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FIELD CHARACTERISTICS AND OTHER PROPERTIES OF A FIRECLAY

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ABSTRACT

Fireclay from Enugu coalfield in Nigeria was studied for its in-situ characteristics and properties relevant to its use as refractory raw material and other applications. The clay has silica content which is higher, and alumina content which is lower than the usual ranges for fireclays. The low contents of iron oxide and alkali are characteristic of high quality fireclay. The desirable low dimensional change quality is due to the low plasticity of the fireclay which manifests too, in low air-drying and firing shrinkages. At elevated temperature up to 900^{o}C the colour changes from pale grey to white. Other qualities which make the fireclay attractive refractive raw material are the abundance and comparative cheapness. The low in-place moisture content in relation to the liquid and the plastic limits, and the shape of the void ratio-log pressure consolidation curve, all suggest apparent preconsolidation of the in-situ fireclay.

KEYWORDS: Fireclay, refractory material, plasticity, shrinkage, moisture content, overburden.

1.0 INTRODUCTION

Fireclays differ from other clays significantly. They are highly rich in silica, are not fissile and so are more or less mudstone in unweathered state. Fireclays are associated with Coal Measures sequence where they usually underlie coal seams. Coal Measure sequences worldwide consists of repeating unit of rocks called cyclotherm. In the cyclotherm can be seen a sequence of events where a return to the same environment for varying periods of time is recorded. Between these periods, changes in sedimentation occurred, sometimes in a predictable manner. The fire attribution is given for the refractory characteristics of fireclays. The clay minerals are mainly kaolinite. These are extremely of small particle size and relatively poorly crystallized (Grim, 1962**)**. Also, the grains are mostly interlocking-a textural feature observed, too, in volcanic breccias and other very fine- grained extrusive igneous rocks. Unlike conventional brick- making clays, fireclays are usually mined at depth, usually as seatearth. As fossil soil they are particularly useful marker beds.

2.0 METHODOLOGY

Samples of the fireclay, 42 mm in diameter and with length-to-diameter ratio (aspect ratio) of 2.0 and more, were taken from the indurated mudstone blocks. Properties investigated in the laboratory and the test procedures (in parentheses) adopted include specific gravity (ASTM D854), loss on ignition, grain size analysis (ASTM D422), liquid limit (BS 1377, Test 2, 1975), plastic limit (BS 1377; Test 3, 1975), linear shrinkage, compaction (ASTM D698), one-dimensional consolidation (BS 1377, Test 17, 1975), direct shear (ASMT D3080) and chemical analysis, all on the soft fireclay. Tests carried out on the indurated fireclay are ultrasonic pulse velocity test (ISRM, 1978), moisture absorption and uniaxial compressive strength (ISRM, 1979). Test values reported are averages of three to four tests for each determination.

2.1 Ultrasonic Pulse Velocity

The test was determined using PUNDIT-abbreviation for portable ultrasonic non-destructive digital indicating tester- in which the time of passage between two ends of a prepared test piece is recorded between two transducers,

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one a transmitter and the other a receiver.

3.0 TEST RESULTS AND ANALYSIS

The physical properties of the fireclay are given in Table 3.1, while the chemical composition is shown in Table 3.2. The composition of the fireclay is related to the ranges in chemical composition of high alumina fireclay bricks in Table 3.3. Other laboratory test data are presented in Figs 3.1- 3.5. That the fireclay is of low plasticity is borne out by the liquid limit, plastic limit and linear shrinkage values of 34, 19 and 9.2 %, respectively. The fireclay plots above the A-line of the plasticity chart. The maximum dry density and optimum moisture content of the soil compacted to standard proctor level are 1.83Mg/m^3 and 12.3%, respectively. The compaction curve of the fireclay falls between those of low plasticity inorganic silt (ML), and well graded sand (SW). For sandy materials like the fireclay, the 7.4 % loss on ignition on heating between 100-700^{o}C roughly approximates the organic content, particularly of carbonaceous matter and rootlets.

Table 3.1 Properties of the fireclay

Property	Mean Value
Natural water content, %	12
Moisture absorption, %	6.8
Minus No. 200 sieve size, %	87
Loss on ignition, %	10.6
Specific gravity	2.66
Loss on ignition, %	7.4
Liquid limit, %	35
Plastic limit, %	19
Plasticity index, %	16
Drying shrinkage, %	4.8
Fired shrinkage, %	16.2
Maximum dry density, Mg/m^3	1.83
Optimum moisture content, %	12.3
Shear strength, kN/m^2	180
Angle of internal friction, degree	29.6
Ultrasonic pulse velocity, km/s	2.1
Uniaxial compressive strength, MPa	22

3.1 Particle Size Distribution

The size gradation curve of Fig. 3.1 shows that the fireclay consists of about 70 % silt, 20 % sand, and 10 % clay, and so is a clayey, sandy silt material. The grains are mainly sub angular in shape. The uniformity coefficient of about 10 indicates a well graded soil, but one in which the gravel fraction is lacking. The size distribution is responsible for the high dry density 1.83 Mg/m^3 of the compacted fireclay. The grain size and size distribution also influence the permeability. The continuous grading in which finer particles are disposed in voids between coarser grains favour high permeability. Fine particle size and non-uniform grading are indication of low flowability and refractoriness for a given chemical composition (Beeley, 2001; AFS, 1987**).** The angular and sub-angular grains of the fireclay give rise to poor compaction in a ramming operation due to their poor flowability.

3.2 Moisture Content and Compaction Characteristics

The fireclay has natural moisture content, W_n of 12 % which is lower than the liquid (LL). This is an indication of preconsolidated soil deposit (Sowers & Sowers, 1976). The liquidity index, I_l of the fireclay, given as:

$$I_l = \frac{W_{n-Pl}}{LL-PL} \quad \text{………………..………} (3.1)$$

is negative. This index numerically expresses the softness of clays above the water table.

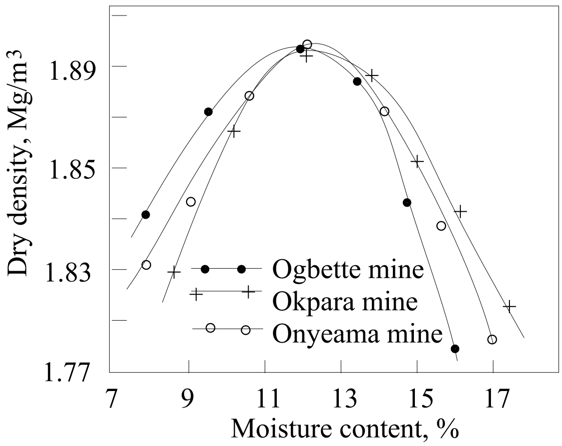

Figure 3.2 Compaction curves of the fireclays

Residual lateritic clays over granite in the Auchi – Afowa area of Edo State, Nigeria have earlier been shown to have negative liquidity index (Ilugbekha, 1989). The dry density-moisture content curve of Fig. 3.2 is typical of clays and shows a maximum dry density of 1.83 Mg/m^3 at optimum moisture content of 12.3%.

3.3 Colour and Dimensional Change Characteristics

The colour of the fireclay was monitored through the entire temperature range of industrial firing operation. Up to 250 ^oC the colour was grey, turning to white at about 900 ^oC. The shrinkage on drying the specimens at room temperature for 14 days was 6.7 %. Some very shallow surface cracks were observed in some specimens. The shrinkage on firing in electric furnace to a temperature of 1100^o C was 16.2 %. Surface cracks on the specimens became more conspicuous and penetrative.

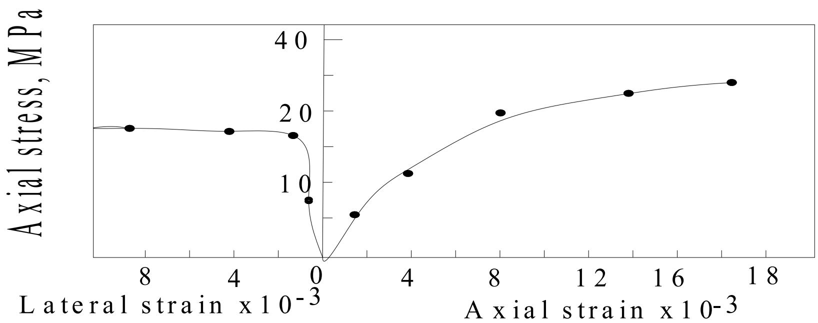

Figure 3.3 Stress strain curves of the fireclay

3.4 Chemical Composition

The oxide percentages of the fireclay are shown in Table 3.2. The alumina and silica contents are high while the contents of lime and the alkalis are low. Table 3.3 lists the ranges in composition of high grade alumina brick in relation to the oxide contents of the fireclay.

3.5 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity of the

indurated fireclay is 2.1 km/s - a value within the range 1.0 - 2.7 km/s for clays (Carmichael, 1990).

3.6 Strength Characteristics

The shear strength test on the soil showed that the fireclay compacted to standard proctor energy level derived its shear strength from both the angle of internal friction and cohesion. The cohesion is 180 kN/m^2, while the angle of internal friction is 29.6^o. The uniaxial compressive strength determined on a 50 mm cylindrical specimens having ratio of 2.0 and more (Fig 3.3) yielded Poisson's ratio of 0.32 and uniaxial compressive strength of 22 MPa. The Poisson's ratio is well within the range of 0-0.5 for most engineering materials (Spangler & Handy, 1982), while the uniaxial strength of 22 MPa compares fairly well with the value 34 MPa for good masonry bricks (Kicklighter, 1997). The secant modulus is 2.08 GPa. The potential for predicting the uniaxial compressive strength of the fireclay using pulse velocity is shown in Fig.3.5. The coefficient of correlation of 0.89 indicates that the uniaxial strength can fairly be predicted from the pulse velocity which is much easier to determine.

Table 3.2. Chemical composition of the fireclay in relation to those of related materials

	Content, %						
Oxide	Fireclay	Abakaliki volcanics (Olade, 1979)	Amaoffia volcanic (Kogbe, 1989)	Gombe volcanics (Kogbe, 1989)	Thorncliffe fireclay (Greensmith, 1978)	Statinnington fireclay (Greensmith, 1978)	Barsham fireclay (Greensmith, 1978)
SiO_2	66	47	44	45	59	45	73
Al_2O_3	21	16	13	16	23	13	15
Fe_2O_3	1.3	3.2	4.6	3.7	2.7	2.3	0.5
MgO	0.18	7.00	7.32	7.00	1.80	0.84	0.73
CaO	0.03	10.0	7.90	9.83	0.26	0.25	0.28
TiO_2	2.3	2.3	2.4	2.3	2.3	0.96	0.98
Na_2O	0.23	3.20	2.90	4.39	0.71	0.03	0.25
K_2O	1.04	1.04	5.81	1.84	2. 87	1.50	2.04

3.7 Consolidation Properties

The void ratio – log P curve of Fig.3.4 is characteristic of preconsolidated soil. The overall void ratio decrease in the void ratio over the applied pressure range of the test is 0.24.

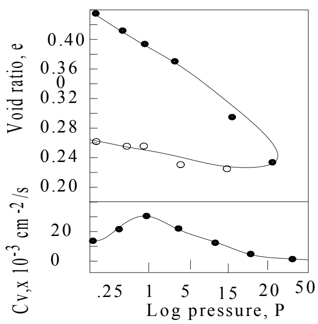

Figure 3.4 Void ratio-, Cv-Log P curves of the indurated fireclay

The compression index represented by the slope of the void ratio-log P curve, and designated C_c is given as:

$$C_c = \frac{\Delta\varepsilon}{\log_{10}\frac{P_2}{P_1}} \quad \ldots \quad \ldots\ldots\ldots\ldots\ldots \quad (3.2)$$

where Δε is the change in void ratio corresponding to pressure increase from P_1 to P_2. The index value for the fireclay is 0.255.

4.0 DISCUSSIONS

The chemical composition of the fireclay fall well within the usually wide percentage limits for fireclays: silica 40-60%, alumina 10 – 40%, iron oxide 1-5%, alkalis < 3%, lime and magnesia < 5 %, and loss on ignition 5-14% (Minerals zone, 2010). Though the chemical analysis of the fireclay gives an indication of its potential as a refractory raw material, the criteria are tests under practical working conditions. Generally, however, higher grade fireclays do not contain more than 3% alkalis, or over 2% iron oxide (Lefond, 1975). Titania and alkalis have appreciable effect on the refractive and the amount of shrinkage of the clay on drying and firing.

As can be seen from Table 3.3, fireclay differs from superduty alumina fireclay brick only in its proportions of silica and alumina. The refractoriness of the fireclay can be improved to that of superduty brick by adding bauxite, as is the common practice in industries. Together, the high content of silica and alumina and the low contents of alkalis, lime and magnesia make the fireclay good-quality refractory raw material.

Table 3.3: Range in composition of high alumina fired bricks and that of the fireclay

Composition	Range in value, %	Fireclay, %
Silica, S_iO_2	45 – 56	66
Alumina, Al_2O_3	39 – 48	21
Iron Oxide	< 2	1.3
Titania, TiO_2	about 2	2.3
Lime, CaO	< 0.5	0.03
Magnesia, MgO	< 0.5	0.18
Potash Soda, (K_2O, Na_2O)	<1.5	1.27

An interesting aspect of the fireclay is the conspicuous absence of staining by the iron oxide, hematite - a common feature of most tropical soils. This can be attributed to in-situ derivation in a rather dry environment devoid of much running water. The in-situ derivation is supported also by the sub-angularity of silica particles which in this regard have not undergone substantial transportation. The gritty feel of the clay is due, to the angularity of the grains.

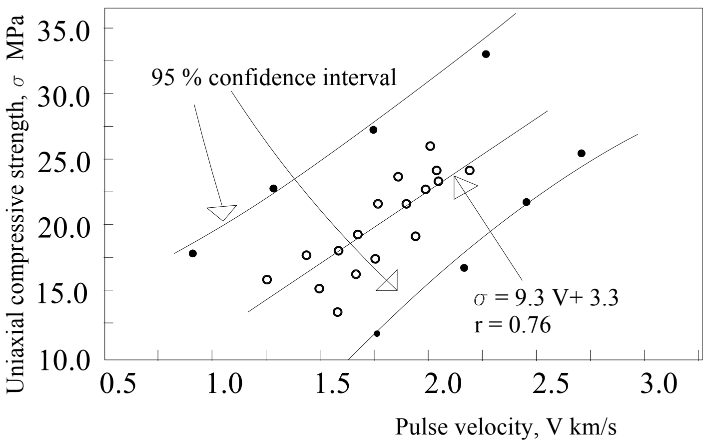

Figure 3.5 Dependence of the unconfined compressive strength, σ on the ultrasonic pulse velocity, V of the fireclay

The low dimensional change characteristics of the low plasticity fireclay obvious in the low dry and fired shrinkages are desirable qualities as such clays yield refractory wares devoid of shrinkage and show good resistance to corrosion and abrasion by furnace charges under operating conditions. However, low drying shrinkage of clay raw material results in a weak, porous body. Product requirements including resistance to shrinkage, cracking, and abrasion are also vital in many products and expressions of requirements for these properties are given in many specifications. Rigid specifications on dimensions also are required of many end-products. Restrictions on raw clay commonly include cutoffs on plasticity, impurities and contents of alkalis, alkaline earths, and other constituents that reduce fusion points.

The moisture absorption of the indurated fireclay, 6.8 % is quite lower than the 10 % absorption limit specified as good for sandstone used as building material (Ghose, 1999).

Based on wave velocity, clay deposits are classified as rippable for velocity < 2.2 km/s; marginally rippable for velocity in the range 2.2 – 2.8 km/s, and non-rippable for velocity > 2.8 km/s (Caterpillar, 1983). The laboratory determined pulse velocity of the fireclay is very likely to be higher than the velocity of the fireclay mass in-situ and so the clay mass rates as rippable.

The angle of internal friction 29.6^{o} of the fireclay is on the high side of the upper limit of the range 15 – 24^{o} for clays (Franklin & Dusseault, 1989). Strain softening suggested in the stress strain curves of the fireclay is characteristic of other soft rocks like shale, limestone and tuffs. The modulus computed for the fireclay, therefore, is the secant modulus. Preconsolidation of the fireclay is supported by the natural moisture content being less than the liquid and the plastic limits. Residual lateritic soils usually exhibit this characteristic though they had not been subjected in the past to stresses in excess of the current overburden (Gidigasu, 1976). Probable causes of preconsolidation in this case include capillary tension due to desiccation and chemical alterations resulting from changes in physicochemical bonds and from expansion or contraction of grains during the alteration process. Many weathered rocks and partially indurated rocks also exhibit preconsolidation arising from the later cause (Sowers & Sowers, 1976). Heavily preconsolidated soils have their in-situ moisture content much less than the plastic limits, particularly if desiccation has been recorded in soils of arid and warm regions (Sowers & Sowers, 1976; Spangler & Handy. 1982). The in-situ moisture content of the fireclay (12 %) is much less than the plasticity index (19 %), also suggesting heavy preconsolidation, but one due to desiccation and chemical alteration.

The compression index for preconsolidated clay above the preconsolidation pressure is also found from the some relations used for normally consolidated clays, such as that between
it and the liquid limit, LL as:

$$C_{c} = 0.007(LL - 10) \quad \text{.............................} (4.1)$$

The compression index computed for the fireclay using this relation is 0.175 which is much lower than that obtained directly from the curve. The relationship is only approximate and such difference in the determined and computed index values are normal. The significance of the compression index is in estimating settlement of the deposit under applied pressure;

In-situ, the fireclay horizons stand out in relief relative to the sandwiching layers in the stratigraphic column in the coalfield. This is probably because it is more indurated and more resistant to weathering. Rhythmically changing rock types in the repeating unit (cyclotherm) mean rhythmically changing properties. In foundation engineering, rocks exhibiting rhythmically changing properties can pose foundation problem arising from interbedding of the hard cemented fireclay and soft layers. The net effect may be more troublesome than either alone. The flexural rigidity and strength to resist bearing forces in the hard clay may complicate such operations as driving of piles or drilling of piers (NCE-I, (2002).

5.0 CONCLUSIONS

The under-utilized fireclay studied has attractive qualities as refractory raw material. These coupled with the abundance and the comparative cheapness make fireclay bricks made from such clays the most common and extensively used in all places of heat generation like boiler furnaces, glass melting furnaces, chimney linings, pottery kilns, blast furnaces, and reheating furnace. The refractoriness and other qualities of the clay as refractory raw material can be improved by addition of bauxite- a common practice in industries. The rhythmically changing properties of the coalfield cyclotherm can pose some foundation problems arising from interbedding of soft and hard layers.

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