GEOMECHANICAL CHARACTERISTICS OF NATURAL AND STABILISED BLACK COTTON SOILS FROM THE ACCRA PLAINS OF GHANA

By

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DECLARATION

I hereby declare that this submission is my own work towards the MPhil and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the university, except where due acknowledgement has been made in the text.

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ABSTRACT

Black cotton soils or tropical black earths or black clays are potentially expansive soils which classify as vertisols in pedological parlance and have been found to occur in all major climatic zones of the world. These soils are considered "problematic" and sometimes as "potential natural hazard" because they are susceptible to seasonal volumetric changes, exhibit severe cracking when dry, swell and yield low bearing strengths when wet, etc. These problems cause extensive damage to light structures founded on them and estimated cost of damage due to expansive soils in general runs into billions of dollars annually. Considering the widespread prevalence of these soils and the problems they pose to structures founded on them, there is the need to conduct studies into the geological and geomechanical characteristics of the black cotton soils to enable effective utilization. Although some works have been done globally on these soils, these rather useful information are scattered in various publications. The need to collect these scattered information, synthesize them and present a hands-on-information regarding the nature, distribution, physical and engineering properties of the black cotton soils for the benefit of the construction industry has long been felt. Secondly, it has also become necessary to conduct studies with the view to enhancing knowledge on the geology and geomechanics of these soils. This study has attempted to address the above mentioned problems through a review of literature on the mode of formation, nature, as well as distribution of these soils around the world and secondly, presents studies on typical black cotton soils from the Accra plains of Ghana. Soil samples were collected from Tsopoli and Doryumu, both in the Accra plains of Ghana and subjected to physical, chemical and mineralogical as well as geomechanical studies. Results of the study reveal that the black cotton soils are formed over the Garnet-Amphibolites Gneisses of the Dahomeyan Supergroup. The chemical compositions of the soils indicate

that the most abundant oxides are silica, alumina and iron oxide. The mineralogy of the two soils from X-Ray Diffraction analyses are similar and are composed of Quartz and montmorillonite. The geomechanical studies also suggest that the natural black cotton soils are unsuitable for subgrade construction and hence require improvement through stabilization. Attempts at stabilising the soils with quarry dust, pozzolana and pozzolana-cement which are readily available local materials, reveal that although the three stabilizing agents improved some geomechanical parameters of the soils the pozzolana-cement appears to be the most effective for stabilising the black cotton soils.

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CHAPTER 1: INTRODUCTION

1.1 General

Around the world, there are many structurally “unstable” and “problematic” geomaterials which are sources of worry to engineers working with or on them. They are considered problematic mostly because they are characterized by unusual in-service behaviour, including such geo-environmental phenomena as heaving, swell, collapse, dispersion, erosion, excessive creep, subsidence, high compressibility etc. According to Gidigasu (2009), such behaviour could be attributed to factors such as composition, nature of pore fluids, fabric and mineralogy, etc. Prominent among these problem soils are the potentially expansive soils such as weathered shales, stiff fissured clays, black cotton soils, etc. Expansive soils in general constitute a major soil group which are known to cause considerable damage to roads, dams, canal linings, shallow foundations either through excessive swell or shrinkage (Chen, 1988). In America alone, these soils inflict over $9 billion in damages annually to engineering structures and facilities, more than twice the combined damage from earthquakes, floods, tornadoes and hurricanes (Krohn and Slosson, 1980; Warren Wray, 1995). According to Bell and Culshaw (2001), loses due to swelling and shrinkage in clays amount to about £3billion in Britain. Black cotton soils are typical expansive soils which occur widely in many countries. Although, some works have been done on black cotton soils locally and internationally, these rather useful information are scattered in various publications and the need to bring these scattered information together has long been felt. Secondly, there is also the need to add value to existing knowledge in terms of technical information relating to geology and geomechanics of the black cotton soils occurring in Ghana through laboratory and field studies. This study considered the formation, nature, engineering geology and geomechanics of typical black cotton soils found in Ghana.

1.2 Problem Statement

Black cotton soils are expansive soils which occur widely in many tropical countries. Their occurrences have been reported in Asia: India (Rao et al, 2001; Michael, 2006; Seehra, 2008); Africa: South Africa (Van Der Merwe, 1964), Nigeria (Ola, 1983; Osinubi, 2006), Sudan (Charlie et al, 1984) etc. The term "black cotton" appears to have originated from India from its colour and from the fact that cotton grows fairly well on it. It is known to be formed mainly by the chemical weathering of mafic igneous rocks in poorly drained areas with well defined wet and dry seasons. Its main clay mineral is montmorillonite and in certain cases with kaolinite (Building and Road Research Institute, 1985). In spite of its black colour, low organic matter content has been reported in these soils which appear to indicate that the black colour is due to the presence of titanium oxide in small concentration (Seehra, 2008).

In highway engineering, the problems associated with black cotton soils are numerous and hence engineers working with such soils try as much as possible to avoid them. The problem appears to stem from the fact that during the dry season the black cotton soils become hard and develop cracks. They are also hard to pulverise for stabilisation in road construction. Secondly, in the wet season subgrade consisting of black cotton soil takes in a lot of water and develop low bearing capacity, ultimately resulting in heavy depressions and settlement or may even heave into the upper layers of the pavement, especially when the sub-base consists of stone soling with lot of voids (Seehra, 2008). Alternating swelling and shrinkage of subgrade material consisting of black cotton soils may invariably lead to premature failure of the road. Mgangira and Paige-Green (2008) reported of excessive longitudinal cracks on a road built on black cotton soil only one year after completion. Ola (1987) has indicated that black cotton soils possess some characteristics that make them unsafe and uneconomical when used for construction without adopting some soil improvement techniques.

Structural failures to building foundations founded on strip footing on expansive soils have been reported in many parts of the world (Lambe, 1960). Specific cases of buildings and shallow foundation failures have been reported, in the USA (Dawson, 1953), South Africa (Jenning, 1953), Ghana (Gidigasu, 1987; Gidigasu and Andoh, 1980) etc.

A site reconnaissance survey to some parts of the Accra plains, reveal that civil engineering structures such as roads and buildings show varied degrees of distresses in the form of cracks and deformations suggesting that the soils may be potentially expansive. Some of the distresses and deformations observed during the current study are shown in Plate 1. The soils become muddy in the wet season and exhibit polygonal cracks in the dry season. The cracks are sometimes very wide and deep with some running as much as one meter deep from ground surface and about twenty-five centimeters wide.

It is in the light of these problems that the project sought to investigate the geological and geomechanical characteristics of black cotton soils in relation to the structures constructed on them and then recommend ways by which the properties of the soils may be improved.

Plate 1a. Deformation in building in the Accra Plains

Plate 1b. Cracking in pavement in the Accra Plains

1.3 Objectives of the Research

The following were the objectives of the research:

i. Review of literature on the geology and engineering properties of black cotton soils

ii. Evaluate the geological characteristics of the black cotton soils occurring in the Accra plains

iii. Evaluate the geomechanical characteristics of natural and stabilised black cotton soils for subgrade construction.

iv. Based on iii, determine the most effective local stabilising agent for improving the black cotton soils.

v. Suggest some relevant recommendations regarding the use of the natural and stabilised black cotton soils for the benefit of geomechanical practice in Ghana.

1.4 Scope of Research Work

The study highlighted salient engineering geological conditions which include:

i) Geology of the sites and its environs including soil profiles and analysis of material encountered.

ii) Hydrologic and geomorphological characteristics within the terrains

iii) Groundwater occurrence and composition.

iv) Pedogenesis and nature of soil deposits.

v) Chemical and physical composition of the soils.

vi) Studies on the physical and geomechanical properties of the soils.

vii) Studies on the soil improvements/stabilization.

1.5 Location of the Accra Plains

The Accra plain is located on the extreme south-eastern part of Ghana. The area is roughly triangular in shape. It lies between longitude 5^o 30’ N to 6^o 15’ N and latitude 0^o 20’ W to 0^o 40’ E. It is bounded on the East and North-East by the River Volta, on the West by the Akwapim-Togo Range and on the South by the Gulf of Guinea. The plain covers approximately 6000km^2 (Kortatsi, 2006). Figure 1 shows the location map of the Accra plains.

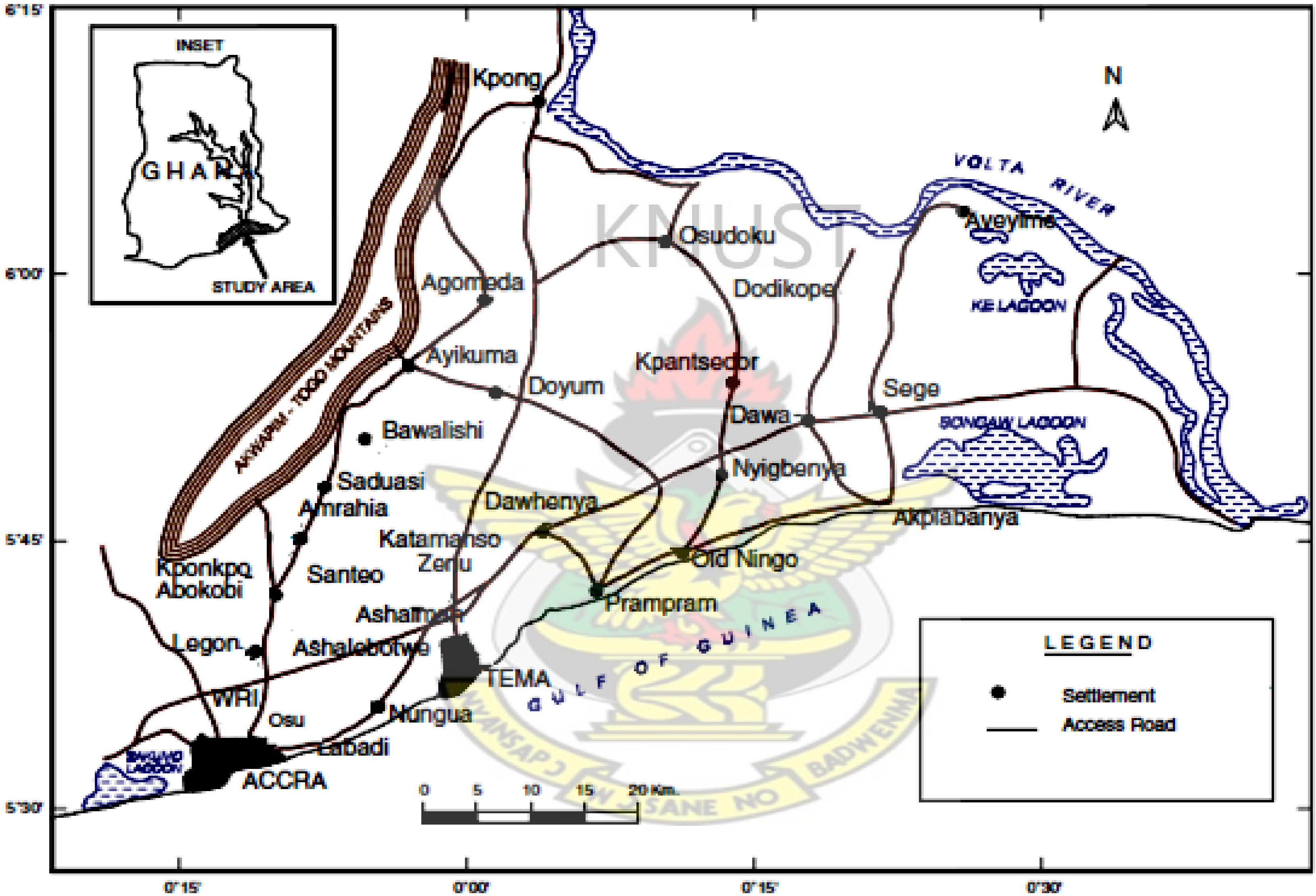


Figure 1. The location map of the Accra Plains (Modified after Kortatsi, 2006)

1.6 Geo-environmental characteristics of the Accra plains

1.6.1 Geology

The geology of the Accra plains has been described in detail by Junner and Bates (1945). Briefly the area is underlain by ancient igneous rocks, but strongly metamorphosed ancient sediments occur along the western boundary with areas of relatively young, unconsolidated sediments in the south and south-east.

The main Akwapim Range in the west is formed by Togo quartzites with minor amounts of phyllite, sericite schist, sandstone and shale. The Accra plains proper are mainly occupied by the Dahomeyan gneisses and schists. These are divided into three belts running north – south across the region and consist of a westerly and easterly felsic gneiss belt separated by a mafic gneiss belt. The felsic belt consists mainly of fine-grained muscovite-biotite schists and gneisses containing numerous quartz veins whereas the mafic gneisses are entirely garnet-amphibolite gneisses. Recent alluvium occupies the Volta flood plains and valleys of the major stream on the plains. Figure 2 shows the geological map of the Accra plains and Table 1 presents the stratigraphic succession of plains from the youngest to the oldest.

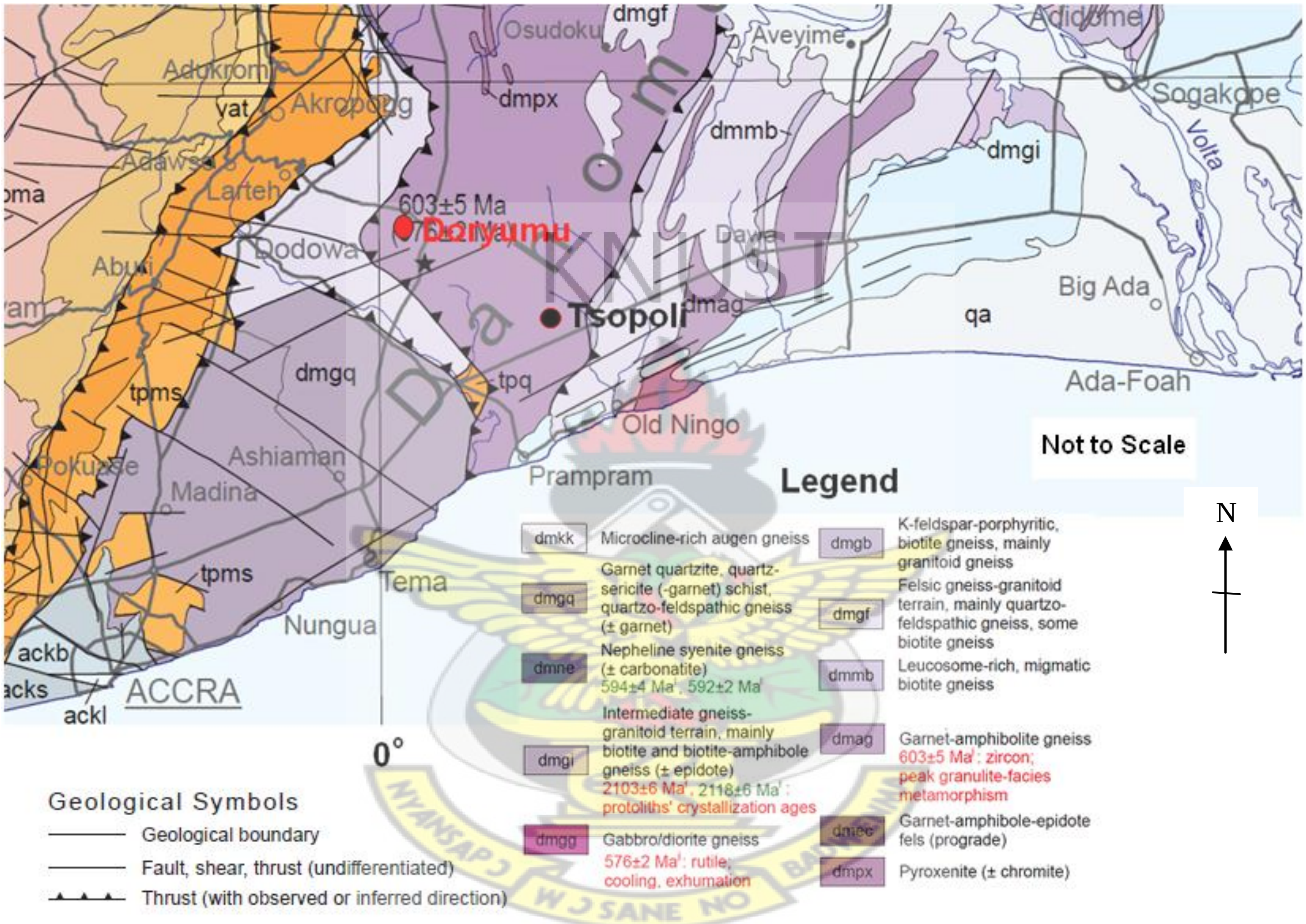


Figure 2. Geological map of the Accra Plains

Table 1. The stratigraphic succession of the Accra Plains (Junner and Bates, 1945)

Quaternary to Recent		Muds, sands, clays, soils and gravels of the river valley; beach and raised beach sand, clays, some with crystals of gypsum and salt of the lagoon area
		Unconformity
Tertiary	Pliocene	Limonitic residuals Unconsolidated and consolidated limonitic argillaceous sands and grits Quartz gravels, sometimes cemented by limonite
		Unconformity
	Eocene	Fossiliferous shallow water marine deposits of sandstone, siltstone, clay, shale, calcareous siltstone and impure and shelly limestone
		Unconformity
Precambrian		Quartzite, quartz-sericite schist, sericite schist and phyllite
		Unconformity
Archean	Basic Group	Mainly garnet-hornblende-granulites and gneisses, hornblendic gneisses
	Acidic Group	Quart-biotite-schist, gneiss, migmatites, augen gneiss, quartz and quartz sericite schists. Pink microcline-rich pegmatite, white muscovite pegmatite, grey porphyry and pegmatite all not much foliated. Foliated porphyritic granite and pink acid granite. Aplite
Intrusives		Pyroxenite

1.6.2 Geomorphology

The Accra plains are generally flat and undulating with few isolated inselbergs (rocky hills) that seldom rise 70 metres above mean sea level (Dickson and Benneh, 1980). The slopes are generally 2% or less over the clay soils formed over the Dahomeyan gneisses. Only the alluvials surrounding the coastal lagoon could be called flat. Slopes up to 5% in the north of the mafic gneiss belt and over coarse-sandy soils over the felsic gneisses as well as around the edges of the tertiary sediments have been reported. Slopes of up to 10% in the extreme west of the plain near the foot of the Akwapim Togo Range can be found.

1.6.3 Climate

The Accra plains lie in subhumid climatic zone of Ghana. The climate is characterised by two rainfall maxima. The major rainy season occurs between September and October with the peak occurring in October. Mean annual rainfall values are about 900mm. The mean annual temperature is around 26^{o}C (Kortatsi, 2006). The total annual evaporative loss from free water surface has been found to be as high as 1800mm (Brammer, 1967). The ratio of precipitation to evaporation ranges from 0.1 in January to about 1.5 in June (Cobbina, 1987).

1.6.4 Vegetation

The plains are covered mainly by grasses and scrubs. Typical vegetative cover is shown in Plate 2.

Plate 2. Vegetation of the Accra Plains

CHAPTER 2: LITERATURE REVIEW

2.1 Weathering and Soil formation

The most familiar geological process responsible for alteration of rock into soil is weathering. Weathering is a pedogenic process by which soils are formed as a result of disintegration or decomposition of rocks. Chemical weathering causes changes in rocks at and near the earth's surface by interaction between the rocks and chemically active components of the earth's atmosphere, principally water, carbon dioxide and oxygen.

Within a given area on the earth's surface and at a given geologic time, the particular effects of weathering is assessed in terms of at least five variables: (1) climate, (2) biological activity, (3) topography, as it effects underground movement of water, or contributes to erosional removal of weathered material (4) parent material (rocks) and (5) time.

A great variety of physical, chemical, and biological processes act to break down rock masses. Physical processes reduce particle size, increase surface area, and increase bulk volume. Chemical and biological processes may cause complete changes in physical, chemical and mineralogical composition of the end products. Robinson (1949) recognized two main stages in chemical weathering. The first stage involves the destruction of mineral phases, and the second stage the formation of secondary products. These two stages involve various processes which result in two main types of materials of morphogenic interest i.e., (i) weathering residues and secondary materials that occur insitu, and (ii) materials which are transported before deposition.

The first process of physical or mechanical weathering is also designated as disintegration while the second stage is designated decomposition. Disintegration results in a decrease in size of rocks and minerals without appreciably affecting their composition. In the case of decomposition, however, definite chemical and physico-chemical changes take place, soluble materials are released, and new minerals are synthesized or are left as resistant end products.

Physical weathering of rocks

Rocks exposed to environmental conditions are subjected to differential expansion and contraction resulting in disintegration. The rock pieces retain the chemical and petrological composition of the original parent rock. They usually occur in the surficial environments. Physical weathering processes cause insitu breakdown without chemical change. Five processes are important (Mitchell and Soga, 2005):

1. *Unloading*
2. *Thermal Expansion and Contraction*
3. *Crystal Growth, Including Frost Action*
4. *Colloid Plucking*
5. *Organic Activity*

Physical weathering processes are generally the forerunners of chemical weathering. Their main contributions are to loosen rock masses, reduce particle sizes, and increase the available surface area for chemical attack.

Chemical weathering of rocks

Chemical weathering involves the decomposition of rocks resulting in the production of secondary minerals, thus the chemistry and petrological characteristics of the parent rock is greatly altered. The process of chemical weathering is started by the ingress and percolation into the soil of slightly acidic rainwater contaminated with organic impurities.

The rainwater at tropical climatic conditions tends to dissolve soluble minerals such as silica, alkalis, alkali-earth metals etc. from the soil and bedrock leaving behind concentrates of iron and aluminium oxides.

Continual drainage and leaching of these soluble minerals with time deplete them. The processes of chemical weathering are listed below and have been discussed elsewhere (e.g. Blyth and De Freitas, 1976; Mitchell and Soga, 2006).

1. *Hydrolysis*
2. *Hydration*
3. *Carbonation and related activity processes*
4. *Oxidation*
5. *Solution*

Products of weathering

The rock forming minerals such as quartz, feldspar, mica, amphibole, olivine, pyroxene, are the main constituents of crystalline rocks which are formed at great depth at phases which are only stable at very high temperatures and pressures (particularly true for mafic and ultramafic rocks than felsic rocks). When these rocks are exposed to the surface (environment) the equilibrium of the minerals is disturbed and the more the new conditions differ from the original, the more the minerals are inclined to adjusting themselves to the new environment (Weinert, 1980) and are most likely to decompose under suitable conditions. The products of weathering, several of which will generally coexist at one time, include (Mitchell and Soga, 2006):

1. Unaltered minerals that are either highly resistant or freshly exposed
2. Newly formed, more stable minerals having the same structure as the original mineral

3. Newly formed minerals having a form similar to the original, but a changed internal structure
4. Products of disrupted minerals, either at or transported from the site. Such minerals might include:
    a. *Clay minerals*
    b. *Colloidal gels of* Al_2O_3 *and* SiO_2
    c. *Zeolites*
    d. *Cations and anions in solution*
    e. *Mineral precipitates*
5. Unused guest reactants

2.2 Problematic Soils

Problematic soils are structurally unstable soils or geomaterials which pose engineering problems in the design and construction of civil engineering structures. They are considered problematic because, firstly, these geomaterials cannot be classified by grain size and plasticity parameters alone due to non-reproducibility and inconsistency of test results using standard sample preparation methods and testing procedures. Secondly, these geomaterials are characterized by unusual in-service behaviour, including such geo-environmental phenomena as heaving, swell, collapse, dispersion, erosion, excessive creep, subsidence, high compressibility etc which could be attributed to factors such as composition, nature of pore fluids, fabric and mineralogy (Gidigasu, 2009; Bell and Culshaw, 2001).

There are many problematic geomaterials. Some of which are:

1. Basic rocks subjected to rapid physico-chemical weathering in tropical environment
2. Pedogenic materials (lateritic rocks, calcretes, ferricretes, silcretes, etc)

3. Expansive/shrinkable soils (weathered shales, fissured stiff clays, mudstone, black cotton soils, etc)
4. Some lateritic and saprolitic soils
5. Tropical compressible residual red silty clay soils and sensitive halloysitic soils
6. Dispersive and erodible soils
7. Volcanic soils

Some of the peculiar characteristics associated with these problematic geomaterials from literature are:

1. Unstable mineralogical composition (commonly, montmorillonite, allophone, halloysite etc)
2. High insitu moisture contents
3. Unstable soil structure and fabric
4. High water absorption capacity
5. Low insitu density
6. Variable degree of desiccation with depth
7. Variable density-moisture relations with pre-test sample preparation methods
8. Liquefaction prone
9. Erodible/dispersive
10. Collapse phenomena
11. Shrinkage and expansivity
12. Difficulty to stabilize in terms of controlling volume, strength, water absorption capacity, durability, etc
13. Post construction problems

2.3 Expansive soils

Expansive soils are one of the most important problematic soils which occur all over the world and have been subject of considerable research. Nelson and Miller (1992) defined expansive soil as "a general term applied to any soil or rock material, that has the potential for shrinkage or swelling under changing moisture condition but does not include the class of soils generally referred to as collapsible soils". Terms such as "active soils", "shrink-swell soils" and "heavable soils" are used to describe expansive soils. A potentially expansive soil is not necessarily dangerous unless it is subjected to moisture changes which may result from seasonal climatic conditions, changed surface situations and extraneous influence (Bucher and Sailie, 1984). Expansive soils are considered potential natural hazard which can cause extensive damage to various structures and utility if not adequately treated.

These soils have caused considerable damage to civil engineering infrastructure especially roads, dams, canal lining, shallow foundations, etc., either through excessive swell or shrinkage or both. Table 2 summarises some estimated cost of damage caused by expansive soils. The problems with foundation on expansive soils include heaving, cracking and breaking of pavement, building foundation, slab–on–grade members, channel and reservoir linings (Chen, 1988). Typical examples of expansive soils are the black cotton soils (vertisols), stiff fissured clays, weathered shales, etc.

Table 2. Estimated cost of damages due to expansive soils

Country	**Amount**	**References**
Britain	£3 billion (2001)	Bell and Culshaw (2001)
China	¥100 million	Ng et al. (2003)
France	€3.3 billion (2002)	Zemienu et al. (2009)
India	several lakhs of rupees	Gourley et al. (1993)
Saudi Arabia	>US$ 300 million (1977 and 1987)	Ruwaih (1987)
Sudan	>US$ 6 million in 1983	Osman and Charlie (1983)
USA	US $2 billion annually	Nelson and Miller (1992)

2.4 Black Cotton Soils

2.4.1 Definition and Nomenclature

Black clays or tropical black earth or black cotton soils are known to be potentially expansive soils which are "black" or "greyish black" or in their eroded phase "greyish white" in colour. The predominant clay mineral in the soil is the smectite group. Although the soil is rich in alkali earth elements, they may sometimes contain calcium carbonate or magnesium oxide concretions. Many other terms have been applied locally, such as *"regur"* soils in India, *"margalitic"* soils in Indonesia, *"black turf"* in Africa and *"tirs"* in Morocco. Although there are several names, the term "black cotton soil" is adopted in this work because of its extensive use in literature. The term "black cotton" soil is believed to have originated from India where the locations of the soils are favourable for growing cotton. Pedologically, black cotton soils classify as vertisols (Table 3) and both terms are used interchangeably in this thesis.

Table 3. Pedological classification of black clays (Wesley, 1988)

Commonly Used Names	Rigoros Pedological Names			Dominant Clay Minerals
	FAO	US Soil Taxonomy	French	
Black cotton soil, Black clays, Tropical black earths, Grumusols	Vertisols	Vertisols	Vertisols	Smectite (Montmorillonite)

FAO- Food and Agriculture Organisation

The main characteristics of black cotton soils are:

1. They are black or darkish grey to brown in colour
2. They have high content of expansive clay mineral montmorillonite
3. They possess the tendency to shrink and swell with change in moisture condition
4. They exhibit heave and crack as geo-environmental phenomena.

2.4.2 Formation of black cotton soils

The formation of the black cotton soil like any soil is a function of parent rock material or geology, climate, topography and time (age). The formation with respect to the above factors is discussed.

Parent rock material

Black cotton soils have been identified on igneous, sedimentary and metamorphic rocks. They are formed mainly by the chemical weathering of mafic (basic) igneous rocks such as basalt, norite, andesites, diabases, dolerites, gabbros and volcanic rocks and their metamorphic derivatives (e.g. gneisses) which are made up of calcium-rich feldspars and dark minerals which are high in the weathering order, in poorly drained areas with well defined wet and dry seasons. All constituents weather to form amorphous hydrous oxides and under suitable conditions clay minerals develop. The absence of quartz leads to the formation of fine-grained, mostly clay-size, plastic soils which are highly impermeable. In addition, the abundance of magnesium and calcium in the rock gives black cotton soil their swelling potential (Ola, 1983). Black cotton soils also form over sedimentary materials such as shales, limestones, slates etc.

Typical parent rocks that have formed black cotton soils are presented in Table 4. Most parent rocks are rich in feldspar and ferromagnesian minerals which yield clay residue on weathering (Ahmad, 1983). Where the parent rock is not mafic (basic), alkali earth elements can be added by seepage or by flooding waters.

Climate

It was first thought that black cotton soils occur only in monsoonal type of climate with distinct annual wet and dry seasons in the tropics and subtropics, because of earlier recognition of their associations with these climates. However, now they are known to occur in almost every major climatic zone of the world (Ahmed 1996). Annual rainfall between 300-900 mm per year favours the formation of black cotton soils (Katti et al, 2002); however, higher rainfall values 1270mm/year have been recorded in some countries (Table 4).

Table 4. The relationship between parent rock and black cotton soils of some countries

Location	Parent material	Soil Type	Clay Mineralogy	Rainfall (mm/yr)	Drainage	Reference
Nigeria	Olivine basaltic rocks.	Residual	Montmorillonite, Kaolinite	<1270	Poor	Ola (1983); Nwaiwu and Nuhu (2006); USAID/BRRI (1971)
Nigeria	Calcareous materials such as ancient alluvium; clayey and shaly sediments or lagoonal clays	Transported	Montmorillonite	<1270	Poor	Nwaiwu and Nuhu (2006)
South Africa	Norites of the Bushveld igneous complex	Residual	Montmorillonite	609.6		Van Der Merwe (1964; 1967)
Ghana	Garnetiferous Hornblende Gneiss	Residual	Montmorillonite (tr. of Kaolinite)	<1270	Poor	Brammer (1955) ;Stephen (1953)
India	Granites, granite-gneiss, Basalt, etc	-	-	-	-	Michael (2006)
Sudan	Volcanic Ethiopian Mountains	-	-	-	-	Charlie et al (1984)
Sudan	Alluvium from basalt	-	Montmorillonite, Illite, Kaolinite, Chlorite	-	-	USAID/BRRI (1971)
Horn of Africa	Cenozoic basalt	Residual &Transported	Montmorillonite, Kaolinite, Halloysite	-	-	Mgangira and Paige-Green (2008)
Australia	Alluvial deposits derived from carboniferous shale, slate and clay	Transported	--	-	-	Hosking (1935)
Chad Basin	Alluvium	-	Kaolinite, illite and Montmorillonite	-	-	USAID/BRRI (1971)
Kenya	Basalt	-	Montmorillonite, Kaolinite	-	-	USAID/BRRI (1971)
West Cameroon	Basalt	-	Vermiculite, metahalloysite	-	-	USAID/BRRI (1971)
Honduras	Chalk or Marl	-	Montmorillonite	-	Poor	USAID/BRRI (1971)

Topography

Katti et al., (2002) reported that black cotton soil deposits are formed under conditions where the slope of the terrain is less than 3^o. The most frequent physiographic position of black cotton soils is flat, alluvial plain (Dudal and Eswaran, 1988; Eswaran et al., 1988) such as those found in Sudan, Texas in the USA, Darling Downs in Australia, Accra plains, the Ho-Keta plains and the Winneba plains in Ghana (USAID/BRRI, 1971; Building and Road Research Institute, 1985). Other fewer occurrences are the Lufina valley of Zaire, the Kafue Flats of Zambia and the Panamalenga plains and the Springbok flats in Botswana, and South African respectively, however, black cotton soils also occur in surfaces with greater slopes (Ahmad, 1983).

Time

Clemente et al. (1996) reported that time of formation of vertisols are usually inferred from the age of the underlying parent material from which the soil has developed. Furthermore, they realised that most vertisols are derived from Cenozoic era materials including Tertiary and Quaternary. Some sediments of Cretaceous age have also formed vertisols. They indicated however, that the age of the parent material gives information only on the maximum chronological point, the age of the geomorphic surface and the soils would be much younger.

2.4.3 Distribution of Black cotton soils

Black cotton soils (vertisols) have been reported all over the world and have been found to occupy about 2% (257 million hectare) of the total ice-free land area of the earth with 72 million hectares occurring in India, 71 million hectares in Australia (Swindale, 1988) and 43 million hectares is in Africa (Virmani, 1988). Countries reported to have black cotton soils are Australia (Aitchison, et. al., 1962; Ingles and Metcalf, 1972), Algeria (Afes and Didier, 2000), Botswana, Ethiopia (Mgangira and Paige-Green, 2008), Bulgaria, Hungry, Italy (Dudal and Eswaran, 1985), Togo (Oscar et al., 1977), Nigeria (Ola, 1976, 1983; Osinubi, 2006), South Africa (Van Der Merwe, 1964), Morocco, Chad, Cameroon, Kenya, Zambia, (USAID/BRRI, 1971) Tanzania (Bucher and Sailie, 1984), Sudan (Charlie et al., 1984), India (Michael, 2006; Rao et al., 2001), Ghana (Building and Road Research Institute, 1985; USAID/BRRI, 1971) etc. Figure 3 shows the major distribution of black cotton soils in the world.

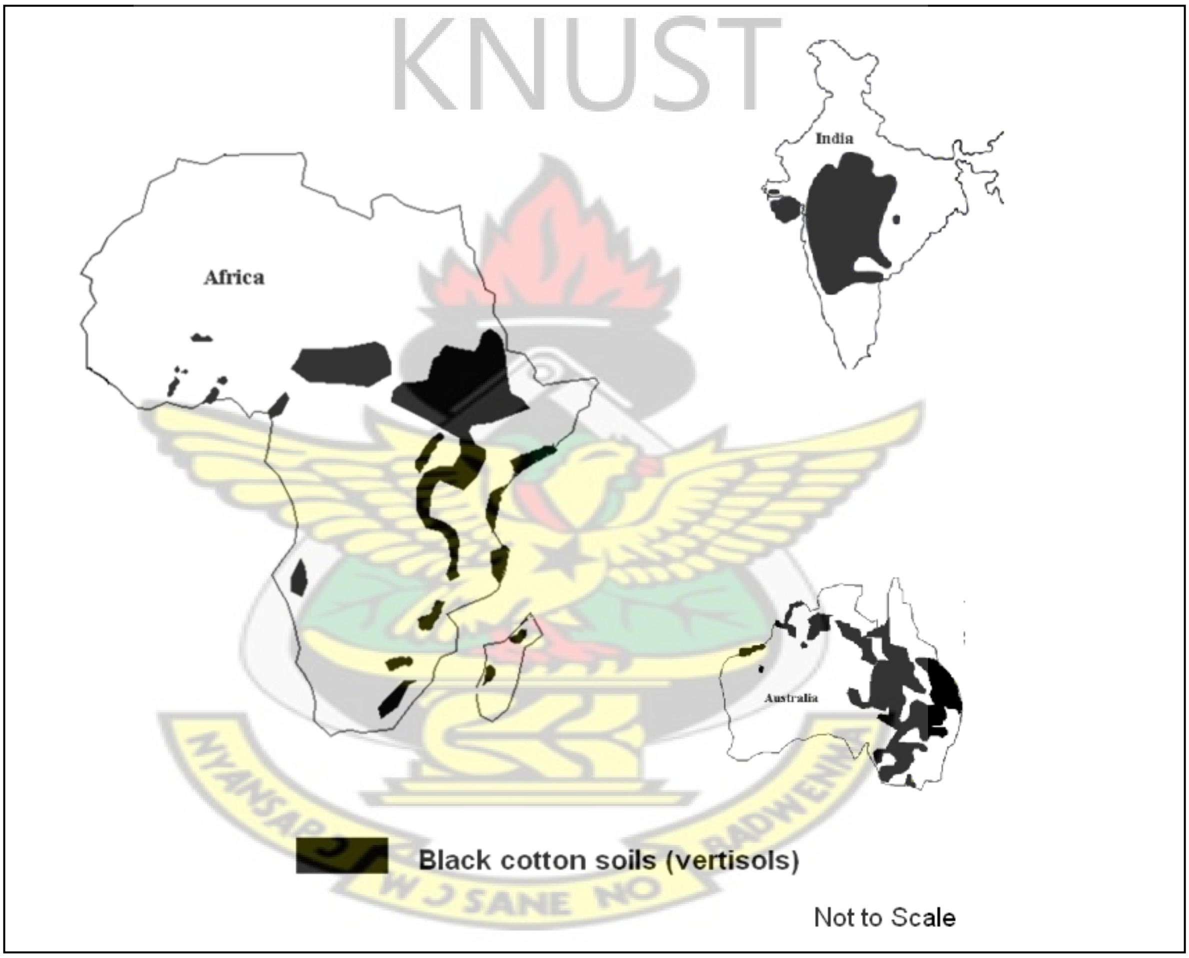


Figure 3. Distribution of black cotton soils (vertisols) with special reference to areas of major concentrations (redrawn from Swindale, 1988; USAID/BRRI, 1971 and Soils and Land Resources Division (Undated)

In Ghana, black cotton clays cover over 168 000 hectors of the land area (Cobbina, 1987) and are mainly found in the south eastern part of the country: Accra-Ho-Keta plains and Winneba plains. Other deposits have been reported on the Bamboi-Bole Road near Kwaman Kwesi, Wa, Grupe, Tamale and some parts of the Volta Region (Building and Road Research Institute, 1985).

2.4.4 Profile characteristics of black cotton soils

The black cotton soils (vertisols) have been found to develop on varied topography from the summit to the valley bottom of the terrain (Cobbina, 1988; Ahmad, 1983; Clemente et al., 1996) and different climatic zones. In terms of general profile characteristics, these soils vary with parent rock, topography, climate, time etc. Vertisols lack the horizon development diagnostic of other horizons. They have "vertic" horizon which is a clayey subsurface horizon with slickensides or edge shape or parallelpiped structure aggregates and are characterised by argillipedoturbation (disruption and mixing caused by swell-shrink of the soil mass). Anon (2009) reported that the swell and shrinkage cause self mulching in which the soil materials consistently mix themselves causing vertisol to have extremely deep A-horizon and no B-horizon. Usually the soils are called A/C soils. The heaving of the underlying material to the surface often creates micro-relief known as gilgai.

Cobbina (1988) recognised that the depths of the soil profiles are variable ranging from a few to 180 cm or even more. Also the soils lack distinct horizons in the profiles with only the "A" and "C" horizons being discernable for Ghanaian black cotton soils. Some typical profile characteristics of black cotton soils from Australia and South Africa are shown in Figure 4.

The colour of the upper horizons of black cotton soils is usually dark grey to black whilst the bottom varies from grey brown, reddish brown to whitish colour.

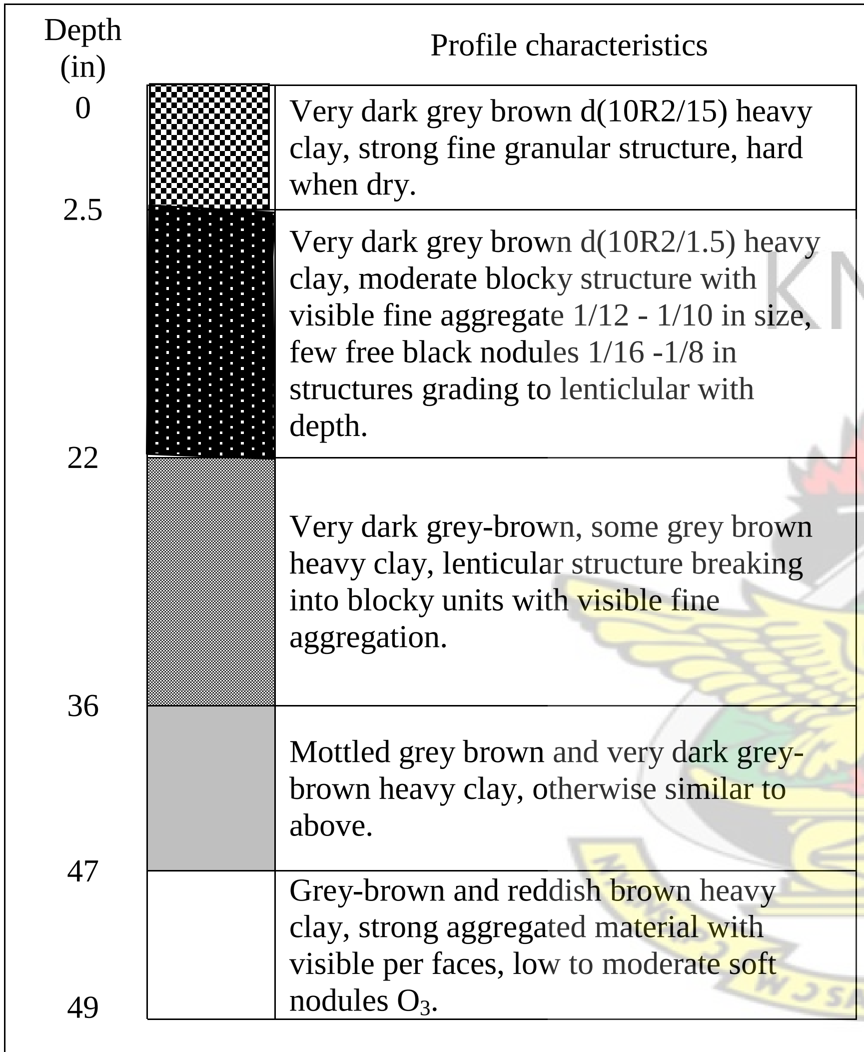


Figure 4a. Typical black cotton soil profile from Australia (Aitchison, et al., 1962)

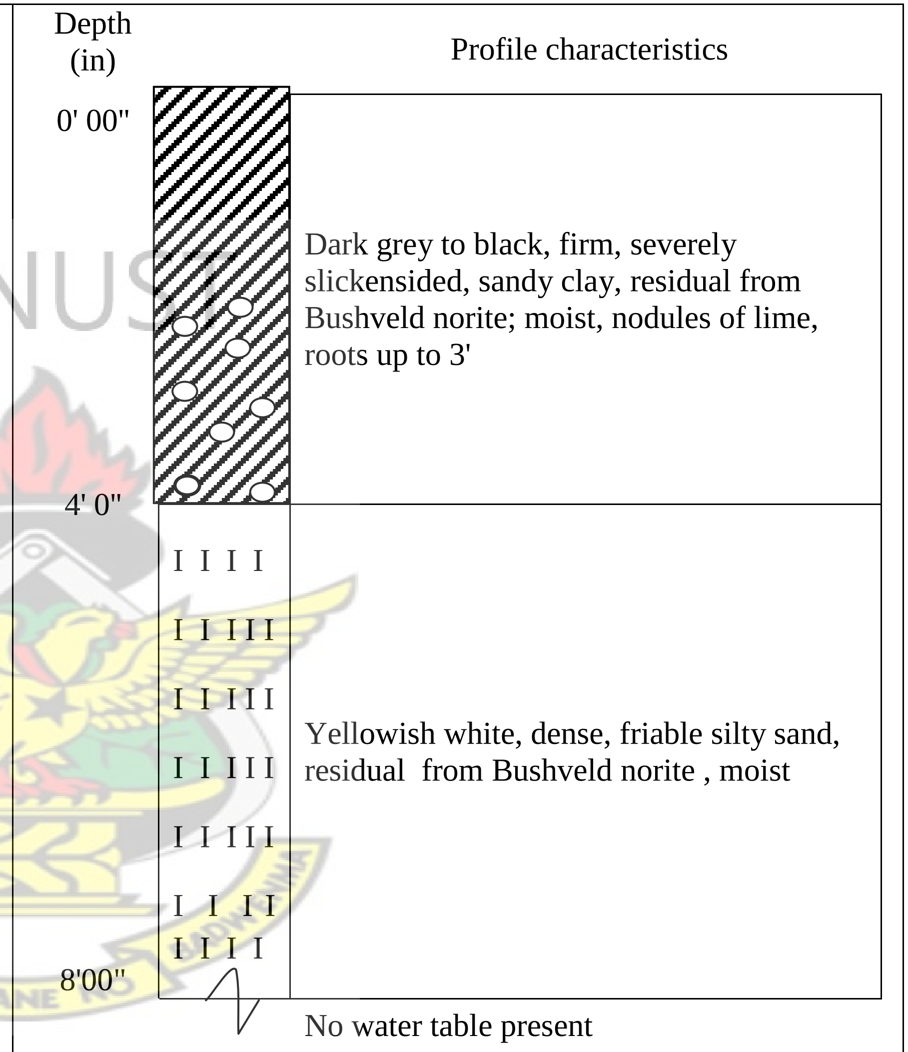


Figure 4b. Profile of black clay from South Africa (Weinert, 1980)

The soil profiles may contain spherical hard, dark coloured ironstone concretions, magnesium oxides, calcium carbonate concretions and sometimes quartz gravels or pebbles at varying depths (Cobbina, 1988; Michael, 2006). Studies by Brammer (1967) indicated that black cotton soils are neutral to slightly acidic in reaction in the upper horizon and moderately alkaline in nature in the lower layers.

2.4.5 Chemical and clay mineralogical status of black cotton soils

Chemistry

Chemical weathering is the main soil forming process of black cotton soils. In this process, the minerals in the rocks are decomposed resulting in chemical alteration. It is therefore important to indicate the chemical composition of the soils which will vary with such factors as parent rock, genetic characteristics of soil (transported or residual), degree of weathering, etc. Typical oxide composition of some typical black cotton soils from some countries are presented in Table 5.

Table 5. Chemical composition of black cotton soils from some countries

Major Oxides	Concentration weight percent (wt %)			
	India[1]	Nigeria[2]	Togo [3]	Indonesia[4]
SiO_2	49.3	31.01	46.32	42.80
TiO_2	1.9	1.34	0.85	0.02
Al_2O_3	13.7	16.19	22.04	19.03
Fe_2O_3	14.8	4.74	12.83	8.68
CaO	6.9	-	0.37	1.73
MgO	4.8	-	2.2	1.81
MnO		0.13	-	0.05
K_2O	-	-	0.2	0.08
Na_2O	-	-	0.18	0.75
P_2O_5	-	-	-	0.06
SO_3	1.6	-	-	-

[1.] Katti et al., 2002, [2.] Osinuobi and Ijimdiya, 2008, [3] Oscar et al., 1977; [4] Mohr and Van Baren, 1959

Black cotton soils are rich in silica, lime, iron, magnesia and alumina. Titanium oxide also occurs in very small concentrations, but, its presence is believed to give the soil the characteristic black colour (Building and Road Research Institute, 1985). Inspite of its black colour, low organic matter contents (less than 5%) have been recorded for these soils. USAID/BRRI (1971) found that silica-sesquioxides ratios of the soils are greater than 2.50 indicating that they are non-lateritic soils.

Clay mineralogy

The main clay mineral reported in black cotton soils is the smectite group of which montmorillonite is predominant. Accessory minerals may be kaolinite, illites, etc. Figure 5 shows typical mineralogical composition of black cotton soils from X-Ray diffractogram. According to Rao (2006) low rainfall hinders the weathering of the active montmorillonite minerals into low active clay mineral such as illite and kaolinite.

Mermut et al. (1996) recognised that the formation and stability of smectite are dependent on the Si activity as well as pH. At high pH, in the presence of high potentials of Si as well as Mg, smectite develops (a process which is also favoured by poor drainage). Transformations of some primary or secondary minerals into smectite may take place (Eswaran et al., 1988). The micro-environmental condition for this transformation is well established as essentially a pH of 7 or higher. If leaching occurs in the upper part of the soil with the generation of an acid environment, montmorillonite tends to be destroyed and other soil forming processes initiate. The environment of formation of montmorillonite, illite and kaolinite is shown in Figure 6.

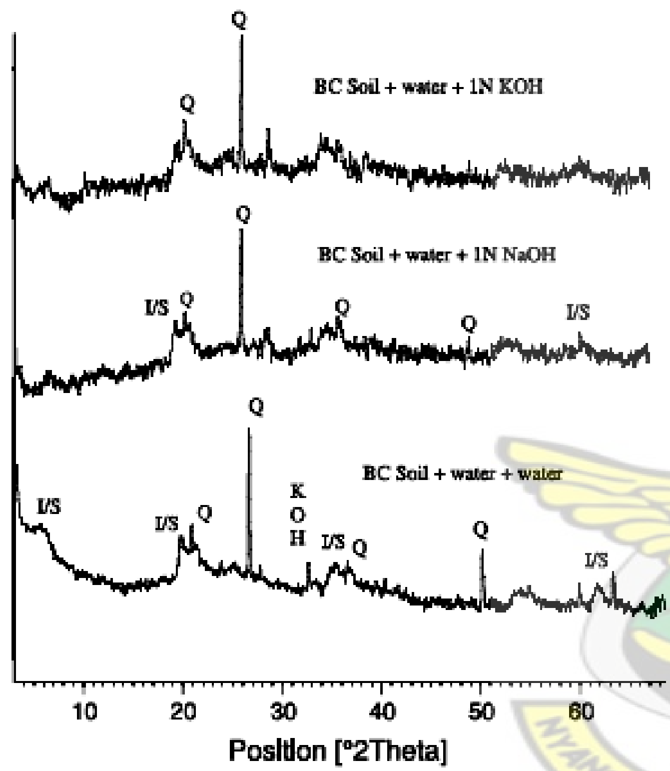


Figure 5. Typical X-ray diffractogram of black cotton soils (from Sivapullaiah and Reddy, 2010)

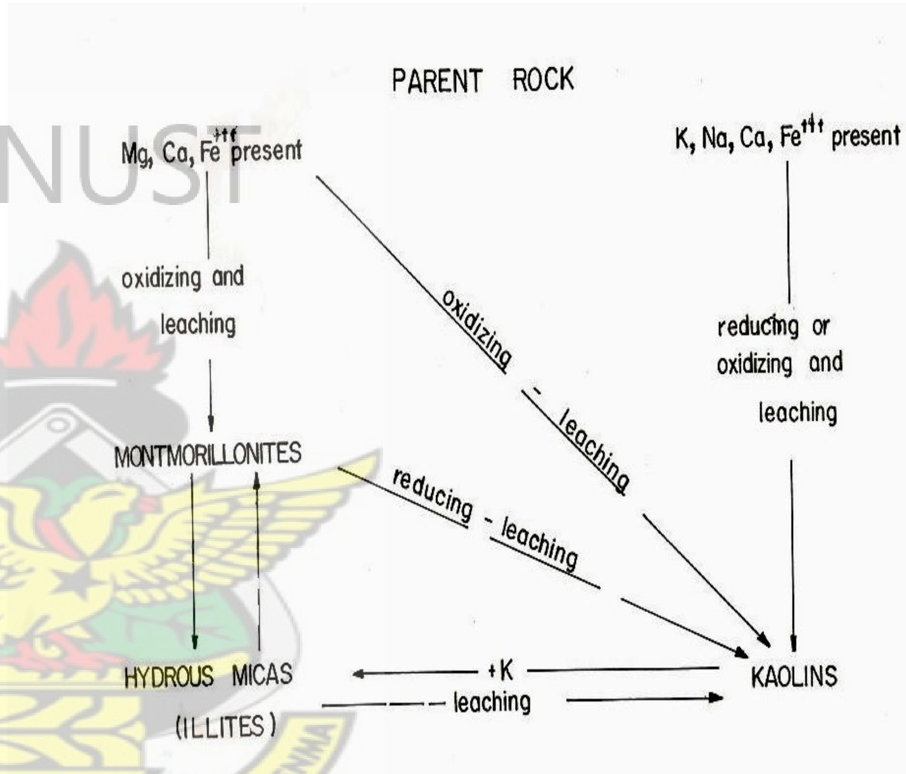


Figure 6. The environment of formation of illite, kaolinite and Montmorillonite (Frederickson, 1952)

2.4.6 Basic Geotechnical characteristics of black cotton soils

Introduction

Table 6 presents a compilation of some available geotechnical characteristics of black cotton soils and are discussed in this section.

Natural Moisture content

The natural moisture content of a black cotton soil in a profile is variable, for instance, the Building and Road Research Institute (1985) reported natural moisture contents for Ghanaian black cotton soils to be between 20% and 45%; Mgangira and Paige-Green (2008) reported that the moisture contents of subgrade black cotton soils in the Horn region of Africa range between 24% and 54%. A typical monthly variation of natural moisture content with depth of a Ghanaian black cotton soil is shown in Figure 7 (Building and Road Research Institute, 1985).

Grading and textural classification

The gradation of these soils varies considerably. There are little or no gravel size in most black cotton soils and those that have, show percentages of less than 8% (USAID/BRRI, 1971). The amount of sand varies between 2% and 50 % whilst silt is between 11% and 58%. The clay size contents also range from 40% to 75%. Low clay size contents (22%) have been reported for some Tanzania black cotton soils (Bucher and Sailie, 1984). The soils classify as clay, sandy-clay and silty-clay on the U.S. Engineers textural classification chart (Figure 8).

Table 6. Summary of Geotechnical characteristics of black cotton soils (Data from Literature)

Location	Grading (%)			sg	LL (%)	PL (%)	PI (%)	Activity	SL	Soil Group		MDD (Kg/m^3)	OMC (%)	Free Swell (%)	References
	Sand	Silt	Clay							ASTM	ASSHTO				
	6	54	40		82	35	47		10.0	CH		1290	35		Sivapullaiah (2010)
	2	37	61	2.6	86	32	54			CL		1400	36.3		Rao et al. (2008)
	16	29	55		84	23	61		10.0	CH					Mishra et al. (2008)
	7	41	52	2.68	85	38	47		12.0			1320	28		Sahoo & Pradhan (2010)
	31	28	41		63	24	39		10.0					132	Shankar et al. (undated)
	11	28	61	2.7	77	31	46		10.0	CH		1410	30		Rao & Shivananda (2005)
	3	28	69	2.6	190	45	145		15.3	CH				690	Ameta et al (2007)
	6	54	40		82	35	47		10.0	CH		1290	35		Sivapullaiah (2010)
India				2.74	56	23	33		10.3			1510	27.76		Sivapullaiah et al (2007)
	28	32	40		65	19	46					1730	20		Rao et al. (2001)
	20	29	51		55	25	30					1690	21		
				2.36	28	14	24			CL		1440	21.04		Gosavi et al. (2004)
	2	37	61	2.65	86	32	54			CH		1400	36.3	180	Rao & Rao (2008)
	2	79	19	2.7	85	44	41		23.7	CH				75	Ameta et al. (2007)
	30	34	36		45	23	22		11.0		A-7-6(13)				
	15	29	56		82	23	59		10.0			1240	28		
	17	30	53		69	34	35		10.0		A-7-5(20)				BRRI/USAID (1971)
Honduras	2	23	75	2.64	126	58	68		25.0		A-7-5(20)				
Rodesia	34	11	55		72	24	48		11.0		A-7-6(17)				
Ghana	10	40	50		99	29	70		11.0		A-7-6(20				
					60-100		30-60				A-7-5 (10-20)	1601-1762	18-16		Gidigasu & Appiagyei (1980)
Horn of Africa	3-12	25-70	18-73	2.43-2.45	43-103	17-49	26-54	0.6-1.11				1108-1278	22-49		Mgangira & Green (2008)
	14	32	54		56	24	32	0.59			A-7-6				
	19	25	56		59	31	28	0.5			A-7-5				BRRI/USAID (1971)
Moroco	5	25	70		60	20	40		10.0						
	12.4	17.5	70.1	2.5	65.5	30.5	35		10.2	CH	A-7-6			90	
	12.58	12.47	74.95	2.48	63.9	31.25	32.65		11.2	CH	A-7-6			110	
	12.47	12.49	75.05	2.56	65.6	32.3	33.3		11.0	CH	A-7-6			105	Nwaiwu and Nuhu (2006)
	11.54	31.91	56.55	2.58	62	31.85	30.15		10.4	CH	A-7-6			70	
Nigeria	12.18	32.04	56.78	2.57	63.3	27.5	35.8		11.7	CH	A-7-6			60	
	13.7	29.55	56.75	2.55	64.1	33.15	30.95		11.9	CH	A-7-6			60	
	12.39	14.99	72.56	2.34	62.3	24.2	38.1		18.6	CL	A-7-6(24)	1710	18	76.25	Osinubi (2000)
	20	5	75	2.66	65	19	46		13.0	CL	A-7-6(6)	1630	19.2	70	Osinubi & Iiimdiva (2008)
	51	23	28		70	27	43		20.7			1417.6	28.7		Ola (1983)

Table 6. Continued

Location	Grading (%)			SG	LL (%)	PL (%)	PI (%)	Activity	SL	Soil group		MDD (Kg/m^3)	OMC (%)	Free Swell (%)	References
	Sand	Silt	Clay							ASTM	ASSHTO				
Nigeria				2.5	93	21	72				A-7-6	1410	24.3		Oriola et al.(2010)
				2.56	78	31	47					1412.8	27	50	Ola (1979)
Chad Basin	10	20	70		58	16	42	0.61	12.0			2970	20.2	70	
	19	28	53		44	14	30	0.59	9.0			2162	13	55	
	10	30	60		52	19	33	0.82		CL	A-7-6			50	
Chad Basin	14	34	52		56	30	26	0.4	15.0			1650	18.6	50	BRRI/USAID (1971)
Kenya	30	8	62	2.28	104	34	70	1.15						92	
	8	37	55	2.47	72	24	48	0.88			A-7-5			87	
Ethiopia	4	38	56		109	28	81	1.36	14.0			1485	23	88	
					35	21	14		7.0						Van der Merwe (1964)
south Africa					78	32*	46		18.0						
Tanzania	19	31	48		60	30	30					1730	18.7	65	BRRI/USAID (1971)
	15	43	42		57	29	28	0.7				1660	10.2	660	
	6	34	60		79.8	34.9	44.9	1				1400	28.5	220	
	12	38	50		84	32.6	51.4	0.8							
	35	38	27		60	25.9	34.1	1.3							
	28	37	35		79.8	29.9	49.9	1.4							Bucher&Sailie (1984)
	45	20	35		55.4	21	34.4	1				1560	22		
	32	41	27		59.2	18	41.2	1.5							
	8	27	65		90.4	38	52.4	0.8				1580	17		
	48	30	22		51	19.2	31.8	1.5							
	25	37	38		73.2	29.5	43.7	1.2			A-7-6(20	1260	36		
Palistine	16	26	58	2.79	69		42		10.0						
Zambia	14	35	51	2.58	49	16	33	0.65	16.0			1802	16	57	
	30	20	50	2.61	50	17	33		15.0					58	BRRI/USAID (1971)
Cameroon	42	58	0		64	37	27	1.7			A-7-5				
	19	43	38		62	35	27	0.71			A-7-6				
Algeria	8	28	62		47.7	24	23	0.37							Afes and Didier (2000)
Australia	11	22	67	2.83	88	34	54		22.0	CH	A-7-5(20)	1538	21		
	3	26	71	2.84	91	31	60		24.0	CH	A-7-5(20)	1561.8	25.5		
	14	18	68	2.86	101	36	65		22.0	CH	A-7-5(20)	1553.791	27		Ingles and Metcalf (1972) Aitchison at al. (1962)
	20	23	57	2.93	102	29	73		24.0	CH	A-7-6(20)	1554	28		
	1	29	70	2.87	100	27	73		23.0	CH	A-7-6(20)	1513.745	29		
Botswana			47-58	2.58-2.69	53-55	24-28	27-29					1236	22		Abadjieva (2001)

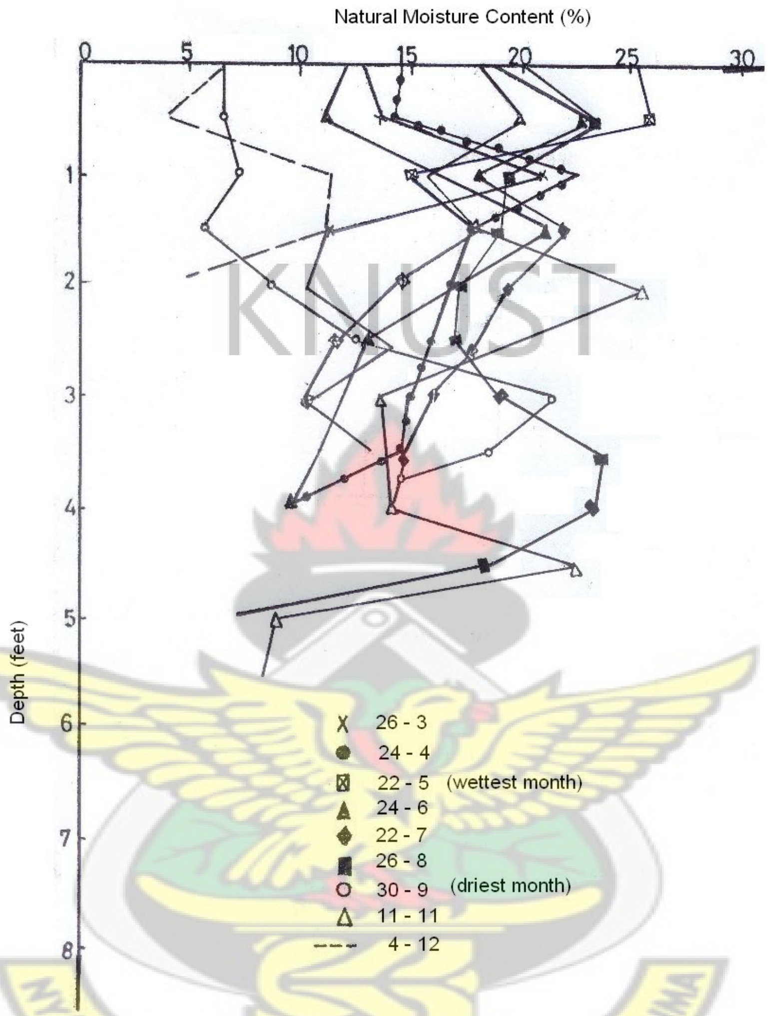


Figure 7. Variation of natural moisture content with depth of typical Ghana black cotton soil profile (Building and Road Research Institute, 1985)

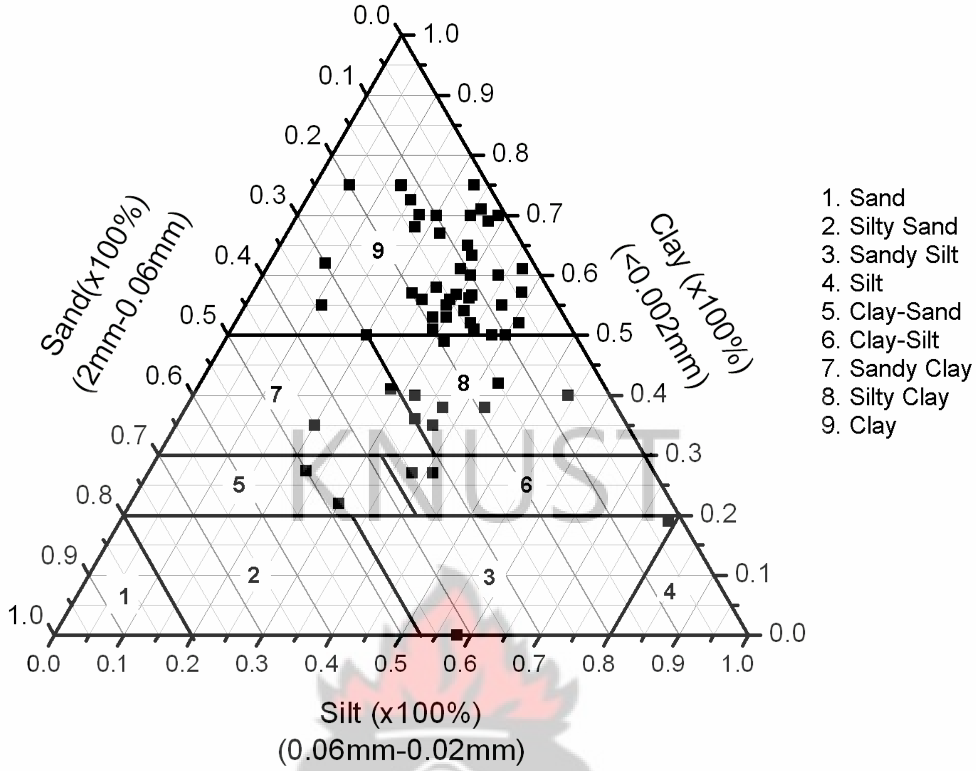


Figure 8. Textural characteristics of black cotton soils on US Engineers Soil Classification chart (53 data sets)

Plasticity characteristics and Activity

The Liquid Limit of black cotton soils are variable and range from 28%-190%, and the Plasticity Index ranges between 14% and 145%. Black cotton soils normally plot above the A-line and classify as inorganic clay of low to very high plasticity on the Casagrande's chart (Figure 9). The shrinkage limits range between 7% and 26%.

Most black cotton soils classify as A-7-5 and A-7-6 by the AASHTO Classification System (AASHTO, 1986) with group index values varying from 13-89 (USAID/BRRI, 1971) and CH and CL on the Unified Soil Classification System (ASTM, 1992).

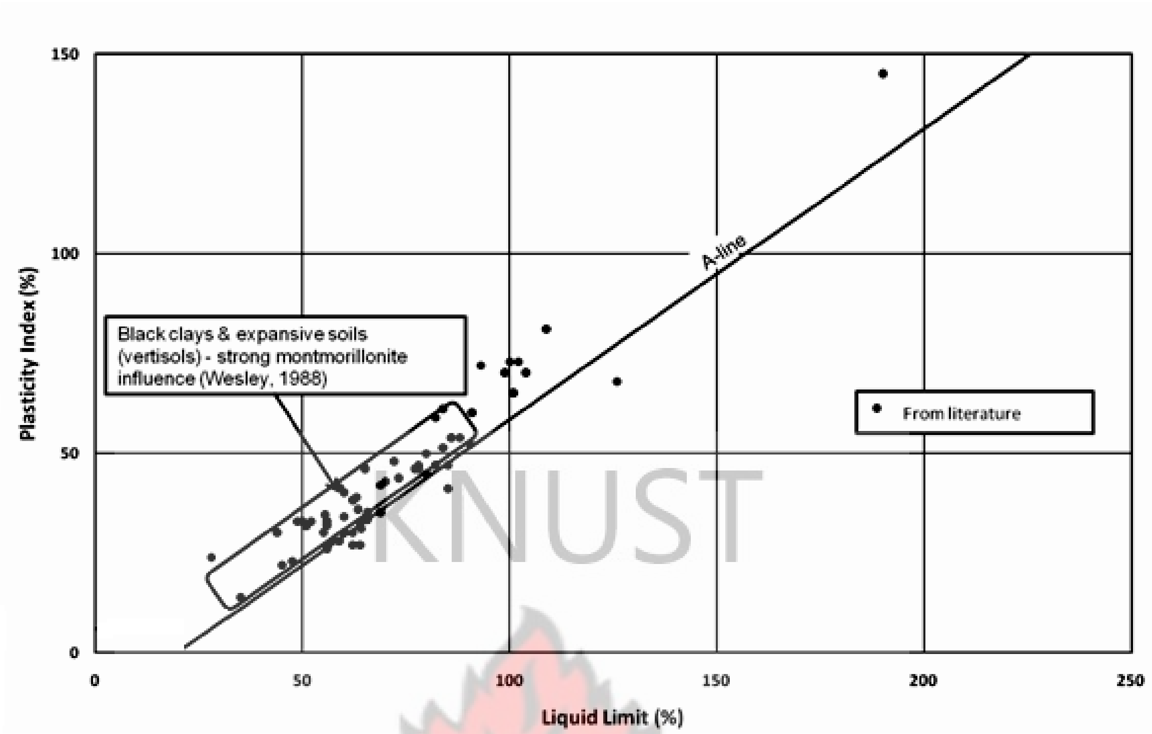


Figure 9. Plasticity characteristics of black cotton soils

The activity of the black cotton soils from the data collected (Table 6) was found to range between 0.37-1.70, thus indicating that the soils have low to high expansion potential based on the criteria proposed by Skempton (1953) (see Table 7).

Table 7. Rating of soils based on Activity of the clay fraction (Skempton, 1953)

Activity	Potential expansion
<0.75	Low
0.75-1.25	Medium
>1.25	High

Free swell and permeability characteristics

Generally, free swell of black cotton soils varies between 50% and 220%. However, values of 660% have been reported for a Tanzanian black cotton soil (Bucher and Sailie, 1984) and 690% for an Indian black cotton soil (Ameta et. al. 2007).

Ola (1978) found the permeability of typical black cotton soil from oedometer test to be of the order of 10^{-10} cm/sec, very similar to those reported by Ranganathan (1961) for Indian black cotton soils.

Compaction characteristics

The Maximum Dry Density (MDD) and Optimum Moisture Contents range from 2970kg/m^3 to 1108kg/m^3 and 10%-49% respectively. The correlation between MDD and OMC (Figure 10) shows $\boldsymbol{MDD = 1971.7 - 18.59OMC}$ and a coefficient of correlation as **0.699**

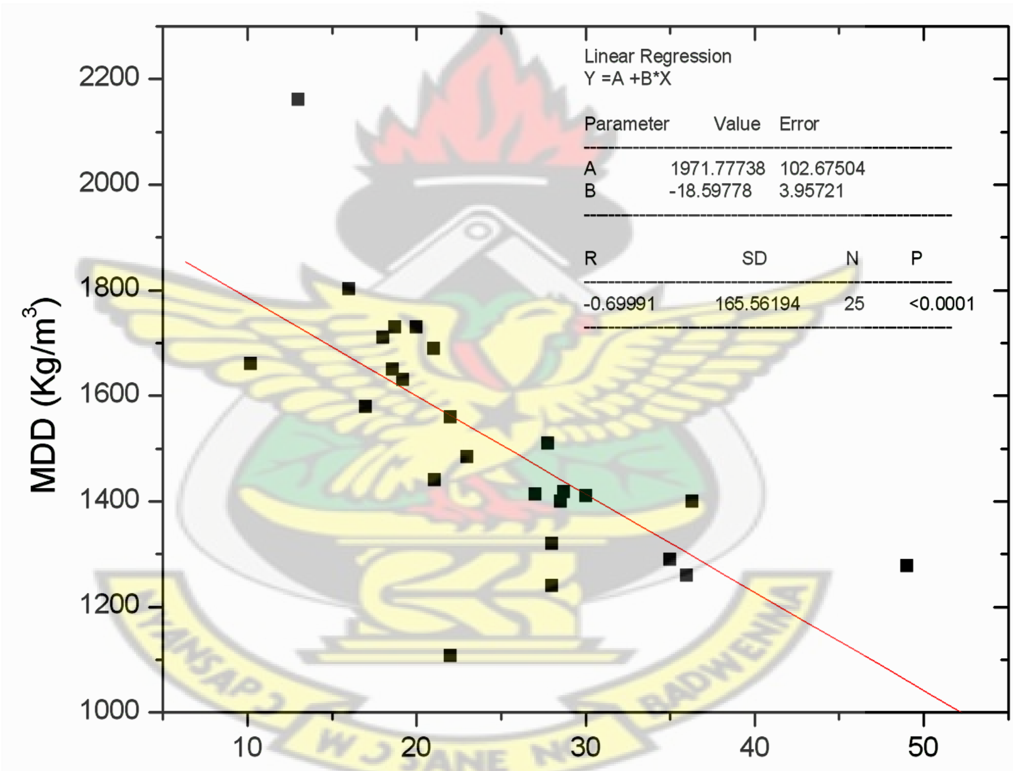


Figure 10. The relationship between MDD and OMC

Unsoaked California Bearing Ratio (CBR) values of black cotton soils are generally high but soaking reduces them greatly. According to the Building and Road Research Institute (1985) the CBR of typical Ghanaian black cotton soils compacted at West African Standard and Modified ASSHTO standard were 35% and 40% respectively but due to the sensitivity of the soils to water, the 96-hour soaked CBR values reduced drastically to between 0.5% and 2%.

2.4.7 Stabilisation of Black Cotton Soils

The alteration of existing soil properties to meet specific engineering requirements is known as *soil stabilization*. Soil properties can be improved in a number of ways such as mechanical, chemical, electrical, geosynthesis and thermal treatment.

Many materials such as chlorides, pozzolans, geosynthetics have been used as additives to stabilise black cotton soils (Sivapullaiah, 2010; Sivapullaiah et al, 2010; Osinubi and Ijimdya, 2008; Oriola and Moses, 2010; Gosavi et al, 2004) etc, however, the most common ones that are widely used include cement, lime and bitumen (Ola, 1975; USAID/BRRI, 1971; Phanikumar, 2009). The effect of these stabilisers on black cotton soils is discussed.

Cement stabilization

The addition of cement to soil produces some chemical reaction which alters the behaviour of the soil. These changes result from the hydration of the cement and therefore are highly dependent on the amount of cement. The hydration of cement produces calcium aluminate and silicate bonding materials which form bonds between and around the soil grains; these result in a matrix that encloses the soil particles. In some fine-grained soils, the free lime produced during cement hydration reacts with the soil to increase the strength with curing time.

Fine grained soils require large amounts of cement, and very heavy clays may not be economical to stabilise with cement alone.

Ola (1983) reported that stabilization of black cotton soils with cement alone is not suitable. The non-suitability of cement as good stabilizer is based on the economics/cost of application, because the presence of montmorillonite in the soils retards hydration and hence high percentages of cement would be required for adequate stabilization. Furthermore, the effect of cement on the Atterberg limits is minimal and workability is not improved.

Bitumen stabilization

Stabilization with bitumen is unsatisfactory for clays with liquid limits greater than 40% and plasticity index exceeding 20% (Ola, 1983). Usually, black cottons soils have plasticity values greater than the above and hence cannot be stabilised with bitumen.

Lime stabilization

Lime stabilization is one of the most effective methods of stabilizing expansive soils especially black cotton soils (USAID/BRRI, 1971). Some advantages of lime stabilization according to Ola (1983) are:

i. Workability is improved
ii. Lime effect on the Atterberg limits are beneficial and considerable
iii. Lime dries the soil if moisture is over optimum
iv. Lime normally increases the optimum moisture content (OMC) and reduces the optimum density, which are desirable effects.
v. Lime stabilized soils act as a water resistant barrier against the penetration of both gravity and capillary water in the soil.
vi. Unconfined compression strength and California bearing ratio values of the clay increase considerably with the addition of lime and the lime treated soil gains strength with age.
vii. Limes stabilized soils shed water readily and act as a “workable table “for construction to continue in the rainy season.

These positive effects notwithstanding, stabilising black cotton soils with lime is a problem because of the low solubility of lime and difficulty of mixing (Manchikanti and Raju, 2008).

Mechanical stabilization

Subgrades and bases of roads and airfields should be stable thus they should be resistant to lateral displacement under loading. Well graded and well compacted soils are naturally stable and generally require no treatment. Where the grading is deficient, it may often be improved by mixing with another soil so that the combined grading is near ideal. This process is called *mechanical stabilisation*. Fuller et al. (1909) have shown that for a material to have greatest maximum density, the grading should be such that the percentage passing any sieve is approximately: $\mathbf{100}\sqrt{\frac{D}{D_{max}}}$, where D is the aperture of the sieve and D_{max} is the largest particle size. Adequate mixing and good compaction is essential if stable condition is to be achieved.

Mechanical stabilization of clays by the addition of sand for instance, is difficult due to problems involved with the proper pulverization of clay clogs and mixing with sand. Adding sand in combination with lime has been found to be more effective, particularly for water sensitive clays (Ola, 1983).

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

Three sites were initially selected for preliminary studies and only two sites adopted for the detailed investigation. The sites were explored using test pitting and auguring. Representative samples were collected for field and laboratory investigations. The methods of sampling and sample preparation as well as test conducted are discussed.

3.1.1 General reconnaissance survey

A field reconnaissance survey was carried out in the Accra plains to collect relatively simple information about surface and subsurface conditions of the site for the design and planning of the detailed investigation. Information was collected on:

i. Accessibility to the site
ii. Topography
iii. Vegetation
iv. Soil profiles determined from shallow test pits
v. Land use
vi. General drainage conditions
vii. Condition of engineering structures on site (evidence and extent of damages observed)
viii. Occurrences of gilgais, desiccation cracks, slickensides in soils

Based on the reconnaissance survey, detailed sub-soil investigation was carried out to provide comprehensive information on the nature of sub-soil and groundwater conditions so as to enable a complete geomechanical assessment of the effect of black cotton soils on the economy, service life, safety and integrity of civil engineering structure built on such soils in the Accra plains.

3.2 Soil Sampling

Test pits were excavated using pick axe and shovel. The pits were sometimes supplemented with auger boring. The dimension of the test pit was 1meter-length by 1.5meter-breadth by 3meter-depth. A depth of three meters was chosen because the swell and shrinkage phenomena of expansive soils have greatest effect on light weight structures such as pavements, one- and two- storey buildings usually founded at depths shallower than three meters. Disturbed samples were taken from within 0.3m-1.4m from the Tsopoli area and 0.2m-0.7m in the Doryumu area, packaged, labelled and sent to the laboratory for testing.

3.3 Testing of Soils

Field and laboratory tests were conducted on selected samples retrieved from the pitting and borings to evaluate their physical and geomechanical characteristics. The tests performed include the evaluation of the following:

Physical characteristics

- Textural characteristics of the soils
- Colour
- Lithological characteristics
- Insitu strength and structure of the soil

Geomechanical Parameters

- Natural moisture content
- Particle size analysis
- Atterberg limits (liquid limit, plastic limit, linear shrinkage)
- Particle density
- Organic matter content, carbonate content, cation exchange capacity, exchangeable ions, etc
- pH value
- Free swell test

- Clay mineral and chemical analysis
- Swell test on compacted materials
- Compaction and stabilization characteristics using pozzolana, pozzolana-cement and quarry dust
- California Bearing Ratio (CBR) on raw and stabilized compacted materials

3.3.1 Test Procedure

Physical characteristics of the soils

The physical characteristics of the soils were determined based on visual examination and how the soils samples feel in the palm of the hands.

Index Properties

Natural moisture content, Atterberg limits, particle size and particle density were determined in accordance with the British Standard (BS1377, 1990). For the particle size analysis only the hydrometer test was conducted for the raw black cotton soils as the materials were fines. Sodium Hexametaphosphate was used as the deflocculating agent. The particle density was determined using the pycnometer method.

Strength tests

The Modified AASHTO (ASTM D1557-91) standard was used for the compaction related tests. CBR tests were conducted on samples compacted to Modified AASHTO standards and then soaked for 96 hours prior to testing.

Chemical and Mineralogical Analysis

Representative soil samples were sent to the Ghana Geological Survey, Accra for chemical analysis. Major oxides and minor elements were analysed using the X-Ray Fluorescence Spectrometer method. Some samples were also analyzed for their mineralogical composition using the X-Ray diffraction method at the Department of Materials Engineering, KNUST. Organic matter content, carbonate content, cation exchange capacity, exchangeable ions were carried out at the Soil Science Laboratory at the Faculty of Agriculture and Natural Resources, KNUST.

Swell characteristics

The swell characteristics of the soils were determined using three methods: free swell, free swell index and swell measurements taken during the soaking of CBR samples. The free swell was determined using methods proposed by Holtz and Gibbs (1956) and the free swell index by Indian Standard Institution (IS 1498, 1987).

The free swell test consisted of pouring slowly 10 cm^3 of oven dried soil (passing 425 mm sieve) into a 100 cm^3 measuring jar filled with distilled water and noting the volume of the soil after it comes to rest at the bottom of the jar. The free swell was then reported as the increase in the volume of the soil expressed as a percentage of the initial volume.

IS 1498 gives a criterion to predict the expansivity of soils, based on the free swell index.

$$FSI = \frac{(Vw - Vk)}{Vk}$$

where Vw is the sediment volume of 10 g of oven dried soil passing 425 mm sieve placed in a 100 ml graduated measuring jar containing distilled water, and Vk is the sediment volume of 10 g of oven dried soil passing 425 mm sieve placed in a 100 ml graduated measuring jar containing kerosene.

The CBR swell was determined by the relation:

$$Swell = \frac{change\ in\ \ height\ of\ sample}{Height\ of\ sample\ in\ mould} \times 100\%$$

pH

The pHs of the raw soils were determined at the Soil Science Laboratory of the Faculty of Agriculture and Natural Resources, KNUST.

Stabilisation studies

The black cotton soils were subjected to both mechanical and chemical stabilization with local stabilizing materials. Quarry dust was used for the mechanical stabilization whereas commercial pozzolana and pozzolana-cement mixes were used for the chemical stabilisation.

1. Sample preparation and testing

The soils were air-dried and lumps broken into pieces passing 19mm sieve size. The air-dried soil samples were then mixed with calculated amount of stabilizer before testing. The geomechanical tests conducted on the stabilized soils were: the Atterberg limits (liquid limit, plastic limit, and linear shrinkage), free swell /free swell index, grading, compaction and CBR related test

2. Mix designs

Quarry dust stabilisation

The soil-quarry dust mixtures were prepared for 0%, 10%, 30%, 50% and 100% by weight of the quarry dust. The soil-quarry dust composite materials were then subjected to the various geomechanical tests.

Pozzolana stabilisation

The black cotton soils were stabilized with locally produced pozzolana. The pozzolana was acquired from the Building and Road Research Institute, Kumasi. The soil-pozzolana mixes were prepared by mixing 0%, 3%, 6%, 12% and 15% pozzolana contents by weight of dry black cotton soil. The soil-pozzolana composite materials were then subjected to the various geomechanical tests.

Pozzolana-cement

The pozzolana-cement admixture was produced by mixing two parts of ordinary portland cement to one part of pozzolana. The pozzolana-cement was then blended with the black cotton soils in 0%, 3%, 6%, 9% and 12% by weight of dry soil. The soil-pozzolana-cement composite materials were then subjected to the various geomechanical tests except the free swell and free swell index.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Nature and characteristics of the black cotton soils

The black cotton soils used in the study were collected from between 0.3-1.4m below ground level from Tsopoli and 0.2m–0.7m from Doryumu in the Accra Plains of Ghana. The sites are underlain by the Garnet-amphibolite gneiss of the Dahomeyan Supergroup. The gneisses have undergone chemical weathering to produce the black cotton soils under sub-humid climatic conditions of Ghana. The presence of mafic minerals in the rock favours the formation of clay minerals.

Typical profiles associated with the soils are shown in Figure 11. The Tsopoli profile consists of 0.3m topsoil which is underlain by a black, moist, firm clay of homogeneous characteristics from 0.3m-1.4m. The clays exhibit slickensides and have few black concretions. This is then followed by a greyish, firm clay with lime nodules scattered throughout the horizon at a depth of between 1.4m and 2.75m. From the depth of 2.75m to 3m a greyish stiff, homogeneous clay with black concretions scattered in the horizon was encountered.

The generalised profile of Doryumu soil consists of dark, compact, clayey topsoil from 0-0.2m from the ground surface. This is underlain by a dark grey, firm, moist clay with few black concretions and occasional pebbles up to a depth of 0.7m. Between a depth of 0.7m to 1.36m a grey, firm, dense clay with pebbles and lime nodules occur at the base. Between a depth of 1.34m and 1.4m is decomposed rock with lime nodules and corestones.

No groundwater was encountered in both pits.

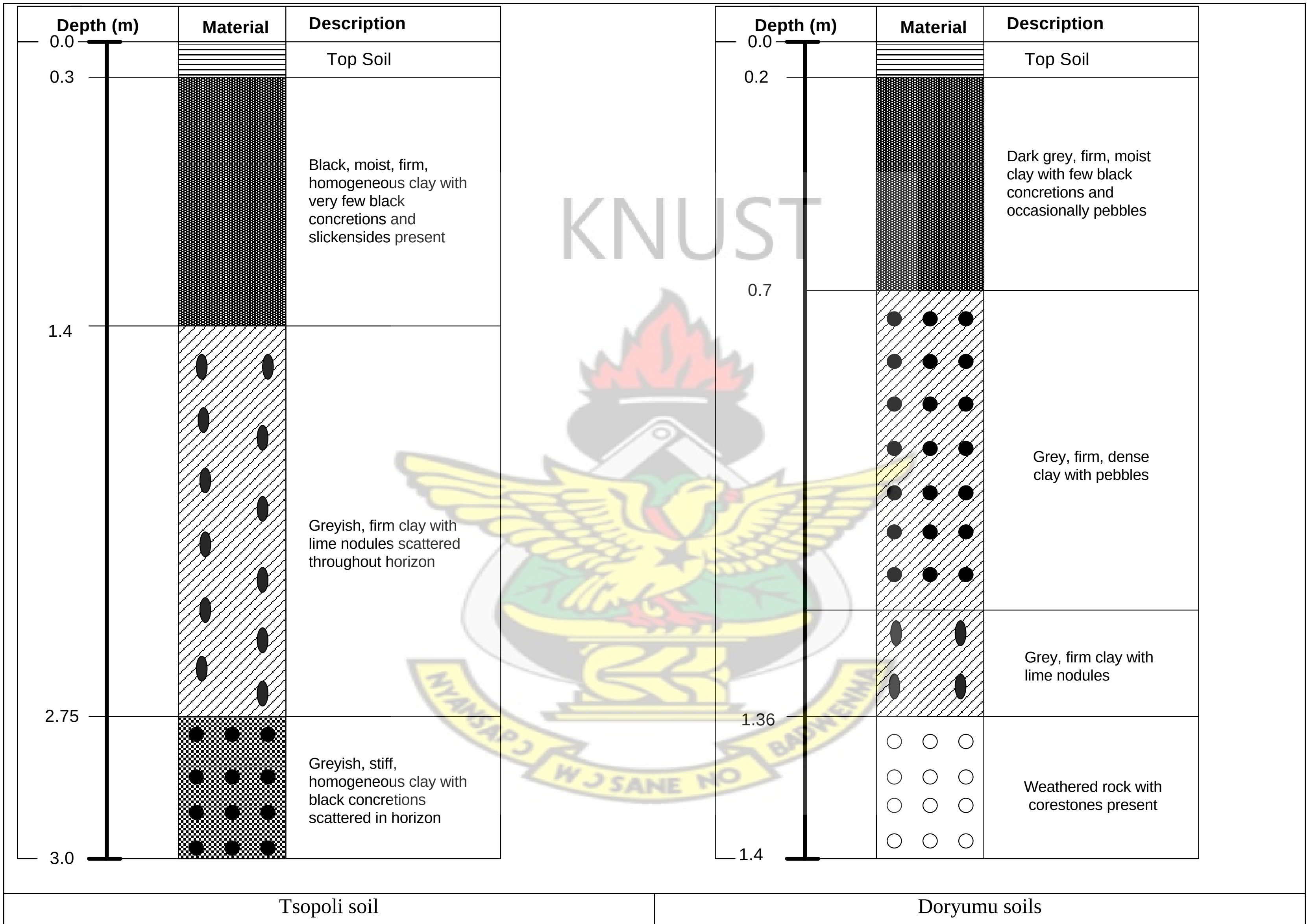


Figure 11. Profile characteristics of the black cotton soils

4.1.1 Chemistry and mineralogy of the soils

The chemical compositions of the two soils are shown in Table 8. It is found that the two soils differ in chemistry. Even though silica, alumina and iron oxide were the dominant oxides in both soils, the concentrations of silica, sodium oxide, potassium oxide, phosphorus oxide, and sulphate contents were much higher in the Tsopoli soils than that in the Doryumu soils. Titanium oxide which has been reported by some researchers as being the cause of the dark colour of the soils is 1.09% and 1.42% for Tsopoli and Doryumu soils respectively. Concentrations of heavy metals (Nickel, Chromium and Molybdenum) are higher in the Doryumu soils than in the Tsopoli soil. The variation of the major oxides with soils is presented in Figure 12.

Table 8. Chemical composition of the soils

Major Oxides	**Concentration (wt %)**	
	Tsopoli	**Doryumu**
SiO_2	62.18	54.26
Al_2O_3	18.23	20.29
Fe_2O_3	6.7	10.22
TiO_2	1.09	1.42
CaO	0.7	1.6
Na_2O	2.07	1.12
K_2O	0.11	0.05
MgO	2.45	2.78
P_2O_5	0.05	0.004
MnO	0.07	0.29
SO_3	0.1	0.04
LOI	6.2	7.90
Heavy metal concentrations (ppm)		
Ni	32.6	142
Cr	127	453
Mo	18.4	23.8
Pb	11.5	2

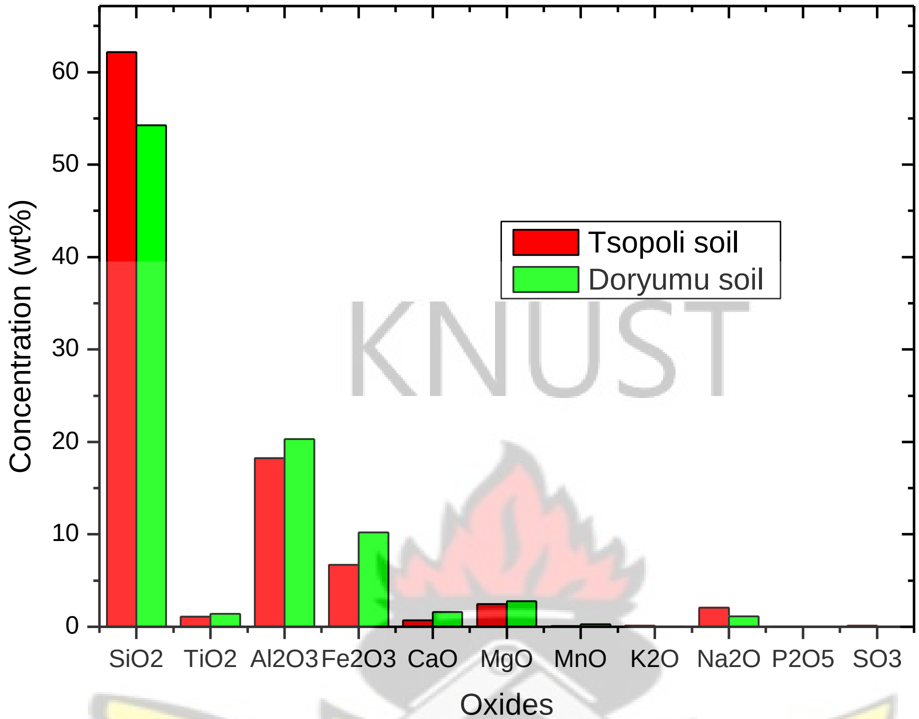


Figure 12. Variation of major oxides with soils

The diffractogram of the two soils (Figure 13) show similar phases indicating similar mineralogy. The minerals identified were Quartz and Montmorillonite, suggesting that the main clay mineral in the black cotton soils occurring in the Accra Plains are the montmorillonite clay and therefore the soils are potentially expansive.

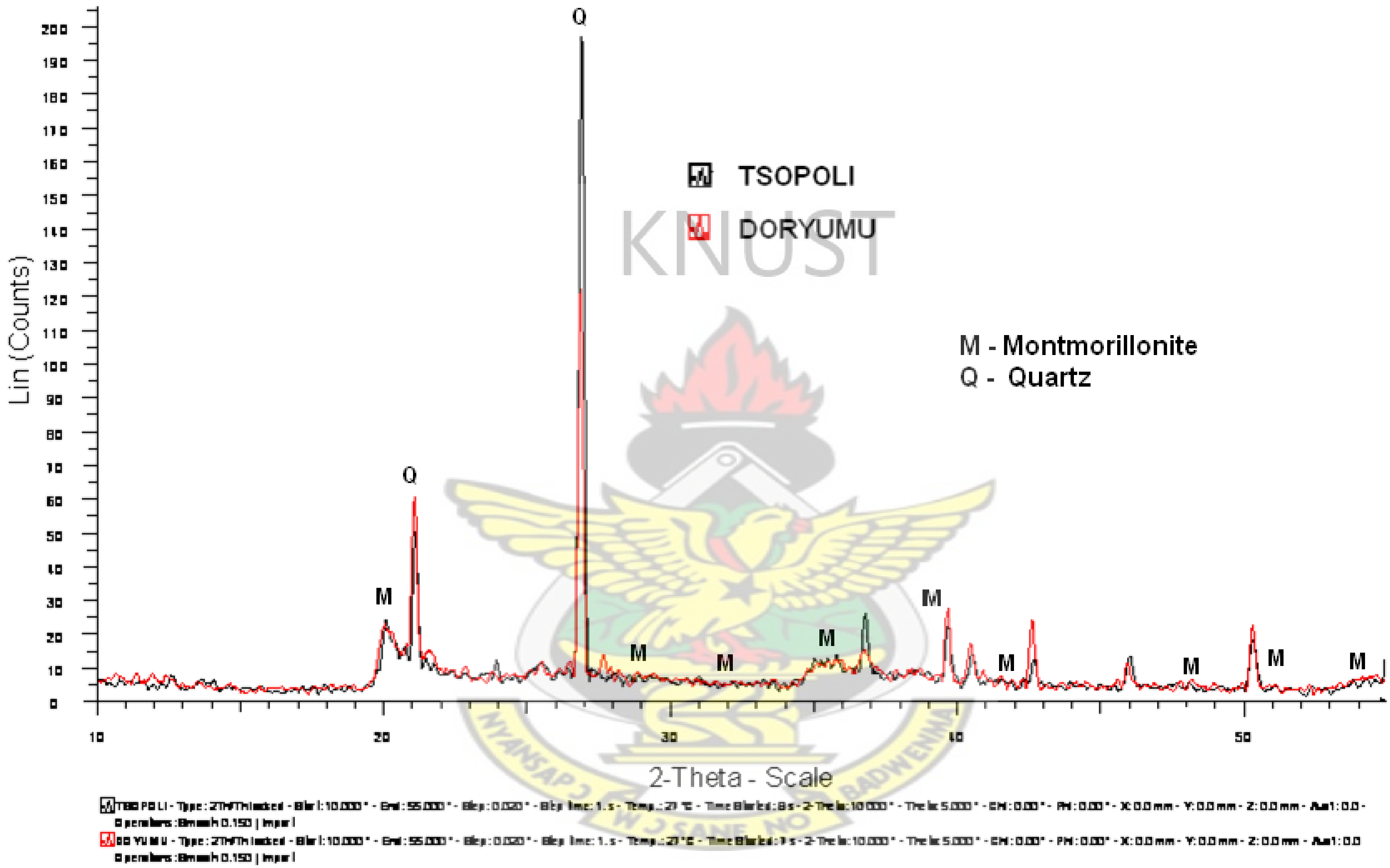


Figure 13. Diffractogram of the two soils

4.1.2 Physico-chemical characteristics

Results of the physico-chemical characteristics of the Tsopoli and Doryumu black cotton soils are shown in Table 9. The soil forming medium inferred from the pH of the soils shows that the Tsopoli soil is nearly neutral whereas the Doryumu soil is alkaline. Organic matter contents of the soils are 2.97 and 3.00 for Tsopoli and Doryumu respectively. The organic matter contents are within the range reported by BRRI (1985) of less than 5%. The cation exchange capacity (CEC) of clayey soil is the sum of exchangeable cations, which is a measure of the adsorption characteristics of the clay minerals and an indicator of the type and amount of free cations that are adsorbed expressed in milliequivalent per 100grams of the soils. The CEC values of the black cotton soils were found to be 49.65 for Tsopoli soil and 38.11 for Doryumu soils. It is noticed that the most abundant cations in the soils are the calcium, magnesium and sodium cations.

Table 9. Physico-chemical characteristics of the soils

PARAMETER	TSOPOLI SOIL	DORYUMU
Calcium* (meq/100g)	30.00	25.60
Magnesium* (meq/100g)	13.00	10.20
Potassium* (meq/100g)	0.58	0.13
Sodium* (meq/100g)	5.47	1.38
Aluminium* (meq/100g)	0.20	0.40
Hydrogen* (meq/100g)	0.40	0.40
CEC (Σ cations)	**49.65**	**38.11**
pH	6.94	7.25
Organic matter content (%)	2.97	3.00

*cations

4.2 Geomechanical characteristics of the black cotton soils

The geomechanical characteristics of the soil studied are presented in Table 10.

Table 10. Geomechanical properties of the natural soils

Sample ID	**Tsopoli**	**Doryumu**	**GHA Specification for subgrade**
Depth(m)	0.3-1.4	0.2-0.7	
Natural Moisture Content (%)	39.80	27.00	
Specific gravity	2.37	2.30	
Grading			
Gravel (%)	0.00	1.30	
Sand (%)	19.70	37.00	
Silt (%)	18.00	15.20	
Clay (%)	63.30	46.50	
Atterberg limits			
Liquid Limit (%)	91.72	74.68	≤ 35
Plastic Limit (%)	29.60	26.55	
Plasticity Index (%)	62.12	48.13	≤ 16
Linear shrinkage (%)	24.22	20.36	≤ 8
Activity	0.98	1.03	
Free Swell (%)	140.00	70.00	
Free Swell Index (%)	164.00	73.00	
Compaction			
Max. Dry Density (Mg/m^3)	1.68	1.82	
Opt. Moisture Cont. (%)	19.48	17.54	
CBR –soaked (%)	0.003	0.007	≥ 30
CBR swell (%)	16.29	15.96	≤ 1
Classification			
AASHTO	A-7-6	A-7-6	
USCS	CH	CH	

Natural Moisture Content and Specific Gravity

The insitu moisture content of the black cotton soils occurring at Doryumu and Tsopoli are 27% and 39.80% respectively. The results are within the range of natural moisture contents of Ghanaian black and brown clays reported by the Building and Road Research Institute (1985), which is between 20% and 45%.

The specific gravities of the solid particles in the soils are 2.30 and 2.37 for Doryumu and Tsopoli black cotton soils respectively.

Particle Size Distribution and Textural Classification

The particle size distributions curves of the two soils are shown in Figure 14. The Tsopoli soil had sand size content of 19.7%, silt size content of 18.0% and clay size content of 63.3%, whereas the Doryumu soils had 1.3% gravel, 37.00% sand, 15.2% silt and 45.5% clay. Based on the particle size distribution the Tsopoli soil classifies as clay and the Doryumu soil as sandy clay soils.

The textural classification of the two soils is shown in Figure 15. The Tsopoli soil classifies as clay and Doryumu soils as sandy clay on the United States Corp of Engineers classification chart.

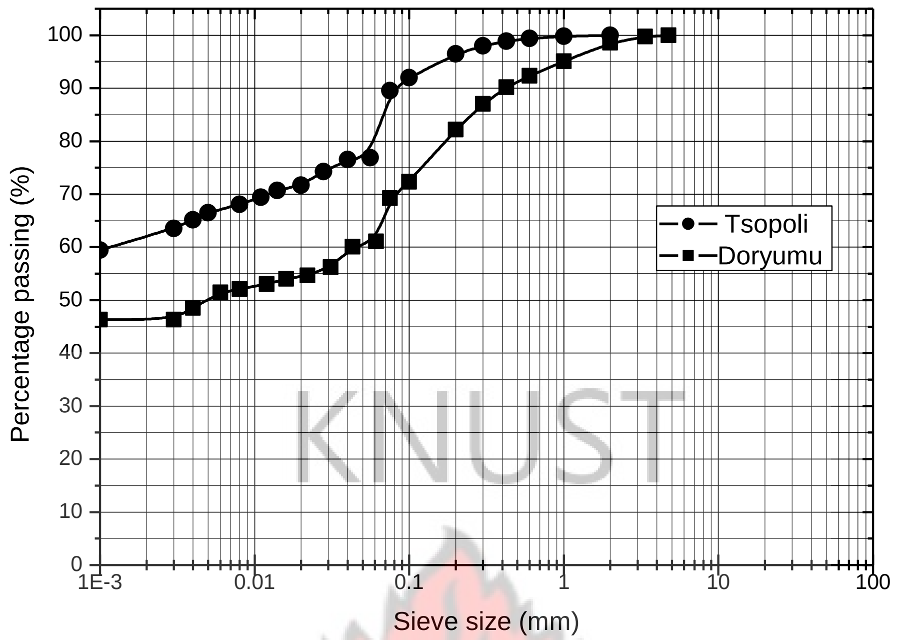


Figure 14. Particle size distributions of the soils

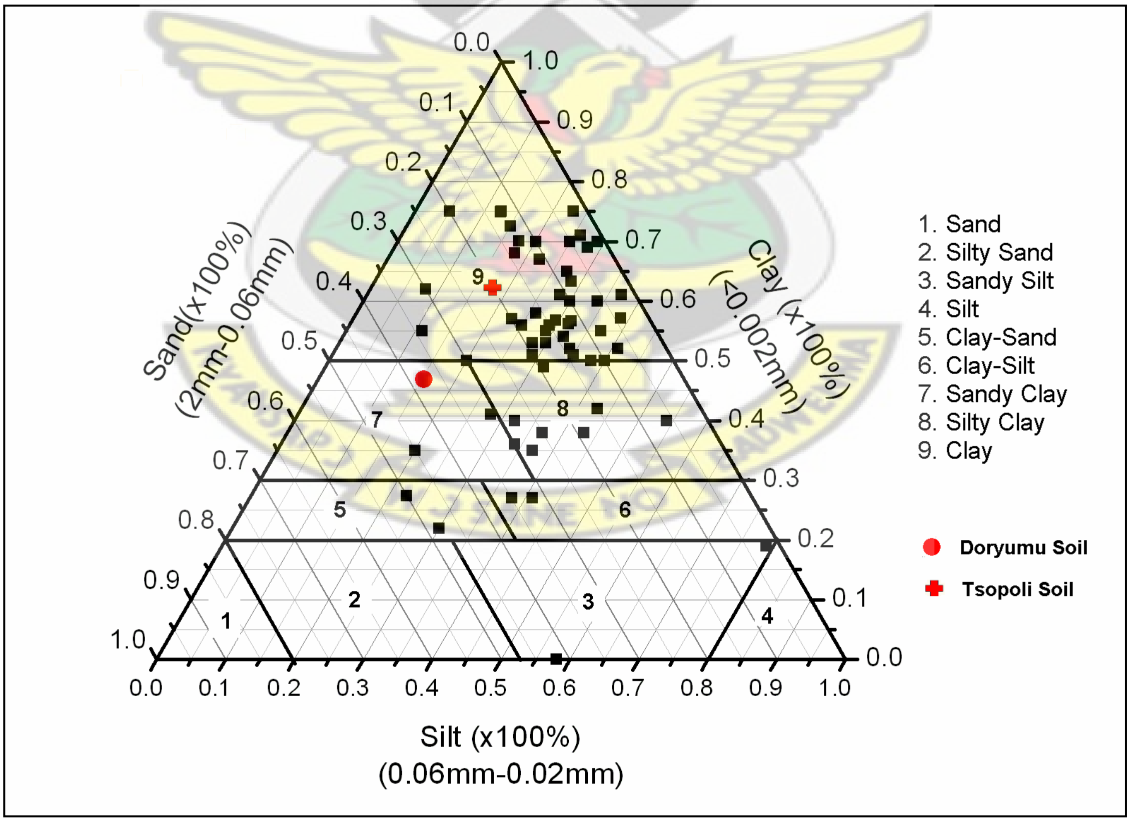


Figure 15. Textural classification of the soils with reference to black cotton soils reported in literature

Atterberg Limits and Plasticity Characteristics

The plasticity characteristics of the soils are shown in Figure 16. All the soils plotted above the A-line. Based on the Unified Soil Classification System (USCS) the soils are inorganic clays of high plasticity (CH). They also classify as A-7-6 by the AASHTO Classification System, which means that they are fair to poor material for subgrade of roads. From studies by Wesley (1988), it appears that the Doryumu black cotton soil has strong montmorillonite influence than the Tsopoli soil.

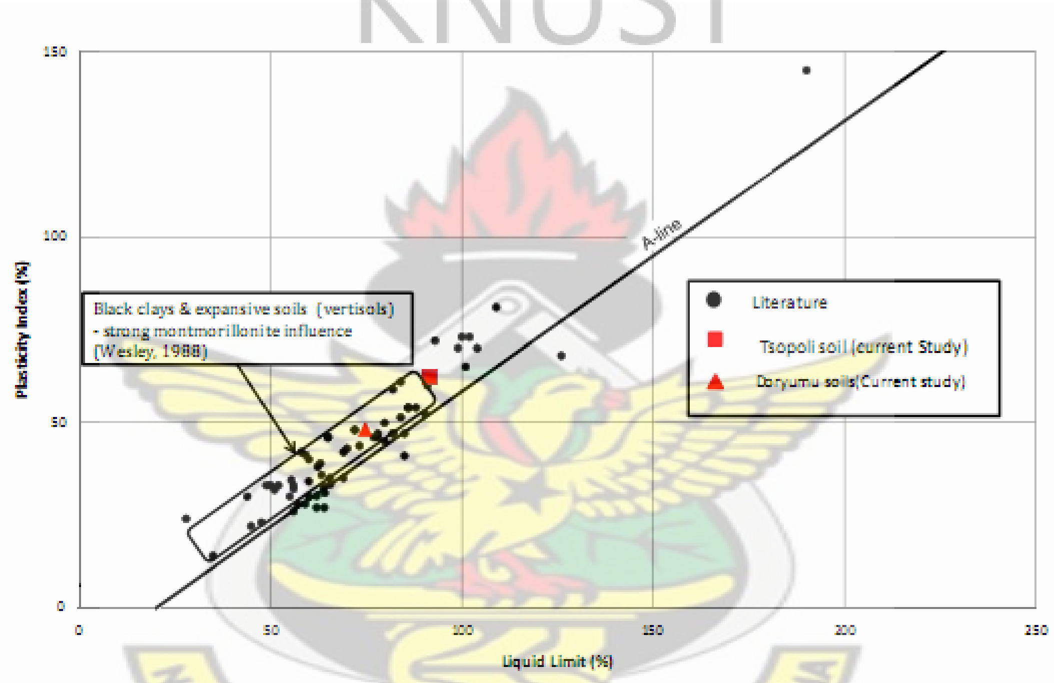


Figure 16. Plasticity characteristics of the soils

The Activity defined as the ratio of the plasticity index to the clay size content of a soil based on Skempton's classification are 0.98 for Tsopoli soil and 1.03 for Doryumu soil. This indicates that the soils have medium expansion potential because they fall between 0.75-1.25 (see Table 7). The values of activity of the two soils are however, not different from those reported in literature which ranges from 0.37-1.70.

The free swell test on the soils gave values of 140% for Tsopoli soil and 70% for the Doryumu soil. Holtz and Gibbs (1956) indicated that soils having free swell values above 100% can cause considerable damage to lightly loaded structures; soils having free swell below 50% seldom exhibit appreciable volume change. It is clear, therefore that the Tsopoli soil can be expected to cause more damage to light loaded structures than the Doryumu soil when exposed to moisture changes. A good indication of the soil expansivity is the free swell index (IS 1498, 1987). The free swell indices of the study soils are 164% and 73% for the Tsopoli and Doryumu soils respectively. Again, this implies that the Tsopoli soil has a high degree of expansivity whereas the Doryumu soil possesses medium degree of expansivity (Appendix 1).

Strength characteristics

The strength properties of the soils were determined from compaction and CBR tests. The compaction characteristics of the soils are shown in Figure 17. It is noted that the Maximum Dry Density (MDD) of the Tsopoli soil is 1.68Mg/m^3 corresponding to an optimum moisture content (OMC) of 19.48%. The Doryumu soil recorded a higher MDD of 1.82Mg/m^3 and a lower OMC of 17.54% relative to the Tsopoli soil. The values of MDD and OMC are quite in agreement with those gathered from literature for natural soils that is between 1108kg/m^3 – 2970kg/m^3 (1.108-2.97Mg/m^3) and 10%-49%.

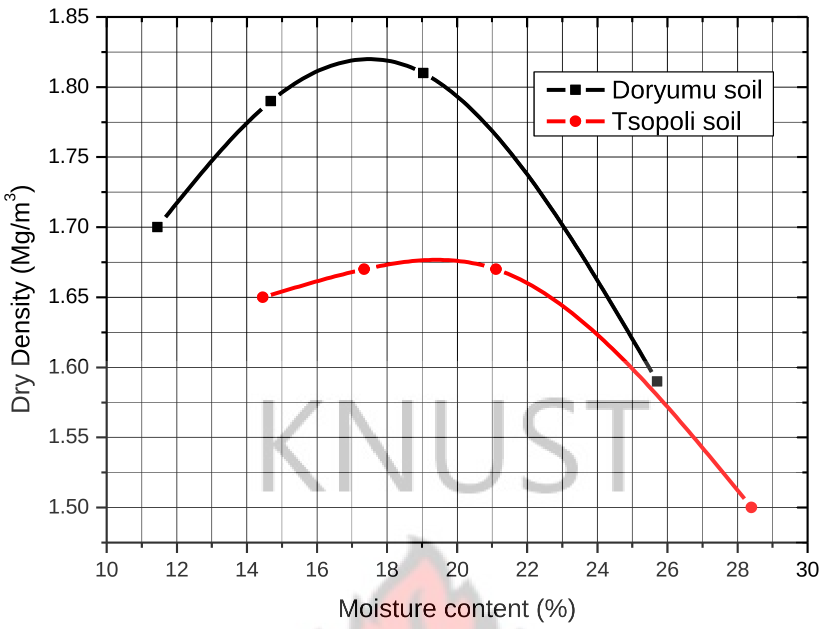


Figure 17. Compaction characteristics of the black cotton soils

The CBR values determined on soil samples compacted at OMC and soaking for 96 hours (4-days) were 0.003% and 0.007% for Tsopoli and Doryumu soils respectively which indicate a total loss of strength of the samples on soaking. The CBR swells recorded were 16.29% for the Tsopoli soils and 15.96% for the Doryumu soil.

Conclusion

Laboratory results of the geomechanical properties of the black cotton soils studied (Table 10) reveal that, they are unsuitable/poor materials for road construction. For instance; the liquid limits of both soils are more than two-fold the Ghana Highway Authority standard (GHA, 2006) requirement of 35%. The plasticity index and linear shrinkage limits also failed to meet specification. The plastic limits of the Tsopoli and Doryumu soils were 62% and 48% respectively, about four-fold the standard requirements (Maximum 16%). The linear shrinkage limits were also about two-fold more than the recommended 8%.

The California Bearing Ratio (CBR) values which are considered very important in the selection of road construction materials in terms of the load bearing capacity and swell failed to meet specifications. The minimum CBR-value recommended by GHA for subgrade material is 30% and CBR-swell, maximum of 1%. The soils however, recorded CBR values less than 1% and swell in excess of 15%.

4.3 Stabilisation of the soils

The effects of the various stabilising agents on the geomechanical characteristics of the soils are presented and discussed.

4.3.1 Quarry dust stabilisation

The summary of results on the effects of quarry dust on the geomechanical characteristics of the black cotton soils are shown in Table 11 and are discussed.

Particle size distribution and textural classification

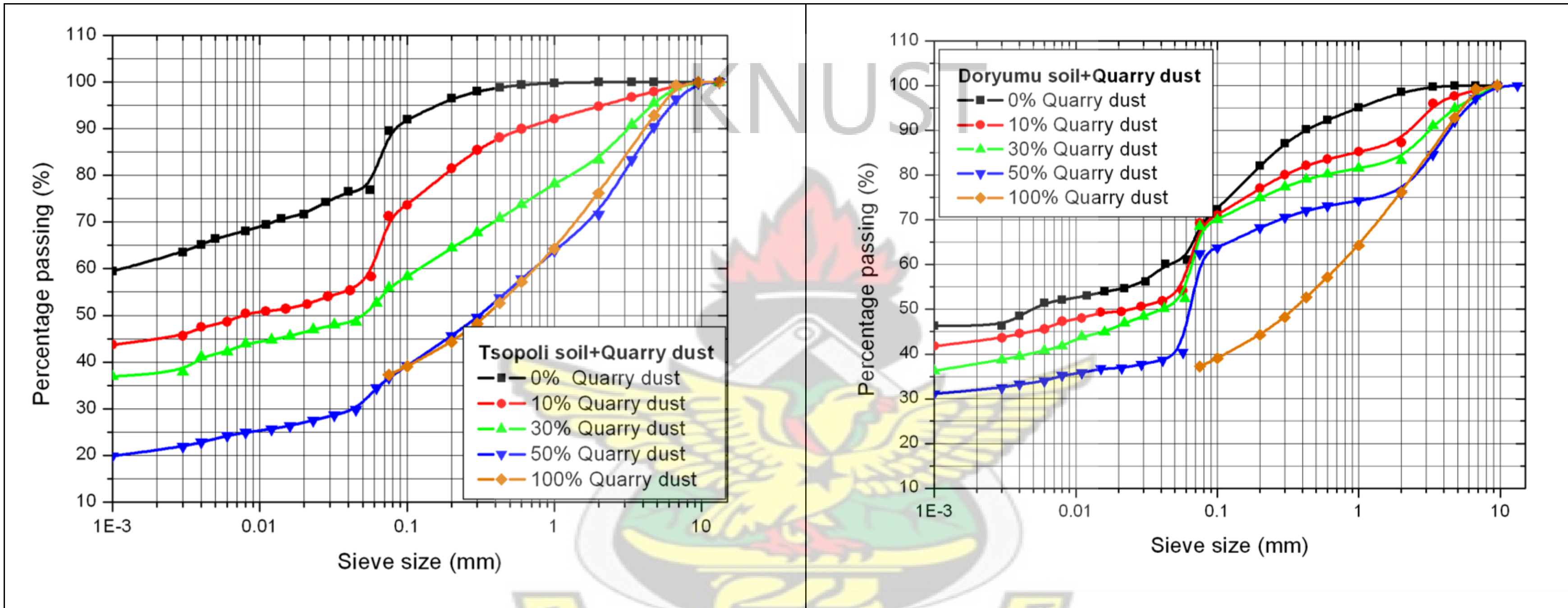
The grading characteristics of the quarry dust stabilised black cotton soils are shown in Figure 18. The quarry dust had greater effect on the grading curves of the Tsopoli soil than on the Doryumu soil.

For the Tsopoli soil, there was a general reduction in the clay size content with increasing quarry dust content. No significant reduction of the silt contents with increasing quarry dust content was observed. The sand size and gravel size contents both increased with increasing quarry dust.

There was a general reduction in the clay size and silt contents whereas gravel size increased with increasing quarry dust content, however, sand content increased marginally with increasing quarry dust for the Doryumu soil.

Table 11. Geomechanical characteristics of quarry dust stabilised black cotton soils

Sample ID	Tsopoli Soil + Quarry dust				Doryumu Soil + Quarry dust				100% Quarry dust
	0%	10%	30%	50%	0%	10%	30%	50%	
Grading									
Gravel (%)	0.00	5.09	16.03	27.73	1.30	11.63	15.7	22.83	24
Sand (%)	19.70	32.30	31.17	37.95	37.00	30.13	30.43	30.64	76
Silt (%)	18.00	17.5	15.06	13.15	15.20	15.13	15.82	14.28	0
Clay (%)	63.30	45.11	37.74	21.17	46.50	43.11	38.05	32.25	0
Atterbergs									
Liquid Limit (%)	91.72	80.88	62.28	48.81	74.68	69.18	55.16	44.54	28.00
Plastic Limit (%)	29.60	27.99	20.41	18.25	26.55	23.73	22.60	16.91	Non Plastic
Plasticity Index (%)	62.12	52.89	42.87	30.56	48.13	45.45	32.56	27.63	N/A
Linear shrinkage (%)	24.22	23.74	19.42	14.64	20.36	20.14	16.90	12.50	-
Activity	0.98	1.17	1.14	1.44	1.03	1.05	0.86	0.86	N/A
Free Swell (%)	140	120	100	90	70	60	50	45	0
Free swell index (%)	164	145	75	60	73.00	70	65	50	0
Compaction									
Max. Dry Density (Mg/m^3)	1.68	1.82	1.93	2.07	1.82	1.84	1.98	2.14	2.193
Opt. Moisture Cont. (%)	19.48	18.68	15.15	11.32	17.54	14.19	11.64	10.44	7.68
CBR (%)	0.003	0.0035	0.0174	0.0081	0.007	1.03	1.29	1.42	5.40
CBR swell (%)	16.29	15.58	15.96	17.83	15.96	9.63	9.21	6.89	2.26
Classification									
AASHTO	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	-
USCS	CH	CH	CH	CI	CH	CH	CH	CI	-



Tsopoli soil	Doryumu soil

Figure 18. **Grading characteristics of the quarry dust stabilised black cotton soils**

The classification of the soils based on textural characteristics is presented in Table 12. It is noted that the Tsopoli soil which in its natural state classified as clay, classified as sandy clay upon addition of 10% and 30% quarry dust and then classified as sandy-gravel with the addition of 50% quarry dust. The addition of quarry dust to the Tsopoli soil reduced the clay size content and caused an increase in the sand content.

The addition of quarry dust to the Doryumu soil, however, did not cause any change in the textural classification of the soil which in its natural state classified as sandy clay. This is due to the fact that the natural soil had some amount of sand and so the addition of quarry dust only reinforced the sand size content with no textural change.

Table 12. Classification of the soils based on textural characteristics

Sample ID	**Textural classification of soil**	
Quarry dust content (%)	**Tsopoli soil**	**Doryumu**
0%	Clay	Sandy clay
10%	Sandy clay	Sandy clay
30%	Sandy clay	Sandy clay
50%	Sandy gravel	Sandy clay

Atterberg limits and Plasticity Characteristics

Quarry dust had a significant effect on the Atterberg limits of both soils. There were general reductions in Atterberg limits with increasing quarry dust content. This phenomenon could be attributed to the reduction in clay content of the soils as the non-plastic quarry dust was increased. This results in a reduction in water absorption capacity of the black cotton soils greatly.

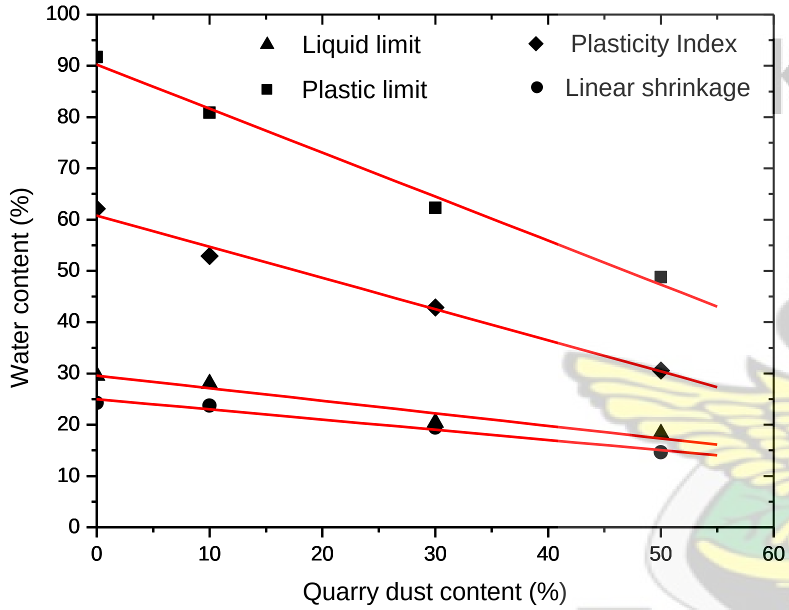
The effect of quarry dust on the plasticity characteristics of the soils is shown in Figure 19. It is noted that as quarry dust content was increased there was an accompanied reduction in the liquid limit as well as the plastic limit with subsequent reduction in the plasticity index for both the Tsopoli and Doryumu black cotton soils. The linear shrinkage reduced with increasing quarry dust content for both soils.

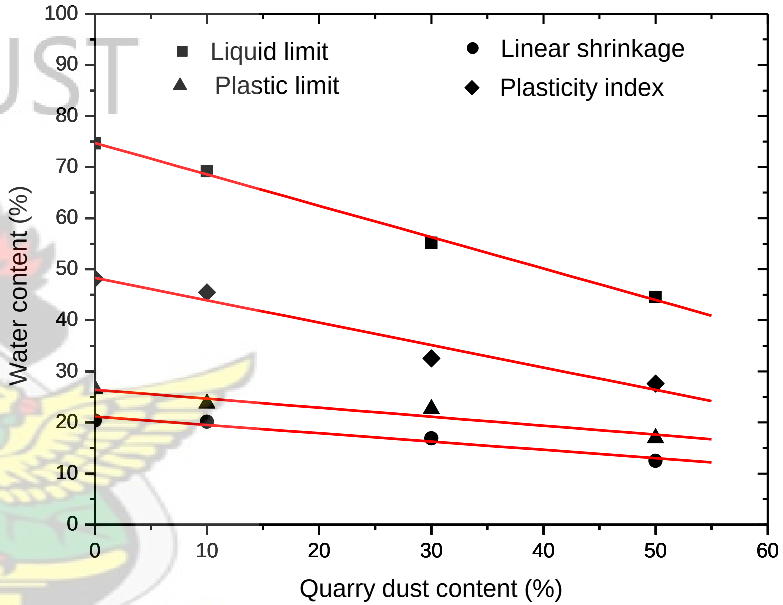
The reduction in both liquid and plastic limits altered the classification of the soils. The soils which classify under the Unified Soil Classification System as clay with high plasticity (CH) for 0%, 10% and 30% dust contents classified as clay with intermediate plasticity (CI) upon addition of 50% quarry dust for both the Tsopoli and Doryumu soils (Figure 20).

Activity and Free swell

The activity of the clay fraction in the soils ranges between 0.86 and 1.44 for both soils. All the soils with the exception of Tsopoli soil plus 50% quarry dust classified as soil with medium expansion potential. Tsopoli soil plus 50% quarry dust classified as soils with high expansion potential.

The free swell and free swell index of both soils reduced with increasing quarry dust. The Tsopoli soil had free swell ranging between 90% and 140% and free swell index ranging between 60% and 164%. The Doryumu soil also recorded free swell values in the range of 45% and 70% and free swell index between 50% and 73%.





Tsopoli soils	Doryumu soil

Figure 19. The effect of quarry dust on the Atterberg limits of the soils

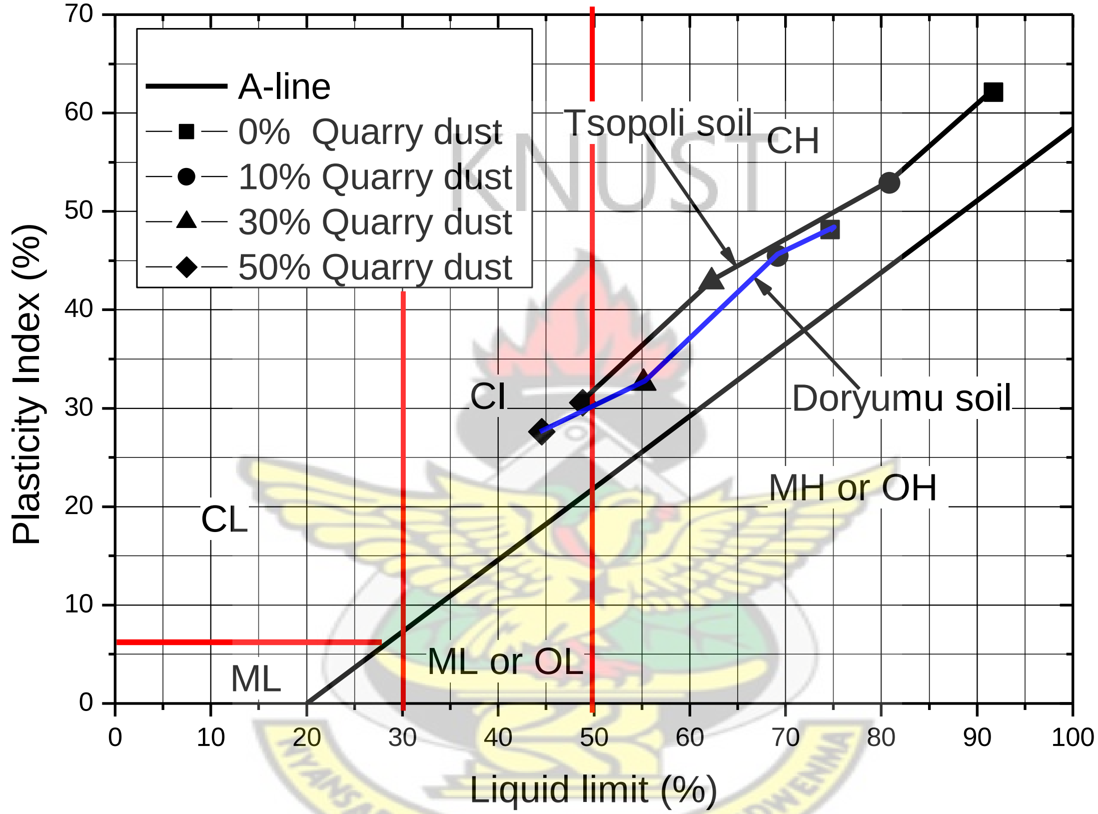
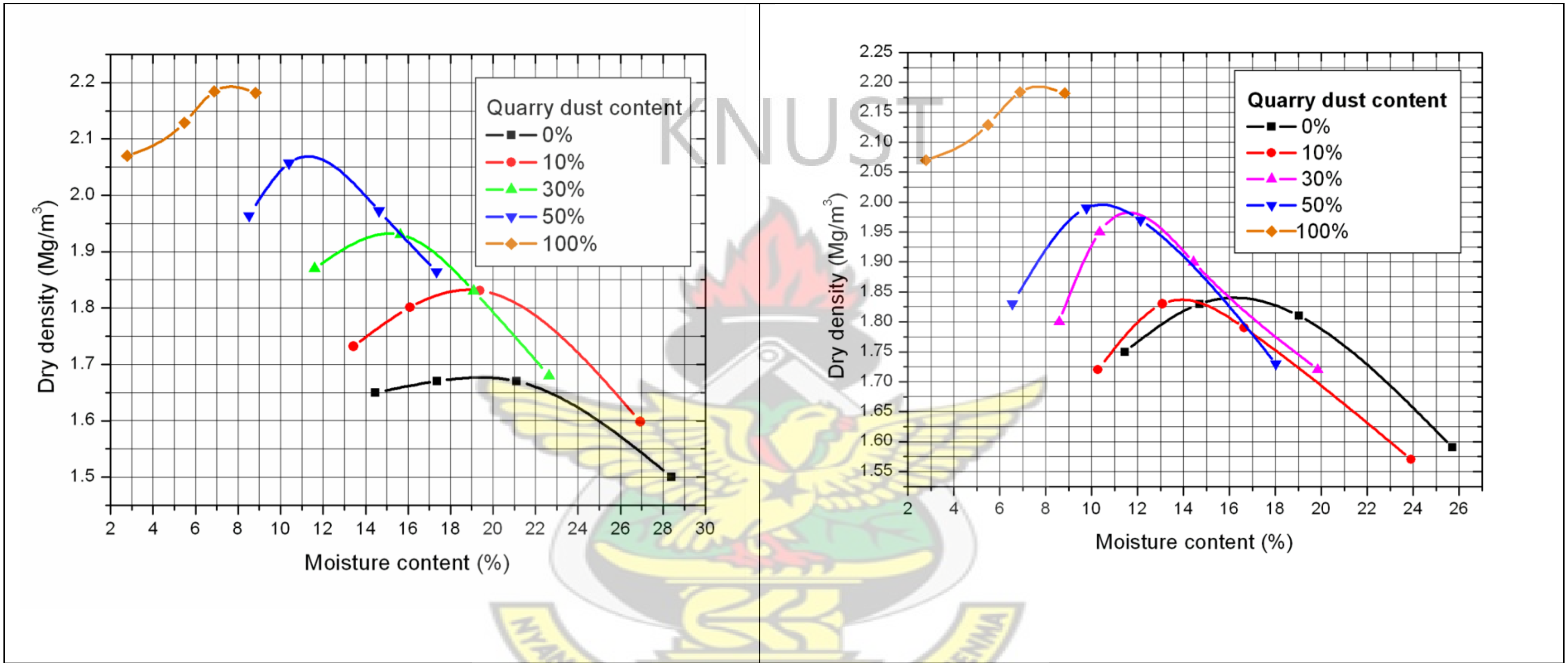


Figure 20. The effect of quarry dust on the plasticity classification of the soils

Compaction characteristics

Compaction characteristics and CBR were used as proxy for the strength parameters of the soil-quarry dust mixtures. The compaction characteristics of the natural and quarry dust stabilised soils are presented in Figure 21. It is noted that as quarry dust content is increased, there is an increase in the maximum dry density (MDD) and a reduction in the optimum moisture content as demonstrated by Figure 22 and Figure 23 for the two soils. The increase in MDD and reduction in the OMC could be attributed to the fact that, as the low density particle black cotton soils (specific gravity of 2.30 and 2.37) are replaced by a relatively high density quarry dust (specific gravity of 2.60), an increase in the density of the composite material is expected. The reduction in the OMC could also be due to the reduction in the clay content which causes a reduction in the water absorptive capacity of the composite material and subsequent increase in dry density (dry density is inversely proportional to moisture content).

Figure 24 and Figure 25 show the effects of the quarry dust on the CBR of the black cotton soils. The soaked CBR values increases with increasing quarry dust content. The CBR increase may be because the grains of the quarry dust form an interlocking system which results in increase in resistance to penetration. General reductions in CBR swell were observed with increasing quarry dust content for both black cotton soils (Figure 25). This is definitely due to the reduction of the swelling clay content and increase in the non–swelling quarry dust.



Tsopoli soil	Doryumu soil

Figure 21. Compaction characteristics of Quarry dust treated black cotton soils

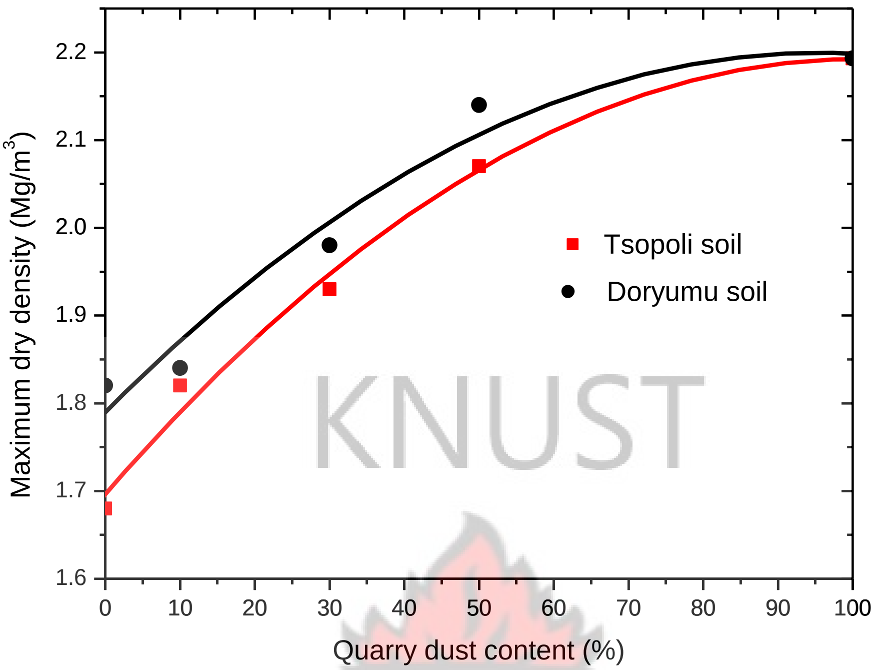


Figure 22. The variation of MDD with quarry dust content

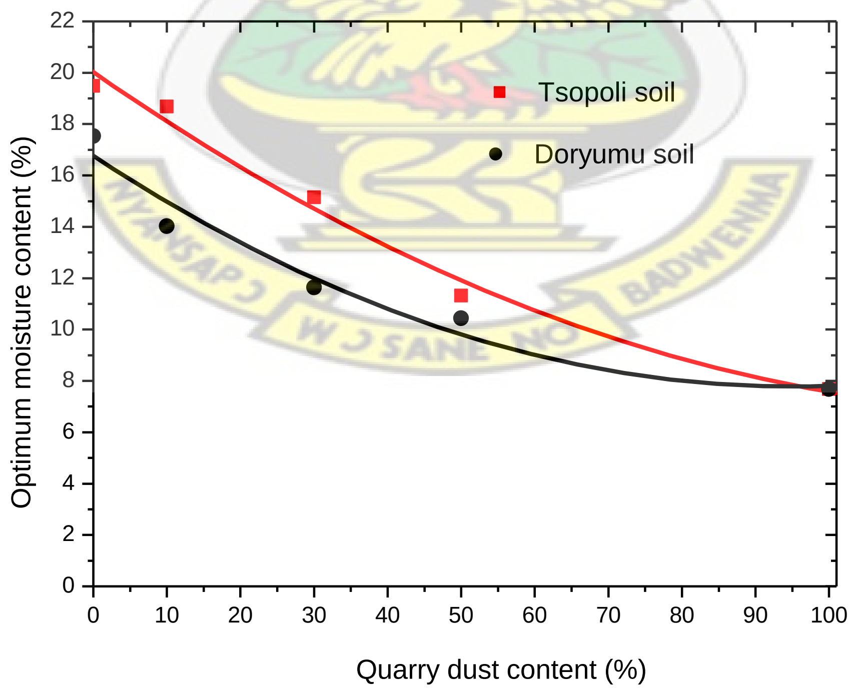


Figure 23. The variation of OMC with quarry dust content

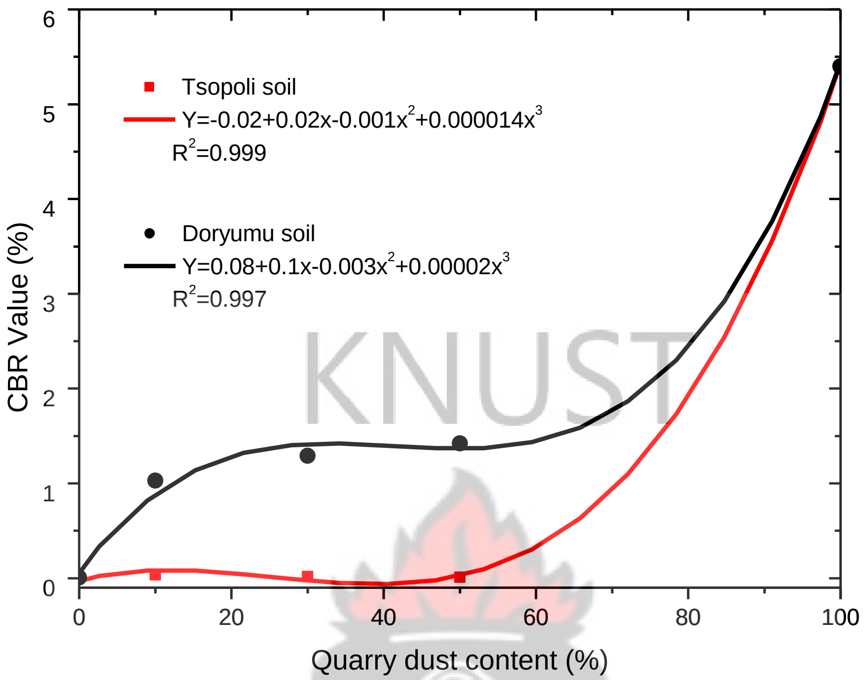


Figure 24. Variation of CBR with quarry dust content

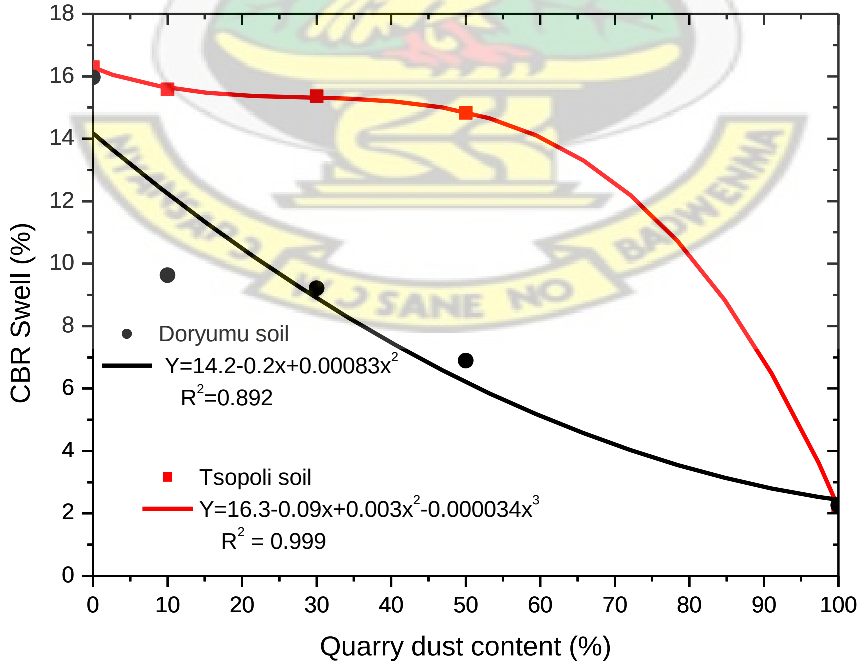


Figure 25. Variation of CBR swells with quarry dust content

Summary of results

There were reductions in soil plasticity thus the liquid limit, plastic limit, plasticity index and linear shrinkage with increasing quarry dust content. This phenomenon could be attributed to the reduction in clay content as the non-plastic quarry dust is increased. This results in a reduction in water absorption capacity of the black cotton soils greatly.

The quarry dust had a more pronounced effect on the grading characteristics of the Tsopoli soil than on the Doryumu soil. The textural classification of the Tsopoli soils also changed as the quarry dust content increased whereas there was no change in that of the Doryumu soils. Because of the high clay content of the Tsopoli soil, the addition of quarry dust reduced the clay size content and caused an increase in the coarse grain (sand) content. On the other hand, because the Doryumu soil had some amount of sand already the addition of quarry dust only increased in the sand content with no significant change in the textural classification.

Compaction results show that the maximum dry density (MDD) increased as quarry dust content increased up to a point and then decreased. The optimum moisture content (OMC) corresponding to the MDD also showed reduction as the quarry dust content was increased. The increase in MDD and reduction in the OMC could be attributed to the gradual replacement of the low particle density materials (black cotton soils) by a relatively higher density material (quarry dust) as the quarry dust content increased. The reduction in the OMC could be attributed to the reduction in the clay content which causes a reduction in the water absorptive capacity of the composite material.

General increases in California bearing ratio (CBR) values and reduction of CBR swell were observed. The CBR increased because it is thought that the grains of the quarry dust form an interlocking system which results in increase in resistance to penetration under load.

From the results, quarry dust can be said to be a good stabiliser for the black cotton soils, however, considering the large amounts of quarry dust used, it may be uneconomical to stabilise the black cotton soils with such materials.

4.3.2 Pozzolana stabilisation

The summary of results on the effects of pozzolana on the geomechanical characteristics of the black cotton soils are shown in Table 13 and are discussed.

Particle size distribution and textural classification

The grading characteristics of the natural and stabilised soils are shown in

Figure **26**. It is noted that the addition of pozzolana to both soils did not have significant effect on the particle size distribution; however, some changes in particle size fractions were noted. For instance, there was a reduction in clay size content, with increases in silt and sand contents and no net change in the gravel size of the Tsopoli soil. The Doryumu soil, on the other hand had not net change in both clay and gravel size fractions, but increased in silt and reduced in sand fractions.

The classification of the soils based on textural characteristics is presented in Table 14. The Tsopoli soil in its natural state and pozzolana improved state classified texturally as clay. The Doryumu soil, also classified as sandy clay for the natural as well as pozzolana improved samples. This implies that the pozzolana does not have any effect on the grading and textural characteristics of the two soils.

Table 13. Geomechanical characteristics of pozzolana stabilised soils

Sample ID	Tsopoli Soil + Pozzolana					Doryumu Soil + Pozzolana				
	0%	**3%**	**6%**	**12%**	**15%**	**0%**	**3%**	**6%**	**12%**	**15%**
Grading										
Gravel (%)	0.00	0.00	0.01	0.54	0.29	1.30	1.83	2.13	1.56	1.32
Sand (%)	19.70	17.27	15.64	17.16	22.38	37.00	31.08	29.25	30.84	33.16
Silt (%)	18.00	22.33	22.30	24.12	19.83	15.20	15.12	17.61	18.25	17.11
Clay (%)	63.30	60.4	62.05	58.61	57.50	46.50	51.97	51.01	49.35	48.41
Atterbergs										
Liquid Limit (%)	91.72	88.80	84.48	80.90	77.98	74.68	71.10	65.56	66.97	65.77
Plastic Limit (%)	29.60	25.01	26.00	26.26	26.57	26.55	21.47	20.78	23.09	24.91
Plasticity Index (%)	62.12	63.79	58.48	54.64	51.40	48.13	49.63	44.78	43.88	40.86
Linear shrinkage (%)	24.22	23.20	20.31	22.66	23.75	20.36	20.32	19.78	20.50	20.7
Activity	0.98	1.06	0.94	0.93	0.89	1.03	0.95	0.88	0.89	0.84
Free Swell (%)	140	115	110	100	100	70	65	60	60	60
FSI(%)	164	140	120	100	81	73	70	50	60	50
Compaction										
Max. Dry Density (Mg/m^3)	1.68	1.78	1.82	1.81	1.82	1.82	1.83	1.84	1.80	1.86
Opt. Moisture Cont. (%)	19.48	17.61	15.80	13.24	12.60	17.54	15.30	14.44	14.38	11.75
CBR (%)	0.003	0.35	0.52	0.52	0.31	0.007	0.42	0.52	0.58	0.47
Swell (%)	16.29	18.03	22.30	32.10	35.68	15.96	17.00	20.60	25.70	31.50
Classification										
AASHTO	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6
USCS	CH	CH	CH	CH	CH	CH	CH	CH	CH	CH

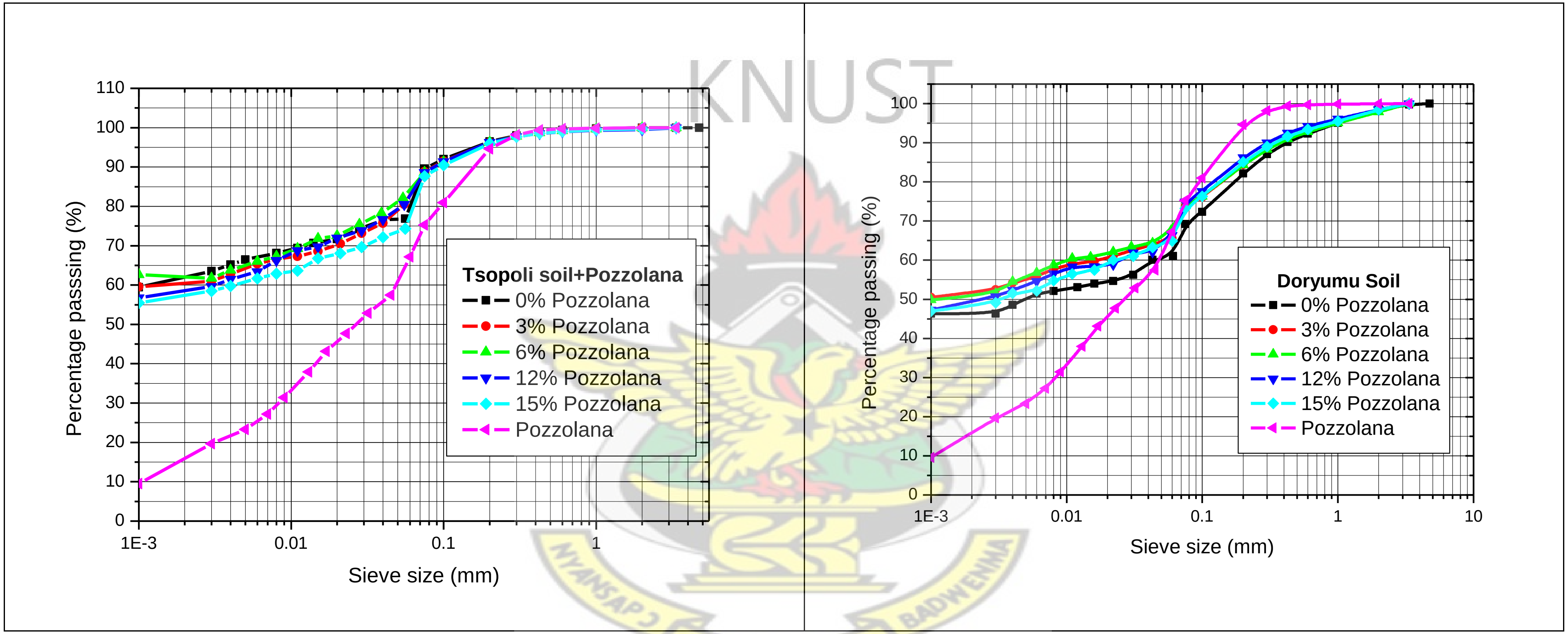


Figure 26. The particle size distribution curves of the pozzolana stabilised soils

Table 14. Classification of the soils based on textural characteristics

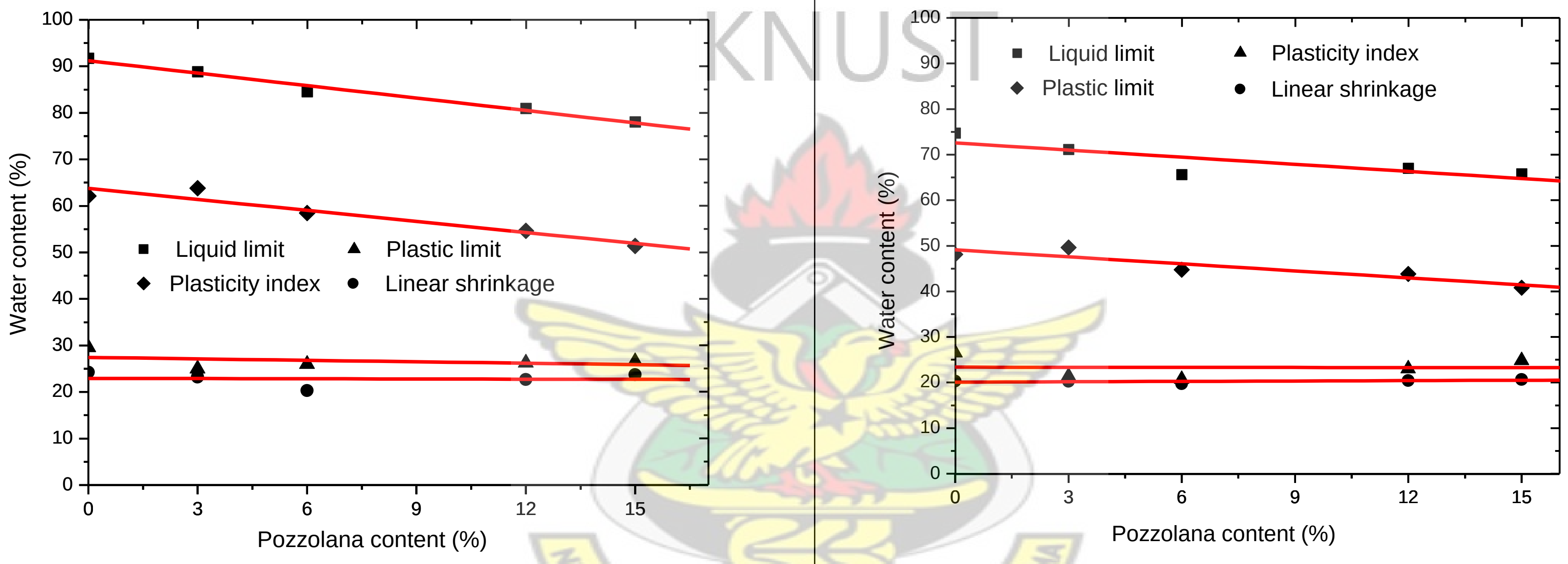
	Textural classification of soil	
Pozzolana content (%)	**Tsopoli soil**	**Doryumu**
0%	Clay	Sandy clay
3%	Clay	Sandy clay
6%	Clay	Sandy clay
12%	Clay	Sandy clay
15%	Clay	Sandy clay

Atterberg limits and Plasticity Characteristics

The results of the variation of Atterberg limits test with pozzolana content determined on raw and stabilised soils are given in Figure 27. There were reductions in the plasticity characteristics of the soils with increases in pozzolana content. There were reductions in the liquid limits as well as the plastic limits with subsequent reduction in the plasticity indices for both the Tsopoli and Doryumu black cotton soils. There were however, general decreases in the linear shrinkage of the soils with addition of between 0%-6% of pozzolana but beyond this point further addition of pozzolana resulted in an increase in the linear shrinkage of both the Tsopoli and Doryumu soils.

The reduction in plasticity characteristics of the soils could be due to the addition of the less plastic pozzolana and also the reaction between the clay size fraction of the black cotton soils and the pozzolana. According to Hammond (1980), when clays, shales and some other geomaterials are calcined at some optimum temperature they become pozzolanic and thus when finely divided in the presence of water react with the soil resulting in reduction in plasticity of the soils.

The reduction in Atterberg limits did not, however, alter the plasticity classification of the pozzolana stabilised soils as they all classified as inorganic clay of high plasticity (Figure 28).



Tsopoli soil	Doryumu soil

Figure 27. The variation of Atterberg limits with pozzolana content

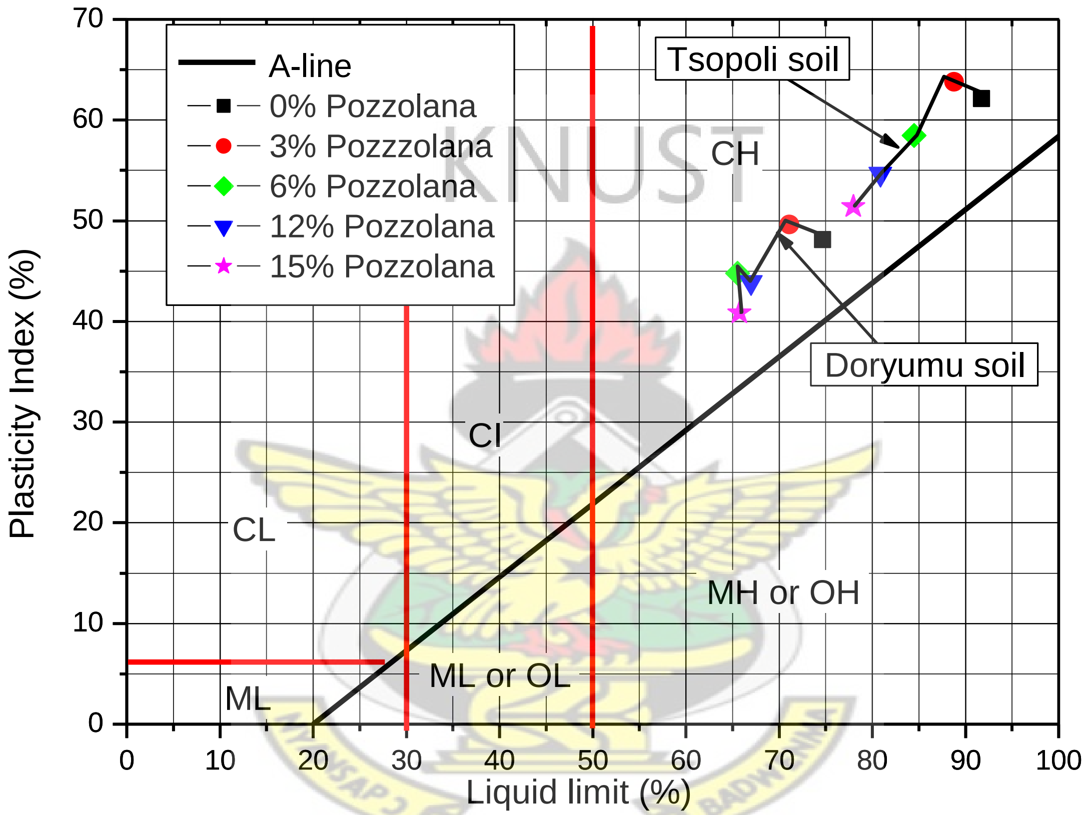


Figure 28. Plasticity classification of the pozzolana stabilised soils

Activity and Free swell

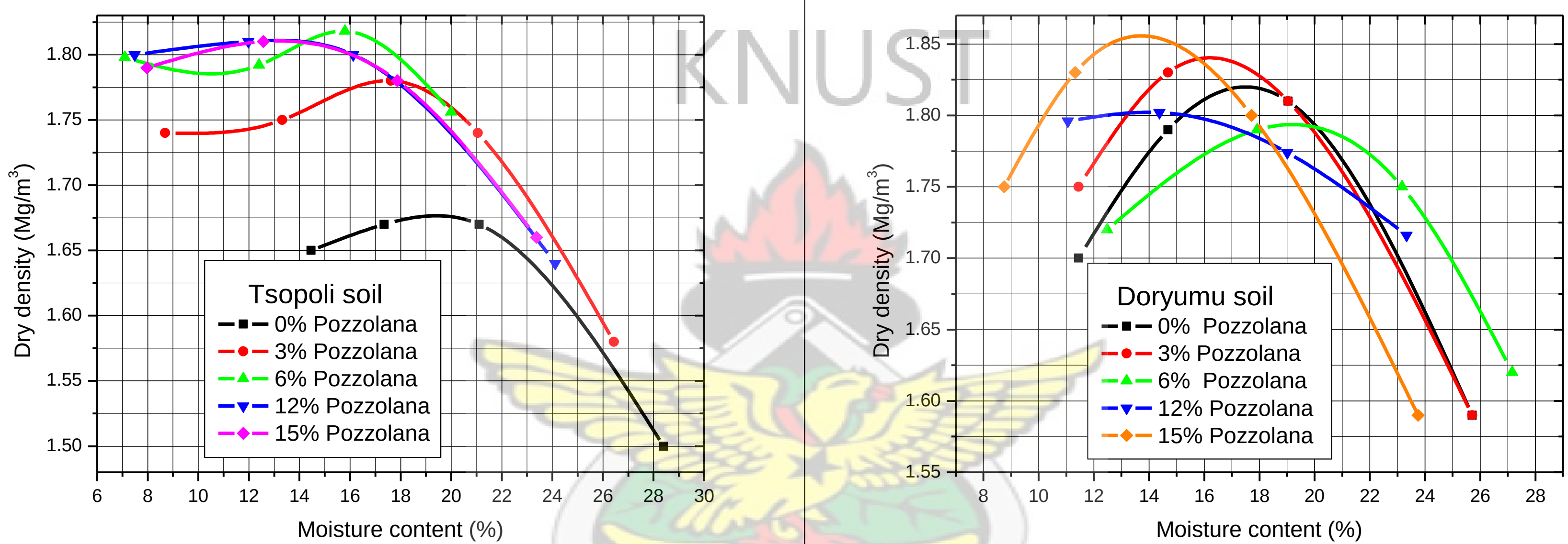
The activity of the Tsopoli-pozzolana improved soils ranges between 0.89 and 1.06 whereas the Doryumu–pozzolana soil recorded ranges from 0.84-1.03. This indicates that both stabilised soils have medium expansion potential.

There is a general reduction in the free swell and free swell index of both soils with increasing pozzolana. The Tsopoli soil had free swell and free swell index ranging from 90%-140%and 60%-164% respectively. The Doryumu soil also recorded values of from 45%-70% and 50%-73% for free swell and free swell index.

Compaction characteristics

The density-moisture relationship of the natural and pozzolana-stabilised soils determined from modified AASHTO standard compaction test are presented in Figure 29. The increase in pozzolana content caused an increase in the maximum dry density (MDD) and a reduction in optimum moisture content (OMC) of both soils.

The variation of MDD with pozzolana content of the soils is shown in Figure 30. The MDD increases linearly for the Doryumu soil and polynomially for the Tsopoli soil with increasing pozzolana content. The variation of optimum moisture content (OMC) with pozzolana-stabilised soils is shown in Figure 31. There is a general reduction in OMC with increasing pozzolana content and this phenomenon could be due to the fact the pozzolana absorbs water during the hydration process resulting in reduction in OMC.



Tsopoli soil	Doryumu soil

Figure 29. Compaction characteristics of pozzolana stabilised soils

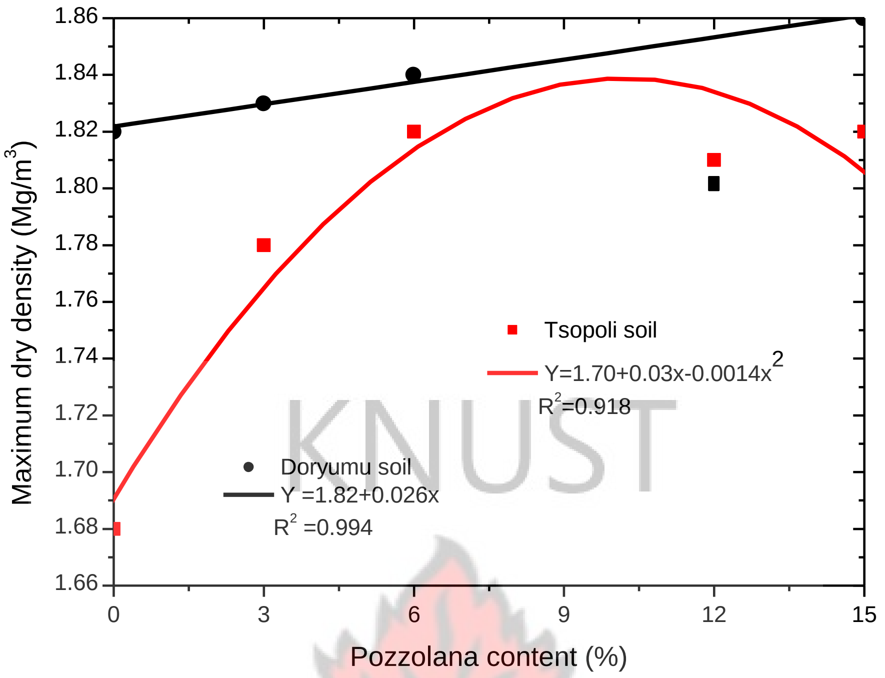


Figure 30. Variation of MDD with pozzolana content

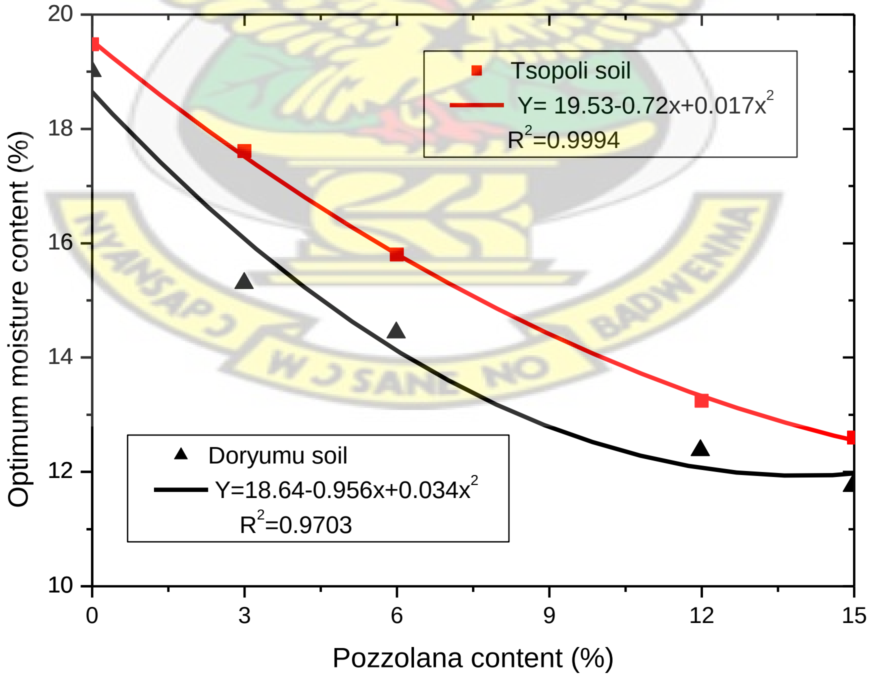


Figure 31. Variation of OMC with pozzolana content

The results obtained from the soaked CBR tests on the samples compacted at various pozzolana contents are presented in Figure 32. It is noted that CBR values increases up to a point and then drops with increasing pozzolana content. The maximum CBR value occurred at about 9% pozzolana content for the Doryumu soil and 10% for the Tsopoli soil. The variation of CBR swell with pozzolana content is shown in Figure 33. It is observed that as pozzolana content is increased CBR swell increases. The increase in CBR swell with pozzolana content may be due the absorption of water by both the soil and the pozzolana.

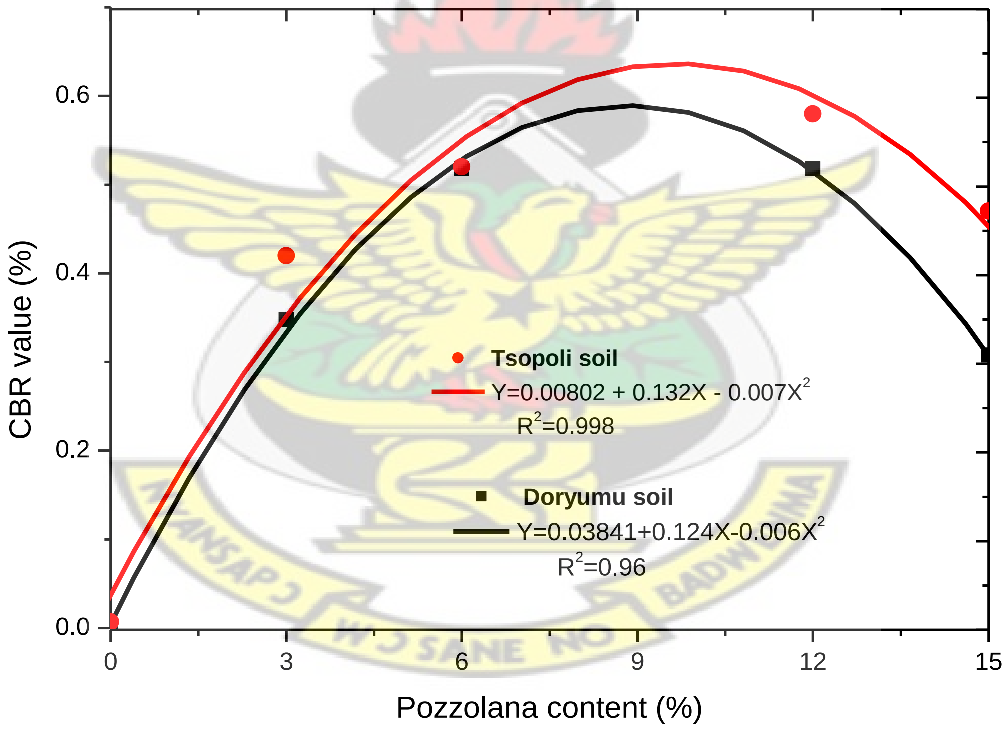


Figure 32. Variation of CBR value with pozzolana content

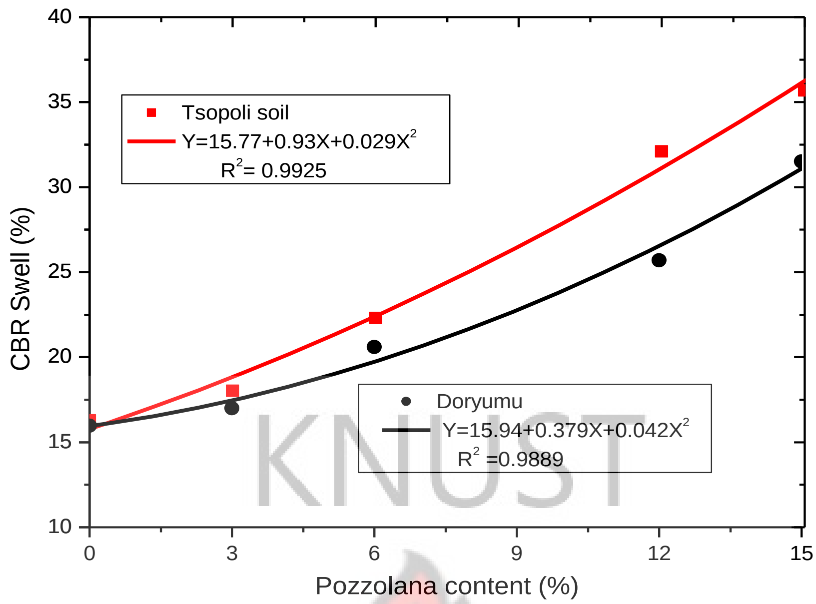


Figure 33. Variation of CBR swells with pozzolana content

Summary of results

The addition of pozzolana to the black cotton soils did not have much influence on the particle size distribution and therefore, no changes in the textural classification of both the Tsopoli and Doryumu black cotton soils were recorded. However, there was reduction in the Atterberg limits of both soils. The reduction in plasticity characteristics of the soils was due to the addition of a less plastic pozzolana and also the reaction between the clay size fraction of the black cotton soils and the pozzolana. The reduction in the Atterberg limits did not however cause any change in the classification of the two soils.

Increase in pozzolana content caused an increase in the maximum dry density (MDD) and a reduction in optimum moisture content (OMC) of both soils. It is thought that the pozzolana absorbs water from the clay fraction of the soil causing a reduction in OMC with increasing pozzolana content and an increase in the MDD.

The maximum California bearing ratio (CBR) value occurred at about 9% pozzolana content for the Doryumu soil and 10% for the Tsopoli soil. CBR swell increased with increasing pozzolana content. The increase in CBR value may be due to the reaction between the pozzolana and the soil. The increase in CBR swell with pozzolana content may be due the absorption of water by both the soil and the pozzolana.

Although there were some improvements in some geomechanical parameters, it appears pozzolana alone is unsuitable for stabilising the black cotton soils adequately.

4.3.3 Pozzolana-cement stabilisation

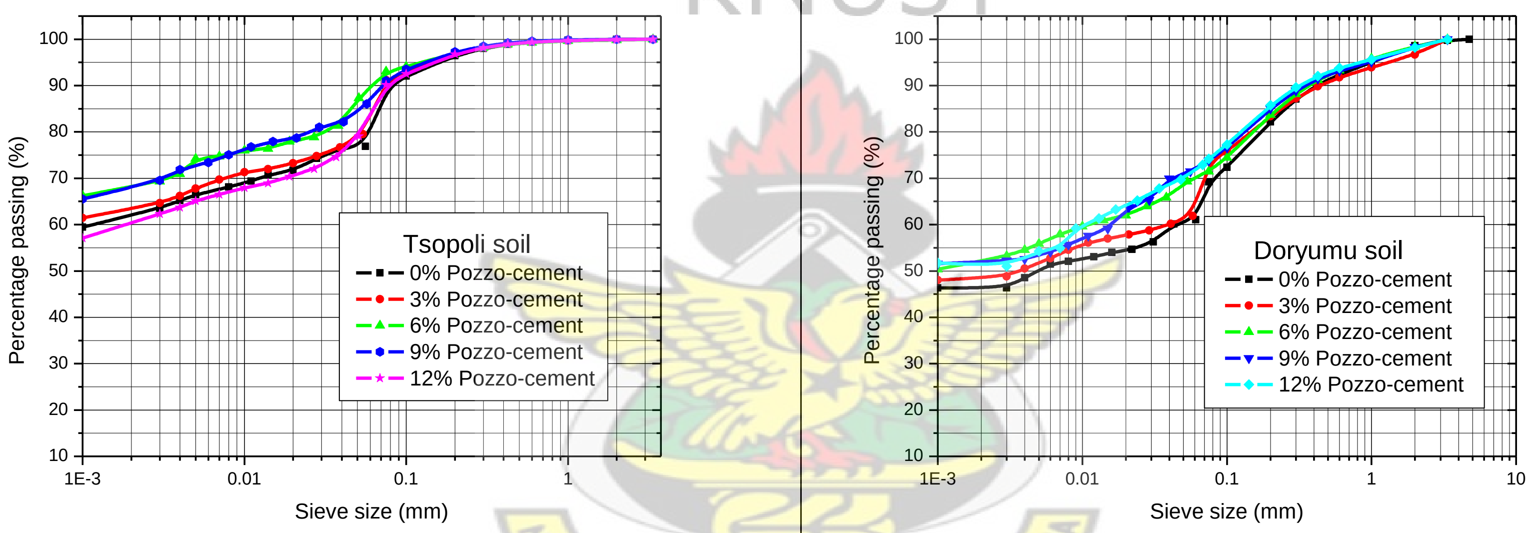
The summary of results of the pozzolana-cement stabilisation of the black cotton soils are presented in Table 15 and are discussed.

Particle size distribution and Textural classification

The grading characteristics of the natural and pozzolana-cement-stabilised soils are shown in Figure 34. It is noted that, the addition of pozzolana-cement to both soils had an effect on the particle size distribution. For instance, there was no net change in the clay and gravel size fractions of the Tsopoli soil but increase in silt and reduction in sand size contents were observed for increasing pozzolana-cement contents. The Doryumu soil also had increases in clay and silt size fractions with reduction in the sand size with no net change in the gravel size fraction with increasing pozzolana-cement content. The classification of the soils based on textural characteristics is presented in Table 16. The Tsopoli soil in its natural state and pozzolana-cement improved state classified texturally as clay. The Doryumu soil, also classified as sandy clay for 0%, 3%, but classified as clay for 6%, 9% and 12% pozzolana-cement.

Table 15. Geomechanical characteristics of pozzolana-cement stabilised black cotton soils

	Tsopoli Soil + Pozzolana-cement					Doryumu Soil + Pozzolana-cement				
Sample ID	**0%**	**3%**	**6%**	**9%**	**12%**	**0%**	**3%**	**6%**	**9%**	**12%**
Grading										
Gravel (%)	0.00	0.00	0.00	0.00	0.00	1.30	3.16	1.48	1.48	1.48
Sand (%)	19.70	16.92	11.09	13.45	17.15	37.00	32.59	28.15	26.32	27.05
Silt (%)	18.00	19.56	20.64	18.60	22.27	15.20	15.70	18.19	20.02	20.02
Clay (%)	63.30	63.52	68.27	67.95	60.58	46.50	48.55	52.18	52.18	51.45
Atterbergs										
Liquid Limit (%)	91.72	86.98	81.46	79.21	75.54	74.68	71.31	67.80	67.69	64.40
Plastic Limit (%)	29.60	28.46	29.12	29.45	30.33	26.55	25.85	26.89	30.66	30.73
Plasticity Index (%)	62.12	58.52	54.34	49.76	45.21	48.13	45.46	40.91	37.03	33.67
Linear shrinkage	24.22	25.78	24.46	23.74	22.14	23.20	22.3	21.43	20.86	17.86
Activity	0.98	0.92	0.80	0.73	0.75	1.03	0.94	0.78	0.71	0.65
Compaction										
Max. Dry Density (Mg/m3)	1.68	1.78	1.83	1.84	1.81	1.82	1.86	1.87	1.87	1.89
Opt. Moisture Cont. (%)	19.48	17.6	14.89	12.61	12.54	17.54	16.41	16.18	15.16	13.79
CBR (%)	0.003	1.65	1.90	4.00	8.40	0.003	3.11	4.61	6.11	9.22
CBR Swell (%)	16.29	21.05	23.07	24.25	25.00	15.96	14.00	14.90	15.8	16.70
Classification										
AASHTO	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6
USCS	CH	CH	CH	CH	CH	CH	CH	CH	CH	CH



Tsopoli soil	Doryumu soil

Figure 34. Grading characteristic of the soils

Table 16. Classification of the soils based on textural characteristics

	Textural classification of soil	
Pozzolana-cement content (%)	**Tsopoli soil**	**Doryumu**
0%	Clay	Sandy clay
3%	Clay	Sandy clay
6%	Clay	Clay
9%	Clay	Clay
12%	Clay	Clay

Atterberg limits and Plasticity Characteristics

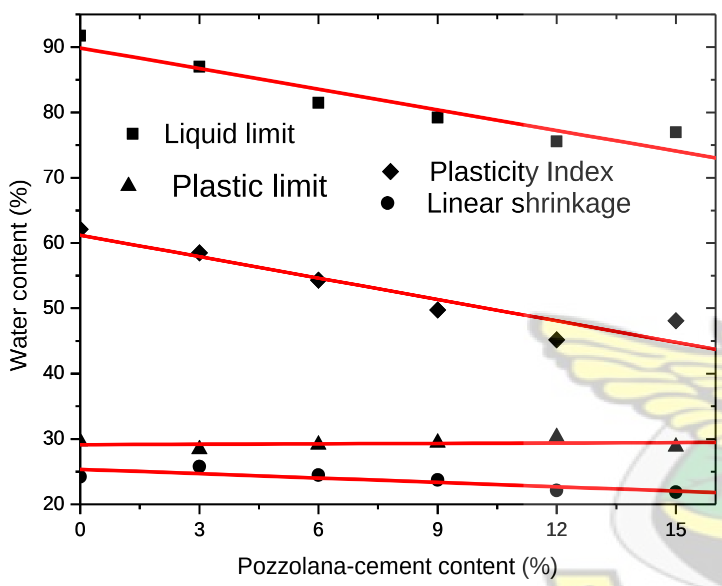
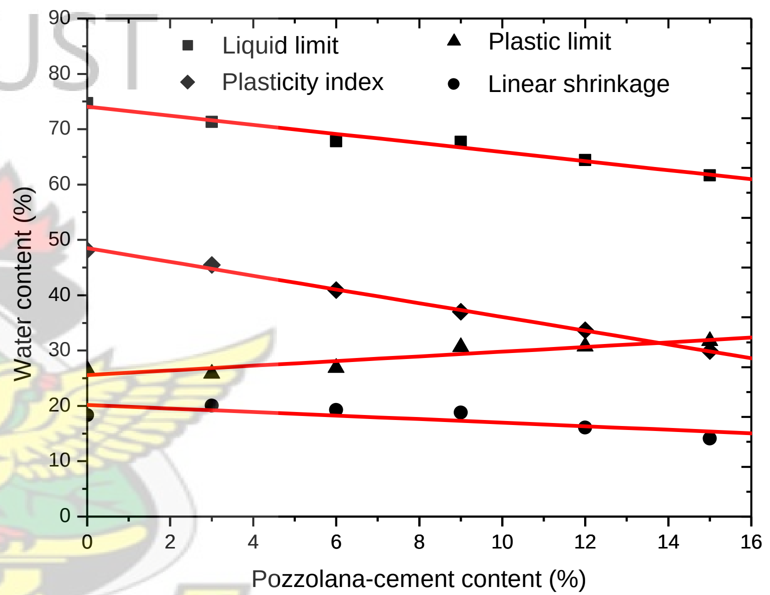
The results of the Atterberg limits test determined on raw and pozzolana-cement-stabilised soils are given in Figure 35. The liquid limit of the both the Tsopoli and Doryumu black cotton soils reduced as the pozzolana-cement content increased. General increases in the plastic limits were observed with increasing pozzolana-cement for both soils. The addition of 3% of pozzolana-cement to both soils caused a reduction in plastic limits and beyond that, general increase in plastic limits were noted. The reduction in liquid limits and the plastic limits resulted in the reduction of the plasticity indices of both soils with increasing pozzolana-cement content. General reductions in linear shrinkage of both soils with increasing pozzolana-cement contents were also observed.

The reduction in Atterberg limits did not, however, alter the plasticity classification of the pozzolana stabilised soils as they all classified as inorganic clay of high plasticity (CH) except Dorytum+15% pozzolana which classified as inorganic silts of high plasticity (MH) or organic soils (OH) as presented in Figure 36.

Activity and Free swell

The activity of the soils generally reduced with increasing pozzolana-cement content. For instance, the Tsopoli soil reduced in activity from 0.98 to 0.75 and Doryumu soils from 1.03

to 0.65 over the range of pozzolana-cement content used in the study. The ranges of values suggest that the soils have medium expansion potential. The free swell characteristics of the soils were not determined because the soil-pozzolana-cement had the tendency of solidifying in the presence of water.

Tsopoli soil	Doryumu soil
	

Tsopoli soil

Doryumu soil

Figure 35. The effect of Pozzolana-cement content on the Atterberg limits of the soils

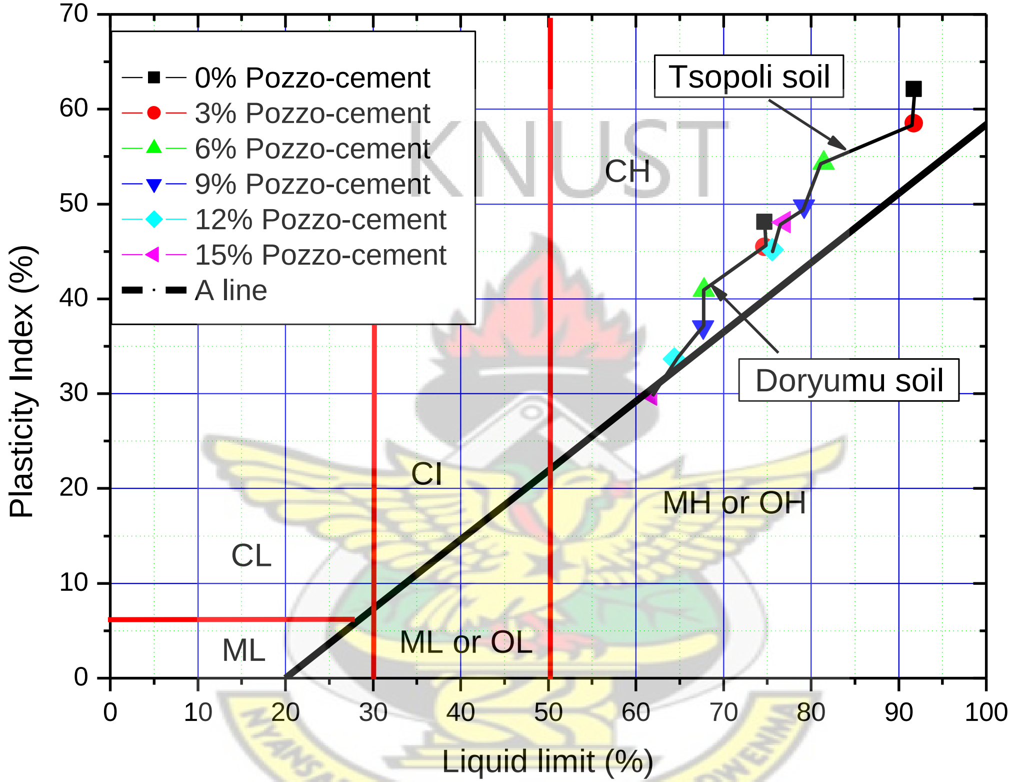


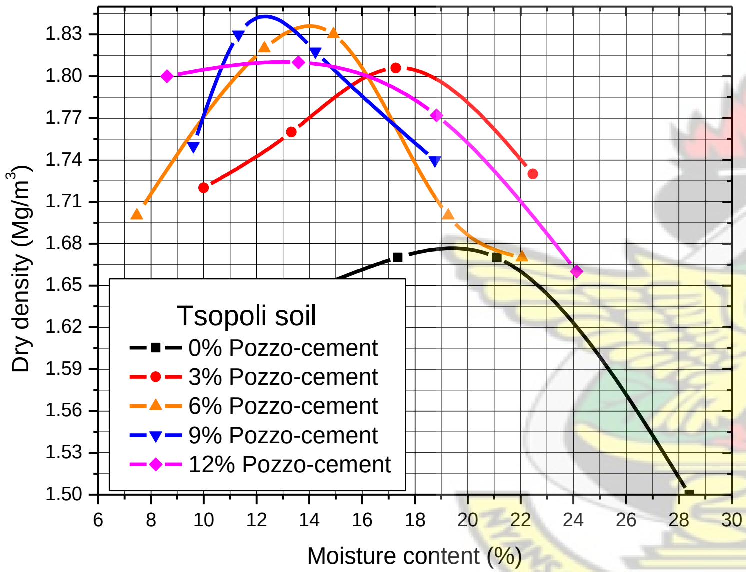
Figure 36. Plasticity classification of the soils

Compaction characteristics

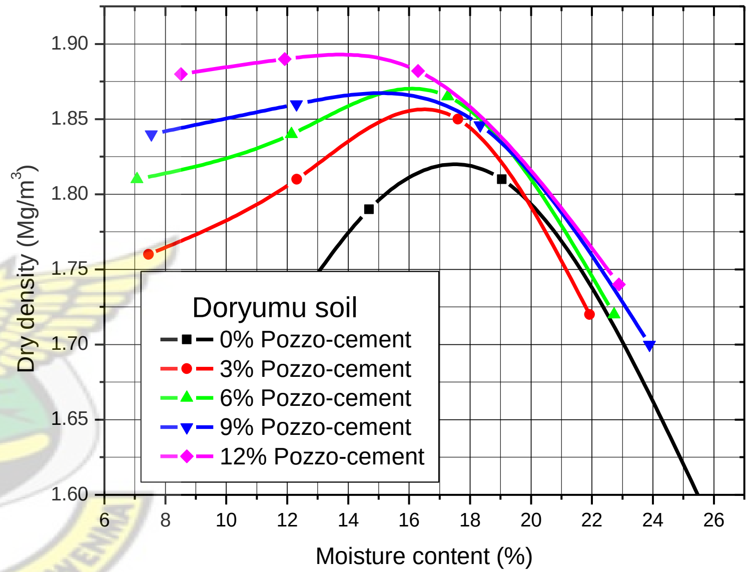
The compaction characteristics of the natural and pozzolana-cement-stabilised soils are presented in Figure 37. It is noted that as pozzolana-cement content was increased, there was an increase in the maximum dry density (MDD) and a reduction in the optimum moisture content (OMC). The increase in MDD could be due to the high specific gravity of pozzolana-cement. Figure 38 and Figure 39 distinctly show the effect of pozzolana-cement content on the MDD and OMC of the two soils. After some optimum pozzolana-cement content, the MDD began to fall. The reduction in the OMC corresponding to the various MDD reduced with increasing pozzolana-cement as depicted by Figure 39.

The results from the soaked CBR tests on the samples compacted at various pozzolana-cement contents are presented in Figure 40. It is noted that CBR values increased with increasing pozzolana-cement content for both Tsopoli and Doryumu black cotton soils.

The CBR swell of the compacted soils is shown in Figure 41. It is found that CBR swell increases with pozzolana-cement content for the Doryumu soil. The Tsopoli soil on the other hand showed reduction in CBR swell up to 3% pozzolana-cement beyond which the swell value began to increase.



Tsopoli soil



Doryumu soil

Figure 37. Compaction characteristics of the pozzolana-cement stabilised soils

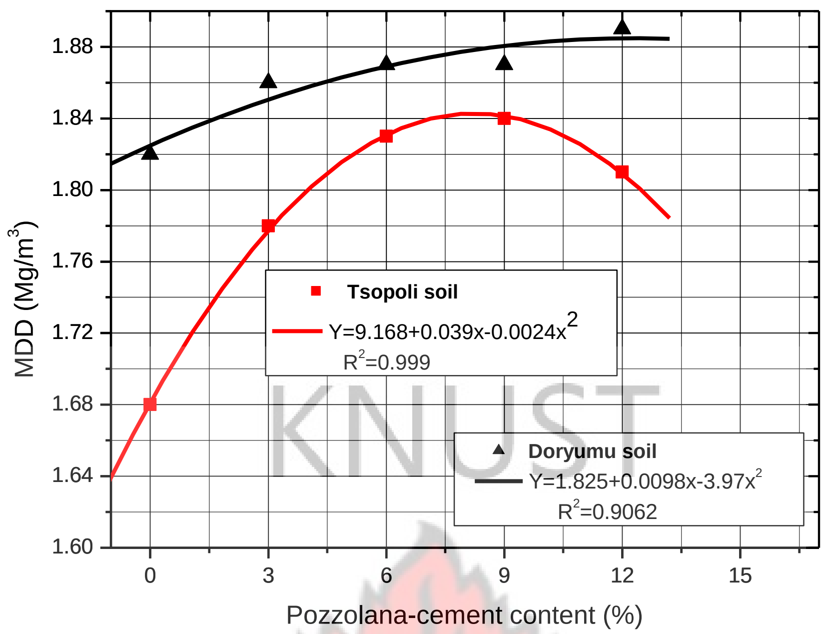


Figure 38. Variation of MDD with Pozzolana-cement

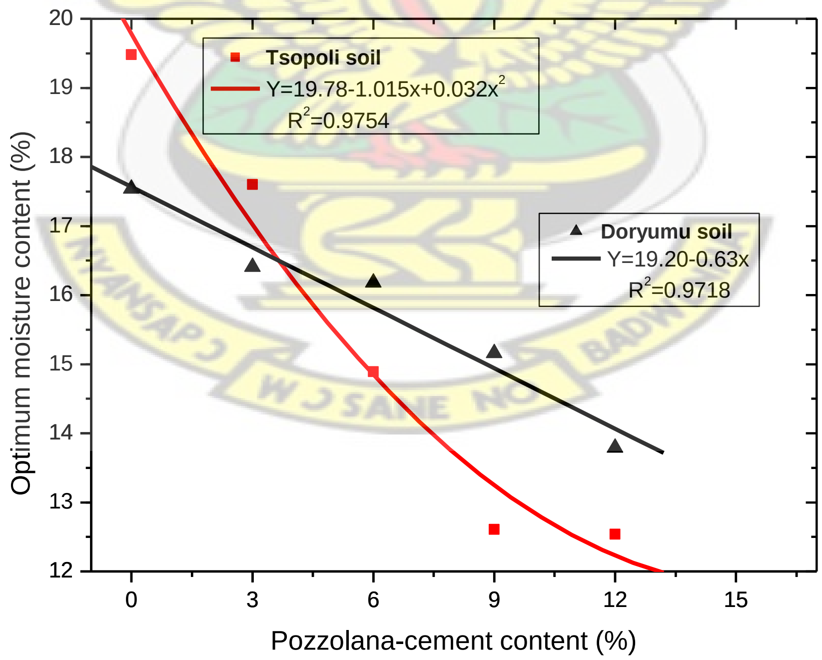


Figure 39. Variation of OMC with Pozzolana-cement

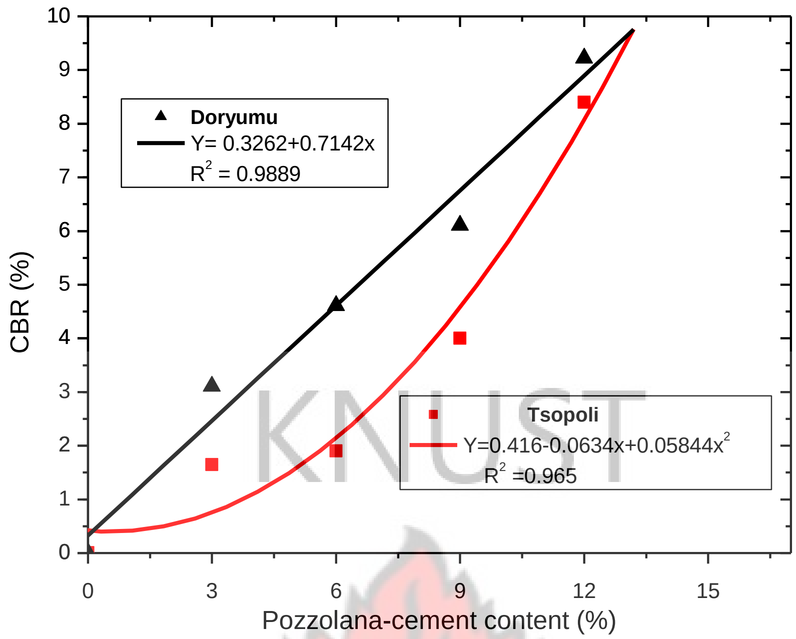


Figure 40. Variation of CBR value with Pozzolana-cement content of the soils

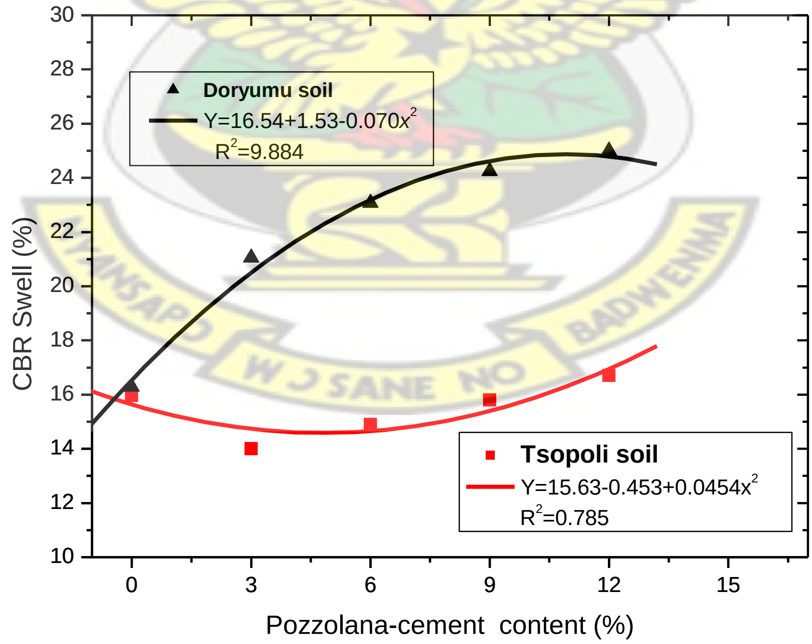


Figure 41. Variation of CBR swells with Pozzolana-cement content

Summary of results

The addition of pozzolana-cement to the black cotton soils had effect on the particle size distribution. However, the textural classification of the natural Tsopoli soil as clay was unaltered. On the other hand, the Doryumu soil which classified as sandy clay in its natural state changed texturally to clay upon addition of pozzolana-cement content greater than 3%.

There was reduction in the Atterberg limits (liquid limit, plasticity index, linear shrinkage) of both the Tsopoli and Doryumu soils but the plastic limits increased with increase in pozzolana-cement content. The reduction in plasticity characteristics of the soils was due to the chemical reaction between pozzolana-cement and the clay size fraction of the black cotton soils. The reduction in the Atterberg limits, however, did not cause any change in the classification of the two soils.

Increase in pozzolana-cement content caused an increase in the maximum dry density (MDD) up to some optimum pozzolana-cement content beyond which the MDD began to decrease. The optimum moisture content (OMC) of the soils decreased with increasing pozzolana-cement content.

The California Bearing Ratio values (CBR) increased with increasing pozzolana-cement content for both the Tsopoli and Doryumu soils. The CBR swell increased with pozzolana-cement content for the Doryumu soil but the Tsopoli soil showed reduction up to 3% pozzolana-cement and then increased beyond 6% pozzolana-cement. The increase in CBR value may be due to the reaction between the pozzolana-cement and the soil. The increase in CBR swell with pozzolana-cement content may be due to the increase absorption of water by both the soil and the increasing amount of pozzolana-cement.

The increase in strength of the soil could be due to the production of cementitious materials due to the hydration of the pozzolana-cement.

The pozzolana-cement caused significant improvement in the geomechanical characteristics of the black cotton soils especially the bearing strength and could be said to be a good stabilising agent.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The research work evaluated the geological and geomechanical characteristics of two black cotton soils in their natural and stabilised states. The main objectives of the study were:

i. Evaluate the geological characteristics of the black cotton soils occurring in the Accra plains

ii. Determine the chemical and mineralogical composition of the black cotton soils in the Accra plains of Ghana.

iii. Evaluate the geomechanical characteristics of natural and stabilised black cotton soils for subgrade construction.

iv. Attempt to provide an effective soil improvement method applicable to local black cotton soils for engineering purposes.

v. Suggest some relevant recommendations regarding the use of the natural and stabilised black cotton soils for the benefit of geomechanical practice in Ghana.

From the study the following conclusions may be drawn:

- The chemical composition of the black cotton soils studied reveal that the most abundant oxides are silica, alumina and iron oxide. The mineralogy of the soils from XRD analyses are similar and are composed of Quartz and Montmorillonite.
- The distresses and failures evident in civil engineering structures built on the black cotton soils in the Accra plains of Ghana are due to the presence of expansive clay mineral montmorillonite occurring in the soils. The soils are therefore susceptible to volume change when there is alteration of moisture conditions.

- Attempts to stabilise the soils for use as subgrade material using quarry dust, pozzolana and pozzolana-cement admixtures showed some improvement in some geomechanical parameters. Amongst the three stabilisers considered in the study, pozzolana-cement appears to be the most promising for stabilising the black cotton soils and it is believed that pozzolana contents greater than those used in the study could improve the material for possible use as subgrade material.

5.2 Recommendations

From the study it is recommended that:

- Studies be conducted using pozzolana-cement contents greater than those used in this study to stabilize black cotton soils.
- The effect of curing time on the engineering properties of the pozzolana and pozzolana-cement stabilized black cotton soils be evaluated since pozzolanic reactions are time bound.
- Studies should be conducted on the potential use of geosynthetics in improving the black cotton soils

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APPENDICES

Appendix 1 The rating of soils based on Free Swell Index (IS 1498, 1987)

Free Swell Index	Degree of expansivity
<50%	Low
50-100	Medium
100-200	High
>200	Very High

KNUST

Appendix 3: Sample Test Data

Natural moisture content determination sheet

NATURAL MOISTURE CONTENT DETERMINATION

PROJECT:- Black cotton soil Research SITE Tsopoli

DATE

SAMPLE No		TP1		TP1		TP1		TP1		TP1	
SAMPLE DEPTH	m	0.5		1		1.4-1.85		1.85-2.7		2.75-3.0	
CONTAINER No		D4	X1	X4	X11	D6	D2	D4	D5	D16	D15
MASS OF CONTAINER	g	18.2	18.33	18.19	17.85	9.79	9.41	9.75	9.72	9.42	9.57
MASS OF CONTAINER + WET SOIL	g	66.59	66.89	58.3	55.01	58.24	66.02	60.27	56	81.39	71.23
MASS OF CONTAINER + DRY SOIL	g	54.01	54.38	46.8	44.48	45.96	51.2	47.37	44.34	63.79	56.33
MASS OF WATER	g	12.58	12.51	11.45	10.53	12.28	14.82	12.90	11.66	17.60	14.90
MASS OF DRY SOIL	g	35.77	36.05	28.61	26.63	36.17	41.79	37.62	34.62	54.37	46.76
MOISTURE CONTENT	%	35.17	34.70	40.02	39.54	33.95	35.46	34.29	33.68	32.37	31.86
AVERAGE MOISTURE CONTENT	%	34.9		39.8		34.7		34.0		32.1	

Typical specific gravity data sheet

SPECIFIC GRAVITY DETERMINATION												
SAMPLE ID	TSOPOLI 1.4-2.0		TSOPOLI 0.5		QUARRY DUST		TSOPOLI 0.3-1.4		DORYUMU 1-1.36		DORYUMU 1.36	
Pycnometer Bottle No.	**A**	**B**	**C**	**D**	**E**	**F**	G	H	I	J	K	L
Mass of empty pycnometer + stopper (m1)	20.0	22.9	27.1	24.1	23.7	30.6	20	22.9	27.1	24.1	23.7	30.6
Mass of empty pycnometer + soil (m2)	30.0	32.9	37.1	34.1	33.7	40.6	30	32.9	37.1	34.1	33.7	40.6
Mass of empty pycnometer + soil + Liquid (m3)	74.3	78.9	83.1	82.5	83.9	78.4	74.4	78.9	83.1	82.7	83.5	78
Mass of pycnometer Bottle + Liquid (m4)	67.8	72.4	76.5	76.0	76.9	71.4	67.8	72.4	76.5	76	76.9	71.4
Specific Gravity, ρs = ((m2-m1)/(m4-m1)-(m3-m2))× ρ*L*	2.33	2.33	2.40	2.33	2.72	2.72	2.40	2.33	2.40	2.48	2.40	2.40
Average Specific Gravity	2.33		2.37		2.72		2.37		2.44		2.40	

Typical Grading test data

PROJECT: BLACK COTTON SOIL RESEARCH **DESCRIPTION:**

SAMPLE : DORYUMU15%Pozzo

GRADING TEST Total Dry Weight = 50.0 Total Dry Weight = 50.22

Sieve size		Weight	Percentage	.
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			100.00
1 in	26.50		0.0	100.00
¾ in	19.00		0.0	100.00
½ in	13.20	0.00	0.0	100.00
⅜ in	9.50	0.00	0.0	100.00
¼	6.70	0.00	0.0	100.00
3/16	4.75	0.00	0.0	100.00
1/8	3.35	0.00	0.0	100.00

Sieve size		Weight	Percentage	Percentage
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
No. 7	2.00	0.76	1.51	98.49
No. 14	1.00	1.50	2.99	95.50
No. 25	0.600	1.04	2.07	93.43
No. 36	0.425	0.89	1.77	91.66
No. 52	0.300	1.31	2.61	89.05
NO. 72	0.200	1.99	3.96	85.09
No. 100	0.100	4.40	8.76	76.32
No. 200	0.075	1.56	3.11	73.22

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings Rh'	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	27.50	1.0220	22.00	22.500	111.725	0.837	0.060	1.654	20.054	64.89
1.00	7:51	27.50	1.0215	21.50	22.000	113.700	0.837	0.043	1.654	19.554	63.27
2.00	7:52	27.50	1.0208	20.80	21.300	116.465	0.837	0.031	1.654	18.854	61.01
4.00	7:54	27.50	1.0205	20.50	21.000	117.650	0.837	0.022	1.654	18.554	60.04
8.00	7:58	27.50	1.0197	19.70	20.200	120.810	0.837	0.016	1.654	17.754	57.45
15.00	8:05	27.50	1.0194	19.40	19.900	121.995	0.837	0.011	1.654	17.454	56.48
30.00	8:20	27.00	1.0190	19.00	19.500	123.575	0.847	0.008	1.525	16.925	54.77
60.00	8:50	27.00	1.0182	18.20	18.700	126.735	0.847	0.006	1.525	16.125	52.18
120.00	9:50	27.00	1.0180	18.00	18.500	127.525	0.847	0.004	1.525	15.925	51.53
240.00	11:50	26.00	1.0175	17.50	18.000	129.500	0.867	0.003	1.275	15.175	49.10
1440.00	7:50	27.00	1.0166	16.60	17.100	133.055	0.847	0.001	1.525	14.525	47.00

PROJECT: BLACK COTTON SOIL RESEARCH

SAMPLE: **TSOPOLI 0.5m**

GRADING TEST Total Dry Weight = 50.0

Sieve size		Weight	Percentage	.
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
3 in	75.00			
2 1/2 in	63.00			
2 in	53.00			
1 1/2 in	37.10			100.00
1 in	26.50		0.0	100.00
3/4 in	19.00		0.0	100.00
1/2 in	13.20		0.0	100.00
3/8 in	9.50		0.0	100.00
1/4	6.70		0.0	100.00
3/16	4.75	0.00	0.0	100.00
1/8	3.35	0.00	0.0	100.00

Total Dry Weight = 50.0

Sieve size		Weight	Percentage	Percentage
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
No. 7	2.00	0.00	0.00	100.00
No. 14	1.00	0.10	0.20	99.80
No. 25	0.600	0.20	0.40	99.40
No. 36	0.425	0.27	0.54	98.86
No. 52	0.300	0.44	0.88	97.98
NO. 72	0.200	0.75	1.50	96.48
No. 100	0.100	2.23	4.46	92.02
No. 200	0.075	1.24	2.48	89.54

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings Rh'	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	27.50	1.0256	25.60	26.100	97.505	0.837	0.056	1.654	23.654	76.88
1.00	7:51	27.50	1.0255	25.50	26.000	97.900	0.837	0.040	1.654	23.554	76.55
2.00	7:52	27.50	1.0248	24.80	25.300	100.665	0.837	0.028	1.654	22.854	74.28
4.00	7:54	27.50	1.0240	24.00	24.500	103.825	0.837	0.020	1.654	22.054	71.68
8.00	7:58	27.50	1.0237	23.70	24.200	105.010	0.837	0.014	1.654	21.754	70.70
15.00	8:05	27.50	1.0233	23.30	23.800	106.590	0.837	0.011	1.654	21.354	69.40
30.00	8:20	27.50	1.0229	22.90	23.400	108.170	0.837	0.008	1.654	20.954	68.10
60.00	8:50	27.50	1.0224	22.40	22.900	110.145	0.837	0.005	1.654	20.454	66.48
120.00	9:50	27.50	1.0220	22.00	22.500	111.725	0.837	0.004	1.654	20.054	65.18
240.00	11:50	27.50	1.0215	21.50	22.000	113.700	0.837	0.003	1.654	19.554	63.55
1440.00	7:50	28.00	1.0201	20.10	20.600	119.230	0.828	0.001	1.786	18.286	59.43

PROJECT: BLACK COTTON SOIL RESEARCH   DESCRIPTION:

SAMPLE : 100%Pozzolana

GRADING TEST Total Dry Weight = 50.0   Total Dry Weight = 50.0

Sieve size		Weight	Percentage	.
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			100.00
1 in	26.50		0.0	100.00
¾ in	19.00		0.0	100.00
½ in	13.20	0.00	0.0	100.00
⅜ in	9.50	0.00	0.0	100.00
¼	6.70	0.00	0.0	100.00
3/16	4.75	0.00	0.0	100.00
1/8	3.35	0.00	0.0	100.00

Sieve size		Weight	Percentage	Percentage
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
No. 7	2.00	0.02	0.04	99.96
No. 14	1.00	0.05	0.10	99.86
No. 25	0.600	0.08	0.16	99.70
No. 36	0.425	0.16	0.32	99.38
No. 52	0.300	0.60	1.20	98.18
NO. 72	0.200	1.78	3.56	94.62
No. 100	0.100	6.82	13.64	80.98
No. 200	0.075	2.87	5.74	75.24

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (º c)	Direct hydrometer readings Rh'	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	26.00	1.0230	23.00	23.500	107.775	0.867	0.060	1.275	20.675	67.19
1.00	7:51	26.00	1.0200	20.00	20.500	119.625	0.867	0.045	1.275	17.675	57.44
2.00	7:52	26.00	1.0186	18.60	19.100	125.155	0.867	0.032	1.275	16.275	52.89
4.00	7:54	26.00	1.0170	17.00	17.500	131.475	0.867	0.023	1.275	14.675	47.69
8.00	7:58	26.00	1.0156	15.60	16.100	137.005	0.867	0.017	1.275	13.275	43.14
15.00	8:05	26.00	1.0140	14.00	14.500	143.325	0.867	0.013	1.275	11.675	37.94
30.00	8:20	26.00	1.0120	12.00	12.500	151.225	0.867	0.009	1.275	9.675	31.44
60.00	8:50	26.00	1.0107	10.70	11.200	156.360	0.867	0.007	1.275	8.375	27.22
120.00	9:50	26.00	1.0095	9.50	10.000	161.100	0.867	0.005	1.275	7.175	23.32
240.00	11:50	25.50	1.0085	8.50	9.000	165.050	0.877	0.003	1.153	6.053	19.67
1440.00	7:50	25.00	1.0055	5.50	6.000	176.900	0.888	0.001	1.035	2.935	9.54

Typical liquid and plastic limit data

GEOLOGICAL ENGINEERING DEPARTMENT
BLACK COTTON SOIL RESEARCH
ATTERBERG LIMIT DETERMINATION

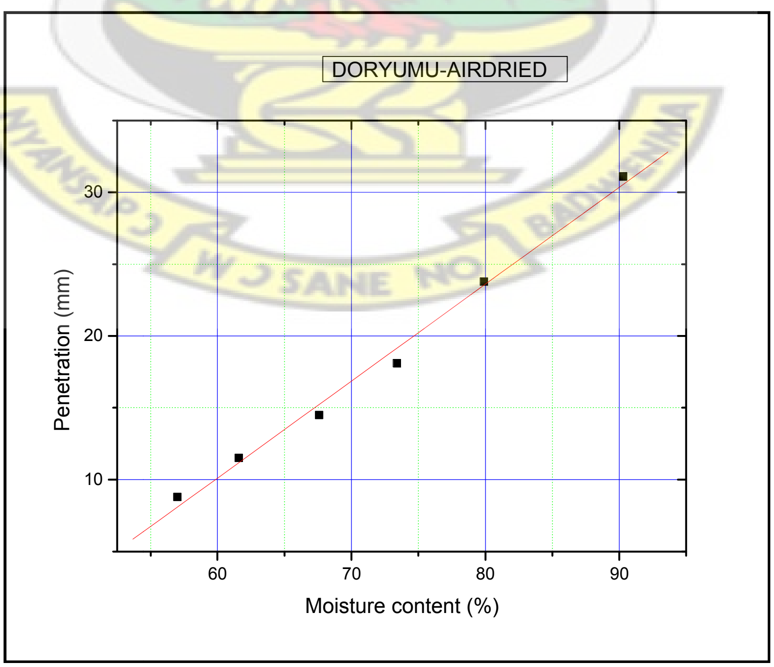
DORYUMU

Liquid Limit

CONT. NO	A25	B30	B15	X6	B6	B14
WEIGHT OF CONT.	3.78	3.69	3.72	3.67	3.68	3.69
PENETRATION (mm)	8.8	11.5	14.5	18.1	23.8	31.1
WET+CONT	14.58	12.92	13.86	16.71	17.57	17.94
DRY SAMPLE+CONT	10.66	9.4	9.77	11.19	11.4	11.18
WEIGHT OF WATER	3.92	3.52	4.09	5.52	6.17	6.76
WEIGHT OF DRY SAMPLE	6.88	5.71	6.05	7.52	7.72	7.49
WATER CONTENT %	56.98	61.65	67.60	73.40	79.92	90.25

plastic limit

CONT. NO	X18	K18			
WEIGHT OF CONT.	3.7	3.72			
WET+CONT	17.9	15.09			
DRY SAMPLE+CONT	14.89	12.73			
WEIGHT OF WATER	3.01	2.36			
WEIGHT OF DRY SAMPLE	11.19	9.01			
WATER CONTENT %	26.90	26.19	LL	PL	PI
	26.55		74.68	26.55	48.13



GEOLOGICAL ENGINEERING DEPARTMENT
BLACK COTTON SOIL RESEARCH
ATTERBERG LIMIT DETERMINATION

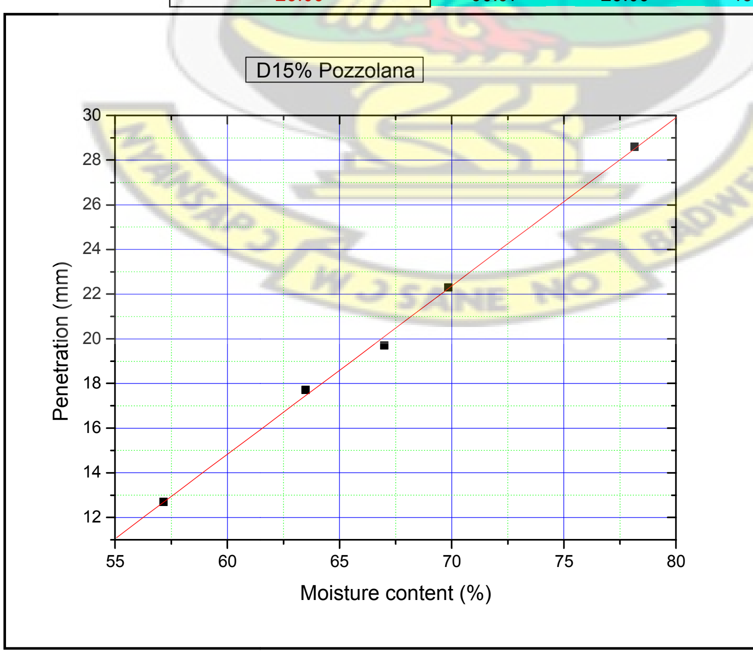
Doryumu 15% Pozzo

Liquid Limit

CONT. NO	B10	A30	B23	B1	C6
WEIGHT OF CONT.	3.55	3.58	3.71	3.76	3.61
PENETRATION (mm)	12.7	17.7	19.7	22.3	28.6
WET+CONT	16.17	15.4	15.3	14.75	18.86
DRY SAMPLE+CONT	11.58	10.81	10.65	10.23	12.17
WEIGHT OF WATER	4.59	4.59	4.65	4.52	6.69
WEIGHT OF DRY SAMPLE	8.03	7.23	6.94	6.47	8.56
WATER CONTENT %	57.16	63.49	67.00	69.86	78.15

plastic limit

CONT. NO	A12	C9			
WEIGHT OF CONT.	3.69	3.69			
WET+CONT	14.89	13.67			
DRY SAMPLE+CONT	12.82	11.77			
WEIGHT OF WATER	2.07	1.9			
WEIGHT OF DRY SAMPLE	9.13	8.08			
WATER CONTENT %	22.67	23.51	LL	PL	PI
	23.09		66.97	23.09	43.88



GEOLOGICAL ENGINEERING DEPARTMENT
BLACK COTTON SOIL RESEARCH
ATTERBERG LIMIT DETERMINATION

TSOPOLI - 6% Pozzolana- cement

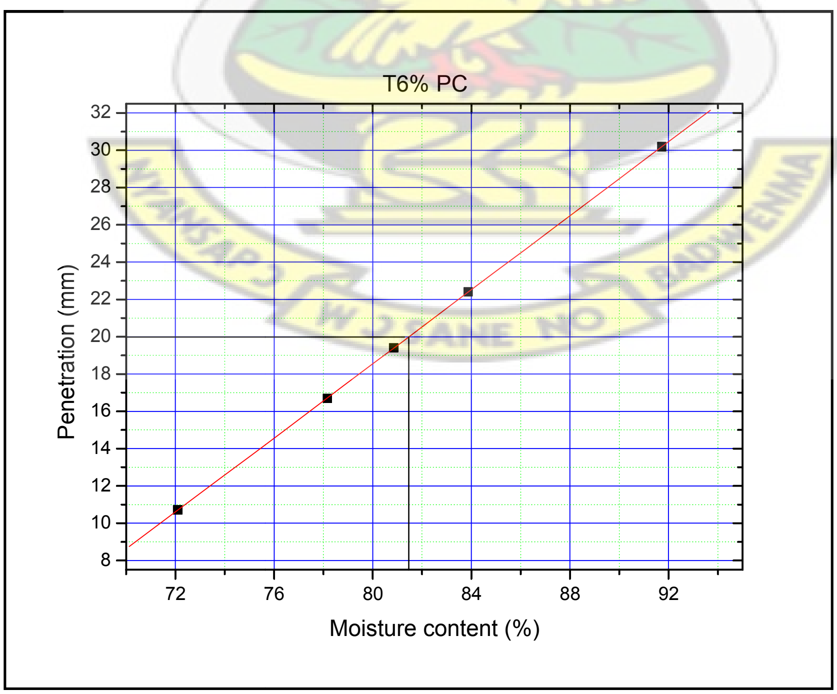
Liquid Limit

CONT. NO	K6	C4	A2	C17	B16
WEIGHT OF CONT.	3.65	3.57	3.59	3.62	3.64
PENETRATION (mm)	10.7	16.7	19.4	22.4	30.2
WET+CONT	14.94	19.07	17.1	17.65	21.26
DRY SAMPLE+CONT	10.21	12.27	11.06	11.25	12.83
WEIGHT OF WATER	4.73	6.8	6.04	6.4	8.43
WEIGHT OF DRY SAMPLE	6.56	8.7	7.47	7.63	9.19
WATER CONTENT %	72.10	78.16	80.86	83.88	91.73

plastic limit

CONT. NO	C23	X17
WEIGHT OF CONT.	3.77	3.77
WET+CONT	13.97	13.08
DRY SAMPLE+CONT	11.67	10.98
WEIGHT OF WATER	2.3	2.1
WEIGHT OF DRY SAMPLE	7.9	7.21
WATER CONTENT %	29.11	29.13
	29.12	

LL	PL	PI
81.46	29.12	52.33993118



Linear shrinkage data sheet

linear shrinkage				
Soil	Initial length lo	Final length lf	lf/lo	1-(lo/lf) *100
Doyumu Raw	14	11.15	0.796429	20.36
Tsopoli Raw	12.8	9.7	0.757813	24.22
T15% Pozzo	14	10.675	0.7625	23.75
T12% Pozzo	13.9	10.75	0.773381	22.66
T9% Pozzo	12.7	9.775	0.769685	23.03
T90D10	13.9	10.6	0.76259	23.74
T50D50	14	11.95	0.853571	14.64
T70D70	13.9	11.2	0.805755	19.42
D 6% Pozzo	13.9	11.15	0.802158	19.78
D 12% Pozzo	13.9	11.05	0.794964	20.5
D 18% Pozzo	14	11.1	0.792857	20.86
T3%Pozzo	13.9	10.35	0.744604	25.54
T6%Pozzo	12.8	10.2	0.796875	20.31
S90D10	13.9	11.1	0.798561	20.14
S70D30	13.9	11.55	0.830935	16.5
S50D50	14	12.25	0.875	12.5

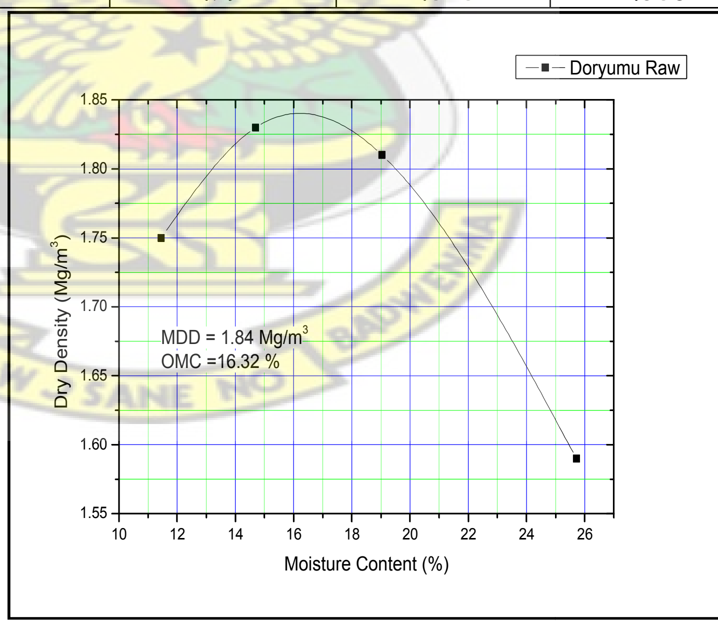
Typical compaction test data sheets

GEOLOGICAL ENGINEERING DEPARTMENT

GEOTECHNICAL LABORATORY

COMPACTION TEST

PROJECT SAMPLE No.	**Black cotton soil** **Doyumu**							
TRIAL NO.	1		2		3		4	
Mass of cylinder + wet sample (g)	11507		11716		11916		11593	
Mass of cylinder (g)	7505		7505		7505		7505	
Mass of wet sample (g)	4002		4211		4411		4088	
Bulk Density (Mg/m^3)	1.95		2.05		2.15		1.99	
Container No.	D12	X5	H2	D61	D2	D1	E1	A3
Mass of container + wet soil (g)	120.34	116.78	119.73	113.28	91.24	100.12	118.71	92.00
Mass of container + dry soil (g)	109.63	106.87	106.64	101.20	79.42	87.13	98.60	75.89
Mass of container (g)	18.15	18.38	17.92	18.62	18.04	18.12	18.88	14.39
Mass of water (g)	10.71	9.91	13.09	12.08	11.82	12.99	20.11	16.11
Mass of dry soil (g)	91.48	88.49	88.72	82.58	61.38	69.01	79.72	61.50
Water content (%)	11.71	11.20	14.75	14.63	19.26	18.82	25.23	26.20
Average Water Content (%)	11.45		14.69		19.04		25.71	
Dry density (Mg/m^3)	1.752		1.791		1.808		1.586	
Height of mould (cm)	11.6							
Diameter of mould (cm)	15							
Volume of mould (cc)	2049.89							

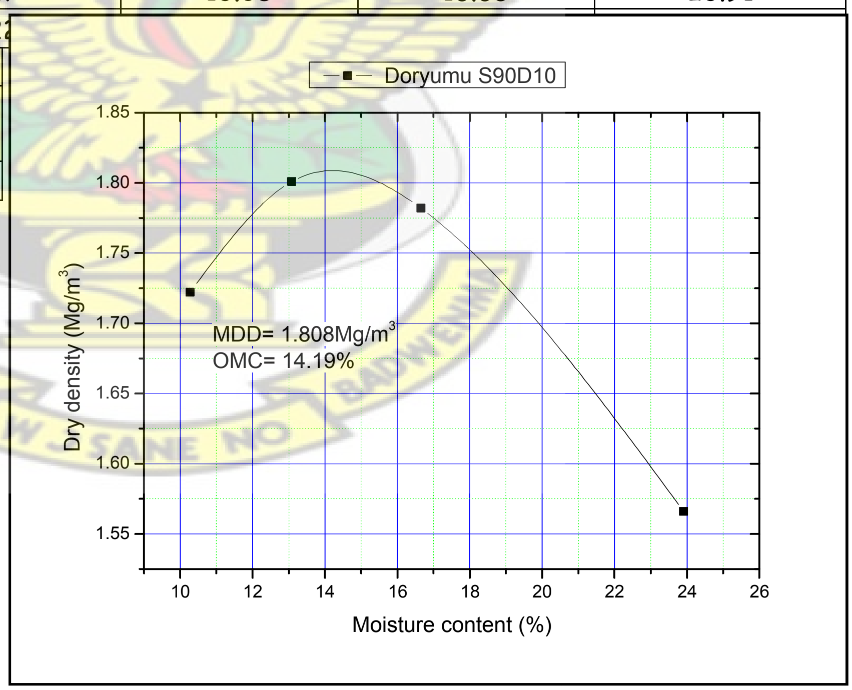


GEOLOGICAL ENGINEERING DEPARTMENT

GEOTECHNICAL LABORATORY

COMPACTION TEST

PROJECT SAMPLE No.	**Black cotton soil** **Doryumu S90D10**							
TRIAL NO.	1		2		3		4	
Mass of cylinder + wet sample (g)	8625		9015		9072		8725	
Mass of cylinder (g)	4150		4150		4150		4150	
Mass of wet sample (g)	4475		4865		4922		4575	
Bulk Density (Mg/m³)	1.90		2.06		2.09		1.94	
Container No.	99	188	42	131	341	407	368	475
Mass of container + wet soil (g)	77.50	87.50	64.90	62.80	79.50	90.30	102.70	85.70
Mass of container + dry soil (g)	71.20	80.90	58.50	56.80	69.40	80.00	86.00	71.10
Mass of container (g)	10.30	16.10	10.10	10.40	9.80	17.00	17.00	9.30
Mass of water (g)	6.30	6.60	6.40	6.00	10.10	10.30	16.70	14.60
Mass of dry soil (g)	60.90	64.80	48.40	46.40	59.60	63.00	69.00	61.80
Water content (%)	10.34	10.19	13.22	12.93	16.95	16.35	24.20	23.62
Average Water Content (%)	10.27		13.08		16.65		23.91	
Dry density (Mg/m³)	1.72							
Height of mould (cm)								
Diameter of mould (cm)								
Volume of mould (cc)	2357.16							

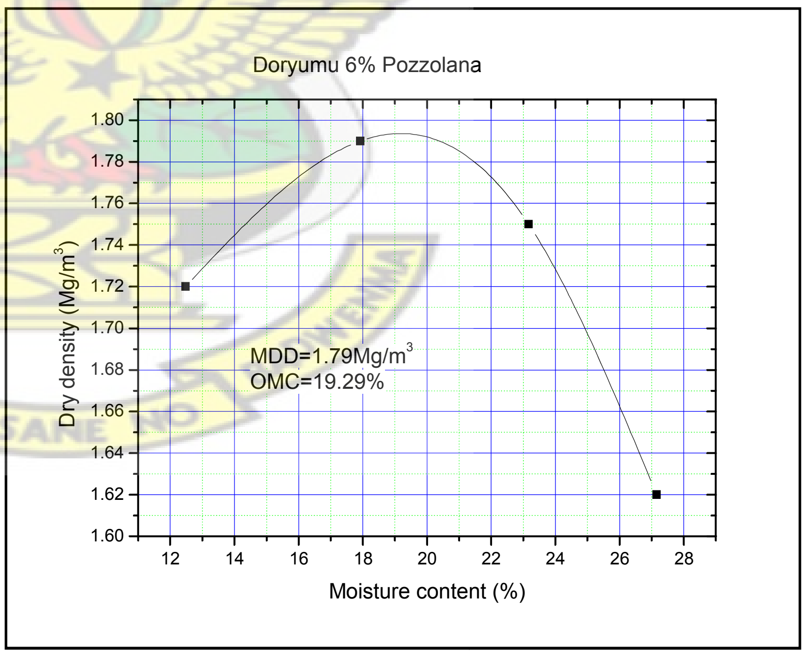


GEOLOGICAL ENGINEERING DEPARTMENT

GEOTECHNICAL LABORATORY

COMPACTION TEST

PROJECT	**Black cotton soil**							
SAMPLE No.	**Doryumu 6% Pozzolana**							
TRIAL NO.	1		2		3		4	
Mass of cylinder + wet sample (g)	11322		11689		11786		11586	
Mass of cylinder (g)	7363		7363		7363		7363	
Mass of wet sample (g)	3959		4326		4423		4223	
Bulk Density (Mg/m³)	1.93		2.11		2.16		2.06	
Container No.	H2	D8	TB	C2	M1	D3	D11	D7
Mass of container + wet soil (g)	92.95	96.13	88.51	104.87	99.89	117.64	106.87	127.81
Mass of container + dry soil (g)	84.69	87.39	78.45	90.87	84.19	99.39	86.13	106.65
Mass of container (g)	17.90	18.00	17.97	18.01	18.18	18.47	18.05	17.94
Mass of water (g)	8.26	8.74	10.06	14.00	15.70	18.25	20.74	21.16
Mass of dry soil (g)	66.79	69.39	60.48	72.86	66.01	80.92	68.08	88.71
Water content (%)	12.37	12.60	16.63	19.21	23.78	22.55	30.46	23.85
Average Water Content (%)	12.48		17.92		23.17		27.16	
Dry density (Mg/m³)	1.717		1.790		1.752		1.620	
Height of mould (cm)	11.6							
Diameter of mould (cm)	15							
Volume of mould (cc)	2049.89							



Typical CBR penetration test data sheets

BEFORE SOAKING BULK DENSITIES						
Mould No.	JOO7 (T15)		H17(T3%)		T12%	
No. of blows per layer	55		55		10	
Wet sample + Mould (g)	11,677		11,656		11,594	
Mass of Mould	7,471		7,363		7,404	
Mass of wet sample	4,206		4,293		4,190	
Volume of mould	2049.89		2049.89		2049.89	
Bulk density (g/cc)	2.052		2.094		2.044	
BEFORE SOAKING DRY DENSITIES						
Test.	1	2	C9	2	1	2
Container No.	C18	x5	D4	C9		
Wet sample + container (g)	113.05	116.92	89.59	103.54	101.39	101.18
Dry sample + container (g)	102.34	105.99	79.94	90.36	91.89	92.07
Mass of container	17.96	18.56	17.93	18.36	18.31	18.09
Mass of water	10.71	10.93	9.65	13.18	9.50	9.11
Mass of dry sample	84.38	87.43	62.01	72.00	73.58	73.98
Water content	12.69	12.50	15.56	18.31	12.91	12.31
Average Water Content	12.60		16.93		12.61	
Dry density	**1.822**		**1.791**		**1.815**	

								Proving Ring constant:kN/div	**0.023**
Penetration (mm)	**T15**		**CBR (%)**	**T3%**		**CBR (%)**	**T12%**		**CBR (%)**
	Load (div)	(kN)		Load div	kN		Load div	kN	
0.00	0	0		0	0		0	0	
0.25	1.1	0.0253		1	0.023		1.25	0.02875	
0.50	1.1	0.0253		1.1	0.0253		2	0.046	
0.75	1.1	0.0253		1.1	0.0253		2.25	0.05175	
1.00	1.1	0.0253		1.2	0.0276		3	0.069	
1.25	1.1	0.0253		1.2	0.0276		3	0.069	
1.50	1.1	0.0253		1.25	0.02875		3	0.069	
1.75	1.2	0.0276		1.29	0.02967		3	0.069	
2.00	1.25	0.02875		2	0.046		3	0.069	
2.25	1.25	0.02875	0.217	2	0.046	0.347	3	0.069	0.521
2.50	1.7	0.0391		2	0.046		3	0.069	
2.75	1.9	0.0437		2	0.046		3	0.069	
3.00	2	0.046		2	0.046		3	0.069	
3.50	2.1	0.0483		2.1	0.0483		3	0.069	
4.00	2.25	0.05175		2.2	0.0506		3	0.069	
4.50	2.7	0.0621	**0.311**	2.25	0.05175	**0.259**	3	0.069	**0.346**
5.00	3.1	0.0713		2.5	0.0575		3	0.069	
5.50	4	0.092		2.8	0.0644		3	0.069	
6.00	4	0.092		2.9	0.0667		3	0.069	
6.50	4	0.092		2.9	0.0667		3	0.069	
7.00	4	0.092		3	0.069		5	0.115	
		0			0			0	

BEFORE SOAKING BULK DENSITIES						
Mould No.	T3% PC		T6% PC		T9% PC	
No. of blows per layer	55		55		55	
Wet sample + Mould (g)	11,650		11,810		11,687	
Mass of Mould	7,373		7,495		7,430	
Mass of wet sample	4,277		4,315		4,257	
Volume of mould	2049.89		2049.89		2049.89	
Bulk density (g/cc)	2.086		2.105		2.077	
BEFORE SOAKING DRY DENSITIES						
Test.	1	2	1	2	1	2
Container No.						
Wet sample + container (g)	94.91	99.98	106.37	101.73	103.11	112.33
Dry sample + container (g)	82.93	87.83	95.63	90.21	94.04	101.32
Mass of container	18.11	17.75	18.26	17.94	18.12	18.31
Mass of water	11.98	12.15	10.74	11.52	9.07	11.01
Mass of dry sample	64.82	70.08	77.37	72.27	75.92	83.01
Water content	18.48	17.34	13.88	15.94	11.95	13.26
Average Water Content	17.91		14.91		12.61	
Dry density	**1.77**		**1.83**		**1.84**	

							Proving Ring constant:kN/div		**0.023**
Penetration (mm)	**T3%PC**			**T6%PC**			**T9%PC**		
	Load (div)	(kN)	**CBR (%)**	Load div	kN	**CBR (%)**	Load div	kN	**CBR (%)**
0.00	0	0		0	0		0	0	
0.25	2.5	0.0575		3.5	0.0805		7	0.161	
0.50	4	0.092		4.5	0.1035		11	0.253	
0.75	5	0.115		5	0.115		13	0.299	
1.00	6	0.138		7	0.161		15	0.345	
1.25	6.5	0.1495		7.5	0.1725		17	0.391	
1.50	7.25	0.16675		8.5	0.1955		18	0.414	
1.75	8	0.184		9	0.207		19.5	0.4485	
2.00	9	0.207		10	0.23		22	0.506	
2.25	9.5	0.2185	1.6503	11	0.253	1.91088	23	0.529	3.99547
2.50	10	0.23		11.8	0.2714		24	0.552	
2.75	10.5	0.2415		12.2	0.2806		25	0.575	
3.00	11	0.253		13	0.299		27	0.621	
3.50	11.5	0.2645		14	0.322		29	0.667	
4.00	12	0.276		14.8	0.3404		31.5	0.7245	
4.50	12.5	0.2875	**1.4404**	15.2	0.3496	**1.7515**	34	0.782	**3.9178**
5.00	13	0.299		16	0.368		37.5	0.8625	
5.50	13.2	0.3036		16.5	0.3795		40	0.92	
6.00	13.25	0.30475		16.9	0.3887		42.5	0.9775	
6.50	13.75	0.31625		17	0.391		45.5	1.0465	
7.00	14	0.322		17.2	0.3956		48	1.104	
		0			0			0	