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Geological Investigation of Alkaleri Kaolin Deposit, Bauchi State, Nigeria and the Assessment of Its Ceramic Properties

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Abstract
A sedimentary kaolin deposit at Alkaleri, 74 kilometres east of Bauchi town along the Bauch-Gombe road, was studied. A target area of about 216,684m^2 was chosen for a detailed geological investigation. The objective of the study was to prove adequate quality reserve sufficient for the economic lifetime of a large scale ceramic plant. The results of the study will help potential investors in the ceramic industry in Nigeria in decision making as it pertains to raw material. A total of 25, 6-inch boreholes were carefully sited on a 100m^2 grid. The drilling was undertaken by 4 Banka drill teams supplied by the defunct Nigerian Mining Corporation. The reserve contained under the investigated area, is 8,672,476.8 tonnes. The silica content (47.99±6.12%) alumina content (32.55±3.99), loss on ignition (12.46±1.40%) and plastic limit(36.61±11.02) of the kaolin fall within the values of ceramic-grade kaolin.A high alumina content against low ferric oxide content (3.03±2.08%) produces a modifying effect on the fired colour. The light gray natural colour of the kaolin at 1000^{o}C produces a turns into shades of pink a colour that is generally seen as good in ceramics.The plasticity index of 60-68% obtained for Alkaleri kaolin surpasses plasticity index of 10-30% for ceramic clays. The average linear and volume shrinkage for the five samples tested are 3.73±0.99 and 10.77±2.75 respectively.The studied kaolin plots on the Casagrande plastic index-liquid limit chart as an inorganic clay and on the plastic limit-plasticity chart as a plastic kaolin.

Keywords: geological investigation; kaolin; atterberg limits; firing shrinkage; ceramic industry

INTRODUCTION

Kaolin is a white, soft, plastic clay composed mainly of kaolinite, $Al_4(OH)_8[Si_4O_{10}]$, and other related clay minerals such as nacrite and dickite (Baker and Uren, 1982). Kaolin deposits are classified as primary or secondary according to their genesis; primary deposits originate *in situ* by alteration, whereas secondary deposits are of sedimentary origin (Murray, 1988). The formation and localization of sedimentary clay is controlled by the location of the sedimentary basin and the presence of weathered feldspar-rich rocks such as granite, syenite or gneiss adjacent to the basin, particularly rapidly eroding paleotopographic highs. Ideal conditions to produce kaolinitic by chemical weathering are high rainfall, warm temperatures, lush vegetation, low relief and high groundwater table (Cravero and Dominguez, 1999). The kaolin is eroded and transported by streams to a quiet, fresh or brackish water environment. Post-depositional leaching, oxidation, and diagenesis can significantly modify the original clay mineralogy with improvement of kaolin quality (Hassan, 2014).Kaolin has wide range of application among which is the ceramic industry. Each specific use of kaolin requires the kaolin to possess some specific properties.

Location, Accessibility And Infrastructure

The village of Alkaleri is situated 74 kilometres east of Bauchi town along the Bauch-Gombe road. Massive exposures of kaolin deposits occur on the Jalgalwa River bank on both sides of the bridge over the river at Alkaleri.The deposit outcrops along the bank of Jalgalwa River which remains dry from May to October. Infrastructural facilities like industries, hospitals and water supply are lacking in Alkaleri. There is, however, a reliable public power supply in the village.

Geological Setting

Alkaleri is underlained by Paleocenecontinental strata of Kerri Kerri Formation which forms one of the stratigraphic sequences and youngest formations of the Gongola Basin in Nigeria. This formation is a sequence of fine grained sandstones, clays, and silts with some thin coal bands.The sequence is often capped with thick laterite which is in most cases vesicular in texture. Falconer (1911) described a characteristic section of the formation as white clay with gritly and sandy bands in its upper part with some iron stains in the lower sections. The formation is capped by dark red sandstones and pebbly grits passing in places into flaggy or oolitic ironstone. Adegoke*et al*. (1978), based on palynomorphs, dated the formation as Paleocene. The continental clastics of the Kerri-Kerri Formation reaches a thickness of over 320m (Zarboski, *et al*., 1997). Ola-Buraimo (2005) established an unconformity relation between Kerri Kerri Formation and Gombe Formation while Dike and Egbuniwe (1994) recognized a nonconformity between the Kerri-Kerri Formation and the Basement Complex along its western margin.

Different workers have identified different origins for the sediments of Kerri Kerri Formation. According to Carter *et al*., (1963) and Wright (1976) the Kerri Kerri deposits were derived from older sedimentary beds at the end of Maastrichtian folding, uplift and erosion. Burke (1972) attributed their origin to materials derived from the Neogene uplift of Jos Plateau.

Kerri-Kerri Basin according to Benkhelil (1989) was controlled by a set of NNE-SSW trending faults occurring along its western margin which separates it from the Basement Complex of the Jos Plateau. Kerri-Kerri basin is bounded in its western and eastern margin by two parallel faults trending N15ºE. The fault in the west passes through Alkaleri (Okafor, 1982).

The terrain of Alkaleri is generally flat. Alkaleri has a typical savannah vegetation characterised by small grasses and shrubs. The area of the deposit and its environs are completely uninhabited. There are two distinct seasons- the rainy season and the dry season. The dry season starts from November and ends in April while the rainy season lasts from May to October with an annual rainfall of about 1000mm.Jalgalwa River which is the main river in the area dries up during the dry season.

Geological Investigation

A target area of about 216,684m^{2}was chosen for a detailed geological investigation. The area was divided into blocks of north and south of Jalgalwa River. The objective of the study was to prove adequate quality reserve sufficient for the economic lifetime of a large scale ceramic plant. A total of 25, 6-inchboreholes werecarefully sited on a 100m^{2}grid.The drilling was undertaken by 4 Banka drill teams supplied by the defunct Nigerian Mining Corporation. Banka drilling is a labour intensive method and which is suited where minimal sophistication and maximum use of unskilled labour are advantages like the case of Alkaleri. This type of drilling has been found suitable for the prospection of shallow alluvial ore-deposits and tailings, bauxite and lateritic iron ore. By working with casings, the most valuable information can be obtained from the bore hole. The detailed drilling was aimed at determining both the extent of the area and thickness of the deposit with a view to calculating the reserve.

A casing was fitted with a casing shoe, placed in a shallow hole in the ground and fitted with a working platform for the four drillers on top of the casing. The entire system was then rotated slowly by another set of four men. In this way, the casing was forced down by a combination of the weight of the platform, and the four drillers, the jerking movement of the drilling tool, and the reduction of friction resulting from the rotation of the casing. A bailer was used to remove the sample from the casing and for obtaining accurate samples that was ensured by not allowing the end of the bailer to go below 20cm above the casing shoe. Each hole was drilled to at least one metre below the base of the Kaolin. The drill cuttings were sampled at an interval of 0.5m and logged in the field. The samples were generally free of contaminations and considered true representatives of the deposit.

The Deposit

A secondary kaolin deposit of considerable economic importance occurs in Alkaleri, a village north of Bauchi in Bauchi State of Nigeria. Alkalerikaolin deposit is a sedimentary deposit formed most probably by the decomposition of some igneous rocks and later deposited in its present position or by an *in situ*kaolinisation of a sedimentary rock.Contacts between the kaolin concentrations and the overlying laterite are sharp suggesting transported rather than *in situ* decomposition. A sedimentary deposit of commercial importance may be produced where conditions are favourable for an adequate amount of the clay to be separated from associated non-clay material, deposited without appreciable "dilution" by other detritus or chemical precipitates and preserved from subsequent alteration or erosion (Bates,1964).

The deposit has well exposed sections along the Jalgalwa River bank. The Kaolin occurs as a continuous massive body overlain by a ferruginous laterite top soil which constitutes the overburden. Generally, the Kaolin occurs as light gray to pale orange, with variable iron oxide staining which results in red colouration in some places.The deposit trends approximately in an east–west direction.

Laboratory Analysis

The samples were bulked to reduce the variability and also reduce the number of laboratory analyses. The bulking encompassed different depths as most variations arise through the increase indepth. Fivebulksamples were sent to the laboratory of the defunct Nigerian MiningCorporation (NMC) for physical and chemicalanalyses.The Atterberg limits(liquid limit, plastic limit, and plasticity index) were also determined.

RESULTS AND DISCUSSIONS

Reserve

The exploration study did not establish the maximum length and width of the deposit as the deposit extends beyond the 216.684m^2 area of investigation. The average overburden thickness is 6.0m while the kaolin average thickness is 14.6m. The reserve contained under the investigated area, with a specific gravity of 2.51, is 8,672,476.8 tonnes (Table 1). The average stripping ratio is 0.41.

Table 1: Proven Reserve of Kaolin in Alkaleri

	Area (m^2)	Average overburden (m)	Kaolin thickness (m)	Specific gravity	Reserve (tonnes)	Comments
Block A	46,920	6.5	13.2		1,610,294.4	Proven
Block B	169,764	5.5	16.0	2.51	7,062,182.4	Proven
Total	216,684				8,672,476.8	Proven

Mine development in the target area will involve the removal of overburden of about 1.3 million cubic metres of soil from an area of about 216,684m^2.

Natural and Fired Colour

The market value of ceramic products depends on colour among other factors such as texture and durability. Sometimes colour may be considered more important than the quality of ceramics. Iron oxides are known to have the greatest effect on colour formation of clays. The fired colour of clay is determined by the oxides, mostly iron oxide. Regardless of its natural colour, clay rich in iron burns red when exposed to an oxidizing fire, due to the formation of ferrous oxide (Khan, 1998). The effect of other oxides depends on their relative proportion to iron oxide. When ferric oxide is low (1-3%) and Al_2O_3 is up to 25%, there is a modifying effect by the alumina. With this combination, the fired colour is faint pink to white at a temperature of 1000^oC (Worrall, 1986). Alkaleri kaolin fits into this combination of iron and alumina and the fired colour agrees with Worrall's observations. The natural colour of the kaolin is light gray which at 1000^oC produced a fired colour of shades of pink (Table 2). Karaman*et al*., (2006) established a relationship between the fired brightness colour component and the compressive strength of clay products. Dark and pinkcolours are generally stronger than light fired colour.

Table 2: Natural and Fired Colour of AlkaleriKaoloin

Sample No.	Natural Colour	Fired Colour at 1000^oC
Alk1	Very light gray N8	Pale pink 5RP 8/2
Alk2	Very light gray	White N9
Alk3	Very pale orange (10YR 8/2)	Grayish orange pink (10R 8/2)
Alk4	Very light gray N8	Pale pink 5RP 8/2
Alk5	Moderate orange pink (10R 7/4)	Moderate orange pink (10R 7/4)

The natural and fired colours are in conformity with the rock colours chart of Geological Society of America.

Chemical Composition

The results of the chemical test of Alkalerikaolin are shown in Table 3

Table 3: Chemical Composition of Alkaleri Kaolin

SampleNo.	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	M_gO	Na_2O	K_2O	LOI*	Carbonate Test
Alk1	51.6	31.91	1.88	1.01	1.26	0.45	0.02	0.2	11.2	No observable results
Alk2	48.4	30.29	3.97	1.74	1.05	0.61	0.04	0.13	13.3	
Alk3	39.6	35.51	6.26	1.73	1.05	0.3	0.16	0.17	13.8	
Alk4	44.6	37.5	1.72	1.4	0.77	0.4	0.07	0.02	13.3	
Alk5	55.4	27.56	1.33	1.67	0.91	0.5	0.02	0.04	10.7	
Mean	47.92	32.55	3.03	1.51	1.01	0.45	0.06	0.11	12.46	
STDV	6.12	3.99	2.08	0.31	0.18	0.12	0.06	0.08	1.40	

*Loss on Ignition

Different authors have reported varying SiO_2 content for clays used in the various products in the ceramic industry. Chester,(1973) reviewed the SiO_2 content of clays from five different ceramic industry and gave a range of value of 47-48%. Abubakar*et al*., (2014) recommended clays from Dabagi clay deposit in Kebbi State, Nigeria with an average $SiO_2$of 64.50% for ceramic works. The mean value obtained from the analysis of five samples of Alkaleri kaolin is 47.99±6.12% which is within the reported range of values of ceramic clays.The alumina content (32.55±3.99%) of Alkaleri clay falls within the range of 25-44% recommended for ceramic by Chester, (1973).

A low iron content (<0.9%) is necessary in order to achieve fired brightness in excess of 83% at temperatures of 1000^oC and above (Highley, 1984).The iron oxide content of 3.03±2.08 may inhibit the kaolin from attaining brightness on firing. High level of iron oxide usually imparts reddish colour to clay when fired, and this is capable of making the final product attractive to some users. Where a red colouration is undesirable some form of beneficiation will be required to reduce the effect of high iron content in the final ceramic product.

Firing behaviour is mainly affected by the "fluxing oxides" (i.e. Fe_2O_3+MgO+CaO+Na_2O+K_2O). The fluxing oxides content in the kaolin is4.606. This is against the average value of 15 for some clays. The low flux valuegives the clay a refractory behaviourwhich is an advantage in ceramic products. High concentration of fluxing oxides impacts dark colour after firing. While some people want bright colour ceramics, others interprete dark colour as mark of durability.

Loss on Ignition

Loss on ignition (LOI) is a commonly used method to determine the organic matter content of clay by oxidation at an elevated temperature in a muffle furnace by measuring the weight loss. It is a test designed to measure the amount of moisture or impurities lost when the sample is ignited under the conditions specified in the individual monograph. Organic matter is oxidised at 500-550°C to carbon dioxide and ash. Carbon dioxide is evolved from carbonate at 900-1000°C, leaving oxide (Heiri*et al*., 2001). The weight loss during the reactions is easily measured by weighing the samples before and after heating and is closely correlated to the organic matter and carbonate. The average loss on ignition recorded is 12.46±1.40% and this attested to the inorganic nature of the kaolin thereby making it a good ceramic raw material.Bloodworth *et al*., (1993) put the loss on ignition value of ceramic-grade kaolin as 13.0%, 12.2% and 12.1% for three different samples studied. The value obtained based on the LOI qualifies the Alkaleri kaolin as a ceramic-grade kaolin.

Liquid Limit

Liquid Limit (LL) is the moisture content in percentage at which the clay begins to behave as a liquid material and begins to flow. The liquid limit (83.40±8.50) shown on Table 4is higher than the 49.54% computed from the liquid limit reported byDondi*et al*., (2008) for 20 ceramic kaolin samples. High liquid limit value corresponds to high clay content which is a desirable characteristic of kaolin in ceramic works.

Plastic Limit

Plastic limit is the minimum moisture content, in percent, at which the soil begins to crumble when rolled into a thin thread, approximately 3mm in diameter. The plastic limit of Alkaleri kaolin (36.61±11.02) corresponds to the plastic limit of 36 for Ca-kaolinite according to Worrall, (1986). This class of kaolin is particularly a good raw material for ceramics.

Table 4: The Atterberg Limits and Shrinkage of Alkaleri Kaolin

Sample number	Plasticity			Shrinkage	
	LL	PL (%)	PI	Linear shrinkage at 1000°C	Volume shrinkage at 1000°C
Alk1	97.00	33.38	63.62	2.33	6.83
Alk2	75.00	42.86	92.14	3.49	10.11
Alk3	82.00	52.42	89.58	4.76	13.61
Alk4	78.00	29.31	68.69	3.49	10.11
Alk5	85.00	25.09	59.91	4.60	13.17
Mean	83.40	36.61	74.79	3.73	10.77
STDV	8.50	11.02	15.03	0.99	2.75

LL = Liquid limit. PL= Plastic limit. PI= Plastic index

Plasticity Index

Clays may present a wide range of plasticity values. Plasticity is a fundamental property in the ceramic industry since it defines the necessary shape changes without rupture when a clay body with added water is submitted to an external force. Plasticity index (PI), is a measure of the range of moisture content over which the clay behaves plastically.Typical values of Atterberg's plasticity index for kaolinitic clays range from 5 to 22 (Fernando*et al*., 2010). The more plastic a clay, the more water it will tolerate without becoming fluid. Grimshaw and Searle(1971) recommended plasticity index of 10-30% for ceramic clays. The plasticity index of 60-68% obtained for Alkaleri kaolin surpasses Grimshaw recommendation and presents the kaolin as an excellent ceramic clay.
The lowest plasticity indices are generally obtained from hydrothermal kaolindeposits where the clay is both coarse and well crystallized.Secondary kaolin clays, formed by weathering and eventually carried intosedimentary deposits, are generally finer grained and less well crystallized, bothfeatures producing higher plasticity indices (Bain, 1971). The high plasticity index value of Alkaleri Kaolin is an evidence of it secondary origin.

Classification of Alkaleri Kaolin

Alkaleri kaolin was further classified based on Casagrande plastic index-liquid limit chart for interpreting the Atterberg limit results as reported by Bain (1971). An empirical boundary, "A" line, with a slope expressed by the equation

$$PI = 0.73(LL - 20)$$

separates the inorganic clays from inorganic silts. Alkaleri kaolin mostly tends to plot in the region of inorganic clay with high compressibility as opposed to the inorganic silt. (Figure 1).This further shows the studied deposit as a pure kaolin.

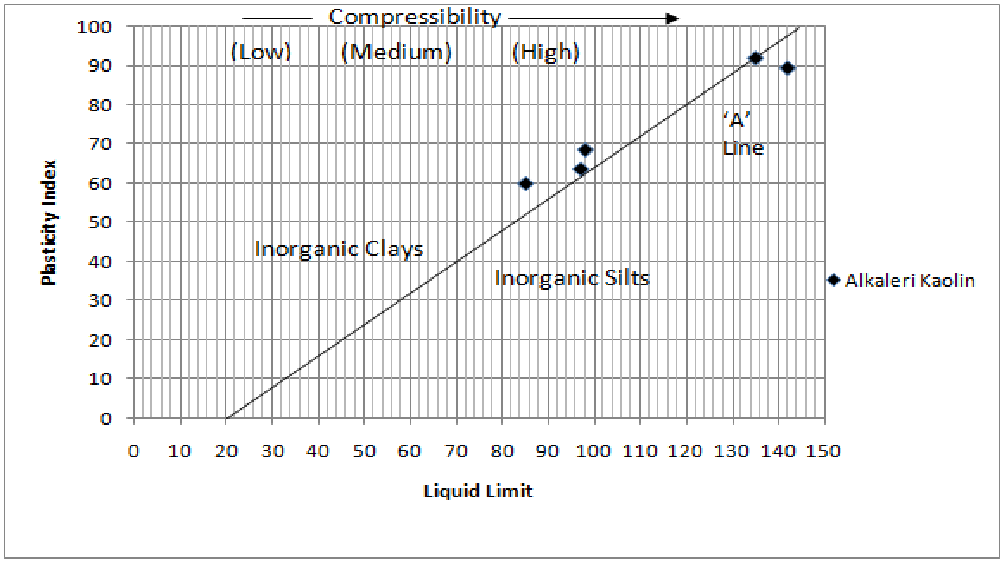

Figure 1: Casagrande Plastic Index-Liquid Limit Classification of Alkaleri Kaolin

Some kaolinites are non-plastic while the majority of kaolinites are plastic. Alkaleri kaolin plots on the plastic kaolin cluster of Bain (1971) as shown in Figure 2. This confirms the results of the Atterberg Limits.

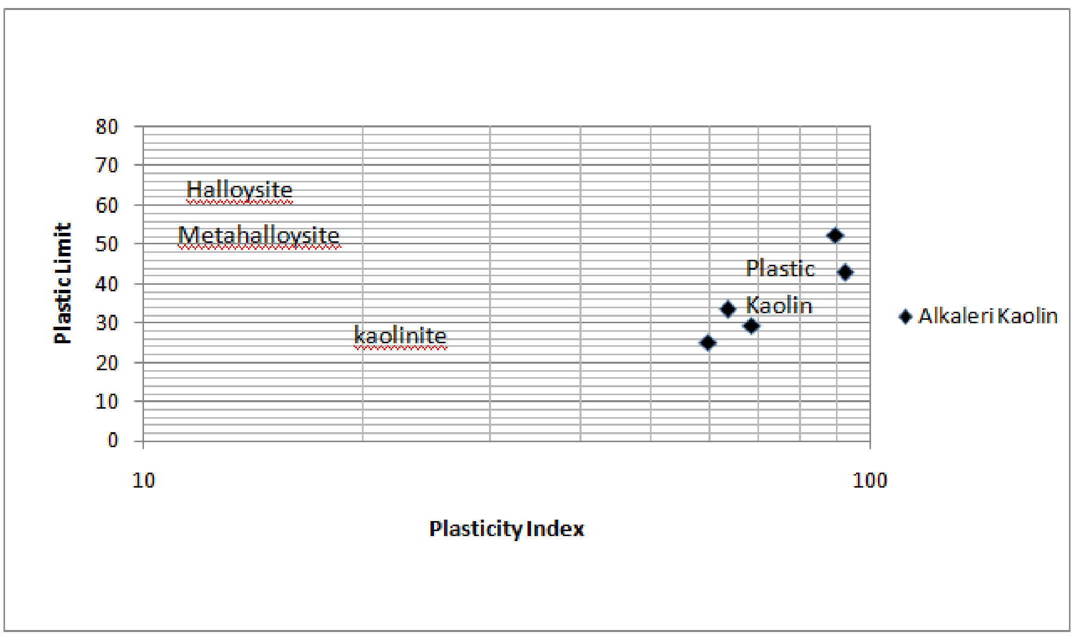

Figure 2: Plastic Limit-Plastic Index Classification of Alkaleri Kaolin.

Fired Shrinkage Limit

Shrinkage is a property of clay which makes it undergo structural changes and disintegration while being heated.High shrinkage values may result in warpping and cracking in the finished products. The usually firing temperature range of commercial ceramic products is 1050°C-1100°C. The samples were fired to 1000°C. The average linear and volume shrinkage for the five samples tested were 3.73±0.99 and 10.77±2.75 respectively. Chester (1973), recommended linear shrinkage range of 7-10% for refractory clays. Alkaleri kaolin has a low linear shrinkage and consequently a low volume shrinkage. Low shrinkage is beneficial in ceramic industry as it implies less cracking. Low linear shrinkage limits of less than 7% are obtained for kaolins of low feldspar or high quartz content. According to Correia (2004), kaolins which exhibit linear shrinkage limit as low as 3% are composed of as much as 65% quartz. The average quartz content of Alkaleri kaolin is however only 47.92±6.12%

CONCLUSIONS

This study has established the origin of Alkaleri kaolin as a sedimentary deposit formed by the decomposition of some igneous rocks and later deposited in its present position.The studied kaolin plots on the Casagrande plastic index-liquid limit chart as an inorganic clay and on the plastic limit-plasticity chart as a plastic kaolin. The average linear and volume shrinkage, silica and alumina content, loss on ignition and plastic limit of the kaolin fall within the values of ceramic-grade kaolin. Adequate quality reserve sufficient for the economic lifetime of a large scale ceramic plant has been proven and this deposit can contribute to the growth of Nigeria's ceramic industry.

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