Laboratory investigation of black cotton soils sampled from Gaborone-Boatle road site in Botswana

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Abstract*—*This paper presents the physical and laboratory properties of black cotton soils (BCS) sampled from Gaborone-Boatle road site in Botswana. The specific gravity, particle size distribution, the Atterberg limits, compaction and unconfined compression tests were performed on the BCS to verify the need for stabilization to enhance density and load-bearing capacity. The soil was chocolate-black in colour with a specific gravity of 2.52. The maximum dry density of the soil was 1418 kg/m3 at an optimum moisture content of 9.8%. Though the BCS samples contained no gravel, it was 90% clay and silt (with 54% clay content). The Atterberg limits were 67.3% liquid limit, 21.3% plastic limit, 46.0% plasticity index and 4.7% linear shrinkage. The PSD of the soil using hydrometer method gave coefficients of uniformity and curvature of 10.87 and 1.06 respectively. The classification of the BCS based on AASHTO and USCS were A-7-6 and CH respectively. It was found from the study that the soil exhibited relatively high swelling/shrinkage properties and very low strength. It can be therefore be concluded that stabilization with industrial by-product such as fly ash is essential to guarantee sustainable development without continually depleting the natural resources.

Keywords*—*Black cotton soil, Atterberg limits, unconfined compressivestrength, geotechnical properties, physical properties, clay content, compaction.

I. Introduction

Problematic soils are soils which causes geotechnical and structural engineering problems due to their compositions or a change in environmental condition [1]. These soils are tremendously challenging in foundation construction because of their ability to expand, collapse, disperse and excessive settlements [2]. Such characteristics contribute to the composition, nature of the soil and mineralogy of problematic soils. Amongst problematic soils, expansive soils are of greater concern worldwide to civil engineers, construction firms, clients and residents. This is because expansive soils occur in many parts of the world specifically arid and semi-arid regions therefore, they pose significant damaging hazard to engineering structures due to their expansive behaviour [3]. Expansive soils tend to exhibit shrink-swell peculiarity due to variation of moisture content. This volume change is influenced by moisture content, void ratio, vertical stress and the clay contents in the soil [1]. This phenomenon is caused by high active content of clay minerals specifically montmorillonite and bentonite [4].

Black cotton soils are expansive soils which exhibit excessive swelling and shrinkage characteristics under variation of moisture condition and they pose geotechnical and structural problems when engineering construction is built on them [5]. This phenomenon of shrink and swell is posed by the presence of montmorillonite and bentonite in the black cotton soils. High contents of active clay minerals render the black cotton soils to possess undesirable physiognomies which are high plasticity, high compressibility, high swell-shrink potential, low strength and durability. These undesirable characteristics contribute to low material quality and tampers with desirable engineering properties of black cotton soils. Therefore, these soils pose significant structural and geotechnical challenges worldwide in civil/building works.

Black cotton soils (BCS) are abundantly found in arid and semi regions of tropical and temperate climate zones [6]. These soils are potential risk to many civil engineering structures such as roads, railways and airport runway foundation constructed on this type of soil. BCS are greyish to blackish in colour cohesive soil material which exhibit unpredictable soil peculiarities and excessive settlement, high compressibility and plasticity, high shrink- swell properties, less bearing capacity, pH varies within ranges of 7.5 ~ 8.5 and high bulk density in dry condition and low value at swollen stage [7-8]. The mineralogy of this soil is dominated by the presence of montmorillonite which is the primary influence the volumetric changes and high degree of expansiveness [9-10]. The engineering behaviour of these soils depends on their water content, which is characterised by the Atterberg limit tests [11]. Liquid limit, plastic limit and plasticity index are important water contents which are the main index parameter for the classification of fine-grained soils. Shrinkage limit is also an important parameter in which soils tend to shrink when they lose moisture.

Soil stabilization is a procedure wherein the engineering properties of the soil are altered and enhanced to increase its suitability for construction purposes [12]. The process involves blending of weak soils with stabilizing agents or binder materials to improve its geotechnical properties such as compressibility, strength, permeability, load bearing capability and durability [4, 13]. Stabilization can also control the shrink-swell properties of a soil, thus improving the load bearing capacity and stability of the underlying soil to support applied loading [14].

The primary goal of the study is to classify the black cotton soils sourced from Gaborone-Boatle project site in Botswana using laboratory experimentation to justify the need for stabilization with industrial fly ash generated as industrial by-product from Morupule Power Station.

II. Description of the Study Area

Botswana is a mineral dependent country with metals such as base metals (copper and nickel), coal, diamond, salt, sand and gravel, semiprecious gemstones, and soda ash being exploited to a significant extent in the country's mining history [15]. Gaborone has a hot semi-arid climate with very hot sunny summer days and cool nights. Good fertile soils are found in depressions and flood plains [16]. Annual generation of tones of fly ash from the Morupule power station which is the mainstay of power supply for domestic and industrial consumption in Botswana calls for reuse of such for soil improvement without any unchecked depletion of natural resources.

III. Materials and Methods

A. Materials

Soil samples were collected from Gaborone-Boatle road site. Soil sampling, preparation and testing were carried out in line with BS 1377 [17]. Geotechnical tests such as the grain size distribution, hydrometer analysis, Atterberg limit tests, specific gravity, compaction and unconfined compression tests were performed on the soil samples for classification purposes and geotechnical analysis.

Black cotton was obtained along Gaborone-Boatle dual carriageway site as shown in Figure 1a. These soil deposits extended from St. Joseph Senior School junction all the way to Boatle. Samples of BCS samples were sourced from different. Black cotton soils are black in colour (see Fig. 1b) and feel hard in dry state with high width shrinkage cracks. During wet seasons it looks muddy and feels like chocolate pastry with very fine particle.

Figure 1. (a) Gaborone-Boatle Road detour and (b) Black cotton soil sample.

B. Particle Size Distribution

Particle size analysis was used to determine the size range and grading of soil particles in order to classify the soil appropriately and to determine which of the different size ranges was likely to control the engineering properties of the soil. The sedimentation or hydrometer method was used to determine the particle size distribution (or gradation) of BCS samples that were finer than size 75 µm (or passing through sieve No. 200) and the results were presented as the percentage of soil passing (or percentage mass finer) versus the log of the particle size.

Particle size analysis was used to determine the size range and grading of soil particles. This was required to determine the engineering properties and properly classify the soil. Particle size distribution and soil classification were based on the AASHTO and the Unified Soil Classification System (USCS).

C. Particle Density Determination

Specific gravity is the ratio of the mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature. The specific gravity of the soil samples were performed by the water pycnometer method in accordance with BS 1377-2 [17] and ASTM [18]. Particle density determination is essential for computing the particle size analysis from a sedimentation procedure (hydrometer analysis). Fig. 2

shows the particle size distribution curves from sieve analysis and the hydrometer method.

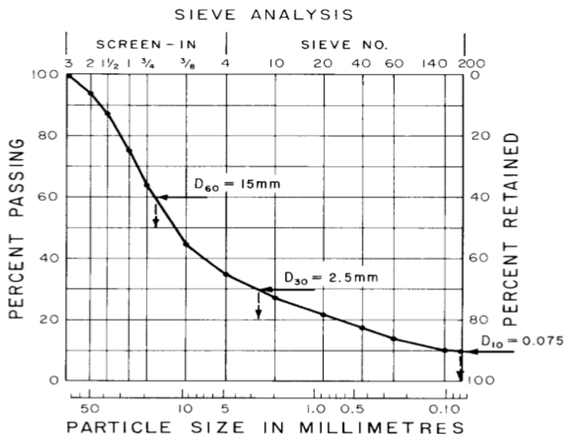

Fig. 2a. Particle size distribution of BCS

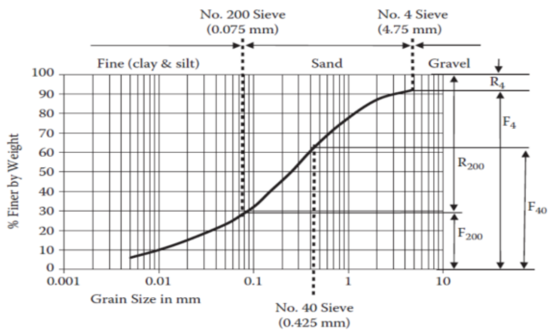

Fig. 2b. Particle size distribution of BCS using hydrometer method

D. Atterberg Limits

The BCS samples were passed though sieve size 0.075 mm and the consistency limit namely, the liquid limit (LL), plastic limit (PL) and the plasticity index (PI) were determined in line with BS 1377 [17]. 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. Liquid limit is the minimum water content at percent on dry bases at which the soil changes its state from liquid to plastic state. The plasticity of the 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.

Shrinkage limit is the maximum water content at which a reduction in water content will not cause a decrease in the volume of a soil mass. It is the lowest water content at which soil can still be completely saturated. If a saturated soil sample is taken (having water content more than the shrinkage limit) and allowed to dry up gradually, its volume will go on reducing till a stage will come after which the reduction in the soil water will not result in further reduction in the total volume of the soil sample. The water content corresponding to that stage is known as the shrinkage limit.

The linear shrinkage (in %) was calculated from the equation:

$$L_s = 100\left(1 - \frac{L_d}{L_o}\right)$$

where

L_s = the percentage linear shrinkage (%)

L_d = the final length of the oven dried specimen (mm)

L_o = the original length of the wet specimen before oven drying (mm)

E. Compaction test

Compaction test based on Proctor method was used to determine the optimal moisture content at which the soil would 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 [19].

IV. Results and Discussion

A. Physical Properties of Black Cotton Soil Samples

The physical properties, the Atterberg limits and the compaction test results of the Gaborone Dam soil samples as conducted in the Geotechnical laboratory of the Department of Civil Engineering at the University of Botswana are summarized in Table 1. The Brunauer-Emmett-Teller (BET) specific surface area of the soil sample passing through 75 µm sieve was 38.17 m^2/g. The average specific gravity of BCS from four locations at the collection site was 2.52. This result is below the average range of 2.60-2.75 obtained from the literature. This is reveals that, although the properties of soils vary from location to location and very few investigations had been reported on BCS in the Southern Africa sub-region particularly in Botswana. Hence, since the results showed that the investigated BCS samples contained finer particles, there is the possibility for soil stabilization to render the soil suitable as subgrade materials for road constructions.

B. Particle Size Distribution

Particle size analysis was used to determine the size range and grading of soil particles in order to classify the soil appropriately and to determine which of the different size ranges was likely to control the engineering properties of the soil. The average coefficients of uniformity and curvature for the soil were 10.87 and 1.06 respectively.

TABLE 1: PHYSICAL PROPERTIES OF SOIL SAMPLES

Percentage passing through Sieve No. 200 (0.075mm)	90%
Soil gradation	
Gravel fraction (%)	0
Sand fraction (%)	10
Silt (%)	36
Clay (%)	54
Specific gravity (G_s)	2.52
Atterberg limits	
Liquid limit (LL) %	67.3
Plastic limit (PL) %	21.3
Plasticity index (PI) %	46.0
Linear shrinkage (LS) %	4.7
Colour	Chocolate-black
Hydrometer analysis (PSD)	
D_{10} (mm)	0.0023
D_{30} (mm)	0.0078
D_{60} (mm)	0.025
Coefficient of uniformity, C_u	10.87
Coefficient of curvature, C_c	1.06
Compaction test	
Maximum dry density (kg/m^3)	1418
Optimum moisture content (%)	9.8
ASSHTO classification	A-7-6
USCS classification	CH

C. Particle size distribution

Hydrometer method was used to measure the density of the solution for specific times. The time-density data wa used to calculate the percentage of particle sizes for the required 48 hours period where observations were required to be made. The PSD of the tested BCS consisted of 10% sand, 36% silt and 54% clay which agreed with the findings of Mamatha et al (2017). Fig. 3 shows the PSD curve of the BCS based on the hydrometer method. The coefficients of uniformity and curvature were 10.87 and 1.06 respectively. The best line of fit for the effective depth, H_R in terms of the hydrometer reading, R_H is $H_R = -0.4R_H + 19.86$ (coefficient of determination, $R^2 = 1.0$).

From the PSD curve and the Atterberg limit test results, the BSC can be classified as A-7-6 by AASHTO while the Unified Soil Classification System (USCS) classified the soil as highly compressible clay with the group symbol CH as shown in Fig. 5 the ordinates of LL against PI are above the A line.

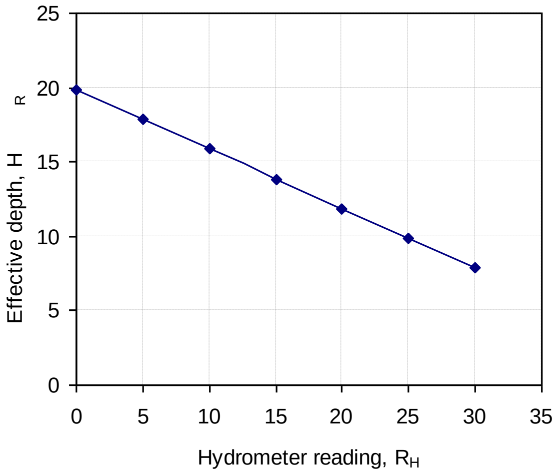

Fig. 3. Calibration curve of hydrometer and sedimentation jar

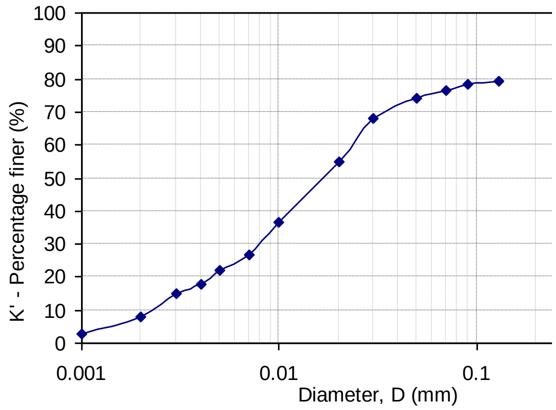

Fig. 4. Particle size distribution of BC soil based on Hydrometer method

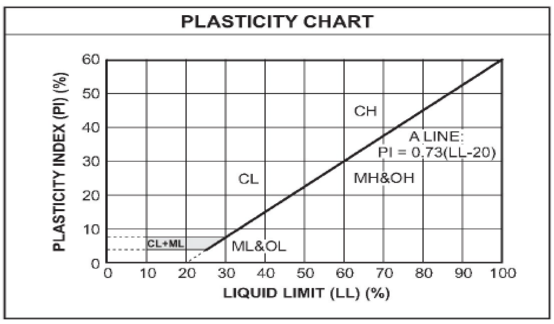

Fig. 5. Plasticity chart for USCS of BCS using Atterberg limit test results

D. Atterberg Limits

Based on the laboratory experimental results from the Atterberg limits (liquid limit, LL=67.3%; plastic limit, PL=21.3%; plasticity index, PI=46.0%). The average linear shrinkage of three BCS samples was 5.1%. The soil can be regarded as highly plastic. These values fall within the standard limits and agree with the literature. The results indicate that the soil is clay and rich in smectite. Smectite tends to absorb more water and thus exhibit greater swelling than non-expansive clays such as chlorite, illite, and kaolinite. Generally, finer soils have a greater capacity to hold water due to their greater particle surface area. On the other hand, clayey soils rich in smectite retain plasticity at lower moisture contents than non-expansive clays such as chlorite, illite, and kaolinite. Therefore, the soil contains montmorillonite clay particles.

E. Compaction Test

Compaction is a relatively an instantaneous mechanical process in which the densification is achieved through the expulsion of air voids at almost constant water content of the soil mass. The two important compaction characteristics are optimum moisture content (OMC) and maximum dry density (MDD). With increasing compactive effort, the maximum dry density increases and the optimum moisture content decreases. The plots of the dry densities against moisture content shifts to the right and the slope of the concave decreased as the ash content increased (as shown in Fig. 6), indicating a drop in the maximum dry density. An increase in the moisture content was probable due to the mass of fines increases more water will be needed to be absorbed. The maximum dry density was 1418 kg/m^3 at an optimum moisture content of 9.8%.

Black cotton soil has a high content of montmorillonite, which is a clay mineral that attracts water molecules at a relatively low MDD. This shows that compaction alone cannot improve geotechnical properties of BCS due to its plasticity property and ability of the clay minerals to absorb water which occupies voids where soil particle could have occupied to densify the soil. It is argued that this may be due to repulsive pressure exerted by the soil which resist compactive effort, thereby allowing particles to not come close the air voids are not expelled.

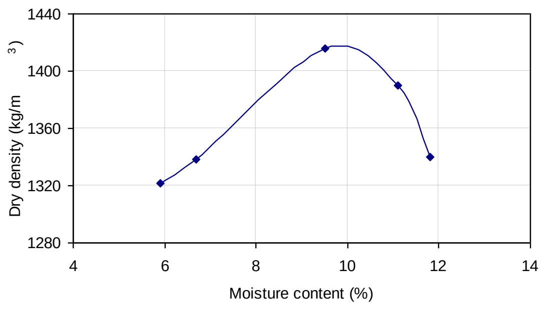

Fig. 6. Compaction test results for BSC samples

F. Unconfined compressive strength

The plot of the unconfined compressive strength (UCS) of the black cotton soil is shown in Fig. 7. The UCS was 5.1 kN/m^2 at 9.8% optimum water content. The gradual increase of moisture up to the optimal value may linked to the fact that the swelling of the soil was not quick until after steady water absorption, thereby reducing the overall strength of the soil as water content increased. This indicated a low and undesirable unconfined compressive strength. It is therefore evident that the soil along Gaborone-Boatle road construction site is problematic, and thus requires improvements for strength and load bearing capacity enhancement. Furthermore, the low strength UCS value of the soil could be attributed to the cohesive and plastic nature of the soil characterized by the poor packing of clay particles, and poor gradation at a very low compactive effort. BCS has clay minerals, particularly montmorillonite which is highly active to react with water to give BCS high expansiveness thereby exerting pressures which renders compaction inactive hence poor UCS value.

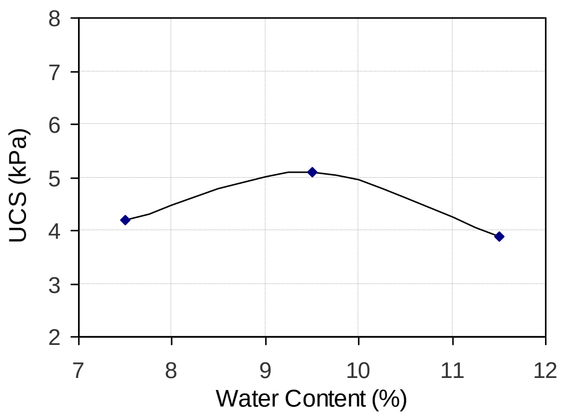

Fig. 7. Unconfined compressive strength of BSC

V. Conclusions

The article presents the properties of the black cotton soil on Gaborone-Boatle road in Botswana. The study was conducted to evaluate the need for soil improvement by stabilization procedure. The physical and geotechnical properties of the BCS samples were analysed and evaluated to justify the need for soil improvement which would be reported in the subsequent studies. The specific gravity, particle size distribution, the Atterberg limits, compaction and unconfined compression tests were performed on the BCS to verify the need for stabilization to enhance density and load-bearing capacity. The following conclusions were drawn from the study.

1. The BCS samples contained no gravel, with 54% clay, 36% silt and 10% sand. The soil is predominantly silt and clay with 90% finer than 75 μm.

2. The soil was chocolate-black in colour with a specific gravity of 2.52.
3. The maximum dry density of the soil was 1418 kg/m^3 at an optimum moisture content of 9.8%. The Atterberg limits were 67.3% liquid limit, 21.3% plastic limit, 46.0% plasticity index and 4.7% linear shrinkage.
4. The PSD of the soil using hydrometer method gave coefficients of uniformity and curvature of 10.87 and 1.06 respectively.
5. The classification of the BCS based on AASHTO and USCS were A-7-6 and CH respectively. It was found from the study that the soil exhibited relatively high swelling/shrinkage properties and very low strength.
6. It can be therefore be concluded that stabilization with industrial by-product such as fly ash is essential to guarantee sustainable development without continually depleting the natural resources.

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