Mineralogical and Physical Characterization of Some Clayey Soils from Parts of Southwestern Nigeria for Ceramic Application.

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ABSTRACT

Clayey soils have long been utilized in various industrial applications, particularly in the production of ceramics. The physical and mineralogical properties of these soils control their intrinsic behavior, which plays a vital role in determining their suitability for industrial applications. This study aims to explore the mineralogical and physical properties of selected clayey soils from Ekiti state in southwestern Nigeria and assess their implications for ceramic applications. The XRD analysis revealed that the soils contain kaolinite and illite as the dominant clay minerals, with significant quantities of quartz as well as considerable percentages of muscovite and goethite. Physical tests indicate that the soils consist of clays, silts, sand, and a subordinate amount of gravels, while the range of clay-sized particles suggests that the soils would not exhibit excessive shrinkage during firing. The plasticity chart reveals that the soils plot in the domain of medium to high plasticity and compressibility. Additionally, most of the clays studied presented liquid limit values in the range defined for raw clayey materials designated for ceramic applications. Moreover, the plasticity index of the clayey soils suggests that they are unlikely to be susceptible to inappropriate extrusion process. The position plots of the clayey soils on the workability chart indicate that the linear shrinkage of these samples would require some amendments prior to their processing. Furthermore, the high linear shrinkage exhibited by the soils could result in deformation and microcracking during the production of bricks, thereby requiring the addition of degreasers to reduce the plasticity of the clays before utilization. A general reduction in the water adsorption capacity with a corresponding increase in the firing temperature was observed. This could significantly affect the durability and mechanical characteristics of the soils. The flexural strength (FS) of the studied soils generally increased with increased firing temperature suggesting that the technological property is highly dependent on the temperature of firing.

Keyword: ceramic, clayey soils, flexural strength, kaolinite, plasticity

INTRODUCTION

The utilization of clayey soils in ceramic production dates back to ancient civilizations, where their unique properties were harnessed to produce durable and functional ceramic goods. The different notable applications of clayey soils in various industries, particularly in ceramics, underscore the importance of understanding their geological and chemical properties. The intrinsic properties of these soils are influenced by their mineralogical and physical characteristics, which play a critical role in determining their suitability for ceramic manufacturing (Bomeni et al., 2018; Ohandja et al., 2020; Nweke et al, 2023). These soils are primarily composed of clay minerals such as kaolinite, illite, and montmorillonite, which influence their plasticity, strength, and firing characteristics (Ntouala et al., 2016; Ohandja et al., 2020; Oumar et al., 2022). Thus, a comprehensive understanding of the mineralogical composition of these soils is essential for enhancing their performance in ceramic applications. Hence, detailed studies of clay mineralogy, including the types and proportions of clay minerals present, are essential for ensuring that these materials meet the specific requirements of ceramic production. The diverse nature of the rock types in the study area contributes to a variety of clayey soil types, which have been historically used in traditional ceramic production. Hence, characterizing these clayey soils is crucial for optimizing their suitability for various ceramic applications, including tiles, pottery, and bricks. However, despite the potential, there is limited comprehensive research on the properties of notable clayey soils in Ekiti State. Previous studies have often focused on broader geological surveys without a detailed analysis of the clay's suitability for ceramics. This research aims to fill this gap by providing a thorough characterization of clayey soils from parts of Ekiti State, focusing on their mineralogical composition, physical properties, and geotechnical behaviour. This is with a view to ascertaining the quality and applicability of these clays for ceramic use by analyzing their mineralogy, plasticity, drying and firing shrinkage, and thermal properties. By employing a range of analytical techniques, including X-ray diffraction (XRD), physical, and technological analysis, this research seeks to provide a comprehensive understanding of the clayey soils and their potential for industrial applications. Understanding these properties will not only contribute to the optimization of ceramic products but also foster sustainable local industries by utilizing indigenous raw materials. Ultimately, this research intends to support the development of a robust ceramics industry in Ekiti State, leveraging local clay resources to meet both domestic and international market demands.

METHODS

2.1 Study area

The study area is part of Ekiti State in southwestern part of Nigeria (Figure 1). It lies between Latitude $7^0 30^1$ and $7^0 80^1$North of the Equator, and Longitude $4^0 96^1$E and $5^0 60^1$ East of the Greenwich Meridian. It is located in the humid tropical part of South-western Nigeria with distinct dry and wet seasons. The study area is principally an upland region rising over 400 m above sea level with an undulating terrain and a typical landscape that comprises old plain separated by steep-sided outcrops occurring singularly or in groups or ridges (Talabi, 2013). The dendritic drainage pattern dominates the area (Figure 1), implying that the underlying rocks are to a large extent uniformly resistant to weathering. The area is well drained by notable rivers such as Elemi, Ogbese, Ose, Ureje, and their system of tributaries, and the main rivers that drain the area flow southwards (Ayodele, 2022).

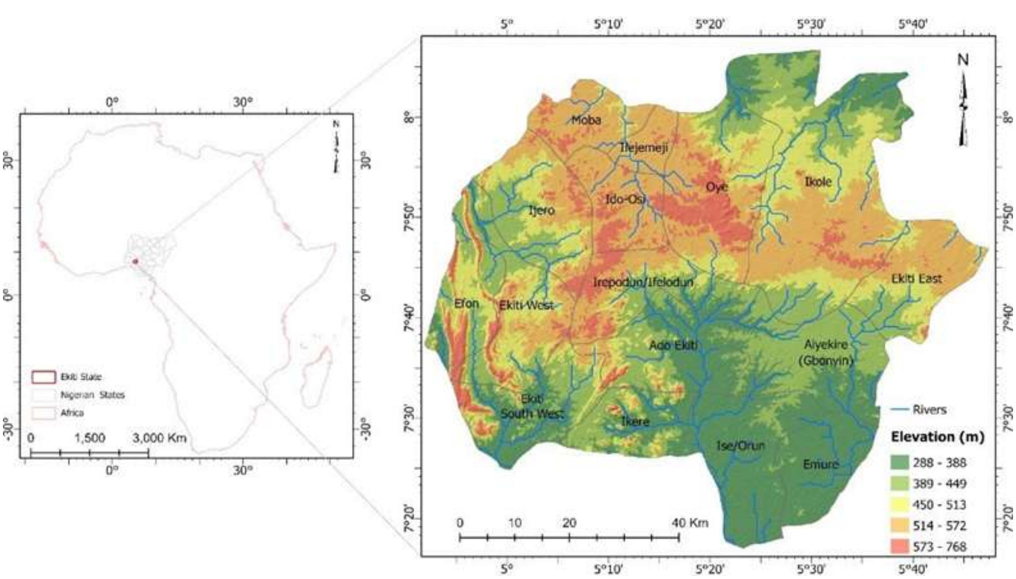

Figure 1: Topographic and drainage map of Ekiti State

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Ekiti State is located within a major part of the Precambrian basement complex of Nigeria (Figure 2), which forms part of the Pan-African belt and is flanked by the Congo and West African Cratons (Talabi *et al.,* 2018). Oyinloye (1998) noted that the rocks of the basement complex were formed as a consequence of four orogenic events, namely, the Liberian (2700 Ma), the Eburnean (2000 Ma), the Kibaran (1100 Ma), and the Pan-African cycle (600 Ma). The Liberian, Eburnean, and Kibaran events were typified by strong deformations with associated regional metamorphism that was later followed by migmatisation. The Pan-African cycle (600 Ma) was accompanied by regional metamorphism, migmatisation, extensive granitization, and gneissification. This resulted in the formation of homogeneous gneisses and syntectonic granites (Rahaman and Ocan, 1978). Late tectonic emplacement of granodiorites, granites, and contact metamorphism complemented the final phases of this latter deformation. Olayinka (1992) noted that fracturing and faulting marked the end of the Pan-African orogeny. Ekiti state is predominantly underlain by Precambrian crystalline rocks of igneous and metamorphic origin (Rahaman and Ocan, 1978; Talabi and Tijani, 2013; Oyelami and Van Rooy, 2018). The notable rock types in the study area are charnockite, Pan African granite, schists with pegmatite, quartzites, and migmatite (Figure 2).

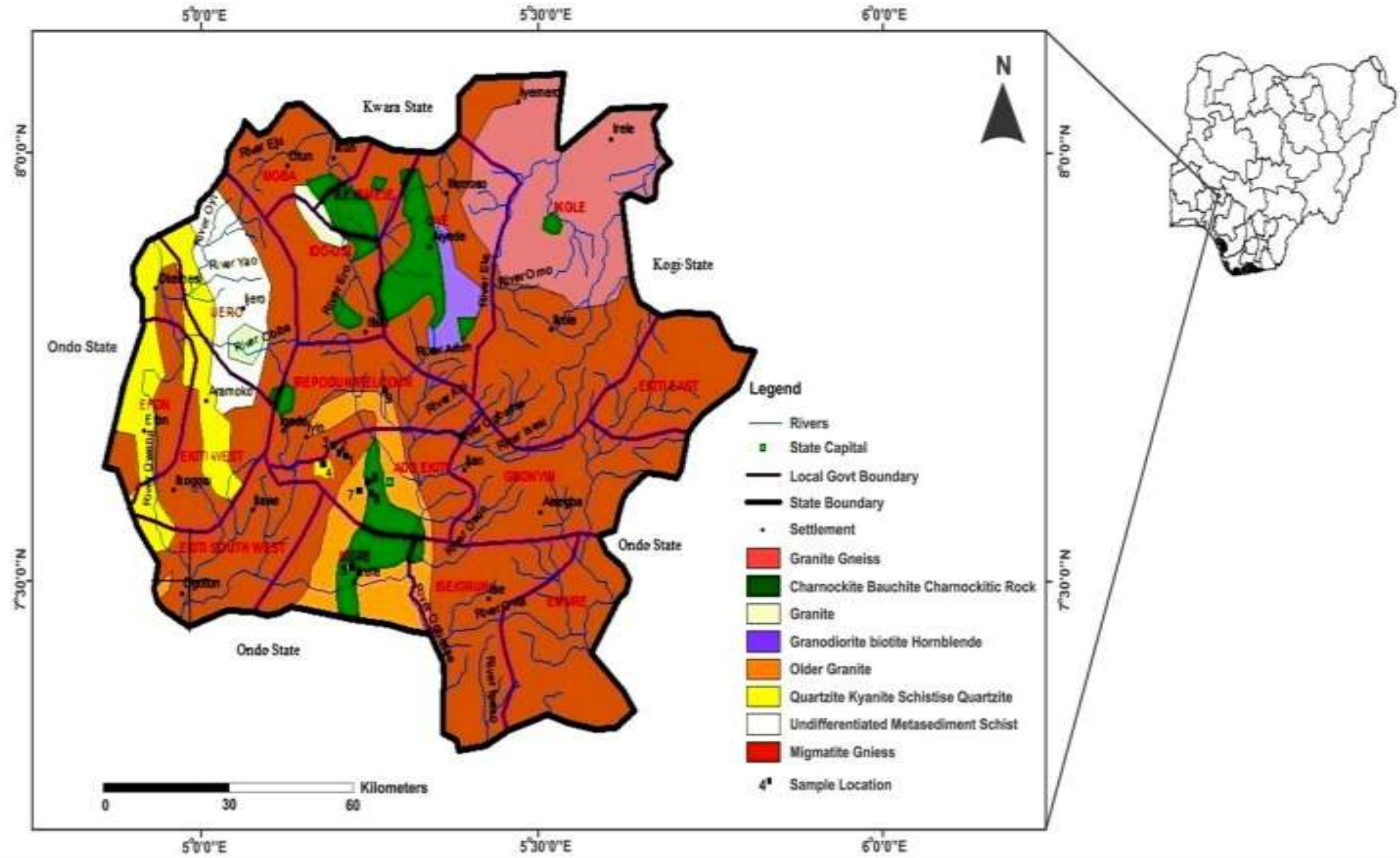

Figure 2: Geological Map of the study area

2.2 Sampling and Laboratory Analysis

The samples were obtained from the representative clay bodies widely distributed in different parts of the study area (Table 1). The mineralogical analysis of the clay soil samples was undertaken by utilizing the Bruker D8 Advance diffractometer equipped with an automated multi-position flip-stick sample stage. Samples were analyzed using the standard open polystyrene sample holder in θ–θ configuration with a Goebel mirror, exit slit, and anti-divergent slit with Nickel-filtered Copper radiation (λ = 1.5506 Å). The identification of the qualitative phase was conducted through the application of the Search/ Match method, where the measured diffraction peak (peak positions and intensities) is matched against the ICDD (International Center for Diffraction Data) PDF-4+ 2021 database entries by employing the software + Sieve. Quantification of the phases was carried out using the Rietveld refinement method (TOPAS v6 software). The particle size analyses were conducted in accordance with the specification of the British Standard Institution (BSI, 1990) by using wet sieving and hydrometer analysis (sedimentometry) methods for particles of size ≥ 80 and ≤ 80 µm respectively. An electric shaker was used for the sieve method, while the sedimentometry was based on the principle of Stokes' law of sedimentation of individual spherical particles falling freely at a steady velocity under the influence of gravity. The liquid Limit (LL) was measured with the Casagrande dish and the Plastic Limit (PL) by the roller method, all according to ASTM D4318 – 2005 standard. Plasticity Index was calculated by the arithmetic difference between LL and PL. Firing was done in a muffle furnace of FP34G type, with a maximum temperature of 1100 °C. The tested specimens were subjected to five firing temperatures: 800 °C, 900 °C, 1000 °C, and 1100 °C. The water absorption (WA), expressed as a percentage of the weight relationship water absorbed after soaking in water for 24 h to the weight of the dry specimen (ASTM C20, 2000). WA was calculated as:

$$WA = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

where W_2 is the weight of soaked specimen and W_1 weight of dry specimen. The loss on ignition was determined by the same formula of water absorption. Here, W_2 is the weight of dry specimen, and W_1 represents the weight of the firing specimen. The flexural strength in MPa was calculated for each specimen using equation 2 (ASTM F417, 1996):

$$\sigma = \frac{3PL}{2lh^2} \quad (2)$$

where P is the load at fracture (N), L= distance between supporting knife edge (50 mm), l is the width of the specimen, and h represents the thickness of specimen (mm). The data derived from the raw materials fired at varying temperatures were characterized and compared with standard specifications.

Table 1: Location and description of the clayey soil samples from the study area.

Sample Name	Coordinates		Sampling depth (cm)	Extension	Colour
	Latitude (N)	Longitude (E)			
Ire-1	7° 42′ 10.6″	05° 24′ 14.2″	102		Reddish brown
Ire-3	7° 42′ 10.6″	05° 24′ 14.2″	124		Grayish white
Ire-2	7° 45′ 59.32″	05° 23′ 44.36″	130	507m²	Yellowish brown
Isan-1	7° 56′ 04.6″	05° 20′ 20.1″	63	564m²	Dark grey
Isan-2	7° 55′ 36.3″	05° 19′ 28.8″	164	647m²	Reddish brown
Ara-2	7° 46′ 00.1″	05° 06′ 41.0″	337	445m²	Dark grey
Ara-3	7° 46′ 00.1″	05° 06′ 41.0″	624		Dark grey

RESULTS AND DISCUSSION

3.1 Mineralogy

Typical X-ray diffractogram of the studied soils are presented in Figures 3a and 3b, while the quantitative proportions of the minerals identified are presented in Table 2. It could be observed that kaolinite and illite are the dominant clay minerals, while quartz and goethite are the non-clay minerals identified in the soils. The ceramic properties of clays depend on the content of the clay minerals, specifically the illite/smectite minerals, and crystallinity of kaolinite and illite (Baioumy et al, 2014). These features influence the grain size distribution and specific surface area of the clays. Hence, optimal clays for ceramic applications should contain higher amounts of low-ordered kaolinite and illite and some amounts of illite-smectite (I/S) minerals. Thus, the studied clays are characterized by an abundance of clay fractions as well as kaolinite and illite, while no smectite minerals were detected. These properties suggest the suitability of the studied clays as good-quality raw materials for ceramic applications. Furthermore, the significant occurrence of illite suggests that the clay soils could be widely utilized as fluxing materials in traditional ceramics for the production of cooking pots, stoneware tiles,

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and bricks (Ferrari and Gualtieri, 2006). Furthermore, the occurrence of quartz as the dominant non-clay mineral in the soils would enhance the strength of ceramics, thereby influencing the quality of the end products.

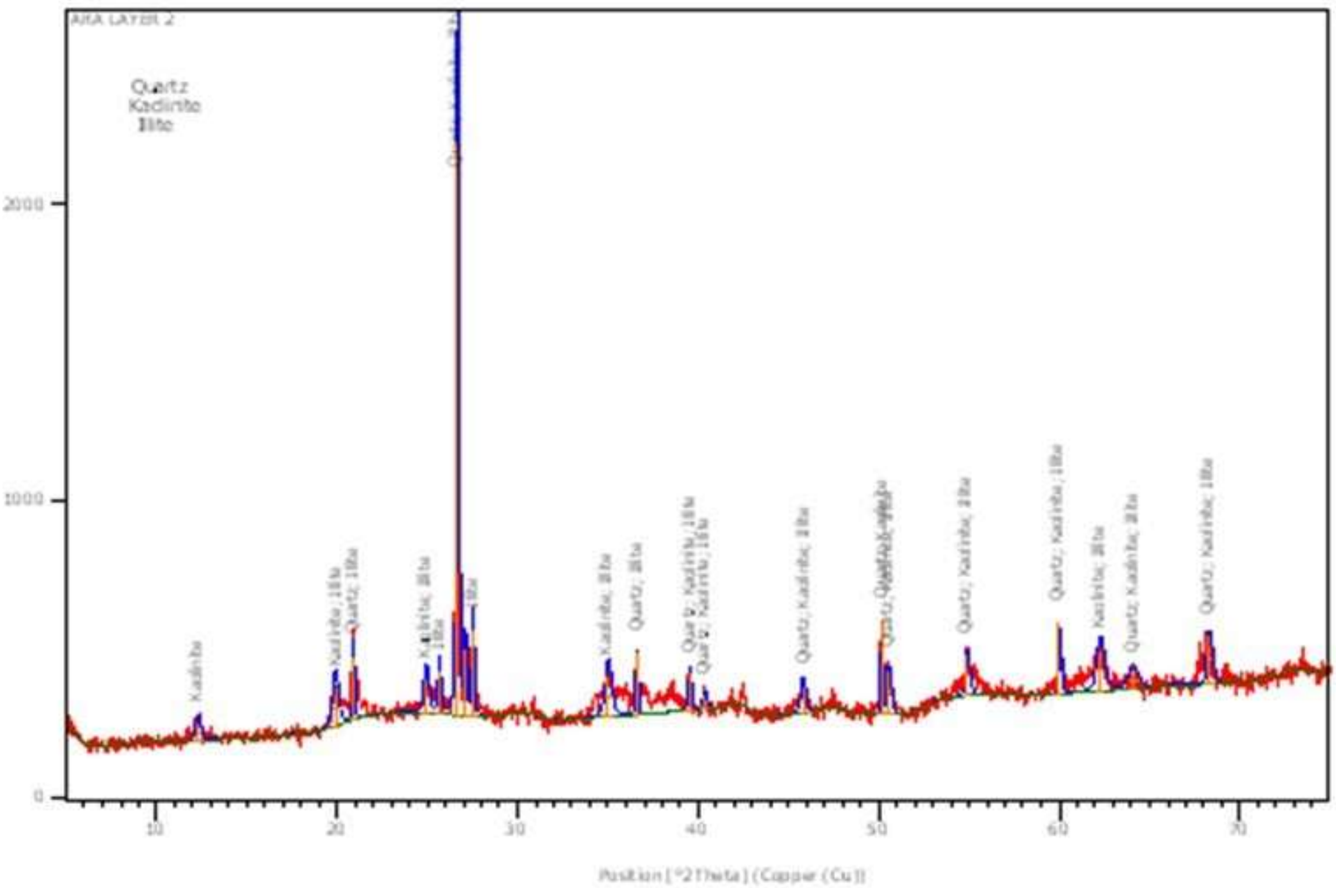

Figure 3a: Typical X-ray diffraction patterns of the clayey soils (Ara-2) analyzed for the study area

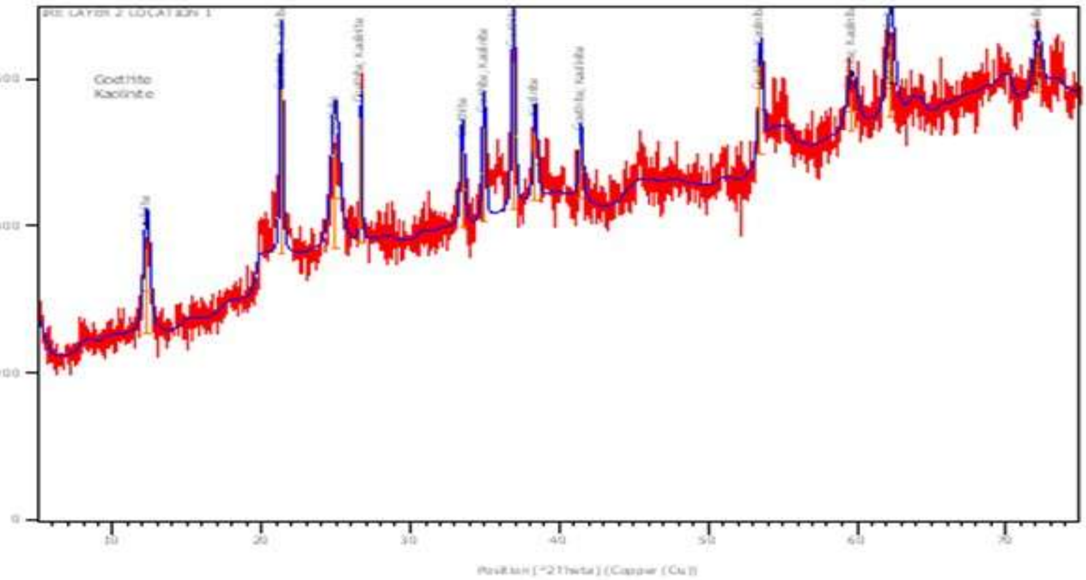

Figure 3b: Typical X-ray diffraction patterns of the clayey soils (Ire-2) analyzed for the study area

Table 2: Mineralogical composition of the clayey soils sampled from the study area

Sample code	Kaolinite	Illite	Quartz	Goethite
Ire-1	34.5	0.0	0.0	65.5
Ire-3	12.5	13.6	73.9	0.0

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Ire-2	9.0	0.0	91.0	0.0
Isan-1	47.4	52.6	0.0	0.0
Isan-2	79.4	20.6	0.0	0.0
Ara-2	16.3	11.2	72.4	0.0
Ara-3	22.2	0.0	77.8	0.0

3.2 Physical

The distribution of the particle sizes of clayey materials plays a prominent role in the determination of their suitability for ceramic applications with particular attention being given to the clay fractions (finer than 2μm). Celic (2010) noted that the particle size influences their technological behavior, particularly the drying and firing processes, thereby affecting several properties of the clay products, such as the mechanical properties of the fired materials. The grain size distribution characteristics of the studied clays, as revealed by the particle size analysis are shown in Figure 4, while the proportions of the different particle sizes are presented in Table 3.

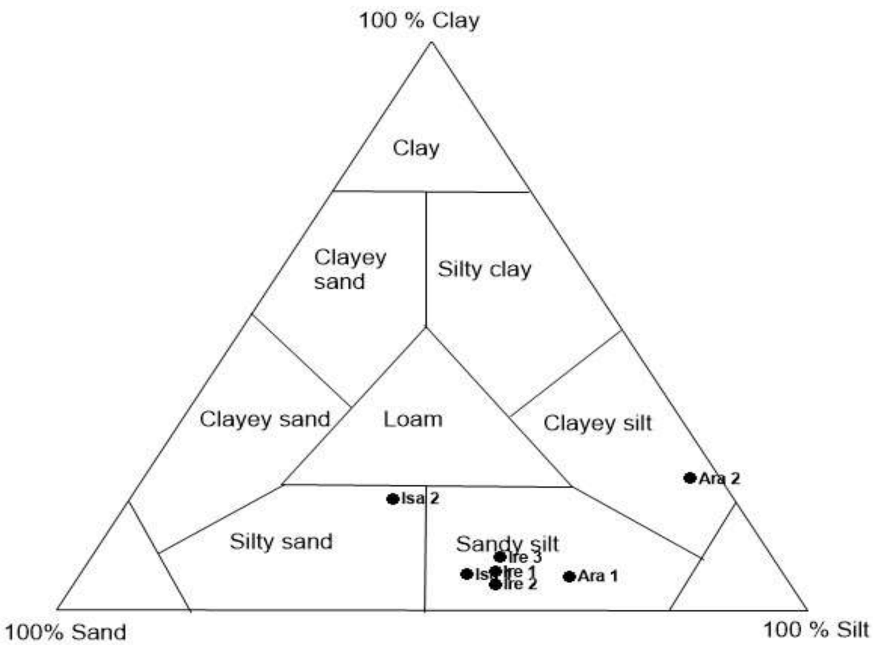

Figure 4: Ternary diagram classification of the studied clay materials

Table 3: Physical parameters of the clayey soils from the study area

Sample No.	Grading (%)					Specific Gravity	Atterberg Limits			Plasticity	Linear Shrinkage (%)
	<0.075 mm	Clay	0.002-0.02μm	<0.02μm	>20μm		Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)		
Ire-1	33.6	5.2	3.1	8.3	91.7	2.6	52.2	30.4	21.9	MH	20.0
Ire-3	76.0	26.0	28.3	54.3	45.7	2.5	75.3	38.1	37.1	MH	10.7
Ire -2	64.1	19.1	21.5	40.5	59.5	2.6	95.0	60.1	34.9	MH	13.6
Isan1	47.4	14.0	28.0	42.0	58.0	2.6	69.9	27.3	42.6	CH	8.6
Isan2	53.1	19.0	24.3	43.3	56.7	2.7	37.3	18.3	19.0	CI	10.7

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Ara-2	74.5	15.8	30.8	46.6	53.4	2.6	41.1	13.8	27.3	CI	17.9
Ara-3	96.1	23.1	41.3	64.4	35.6	2.6	72.1	41.8	30.2	MH	16.4

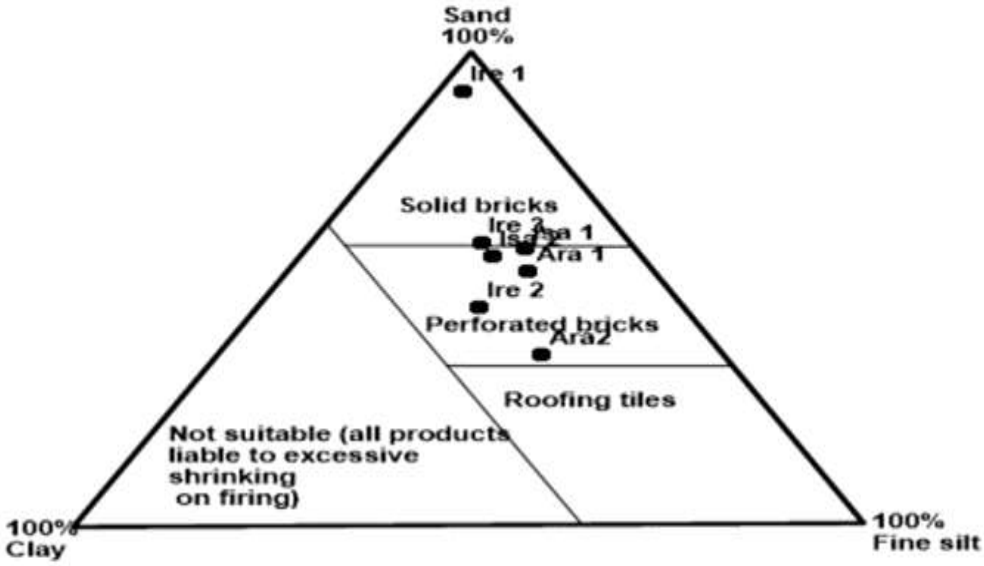

Figure 5. Position plots of the soils on a suitability diagram

It could be observed that the soils consist of particle sizes ranging from clays, silts, sand, and subordinate amount of gravels. Clay size particles range from 5.2 to 26% with some variations observed with depth, as the samples obtained at greater depth presented a higher amount of clay give a reason. Thus, the range of clay-sized particles (finer than 2µm) suggests that the raw materials would not exhibit excessive shrinkage during firing, as raw materials with finer fractions greater than 80% often cause excessive shrinkage during firing. Furthermore, the sample from Ara contains higher clay size fractions with an average value of 19.45%. Also, the average value of the clay fractions is within the range obtained by Ferari & Gualtieri (2006) for clays from Turkey. According to Diko et al (2011), suitable clay materials designated for ceramic applications are commonly classified as silty clay, sandy clays, clayey silt, and loam. Based on the sand-silt-clay ratios, a classification of the studied soils using the ternary diagram of Shepard (1954) presented in Figure 5 reveals that the studied soils are largely sandy silty with isan-1 and ara-2 classifying as silty sand and clayey silt respectively. The plot of the clays on the Winkler's diagram (Figure 6) indicates that the studied clay soils are suitable for utilization as common bricks, perforated bricks, roofing tiles, and masonry bricks. However, Ire-1 may require amendment before use.

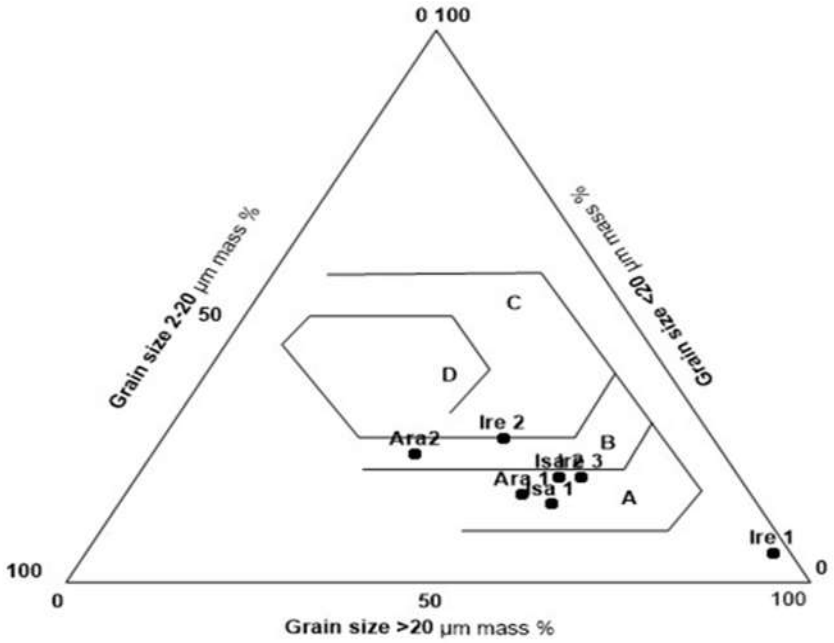

Figure 6. Grain size classification of the soils according to the Winkler diagram. A=common bricks; B= vertically perforated bricks; C= roofing tiles and masonry bricks; D=hollow products.

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The atterberg limits of soils are important parameters in the evaluation of clay soils for ceramic applications as they control their behavior and workability. The results of the atterberg limits reported in Table 3 indicate that the liquid limits range from 37.3 to 95%, plastic limit range from 13.8 to 60.1% while the plasticity index ranges from 19 to 42.6%. The plasticity chart (Figure 7) reveals that the soil plots in the domain of medium to high plasticity and compressibility. Previous studies (e.g., Daoudi et al. 2014, Daramola et al 2018) indicated that plasticity of clayey materials is essentially controlled by grain size distribution, mineralogical composition, and the occurrence of organic matter. Thus, the range of plastic limit is closely related to the values specified for kaolinite and illite Nweke et al 2023. The soils show plastic limit value which indicates the minimum moisture content necessary to reach a plastic condition. Although soil samples are more difficult to dry at high plastic limit, the use of high plastic clays reduces the wearing down of the equipment for grinding and conformation (extruder) (Celik, 2010; Oyebanjo et al 2020, Nweke et al 2023). Furthermore, most of the clays studied presented liquid limit values in the range defined by different researchers (eg Baccour et al, 2009; Semizand and Celik 2020) for raw clayey materials designated for ceramic applications.

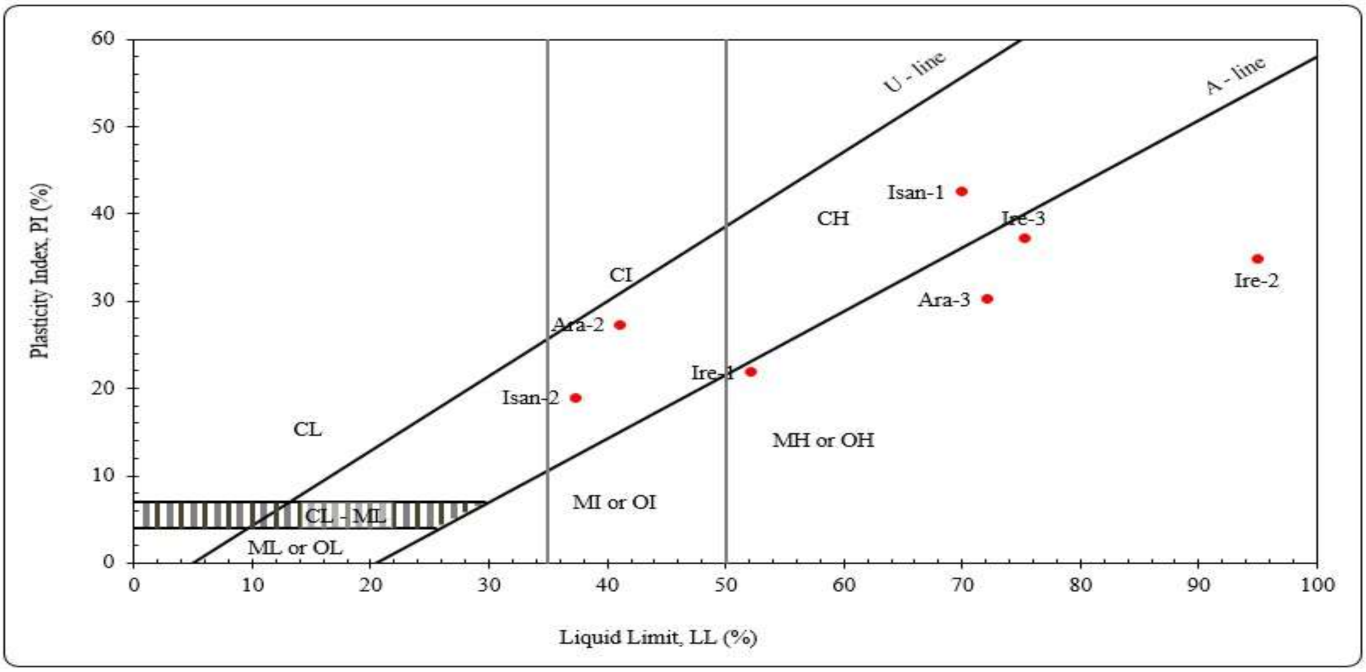

Figure 7. Position of the clayey soil samples on Casagrande plasticity chart.

Moreover, raw materials with low plasticity index (≤10) are considered inappropriate for use in the production of ceramics related to building sometimes usually requires the addition of a polymer so as to achieve adequate plastic behavior and to avoid an inappropriate extrusion process related to cracking during extrusion (Boukoffa et al, 2021; Nweke et al, 2023). On this basis, the plasticity index presented by the clayey soils under consideration are generally greater than 18.97% indicating that they are unlikely to be susceptible to inappropriate extrusion process. Furthermore, the projection of the clays studied on the workability chart is presented in Figure 8. It could be observed that some of the samples exhibit acceptable and optimal molding properties except for Ire-2, Ire-3, Ara-2, and Isa-3. The workability chart (Figure 8) further indicates that the linear shrinkage of these samples (Ire-2, Ire-3, Ara-2, and Isa-3) would require some property improvements prior to their processing. In addition, due to the risk of sticky consistency, Ire-2 and Isa-3 may also require amendment as they exhibit a significantly high plasticity index. The activity values obtained for the clayey soils are generally greater than 0.75, which suggests that the soils are active (Bell, 2007). This could be attributed to the presence of illite clay minerals, which are generally considered essential for improving the plasticity of raw materials and for forming the location of vitreous phases during firing, thereby improving the strength and densification of the ceramic bodies (Nweke et al., 2023). Thus, the presence of illite significantly enhanced the plasticity behavior of the studied clayey soils and would likely influence the firing strength and drying behavior of the final products. The linear shrinkage values of the clayey soils range from 8.6 to 20% with an average of 13% which fails to conform to the range of 7 to 10% specified for fired clays (Diko et al., 2020). The fairly high linear shrinkage values can be attributed to the amount of clays and the occurrence of illite (reference). Moreover, the high linear shrinkage values are inimical to its application for tiles production as minimal shrinkage during the firing of raw materials for ceramic production is vital (Garcia-Valles et al., 2020). Furthermore, the high

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linear shrinkage could result in deformation and microcracking during the production of bricks, thereby requiring the addition of degreasers to reduce the plasticity of the clays before utilization.

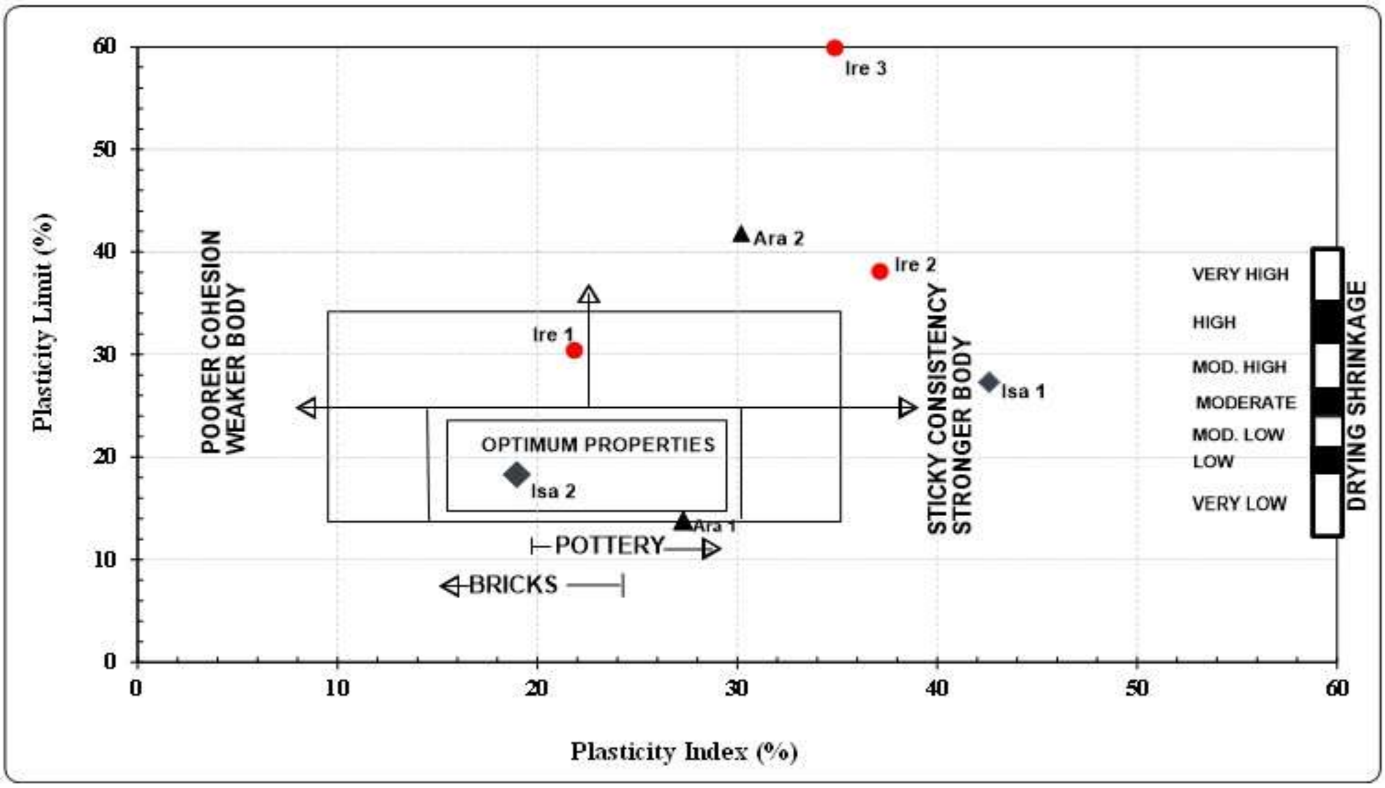

Figure 8. Plots of the clayey soils on the workability chart based on their plasticity characteristics (DikoMakia and Ligege, 2020)

3.3 Technological Properties

The results in Figure 9 show that the water absorption capacity ranges from 15.4 to 39% when fired at 850ºC and ranges from 10.44 to 15.42 % when fired at 1100ºC. The plots of the variations in the water absorption capacity with firing temperature (Figure 9). Reveals a general reduction in the water adsorption capacity with a corresponding increase in the firing temperature. This could be attributed to the combustion of organic matter, decarbonation and dehydration reaction (Ngun et al., 2011). This could significantly affect the durability and mechanical characteristics of the raw materials thereby transforming them into more resistant and more durable materials. Also, the reduction in the water adsorption capacity could be attributed to the glassy phase formation that penetrates into pores closing them and isolating them from the neighboring pores (Lambering 1993; Kagombe et al., 2021). Although, the average values of the water adsorption capacity of the soils fired at 1100ºC conforms to the maximum limit <25%and <20% specified by Souza (2002) for dense brick and roofing tiles respectively. However, the water adsorption capacity of some samples are quite higher than the standard specified thus rendering them unsuitable for such applications. Furthermore, the range of water adsorption capacity at 1000ºC agree with the range (8.03 to 24.27%) specified for quality and process control parameters in the development and manufacturing stages to produce structural ceramics.

The loss on ignition (LOI) is a very important property that reveals the quantity of organic matter present in the raw materials and further reveals the extent of vacuum and the percentage of water absorption (Nweke et al., 2023). The LOI ranged from 13 to 22% at 800°C, while at a higher temperature of about 900°C, it ranged from 16 to 27% after which the values of the LOI remained constant (Figure 10). On a general note, the increase in LOI as the firing temperature increased from 800 to 900ºC may be due to the elimination of organic matter by combustion, loss of structural water, decomposition of some minerals such as clay minerals and sulphate during firing (Bauluz et al., 2004; Tsozue et al., 2017; Kagonbe et al., 2021).

The flexural strength (FS) of the studied soils are presented in Figure 11. It shows a general increase with increasing firing temperature. This further suggests that the technological property is highly dependent on the temperature of firing. The presence of illite in the soils may have significantly influenced the flexural strength of the studied clay samples after firing. Furthermore, the flexural strength values of the studied clayey soils at 1000°C are significantly lower than those earlier reported by Dondi et al. (2002) for Italian brick clays, as well as other authors such as Kagonbe et al. (2021) for roofing tiles, except for the production of massive bricks

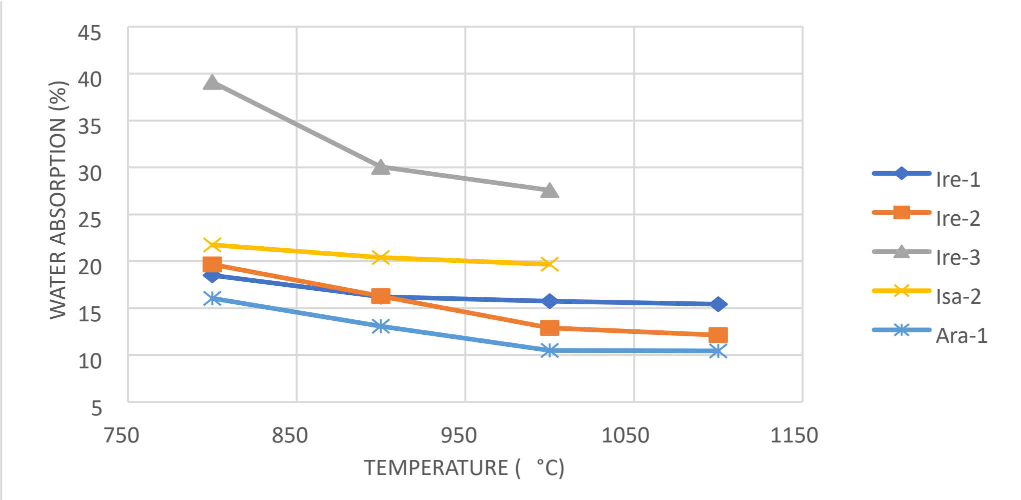

Figure 9. Variation of the water absorption capacity of the soils with firing temperature

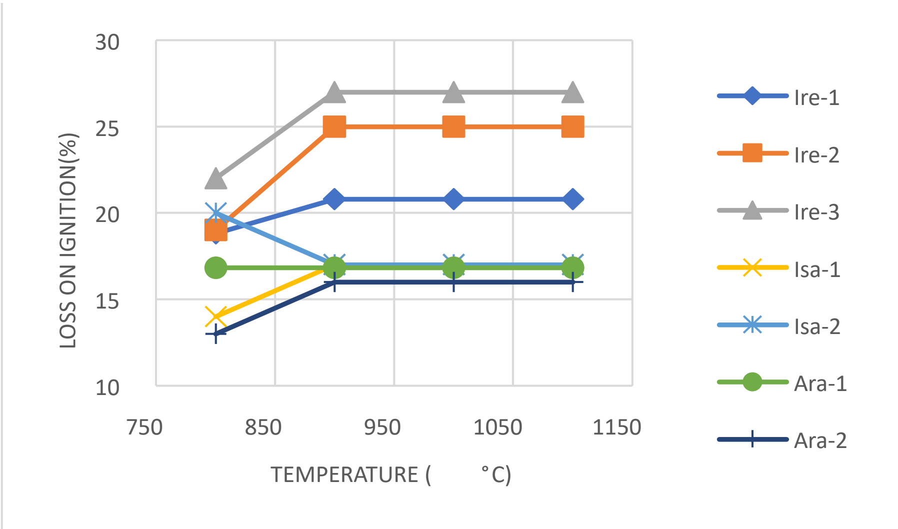

Figure 10. Variation of the LOI of the soils with firing temperature

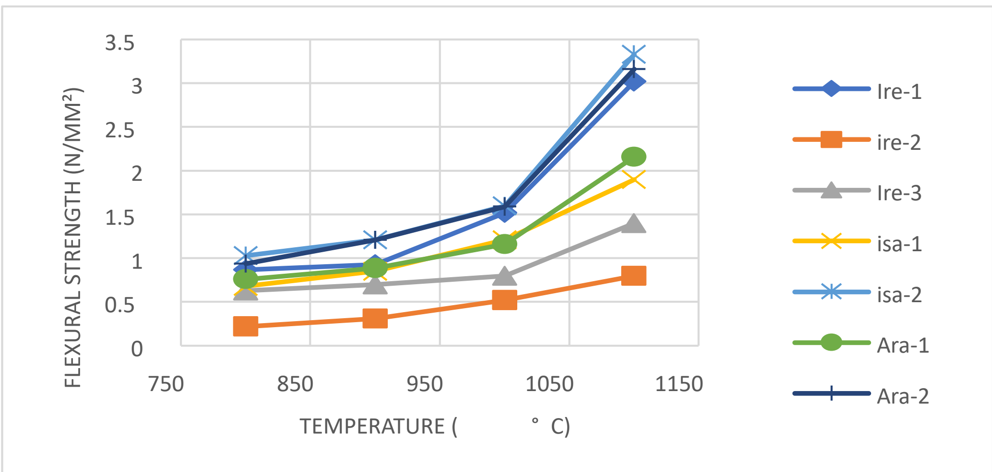

Figure 11. Variation of the flexural strength of the soils with firing temperature

CONCLUSION

The mineralogical and physical analysis of clayey soils from selected sites in Ekiti State was conducted in this study to assess their suitability as raw materials for ceramic production. Based on a comprehensive analysis, the clays examined show significant potential for manufacturing common bricks, perforated bricks, and roofing tiles, provided certain technical adjustments are made. The mineralogical composition revealed that the primary clay minerals are kaolinite and illite, along with notable amounts of quartz, while muscovite and goethite are present in substantial quantities. The high content of clay fractions, especially kaolinite and illite, in the absence of smectite minerals, confirms these clays as suitable raw materials for high-quality ceramics. The considerable presence of illite is particularly beneficial, as it enhances plasticity and promotes vitreous phase formation during firing, thereby increasing the strength and density of the ceramic bodies. Illite-rich clays are commonly used as fluxing agents in traditional ceramics to produce cooking pots, stoneware tiles, and bricks. Additionally, the dominant presence of quartz as a non-clay mineral further strengthens the structural integrity and durability of the final ceramic products. Physical characterization showed that the soils are made up of particles comprising clays, silts, sand, and subordinate quantities of gravel. The clay-sized particles, less than 2μm, varied from 5.2 to 26%; samples from deeper depths had a higher percentage of clays. This range is advantageous as it suggests that the raw materials when fired would not exhibit excessive shrinkage, because the materials with finer fractions greater than 80% show excessive shrinkage. Based on the Winkler diagram, most of the studied clay soils fall within common bricks, perforated bricks, roofing tiles, and masonry bricks, although Ire-1 may require amendment before being used. The liquid limit values obtained from the Atterberg limits analysis ranged from 37.3 to 95%, plastic limits from 13.8 to 60.1%, and plasticity indices ranging between 19 and 42.6%. These classifications using the plasticity chart place the soil within the medium to high plasticity and compressibility region. Most of the samples had liquid limit values within the specified range for raw clayey materials meant for ceramic purposes. It is interesting to note that all samples yielded plasticity indices well above 18.97%, as compared to the threshold value of 10% below which materials are regarded as unsuitable for ceramic production due to susceptibility to cracking during extrusion. Nevertheless, from the analysis of the workability chart, samples Ire-2, Ire-3, Ara-2, and Isa-3 would need amelioration of their properties before processing due to their linear shrinkage characteristics. Furthermore, samples Ire-2 and Isa-3 showed very high plasticity indices, resulting in a sticky consistency; hence, they need to be amended. The linear shrinkage values varied between 8.6 and 20%, with an average of 13%, which exceeds the optimal range of 7 to 10% specified for fired clays. These relatively high values linked to the clay content and the presence of illite may lead to deformation and microcracking during brick production. For this reason, the use of degreasers is highly advisable to reduce plasticity before its application, especially for samples whose linear shrinkage is higher than 15%.

Technological testing uncovered important links between firing temperature and ceramic properties. Water absorption capacity decreased from 15.4-39% at 850°C to 10.44-15.42% at 1100°C, showing better densification at higher temperatures due to combustion of organic matter, decarbonation, dehydration reactions, and the formation of a glassy phase. At 1100°C, most samples achieved water absorption values within the maximum limits of <25% for dense bricks and <20% for roofing tiles, as specified by Souza (2002); however, many of these samples still exceeded those limits, making them unsuitable for such uses without further optimization. At 1000°C, water absorption ranged from 8.03 to 24.27%, meeting quality standards for structural ceramics. Flexural strength increased steadily with higher firing temperatures, confirming that this property relies heavily on temperature. Illite showed the strongest influence on the post-firing flexural strength of the studied samples. Nonetheless, a key technical issue must be addressed: the flexural strength values at 1000°C were significantly lower than those reported by Dondi et al. (2002) for Italian brick clays and Kagonbe et al. (2021) for roofing tiles. At this temperature, the clays are only suitable for producing massive bricks. To reach flexural strength levels that satisfy industry standards for high-quality roofing tiles and structural use, firing temperatures above 1000°C are necessary. Samples fired at 1100°C exhibited improved flexural strength, nearing acceptability for broader ceramic applications; however, further optimization might still be needed for high-value products.

List of Abbreviations

FS flexural strength

LOI Loss on Ignition

XRD X-ray diffraction

ICDD International Center for Diffraction Data

BSI British Standard Institution

ASTM American Standard for Testing Materials

LL liquid Limit

PL Plastic Limit

CL Clays of low plasticity

CI Clays of Intermediate plasticity

CH Clays of high plasticity

ML-OL	Organic clays and silt of low plasticity
MI-OH	Organic clays and silt of intermediate plasticity
MH-OH	Organic clays and silt of high plasticity

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