scale productions further hinder the optimization of the local clays into high-grade refractory products [6]. Policy inconsistency, weak quality control frameworks, and the lack of technical manpower worsen the situation, thereby reinforcing the dependence on imported refractory materials, despite the abundance of suitable clay deposits across Nigeria.

However, locally sourced refractory materials in Nigeria present opportunities for cost-effective furnace linings in the metallurgical, cement, and ceramic industries by reducing the dependence on expensive imports [4]. The proper beneficiation and processing of these clays can be tailored for use in the petrochemical and power plants, where high thermal resistance and durability are required [6]. Furthermore, the exploitation of these resources not only supports economic diversification but also promotes job creation, technology transfer, and community development [7], [8]. Moreover, the local sourcing contributes to environmental sustainability by minimizing the carbon footprints that are associated with long-distance transportation of raw materials [9].

This review explores the suitability of refractory materials, derived from various locally sourced clay deposits across Nigeria, for furnace applications. It focuses on the assessment of the thermal, mechanical, and chemical properties of these clays to determine their potential for cost-effective, high-performance refractory production.

2. Overview and Applications of Refractory Materials

Refractory materials are heat-resistant materials, and they are capable of withstanding high temperatures, thermal shock, and chemical attack, hence making them essential products for furnace linings and high-temperature industrial processes. These materials are used to construct the internal surfaces of furnaces, kilns, incinerators, and reactors, where temperatures can exceed 1500°C. Additionally, they are employed to make crucibles and surfacing flame detector systems for rocket launch systems, as well as molds for casting glass and metals [10], [11]. Their primary functions are to contain heat within the system, protect structural components from thermal damage, and ensure energy efficiency during operation. Refractory materials must, therefore, be able to tolerate temperatures that are higher than those specified. Table 1 lists the melting points of the basic metallurgical elements for which the use of refractory materials is crucial.

Table 1. Melting temperatures of fundamental metallurgical elements.

Elements	Melting Temperatures (°C)
Iron	1537.8°C
Nickel	1454.4°C
Copper	1082.2°C
Aluminum	660.0°C
Zinc	415.6°C
Lead	326.7°C
Tin	232.2°C

2.1. Classification and functional selection of refractory materials

Refractory materials are essential for the protection of equipment and for ensuring the efficiency and safety of high-temperature industrial processes. They are broadly classified, based on their chemical behavior, into three main types, *viz*: acidic, basic, and neutral. Acidic refractories, such as silica (SiO_2) and fireclay, are resistant to acidic slags, but they are easily attacked by basic materials. Basic refractories, e.g., magnesite (MgO) and dolomite [$CaMg(CO_3)_2$], are stable in the presence of basic slags and environments, hence making them suitable for applications in steelmaking. Neutral refractories, including alumina ($A\ell_2O_3$) and chromite ($FeCr_2O_4$), exhibit good resistance to both acidic and basic slags, thus providing versatile applications across various industries [12], [13], [14]. An understanding of the classification and the appropriate selection of refractory types is critical for the optimization of their thermal performances and their durability in specific industrial settings [15].

2.2. Characteristics and industrial relevance of clay as a refractory material

The term clay describes a naturally existing substance that is principally made up of fine grains of minerals. It is typically moldable with an appropriate quantity of water, which solidifies when burnt or dried [16]. Even though clay is made up of sheets of silicates, it can also have other substances, which give it its flexibility and make it harder than the raw material when burnt or dried [17], [18]. Clay has a complicated mixture, whose composition varies according to geographical regions. It is a source for different industrially processed products [19]. The source of clay minerals is predominantly from the weathering of feldspars and micas [19], [20]. They constitute the layer-lattice mineral class, which includes complex alumino-silicates of magnesium and potassium. They have large surface areas because of their flaky shapes, and they have extremely small sizes. The quantity of contaminants present in any clay material frequently influences its level of refractoriness and plasticity. Furthermore, refractory clay's quality and suitability for use as a furnace liner depend on its capacity to withstand high temperatures, as well as chemical and physical corrosion. At roughly 500°C, clays lose their chemically bound water and fluidity when fired; as a result, they gain greater strength within the temperature interval of 950°C and 1350°C [21].

Nigeria is richly endowed with various types of clay deposits, distributed across its geopolitical zones, making it a significant resource for refractory material development. The major clay deposits, including kaolin, fireclay, and bentonite, are found in states such as Ogun, Edo, Plateau, Kogi, Enugu, and Katsina States of Nigeria. For instance, the kaolin deposits in Ekiti, Bauchi, and Katsina States of Nigeria are estimated to be close to 16.6, 10, and 20 million tonnes, respectively, and they are known for their high alumina content, and they are all suitable for refractory applications [22]. Fireclay, commonly found in areas such as the Niger, Anambra, and Benue States of Nigeria, has been extensively studied for its refractory potential; this is due to its good thermal stability and plasticity [23]. These clay types vary in mineralogical composition, depending on the local geology, which influences their suitability for different industrial applications, including furnace lining, ceramics, and cement production. The abundance and diversity of clay resources present an opportunity for Nigeria to reduce its reliance on imported refractory materials by developing the local alternatives that are available in Nigeria [24].

3. Geochemical and Mineralogical Characteristics of Nigerian Clays for Refractory Applications

Nigerian clays possess diverse geochemical and mineralogical compositions that are largely influenced by their geographical origin and depositional environment. Generally, they contain high levels of silica (SiO_2) and alumina ($A\ell_2O_3$), which are the key components for refractory applications [25], [26]. Other common elements include iron oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), sodium oxide (Na_2O), and potassium oxide (K_2O), which, depending on concentration, may affect the thermal behavior and chemical resistance. Mineralogically, kaolinite is the dominant clay mineral, often accompanied by illite, montmorillonite, and quartz [27]. These compositions determine the critical refractory properties, such as refractoriness, plasticity, and sintering behavior, and they have been the subject of numerous beneficiation and optimization studies that are aimed at enhancing their suitability for industrial usages.

Clays sourced from different regions in Nigeria exhibit considerable variations in their physical, chemical, and mineralogical properties, which directly influence their suitability for refractory applications. These regional differences are attributed to the distinct geological formations and the weathering processes in each area. The understanding of these variations is essential for the selection of the appropriate clay sources for specific industrial applications and for the optimization of clay blends, needed to enhance performance in furnace linings and other high-temperature environments.

Clay refractoriness can be described as its capacity to tolerate high temperatures, heat flow across the cross-sectional boundary layer, volume stability at high temperatures, unstable thermal shock, wear, corrosion, and hot fluids (gases and liquids). Mineral kaolinite ($A\ell_2O_3$•$2SiO_2$•$2H_2O$), makes up the majority of the refractory clay, which is categorized as either fireclay or kaolin, based on the proportion (ratio) of alumina to silica. Thus, kaolin-based clays have a 1:2 alumina-silica ratio, whereas the fire clays have more than 30% alumina ($A\ell_2O_3$) and below 1.8% iron(III) sulfide (Fe_2SO_3) content [28]. Table 2 shows the composition of a refractory clay, according to the international standard [29]. The unique qualities of kaolin, especially its fine particle size, non-abrasiveness, chemical stability, and natural whiteness, make it ideal for use in fire bricks [30]. It constitutes the major source of alumina that is used for the manufacturing of fireclay refractories, amongst other industrial minerals. The refractoriness of a kaolin increases with its alumina content. Table 3 and Table 4 show, respectively, the chemical and thermo-physical properties of the Nigerian kaolin materials [31].

Table 2. Chemical composition of refractory clays by international standard.

Constituent	Fired clay (%)	Refractory bricks (%)
SiO_2	55 – 75	51 – 70
$A\ell_2O_3$	25 – 45	25 – 40
Fe_2O_3	0.5 – 2.0	0.5 – 2.4
K_2O	< 2.0	
MgO	< 2.0	
LiO	12.15	

The whiter hues, coarse particles of kaolin, its low plasticity, and minimal impurities distinguish kaolin refractory clays from fire clays. Fire clays contain impurities, such as calcites, quartz, pyrites, limonite, ferrous carbonates, and certain compounds. Iron and quartz are examples of impurities that decrease the refractoriness of clays, whereas the organic impurities accord them flexibility. Nevertheless, refractory clay obtained from a single site cannot have all the requisite qualities. Therefore, the choosing of clays, according to samples' physical, chemical, and thermal analyses, becomes essential [40].

Table 3. Chemical properties of selected Nigerian kaolin.

Researcher	Location	$A\ell_2O_3$ (%)	SiO_2 (%)	K_2O (%)	CaO (%)	Ti_2O (%)	MnO (%)	Fe_2O_3 (%)	Others
Borode *et al.*, [6]	Onibode	36.60	46.10	1.20	0.14	1.32	-	0.76	13.88
	Ara	28.60	56.66	0.08	0.15	1.88	-	1.47	11.16
	Ibamojo	22.80	54.44	1.00	0.30	0.86	-	1.00	19.60
	Ijoko	37.24	47.11	0.04	0.07	0.92	-	0.56	14.06
	Ijapa	30.79	45.50	1.92	4.77	-	-	0.49	14.53
	Ikere	31.46	47.38	0.30	0.02	1.14	-	9.78	9.83
	Ishan	19.51	51.10	2.53	0.33	1.48	-	9.82	15.23
	Ezinachi-Okigwe	34.73	45.00	0.14	Traces	4.02	-	1.27	14.84
Akinlabi, *et al.*, [29]	Ijero	39.60	58.00	0.90	-	0.02	0.0510	0.6380	0.80
Titiladunayo and Fapetu [32]	Ikere	30.46	50.92	0.33	0.19	1.78	0.01	2.07	14.24
	Fagbohun	18.75	53.90	3.30	0.72	2.29	0.03	11.80	9.21
	Ishan	13.48	40.68	2.88	1.12	2.68	0.15	25.55	13.46
	Ara	10.92	59.90	3.25	1.90	2.76	0.19	11.40	9.68
Yami and Umar [33]	Gur	21.25	59.20	-	1.92	-	-	15.70	1.93
	Yamarkumi	19.68	41.80	-	1.52	-	-	8.89	28.11

Table 3 continued

Table 3 (continued). Chemical properties of selected Nigerian kaolin.

Researcher	Location	$A\ell_2O_3$ (%)	SiO_2 (%)	K_2O (%)	CaO (%)	Ti_2O (%)	MnO (%)	Fe_2O_3 (%)	Others
Ogunniyi [34]	Ijapo	28.83	52.20	-	-	-	-	3.58	15.39
	Igbokoda	1.130	92.54	-	-	-	-	1.19	5.14
Okoli [35]	Onibode	39.30	42.30	-	-	-	-	Traces	18.40
	Ozubulu	19.31	58.30	-	-	-	-	1.55	20.84
	Kankara	38.64	44.50	-	-	-	-	Nil	16.86
	Sabon-Gida	25.88	25.32	-	-	-	-	13.10	35.70
Folorunso *et al.*, [36]	Ifon	22.42	63.35	2.88	0.69	0.92	0.11	6.11	3.52
	Igbara Odo	25.74	56.64	2.94	0.91	0.90	-	9.23	3.66
	Ipetumodu	25.03	59.48	1.26	0.76	1.51	0.05	8.65	3.26
	Ihan	23.98	54.66	2.51	0.84	1.58	0.11	10.41	5.91
	Iseyin	22.73	62.29	1.36	0.54	1.05	0.05	7.27	4.72
Manukaji [37]	Uhodo	35.00	44.00	1.50	0.50	2.40	-	1.30	15.30
	Oguma	34.00	45.00	1.40	0.40	1.50	-	1.50	16.20
	Odoji	34.00	46.00	1.20	0.20	3.00	-	0.90	14.70
Ijagbemi [38]	Ikeji- Arakeji	19.70	48.24	3.00	0.55	1.51	-	10.81	16.20
	Ibule	19.25	56.09	7.21	0.32	1.48	-	7.21	8.44
	Ikere	30.82	47.14	2.53	0.25	0.50	-	2.00	16.76
Delta Steel Company ltd., Aladja [39]	Nsu	30.22	50.60	-	-	-	-	1.90	17.28
	Ukpor	33.20	48.00	-	-	-	-	1.20	17.60
	Ozubulu	19.31	58.30	-	-	-	-	1.55	20.84
	Enugu	22.71	55.00	-	-	-	-	2.32	19.97
	Onibode	39.30	42.30	-	-	-	-	Traces	18.40
	Orun	34.55	50.50	-	-	-	-	2.05	12.90
	Oshiele	28.30	53.40	-	-	-	-	1.35	16.95
	Werromi I	36.12	45.16	-	-	-	-	2.30	16.42
	Werrom II	38.14	41.92	-	-	-	-	-	19.94
	Alkaleri	25.43	54.50	-	-	-	-	1.05	19.02
	Kankara	38.67	44.50	-	-	-	-	-	16.83
	Giro	38.72	41.26	-	-	-	-	2.10	17.92
	Sabon Gida	25.58	25.32	-	-	-	-	13.10	36.00
	Ifon	36.80	47.90	-	-	-	-	0.67	14.63
	Okpekpe	24.30	53.20	-	-	-	-	1.45	21.05

Table 4. Thermo-physical characteristics of selected Nigerian kaolin.

Researcher	Specimen location	Bulk density (g/cm^3)	Apparent porosity (%)	Permeability	Linear shrinkage (mm)	Thermal shock resistance (cycle)	Refractoriness temperature (°c)
Borode *et al.*, [6]	Onibode	2.60	28.40	87.00	4.00	30.00	1760.00
	Ara-Ekiti	1.84	18.00	75.00	8.00	26.00	1650.00
	Ibamojo	1.76	16.00	78.00	4.00	30.00	1630.00
	Ijoko	2.60	22.00	88.00	6.00	28.00	1680.00
	Ikere- Ekiti	-	43.10	-	3.59	20.00	1450.00
	Isan	-	49.70	-	3.89	32.00	1520.00
	Ezinachi-Okigwe	-	20.00	-	7.23	20.00	1350.00
Titiladunayo and Fapetu [32]	Ikere	1.74	31.44	-	5.00	-	1500.00
	Fagbohun	2.00	20.69	-	2.00	-	1500.00
	Ishan	2.00	19.10	-	1.50	-	1300.00
	Ara	1.99	23.31	-	1.90	-	1300.00
Yami and Umar [33]	Gur	2.11	19.50	215.00	1.11	7.00	1370.00
	Yamarkumi	2.06	22.26	489.00	1.00	5.00	1400.00
Ogunniyi [34]	Ijapo	1.38	50.15	-	-	-	-
	Igbokoda	1.77	28.18	-	-	-	-
Okoli [35]	Onibode	-	23.00	Moderate	-	Fair	High
	Ozubulu	-	25.00	Moderate	-	Fair	High
	Kankara	-	18.00	Low	-	Fair	High
	Sabon-Gida	-	20.00	Low	-	-	High

3.1. Formulation and processing of Nigerian local clay

The formulation and blending of local clays for refractory use involves the optimization of the clay's physical and chemical properties, to meet high-temperature industrial requirements. A study by Obidiegwu et al. [41] demonstrated that the incorporation of between 25–30% of coconut shell particulates into Nigerian fireclays, such as the Ukpor, Osiele, and Kankara clays, and firing the mixture at temperature of between 1150–1200°C, enhanced the mechanical strength, thermal insulation, and the porosity of the resulting refractory bricks. This process led to the formation of mullite phases, which are beneficial for refractory applications. Similarly, the research by Chima et al. [42] on Elu-uhu Nguzu and Amaiyi Edda clays showed that the addition of rice husk ash (RHA) and groundnut shell ash (GSA) improved the bricks' compressive strength and thermal stability, thereby making them suitable for lining furnaces, kilns, and crucibles. These studies highlighted the potential of utilizing the locally sourced clays and agricultural waste additives to produce cost-effective and efficient refractory materials.

The processing of local clays for refractory applications involves several steps that are aimed at enhancing their thermal and mechanical properties to meet industrial standards. These steps, typically, include mining, crushing, drying, sieving, and beneficiation to remove impurities, such as organic matter, iron oxides, and quartz, which could lower refractoriness or cause thermal instability (Figure 1). Calcination is also often employed to reduce plasticity and increase the material's thermal shock resistance [43]. Techniques, such as blending different clay types and the addition of stabilizing agents (e.g., alumina or grog), are also used to tailor the properties of the processed clay for specific applications, such as furnace linings and kiln bricks [44]. A proper processing scenario is essential to unlock the full potential of Nigeria's abundant clay resources for high-temperature industrial uses.

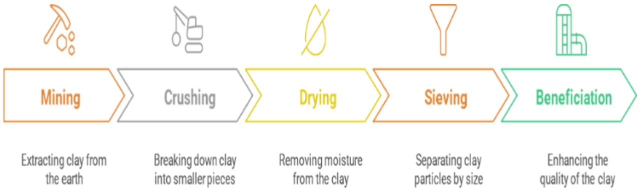

Figure 1. Steps in the processing of local clay.

Processing parameters, such as firing temperature, sintering duration, and clay composition, significantly influence the final properties of local clays that are used in refractory applications. Elevated firing temperatures, typically between 900°C and 1200°C, promoted densification and the formation of the mullite phases, which enhance the mechanical strength and reduce porosity [45], [46]. The chemical and granulometric composition of the clays, along with processing variables, e.g., the shaping and drying techniques, also affected the physical-mechanical properties of the final product [47]. Therefore, careful control of these processing parameters is essential to optimize the performance of refractory materials derived from local clays.

3.2. Refractory lining materials for efficient furnace operation

A furnace, being an equipment specifically designed for heating, utilizes heat to accomplish its functions. It is a device that releases heat and transfers it, either directly or otherwise, to either a solid or a liquid substance that is placed in its enclosure to alter the material's properties [48]. Solar energy, electrical energy, nuclear fission or fusion, and fuel combustion are the sources of heat generation that can be used to directly deliver energy to furnaces. The furnace linings play a crucial role in the efficiency and longevity of industrial furnaces, thereby impacting both the thermal performance and the material integrity of the furnaces. These linings are designed to withstand extreme temperatures and corrosive environments, often made from materials such as refractory bricks, castables, and ceramic fibers. The choice of the lining material significantly affects the heat retention, energy consumption, and the overall operational cost of the furnace. Recent advancements in lining technologies, including the use of high-alumina and silicon carbide materials, have demonstrated improved thermal conductivity and resistance to wear and chemical attack, thereby enhancing performance and reducing the maintenance needs [49], [50]. Furthermore, the integration of advanced monitoring systems allows for the real-time assessment of the lining conditions, hence, enabling the predictive maintenance and the optimization of the furnace operation [51].

The refractory materials, commonly used in furnace applications, include fire clay, high alumina, and silica refractories; each selected based on their thermal and chemical performances in specific environments. The fireclay refractories, composed primarily of alumina ($A\ell_2O_3$) and silica (SiO_2), are widely used due to their moderate cost, good thermal shock resistance, and their suitability for temperatures often up to 1500°C; hence, making them the ideal materials for linings in the general-purpose furnaces [13]. High alumina refractories, of >45% alumina, offer superior resistance to slag attack, higher refractoriness, and better mechanical strength, thereby making them suitable for steel-making furnaces and incinerators [52]. Silica refractories, composed of >93% SiO_2, are known for their excellent load-bearing capacity at high temperatures and good resistance to acidic slags, hence making them suitable for coke ovens and glass-melting furnaces [15]. The choice among these refractories depends on the specific operational conditions, including the nature of the processed material and the furnace temperature regime.

3.3. Properties of refractory materials

Refractory materials are distinguished by several key properties that make them suitable for high-temperature industrial applications. The performance of refractory materials, in each application, depends on a balanced combination of these properties, and they are tailored towards specific operational conditions.

3.3.1. Melting Point

The capability of a material to tolerate excessive temperatures, without experiencing chemical or physical changes, indicates its melting point. A few elements of the refractory structure have their melting points that range between 1704.4 – 3482.2°C, in their pure state, as can be seen in Table 5. The melting point is a crucial property that specifies the highest temperature used, and it serves as an adequate platform for the evaluation of the thermal stability of refractory mixtures [53].

Table 5. Melting temperatures of refractory compositions.

Refractory element	Melting temperatures (°C)
Graphite, C	3482.2°C
Thoria, ThO_2	2998.9°C
Magnesia, MgO	2798.9°C
Zirconia, ZrO_2	2698.9°C
Lime, CaO	2571.1°C
Beryllia, BeO	2550.0°C
Silicon Carbide, SiC	2248.9°C
Magnesia, 90-95%	2193.3°C
Chromite, $FeO\text{-}Cr_2O_3$	2182.2°C
Chromium Oxide	2137.8°C
Alumina, $A\ell_2O_3$	2048.9°C
Chromite, Cr_2O_3 (38%)	1960.0°C
Alumina Fused Bauxite	1871.1°C
Silicon Carbide, (80-90%)	1871.1°C
Fireclay	1871.1°C
Titania, TiO_2	1850.0°C
Kaolin, $A\ell_2O_3$ -, SiO_2	1815.6°C
Silica, SiO_2	1715.6°C

3.3.2. Bulk Density

The weight per unit volume of a refractory material, incorporating pores, is its bulk density. Since the bulk density of most refractories gives a broad measure of the product quality, a refractory with enhanced bulk density will possess high quality. The clay is used to produce test samples, which are oven-dried at a temperature of 110ºC for 24 hours. The dried weight (W_d) of the sample is recorded, and then, the refractory material is fired in a furnace. They are put in a beaker of water, inside a vacuum desiccator after firing, where the water displaces the air in the samples. After drying, the soaked weight (W_s) of the specimen is noted [54], [55]. The specimens are then suspended one after another in a beaker of water, and the suspended weight (W_p) is recorded. The mean bulk density (B_d) is then computed by using Equation (1):

$$B_d = \frac{W_d}{W_s - W_p} \tag{1}$$

3.3.3. Moisture Content

Moisture content is the proportion of the mass of water to that of dry material; it is usually expressed as a percentage. It is measured when the quantity of the clay sample mixture is weighed, placed on a thin film inside a sand glass, and dried at 110°C; thereafter, it is cooled in a desiccator and weighed again [56]. The change in weight is expressed as a percentage shown in Equation (2):

$$MC = \frac{G_W - G_D}{G_D} \times 100\% \tag{2}$$

where MC is the moisture content, G_W and G_D are the masses of the wet and dried samples, respectively.

3.3.4. Firing Shrinkages

The Firing Shrinkage is an irreversible change in a form, which occurs in a refractory material during the heating processes, under specific conditions. The test specimens are oven-dried at 110°C for 24 hours and gradually heated to 1100°C in a furnace at subsequent intervals [57]. The fired shrinkage (FS) is then calculated by using Equation (3):

$$FS = \frac{\Delta L}{L} \times 100 \tag{3}$$

where ΔL- change in length and L- original length.

3.3.5. Water Absorption

This property establishes the rate of water absorption, and it is crucial since it shows how much moisture the clay can take in, without breaking down [58]. An oven is used to dry the clay test samples until their weights become constant. The samples are then immersed successively in hot water, without encountering the bottom of the containing vessel, and the boiling water is used to replace the evaporated water. After 4 hours of boiling, the vessel is cooled to ~25°C and the specimens are weighed once more. Both the soaked and the dried weights are determined and recorded [55], [59]. The percentage water absorption (WA) is computed by using Equation (4):

$$WA = \frac{SW - DW}{DW} \times 100\% \tag{4}$$

where SW and DW are saturated and dried weights, respectively.

3.3.6. Thermal Shock Resistance

The thermal shock resistance is the capacity of a refractory material to tolerate sudden temperature changes that are essential for use in furnaces and kilns [13]. Samples made from clay are cut to the required dimensions and then inserted into the furnace that is maintained at a temperature of 900°C. After 10 minutes in the furnace, the samples are taken out and allowed to cool in a stream of air before being returned to the furnace, which is again maintained at 900°C for an additional 10 minutes. The procedure is sustained to a point where, after cooling, the test specimens are freely pulled apart. Thereafter, the number of full cycles needed for the samples to fail is recorded [60].

3.3.7. Apparent Porosity

The porosity in a refractory material refers to the volume of all the pores through which molten metal, slag, fluxes, vapors, etc., can permeate, thereby causing the structure to deteriorate over time [59]. The porosity in refractory materials is measured as the mean percentage of the open pores, relative to the total volume of the refractory material. Since air possesses low thermal conductivity, materials with high porosity typically trap a considerable amount of air, thereby making them highly insulating. Thus, low-porosity materials are utilized in hot regions, whilst high-porosity materials are employed for thermal backups. A cut-off wheel is used to cut the test samples from the core of a burned refractory brick, and they are then cleaned of the available dust for the porosity test. After being thoroughly oven-dried at 110°C for 24 hours, the samples are subsequently burnt in a furnace at 1100ºC. After the dry weights have been measured and recorded, they are suspended in distilled water so that they do not encounter the walls or the bottom of the container. They are then heated for two hours, and thereafter, submerged and cooled to ambient temperature before their weights are recorded [55].

The apparent porosity (P) is then calculated by using Equation (5):

$$P = \frac{V_1 \times 100}{V} \quad (5)$$

where V_1 is the actual volume of pores in the sample (W-D), while V is the outer volume of sample (W-S)

This can be obtained by using Equation (6):

$$P = \frac{W - D}{W - S} \times 100 \quad (6)$$

where W, D, and S are the soaked, dried, and suspended weights, respectively.

3.3.8. Specific Gravity

The specific gravity of a material is the ratio of its density to that of water. A sample of powdered clay is added to a specific gravity container (W_P) that has already been weighed, and the weight (W) is then determined. After covering the powdered sample in distilled water, while in a vacuum, the container is suspended in water at a known temperature for about 0.25 hour (15 minutes) to allow it to equilibrate before being weighed (W_2). The container is then cleansed, refilled with distilled water, and left to equilibrate for an additional 0.25 hour before weighing (W_1) [55]. The specific gravity (SG) is then computed by using Equation (7):

$$SG = \frac{W - W_P}{\left(W - W_P\right) - \left(W_2 - W_1\right)} \quad (7)$$

3.3.9. Refractoriness

The term refractoriness refers to a material's degree of fusibility, which shows the temperature at which it softens [15]. To measure refractoriness, cones made from clay specimens are dried and attached with cement at the center of a refractory plaque, alongside the pyrometric cone equivalent (PCE). The cones are loaded in the furnace, and an optical pyrometer is used to monitor the rate of heat, below 200°C, used as an estimate of the fusion temperature, which is carefully regulated at a rate of 10°C per minute. The test cone is heated until its tip bends and contacts the refractory plaque. The cone is checked once it has cooled, after the plaque containing it has been taken out of the furnace. The equivalent temperature of the standard cone allows it to bend relatively, in comparison to the cone that primarily determines its refractoriness. The refractoriness can also be estimated by using Shuen's formula [61], shown in Equation (8):

$$Refractoriness = \frac{360 + Al_2O_3 - RO}{0.228} \quad (8)$$

where Al_2O_3 is the clay alumina and RO represents the other oxides that are present in the clay.

3.3.8. Refractoriness under load

The refractoriness under load (RUL) is an empirical measure used to quantify how the refractory ceramic goods deform when exposed to a continuous load at rising temperature [62]. To measure the RUL, a cylindrical test piece of a given size is subjected to a predetermined compressive force and then fired to a predetermined temperature. The deformation developed within the test piece is then recorded. The refractoriness underload, for the samples, can also be determined by means of an instrument known as the RUL/CIC-421, which operates under the Proteus software, on Windows.

3.3.9. Cold Crushing Strength

The cold crushing strength (CCS) describes the load that causes cracks to develop in a sample. The original surfaces of the test samples are preserved when they are cut from the refractory profiles. To measure the cold crushing strength, test samples are placed on a level platform and subjected to a consistent load by using the hydraulic compression testing machine [54], [63]. The stress, which causes cracks to occur in the refractory sample, shows the extent of the CCS of the sample.

The cold crushing strength is then determined by using Equation (9):

$$CCS = \frac{Length}{Area} \quad (9)$$

3.3.10. Grain Size Analysis

The grain size analysis measures the diameter of the individual sedimentary grains [10]. The particle size patterns of the samples are established by means of the British Standard (B.S.) test sieves. A predetermined amount of clay is weighed and transferred to the already arranged sieves on a mechanical shaker. It is then shaken for a predetermined period, following which the mass on the individual sieve is measured. The percentage passed and the percentage retained (PR) for every sieve and pan are then determined by using Equation 10:

$$PR = \frac{WR}{WI} \times 100 \qquad (10)$$

where WI is the initial weight and WR is the retained weight.

3.3.11. Thermal Expansion

Thermal expansion is the propensity of refractory materials to increase in length, area, or volume, by changing their size and density, when their temperature increases/changes. To measure the coefficient of thermal expansion of a refractory material, a test sample is clamped on the expansion base of a thermal conductivity meter. The length (L) of the sample is determined by measuring, from the interior edge of the sample, on one end at room temperature, to the interior edge of the angle bracket at the other end. At that point, the initial expansion of the sample is usually 0 mm. The heater is then switched on to raise the temperature of the material under test, which results in an increment in length (ΔL) [30]. A thermal expansion (mm) curve is then plotted to display the trajectory as the increment occurs, as exemplified by Equation (11):

$$\alpha = \frac{\Delta L}{(L\Delta T)} \qquad (11)$$

where $\propto$ is a constant, known as the coefficient of thermal expansion of a material.

4. Performance and Characterization of Nigerian Clay-Based Refractory Materials

Several case studies have explored the use of the Nigerian clay-based refractories in furnace applications, particularly in industries such as steel and cement production. The Nigerian clay, often rich in alumina and silica, has been utilized to develop refractory materials that can withstand high temperatures and abrasive conditions in furnaces. Akinfolarin and Awopetu [3] examined the impact of sawdust on the insulating properties of the Ikere clay, in Ekiti State of Nigeria, specifically, for refractory lining. The clays collected were processed in a ball milling and pulverizing machine after being sun-dried and then sieved through a 150μm mesh size. This was later blended with varying proportions of sawdust and water and moulded into a cylindrical shape. The results obtained showed that the addition of sawdust to the clay sample improved its porosity by up to 54%, without losing its refractoriness at 1200°C.

Mokwa et al. [4] characterized and evaluated some selected kaolin clay deposits of Ikpeshi in Edo State, Kasadi in Kebbi State, Alasan in Osun State, and Badeggi in Niger State, all locations in Nigeria, for furnace lining application. The major raw material was kaolin, with ball clay as a binder. The mixture of kaolin and ball clay was in a ratio of 70:30 to produce the fire clay bricks, and the chemical analysis conducted on the various clays revealed slightly higher silica and alumina content proportions. The results from the refractoriness, under load test (RUL), showed that the Alasan clay from Osun state was suitable for use in the oven and furnace linings, with a temperature limit of 1400°C. Olalere et al. [31] assessed the chemical and thermophysical characteristics of the locally sourced kaolin-based refractory materials, composed of the Ipinsa clay, termite hill, and treated bentonite in a 5:4:1 mass ratio. The results obtained showed that the Ipinsa clay, termite hill, bentonite, and their aggregates contained a higher percentage of silica than alumina, hence, confirming their kaolinic nature**.** The Ipinsa kaolin was found to be applicable in furnaces, kilns, and stoves refractories. The bentonite, termite hill materials, and the aggregated clay from Ipinsa kaolin were found to be useful in the super-duty refractories. Given its pyrometric cone equivalent of 1900°C, the aggregated clay was also found to be useful for ceramic materials that are operable in the temperature range of between 1800 and 2000°C. Except for the bulk density, all the thermophysical properties examined met the acceptable standard, thereby confirming their competitiveness with foreign refractory materials.

Agbo et al. [61] investigated the characteristics of the Agbani clay deposit in Enugu State, Nigeria, as a refractory material for furnace linings application. The clay sample was collected, crushed, and its chemical analysis was carried out by using X-ray fluorescence spectroscopy, while the physical analysis was done by using standard procedures. The samples were then subjected to sieving, measured, and soaked in a known quantity of water to make them plastic, and thereafter, de-watered and oven-dried for 5 hours for mechanical tests. The results showed that the clay had between 25-20% $A\ell_2O_3$, 53.41% SiO_2, and its estimated refractoriness was ~1659°C. Generally, the apparent density and porosity, water absorption, dry shrinkage, total shrinkage, rupture modulus, and bulk density all fell within the range of the International Standard Organization specification for alumino-silicate refractories of fire clay. Aremu et al. [62] examined the analysis of the Mubi clay deposit in Adamawa State, Nigeria, for furnace lining. The result showed that the clay had 13.70% apparent porosity, 9.6% firing shrinkage, thermal shock resistance of 8 cycles, bulk density of 2.3g/cm^3, cold crushing strength of 253 kg/cm^2, and a refractoriness of 1300°C. According to the results obtained from the study, the clay was found to be suitable for the heat treatment of furnace linings.

Aramide and Seidu [63] investigated the use of the locally produced kaolin and the Potter's clay in Osun State of Nigeria, to produce refractory lining for diesel-powered rotary furnaces. A known quantity of clay that was thoroughly blended with kaolin in an appropriate proportion was sieved through a 1000 μ-sieve size. Thereafter, a known quantity of kaolin clay was calcined at 1200˚C for 8 hours, in a furnace, and cooled to obtain chamotte. The results showed that an increase in the chamotte content improved the cold crushing strength and thermal shock resistance, with a reduction in shrinkage, bulk density, and specific gravity.

Hassan and Aigbodion [64] investigated how the coal ash influenced some of the alumino-silicate clay refractory characteristics of the Kankara, Katsina State, Nigeria clay,for furnace lining. Dead organic debris was removed from the raw clay by soaking it in water for three days and thereafter, letting it dry in the air for a week. Chemical analysis was carried out, and test samples preparation was done by mixing the sieved clay with varied weight percentages of the coal ash to attain plasticity. The findings indicated that the mixture with 25 wt% coal ash produced an average task fireclay that was efficiently found suitable for thermal shock resistance, and the values obtained agreed with the recommended standard. Ibitoye and Alo [65] investigated the conformation of the Odolewu clay in Ogun State, Nigeria, for application as a refractory material. Samples of the clay were collected and impurities removed, following which, they were dried and mixed with dolomite, varying from 0 to 30 wt.%. The mechanical and physical properties of the product were determined on the samples prepared, according to the American Foundrymen Society Standard. From the results, the clay that was mixed with 10 wt.% dolomite provided the optimal properties for refractory material, thereby making it suitable for an alumino-silicate refractory material. Folorunso [66] examined the purification and the conformation of termite hill clay (sourced from Ondo State, Nigeria), for furnace lining, through the graphite and rice husk additions. The results showed that the termite hill clay was suitable for furnace lining, if processed hydro-metallurgically, to get rid of Fe_2O_3, which lowered its refractoriness. Graphite addition (15%) significantly enhanced the refractory performance, and the porosity increased significantly with 3% husk addition.

Adindu et al. [67] investigated the effect of a grog size on the efficiency of the Nsu clay-based refractory bricks in Imo State, Nigeria. The Nsu grog was produced by calcination and thereafter, cooled, ground, and sieved to a size of ~100 µm. Various clay proportions were mixed with water and pressed into moulds to form bricks, which were dried and subsequently fired in a kiln at 1250°C. Results indicated that both the bulk density and linear shrinkage reduced as the proportion of the grog increased. Meanwhile, the additional increase of the grain size above 30% showed no improvement in the linear shrinkage, but decreased the bulk density, apparent porosity, and the cold crushing strength. Amkpa and Badarulzaman [68] examined the thermal behaviour of Barkin-ladi fireclay brick from Plateau State, Nigeria, for refractory lining. The clay sample was collected, sun-dried, impurities removed, and crushed into powder. The crushed powder was sieved by using the ASTM standard sieve mesh size of 63 µm and then compacted by using the hydraulic pressing machine. From the results, the thermal conductivity, specific heat capacity, refractoriness, and thermal shock fell within acceptable standard values, thus making it appropriate for usage in the manufacturing of refractory fireclay brick for furnace lining.

A study by Oyedeko and Olugbade [69] investigated the potential of the Nigerian clay as a raw material for refractory production. They highlighted its suitability for usage in blast furnaces, electric arc furnaces, and cement kilns; this is due to its desirable thermal stability and cost-effectiveness. Similarly, a case study, carried out by

Osarenmwinda and Abel [70], demonstrated the fact that the locally sourced clay-based refractories in the Nigerian steel plants performed comparably to the imported refractories, with the added benefit of reduced material costs and the associated environmental impact. These studies emphasized the viability of using Nigerian clays in furnace linings, thereby suggesting that the materials not only offer reliable performance but can also support the local economy by reducing the reliance on imported refractories.

Outside Nigeria, Kipsanai [71] studied the refractory characteristics of certain clay sites in Chavakali, Kenya. The clay specimen collected was crushed and sieved, and the chemical composition indicated that the clay was rich in alumina ($A\ell_2O_3$) and silica (SiO_2), hence making it a good choice for refractory materials. The samples were moulded into rectangular shapes, dried, and fired to 1000°C, and the properties were determined by using the standard tests. Results indicated that the clay was appropriate for producing thermal insulators. Lomertwala et al. [72] also characterized clays from selected sites (Githima, Kimathi, and Ithanje) in Kenya for refractory application. The samples produced were air-dried before being oven-dried to a constant weight at 105°C. The samples were subsequently burnt in a furnace at 1000°C for 6 hours before subjecting them to physical and chemical tests by using the standard test procedures. Results showed that the Githima, Kimathi, and Ithanje clays can be used as sources of alumino-silicate refractories because they consist of SiO_2 and $A\ell_2O_3$ as the main constituents.

5. Challenges and Limitations of Locally Sourced Nigerian Clays in Refractory Applications

Refractory materials produced from the locally sourced clays in Nigeria face several challenges and limitations that affect their performance in furnace applications. While the Nigerian clays offer a cost-effective alternative to the imported refractories, their mineral composition can vary significantly, from one region to another, thereby leading to inconsistencies in thermal resistance, strength, and durability. For instance, clays with high amounts of silica or alumina are more suitable for high-temperature applications, but many Nigerian clays have low alumina content, hence limiting their effectiveness in extreme furnace environments [70]. Additionally, impurities, such as iron oxide, quartz, and organic matter, which can be present in varying amounts, may degrade the refractory's performance by reducing its thermal stability and causing premature failure [69]. Furthermore, the processing and firing techniques for these clays are not always optimized, thereby leading to difficulties in achieving the desired and necessary density and porosity for optimal performance in furnaces [73].

Moreover, many clay deposits are exploited by using artisanal methods, hence leading to low-quality products and limited scalability for industrial applications [6]. The lack of modern processing technology, quality control standards, and certification frameworks makes the industries reluctant to adopt local clays in place of imported refractories [74]. In addition, poor infrastructure, insufficient funding, and weak linkages between research institutions and industries hinder large-scale utilization and technological innovation that are needed to upgrade the Nigerian clays for advanced applications. These challenges underscore the need for further research into improving the quality control of the locally sourced clays to make them more reliable and competitive for industrial furnace usage.

6. Conclusion and Future Trends

Current trends in the development of refractory materials for furnaces that are produced from locally sourced clay sites in Nigeria indicate a growing emphasis on the enhancement of material properties through beneficiation, blending, and the incorporation of additives. Studies have focused on the evaluation of the chemical, mineralogical, and physical properties of clays from various regions. These investigations are aimed at ascertaining the suitability of these clays for refractory applications by assessing various parameters. These parameters include alumina and silica content, firing shrinkage, apparent porosity, bulk density, cold crushing strength, thermal shock resistance, and refractoriness under load. Furthermore, the blending of local clays with additives, such as rice husk ash and groundnut shell ash, has been explored to improve properties, such as compressive strength and shrinkage, thereby making the resulting materials suitable for furnace linings. These trends reflect a concerted effort to utilize Nigeria's abundant clay resources to produce high-performance refractory materials, thereby reducing Nigeria's dependence on imported alternatives and hence supporting local industrial development.

The future trends in the development of refractory materials for furnaces, produced from locally sourced clay sites in Nigeria, are currently focusing on the enhancement of the material properties, reduction in costs, and the promotion of sustainability. Research is increasingly directed towards the optimization of the chemical and mineralogical compositions of Nigerian clays to improve their thermal stability, strength, and resistance to thermal shock. For instance, studies have shown that the blending of local clays with additives, e.g., magnesia, can enhance their refractoriness and thermal shock resistance, making them more suitable for high-temperature applications in industries, such as steel and cement domains. Additionally, the incorporation of agricultural by-products, such as coconut shell ash, into the refractory formulations is being explored to improve the insulating properties and reduce the negative environmental impact of clays. These advancements aim to reduce Nigeria's reliance on imported refractory materials, thereby lowering costs and supporting the local industries. Furthermore, there is a growing emphasis on sustainable practices, including the use of waste materials and the development of energy-efficient production processes, to align with the global environmental standards and promote economic growth through industry self-reliance.

Conflict of Interest

The authors disclosed no potential conflicts of interest.

Data Availability Statement

All data analysed during this review are included in this article.

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Author Contributions Statement

Oryina Mbaadega Injor: Development of ideas, Approach, Analysis, Writing - original draft. **Emmanuel Rotimi Sadiku:** Development of ideas, Resources, Supervision, Writing - review & editing. **Moipone Linda Teffo, Munyadziwa Mercy Ramakokovhu, Agbogo Ugbetan Victor, and Williams Kehinde Kupolati: Resources,** Writing—review & editing.

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