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Characterization of Agyereku Clay as a Binder for Composite Insulators Production

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ABSTRACT: This study investigates the characterization of Agyereku clay to determine its suitability as a binder in the production of egg shell-reinforced clay composite insulators. The problem addressed is the need for sustainable, cost-effective, and high-performance insulating materials for various industrial applications, including electrical and construction sectors. Characterization of clay was focused on its such Atterberg's limits, sieve analysis, and chemical analysis. The Atterberg's limit test revealed a plastic limit of 47%, a liquid limit of 66%, a plasticity index of 19, and a shrinkage limit of 25%, indicating moderate plasticity and shrinkage properties suitable for molding and shaping. X-ray fluorescence (XRF) analysis showed that the clay primarily consists of silica (42.1%) and alumina (29.26%) essential for thermal stability and mechanical strength; with notable amounts of Na_2O (18.96%), K_2O (7.01%), and trace elements like Fe_2O_3 (0.173%) influencing the sintering process. Sieve analysis demonstrated that 79.6% of the clay passed through a 5 mm sieve, with 66.6% through 2.5 mm, 55.2% through 1.25 mm, and finer fractions enhancing uniformity and bonding in the composite. Balance in particle size distribution ensures structural integrity and porosity, crucial for insulation properties. These findings confirm the suitability of the Agyereku clay as a binder for clay-eggshell composite which is cost-effective and thermally efficient insulating material.

KEYWORDS: Clay,insulator, Atterberg's limit, sieve analysis, chemical composition.

I. INTRODUCTION

The increasing demand for insulators especially in electrical power sector across various sectors has led to a greater reliance on high-voltage transmission systems; which, in turn, requires the use of insulators to ensure the safe and efficient transmission of electricity. Insulators, primarily made from materials such as porcelain, glass, and ceramics, play a critical role in preventing electrical currents from passing through conducting supports. However, the production and disposal of conventional insulators contribute significantly to environmental degradation, as the raw materials used in their manufacturing are energy-intensive and their disposal often results in waste that cannot be easily recycled. The magnitude of this issue is particularly pronounced in developing regions where the infrastructure for the recycling of such materials is limited, thereby aggravating environmental pollution and contributing to long-term ecological damage [1]. Given the global environmental concerns and the increased demand for affordable and eco-friendly alternatives, there is an urgent need to explore and develop alternative materials for insulator production that are both sustainable and cost-effective.

Clay, being an abundant and low-cost material, serves as an ideal binder, potentially enhancing the stability and durability of the composite material. The mineral composition of clay affects its binding properties. Different types of clay minerals, such as kaolinite, montmorillonite, and illite, exhibit varying degrees of bonding ability based on their crystal structure, particle size, and surface charge. For example, montmorillonite, a smectite-type clay, has a large specific surface area and a high cation-exchange capacity, which allows it to bond more effectively with other materials than kaolinite [2]. This mineral composition plays a key role in determining the strength and durability of the final composite.

Additionally, clays with higher amounts of silica (such as kaolinite) contribute to the hardness and thermal stability of the composite, while clays rich in alumina (such as bentonite) enhance the composite's resistance to moisture and environmental degradation. Understanding the specific mineral content of the clay used as a binder helps in designing composites with tailored properties for specific applications [3].

Several studies show the suitability of clay to be used as a binder and enhance thermal insulation. Oladiji et al. [4] varied composition of kaolin, ball clay, feldspar and quartz to produce different samples of porcelain insulators to investigate their resulting properties and suitability for mass production and commercial viability. The sample with composition of 33% Kaolin, 15% ball clay, 32% feldspar and 20% quartz was found to possess the highest failing load of 8.0 kN, corresponding to water absorption (1.55%), porosity (4.64%), bulk density (1.73 g/cm3), with appreciable insulation resistance of 6,630 Mega ohms at injection of 5,000 volts. The investigation had shown that high quality electrical porcelain insulators could be achieved from locally sourced materials.

Okolo et al. [5] developed of electrical porcelain insulators based on local clays. Test samples were made by varying the quantities of silica and feldspar required to form a mouldable plastic body with each clay sample. Electrical properties such as electrical resistance were determined for each test sample that survived the high temperature. Porcelain insulators containing 50-70% clay, 20-30% feldspar and 10-20% silica were found to possess requisite properties that make them suitable for domestic production of porcelains insulators from the clays studied. Akpanko and Stephen, [6] evaluated the physical properties of clay used for manufacturing of burnt bricks The clay was sampled for physical tests which included natural moisture content, sieving analysis, consistency limit (Atterberg limit), specific gravity, water absorption, compaction, compressive strength and porosity. The bricks produced under standard compaction methods gave cold water absorption of 1.75%; compressive strength between 1.30N/mm2 and 1.43N/mm2; plastic limit of 51%; porosity of 0.99% and Atterberg liquid limit of 80.5%. The bricks on examination exhibited change in colour due to thermal stress (high temperature). If properly harnessed, these widely available raw materials and their cheap products will readily substitute cement blocks for most housing, and other structural work as well as ceramic production.

[5] focused on the chemical analysis of electrical porcelain insulators based on local clays by conducting some chemical composition test using the Atomic Assumption Spectrophotometer (AAS). The clay samples were also tested for linear shrinkage and apparent porosity. Based on the results obtained, the linear shrinkage values recorded range from 7.29% to 14.29% for Iva Valley formulations, 5.14% to 14.71% for Nawfija and 7.74% to 10.29% for Ekwulobia. It was observed that linear shrinkage decreases as the content of non-plastic materials increases and increases as clay content increases. Porcelain insulators that constitute the above results were found to have requisite properties that make them suitable for domestic production of porcelains insulators from the clay samples studied. Hence, this study characterized Agyereku clay as a binder for composite insulators production.

II.MATERIALS AND METHODS

Clay used in this study was collected from a clay deposit in Agyereku town, Lafia Local Government Area of Nasarawa state, Nigeria at depth of 15 cm to 30 cm. The clay sample was washed and dried to get rid of some associated impurities (sieving). This was achieved by first drying the wet excavated sample for about 7 days. The dried clay was crushed and sieved using sieve size of 150 micro meter to obtain the clean sample.

Characterization of clay

Prior to characterization of clay, clay sample was pounded in a mortar with pestle to break the lumps into workable particles. The pounded clay was sieved using the sieve shaker to obtain fine particle size of up to 150µm. The properties considered in the characterizations of Agyereku clay were Atterberg's limit, liquid limit, plastic limit, shrinkage limit, porosity and chemical analysis,

Atterberg's Limit Test on Clay

Atterberg's limits were used to classify the consistency of clay and its ability to undergo plastic deformation. The following tests—liquid limit, plastic limit, and shrinkage limit—were standard methods for determining the behavior of clay under varying moisture contents.

Limit (LL): The liquid limit was determined using the Casagrande method, as described in ASTM D4318-17 for testing the liquid limit of soils (American Society for Testing and Materials, 2017). This test determined the moisture content at which a soil passes from a plastic state to a liquid state. The liquid limit for the Nakka clay was determined as per ASTM-D4318

Plastic Limit (PL): The plastic limit is defined as the moisture content at which a soil becomes too dry to be molded into a thread of 3 mm diameter without crumbling. This test follows the method outlined in ASTM D4318-17. The plastic limit for the Agyereku clay was determined as per ASTM-D4318.

Shrinkage Limit (SL): The shrinkage limit was determined by measuring the moisture content at which further drying of the clay does not result in a decrease in volume. This test was carried out according to ASTM D427-08. A clay sample was prepared into a uniform size and dried in a controlled environment. The volume change was recorded, and the shrinkage limit was determined when further drying did not cause volume reduction.

Clay porosity: Porosity refers to the number of pores, or open space, between soil particles. It refers to the volume fraction of void spaces in a soil sample, which can be filled with water or air. The porosity of soil affects its water-holding capacity, permeability, and other physical properties. Porosity of the clay sample was determined in accordance with ASTM-C830.

Sieve Analysis of Clay

Sieve analysis was used to determine the particle size distribution of the clay. This was important for classifying the texture of the clay, which influences its suitability for various applications such as binding materials for composites insulator production. The test was carried out according to ASTM D422-63 for particle-size analysis of soils. From the sieve analysis, a particle size distribution curve was plotted, and parameters like the uniformity coefficient (Cu) and coefficient of gradation (Cc) were calculated. Particle size analysis is the measurement of the proportions of primary solid particles from soil and sediment. The various particle sizes were determined either by their capacity to pass through different mesh sieves or by their rates of settling in water. This was achieved by ASTM-D7928.

Chemical Analysis of Clay

Chemical analysis is essential for identifying the mineralogical and elemental composition of the clay. This helps in understanding the reactivity of the clay, its potential as a binder, and its role in composite systems. X-Ray Fluorescence (XRF) Analysis was used to determine the elemental composition of the clay. This was done following ASTM E1621-16, which provides guidelines for X-ray spectrometry of soils and sediments. A small amount of clay was placed in the XRF machine. The sample was irradiated with X-rays, causing the emission of characteristic X-ray spectra from each element. The results were processed to quantify the elemental composition. The elemental contents of the clay samples were determined at raw state and fired state (1100 ^{0}C) using X-ray fluorescent (XRF) analysis.

III. RESULTS AND DISCUSSION

Atterberg’s Limit of the clay

Results for Atterberg’s test of clay are presented in Table 1.

Plastic Limit

The plastic limit indicates the moisture content at which the soil transitions from a plastic to a semisolid state. A value of 50% (Presented in Table 1 and Plate 1) suggests the clay is moderately flexible. This is favorable for molding and shaping, which signifies that it could be used as binder especially when with some agricultural wastes like eggshells and palm kernel fibres for insulators production. Previous studies [7]indicated that materials with higher plasticity tend to form better molds for ceramic products. In this case, the addition of eggshells might slightly reduce flexibility but can still allow for effective shaping.

Table 1:Atterberg Limits Test for Clay

S/N	Atterberg Limit Test	Value
1	Plastic limit	50%
2	Liquid limit	66%
3	Plasticity index	19
4	Shrinkage limit	25 blow at 66%

Plate 1: Picture showing plastic limit result of clay

3.1.2 Plasticity Index

A plasticity index of 19 indicates moderate plasticity, meaning the clay can be shaped easily without becoming too sticky or too brittle. Previous research [8] suggests that materials with a moderate PI offer a balance between moldability and strength, making them suitable for creating insulator shapes. The addition of eggshells may influence this balance, either improving or reducing the material’s workability, depending on their proportion.

Liquid Limit

The liquid limit of 66% suggests (presented in Table 1that the clay becomes fluid at higher moisture content, which is useful for mixing and molding. Studies [9] show that higher liquid limits in clays are beneficial for ensuring uniformity in mixtures, which could help inachieving consistent dispersion of fibres or particulate for composite insulators production. However, managing this fluidity is crucial to prevent loss of form before processing.

Shrinkage Limit

The shrinkage limit of 25% (Table 1)suggests significant shrinkage as the material dries or is fired. This is typical for clays, but studies (e.g., Chidambaram & Ramasamy, 2014) show that the incorporation of fillers like eggshells can help reduce shrinkage. The eggshells might provide added structural stability, thus potentially reduce cracking and improve dimensional stability during drying or firing. Previous studies on clay and eggshell mixtures [10] suggest that adding eggshells to clay can enhance the material’s thermal insulation properties while maintaining its workability. Eggshells, being lightweight and porous, could reduce shrinkage and improve the insulation qualities of the final product. This aligns with the findings of our limits test, where the clay’s plasticity and shrinkage characteristics make it a promising candidate for insulator production when mixed with eggshells.

The results from the limits test indicated that the clay-eggshell mixture can be effectively molded into insulators. The moderate plasticity and high liquid limit make the material flexible enough for shaping, while the shrinkage limit suggests potential for distortion during drying or firing. The addition of wastes like eggshells could mitigate some of these challenges and enhance the thermal insulation properties of the final product. However, the proportion of eggshells should be carefully controlled to balance workability, shrinkage, and strength.

Sieve Analysis of Clay

Sieve analysis as presented in Figure 1 and Plate 2 showed that approximately 79.6% of the clay passed through the 5 mm sieve, indicating that the clay has a significant portion of coarser particles. This proportion of larger particles can influence the material's bulk structure but could also impact the consistency of the final ceramic or composite when mixed with binders such as egg shell powder. In a study by [11], a similar clay-based composite showed that coarse particles could enhance the mechanical strength of the final material. However, too high a content of coarse particles might affect the compactness and uniformity of the insulation, so a balance is necessary.

With 66.6% of the material passing through the 2.5 mm sieve, indicated that a substantial portion of the clay is already finer than this size, which is desirable for producing a smooth, moldable composite material. The coarser fraction, 33.4%, may influence the porosity and density of the final product. In previous works by [12], it was noted that the optimal ratio of coarse and fine particles in ceramics affects both thermal insulation and mechanical properties.

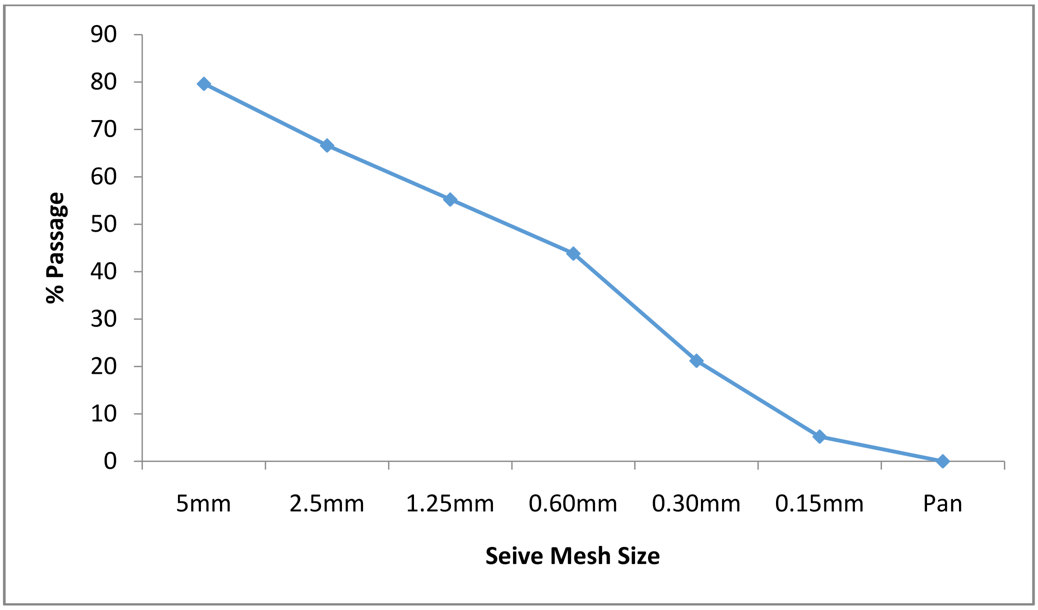

Figure 1: Sieve analysis of clay for production of insulator samples

Plate 2: Picture showing results for sieve analysis of clay

For 1.25 mm sieve, 55.2% of the material passed through, suggesting that the clay has a mix of medium-sized and fine particles. Samani et al. [13] demonstrated that clays with medium-sized particles (less than 2 mm) contribute to smoother, more uniform composites, which enhances the molding and sintering process. This range of particle sizes is ideal for producing high-quality ceramic insulators with good mechanical properties.

In 0.60 mm sieve, 43.8% of the material passed through this sieve. Finer particles generally lead to better densification during the sintering process, which is important for creating insulating ceramics. [14] found that finer particles, when combined with specific binders, improve the uniformity and porosity of ceramics, which is essential for thermal insulation.

At 0.30 mm sieve, a substantial 21.2% of the material passed through this sieve, meaning that a significant proportion of the clay is finer than 0.30 mm. Fine particles play an important role in increasing the surface area, which aids in bonding with egg shell powder. As [12] found, adding finer particles to ceramic composites improves thermal insulation by creating a more compact structure and reducing porosity. This is particularly beneficial in enhancing the material's thermal resistance.

For 0.15 mm sieve only 5.2% of the material passed through the 0.15 mm sieve, indicating that the clay contains a relatively low amount of ultra-fine particles. While a small amount of ultra-fine material may be beneficial for increasing density and improving bonding, an excessive number of fines may lead to excessive densification, reducing the overall porosity required for insulation. This aligns with findings from [15], who reported that too much fine material could negatively affect the insulation properties of ceramics by decreasing porosity.

The material that passed through the pan sieve (26 g) represents the finest fraction of the clay. The finer particles contribute to the high surface area, which can improve the interaction with egg shell binder. Jusoh et al. [11] highlighted that finer materials are beneficial for achieving a smooth, homogeneous paste, which is crucial for consistency in insulation products.

The sieve analysis indicated that this clay material has a good distribution of coarse and fine particles, which is advantageous for creating a balanced insulating material. Coarse particles will provide the structure and support needed for strength, while fine particles will reduce porosity, which is critical for insulation. The presence of fine particles, particularly those passing through the 0.30 mm and 0.15 mm sieves, will help create the necessary air pockets that contribute to thermal insulation. As [13] noted, fine particles reduce thermal conductivity by increasing air entrapment within the material, making it an effective insulator. In fact, the fine fraction of this clay is low enough to prevent the material from becoming too dense, which could compromise its insulating properties. The balance between coarser and finer particles ensures that the clay can be easily shaped and molded, and the sintering process will not be hindered. The coarser fraction provides the structural integrity needed for molding, while the fine particles improve the material's sintering behavior. Previous studies, such as [14], emphasize that a clay mixture with a well-balanced particle size distribution aid in achieving uniform sintering and enhanced final material properties.

The sieve analysis of the clay material used in this study shows a good distribution of particle sizes that will be advantageous for producing effective insulating materials. The clay's combination of coarse and fine particles ensures both structural integrity and porosity, which are critical for thermal insulation. When combined with agricultural waste like egg shell powder, will likely form a composite material that offers both good mechanical strength and excellent thermal resistance.

3.3 Chemical Composition of clay

The chemical composition of clay, as shown in Figure 2, suggest that it is primarily composed of silica (SiO_2, 42.1%) and alumina (Al_2O_3, 29.262%), which is typical for clays used in the production of ceramics. This is consistent with [11] findings, where kaolin used in their study was primary dominated by15] oxides of silicon and aluminium (SiO_2 and Al_2O_3).These two components are well-known for their high refractory properties, making them ideal candidates for use in insulating materials. In the context of insulating materials, especially those used in high-temperature environments, the role of silica and alumina in promoting thermal stability is critical.

Silica is one of the most significant components of clay, contributing 42.1% to the composition. SiO_2 is known for its high melting point and excellent thermal stability, which is why it is commonly used in the production of insulating ceramics (Samani et al., 2021). The high content of SiO_2 in clay may enhance the thermal resistance of agro waste-based composites, making them suitable for insulation applications, as demonstrated in previous works on clay-based composites (Jusoh et al., 2019). Silica also contributes to the formation of a strong, stable silicate network when mixed with other oxides, such as alumina, which further strengthens the ceramic matrix.

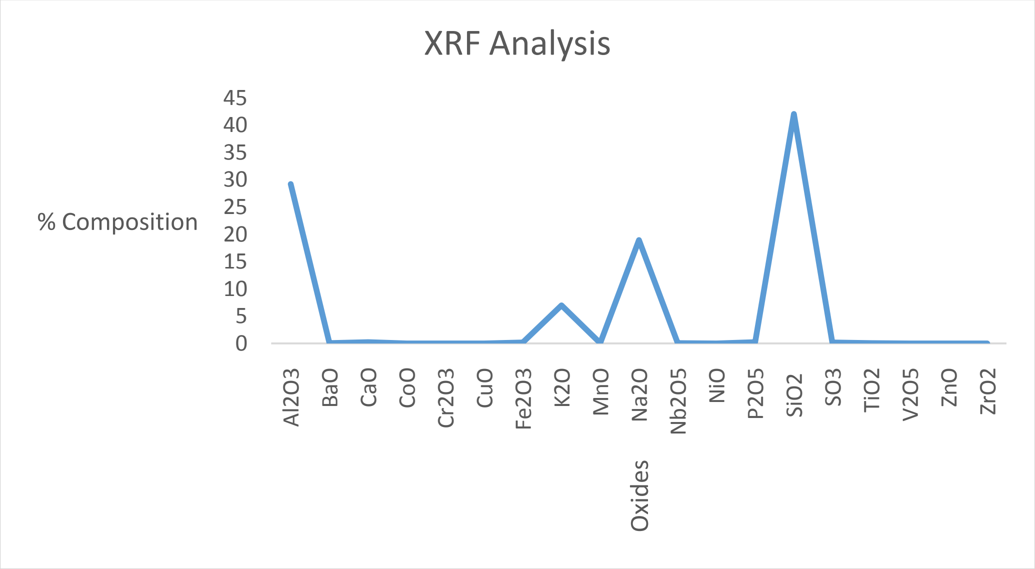

Figure 2: Chemical composition of clay

Alumina (Al_2O_3), contributing 29.262% to the clay composition, is another essential oxide. Al_2O_3 enhances the mechanical strength and thermal stability of ceramic materials. Alumina is well-documented for its electrical insulating properties and resistance to high temperatures, which makes it an attractive component for insulating materials [14]. In the context of egg shell composites for instance, alumina may improve the material's ability to withstand elevated temperatures while maintaining structural integrity, as observed in similar works on ceramic composites [12]. The combination of high alumina content with silica forms a durable and effective insulating matrix, which could be ideal for high-performance applications.

The presence of other oxides, such as Na_2O (18.962%), K_2O (7.007%), and CaO (0.234%), indicated the potential for modifying the thermal and mechanical properties of the composite. Sodium oxide (Na_2O) and potassium oxide (K_2O) are often present in clay-based materials and can influence the sintering process. They lower the sintering temperature, which can facilitate the formation of a more cohesive structure without requiring excessive heat[16]. This could be an advantage when producing composite materials from agro wastes like egg shells and palm kernel fibres using the clay, as it might reduce energy consumption during production while still achieving desirable thermal and mechanical properties.

However, the high content of Na_2O and K_2O could also have drawbacks, such as the potential to reduce the material's resistance to certain environmental conditions, such as water absorption, which can affect its long-term stability [17]. Therefore, balancing the proportions of these oxides is critical to ensuring that the final composite performs well as an insulator.

The trace elements such as Fe_2O_3 (0.173%), TiO_2 (0.065%), and ZnO (0.004%) can influence the color, microstructure, and durability of the composite material. Iron oxide (Fe_2O_3) is commonly present in clay-based materials and contributes to the overall strength of the material, as well as providing a degree of resistance to wear and tear . The presence of TiO_2, though in smaller amounts, can also enhance the material's resistance to UV degradation and increase its hardness, making it more resilient under mechanical stress.

IV. CONCLUSION

The characterization of clay for use as a binder for composite insulator has provided valuable insights into its suitability for insulation applications. The Atterberg's limit test results indicated that the clay possesses moderate plasticity (plasticity index of 19) and shrinkage properties (shrinkage limit of 25%), making it moldable while maintaining structural integrity. Sieve analysis results show a well-distributed particle size composition, with 79.6% passing through the 5 mm sieve, supporting a balance between workability and porosity. The XRF analysis confirms the dominance of silica oxide (42.1%) and alumina (29.26%), which contribute to thermal stability and mechanical strength, while the presence of Na_2 O (18.96%) and K_2 O (7.01%) suggests potential effects on sintering behavior. These findings suggested that Agyereku clay is a suitable candidate for use in composite insulator production, with the potential to achieve enhanced thermal insulation when reinforced with agro based wastes like egg shell and palm kernel fibre. However, further optimization of reinforcements to be used with the clay proportions and processing conditions was recommended to maximize performance.

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