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Investigating the Mineralogy and Geotechnical Properties of Gaborone Dam Soil for Brick Production

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***Abstract*—The benefits of clay as building materials range from its simplicity and low cost, good thermal and acoustic properties, and reusability or safe disposal at the end of building's service life. Gaborone Dam clay has been utilized for production of bricks for building, albeit, in a crude manner. In order to better enhance the quality and performance of the brick products, a series of experimental studies were performed to characterize the soil materials based on the mineralogy and chemical composition, as well as the physical and geotechnical properties. The chemical and mineralogical compositions of the soil samples were determined by X-ray fluorescence (XRF) and X-ray diffraction (XRD) methods respectively. The mineralogical analysis showed that the soil is predominantly quartz, while the combined composition of silica and alumina account for over three-quarters of the entire soil mass. Silt/clay content of the soil is 72%, 28% sand and no gravel. The soil can be classified as inorganic lean sandy clay of group A-2-6. The maximum dry density and the optimum moisture content were 1868 kg/m^3 and 15%, respectively. From the triaxial test results, the cohesion and the angle of internal friction of the soil is 157 kPa and 11° respectively. The average modulus of elasticity of the soil was 38.9 MPa. The soil is basically unweathered over-consolidated clay and is suitable for brick and pottery production.**

Keywords— Atterberg limits, mineralogy, shear strength, Chemical composition, geotechnical properties, compaction

I. INTRODUCTION

Central to the United Nations' Sustainable Development Goals is the provision of housing, which is predicated on reduction of production costs, utilization of locally available resources, and minimization of environmental impacts. With the increasing demands for low cost, sustainable and environmental-friendly buildings, clay soil had been wholly utilized to build houses directly with or without the use of hydraulic cement or blended cementitious materials. Clay has the property of forming a coherent plastic mass when mixed with water, readily mouldable to any desired shape in plastic state and taking the shape and form when dry. The benefits of this type of buildings include its simplicity and low cost, good thermal and acoustic properties, and reusability of the material at the end of the service life of buildings or safe disposal of crushed materials for earth filling without any adverse interference with the environment [1-3].

Clay bricks are one of the oldest natural materials utilized for building and construction purposes [4]. Vast amount of existing traditional buildings and cultural heritage infrastructure with enduring properties were made of clayey materials. However, the quality of the finished products and aesthetics still call for concern [5].However, due to strength reliability, weather resistance, simplicity and durability, bricks have been extensively used and given a leading place in history. Nowadays, different fancy bricks are produced from fired or unfired clays to construct more beautiful, modern buildings.

Botswana is a developing country of population of two million people. The 52-year post-independence experience has seen the country transformed into one of the fastest growing economies in the world. Despite having one of the fastest growth rates in per capita income, a number of the people still live in abject poverty even in Gaborone, the nation's capital city, where around 10 percent of the population lives. Gaborone dam clay has been utilized essentially by the local artisans to produce fired clay bricks for building purposes, however without any scientific knowledge. Currently, there is no evidence of scientific background or engineering content from the soil description and classification, geotechnical properties, mix proportioning of materials and firing/finishing procedure of moulded bricks. The artisans working on the site have consistently depended on the unsubstantiated rule of thumb for the brick-making venture. The clayey soil is often blended with foal ash from breweries and mixed with water to ensure that the brick mixture stays intact to avoid cracking when drying. It is evident that this group of artisans belongs to the very low-income class in the society whose livelihoods depends on the sales made from the burnt Gaborone Dam clayey bricks.

Large mass of clayey deposits near Gaborone dam has, for decades, been mined and used for pottery and building bricks production. The deposits, like most clayey materials, are pretty complex, most certainly consisting of several minerals. Classification of such soil depends heavily on the chemical analysis and subdivision according to the composition which ensures the determination of elements making up the soil and their distribution ratios [6]. The physical, chemical and strength properties of the brick products are essentially a function of the properties of the minerals present in the soil and the admixture. Rapid urbanization of Gaborone and its environs has created high demand for locally produced, environmentally friendly and affordable construction materials. Thus, the objective of the study was to determine the physical, chemical, mineralogical and the geotechnical properties of Gaborone Dam clay soil with the overall aim of determining its suitability for clay bricks production.

II. Description of the Study Area

Gaborone Dam is located south of Gaborone and at the geographical co-ordinates of 24° 43′ 5.87″ S, 25° 54′ 26.92″ E [7]. Gaborone has a hot semi-arid climate with very hot sunny summer days and cool nights. Gaborone Dam was first built in 1963 to supply water to the urban centre of Gaborone when demand for water exceeded the supply from the older Notwane Dam. The dam is the biggest in Botswana, able to hold 141,400,000 cubic metres of water. The dam is used to provide water for both Gaborone and Lobatse, but with the effects of climate change coupled with sparse and unpredictable precipitation, the water level of the reservoir has dropped drastically. Soils in the vicinity of the dam generally consist of sandy loams, clays and sandy clay loam types. Good fertile soils are found in depressions and flood plains [8]. The area around the dam is underlain with the Gaborone granite and the dominant soil types are sandy loam and clays soils which are conducive for vegetation.

III. Experimental Programme

Soil samples were sourced from Gaborone Dam Clay site and collected in several polythene bags for physical, mineralogical chemical, and geotechnical analyses. The chemical composition of the soil sample was determined by X-ray fluorescence (XRF) using dispersive energy spectrophotometer. The mineral composition to characterize the major crystalline phases of the clay sample was analyzed by random X-ray diffraction (XRD) procedure in line with ASTM C204. The specific gravity of the samples was determined by pycnometer and the grain size distribution was determined by a laser-beam particle size analyzer Malvern Mastersizer 2000.

Atterberg limits and particle size distribution tests were also conducted on the soil. Atterberg limits are the basic parameters in the characterization of soils and were used to determine the liquid and plastic limits and the plasticity index of the two raw materials on the basis of their water content in accordance with BS EN 1377-2 [9]. The liquid limit (LL) was the water content at which the soil sample changed from plastic to liquid behaviour. The plastic limit (LP) was measured as the lowest water content at which 3 mm diameter cylindrical threads could be moulded without crumbling. The plasticity index (PI) was determined as the difference between LL and LP and represents the range of water content in which the soil has a plastic consistency. Other geotechnical properties such as compaction test and triaxial shear test were performed in accordance with BS EN 1377-7 [10]. The geotechnical properties were tested in triplicate and the average values of the results were reported for further analyses. Proctor compaction test method was used to determine the maximum dry density and the corresponding optimum water content of the soil.

IV. Experimental Results and Discussion

A. Chemical Composition and Mineralogical Properties

The XRD pattern of the soil shown in Fig. 1 indicated the presence of quartz (SiO_2) in highest proportion along with some quantities of feldspar (in general), calcite ($CaCO_3$), illite, hematite (Fe_2O_3), and alumina (Al_2O_3). The chemical constituents of clay as obtained from XRF analysis is summarized in Table 1.

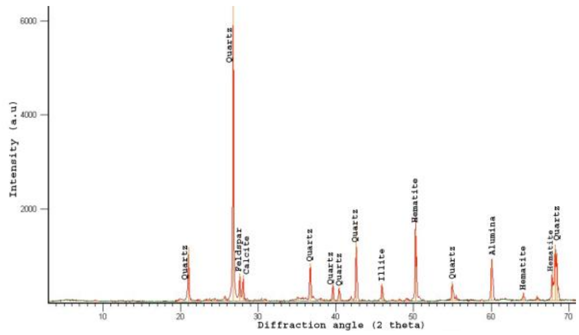

Fig. 1. XRD pattern of clay samples

TABLE 1: CHEMICAL COMPOSITION OF SOIL SAMPLES

Constituents	% by weight of dry sample (average of three samples)
SiO_2	61.48
Al_2O_3	14.95
Fe_2O_3	5.23
CaO	4.53
MgO	0.70
K_2O	3.69
Na_2O	1.81
MnO	0.47
TiO_2	1.4
P_2O_5	0.39
LOI	5.35

It is evident from these results that silica and alumina jointly account for 76.43% of the constituents of the clay samples which qualified the clay as pozzolanic. Also, Fe_2O_3 content of 5.23% also showed the reactive property of the soil and thus an active mineral for building or masonry bricks. Calcium oxide content in the clay is expected to behave as an inert mineral residue.

B. Physical Properties and Grain Size Distribution

The properties of the Gaborone Dam soil samples as tested in the Geotechnical laboratory are summarized in Table 2. The specific gravity of the clay samples was 2.76 and the Brunauer-Emmett-Teller (BET) specific surface area of soil sample (≤ 75 µm) was 35.72 m^2/g. The specific gravity obtained in this study was slightly lower than the findings of Kazmi et al. [11] and comparable with the results of Ukwatta et al. [12].

TABLE 2: PHYSICAL PROPERTIES OF SOIL SAMPLES

Soil gradation	
Gravel fraction (%)	0
Sand fraction (%)	28
Silt and clay (%)	72
Specific gravity	2.76
Liquid limit (LL) %	28
Plastic limit (LL) %	17
Plasticity index(PI) %	11
Colour	Reddish-brown
Effective grain sizes	
D_{10} (mm)	0.03
D_{30} (mm)	0.12
D_{60} (mm)	0.3
Coefficient of uniformity, C_u	10
Coefficient of curvature, C_c	1.6
Maximum dry density (kg/m^3)	1868
Optimum moisture content (%)	15

C. Particle Size Distribution

Particle size analysis was used to determine the size range and grading of soil particles. This was required to classify the soil appropriately and to determine which of the different size ranges was likely to control the engineering properties of the soil. Particle size distribution was in accordance with the AASHTO method and the soil was classified based on the Unified Soil Classification System (USCS). The particle size distribution of the fine grained soil (≤ 75 µm) is shown in Fig. 2. The soil sample was well-graded and the average particle size was about 5 µm. The average coefficients of uniformity and curvature were 10 and 1.6 respectively.

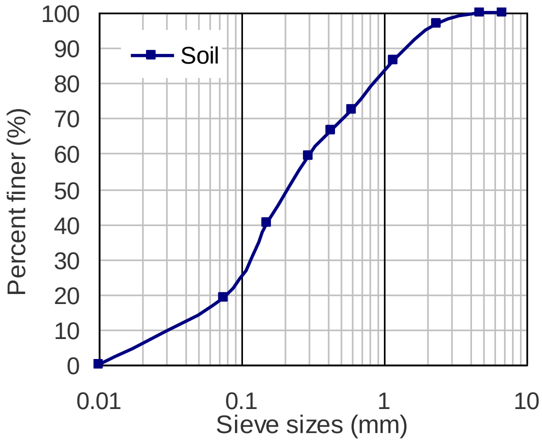

Fig. 2. Particle size distribution of soil sample (≤ 75 µm)

D. Particle Density Determination

Hydrometer analysis of the soil sample was employed to compute the particle size analysis based on sedimentation procedure. The percentage of various fine soil particles were determined by hydrometer analysis. About three quarters of the soil mass comprised clay and silt. Fig. 3 shows the hydrometer analysis of soil samples passing through 75 µm sieve.

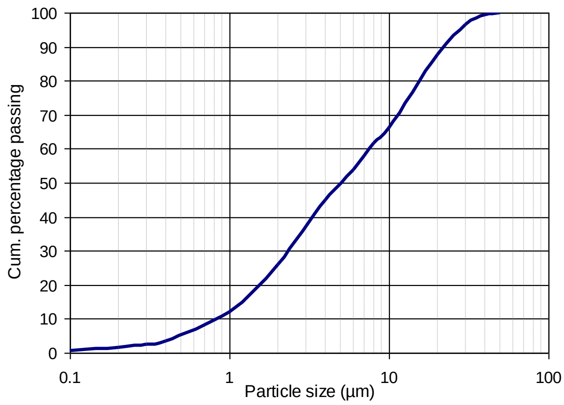

Fig. 3. Particle size distribution of soil (≤ 75 µm)

It is obvious from the hydrometer analysis that the higher the percentage of fine particles the higher the rate of settlement of particle. These results agree with the soils from Northwest Sardinia Alghero district used for traditional brick production [5]. The soil was predominantly composed of sand, silt and clay – lean clay with sand.

E. Atterberg Limits

The soil sample was passed though sieve size 75 µm and the consistency limits - the liquid limit (LL), plastic limit (PL) and the plasticity index (PI) were determined in line with BS 1377 (1990). These tests were the basic measure of the critical water content of a fine grained soil. Liquid limit (LL) is the minimum water content (expressed as a percentage of the weight of the oven-dried soil) at which a part of soil cut by a groove of standard dimension will flow together for a distance of 12 mm at the boundary between the liquid and plastic states of consistency. The LL was determined by a cone penetrometer apparatus. The plasticity of a soil is the ability of the soil to undergo deformation without cracking. The plastic limit (PL) is the moisture content where the thread breaks apart at a diameter of 3 mm. It is the moisture content (expressed as a percentage of the weight of the oven-dry soil) at the boundary between the plastic and semisolid states of consistency.

The Atterberg limit tests gave the following results - 28% liquid limit (LL), 17% plastic limit (PL) and the 11% plasticity index (PI). These results were comparable with the results of Kazmi et al. [11] and Ukwatta et al. [12]; but at variance with the Lower Oxford Clay reported by Oti *et al*. [1]. On the basis of these limits, since the PI is within the range 3 – 15%, it can be inferred that the soil is slightly plastic clay. The PL is roughly below 20 and the LL in the range of 25 and 40. Since the soil sample contains 28% sand, the soil can be described as lean clay with sand or lean sandy clay. Moreover, according to the Unified Soil Classification System (USCS), the soils can be classified as CL-Inorganic clays of low plasticity (LL<50, PL >7 and the plots were above A-line of the plasticity chart). According to the AASHTO classification system, the group of the soil was A-2-6.

F. Compaction Test

Proctor method of compaction test was adopted. Compaction test was used to determine the optimal moisture content at which the soil will become most dense and achieve its maximum density. Maximum density depends on the type of material and the input energy during compaction. Compaction test was carried out in accordance with BS 1377- 4 (1990). The Proctor compaction test gave a maximum dry density of 1868 kg/m^3 and the corresponding optimum water content of 15% as shown in Fig. 4.

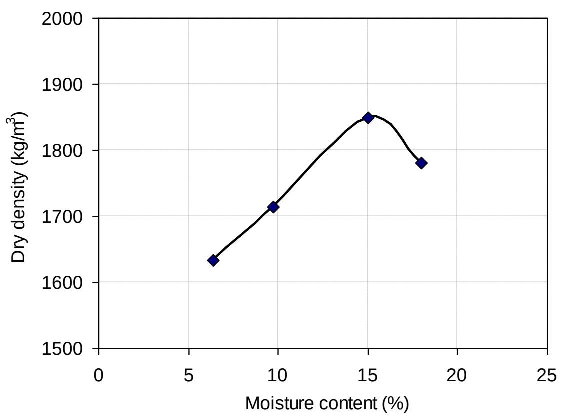

Fig. 4. Dry density vs moisture content curve from the compaction test results

G. Triaxial Compression Test

Triaxial test setup shown in Fig.5 is a common laboratory testing method widely used to obtain shear strength parameters for a variety of soil types under drained or undrained conditions. The triaxial test procedure involved subjecting a cylindrical soil sample to radial stresses (confining pressure) and controlled increment in axial stresses or axial displacements. The cylindrical soil specimen was of the dimension of 100 mm diameter and 200 mm height.

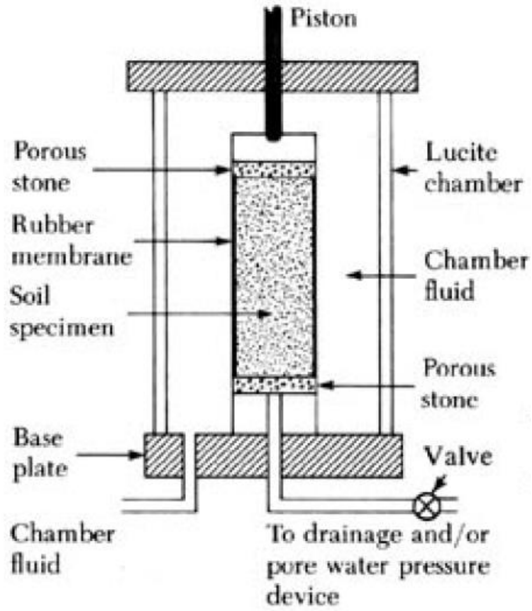

Fig. 5: Schematic setup of triaxial test

A stress-control method was adopted by progressively increasing the loading in order to study the behaviour of the specimen. Three cell pressures - 150, 300 and 450 kPa were in turn applied to the specimens. As shown in Fig. 6, the soil's angle of internal friction, which is the angle between the failure envelope and the horizontal, was 11º. The cohesion of the soil, indicated by the interception of the failure envelope and the ordinate, was 157 kPa (or 157 kN/m^2).

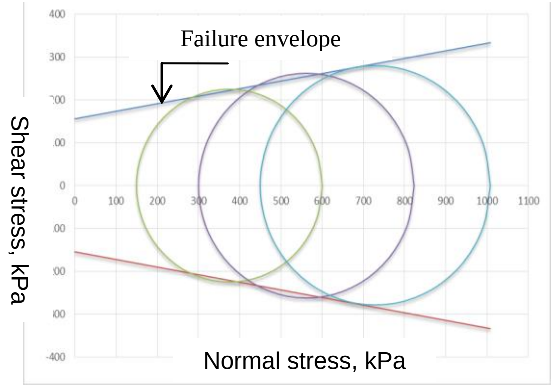

Fig. 6. Mohr circle diagram of soil samples under triaxial pressure

In this shear test procedure, the confining pressure on the specimen was held constant at 150, 300 and 450 kPa, while the deviatoric stress was increased and the response of the soil was plotted in terms of the deviatoric stress against axial strain as shown in Fig. 7. The elastic modulus of the soil sample, given by the slope of the deviatoric stress-axial strain curve, was 38.85 MPa. This value falls within the class of unweathered overconsolidated clays and is suitable for clay bricks production.

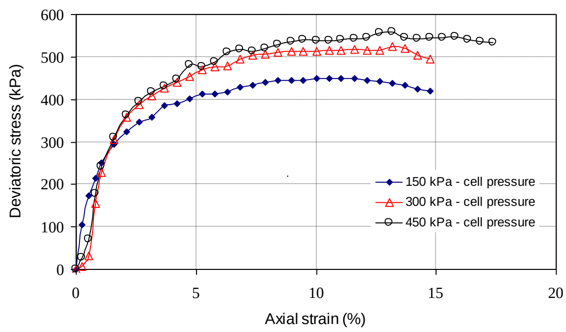

Fig. 7. Deviatoric stress-axial strain relation from triaxial testing of clay samples

V. CONCLUSIONS

This article presents the properties of Gaborone Dam soil to evaluate its suitability for building bricks production. The following conclusions can be drawn from the study.

1. Gaborone Dam soil is predominantly silt and clay (72% finer than 75 μm) with 28% sand.
2. The soil is predominantly quartz (SiO_2) with some quantities of feldspar, calcite ($CaCO_3$), illite, hematite (Fe_2O_3), and alumina (Al_2O_3).
3. Combined composition of silica and alumina account for over three-quarters of the soil.
4. The class of the soil is CL-inorganic clays of low plasticty. It soil is lean clay with sand based on the Unified Soil Classification System (USCS). The soil belongs to group A-2-6 based on the AASHTO classification system.
5. The maximum dry density and the corresponding optimum water content of the soil were 1868 kg/m^3 and 15%, respectively.
6. The cohesion and the angle of internal friction of the soil were 157 kPa and 11º, respectively.
7. The soil is the class of unweathered overconsolidated clay with the modulus of elasticity of 38.85 MPa.

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