Geomechanical Appraisal of Clay Soils from Sedimentary and Basement Areas of Ondo State, Nigeria: Implications on Engineering Applications

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Abstract: The geomechanical properties of clay soils from the sedimentary and basement areas of Ondo State, Nigeria were studied. The moisture content, specific gravity, consistency limit, activity values, linear shrinkage and grain sizes of the collected clay soil samples were determined in the laboratory. Mean moisture contents of the two clay soil samples were 18.66 and 8.62% for sedimentary clay (SC) and basement clay (BC) indicating better shear strength for BC. The specific gravity value ranges from 2.64 to 2.73% for SC and 2.62 to 2.72 % for BC indicating similarities in mineralogical and chemical compositions. The grain size results revealed an average value of sand, silt and clay contents as 25.36, 28.94 and 45.01% for SC and 44.14, 22.88 and 31.74% for BC indicating better compaction and workability properties for BC. Linear shrinkage values were 9.58% for SC and 8.46% for BC suggesting lower swelling potential for BC. Mean plasticity index of 24.74% and 20.82% were obtained for SC and BC respectively, suggesting high compressibility and settlement for SC and medium compressibility for BC. The soil samples were classified as CI, CH and MH and A-7-6 and A-7-5 according to USCS, 2000 and AASHTO, 2004 systems and grouped in behaviour as VI and VIII for SC and as CI and A-7-6 and grouped as VI for BC respectively. It was concluded that BC has better shearing strength, compressibility, compaction and workability properties compared to SC. Though both SC and BC could find applications in engineering construction work, BC soil samples are safe and fairly competent for such work than SC. Consequently, BC is recommended as more suitable for all civil engineering works.

Keywords: *Geomechical properties, Sedimentary Clay (SC), Basement Clay (BC), plasticity, behaviour group*

I. INTRODUCTION

The comprehensive information on the soil properties required to ensure safe design and the construction of civil engineering structures is very crucial. Geomechanical properties of soil are useful in the identification and classification of soils. These properties indicate the type and conditions of the soil and provide a relationship with the structural properties which are used extensively by engineers to discriminate between the different kinds of soil within a broad category (ELE, 2013). Vast quantities of earth materials contain clays which are important to the construction engineer because their structures frequently rest on clayey formations.

In engineering practices, clay is generally seen as a problematic soil. When these soils are used as embankments and substructure fills, to impound water such as earth dams, during construction of slurry walls and landfills, it becomes more important to address. Through recognition of the characteristics of clay, the challenges associated with clayey formations in construction and operation of engineering works can be understood.

Clay soils are chemically weathered materials from parent rock especially from feldspar. Basement clay is a residual soil material produced by in-situ rock weathering and can be commonly found in the surface and subsurface profiles across Nigeria. Due to their in-situ formation, residual soils generally possess significant microstructure (rock fabric) and material characteristics closely related to those of their parent rock. The sedimentary clay is transported material deposited in an environment different from site of origin.

The engineering properties of soils will reveal their suitability for construction work. Investigating the properties will also show the variability of selected parameters in the area under study. Hence, proper recommendations could be made for their uses.

II. METHODOLOGY

Geology of the Study area

The study area lies within latitudes 07°23′ and 07°52′N and longitudes 04°58′ and 05°31′E. The geology of Nigeria is dominated by sedimentary and crystalline basement complex rocks and this occurs in almost equal proportions. (Rahaman and Malomo, 1983; Shitta, 2007). The sedimentary is mainly upper Cretaceous -Recent in age while the basement complex rocks are Precambrian. The study areas fall into the sedimentary and basement rocks of Ondo State (Figure 1). The towns in the sedimentary section are underlain by coastal plain sands typical of the coastal sedimentary basin of the eastern Dahomey basin (Rahaman, 1988). The quaternary coastal plain sands of the eastern Dahomey basin constituted the major shallow hydrogeological units of the areas due to its porosity and permeability (Onwuka 1990; Omosuyi *et al*., 2008). The section that falls within the basement complex rocks of the study area comprises Akure and Akoko areas and they are underlain by the migmatite-gneiss-quartzite complex of the basement complex. The Nigerian Geological Survey Agency (NGSA, 2006) suggested other distinguishing lithological units in the area to include granite-gneiss migmatite, quartz-schist, fine-grained quartz schist and undifferentiated schist.

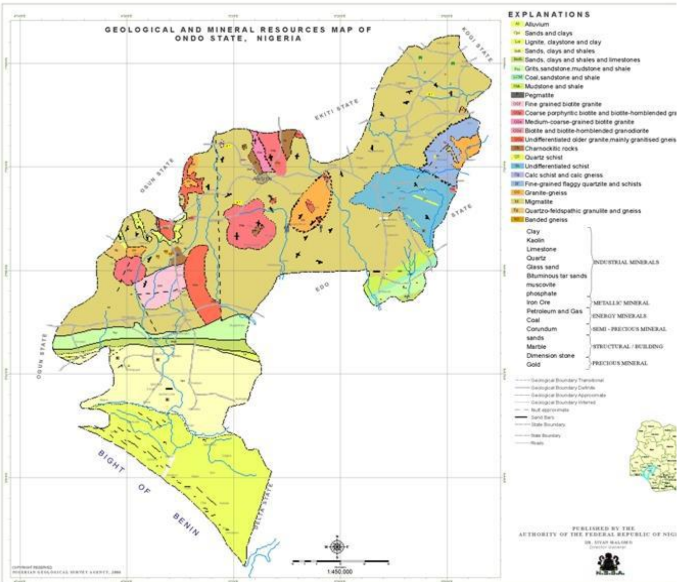

Figure 1: Geological Map of Ondo State (Adapted from NGSA, 2006)

Sampling

The samples used for the analysis were collected from ten (10) different locations within the study area (Figure 2). A disturbed method of sampling was employed in collecting the samples. Care was taken when collecting the samples to ensure that the analyzed samples were true representatives of the in-situ materials. The samples were sent to the Geology department of the Federal University of Technology, Akure for laboratory tests. The tests were carried out to classification and deduce the suitability of sampled soils for engineering use. The tests were moisture content, particle size and hydrometer analysis, consistency limits (liquid limit, plastic limit and plasticity index, linear shrinkage) and specific gravity. All the tests were carried out following the guidelines of BS1377 (1990). The tests provide data from which soils can be classified and predictions made of their behavior under foundation loading.

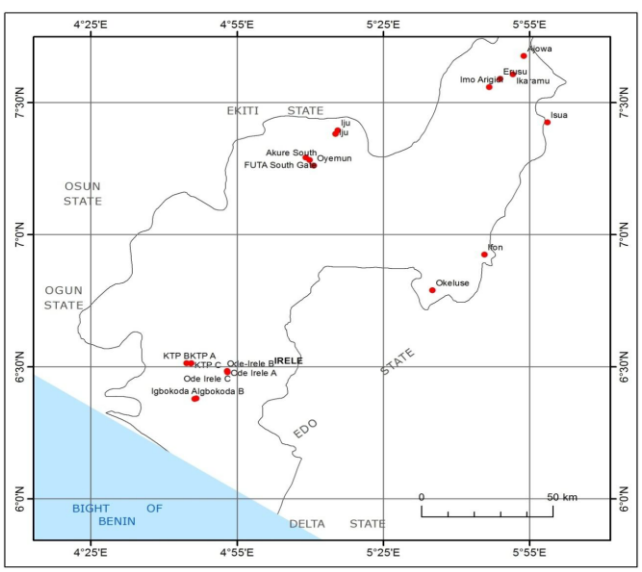

Figure 2: Soil Samples Location Map

Moisture Content Determination

The natural moisture content of the soil samples was determined immediately they were brought from the field to the laboratory in order to know the amount of moisture present in the natural state and setting. Apparatus like moisture cans, paper tapes, weighing balances, oven and permanent marker were used.

The aluminum cans use were cleansed, dried and labeled for easy identification. They were weighed (M_1) and their masses recorded against their labels on the data sheet. Sample representatives of the wet soils were put into the cans and their masses, with that of the moisture cans and were then taken and recorded (M_2). The moisture can and the samples were then put into the oven, already set to a temperature of 105^{o}C and left overnight to allow the sample achieve a constant mass. The dried samples were then taken out of the oven the next day and their masses obtained by weighing them on a weighing balance (M_3) using Equation (1).

$$Wn = \frac{Ww}{Ws} \times 100 \qquad (1)$$

Where, Wn = moisture content; Ww = weight of water present in the soil mass

Ws = weight of the soil mass

Determination of Specific Gravity

Fifteen gram of the soil samples that passed through sieve of 0.425 mm was added to the pycnometer and weighed. Sufficient air-free distilled water was added to soil sample in the bottle and shaken to eliminate air indirection. The bottle and its content was weighed. The pycnometer was later filled with distilled water and weighed. Equation (2) was used to calculate the specific gravity (Ys) of the samples:

$$Ys = (P_2 - P_1) / (P_4 - P_1) - (P_3 - P_2) \qquad (2)$$

Where P_1 is the weight of the pycnometer, P_2 is the weight of pycnometer containing sample, P_3 is the weight of the bottle containing air-free distilled water and sample and P_4 is the weight of the pycnometer filled with distilled water.

The particle size test of the soil samples was carried out on a mechanical sieve shaker in accordance with wet sieving British Standard, BS 1377 [1990] test 7a standard. The sample materials were allowed to drain and carefully transferred to a tray and placed in the oven to dry at temperature of 105 to 110°C overnight. The dry soil was then passed through a nest of the complete range of sieves to cover the size of particles present down to 63 μm sieve. The percentage weight retained and the percentage passing in the sieves were determined. The percentage passing versus particle size distribution is plotted as shown in Figures 3 and 4 respectively.

Atterberg Limits Test

The liquid limit was taken as the moisture content that correspond to 25 blows. The test for plastic limit determination was carried out in accordance with BS 1377 [1990] test 3 standard. 20 grams of reworked -clay soil samples were thoroughly mixed with distilled water and kneaded for about 10 minutes to form a plastic ball. The ball was molded between the fingers and rolled between the palms such that the warmth from the hand slowly dried it. The thread was rolled between the fingers and a glass plate using steady pressure which reduced the diameter to about 3 mm, the pressure being maintained until the thread crumbled. This crumbling point is the plastic limit.

III. RESULTS AND DISCUSSION

Moisture Content (MC)

The results of moisture content of the studied soils are presented in Table 1. The Sedimentary clay soil samples are found with an average of 18.8% while the Basement clay has an average of 8.62%. This may be attributed to higher clay content of the SC soil samples in addition to its nearer proximity to subsurface water (80m above sea level) compared with BC (350 m above sea level).

Higher amount of clay content of SC must have resulted from higher degree of weathering which is associated with sedimentary environment due to higher rainfall. Owoyemi and Adeyemi (2018), reported 2500 mm rainfall for Sedimentary and 2000 mm rainfall Basement terrains cited from Federal Ministry of Works (2013). This result classifies SC soil samples as marginally suitable engineering material and BC suitable engineering materials according Underwood (2013). This observation implies that BC terrain possess better engineering properties than SC terrains.

Specific Gravity

Specific gravity is an important index property of soils that is closely linked with mineralogy or chemical composition and also reflects the history of weathering (Oyediran and Durojaiye, 2011). The results of the specific gravity of the tested soils are presented in Table 1. The values for SC soil samples range from 2.64 to 2.73%, and from 2.62 to 2.72 % for BC. This result revealed close values for both soil samples which indicates similarity in terms of mineralogical and geochemical compositions of both terrains soil samples (Table 2).

This may be due to clayeyness of both samples. Meanwhile, the result classifies both terrain soil samples as clay soils according to Mukherjee, (2013). The value ranges indicate closeness in engineering properties and performance.

Table 1: Summary of Geomechanical Properties, Classifications and Group behavior of the Study Soil Samples

Terrain	GS	G	S	silts	C	Fines	MC	LL	PL	PI	SL	LS	A	ICM	USCS	AASHTO	BG
SC 1	2.67	0.0	14.2	39.1	46.8	86	11.4	52.3	31.1	21.2	9.1	9.3	0.45	K	MH	A-7-5(7)	VIII
SC 2	2.64	1.3	37.6	25.7	35.4	61	11.1	41.2	24.4	16.8	9.8	8.6	0.47	K	CI	A-7-6(2)	VI
SC 3	2.73	0.0	23.0	19.9	57.1	77	34.1	64.3	26.8	37.6	7.7	11.4	0.66	K	CH	A-7-6(19)	VII
SC 4	2.68	1.9	24.1	38.1	35.8	74	18.4	55.8	24.3	31.5	8.2	10.7	0.88	I	CH	A-7-6(5)	VII
SC 5	2.68	0.0	27.9	21.9	50.2	72	18.3	38.8	22.2	16.6	10.1	7.9	0.33	K	CI	A-7-6(5)	VI
Average	**2.68**	**0.6**	**25.4**	**28.9**	**45.1**	**74**	**18.7**	**50.5**	**25.8**	**24.7**	**8.98**	**9.58**	**0.56**	**K**	**CH**	**A-7-6(10)**	**VII**
BC 1	2.64	0.0	22.0	37.8	40.2	78	7.2	42.4	23.0	19.4	9.6	8.6	0.48	K	CI	A-7-6(2)	VI
BC2	2.72	2.0	53.8	19.2	25.1	44.3	6.2	36.3	19.3	17.0	10.1	7.9	0.68	K	CI	A-7-6(2)	VI
BC3	2.64	1.4	48.7	18.6	31.4	50	8.1	42.3	20.8	21.5	10.1	7.9	0.68	K	CI	A-7-6(1)	VI
BC4	2.62	1.2	46.0	20.1	32.7	52.8	7.3	44.2	19.2	24.5	9.6	8.6	0.75	K	CI	A-7-6(2)	VI
BC5	2.66	1.9	50.2	18.7	29.3	48	14.3	46.0	24.3	21.7	9.1	9.3	0.74	K	CI	A-7-6(0)	VI
Average	**2.66**	**1.3**	**44.2**	**22.9**	**31.7**	**54.6**	**8.6**	**42.2**	**21.3**	**20.8**	**9.7**	**8.5**	**0.67**	**K**	**CI**	**A-7-6(2)**	**VI**

Particle Size Analysis

The results of the grain size distribution and the fraction distribution patterns of the studied soils are presented in Table 1 and in Figures 3 and 4. The average values of sand, silt and clay contents are as follows; 25.36, 28.94 and 45.01% for SC and 44.14, 22.88 and 31.74% for BC. SC samples contain higher clay content than BC; this observation may be due to higher degree of weathering which is associated with sedimentary terrain. The results showed that BC soil samples have higher amounts of sand-size particles, lower amount of clay fractions and higher strength than those from SC terrains. It is, therefore, reasonable to use soils for construction purpose from BC terrains since such soils are likely to possess better engineering properties than those from SC terrains. This is line with the comparative analysis result of unified soil classification system (USCS, 2000) (Table 3). Hence, BC soil samples possess better engineering properties to serve as filler, use in dam construction, road stabilization and in brick making due to higher shear strength properties.

Consistency Limits

The results of the consistency limits and plasticity classes are presented in Table 2. The Liquid limits varies between 38.80 to 64.30% for SC and 36.30 to 46.00% for BC, This showed that SC soil samples comprises intermediate and fat clay soils while BC comprises only intermediate clay soil samples in similarity with Bell (2007). This is reflected in better compressibility, compaction and workability properties of BC over SC (Table 3).

On the plasticity classification chart, BC soil samples fall within clay of medium plasticity, while the SC soil samples plot on both medium and high plasticity portions, Figures 5 and 6. This suggests higher compressibility and degree of settlement for SC compared with BC in engineering construction works. The plasticity chart result suggests moderate compressibility, workability and good compaction properties for BC. Hence, BC will not pose serious settlement challenges in engineering construction works.

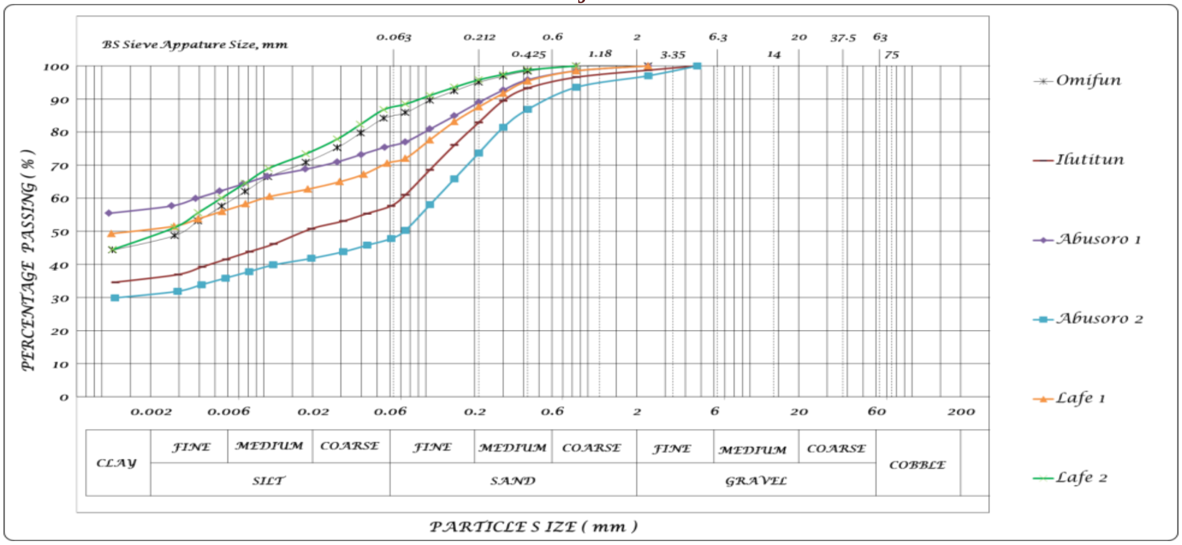

Figure 3: Grain Size Distribution Fraction for Sedimentary Clay

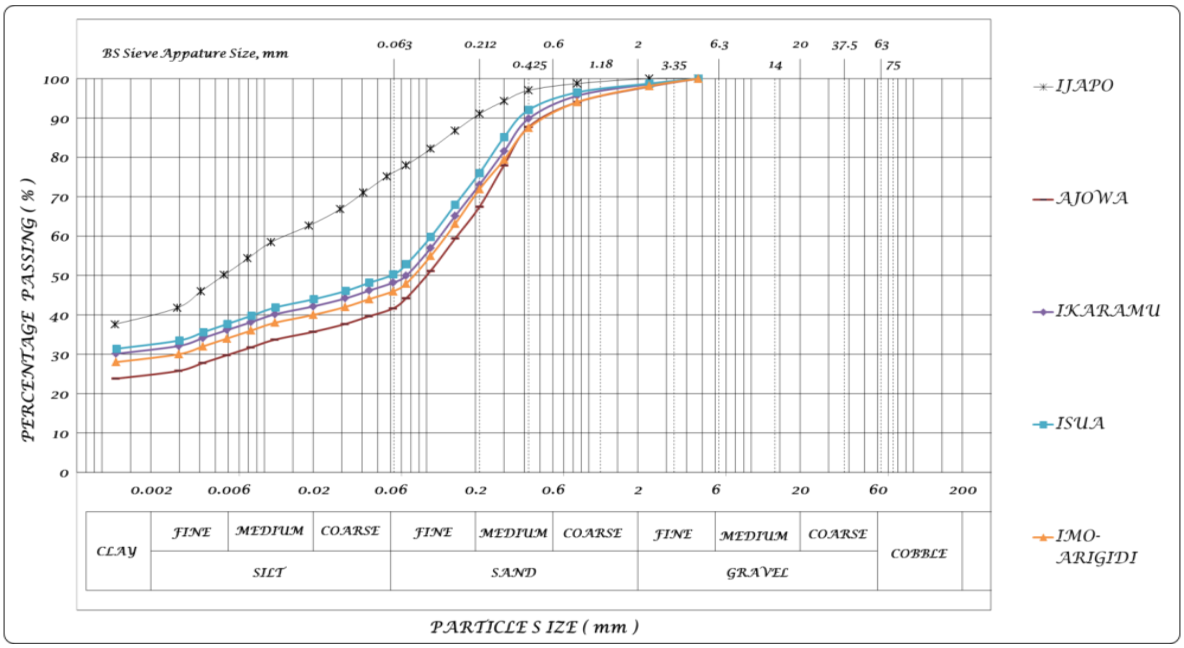

Figure 4: Grain Size Distribution Fraction for Basement Clay

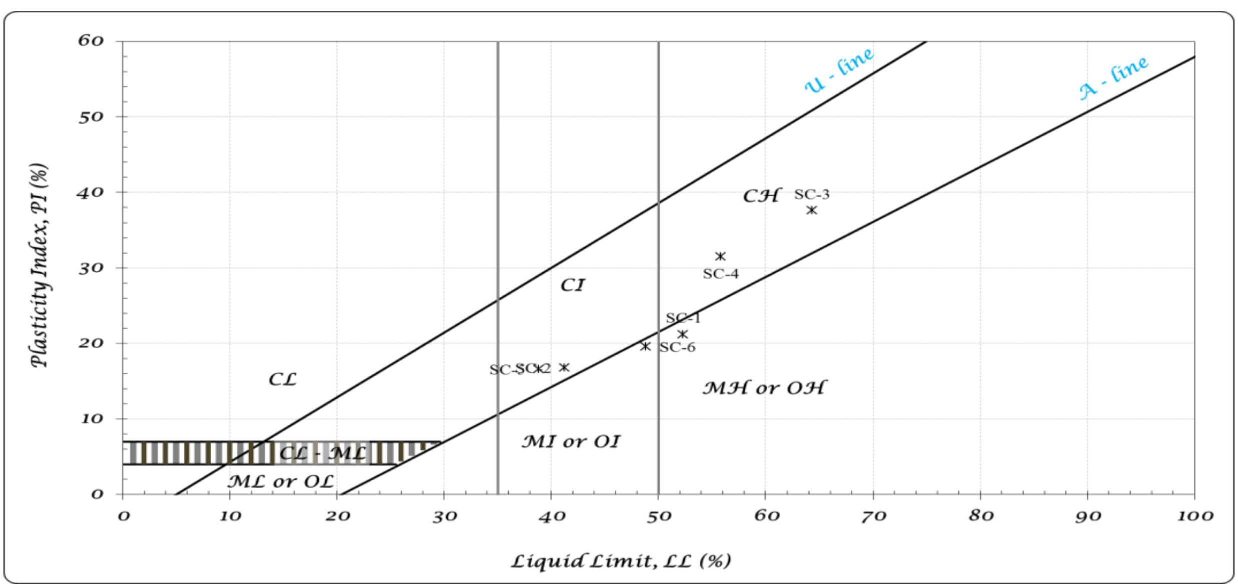

Figure 5: Plot of Plasticity Index versus Liquid Limit for the Sedimentary Clay Soil

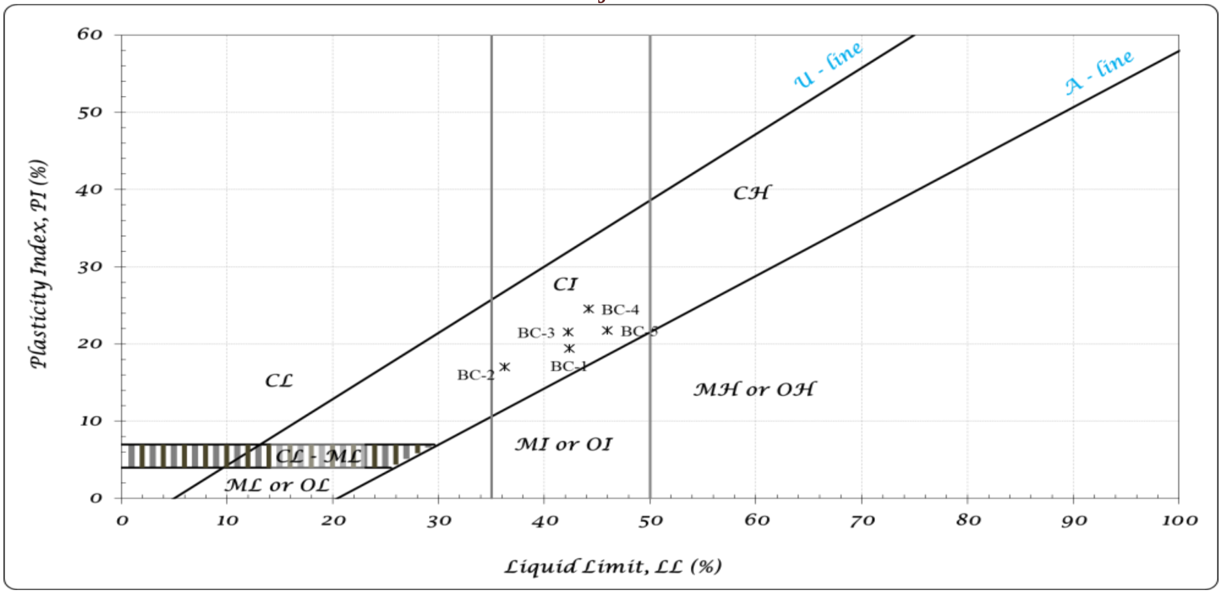

Figure 6: Plot of Plasticity Index versus Liquid Limit for the Basement Clay

Linear shrinkage

Linear shrinkage points toward the swelling potential of a soil (Brink *et al.*, 1992). The results of the linear shrinkage values of the studied samples are presented in Table 1. SC soil samples have an average value of 9.58% while BC ones have an average value of 8.46%. In comparison, the SC possesses higher amount of linear shrinkage value than BC. This can be attributed to a higher amount of clay content in SC. Thus BC possesses lower swelling and shrinkage potentials and more stability than SC. It is, therefore, reasonable to get soils for foundation fills from basement terrain. Soils having linear shrinkage values greater than 8% will be active, expansive and have swelling potential, susceptible to shrinkage problems and are not good foundation materials (Ola 1983; Brink *et al.*, 1992). Soils with higher linear shrinkage values will have tendency to change their volume with alternate wet and dry seasons due to the amount and type of the clay mineral present (Jegede, 1998).

Clay Activity

Activity of the soil is obtained by combining Atterberg limits and clay content into a single parameter (Skempton, 1953) and it is related to the mineralogy and geologic history of clays. The ratio of plasticity index to the clay fraction is approximately constant in any particular stratum. The results of the activity values of the study soil samples are presented in Tables 2 and 5 and Figure 7. The values range from 0.33 to 0.88 for SC soil samples and from 0.48 to 0.75 for BC. While on chart, two soil samples of SC were found plotted within the high expansion range but for the BC soil samples all were found plotted within medium expansion range Figure 8. This indicates SC soil samples consist majorly of inactive and slight amount of normal clays, while BC soil samples consist of only inactive clay. This trend was also observed in linear shrinkage, liquid limit and plasticity properties in Table 6. This is also attributed majorly to the less clay content and more sand content of the BC soil samples. Hence, BC possess better expansibility potential for engineering construct works than SC.

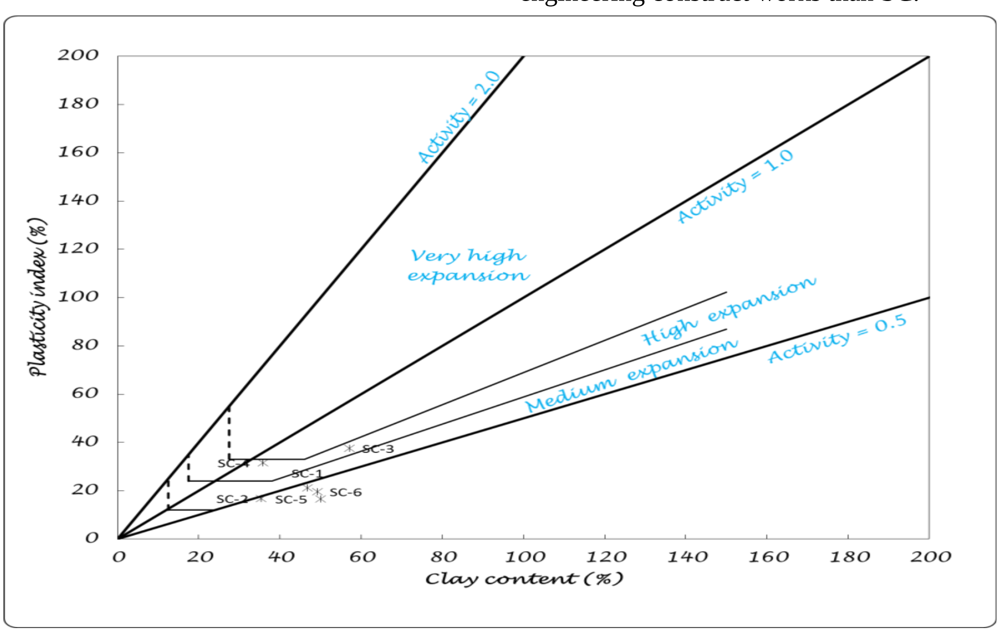

Figure 7: Activity chart for the soils of the Sedimentary derived clay soils of the study area

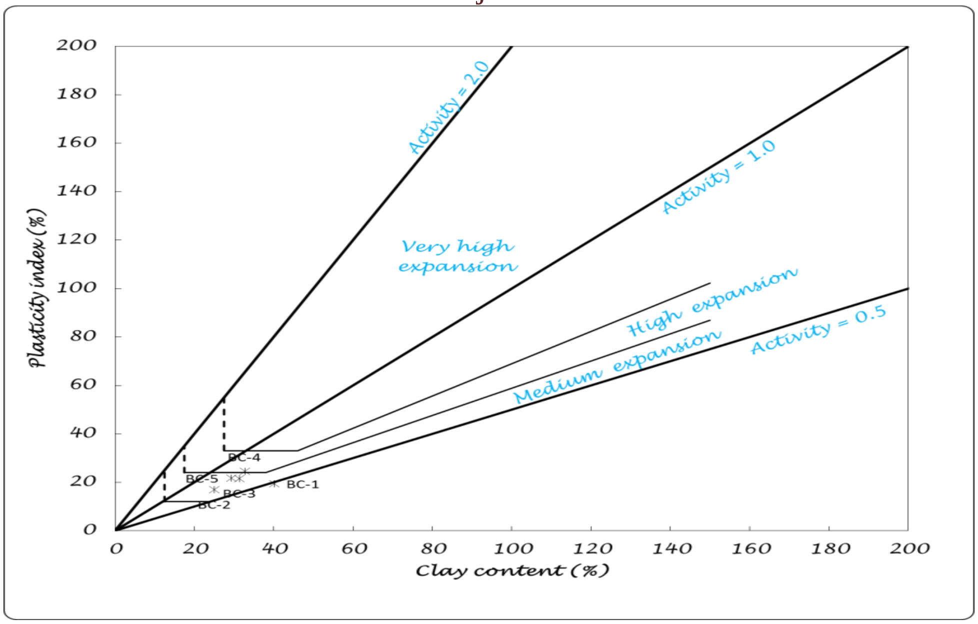

Figure 8: Activity chart for the soils of the Basement derived clay soils of the study area

The values of plasticity parameters for pure clays according to Mitchell 1993 is shown in Table 4. The characteristics of compacted fill materials according to USCS< 2000 is presented in Table 7.

Table 2: Consistency Limits, Activity Values and Clay Mineralogy Classifications of the Study Soils

Samples	Liquid Limit (L1) % Range	Plastic Limit (PL) % Range	Inferred clay mineral(s)	Activity Values	Interpretation
SC	38.8 – 64.3	22.20 - 31.10	Kaolinite/illite	0.33 - 0.88	Inactive/Normal
BC	36.3 – 46.00	19.20 – 24.30	Kaolinite	0.48 – 0.75	Inactive

Table 3: Summary Comparative analysis of Study Soil Samples Engineering Performances (USCS, 2000)

Name/Properties	Groups	shearing	Piping	Cracking	Permeability	Compressibility	Compaction	Workability
SC	VI - VIII	least	Excellent	Excellent	low	High – Very High	Pale - Poor	Poor
BC	VI	Pale	Good	Good	low	Medium - High	Good	Pale

Where SC: Sedimentary derived clay soil. BC: Basement derived clay soil.

Table 4: Values of Plasticity Parameters for Pure Clays (Mitchell 1993)

Class	Standard	Standard
Mineral	Liquid limit %	Plastic limit %
Montmorillonite	100-900	50-100
Illite	60-120	35-60
Kaolinite	30-110	25-40

Table 5: Classification of Soils According to Activity Values After, Skempton, 1953

Activity Value	Interpretation
Less than 0.75	Inactive
0.75-1.25	Normal
Greater than 1.25	Active

Table 6: Classification of Plasticity Using Liquid Limit (Bell, 2007).

Description	Plasticity	Range of liquid limit (%)
Lean or Silty	Low plasticity	Less than 35
Intermediate	Intermediate plasticity	35-50

Fat	High plasticity	50-70
Very fat	Very high plasticity	70-90
Extra fat	Extra high plasticity	> 90

Table 7: Characteristics of Compacted Fill Materials (USCS, 2000)

Behaviour group	**Relative Resistance to Failure (1) Greatest (6) Least**			**Relative Characteristics**	
	shearing	**piping**	**cracking**	**permeability**	**compressibility**
1	2	3	4	5	6
I	1	-	-	High	Very Slight
Ii	3	3	4	Low	Slight
Iii	2	5	3	Medium	Slight
Iv	3	6	6	Medium	Slight to medium
V	4	4	5	Low	Medium
Vi	5	2	2	Low	Medium to High
Vii	6	1	1	Low	High
Viii	6	variable	variable	Medium to Low	Very High
Ix	6	variable	variable	Medium	Very High

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