ASSESSMENT OF BLACK COTTON SOIL AS SUBSTITUTE FOR BENTONITE IN LINER AND DRILLING APPLICATIONS

By

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DECLARATION

I hereby declare that this submission is my own work towards the MPhil degree 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

Bentonite is an essential component of drilling fluids and geosynthetic clay liners, which are mostly used in the geotechnical engineering industry for oil well drilling and lining of tailings storage facilities as well as landfill sites. The Ghana Environmental

Protection Agency (EPA) is advocating for a shift from the compacted clay liners to geosynthetic clay liners since the latter has superior hydraulic properties and longer service life in terms of preventing groundwater and soil pollution than the former. In Ghana, several metric tonnes of bentonite are imported for drilling purposes costing millions of dollars. In order to save much needed foreign exchange for other sectors of the economy, there is the need to source for local material to substitute commercial bentonite. Bentonite is used due to its unique properties, which are dictated by its mineralogical composition. It is mainly composed of the clay mineral montmorillonite. Montmorillonite is reported to be the major clay mineral in black cotton soils occurring in Ghana. Black cotton soils are reported to occur widely in Ghana covering an area of over 168,000 hectors, which are largely unexploited. This study therefore looked at black cotton soil with the aim of using it as substitute for bentonite in liner and drilling applications. Sample of black cotton soils were collected from Dawhenya, Prampram and Tsopoli which are located within the Accra Plains of Ghana. The samples were air dried, crushed and sieved to -0.075mm. The physical, chemical, mineralogical properties as well as the plastic viscosity, apparent viscosity, gel strength and yield point were determined and the results compared to those of commercial bentonite and some local and international standards. The physical properties included textural characteristics, colour, lithological characteristics by visual inspection and some index properties such as particle size distribution, Atterberg's limits, specific gravity and moisture content by BS 1377. The chemical and mineralogical properties were determined using x-ray fluorescence and x-ray diffractometry respectively. The organic matter content, cation ion exchange capacity (CEC) and exchangeable ions were also determined by the Walkley and Black method and ammonium displacement method respectively. The pH of the soils was determined using the glass electrode. Swell index and permeability were determined in accordance with IS 1498 and ASTM D5887 respectively. The plastic viscosity, gel strength and yield point were determined as stipulated in the API 13B-1 standard. The rheological properties were determined for concentrations of 22.5g/350ml, 32.5g/350ml, 42.5g/350ml, 52.5g/350ml and 62.5g/350ml. In order to improve the rheological properties, the tests were repeated for the same concentrations dosed with 10% Na_2CO_3. The results of physical, chemical and mineralogical test showed that the black cotton soils contain calcium montmorillonite as the dominant clay mineral. The permeability results obtained were of the order of 10^{-9}cm/s, which compare well with those of commercial bentonite and are within the Ghana Minerals Commission LI 2182 requirements as well as the USA EPA (most widely used in other parts of the world) requirements. The plastic viscosity, gel strength and yield point before the addition of Na_2CO_3 were 5 mPa.s, 4.8 mPa for 10sec and 10mins, 5-10 mPa respectively for a concentration of 22.5g/350ml. Upon the addition of 10% of Na_2CO_3, the plastic viscosity, gel strength and yield point increased to between 24-28.8 mPa.s, 5-12 mPa for 10sec, 11-26 mPa for 10mins, and 4.8-33.6 mPa respectively at the concentration of 22.5g/350ml and these values fulfill the requirements of the API 13B-1. An economic evaluation indicated a possible cost savings of about 58% when black cotton soil is used as drilling fluid and a cost saving of about 94% when used to substitute bentonite in geosynthetic clay liners.

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CHAPTER ONE

INTRODUCTION

1.1 General

All over the world, hydrocarbons and minerals industries are very lucrative sectors and international companies are always looking to invest in these sectors. The discovery of oil in commercial quantities in Ghana brought in many international companies who obtained licenses for offshore exploration. Since the hydrocarbons can only be extracted through the drilling of wells, clay will continue to be used in drilling activities (Omole et al., 2013). The clay component used in drilling fluid is bentonite and the cost of importing commercial bentonite for drilling purposes runs into millions of dollars. The total expenditure in drilling an oil well is estimated to be between 1 million to 100 million dollars out of which 5 to 15% is spent on drilling fluids (Bloys et al., 1994). There is therefore the need for a local substitute that may reduce cost.

In Ghana, huge quantities of rock are mined in open pit mines and processed to extract precious metals, which results in the generation of a lot of waste known as tailings. The waste material generated by mining activities contains chemicals that are harmful to the environment and therefore need to be stored in a manner that the environment will not be adversely affected.

It has therefore become important to safely dispose tailings; hence, mining companies are compelled to contain them behind specifically designed dams with basin liner systems.

The purpose of the liner system is to prevent hazardous chemicals from reaching the soil and ground water (Akayuli et al, 2013).

Natural soil barriers containing clay minerals have been the most widely used material in containment facilities in Ghana. These barriers are referred to as compacted clay liners (CCLs) or recompacted clay liners. Rowe et al, (1995) stated however that, a clay's ability to act as a barrier to chemical, municipal and mining waste could not be determined only from laboratory permeability measurements. They further explained that the permeability of compacted clay depends on factors such as placement and compaction of the clay, the mineral composition of the clay, or the effect of leachate on hydraulic conductivity resulting from the mineral composition.

The use of geosynthetics in Ghana is increasing rapidly. While the use of geosynthetics in civil engineering industry is low, the mineral industry long appreciated the advantages associated with the use of these geosynthetics (Bouazza et al. 2013).

Geosynthetic Clay Liners (GCLs) are made of bentonite glued or stitched between two geotextiles or glued to a geomembrane. The permeability of bentonite dictates the permeability of geosynthetic clay liners except those with geomembranes (Bouazza et al. 2013).

Bentonite is any clay, which has smectite as the most abundant clay mineral and the two main classes of bentonite that are mostly used in industry, are Sodium and Calcium bentonite. Bentonite is also used as a component of drilling fluids for the purposes of lubrication, cooling cutting tools and removal of cuttings from wells. The flow and deformation properties of bentonite are very important in geotechnical engineering (Hosterman et al, 1992). These properties stem from the swelling ability of the bentonite that also depends on the type of smectite clay within the bentonite.

Black cotton soils are defined as being black or greyish black in colour and containing clay of over 50%. The predominant clay mineral in the soil is the smectite group

(Morin, 1971).

Black cotton soils are generally expansive; therefore, pose serious engineering challenges when engineering structures are to be founded on them. The presence of the smectite group in Black cotton soil makes it capable of possessing some of the properties of bentonite that is widely used as drilling mud and in Geosynthetic clay liners. There is therefore the need to evaluate these properties of the black cotton soils with the aim of using them as substitute for bentonite in Geosynthetic clay liners and drilling mud. This study considers the physical, chemical, mineralogical, geotechnical and rheological properties of some typical black cotton soils found in Ghana.

1.2 Justification

Geosynthetic clay liners have become important components in civil engineering projects, especially in waste containment facilities. Stricter regulations by governing bodies have necessitated the isolation of hazardous waste by using specially designed containment systems. In recent times, geosynthetic clay liners have gained widespread acceptance for the purposes of base liners or final covers in landfill sites and mine waste-disposal facilities (Bouazza and Bowders, 2010).

The use of Geosynthetics is increasing rapidly in Ghana and the Environmental Protection Agency (EPA) is advocating for a shift from Compacted Clay Liners to Geosynthetic Clay Liners in line with international best practice.

Geosynthetic Clay Liners and commercial bentonite are very expensive and not readily available locally. Therefore, local production of substitute may reduce the cost and create employment. The cost of geosynthetic clay liners is between US$ 1.00-4.00 with a minimum order of 500 square meters (Anon, 2016). This implies that, for a 5m width by 100m length, which is usually the dimensions in which they are manufactured, will cost between 500 and 2000 US Dollars excluding shipping charges.

There are vast deposits of Black Cotton Soils in Ghana; they cover over 168,000 hectors of land area (Cobbina, 1987). They are mainly found in the southeastern part of the country: Accra-Ho-Keta plains and Winneba plains. Other deposits have been reported on the Bole-Bamboi Road near Kwaman Kwesi, Wa, Grupe, Tamale and some parts of the Volta Region (B. R. R. I., 1985).

1.3 Objectives of the research

The main objective of this research is to assess the applicability of black cotton soils as substitute for commercial bentonite in Geosynthetic Clay Liner Systems and Drilling Mud.

The specific objectives are to:

i. Determine the chemical and mineralogical characteristics of black cotton soil and commercial bentonite.
ii. Determine the geotechnical characteristics of black cotton soil and commercial bentonite. iii. Determine the rheological properties of black cotton soil and commercial bentonite.
iv. Compare the results from the black cotton soils to that of the commercial bentonite and some local and international standards.

1.4 Scope of research work

The research looked at black cotton soils from the Accra plains. Samples were obtained from Dawhenya, Prampram and Tsopoli, all within the Accra plains.

The relevant geotechnical characteristics of the black cotton soil samples and commercial bentonite were determined by the Atterberg limits test, specific gravity test, particle size distribution test and flux (permeability) test. The flux (permeability) test was conducted on a composite of the black cotton soil sandwiched between two geotextiles and the same was done for the commercial bentonite. The chemical properties of the commercial bentonite and black cotton soils were determined using X-ray fluorescence spectrometry. The mineralogical composition of these samples as well as commercial bentonite were determined using X-ray diffractometry while the rheological properties, specifically plastic viscosity, yield point, gel strength and apparent viscosity were determined in accordance with the American Petroleum Institute (API) standards. A comparison was then made between the results obtained from the black cotton soils and that of the commercial bentonite as well as with other local and international standards.

1.5 Location of project site

The Accra plain lies in the southeast of Ghana. The area is roughly triangular. It lies between longitude 5^o30N to 6^o15' N and latitude 0.20' W to 0.40' E. It is bound on the East and Northeast 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 geological map of the Accra Plains indicating sampling locations.

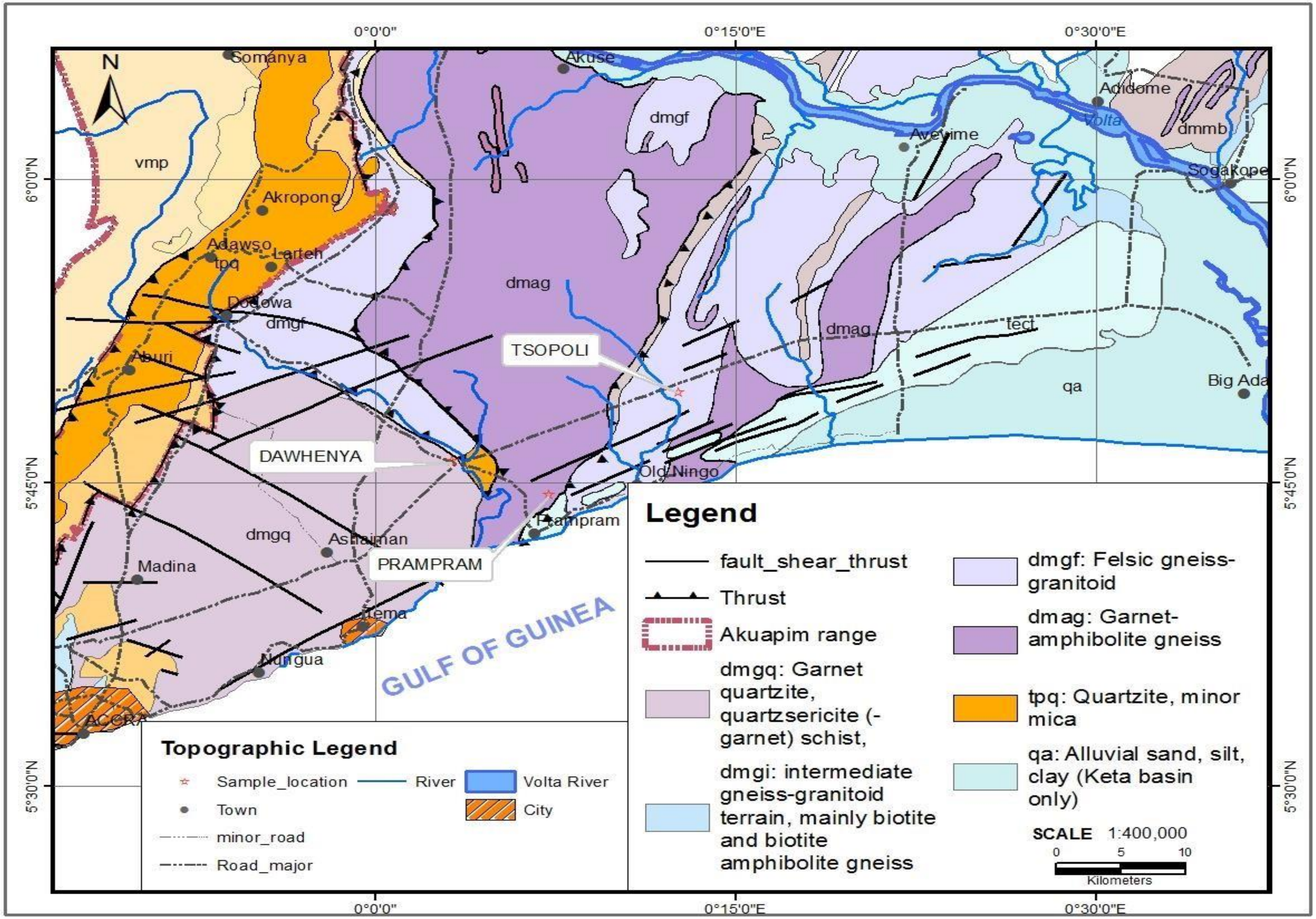
1.6 Geology of the study area

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 southeast.

The main Akwapim Range in the west is composed mainly of quartzite, mica schist and medium grained sandstone. 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 felsic gneiss granitoids whereas the mafic gneisses are entirely garnet-amphibolite gneisses. Recent alluvial sands, silts and clays occupy the Volta flood plains and valleys of the major streams on the plains. Figure 1 shows the geological map of the Accra plains.

The Dawhenya samples were developed over the garnet quartzite, quartz-sericite schist and quartzo-feldspathic gneiss whereas Prampram samples were formed over the garnet amphibolite gneiss with Tsopoli on the quartzo-feldspathic gneiss and granitoids (Ghana Geological Survey Department, 2009). Table 1 gives the stratigraphic succession as described by Junner and Bates (1945).

Figure 1: Geology of study area showing sampling location



0°0'0"
0°15'0"E
0°30'0"E
6°0'0"N
5°45'0"N
5°30'0"N
N
Somanya
Akuse
Adidome
Aveyime
Volta
dmmb
Sogakope
vmp
Akropong
Adawso
tpq
Larteh
Dodowa
dmgf
dmag
Aburi
TSOPOLI
tect
qa
Big Ada
DAWHENYA
Old Ningo
Prampram
dmgq
Ashaiman
Madina
PRAMPRAM
Tema
Nungua
ACCRA
GULF OF GUINEA
Legend
fault_shear_thrust
Thrust
Akuapim range
dmgq: Garnet quartzite, quartzsericite (-garnet) schist,
dmgi: intermediate gneiss-granitoid terrain, mainly biotite and biotite amphibolite gneiss
dmgf: Felsic gneiss-granitoid
dmag: Garnet-amphibolite gneiss
tpq: Quartzite, minor mica
qa: Alluvial sand, silt, clay (Keta basin only)
SCALE 1:400,000
0 5 10
Kilometers
Topographic Legend
Sample_location
River
Volta River
Town
City
minor_road
Road_major

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	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

1.7 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 (Kortatsi, 2006).

1.8 Climate

The Accra plains lie in Subhumid Climatic Zone of Ghana. The climate is categorized into two rainfall patterns. The major rainy season occurs between September and October with the highest occurring in October. Mean annual rainfall value is about 900mm and a mean annual rainfall temperature is around 26^{o}C (Kortatsi, 2006).

Average monthly humidities are highest (75%) during the rainy season and the lowest is about 60% (Dickson and Benneh, 1980). The total annual evaporative loss from free water surface has been found to be as high as 1800mm (Brammer, 1967).

1.9 Vegetation

The type of vegetation that covers the Accra Plains is the coastal scrub and grassland. It consists mainly of grass with isolated patches of scrub. Baobab and Nim trees are quite common and in the wetter parts, particularly east of the Volta, fan palms and wild oil palms are to be found in large numbers (Dickson and Benneh, 1980). Plate 1 shows the typical vegetation cover of the Accra Plains.

Plate I: Vegetation of study area

CHAPTER TWO

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 process where rocks are broken down to form soil. Active elements of the environment such as H_2O, CO_2 and O_2 alter the composition of rocks near or at the surface of the earth in a process known as chemical weathering.

The effects of weathering within an area at a particular time are assessed mostly by the climate, biological activity, topography, parent material and time. Many processes usually combine to cause the breakdown of rock masses. These include physical, biological and chemical processes. According to Robinson (1949), chemical weathering involves two steps. The initial step is the breakdown of the mineral parts, and the final is the development of ancillary products. These processes result in the formation of weathering residues with secondary materials in-situ, and transported materials deposited elsewhere. The first process of weathering which is physical or mechanical is labelled as breakdown and the next step comprising of biological and chemical weathering labelled as decomposition. The first process results in a physical breakdown of rocks and minerals without changing their chemical and mineralogical composition. In the case of decomposition, however, new minerals are created and some of the old ones are left as resilient minerals.

2.1.1 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 and it usually occurs in the surficial environments.

Physical weathering involves the breakdown of rock material without chemical change. The most important steps include *unloading, thermal expansion and contraction, frost action, colloid plucking and organic activity.*

Unloading: This occurs when overburden material is removed mostly by erosion, which results in a decrease in the overburden pressure, resulting in the fracturing of the rock in perpendicular direction to the release of the overburden pressure.

Thermal expansion and contraction: This explains the effects of temperature variation on a rock. Over a period of time, a rock is repeatedly heated and cooled when exposed to fluctuating temperature. This places stresses on the rock eventually causing it to fracture and break.

Frost action: Water contributes to physical weathering through freezing and thawing of water in cracks and crevices of rocks. Occasionally, expansion of water in cracks and crevices due to freezing can cause rocks to shatter.

Colloid plucking: Is the process in which small fragments are pulled off or loosened from rock surfaces by soil colloids in contact with them.

Organic activity: Plants contribute to physical weathering as roots grow up through the ground and rock surfaces. This eventually weakens rocks resulting in subsequent breakdown of the rock (Blyth and De Freitas, 1976).

Physical weathering is usually the precursor to chemical weathering. It mainly acts to breakdown rock masses, decrease particle sizes, and increase the surface area exposing most of the mineral face for chemical reaction.

2.1.2 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 altered greatly. 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 aluminum oxides (Mitchell and Soga, 2006). The processes of chemical weathering include hydrolysis, hydration, carbonation, oxidation and solution.

Hydrolysis: Is an essential stage in chemical weathering. This results from the separation of H_2O into H^+ and OH^- ions. These ions in solution react with minerals causing ion exchange, breakdown of crystalline structure and development of new compounds.

Hydration: Is the association of soil forming minerals with water molecules resulting in the alteration of the structure. These minerals are usually not associated with water in their stable state but upon exposure to moisture, hydration takes place resulting in the swelling of the mineral and subsequently causing the mineral to soften and breakdown.

Carbonation: Carbonic acid is produced when carbon dioxide dissolves in water. This acid when in contact with some rocks and minerals puts them into solution. The gradual dissolution of the soil or rock cementing material eventually breaks down the soil or rock structure.

Oxidation: Is the association of oxygen atoms with soil and rock minerals. This oxygen is usually within soil water and the atmosphere. This process usually occurs in the presence of water resulting in the formation of hydrated oxides.

Solution: Water soluble minerals dissolve directly and are removed through erosion and the rock losses its integrity and ultimately crumble. This process is accelerated in the presence of acidified water.

2.1.3 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, most of which usually occur at the same time include (Mitchell and Soga, 2006):

1. Minerals that are unaltered because they are either very resilient or newly exposed
2. Minerals that are newly created, with a similar structure as the novel mineral
3. Freshly created minerals with an altered interior structure
4. Products of other broken down minerals and these are usually clay minerals, colloids of aluminum oxide etc.
5. Idle guest reactants

2.2 Clays and clay minerals

Clays and clay minerals are very essential minerals, which occur widely around the globe with several industrial uses including environmental remediation and geology. They are largely used due to their mineral composition, which governs the required properties needed in a particular industry. Grim, (1962) defined "a clay material as any fine-grained, natural, earthy, argillaceous material". Clay is also defined in other literature (Wentworth, 1922) as a particle size fraction.

Grim (1968) further stated that, clays are essentially made up of a small group of extremely small crystalline particles known as clay minerals. These minerals are usually hydrous aluminum silicates and in some of these minerals, iron and magnesium substitute for the aluminum and alkaline elements. The major categories of clay minerals are "kaolin, smectite, palygorskite–sepiolite, illite, chlorite, and mixed-layered clays". The properties of these clays are very different which are related to their structure and composition (Murray, 2000a). The structure and composition of the various clay minerals are very different even though the central building blocks are the same. However, the arrangement and configuration of the octahedral and tetrahedral sheets explain the differences in the physical and chemical properties that control the applications of a particular clay mineral.

Prior to the 1920s, geologists making analyses of sediments listed the finest particles as clay with no identification of what this material actually was (Grim, 1988). The required technique for identifying the various particles that make up the clay material were not common, but presently, more accurate equipment and procedures have been developed to identify and measure the specific clay minerals present in a sample. These techniques include X-ray diffraction, electron microscopy, infrared spectroscopy, and differential thermal analysis. In almost all industrial applications, the clays and clay minerals are active component within the system (Murray, 2007).

2.2.1 Some physical and chemical characteristics of clay materials

Some essential properties that make particular clay materials useful include "particle size, shape and distribution, mineralogy, surface area, charge, chemistry, pH, ion exchange capacity and identification, brightness and color, sorption capacity, rheology and ceramic properties". The use of a particular clay depends on its properties, for example, kaolins are used to coat paper and bentonite is used in the formulation of drilling muds (Murray, 2007). The properties relevant to the use of the clay in geosynthetic clay liners and in drilling mud are discussed.

2.2.1.1 Particle size distribution

The particle size distribution is mostly described in relation to the distribution of the dry, granules and the distribution of the dispersed particles made up of those granules. This is achieved by mechanical sieving for the aggregated granules while the dispersed granules are obtained by the hydrometer test method. The best bentonite is usually made up of between 70% to 90% particles smaller than 2µm (Bouazza and Bowders, 2010).

2.2.2.2 Mineralogy

The most efficient way of determining the mineralogy of clayey materials is through X-ray diffraction (XRD). XRD uses the interaction of X-rays with the mineral of a substance to identify it (Bouazza and Bowders, 2010).

2.2.2.3 Surface area, charge and chemistry

The clay minerals with high base exchange are sodium montmorillonite and hectorite ranging between 80 and 130meq/100g. Calcium montmorillonite, however, has a base exchange capacity within 40 and 70meq/100g. Sodium montmorillonite is comprised of very small thin flakes resulting in the sodium montmorillonite having a surface area of about 150 to 200m^2/g. This together with high layer charge gives sodium montmorillonite a high sorptivity and a very high viscosity at low solids concentration. Because of the high layer charge and base exchange capacity, sodium montmorillonite has a great swelling capacity of about 10 to 15 times once placed in water (Bouazza and Bowders, 2010).

2.2.2.4 pH

The pH of a soil contributes a lot to precipitation, movement of ions, dissolution of soluble soil and rock materials and oxidation. It is measured using a glass electrode in a suspension of soil in water. The suspension is prepared in a ratio of 1: 1 for mass of soil and volume of distilled water (Thomas, 1996). Trauger (1994) indicated the range of pH for sodium bentonite to be between 8.5 and 10.5 while that of calcium bentonite falls within the range of 7.0 to 8.5.

2.2.2.5 Cation exchange capacity (CEC)

The ammonium displacement method is used in determining the cation exchange capacity. This is achieved by replacing the cations within the natural structure by other cations whose index is known. The amount of index cations that are taken up into the natural structure is quantified analytically.

Burrafato and Miano (1993) and Kariuki et al. (2003) have all described other methods of determining the cation exchange capacity such as surface tension and spectral absorption.

2.2.2.5 Rheology

Darley and Gray (1988), defined rheology "as the science and study of the deformation and flow of matter" and is most widely used to depict the properties of a drilling fluid in the hydrocarbons industry. They indicated that property of drilling muds is what makes them useful in drill-in fluids, workover and completion fluids, cements and specialty fluids and pills.

2.3 Bentonite

Historically, bentonite obtained its name from Knight, who defined it as a soapy clay material occurring in the Fort Benton unit in Wyoming USA. Condra (1908), identified clays from northern Nebraska as originating from the alteration of volcanic ash and called it bentonite but Hewitt (1917) and Wherry (1917) are generally perceive to be the first to indicate the origin of bentonite as an alteration of volcanic ash. Shannon (1926) gave the most popular definition of bentonite as "a rock made of crystalline clay mineral derived from the chemical alteration of tuffs or volcanic ash". These authors all indicated that the bentonite contains montmorillonite as the dominant clay mineral. Recently, bentonite has been used to represent any clay that contains montmorillonite (smectite in other literature) as the dominant clay mineral that influences the physical properties of the material (Wright, 1968).

Bentonite is categorized into different types depending on the dominant element examples of which are sodium, calcium, aluminum and potassium. The types of bentonite that are most widely used in industry are sodium and calcium bentonite.

The usefulness of bentonite in the drilling industry is to lubricate and cool cutting tools, remove drill cuttings and to support the walls of the well. This usefulness stems from the good rheological properties exhibited by bentonite in that, a little amount of bentonite in water forms a viscous material that shear thins with increasing shear rate. The process of shear thinning with increasing shear rate is known as thixotropy. At some concentrations, a bentonite water mixture turns to behave as a gel that makes it an important component of water based drilling fluid used to prevent formation fluid invasion by its ability to form a mud cake.

The ability of sodium bentonite to swell when hydrated makes it exhibit very low hydraulic conductivity making it very useful in barrier systems. Bentonite is thus used in lining landfill sites, containing metal pollutants and in geosynthetic clay liners (GCL) for containment lining purposes (Hosterman et al, 1992).

2.4 Black cotton soils

2.4.1 Definition and Nomenclature

Black cotton soils also known as black clay or tropical black earth are expansive soils that are black or greyish black in colour that are predominantly composed of montmorillonite (smectite) clay mineral (50%). These soils sometimes have local names such as "magarlitic" soils in Indonesia, "regur" in India and "black tuffs" in some African countries. Of all these names, black cotton soil is the most widely used and therefore this study adopts this name.

According to Gidigasu and Gawu (2013), the name "black cotton" was obtained from India where these soils support the growth of cotton and in pedology they are term as vertisols.

There are various definitions given to black cotton soils some of which include Mohr and Van Baren (1959) definition which says that "black cotton soils are black or greyish black, grey or in the eroded phase greyish-white" in colour, heavy loam or clays; which crack when dry and swell when moistened". Black cotton soils have also been defined by USAID/BRRI (1971) as "dark grey to black soil with a high content of clay usually over 50%, in which montmorillonite is the principal clay mineral and are commonly expansive" which also agrees with the definition given by Morin (1971). Bucher and Sailie (1984) also stated that, with montmorillonite as the dominant clay mineral, black cotton soils are susceptible to volume changes with hydration and drying. According to Gidigasu and Gawu, (2013), the main characteristics of black cotton soils can be categorized as follows:

1. They are black or greyish black in colour.
2. They are composed mostly of montmorillonite.
3. They are susceptible to volume changes with hydration and drying.
4. They expand when hydrated and crack when they dry.

2.4.2 Formation of black cotton soils

The process of soil formation depends on factors such as parent rock, climate, topography and time (age). These processes with regards to the formation of black cotton soils are discussed.

2.4.3 Parent material

Black cotton soils have been found to be formed on the three major rock types (igneous, sedimentary and metamorphic). Chemical weathering of basic igneous rocks such as basalt, norite, andesites, diabase, dolerite, gabbro and volcanic rocks under suitable conditions result in the formation of black cotton soils. The chemical weathering of metamorphic products of the above mention rocks can also form black cotton soils. The process is favored most in areas with poor drainage and distinct wet and dry seasons. Amorphous hydrous oxides are usually formed and in the presence of suitable conditions, clay is formed. Due to the absence of quartz, the resultant material is usually clay size particles with high plasticity displaying a characteristically high impermeability (Ola, 1983). Gidigasu and Gawu (2013) reported that, black cotton soils also occur on sedimentary materials such as shales, limestones, slates etc.

Majority of the minerals that weather to produce black cotton soil contain more feldspar and ferromagnesian minerals whose weathering residue is clay (Ahmad, 1983).

2.4.4 Climate

Ahmed (1996) reported that black cotton soils occur within almost all the major climatic zone of the world in contrast to the earlier notion that black cotton soils could only occur within the tropics with distinct wet and dry seasons. Katti et al (2002), state that black cotton soils occur within areas with rainfall figures between 300 and 900mm per annum but rainfall of over 1200mm per annum have been reported in other countries.

2.4.5 Topography

Black cotton soils generally occur over relatively flat terrain as Katti et al., 2002 have reported that black cotton soils form on slope less than 3^o. Eswaran et al. (1988), indicated that Black cotton soils are formed mostly over flat terrains and alluvial plains such as those in Sudan and in Ghana the Accra plains, the Ho-Keta plains and the Winneba plains. (USAID/BRRI 1971). Ahmad (1983), however, reported that black cotton soils have been formed on surfaces with slope angles greater than 3^o.

2.4.6 Time

According to Clemente et al. (1996), the period of development of black cotton soils are usually inferred from the age of the parent material. They further indicated that black cotton soils are formed from material of Cenozoic era including Tertiary and Quaternary. According to them however, black cotton soils of cretaceous age material also exist.

2.4.7 Occurrence of Black cotton soils

Black cotton soils are reported to occur worldwide covering an area of about 2% (257 million hectare). According to Gidigasu (2012), black cotton soils have been reported to occur in India, Australia, Algeria, Botswana, Ethiopia, Bulgaria, Hungry, Italy, Togo, Nigeria, South Africa, Morocco, Chad, Cameroon, Kenya, Zambia, Tanzania, Sudan and Ghana.

In Ghana, black cotton soils cover over 168 000 hectors of the land area (Cobbina, 1987) and are mainly found in the southeastern 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 (B. R. R. I., 1985).

2.5 Chemical and mineralogical composition of black cotton soils

2.5.1 Chemistry

Black cotton soils are mainly formed by the chemical weathering process. During the process, the mineral fabrics are broken down resulting in a change in the chemical composition. The chemical composition is thus indicated by the parent rock, degree of weathering and the transportation and deposition history. Titanium oxide is reported to occur in minor quantities, that gives the soil its dark colour (B.R.R.I., 1985). Inspite of its dark colour, small quantities of organic matter (less than 5%) have been reported by BRRI (1985).

2.5.2 Clay Mineralogy

Montmorillonite (smectite group) is reported to be the dominant clay mineral in black cotton soils but kaolinite, illite and other clay minerals could coexist. According Rao, (2006) a further weathering of montmorillonite results in the formation of the other clay minerals such as kaolinite, illite etc. that explains the coexistence of these minerals with the montmorillonite in low rainfall areas.

Mermut et al. (1996) also mentioned silicon activity as well as pH as influential in the formation and stability of smectite. High pH and silicon, magnesium and poor drainage results in the formation of stable smectites (Eswaran et al., 1988). The presence of basic conditions results in the formation of montmorillonite and the occurrence of any acidic condition causes the montmorillonite to weather into other clay minerals (Gidigasu, 2012).

2.5.3 Smectite (Montmorillonite)

In clay mineral nomenclature, the hydrated silicates of sodium, calcium, magnesium, iron, lithium, aluminum etc. are called the Smectite or montmorillonite group. These silicates are named by the dominant element within the montmorillonite. The mostly widely known examples are sodium montmorillonite, calcium montmorillonite, saponite (Mg), nontronite (Fe), and hectorite (Li), and beidellite (aluminum montmorillonite). According to Murray (2007), “Smectite minerals consist mainly of two silica tetrahedral sheets with a central octahedral sheet and are designated as a 2:1-layer mineral with water molecules and cations occupying the space between the 2:1 layers”. He gave $(OH)_4Si_8Al_4O_{20}$ NH_2O (interlayer) as the empirical formula of the smectite group of which he said the composition without the interlayer material is SiO_2, 66.7%; Al_2O_3, 28.3%; and H_2O, 5%. The most widely occurring smectite mineral is calcium montmorillonite, which implies that the layer charge deficiency is made up for by calcium ion and water. The smectite is called sodium montmorillonite once the charge deficiency is made up for by sodium ions and water (Murray, 2007).

2.6 Geosynthetic clay liners

Geosynthetic clay liners or GCLs, are a combination of synthetic materials with bentonite. Sarsby (2007), “define GCLs as thin layers of bentonite sandwiched between two geotextiles or bonded to a geomembrane”. To attain a competent structure, the resultant composite is stitched, glued or needle-punched. GCLs are mostly used in lining and capping landfill sites and other waste containment facilities such as tailings storage facilities.

According to Bouazza and Bowder (2010), it is important to understand the various components of a GCL if one needs to consider the product for use. It also important to know that GCLs have also been called by other names as indicated by Zanzinger et al, 2002 such as Geosynthetic Barriers-Clay (GBR-C) by the International Standards Organization (ISO).

2.6.1 Geotextiles

Geotextiles are synthetic materials made of polypropylene with other materials that gives it resistance to high temperature, durability and longer lifespan. The main types are the woven and nonwoven or nonwoven with woven scrim. They are used in geosynthetic clay liners as the support and capping of the bentonite (Bouazza and Bowders, 2010).

2.6.2 Geomembranes

A geomembrane is a synthetic material made from high-density polyethylene (HDPE) mostly used as a barrier in curtailing contaminants from reaching ground water and soil. They come in thicknesses from 1.0mm to 1.5mm and in various surface features (ASTM D4439). They are used in geotechnical engineering as follows:

- geomembrane above the bentonite
- geomembrane below the bentonite
- geomembrane below the bentonite with a geotextile cover above the bentonite (Bouazza and Bowder, 2010).

2.6.3 Other associated materials

The bentonite in geosynthetic clay liners needs to be bonded or glued to the geotextile or geomembrane to attain some level of structural integrity. Therefore, additives such as geofilm are added to the bentonite for this bonding purpose as well as to further lower the permeability of the resultant composite. The geofilm in some cases is used to polymer treat the covering geotextile to lower its hydraulic conductivity (Bouazza and Bowders, 2010).

There is also an emerging technology where the various particles of bentonite are polymer modified resulting in the classification of polymer modification by Jeon, 2009 as internal and external bentonite modification.

2.6.4 GCL Manufacturing

GCLs are also categorized into two types depending on the method of manufacturing which are the reinforced and nonreinforced GCLs. Bentonite in its hydrated state exhibits very low shear strength, it is therefore necessary to give it some form of support hence the two different types of GCLs. The nonreinforced GCLs are mostly used on flat surfaces while the reinforced GCLs could be used on slopes. Figure 2 shows the various types of GCLs based on manufacturing.

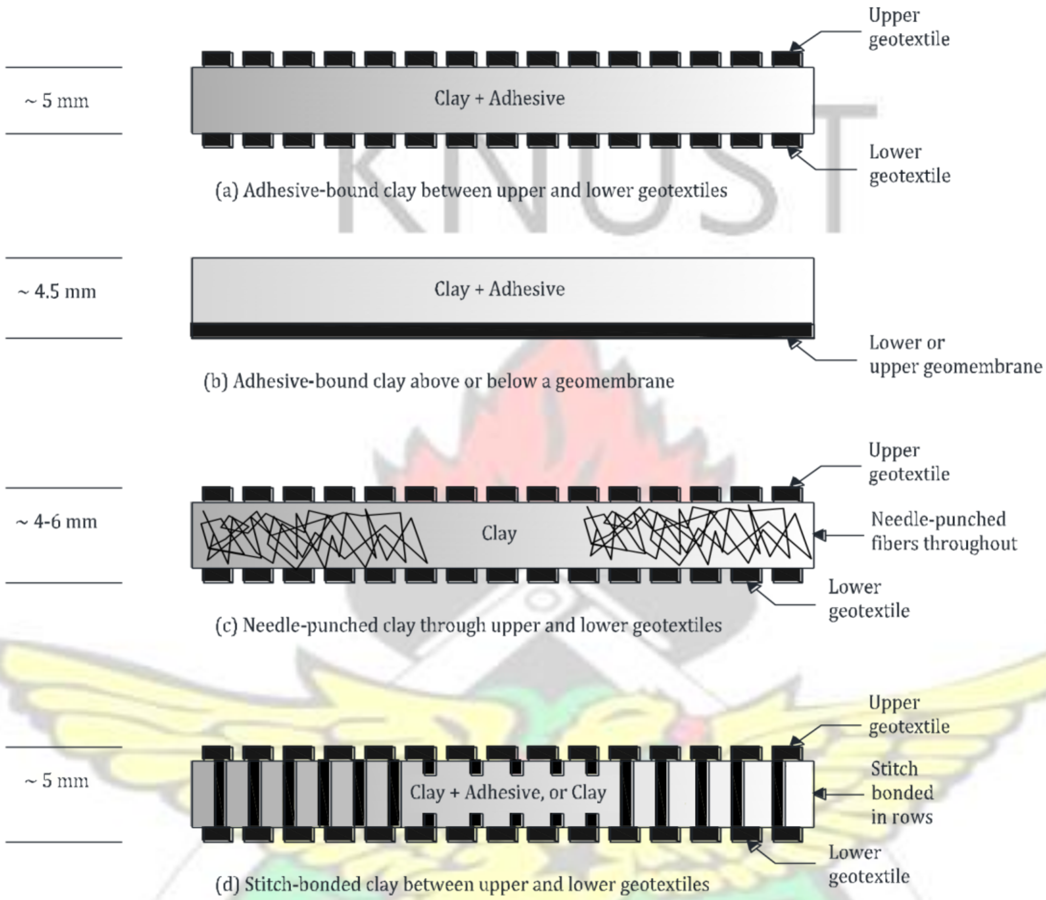


Figure 2: Cross section of current GCLs adopted from Koerner, (2005)

2.6.4.1 Nonreinforced GCLs

Bentonite is said to have the lowest hydraulic conductivity of all soil materials, which makes it useful in containment facility lining. Nevertheless, upon hydration bentonite exhibit very low shear strength. Daniel et al, (1993) also stated that, bentonite has a high affinity for water and will easily hydrate when covered with moist soil. This goes to explain the recommendation of nonreinforce GCLs for flat surfaces only. The only condition where nonreinforced GCLs could be used on a slope is where the GCL contains a geomembrane base and a geotextile cap (Thiel et al., 2004).

2.6.4.2 Reinforced GCLs

The reinforced GCL is obtained by needle punching or stitch bonding from cap to base geotextiles. In this type of GCL, the internal strength is obtained from the connecting fibers. Therefore, these GCLs can be used on slopes depending on the strength of the resultant composite.

2.6.5 Test Methods and Properties

Several deliberations and research are still in progress to categorize and evaluate GCLs and several test have been given by the ASTM and ISO. The relevant tests to this research are described.

2.6.5.1 Physical properties

Thickness of GCLs is a relatively difficult property to quantify and is proposed by Bouazza and Bowders (2010) to be used only as a quality control. The thickness is actually only important in the determination of the hydraulic conductivity of a GCL from the flux test. In this test, the thickness of the hydrated test specimen is essential and the problem is in how it can be measured.

The method of determining the *mass per unit area* GCL is stipulated in ASTM D5993. Most geosynthetic clay liners have a mass per unit area of 3.7kg/m^2. The difficulty of determining this parameter stems from the difficulty in cutting the GCL without losing some of the material. The presence of adhesives also makes the outcome disputable. For this reason, it was not considered in this research, as it will be difficult to compare the results and make a concrete conclusion.

2.6.5.2 Hydraulic properties

The hydraulic conductivity of GCLs is the most important property as the basic purpose of the GCL is as a fluid barrier. The ASTM D5887 describes the test procedure for determining the hydraulic conductivity by measuring flux values in a flexible wall permeameter. The test specimen is saturated for 48 hours using a cell pressure of 550kPa and a back pressure of 515kPa after which period the back pressure is increased to 530kPa to initiate flow. The flux value is then determined from the flow rate through the GCL specimen. Plate II shows a composite of geotextiles and black cotton soil after the flux test.

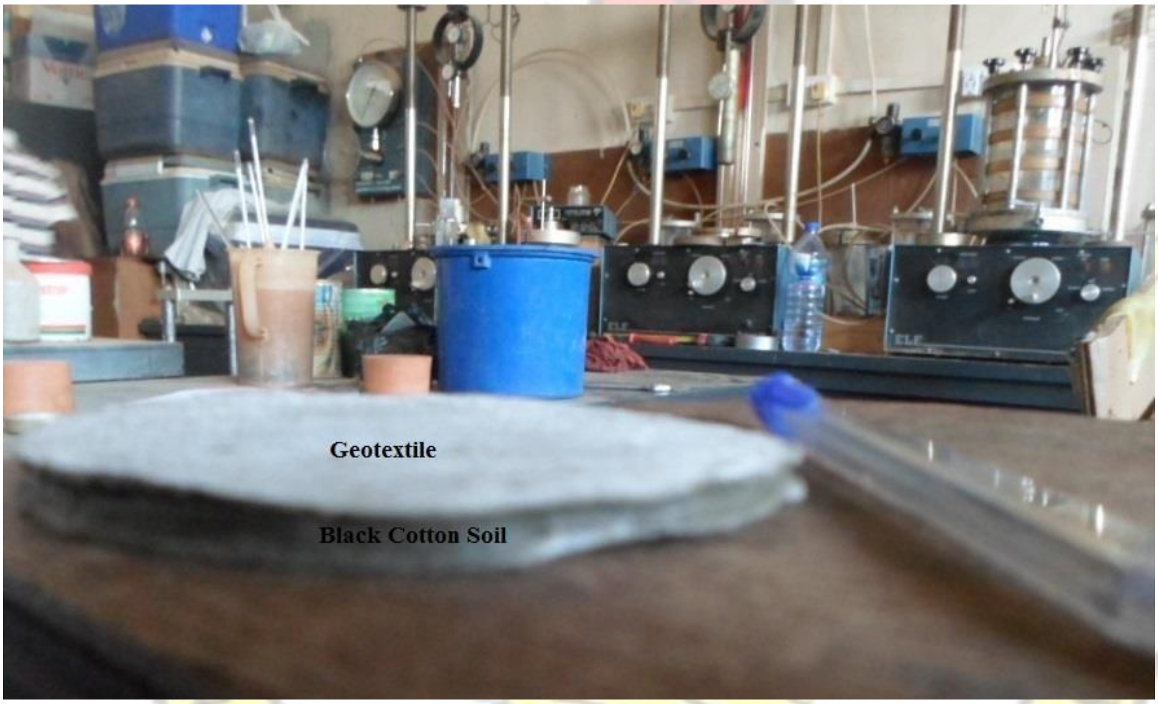


Plate II: Composite of geotextile and black cotton soil after the flux test

2.7

Drilling mud/fluid

For an economically efficient oil well drilling, the properties of the drilling mud are of utmost importance. The cost of the drilling fluid is quite small compared to the entire well but the choice of the drilling mud can either reduce the time of drilling resulting in cost saving or increase the drilling time resulting in an increase in the cost of the well. This is so because of the fact that the rate of penetration of the drill bit depends on the properties of the drilling mud. Furthermore, caving of softer formation, stuck drilling pipe and loss of circulation all depend on the properties of the drilling mud among other things.

2.7.1 Functions of Drilling Fluids

In recent times, the purposes of drilling muds have become numerous though in the past the only purpose was to transport drill cuttings. The most important functions of drilling mud in a modern oil-drilling program include the following:

1. Transport cuttings from the bottom of the well to the surface.
2. Cool and clean the bit.
3. Decrease resistance to the movement of the drilling string.
4. Support the walls of the well.
5. Stop oil, gas or water from entering the well during drilling.
6. Forms a filter cake and prevents loss of drilling fluid.
7. Permits the separation of drill cuttings from the drilling mud at the surface.

2.7.2 Types of Drilling Fluids/Muds

Drilling fluids are generally categorized into:

- Water Base Muds
- Oil Base Muds
- Gas

This research concentrates only on the Water Base Muds.

Clay and other organic and synthetic materials are used as the solids component of water based drilling muds. These are used to increase the viscosity where necessary and barite is added to increase the density. Components of drilling mud are categorized into:

1. Colloids with particle size ranging between 0.005µm to 1.0µm, which play the role of increasing viscosity.
2. Silt of which barite is an example with particle size range of 1.0µm to 50µm, that plays the role of increasing density.
3. Sand with particle size between 50µm to 420µm, whose abrasive properties make it undesirable.

The functionality of the colloidal component of drilling mud is the resultant of the particle size and high surface area.

Clay minerals fall within the colloidal group of the solid component of a drilling mud. This is so because of the tiny crystalline platelets and the molecular structure that gives rise to electrostatic charges on the surface. These electrostatic forces dictate the viscosity and cause the formation of a gel structure when circulation is stopped. Of all the clay minerals, montmorillonite has the most desirable properties for use in drilling muds (Darley and Gray, 1988).

2.7.3 Drilling fluid properties

The circulation system is made up of loops at which a drilling mud is subjected to different forces. The response of the drilling mud to these forces depends on the properties of the drilling mud.

2.7

.3.1 Density

Density is the weight of the mud divided by a unit volume of the mud. The most widely used units for density are pounds per gallon (lb/gal) and metric ton per cubic meter (tonne/m^3) and in SI-unit is kilogram per cubic meter (kg/m^3). The density of a mud can also be in pounds per cubic foot (lb/ft^2) (Darley and Gray, 1988).

Hydrostatic pressure within a well should balance the pore pressure in order to prevent the formation fluid from flowing into the well. The hydrostatic pressure is dependent on the density of the drilling mud therefore; a poor drilling mud density will adversely affect the hydrostatic pressure and would have an overall adverse effect on the stability of the well. Even though a sufficiently high density is required for well safety, excessive density can cause the walls of the well to fracture in a process known as induced fracturing (Murray and Cunningham, 1955).

According to Darley and Gray, (1988), research has proven that the speed of drilling is decreased when a pressure above what is required to balance pore pressure is used.

2.7.3.2 Rheology of fluids

The flow and deformation of fluids within a given vessel is governed by the flow pressure and velocity. These parameters thus influence the properties of the fluid. The relationship between these parameters is governed by a flow regime.

The two main flow regimes in rheology are the laminar flow that governs low velocity flow and depends largely on viscosity and turbulent flow which is influenced by the inertial properties but has an indirect relation with viscosity (Darley and Gray, 1988).

2.7.3.3 Laminar flow

Laminar flow can be explained as thin cylinders sliding over each other in a pipe. This type of flow is such that the velocity increases from the walls towards the center and is maximum at the center. The difference in velocity between two fluid layers, divided by the distance between them defines the shear rate. The axial force divided by the surface area of the fluid layer gives the shear stress. The shear stress divided by the shear rate defines the viscosity that is a measure of the opposition to flow of the fluid. As illustrated by Figure 3, F is the force applied to initiate flow of the fluid layers relative to each other but due to frictional resistance between the various layers, the velocity decreases towards the walls of the pipe.

Where F is Force and r is radius pipe

Figure 3: Schematic diagram illustrating laminar flow adopted from Darley and Gray, (1988)

The graph of the shear stress on the y-axis against the shear rate on the x-axis is called a consistency curve or flow model whose form is dictated by the properties of the drilling fluid under test.

Shear stress (τ) is defined, as the force per unit area, and can be explained as the force needed to keep a fluid in flow and is measured in pascals (Pa). The shear rate (γ) at a given point is the gradient of flow and is the slope of the velocity profile at that given point and is measured as per second (s^{-1}) (Imsland, 2008; White, 2008). Rheology has been used to model laminar flow in terms of the relationship between shear stress, viscous properties and shear rate. The most widely used models are the Newtonian, Bingham plastic, power law and Herschel-Bulkley models. These are presented in the following.

2.7

.3.4 The Newtonian model

The model is used for Newtonian fluids as the name implies. A Newtonian fluid is defined as a fluid that obeys the laws of Isaac Newton and generally is composed of particles less than a molecule. Examples are water, oil, and air in which the shear stress is linear to the shear rate. The model is given by:

$$\tau = \mu\gamma \text{ .... } (1)$$

Where μ represents the viscosity, τ is the shear stress and γ is the shear rate. Figure 4 shows the consistency curve for this model.

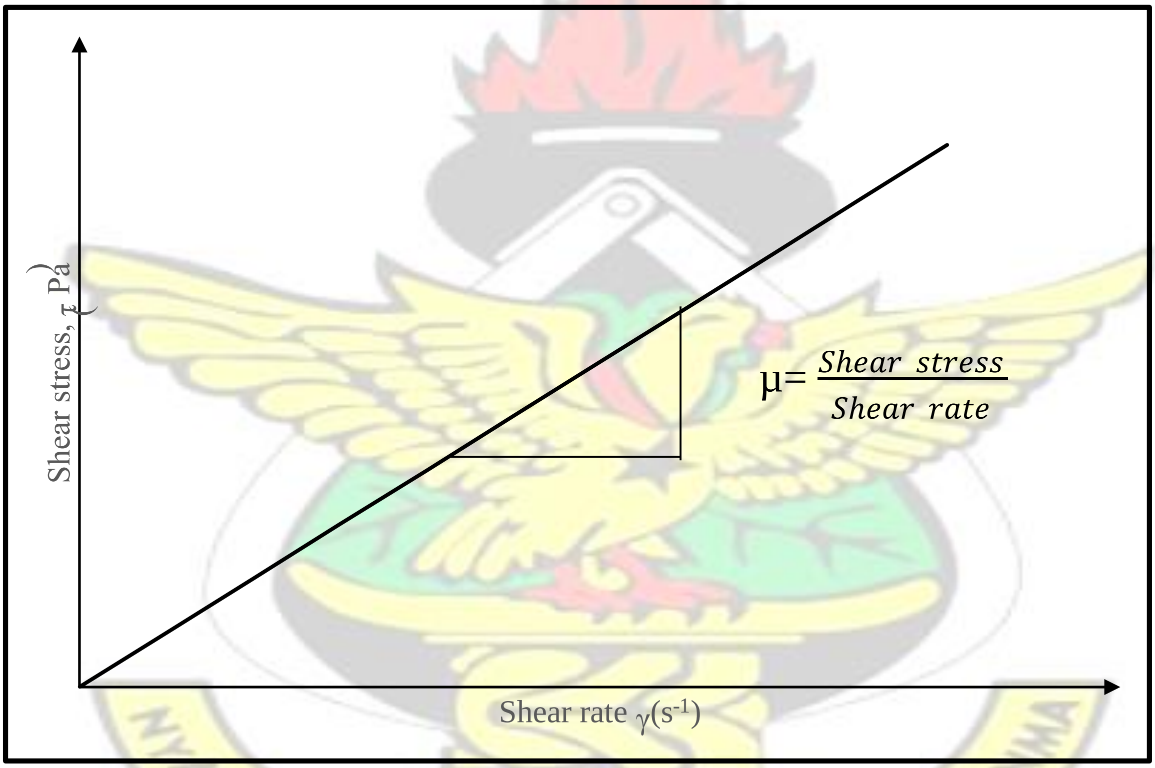


Figure 4: Consistency curve of shear stress versus shear rate for Newtonian model

2.7.3.5 The Bingham plastic model

This model is applied mostly to non-Newtonian fluids. The definition of a non-Newtonian fluid is that which does not obey the simple linear relationship given in the Newtonian model. Examples of non-Newtonian fluids are quicksand, or shear-thinning drilling fluids.

The Bingham plastic model is based non-Newtonian shear thinning fluids known as ideal Bingham plastic fluids. For an ideal, Bingham plastic fluid, a minimum amount of shear stress is required to initiate flow but when this point is passed, the fluid then exhibit a linear flow behavior. Figure 5 below is an illustration of the Bingham plastic model.

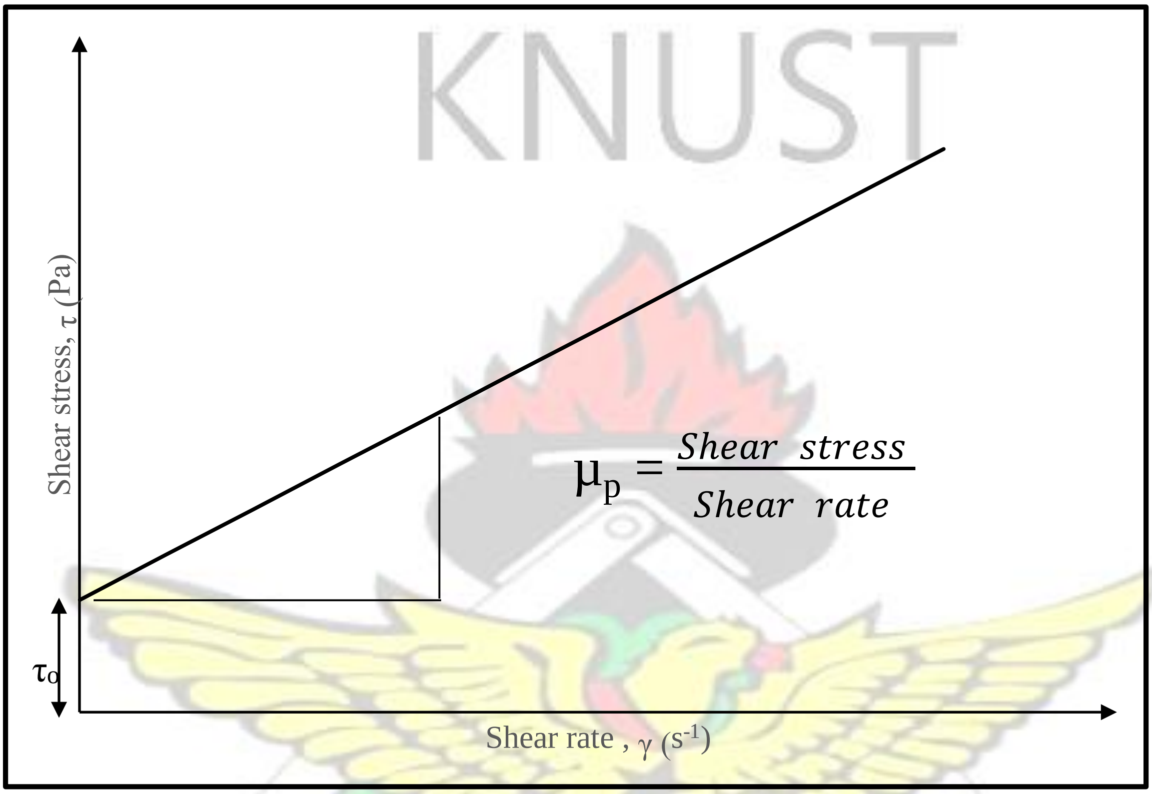


Figure 5: Consistency curve of shear stress versus shear rate for Bingham plastic model

The ratio of shear stress to the shear rate at a particular rate of shear gives the effective or apparent viscosity, which reduces as the shear rate is increased and is thus applicable only at the shear rate at which it was determined. Effective viscosity can therefore not be used to make a comparison between different drilling muds (Darley and Gray, 1988).

The following equation is used to model Bingham plastic fluids:

$$\tau = \tau_o + \mu_p\gamma \ \ldots\ldots\ldots\ldots.. (2)$$

Where μ_p is the plastic velocity the parameters τ_o and μ_p commonly determined using the following equations:

$$(PV)\ \mu_p = R_{600} - R_{300} \ldots\ldots\ldots (3)$$

$$(YP)\ \tau_o = R_{300} - \mu_p \ldots\ldots\ldots\ldots (4)$$

Where τ_o is the yield point in Pascals (Pa) or Pound per 100 square feet (lb/100ft^2), μ_p is the plastic viscosity in millipascal seconds (mPa.s) or centipoise (cP), R_{600} is the dial reading at 600 rpm and R_{300} is the dial reading at 300 rpm. The dial readings can be converted to SI units of Pascals (Pa) by 1.067 degrees = 1(lbf/100ft^2) = 0.4788 Pa (Ljones, 2013).

Drilling fluids usually deviate a little from ideal Bingham plastic fluids, it has however, been reported by Imsland, (2008) that this model can give more accurate flow behavior, at high shear rates.

2.7.3.6 Power law model

The Power law model is also applied to non-Newtonian fluids and is given by the equation:

$$\tau = k\gamma^{n} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where the k represents consistency index and n represents flow behavior index. Figure 6 shows the power law model. The parameter k gives shear strength at a shear rate of 1 s^{-1} and is measured in lb/100ft^2 or Pa, and represents the yield point. n is a measure of how viscosity varies with shear rate and is another way of determining the shear thinning of a fluid. The smaller n is the higher the shear thinning. The behavior of any flow model can easily be determined given the appropriate value of n. Newtonian fluids have n of 1 while nonNewtonian fluids are either less than 1 for shear thinning or greater than 1 for shear thickening.

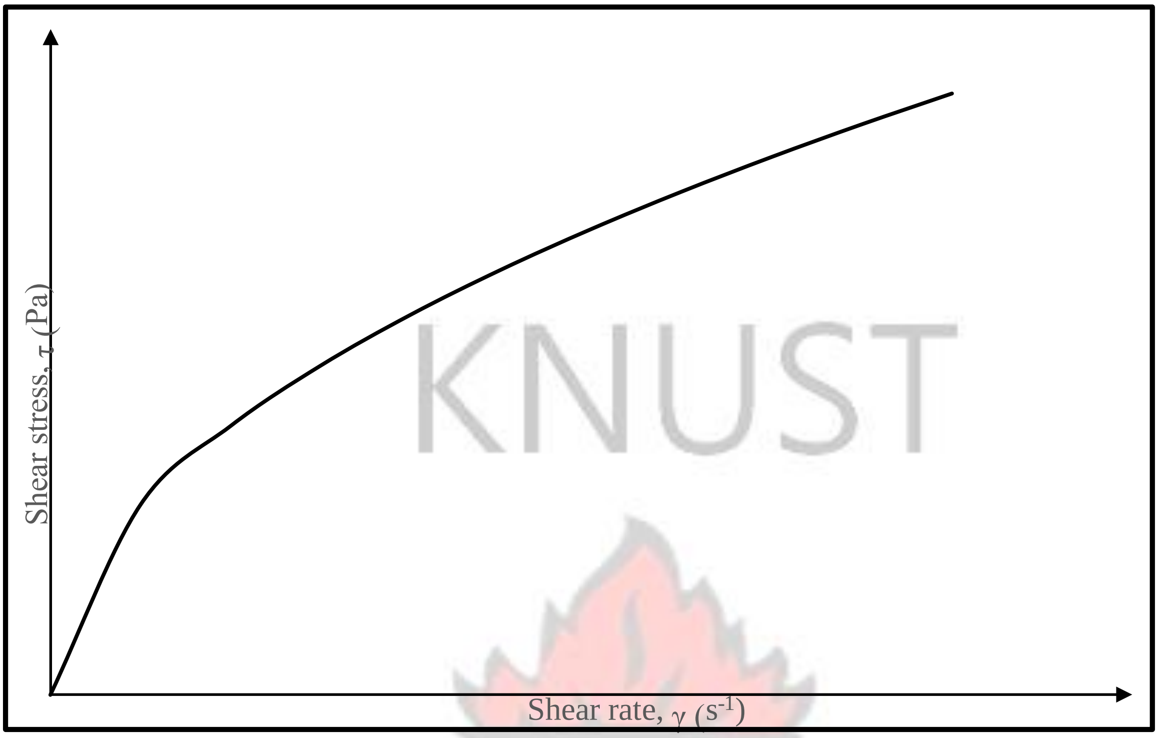


Figure 6: Consistency curve for Power law model

2.7.3.7 The Herschel-Bulkley model

Non-Newtonian fluids are also modelled using the Herschel-Bulkley model and presented as follows:

$$\tau = \tau_y + k\gamma^n \text{ ………… (6)}$$

Where, τ_y represents yield stress, k the proportionality constant, and n is the flow index used to describe the shear thinning or thickening behavior.

There is a third parameter added due to the extra information and this makes the HerschelBulkley model more accurate than the Bingham plastic model (White, 2008).

The parameters of the model are determined from dial gauge readings. Figure 7 illustrates the Herschel-Bulkley model.

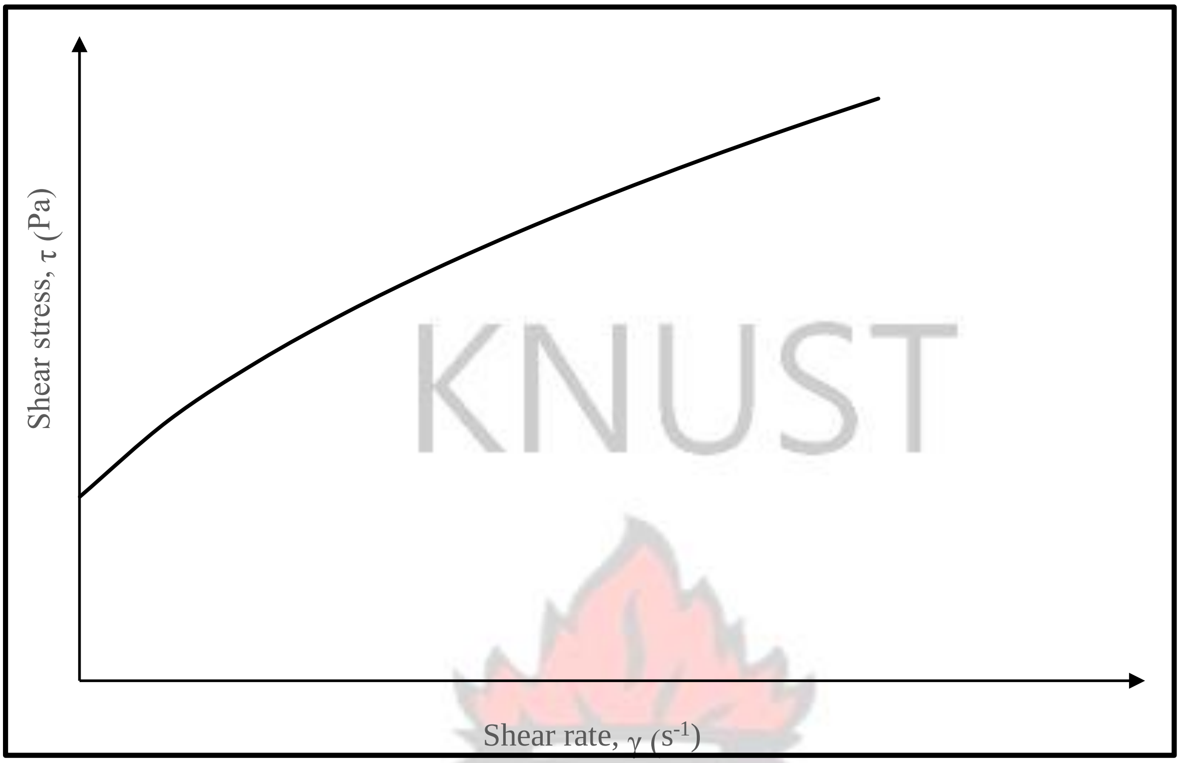


Figure 7: Consistency curve for Herschel-Bulkley model

2.7.3.8 Turbulent flow

This type of flow occurs at high speeds without any orderly flow pattern. The shear rate of fluid under turbulent flow is difficult to measure due the changes in velocity and direction therefore a relation between shear stress and shear rate cannot be established. The nature of this flow can therefore be determined by the Reynolds number (N_{RE}) and Fanning friction (f) which are dimensionless factors. The Reynolds number expresses a relation between "inertial forces" and "viscous forces" of a fluid, while the Fanning friction factor expresses the fluids resistance to flow at the conduit wall (Darley and Gray, 1988).

2.7.3.9 Turbulent flow of Newtonian fluids

The Reynolds number and Fanning friction factor can be determined for Newtonian fluids by the relations

$$N_{RE} = \frac{\rho v d}{\mu} \text{ ……………. (7)}$$

$$f = \frac{d}{2\rho v^2}\frac{Pf}{L} \text{ ……………… (8)}$$

Where ρ is the fluid density, v represent average velocity, d the diameter of the pipe, and Pf represents frictional pressure loss over a length L (Ljones, 2013).

2.7.3.10 Turbulent flow of non-Newtonian fluids

Due to the variation of viscosity of non-Newtonian fluids with shear rates, a problem arises as to which parameter represent the viscosity in the Reynolds number equation. An effective viscosity μ_e is what is mostly used for non-Newtonian rheology model. A comparison between laminar pressure loss equation for Newtonian fluids and Bingham plastic fluids can be used to determine the effective viscosity of Bingham plastic fluids (Ljones, 2013):

$$\frac{128\mu_e}{\pi d^4} q = \frac{128\mu_p}{\pi d^4} q + \frac{16\tau_o}{3d} \text{ …………… (9)}$$

Solving for μ_e, the effective viscosity is then obtain by:

$$\mu_e = \mu_p + \frac{\tau_o \pi d^3}{24q} \text{ ………………. (10)}$$

With the effective viscosity, turbulent flow can then be determined by the Reynolds number:

$$N_{Re}{}' = \frac{\rho v d}{\mu_e} \text{ ……………. (11)}$$

The viscosity of water based drilling fluids is provided by the clay component and drilling fluids generally exhibit non-Newtonian behavior. Grim (1950) stated that clay is an abundant raw material with many uses. This is due to their unique properties that are mostly dependent on their mineral composition and structure.

2.7.3.11 Effect of sodium exchange in clay minerals

Smectite by far has the highest swelling ability than all other clay minerals due to its crystal lattice; that is arranged such that the mineral is able to take up water molecules into its structure. Darley and Gray (1980) pointed out that sodium montmorillonite has the highest swelling pressure that makes the layers separate into individual sheets resulting in very high swelling. Preston (1974), observed that where calcium montmorillonite is dominant in a mud, it inhibits the expansion of the smectite and eventually aggregate it.

Adam et al. (1986) also explain that, to mitigate this effect, it is necessary to eliminate the calcium by chemical treatment in a process called beneficiation. The process is also known as peptizing in other literature (Bouaza and Bowders, 2010). The process of replacing calcium cations with higher concentration of sodium compound is known as beneficiation (Falode et al., 2008).

2.7.3.12 Effect of increase in clay mineral on viscosity

Viscosity is the most important property of drilling fluid in terms of its function in drilling. Without this property, drill cuttings will simply sink to the bottom of the well when the mud is at rest. During drilling, a higher viscosity is attained by increasing the concentration of bentonite, flocculation of colloid solids and addition of specially synthesized polymers (Omole et al., 2013).

CHAPTER THREE

METHODOLOGY

3.1 Introduction

Three sites were selected for preliminary studies and subsequent detailed investigation. The locations, which are Tsopoli, Dawhenya and Prampram, were explored using test pitting and auguring. Representative samples were collected for laboratory investigations. The methods of sampling and sample preparation as well as test conducted are discussed.

3.2 General Reconnaissance Survey

A desk study and field reconnaissance survey was carried out on 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:

- Accessibility to the site
- Topography
- Vegetation
- General drainage conditions

3.3 Soil Sampling

Test pits were excavated using pick axe and shovel down to a depth of 2meters and then augered using a hand-operated auger to 3meters. The dimension of the test pit was 1meterlength by 1.5-meter-breadth by 3meter-depth. Disturbed samples were taken from within 0.3m3.0m at all locations. These samples were bagged, labelled and sent to the laboratory for testing.

3.4 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 following:

3.4.1 Physical characteristics

- Textural characteristics of the soils
- Colour
- Lithological characteristics by visual inspection

3.4.2 Geotechnical and other Parameters

- Natural moisture content
- Particle size analysis

- Atterberg limits (liquid limit, plastic limit and plasticity index)
- Specific Gravity
- Clay mineral and chemical analysis
- Organic matter content, cation exchange capacity, exchangeable ions.
- pH value
- Free swell test
- Permeability
- Rheological tests (Viscosity, yield point, Gel strength)

3.5 Test Procedure

3.5.1 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.

3.5.2 Geotechnical Properties

Natural moisture content, Atterberg limits, particle size and specific gravity were determined in accordance with the British Standard (BS1377, 1990). For the particle size analysis wet sieve analysis, hydrometer test was conducted for the black cotton soils, and only hydrometer test for the commercial bentonite as it was only fines. Sodium Hexametaphosphate was used as the deflocculating agent. The specific gravity was determined using the pycnometer method. These tests were all conducted at the Geotechnical Engineering laboratory of the Building and Road Research Institute, Kumasi-Ghana.

3.5.3 Chemical and Mineralogical Analysis

Soil samples were sieved through the 0.425mm sieve and representative samples were taken and sent to ALS minerals, Canada for chemical analysis. Major oxides and minor elements were determined 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 Physics, University of Ghana-Legon. Organic matter content, cation exchange capacity (CEC), exchangeable ions were carried out by the Walkley and Blacks method (oxidation with dichromate) for organic matter content and ammonium displacement method for the CEC at the Soil Science Laboratory at the CSIR-Soil Research Institute Kwadaso.

3.5.4 Swell characteristics

The free swell index was determined in accordance with the IS 1498 by Indian Standard Institution (IS 1498, 1987).

The free swell index was then reported as the increase in the volume of the soil expressed as a percentage of the initial volume.

IS 1498 gives a standard for determining the expansivity of soils, according to the relation below.

$$FSI = \frac{Vw - Vk}{Vk} \quad \ldots\ldots\ldots\ldots\ldots (12)$$

Where Vw is the sediment volume of 10 g of oven-dried soil passing 0.425 mm sieve placed in a 100 ml graduated measuring jar containing distilled water, and Vk is the sediment volume of 10g of oven-dried soil passing 0.425 mm sieve placed in a 100 ml graduated measuring jar containing kerosene. This test was repeated for the black cotton soils with sodium carbonate in varying concentrations of 0%, 6%, 8%, 10% and 12% to choose the optimum percentage of sodium carbonate that gives maximum swell. The presence of at least 3% of sodium chloride prevents the dispersion of clay in drilling fluids (Darley and Gray, 1988).

3.5.5 pH

Soil pH was determined using a soil-water mixture of mass to volume ratio of 1:1 measured with a glass electrode. The pH of the black cotton soils was determined at the Laboratory of the Building Materials Research Division of the Building and Road Research Institute, Kumasi.

3.5.6 Permeability

Samples were air dried, crushed and sieved through the 0.075mm sieve. The material passing the 0.075mm sieve was collected and tested for the coefficient of permeability within two geotextiles. The soil obtained from the sieving was loosely placed on geotextiles cut into disc shapes with a diameter of 100mm until a thickness of about 5mm was obtained. Another geotextile was now placed on top of the soil to form a composite with the soil sandwiched between the two geotextiles.

The resultant composites were tested in accordance with the ASTM D5887-99. The permeability was now computed using the relation

$$K = \frac{QL}{Ath} \quad \ldots\ldots\ldots\ldots\ldots (13)$$

Where K is the coefficient of Permeability in cm/sec, h is head difference in cm, A is the area of flow, t is the time of flow in seconds, Q is flow rate in cm^3/sec and L is the thickness of the composite in cm.

For each soil represented by the name of sampling location, three tests were conducted and the average of the permeability was computed.

3.5.7 Rheological tests

The rheological test under consideration includes Density test, Viscosity test and Gel strength test. The viscosity tests were done with speeds of 600rpm, 300rpm, 200rpm, 100rpm, 6rpm and 3rpm translating to shear rates of $1022.04s^{-1}$, $511.02s^{-1}$, $340.68s^{-1}$, $170.34s^{-1}$, $10.2204s^{-1}$ and $5.1102s^{-1}$ respectively using the equation:

$$\gamma = \left(\frac{2R_c^2}{R_c^2 - R_b^2}\right)\omega \quad \ldots\ldots\ldots (14)$$

Where $\omega = \frac{2\pi}{60}N$ is angular velocity of spindle; N= dial reading in revolutions per minute (rpm), R_c is the radius of mud container in cm, R_b is the radius of the spindle in cm.

3.5.7.1 Density

The density was measured using the mud balance. The mud balance is made up of the drilling fluid holding cup and a counterweight each at the ends of a graduated scale rod and a levelbubble fixed on the beam to allow for accurate balancing.

The test was conducted in accordance with the API 13B-1, 2003.

3.5.7.2 Viscosity

Viscosity and gel strength are the properties of a drilling fluid that are of utmost importance. The viscometer that is powered by an electric motor was used to conduct this test. The drilling fluid is contained in a cylinder and force into the space between the rotation sleeve and the cylinder containing the fluid. The rotation of the sleeve causes a displacement in the bob that is indicated on a dial gauge. The instrument comes with speeds of 600rpm, 300rpm, 200rpm, 100rpm, 6rpm and 3rpm already fixed such that the plastic viscosity and yield point are obtained from the readings at 300rpm and 600rpm.

The test procedure used is as in the API 13B-1, 2003.

The plastic viscosity and yield point were then computed using the following relations (Equations 3 and 4):

$$(PV)\ \mu_p = R_{600} - R_{300},$$

$$(YP)\ \tau_o = R_{300} - PV$$

Where PV is the plastic viscosity in millipascals seconds, YP is the yield point in Pascals, R_{600} is the dial reading at 600r/min in Pascals and R_{300} is the dial reading at 300r/min in Pascals (API 13B-1, 2003).

3.5.7.3 Gel Strength

The gel strength is reported as gel strength at 10 seconds and gel strength at 10 minutes. The test procedure is as follows:

- The fluid is stirred at 600r/min and the dial reading is recorded when a steady value is reached.
- The speed is then reduced to 300r/min and the steady state value is recorded.
- The fluid is stirred again for 10 seconds at 600r/min. The fluid is then allowed to stand for 10 seconds undisturbed.
- The fluid is stirred again at a speed of 3r/min and the maximum reading attained is the 10-seconds gel strength in Pascals
- The fluid is restirred at a speed of 600r/min for 10 seconds and allowed to stand undisturbed for 10 minutes. It is then stirred again at a speed of 3r/min and the maximum dial reading is recorded as the 10-minutes gel strength in Pascals (API 13B1, 2003).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Nature and characteristics of the soil

Soil samples collected from between 0.3-3.0m below ground level in Tsopoli and Dawhenya and 0.2-3.0m below ground level at Prampram were used in the study. These sites are located within the Accra Plains of Ghana and are underlain by the Garnet-amphibolite and quartzofeldspathic gneiss of the Dahomeyan Supergroup (Ghana Geological Survey Department, 2009). 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 (Giddigasu, 2012).

The schematic diagram of the soil profiles obtained from the test pitting is shown in figure 8. The Dawhenya profile consists of the topsoil from 0.0-0.3m followed by a moist soft greyish homogeneous clay from 0.3-1.0m, which is also underlain by a denser greyish black clay with some grey nodules from 1.0-2.3m. Below this layer is a moist soft greyish clay from 2.3-3.0m.

The profile for Tsopoli soil consists of a gravelly clay topsoil from 0.0-0.3m followed by a moist stiff greyish black clay with greyish nodules from 0.3-2.3m. The above layer is underlain by a moist dense greyish clay with some black nodules from 2.3-3.0m.

The Prampram soil profile generally consists of a dark topsoil from 0.0-0.2m followed by a moist dark grey clay from 0.2-1.0m, which is also underlain by a moist homogeneous dark grey sandy clay from 1.0-3.0m. No groundwater was encountered in the test pits.

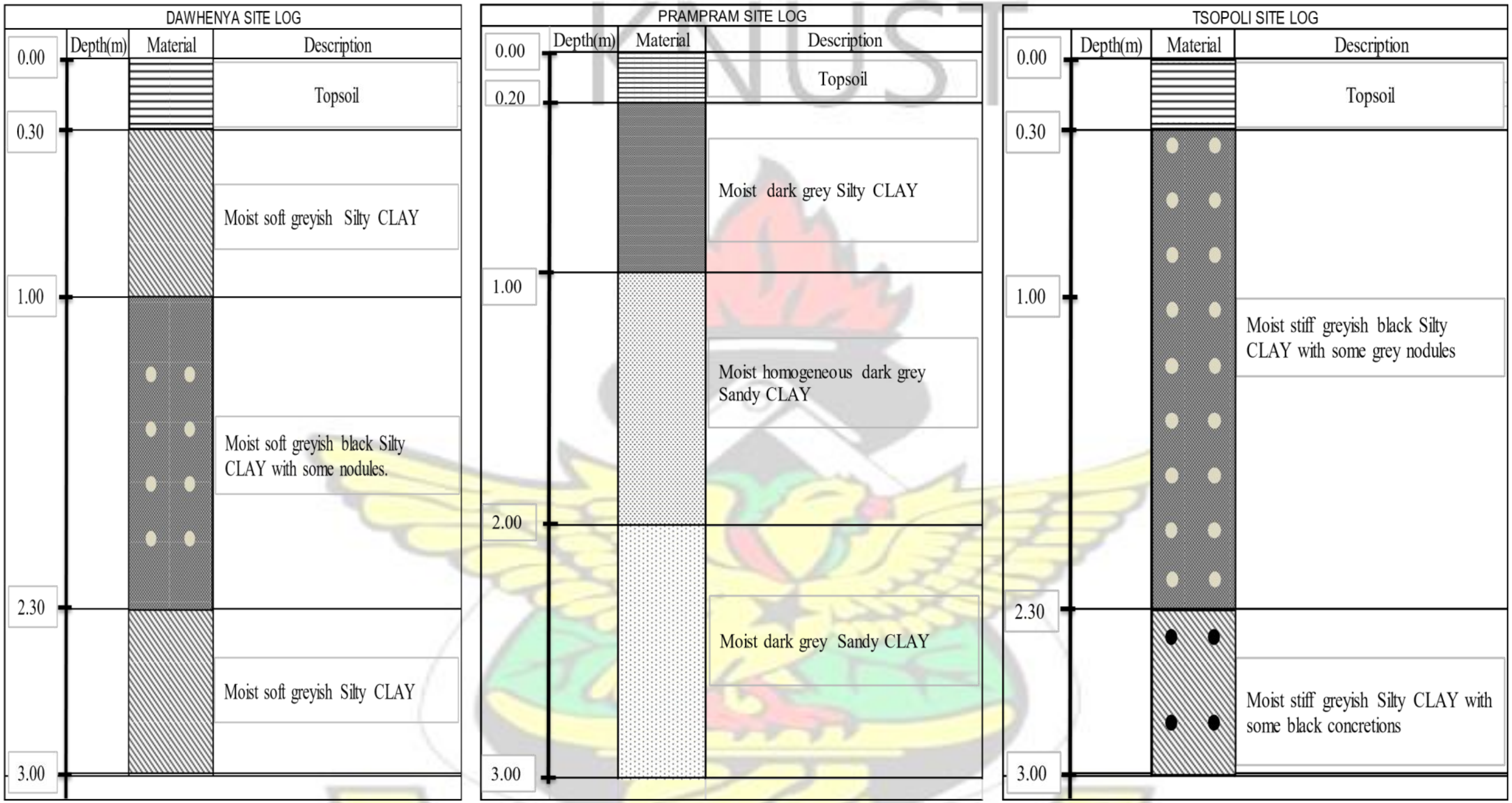


Figure 8: Schematic diagram showing the soil profiles

4.2 Chemistry and Mineralogy of the Soil

4.2.1 Chemistry

It was observed that silica, alumina and iron are the dominant oxides and in comparison with the commercial bentonite, all the oxides within the Dawhenya, Prampram and Tsopoli are below that of the commercial bentonite except iron oxide, manganese oxide and silica. Dawhenya dominates Prampram and Tsopoli in the concentration of sodium and calcium oxides, which are the oxides of interest when considering a clay for use as drilling fluid, and in geosynthetic clay liners.

The concentrations of heavy metals (Nickel, Molybdenum and Lead) are higher in the Tsopoli sample than Dawhenya and Prampram but are all within the World Health Organization standard i.e. 100ppm (Chiroma et al., 2014). However, for commercial bentonite, there are no heavy metals. According to Dutta and Mishra, (2016), the presence of heavy metals cause a decrease in liquid limit, plastic limit, swell pressure and swell potential while increasing the hydraulic conductivity. They further stated that the effect is higher on high swelling bentonite than in lower swelling bentonite. This implies that the black cotton soils that have lower swell potential will be less influenced by heavy metals contamination. They also illustrated that concentrations of heavy metals below 100ppm have very little effect on the properties stated above. The chemical compositions are shown in table 2.

Table 2: Chemical composition of the soils

Oxides	CONCENTRATION (W %)			
	Commercial Bentonite	Dawhenya	Prampram	Tsopoli
SiO_2	55.98	63.89	71.07	63.21
TiO_2	0.35	1.26	0.87	1.2
Al_2O_3	18.29	13.97	11.04	14.78
Fe_2O_3	6.78	9.34	6.85	9.08
SO_3	0.05	0.11	0.11	0.08
MgO	4.28	1.7	1.32	1.52
CaO	1.88	1.58	1.27	1.18
MnO	0.05	0.25	0.14	0.19
K_2O	0.55	0.19	0.22	0.14
Na_2O	3.38	0.91	0.87	0.52
P_2O_5	0.08	0.06	0.04	0.04
Heavy Metals Concentration (ppm)				
Ni	-	29.8	22.8	31.9
Mo	-	14.6	16.3	18.7
Pb	-	7.5	7.1	10.4

4.2.2 Mineralogy

The diffractograms obtained from the XRD test analysis of all the soils show similar phases. As illustrated in Figure 9, all the three soils are similar to the commercial bentonite indicating that the soils have similar mineralogy with commercial bentonite. The minerals identified were quartz and montmorillonite, suggesting that the main clay mineral in the black cotton soils occurring in the Accra Plains are montmorillonite clay consistent with what Gidigasu (2012) stated.

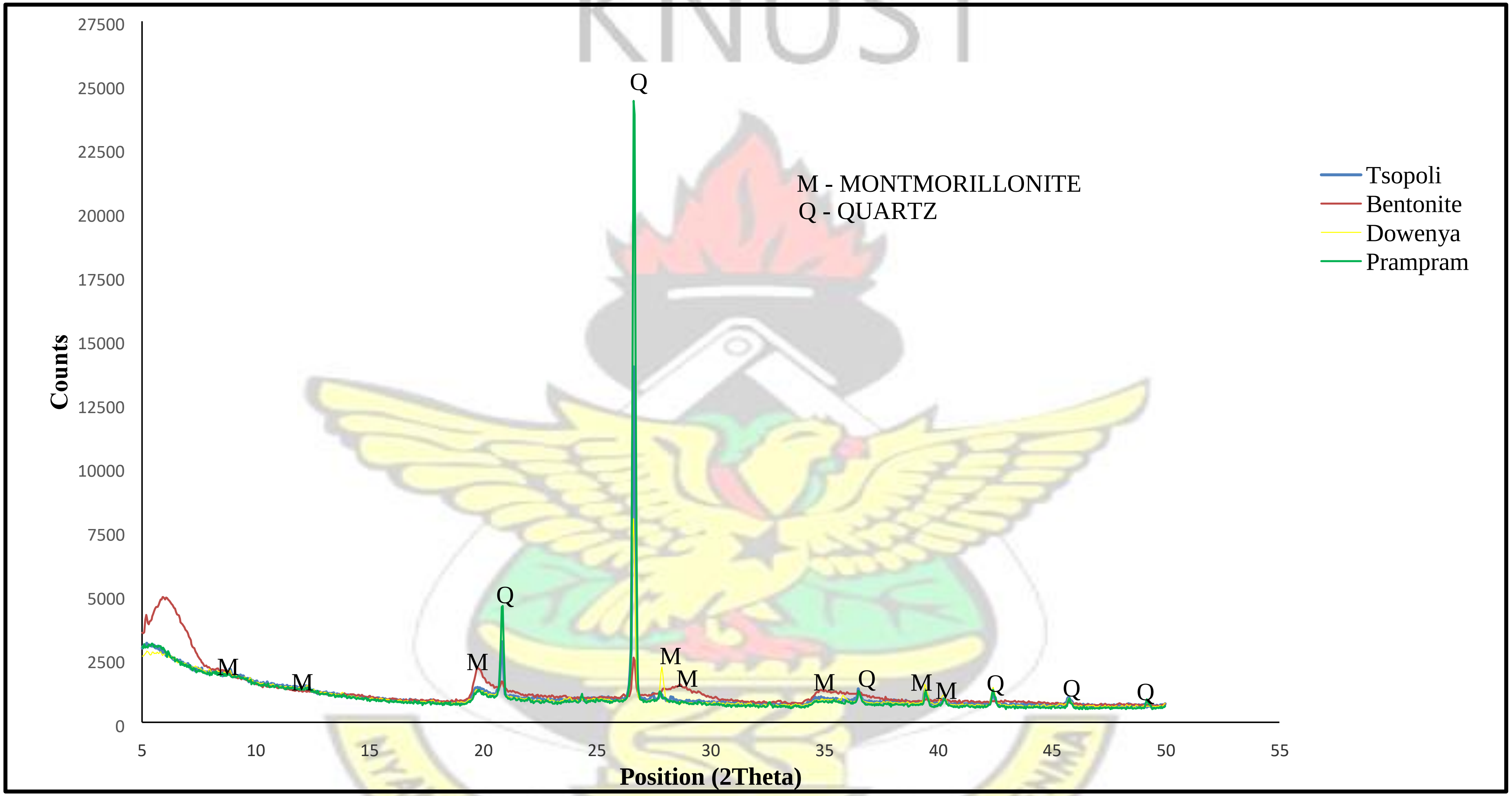


Figure 9: Diffractograms of the three soils and bentonite

4.3 Physico-chemical characteristics

From the physico-chemical tests conducted, the pH of the Dawhenya, Prampram, and Tsopoli are nearly neutral while that of commercial bentonite is alkaline. The commercial bentonite is alkaline due to the higher hydroxyl ions in solution than the hydrogen ions while the black cotton soils are neutral due to the almost equal proportions of hydroxyl ions and hydrogen ions. The pH values are 7.86, 7.82, 7.90 and 10.24 for Dawhenya, Prampram, Tsopoli and commercial bentonite respectively.

The pH values increased to 10.24, 10.42 and 10.22 for Dawhenya, Prampram and Tsopoli respectively after beneficiation with 10% by mass of sodium carbonate. The pH plays a very important role in the movement of ions, precipitation and dissolution occurrences, which determines the flocculation or deflocculion of a clay in a clay-water mixture. The organic matter content of the soils is 0.76%, 0.62%, 0.72% and 0.47% for Dawhenya, Prampram, Tsopoli and commercial bentonite respectively. The organic matter contents are within the range reported by BRRI (1985) of less than 5%. According to Darley and Gray (1988), small amounts of organic matter improve the viscosity of clays. 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 (Gidigasu, 2012). The CEC values of the black cotton soils were found to be 51.02 meq/100g for Dawhenya soil, 46.99 meq/100g for Prampram soils, 38.94 meq/100g for Tsopoli soils and 80.41 meq/100g for the commercial bentonite (Table 3). It is noticed that the most abundant cations in the soils are the calcium, magnesium and potassium cations. According to Murray (2007), sodium montmorillonite and hectorite have high Base Exchange capacities, generally ranging between 80 meg/100g and 130 meq/100 g. Calcium montmorillonite, on the other hand, has a Base Exchange capacity that normally ranges between 40 and 70 meq/100 g. The results of the X-ray diffractometry indicated the dominant minerals to be quartz and montmorillonite and the Cation Exchange Capacity (CEC) showed results typical of calcium montmorillonite, it can therefore be concluded that the soil from Dawhenya, Prampram and Tsopoli have calcium montmorillonite as the dominant clay mineral.

Results of the physico-chemical characteristics of the Dawhenya, Prampram, Tsopoli soils and commercial bentonite are shown in Table 3.

Table 3: Summary results of cation exchange capacity, pH and dominant clay mineral

Sample ID	**Exchangeable cations (meq/100g)**					**C. E. C (meq/100g)**	**Dominant clay minerals**	**pH**
	Na	K	Mg	Ca	H+	Calculated		
Dawhenya	0.08	0.16	21.36	29.37	0.05	51.02	Ca-montmorillonite	7.86
Prampram	0.08	0.14	19.49	27.23	0.05	46.99	Ca-montmorillonite	7.82
Tsopoli	0.06	0.12	17.62	21.09	0.05	38.94	Ca-montmorillonite	7.90
Commercial bentonite	29.41	0.90	22.01	28.04	0.05	80.41	Na-montmorillonite	10.24

4.4 Geotechnical characteristics

The Geotechnical characteristics studied are shown in table 4.

Table 4: Geotechnical characteristics of the three soils and commercial bentonite

Sample ID	**Dawhenya**	**Prampram**	**Tsopoli**	**Commercial bentonite**
Natural Moisture Content (%)	33.88	36.03	27.68	
Specific Gravity	2.30	2.44	2.21	2.20
Grading				

Clay (%)	83.4	71.3	72.9	95.0
Silt (%)	8.4	5.8	15.1	5.0
Sand (%)	8.1	17.0	11.5	0.0
Gravel (%)	0.1	5.9	0.5	0.0
Atterberg's limits				
Liquid limit (%)	91.8	90.7	81.4	432.4
Plastic limit (%)	33.3	37.4	28.3	117.3
Plasticity index (%)	58.5	53.4	53.1	315.1
Free swell index (%)	150	115	163	364
Unified soil classification system	CE	CE	CV	CE

Note: CE = Clay with extremely high plasticity and CV = Clay with very high plasticity

4.4.1 Natural Moisture Content and Specific Gravity

The natural moisture contents of the soils are 33.88%, 36.03% and 27.68% for Dawhenya, Prampram and Tsopoli respectively, which are enough to suggest the presence of the high water holding mineral montmorillonite. These results fall within the range of natural moisture contents given by the Building and Road Research Institute (1985), which is between 20% and 45% for black cotton soils. The water content of the black cotton soils in the powdered state was determined in accordance with ASTM D2216 and was 12.20%, 10.13%, 10.83% and 17.48% for Dawhenya, Prampram, Tsopoli and commercial bentonite respectively. This is an indication that the black cotton soils are within the stable one layer or two-layer hydrate states (Koerner 1998).

The specific gravities of the soils and commercial bentonite are 2.30, 2.44, 2.21 and 2.20 for Dawhenya, Prampram, Tsopoli and commercial bentonite respectively. These values are relatively low and can be attributed to the small particle sizes and high surface area of montmorillonite clay mineral.

4.4.2 Particle size distribution

The particle size distribution curves of the three soils are shown in figure 10. The Dawhenya soil consists of 83.4% clay size particles, 8.4% silt size, 8.1% sand size and 0.1% gravel size particles. Prampram has 71.3% clay size particles, 5.8% silt size, 17.0% sand size and 5.9% gravel size while Tsopoli soil consists of 72.9% clay size, 15.1% silt size, 11.5% sand size and 0.5% gravel size particles. The soils can therefore be classified as silty Clay, sandy Clay and silty Clay for Dawhenya, Prampram and Tsopoli respectively. The commercial bentonite consisted of 95% clay size and 5% silt size particles and therefore classify as Clay.

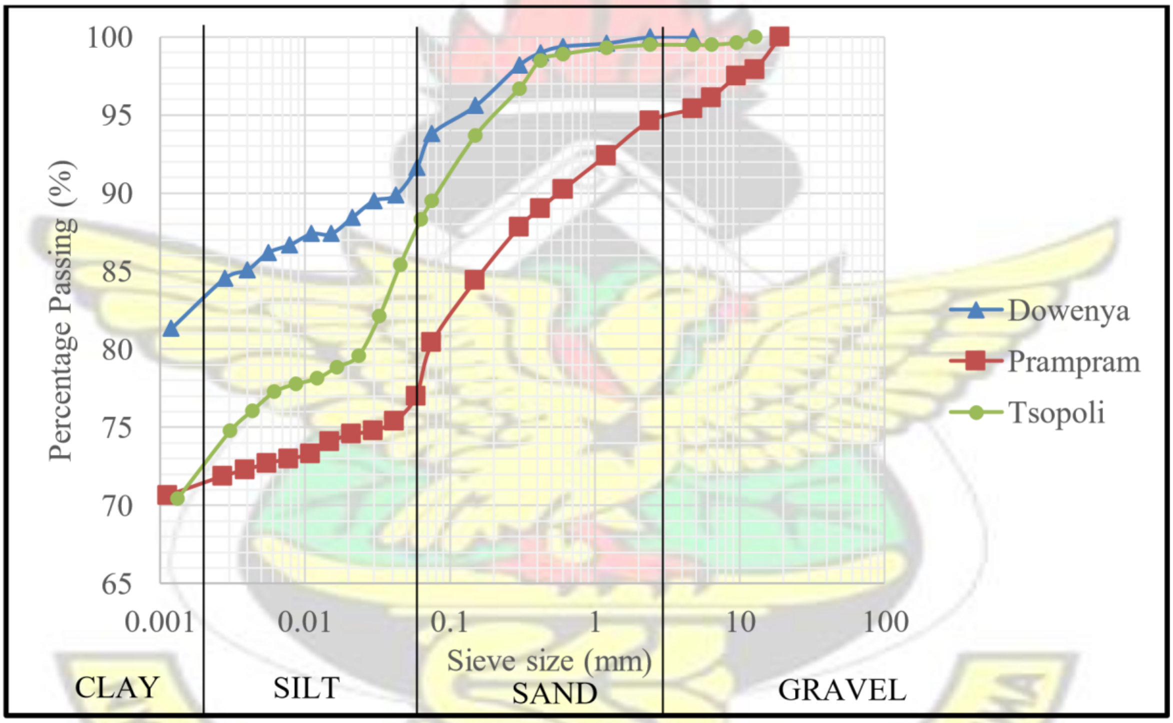


Figure 10: Particle size distribution curves for the three soils

4.4.3 Atterberg's limits and plasticity characteristics

The plasticity characteristics are presented on figure 11. All the soils plotted above the A-line and therefore, classify according to the Unified Soil Classification System as inorganic clays with high to extremely high plasticity.

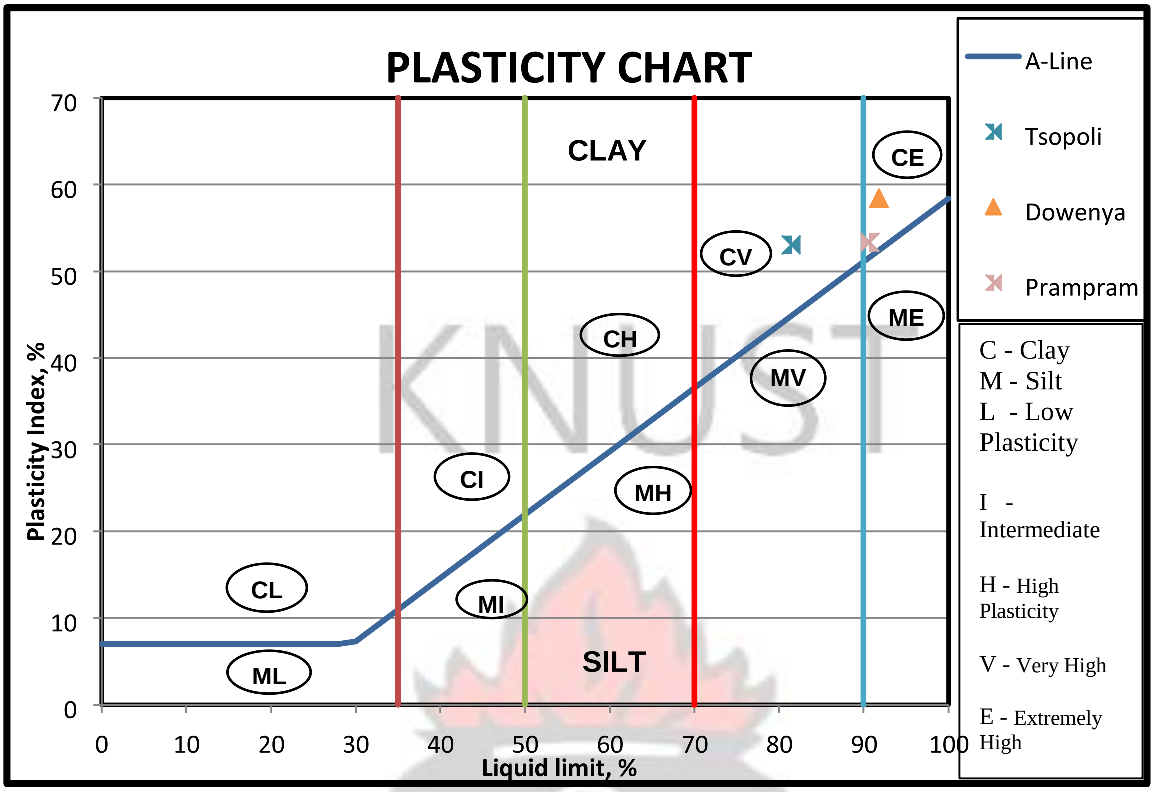


Figure 11: Plasticity characteristics of the soils

4.4.4 Free swell index

The free swell index (IS 1498, 1987) is a good indicator of the expansivity of a soil. The free swell index test conducted gave 150%, 115%, 164% and 364% for Dawhenya, Prampram, Tsopoli and commercial bentonite respectively. According to table 5, the soils exhibit high degree of expansivity while the commercial bentonite exhibits very high degree of expansivity. Flocculation of clay is the ability of the clay to remain in suspension, which is achieved by the absorption of water by the clay minerals resulting in a swell. The swell index is thus a good measure of a clays ability to flocculate.

To improve the swell index and subsequently improve the flocculation, 10% of sodium carbonate was added to the black cotton soils and the swell indices determined. Sodium chloride being more common was used to substitute the 10% sodium carbonate and the swell indices determined. The addition of sodium chloride resulted in the reduction of the swell index consisting with what Darley and Gray (1988) stated. With the addition of 10% sodium carbonate, the swell indices increased to 290%, 190% and 210% for Dawhenya, Prampram and Tsopoli respectively. The black cotton soils with 10% of sodium carbonate for Dawhenya and Tsopoli exhibit very high degree of expansivity while Prampram remained within high degree of expansivity.

Table 5: The rating of soil based on free swell index (IS 1498, 1987)

ITEM	SAMPLE ID			
	Dawhenya	Prampram	Tsopoli	Commercial bentonite
Free swell index of samples (%)	150	115	164	364
Degree of expansivity	High	High	High	Very high

Note: < 50% Low, 50-100% Medium, 100-200% High and > 200% Very High: degree of expansivities (IS 1498, 1987).

4.5 Permeability

The results of the permeability test conducted in accordance with ASTM 5887-99 for Dawhenya, Prampram, Tsopoli and commercial bentonite are presented in table 6. The permeability test results of the black cotton soils were in the order of 10^{-9}cm/s and compares well with commercial bentonite, which is 2.08 x 10^{-9}cm/s. The minerals commission of Ghana LI 2182 specified a permeability of the order 10^{-6}cm/s for compacted clay liners while the United States of America environmental protection agency gave a permeability of the order 10^{-9}cm/s for geosynthetic clay liners.

The permeability of all the black cotton soils fall within the LI 2182 and the USA environmental protection agency requirements.

Table 6: Permeability results of the three soils and commercial bentonite

SAMPLE ID	THICKNESS (mm)	PERMEABILITY (cm/s)	Min.com. LI 2182 STANDARD	USA EPA
DAWHENYA	5	1.03×10^{-9}	10^{-6}	10^{-9}
PRAMPRAM	5	7.61×10^{-9}		
TSOPOLI	5	2.04×10^{-9}		
COMMERCIAL BENTONITE	5	2.08×10^{-9}		

Where Min. com. LI is, Minerals commission of Ghana Legislative Instrument and USA EPA is the United States of America Environmental Protection Agency (most widely used in the geosynthetics industry).

4.6 Rheological Properties

The viscosity and yield stress measurements on prepared black cotton soil-water slurries and commercial bentonite-water slurry were made using Ametek 3500-220 rotational viscometer. The black cotton soil-water slurries were formulated in concentrations of 22.5g/350ml, 32.5g/350ml, 42.5g/350ml, 52.5g/350ml and 62.5g/350ml while 22.5g/350ml concentration was formulated for commercial bentonite according to the American Petroleum Institute (API) required concentration. To improve the rheological properties of the black cotton soils, they were beneficiated with 10% by mass of sodium carbonate (Na_2CO_3) before the slurries were then formulated in concentrations of 22.5g/350ml, 32.5g/350ml, 42.5g/350ml, 52.5g/350ml and 62.5g/350ml. The readings obtained from the viscometer were converted to centipoise or millipascal seconds (Table 7 and 8). The readings were further converted to shear stress and shear rate, and consistency curves were plotted for the various concentrations (Figures 12 and 13). The consistency curves were then compared with that of commercial bentonite while the plastic viscosity, yield point, density and gel strength were compared to the American Petroleum Institute (API) standards.

Table 7: Shear stress in mPa.s for raw samples

SAMPLE ID	DIAL READINGS IN RPM					
	600rpm	**300rpm**	**200rpm**	**100rpm**	**6rpm**	**3rpm**
D-22.5	14.4	9.6	4.8	4.8	4.8	4.8
D-32.5	19.2	14.4	9.6	4.8	4.8	4.8
D-42.5	19.2	14.4	9.6	9.6	4.8	4.8
D-52.5	19.2	14.4	9.6	4.8	4.8	4.8
D-62.5	19.2	14.4	9.6	9.6	4.8	4.8
T-22.5	14.4	9.6	4.8	4.8	4.8	4.8
T-32.5	14.4	9.6	9.6	4.8	4.8	4.8
T-42.5	24	14.4	9.6	4.8	4.8	4.8
T-52.5	24	14.4	9.6	4.8	4.8	4.8
T-62.5	28.8	19.2	14.4	9.6	4.8	4.8
P-22.5	9.6	9.6	4.8	4.8	4.8	4.8
P-32.5	14.4	9.6	9.6	9.6	4.8	4.8
P-42.5	28.8	19.2	9.6	9.6	4.8	4.8
P-52.5	28.8	19.2	14.4	9.6	4.8	4.8
P-62.5	28.8	24	14.4	9.6	4.8	4.8
CB-22.5	148.8	129.6	120.0	110.4	110.4	105.6

Where D = Dawhenya P = Prampram T = Tsopoli CB = Commercial bentonite

Table 8: Shear stress in mPa.s for beneficiated samples

SAMPLE ID	DIAL READING IN RPM					
	600rpm	**300rpm**	**200rpm**	**100rpm**	**6rpm**	**3rpm**

D-22.5+10% Na_2CO_3	91.2	62.4	52.8	43.2	38.4	38.4
D-32.5+10% Na_2CO_3	129.6	96	86.4	81.6	72	62.4
D-42.5+10% Na_2CO_3	196.8	168	163.2	158.4	134.4	129.6
D-52.5+10% Na_2CO_3	307.2	302.4	278.4	254.4	244.8	230.4
D-62.5+10% Na_2CO_3	441.6	422.4	417.6	393.6	336	331.2
P-22.5+10% Na_2CO_3	52.8	28.8	24	14.4	9.6	9.6
P-32.5+10% Na_2CO_3	76.8	52.8	43.2	33.6	28.8	24
P-42.5+10% Na_2CO_3	110.4	76.8	62.4	52.8	43.2	38.4
P-52.5+10% Na_2CO_3	134.4	105.6	96	91.2	72	72
P-62.5+10% Na_2CO_3	302.4	297.6	288	264	249.6	244.8
T-22.5+10% Na_2CO_3	62.4	33.6	28.8	19.2	9.6	9.6
T-32.5+10% Na_2CO_3	86.4	57.6	48	33.6	28.8	24
T-42.5+10% Na_2CO_3	124.8	91.2	81.6	72	52.8	48
T-52.5+10% Na_2CO_3	168	129.6	67.2	120	96	91.2
T-62.5+10% Na_2CO_3	129.6	86.4	67.2	57.6	43.2	38.4
CB-22.5	148.8	129.6	120.0	110.4	110.4	105.6

Where D = Dawhenya, P = Prampram, T = Tsopoli CB = Commercial bentonite and Na_2CO_3 = sodium carbonate

The yield point, plastic viscosity, gel strength and apparent viscosity results are presented in table 9 gives the American Petroleum Institute standards.

Table 9: Results of rheological properties for beneficiated samples

SAMPLE ID	**Plastic Viscosity (mPa.s)**	**Yield Point (mPa)**	**Apparent Viscosity (mPa.s)**	**Density ρ(kg/l)**	**GEL STRENGTH IN mPa**

					@ 10 SECS	@ 10 MINS
D-22.5+10%Na_2CO_3	28.8	33.6	45.6	1.06	12	26
D-32.5+10%Na_2CO_3	33.6	62.4	64.8	1.08	20	63
D-42.5+10%Na_2CO_3	28.8	139.2	98.4	1.10	51	148
D-52.5+10%Na_2CO_3	4.8	297.6	153.6	1.12	98	200
D-62.5+10%Na_2CO_3	19.2	403.2	220.8	1.13	148	261
P-22.5+10%Na_2CO_3	24	4.8	26.4	1.06	5	11
P-32.5+10%Na_2CO_3	24	28.8	38.4	1.08	8	17
P-42.5+10%Na_2CO_3	33.6	43.2	55.2	1.10	14	28
P-52.5+10%Na_2CO_3	28.8	76.8	67.2	1.11	26	33
P-62.5+10%Na_2CO_3	4.8	292.8	151.2	1.13	88	138
T-22.5+10%Na_2CO_3	28.8	4.8	31.2	1.07	5	18
T-32.5+10%Na_2CO_3	28.8	28.8	43.2	1.08	10	27
T-42.5+10%Na_2CO_3	33.6	57.6	62.4	1.10	19	49
T-52.5+10%Na_2CO_3	38.4	91.2	84.0	1.12	37	119
T-62.5+10%Na_2CO_3	43.2	43.2	64.8	1.13	16	32
API standard (22.5g/350ml)	<65	15-45	-	0.9 - 2.64	3-20	8-30

D = Dawhenya   P = Prampram   T = Tsopoli

From figure 12, it was observed that all the black cotton soils showed very low shear stress in the unbeneficiated state at a concentration of 22.5g/350ml as all of them plotted below the commercial bentonite to which they are compared. From table 7, the Prampram sample has the lowest shear stress of 9.6 mPa.s while Dawhenya sample has the highest shear stress of 14.4 mPa.s both at 600 rpm (shear rate of $1022s^{-1}$). The commercial bentonite has a shear stress of 148.8 mPa.s at shear rate of $1022s^{-1}$. These shear stresses translate to 90.32 and 93.55% below commercial bentonite respectively. This could be attributed to the dominance of calcium in the black cotton soils as calcium is said to cause flocculation and subsequently aggregation.

There was however, an increase in the shear stress when the soil samples were beneficiated with 10% by mass of sodium carbonate. Figure 13 shows the black cotton soils plotting closer to the commercial bentonite and there is a clear variation in the performance of the various black cotton soils as Dawhenya performed better than Tsopoli while Prampram plots lowest. From table 8, Prampram soil has the lowest improved shear stress of 52.8 mPa.s while Dawhenya has the highest improved shear stress of 91.2 mPa.s, which translates to a percentage increment of 450.0% and 533.3% respectively at a shear rate of 1022 s^{-1}. This improvement seems to be due to the replacement of the calcium ions by sodium ions thereby increasing the sorption of water resulting in the separation of the clay particles.

Even with this improvement in shear stress, the yield points for Prampram and Tsopoli samples (Table 9) were 4.8 Pa, which is below the 15-45 Pa range given by the API standards. Therefore, in order to improve the gel strength and subsequently increase the viscosity, the concentration of the black cotton soils was increased to 32.5g/350ml. As shown in figure 14, the black cotton soils plot much closer to the commercial bentonite indicating a further improvement in shear stress. From table 8, the shear stresses obtained for Dawhenya, Prampram and Tsopoli at a concentration of 32.5g/350ml were 129.6 mPa.s, 76.8 mPa.s and 86.4 mPa.s respectively compared to the commercial bentonite with a shear stress of 148.8 mPa.s. At a concentration of 32.5g/350ml of the beneficiated samples, the shear stresses were 12.90%, 41.94% and 48.40% for Dawhenya, Tsopoli and Prampram respectively below the commercial bentonite but all the beneficiated black cotton soils at this concentration were found to have fulfilled the plastic viscosity, yield point and gel strength requirements indicated by the API standards.

The concentration of the local soils was further increased to 42.5g/350ml, 52.5g/350ml, and 62.5g/350ml (Appendix B). It was observed that even though the shear stresses obtained increased with increasing concentration, the yield point and gel strength increased to between 139.2-403.2mPa and 51-261mPa respectively for Dawhenya, 43.3-292.8mPa and 14-138mPa respectively for Prampram and 57.6-91.2mPa and 16119mPa respectively for Tsopoli. These results are beyond the range of 15-45mPa for yield point and 3-20mPa for 10sec gel strength and 8-30mPa for 10min gel strength given in the API standards.

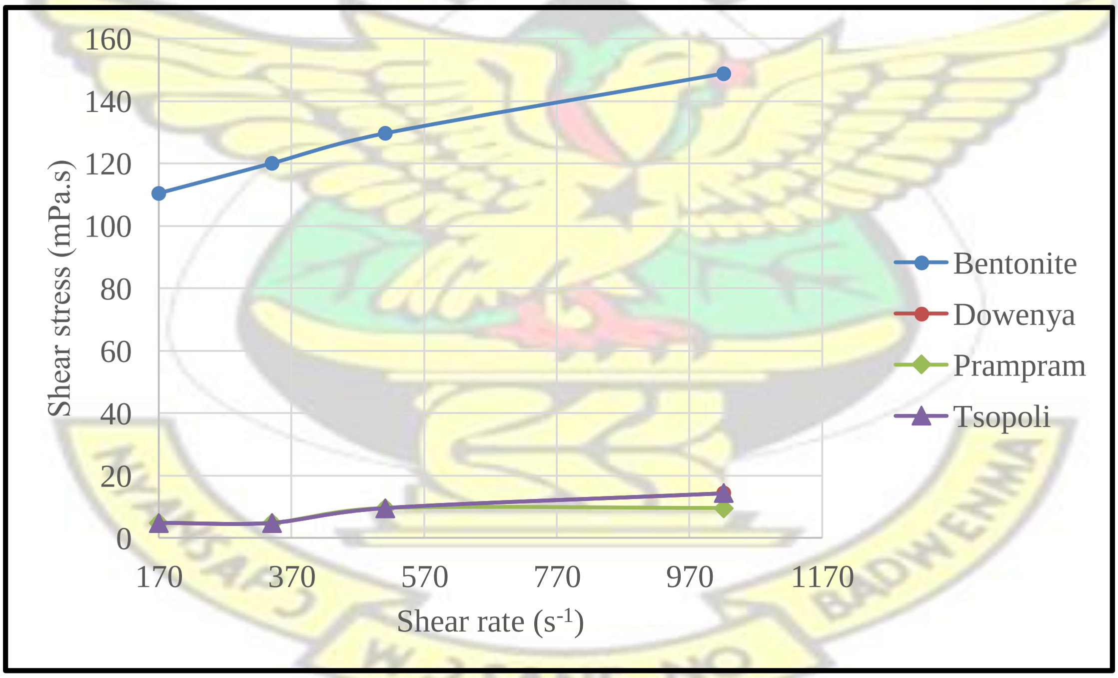


Figure 12: Rheological behavior of unbeneficiated samples at a concentration of

22.5g/350ml

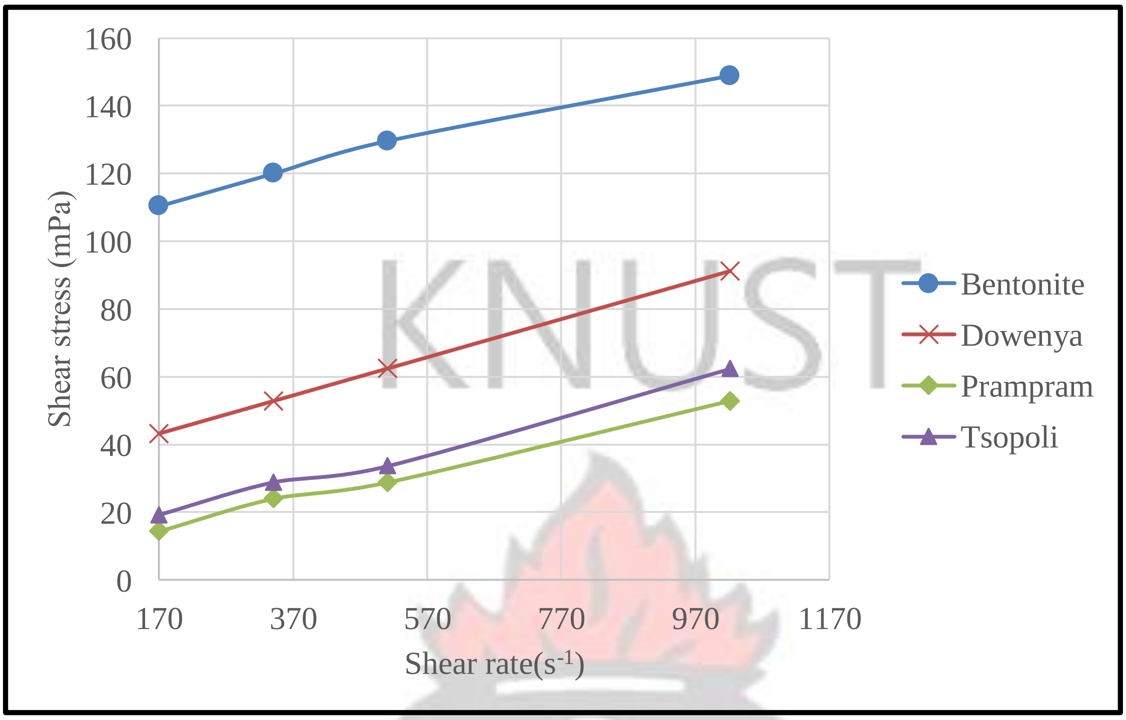


Figure 13: Rheological behavior of beneficiated samples at a concentration of 22.5g/350ml

4.6.1 Density

Density of mud is expressed in pounds per gallon or kilograms per liter. The pressure of mud column in a borehole helps to maintain stability of the borehole walls. This pressure depends on the density and column of mud in the borehole. The density further helps to provide buoyancy to keep drill cuttings floating in the mud. This implies that, the greater the mud density the better but excessive mud density may increase the pressure on the borehole walls resulting in the fracture of the walls. The API standards therefore provide a range of mud density of between 0.9kg/l and 2.64kg/l for safe and efficient drilling. The black cotton soils had density from 1.06kg/l to 1.13kg/l, which falls within the range given by API (Table 10).

4.6.2 Viscosity

The viscosity of a drilling mud generally provides the buoyancy to keep drill cuttings floating and enable their transport to the surface. In order to efficiently remove drill cuttings from the drilling mud and maximize the rate of penetration, the viscosity of the drilling mud should be as low as possible. The API standards provides an upper limit of 65mPa.s for which all the black cotton soils at the various concentrations fall within (Table 9).

4.6.3 Gel strength and yield point

The gel strength and yield point are properties of drilling mud that enables drill cuttings to remain in suspension even when circulation is stopped and the initial stress to overcome to re-establish circulation. Yield point and gel strength largely depend on the presence of colloidal clays. These properties are usually controlled by increasing the clay concentration in the drilling mud. Due to the continual changing of the yield point at low shear rates, the initial gel strength is often preferred over the yield point. Higher gel strengths are unwanted because they make the separation of drill cutting at the surface slower and increase the pressure needed to start circulation after changing bits. In addition, withdrawing of drilling pipes can cause a reduction in the pressure of the mud column when the gel strength is high. If the reduction in pressure surpasses the differential pressure between the mud and formation fluids, the fluids will enter the hole resulting in a blowout. Therefore, after increasing the soil concentration beyond 42.5g/350ml resulted in an increase of these properties beyond the API standards which when used in this concentration could cause the problems indicated above.

It can therefore be said that the beneficiation caused the improvement in the ability of the clay to flocculate resulting in the improvement of the rheological properties. According to Omole et al. (2013), three reasons account for the improvement in the properties of the clay. The first of which is the changing of calcium montmorillonite to sodium montmorillonite. Sodium montmorillonite has already been proven to have superior rheological properties than calcium montmorillonite due the fact that its dispersion in water results in the separation of platelets. The second reason is the high concentration of clay minerals resulting in a higher viscosity due to the higher amounts of colloidal solids in the mud and finally, the edges of the clay sheets formed by the unsatisfied chemical bonds.

The black cotton soils had consistency curves following the Bingham Plastic model with little deviation, which is reported to be normal with most drilling muds.

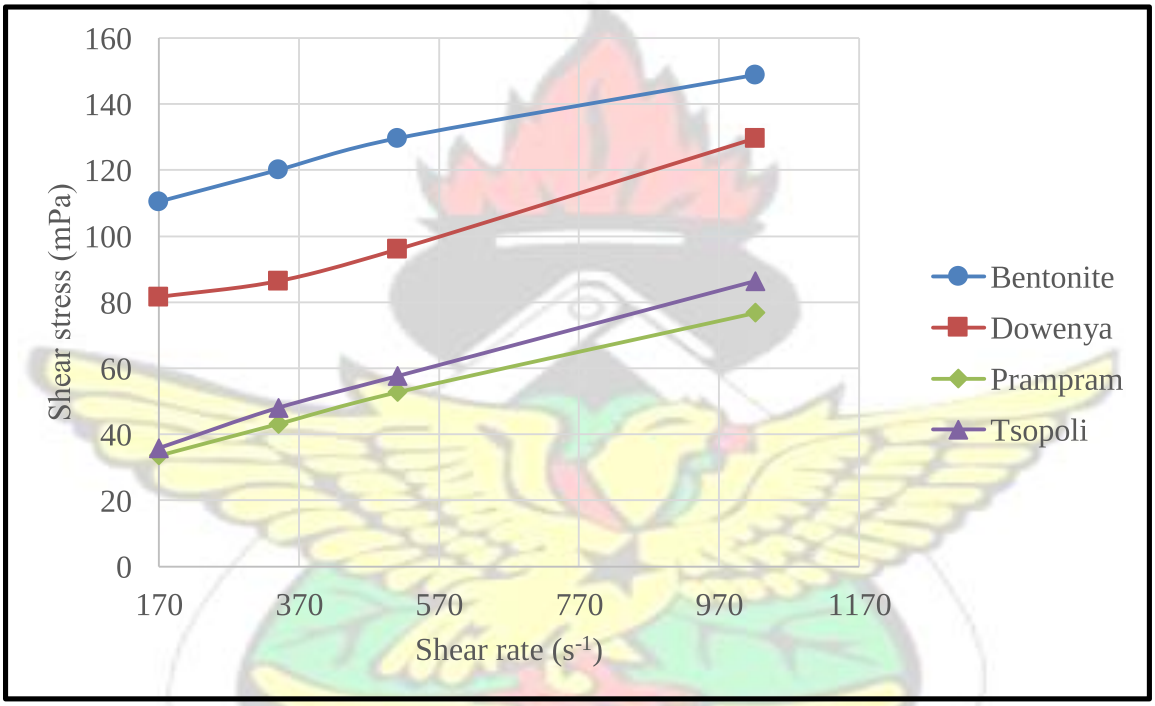


Figure 14: Rheological behavior of beneficiated samples at a concentration of 32.5g/350ml

4.6.4 Economic evaluation

In order to assess the viability of utilizing black cotton soil in place of commercial bentonite, an economic evaluation was done.

In the course of the analysis, the exchange rate on the interbank market for June, 2016 of 3.9 Ghana cedis to 1 US dollar was used.

On the average six wells are drilled annually and ten tonnes of commercial bentonite is used per well 17 inches' diameter. Therefore, on the average 60 tonnes of commercial bentonite is consumed annually in the oil and gas industry in Ghana.

Table 100: Cost of commercial bentonite, black cotton soil, sodium carbonate and percentage savings

Material	**Av. no. of wells per annum**	**Av. amt. of bentonite used per well (Tonnes)**	**Mass (Tonnes)**	**Cost ($)**	**Cost savings (%)**
Commercial bentonite	6	10	60.00	163,694.40	0
Black cotton soil (BCS)	6	10	60.00	4,281.00	0
Sodium carbonate (Na_2CO_3)	6	10	6.00	64,615.38	0
BCS + Na_2CO_3	6	10	60.00	68,896.38	57.91

Table 11 shows the cost of using commercial bentonite and the cost of producing the same quantity of black cotton soil. These were computed from information obtained from Ghana National Petroleum Corporation (GNPC) which include cost of a tonne of commercial bentonite at $2,728.24, an average number of six wells per annum and ten tonnes of bentonite consumed per well, while the black cotton soil figures were arrived at using cost of excavation, haulage, processing and cost of sodium carbonate (Na_2CO_3). From the analysis, it was observed that a possible cost savings of about 58% would be made when the black cotton soil is used. Appendix C gives the economic analysis of replacing bentonite in geosynthetic clay liners.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The research work assesses the applicability of black cotton soils obtained from three locations in the Accra Plains as substitute for commercial bentonite in geosynthetic clay liners and drilling muds.

The specific objectives were to:

i. Determine the chemical and mineralogical characteristics of black cotton soil and commercial bentonite.

ii. Determine the geotechnical characteristics of black cotton soil and commercial bentonite. iii. Determine the rheological properties of black cotton soil and commercial bentonite.

iv. Compare the results obtained from the black cotton soils to that of commercial bentonite as well as some local and international standards.

From the study, the following conclusions were made:

i. It was observed that silica, alumina and iron are the dominant oxides constituting 87.20%, 88.96% and 87.07% for Dawhenya, Prampram and Tsopoli. In comparison with the commercial bentonite, all the oxides within the Dawhenya, Prampram and Tsopoli are lower in concentration than that of the commercial bentonite except iron oxide, manganese oxide and silica. The mineralogical analysis of all the three soils is similar to the commercial bentonite indicating that the soils have similar mineralogy with commercial bentonite. The main minerals identified were quartz and montmorillonite.

ii. The colour and percentage of the clay fraction showed that the soils obtained from the Accra plains all classify as black cotton soils while the chemical, mineralogical and CEC identified calcium montmorillonite as the dominant clay mineral. The permeability test results obtained in comparison with the commercial bentonite tested under the same conditions indicate that the black cotton soils can be used as a substitute for commercial bentonite in geosynthetic clay liners. The Minerals Commission of Ghana LI 2182 specified a permeability of the order 10^{-6}cm/s while the United States of America environmental protection agency gave a permeability of the order 10^{-9}cm/s. The results obtained from the black cotton soils were 1.03×10^{-9}cm/s, 7.61×10^{-9}cm/s and 2.04×10^{-9}cm/s for Dawhenya, Prampram and Tsopoli respectively. These results are all of the order of 10^{-9}cm/s and compare well with that of the commercial bentonite, which is 2.08×10^{-9}cm/s.

iii. The rheological properties considered are the plastic viscosity, yield point and gel strength. The densities as well as the apparent viscosity were also determined. The results obtained were compared to that of commercial bentonite as well as the American Petroleum Institute (API) standards. The results of the unbeneficiated black cotton soils were between 5.0-10.0 mPa.s plastic viscosity, 5.0-19.0 mPa.s yield point and 4.8-9.6mPa gel strength for 10seconds and 10minutes. The commercial bentonite had a plastic viscosity of 19.2 mPa.s, yield point of 23.0mPa and a gel strength of 15mPa for 10seconds and 17mPa for 10minutes. The results obtained from the black cotton soils are all below those of commercial bentonite as well as the API standards.

Upon the addition of 10% of Na_2CO_3, the plastic viscosity, yield point and gel strength increased to between 19.2-38.4 mPa.s, 28.8-43.2 mPa, 5-20 mPa for 10seconds, 11-28 mPa for 10minutes, respectively and these values fulfill the requirements of the API 13B-1.

iv. The economic evaluation that was done indicated a possible cost savings of about 58% when black cotton soil is used as drilling fluid and a cost saving of about 94% when used in geosynthetic clay liners.

v. A 10% by mass of Na_2CO_3 and a concentration of 32.5g/350ml is recommended for optimum plastic viscosity, gel strength and yield point in the black cotton soils.

5.2 RECOMMENDATIONS

From the research, it is recommended that:

i. Field-testing should be conducted to ascertain the workability of the black cotton soils since the conclusion in this work are based on laboratory work.

ii. Further research should be done to find natural or cheaper sources of Na_2CO_3.

REFERENCES

Abdelmalek Bouazza and John J. Bowders, (2010) Geosynthetic Clay Liners for waste Containment facilities. CRC Press, Taylor and Francis Group, 244pp.

Adam T.B. Jr, Chenevert ME, Millheim K.K., Young Jr F.S. (1986). Applied Drilling Engineering, SPE Textbook Series, Richardson, TX, Vol. 2, Edited by Jack FE and David SP.

Ahmad, N. (1996). Occurrence and distribution of Vertisols. In N. Ahmad and A. Mermut (ed.) Vertisols and technologies for their management. Develop. in Soil Science 24. Elsevier, Amsterdam, the Netherlands pp. 1–41.

Akayuli, C.F.A., Gidigasu, S.S.R., and Gawu, S.K.Y., (2013). Geotechnical Evaluation of a Ghanaian Black Cotton Soil for use as Clay Liner in Tailings Dam Construction, Ghana Mining Journal, pp: 21-26.

Anon, (2016). Cost of geosynthetic clay liners. www.alibaba.com/shown/geosyntheticclay-liner-cost-html. Assessed on 19th June, 2016.

API 13B-1, (2003). Recommended practice for field testing water-based drilling fluids. Third edition API publishing services, Washington D.C.

ASTM D2216, (1998). Laboratory determination of water (moisture) content of soil and rock by mass. Annual book of ASTM standards, Vol. 04.08.

ASTM D4439, (1999). Standard terminology for Geosynthetics. Annual book of ASTM standards, Vol. 14.02.

.

ASTM D5887, (1999). Measurement of index flux through saturated geosynthetic clay liner specimen using flexible wall permeameter. Annual book of ASTM standards, Vol.

14.02.

Ben B, Neal D, Brad S, Louise B, Lindsay F, Mike H (1994). Designing and Managing Drilling Fluid, http://www.slb.com/~/media/Files/resources/oilfield_review/ors94/0494/p33_43.ashx.

Bouazza, A., Gates, W. P., Scheirs, J. (2013), Geosynthetics in mining applications, Proceedings of the 2nd International Conference of Geosynthetics 18th- 20th November, 2013, Accra, Ghana, pp:28 .

Blyth, F.G.H and De Freitas, M.H. (1977). A geology for engineers. English Language Book Society, 6th edition, 557pp.

Brammer, H. (1967). Soils of the Accra plains. Soil Research Institute, Memoire No., 3

Building and Road Research Institute (1985). Highway geotechnical characteristics of selected subgrade materials. BRRI Technical Paper HM/5 Paper 10; 134pp

BS 1377 (1990). Methods of testing soils for civil engineering purposes, British Standards Institution, London.

Bucher F, Sailie E. L. (1984). Swelling behaviour of tropical black clays. Proc. 8th African Regional Conference on Soil mechanics and Foundation Engineering, Harare. Pp. 81-86.

Burrafato, G. and Miano, F. (1993). Determination of the cation exchange capacity of clays by surface tension measurements. Clay Minerals 28: 475–481.

Charlie W.A, Osman A. and Ali E.M. (1984). Construction on expansive soils in Sudan. Journal of construction and management, Vol. 110, No.3, pp: 359-374

Chiroma T.M, Ebewele R. O. and Hymore F. K. (2014). Comparative assessment of heavy metal levels in soil, vegetables and urban grey waste water used for irrigation in Yola and Kano. IRJES, volume 3, issue 2, pp 01-09.

Clemente, E., Coulombe, C. E., Dixon, J.B and Widding, L.P. (1996). Chapter five - Vertisols and technology for their management. Developments in Soil Science, vol. 24. Elsevier, New York

Cobbina, J. (1988). Vertisols of Ghana: Uses and potential for improved management using cattle.In Jutz S.C., Haque, I.,McIntire J. and Stares J.E.S.(Eds) Management of Vertisols in sub-Saharan Africa. Proc. of a conference held at ILCA, Addis Ababa-Ethiopia, 31 August-4 September, 1987, pp: 359-378

Condra, G.E., 1908. Geology and water resources of a portion of the Missouri River Valley in northwestern Nebraska. US. Geol. Surv., Water-Supply Pap., 215: 59 pp.

Daniel, D. E., Shan, H.-Y., and Anderson, J. D. (1993). "Effects of Partial Wetting on the Performance of the Bentonite Component of a Geosynthetic Clay Liner," Proceedings of Geosynthetics '93, IFAI, pp. 1483–1496.

Dickson, K.B. and Benneh, G.A. (1988), New Geography of Ghana. Revised Edition, Longman Group, U.K. Ltd, 170pp.

Eswaran, H., Kinble, J and Cook, T. (1988). In classification, management and use potential of swell-shrinkage soils. Transaction of the international workshop on swellshrinkage soils. Oct 24-28, 1988. National Bureau of soil survey and land use planning.

Nagpur, India, pp: 1-12

F. M. White, (2008). Fluid Mechanics, McGraw-Hill, 6th edition, 896pp.

Falode O.A., Ehinola O.A., Nebeife PC (2008). Evaluation of local bentonitic clay as oil well drilling fluids in Nigeria. Appl. Clay Sci. 39:19-27.

Gidigasu S.S.R. and Gawu S.K.Y. (2013), “The mode of formation, nature and geotechnical characteristics of Black Cotton Soils-A Review”. Standard Scientific Research and Essays Vol. 1 (14).

Gidigasu, S.S.R. (2012). Geomechanical Characteristics of Natural and Stabilised Black Cotton Soils from the Accra Plains of Ghana, M. Phil Thesis, KNUST.

Gray G.R. and Darley H.C.H. (1980). Composition and Properties of Oil Well Drilling Fluids. Gulf Publishing Co., Houston, Texas.

Grim, R.E. (1950) Modern concepts of clay materials. J. Geol., 50, 225–275.

Grim, R.E. (1962) Applied Clay Mineralogy. McGraw-Hill, New York, 422pp.

Grim, R.E. (1968) Clay Mineralogy, 2nd Edition. McGraw-Hill, New York, 596pp.

Grim, R.E. (1988). The history of the development of clay mineralogy. Clay Miner., 36, 97 -101.

Hewitt, D.F., 1917**.** The origin of bentonite. J. Wash. Acad. Sci., 7: 196-198.

Hosterman, J.W. and Patterson S.H. (1992). bentonite and Fuller's earth resources of the United States. U.S. Geological Survey Professional Paper 1522. United States Government Printing Office, Washington D.C., USA.

H.C.H. Darley and George R. Gray, (1988). Composition and properties of Drilling and completion fluids, 5th. Ed., 654 pp.

Indian Standards 1498 (1987). Indian Standard Classification and Identification of Soils for General Engineering Purposes. BIS, New Delhi, IS 1498.

Jagori D. and Mishra A. K. (2016). Influence of the presence of heavy metals on the behavior of bentonites. Environmental earth science. Springer-Verlay Berlin Heidelberg pp 75-86.

Jeon, H.-Y. (2009). "Clay Nanoparticle Formulated Geotextiles Used in Geoenvironmental Applications," *Proceedings of GRI-22 Conference,* Salt Lake City, GII, Folsom, PA, USA.

Junner, N.R. and Bates, D.A. (1945). Reports on the geology and hydrology of the coastal areas east of the Akwapim ranges. Ghana Geological Survey Memoir No. 7

Kariuki, P.C., Van Der Meer, F., and Verhoef, P.N.W. (2003). Cation exchange capacity (CEC) determination from spectroscopy. *International Journal of Remote Sensing* 24(1): 161–167.

Katti, R.K., Katti Dinesh R. and Katti, A.R. (2002). Behaviour of saturated expansive soils and control methods. A. A. Balkema Publishers.

Koerner, R.M., Koerner, G.R. (2005). In-situ separation of GCL panels beneath exposed geomembrane. *GRI White Paper No. 5,* Geosynthetics Institute, Folsom, PA, USA, April, 21 pp.

Kortatsi, B.K. (2006). Hydrochemical characterisation of groundwater in the Accra plains of Ghana. Environ. Geology, Springer-Verlag, Vol. 50, pp: 299-311

L. Imsland, (2008). "Modeling of drilling hydraulics for adaptive pressure estimation," Available: http://www.kgs.ku.edu/Publications/Oil/primer12.html.

Mgangira, M.B. and Paige-Green, P. (2008). ―Evaluation of damage to a road and sports complex on expansive clays. Proc., 6th Int. Conf. on Case Histories in Geotechnical Engineering, Missouri University of Science and Technology, Arlington, Va., Paper 8.08b.

Mitchell, J.K. and Soga, K. (2005). Fundamentals of Soil Behavior. 3rd Edition. John Wiley & Sons, Inc. 559pp.

Michael, A.M. (2006). Irrigation theory and practice. Vilcan publishing house PVT Ltd. Reprint, 801pp.

Mohr ECJ, Van Baren F. A. (1959). Tropical soils. W. Van Heove, The Hague. Pp. 498.

Morin W. J. (1971). Properties of African tropical black clays. Proc. 5th African Regional Conference on Soil mechanics and Foundation Engineering, Luanda, Angola. 1: 51-59.

Murray, A. S., and Cunningham, R. A., (1955). Effect of Mud Column Pressure on Drilling Rates, *Trans. AIME*, Vol. 204 pp. 196-204.

Murray, H.H. (1976) The Georgia sedimentary kaolins. Proceedings of the 7th International Kaolin Symposium. Shimoda, S.ed. University of Tokyo, Tokyo, pp.114–125.

Murray, H.H. (2000a) Clays. Ullmann's Encyclopedia of Industrial Chemistry, 6th Edition. Wiley- VCH Verlag GmBH, Weinheim, Germany, 30pp.

Murray, H.H. (2000b) Traditional and new applications for kaolin, smectite and palygorskite: a general overview. Appl. Clay Sci., 17, 207–221.

Murray, H.H. and Lyons, S.C. (1956) Correlation of paper-coating quality with degree of crystal perfection of kaolinite. Clay. Clay Miner., 456, 31–40.

Mermut, A.R., Padmanabham, F., Eswaran, H., and Dosog, G.S. (1996). Pedogenesis. In: Ahmad, N., Mermut, A. (Eds.), Vertisols and Technologies for their Management. Developments in Soil Science, Vol. 24. Elsevier, New York

Ola S. A. (1983). The geotechnical properties of the black cotton soil of Northeastern Nigeria. In Tropical soils of Nigeria in Engineering Practice, Ola S.A. (Ed). A. A. Balkema Publishers, Rotterdam. Pp.85-101.

Omole O., Adeleye J. O., Falode O., Malomo S., and Oyedeji O. A. (2013). Investigation into the rheological and filtration properties of drilling mud formulated with clays from Northern Nigeria. Journal of Petroleum and Gas Engineering Vol. 4(1), pp 1 – 13.

Osinubi, K.J. (2006). Influence of compactive effort on lime-slag treated tropical black clay. Journal of materials in civil engineering, ASCE Vol. 18, No.2, pp: 175-181

Preston LM (1974). Drilling Practices manual, The Petroleum Publishing Co., Oklahoma, USA.

Robinson, G.W. (1949). Soils, their origin, constitution and classification. Thomas Murby and Co., London, 537pp.

Rabia H (2002). Well Engineering and Construction, ISBN 0954108701.

Rao, M.S. (2006). Identification and classification of expansive soils. In Amer Ali Al Rawas, Mathheus F.A., Goosen (edited) Expansive soils: Recent advances in characterisation and treatment. A. A. Balkema Publishers, pp: 15-25

Rao, S.M., Reddy, B.V.V. and Muttharam, M. (2001). The impact of cyclic wetting and drying on the swelling behaviour of stabilised expansive soils

Ross, C.S. and E.V. Shannon, 1926. Minerals of commercial bentonite and related clays and their physical properties. J. Am. Ceram. Sci., 9: 77-96.

Rowe, R. K., Quigley, R. M and Booker, J. R. (1995), Clayey-Leachate Compatibility by Measurement of Hydraulic Conductivity. Clay barrier Systems for Waste Disposal Facilities, E and FN Spoon (Chapman and Hall), London, Chapter 4. 390p.

Sarsby, R. W. (2007). Geosynthetics in Civil Engineering, Woodhead Publishing Ltd., Cambridge, England, 295 pp.

Thiel, R., Daniel, R. E. Erickson, R. B. Kavazanjian, E. and Giroud, J. P. 2004. GSE Gundseal GCL Design Manual, GSE Lining Technology, Inc., Houston, Texas, 200 pgs.

Thomas, G.W. 1996. Soil pH and soil acidity. In D.L. Sparks (ed.), Methods of Soil Analysis, Part 3, Chemical Methods, Soil Science Society of America, Madison, WI.

Tone L. 2013 "Drilling Fluid Properties Estimator," Master of Science in Engineering Cybernetics thesis, Norwegian University of Science and Technology, Trondheim.

Trauger, R.J. 1994. The structure, properties, and analysis of bentonite in geosynthetic clay liners. Proceedings of the 8th GRI Conference, Philadelphia, PA: 185–197.

United States Agency for International Development (USAID)/Building and Road Research Institute (BRRI), (1971). Laterite and Lateritic Soils and other Problem Soils of Africa. An Engineering Study Report, AID/CSD – 2164, 290 pp.

Van Der, D.H. (1964). The weathering of some basic igneous rock and their engineering properties. Trans. South African Institution of Civil Engineers, pp 213-222

Wherry, E.T., 1917. Clay derived from volcanic dust in the Pierre of South Dakota. J. Wash. Acad. Sci., 7: 576-583.

Weinert, H.H., (1980). The natural road construction materials of Southern Africa. Academica Press, Pretoria, 298pp.

Wentworth, C.K. (1922). A scale of grade and class terms for clastic sediments. J. Geol., 30, 377–392.

Wright, P.C., 1968. Meandu Creek commercial bentonite - a reply. J. Geol. SOCA. ust., 15: 347-350.

Zanzinger, H., Koerner, R. M. and Gartung, E., Eds. 2002. *Clay Geosynthetics Barriers*, A. A. Balkema, 399 pgs.

APPENDICES

APPENDIX A

Percentage variation of sodium carbonate by mass with black cotton soils

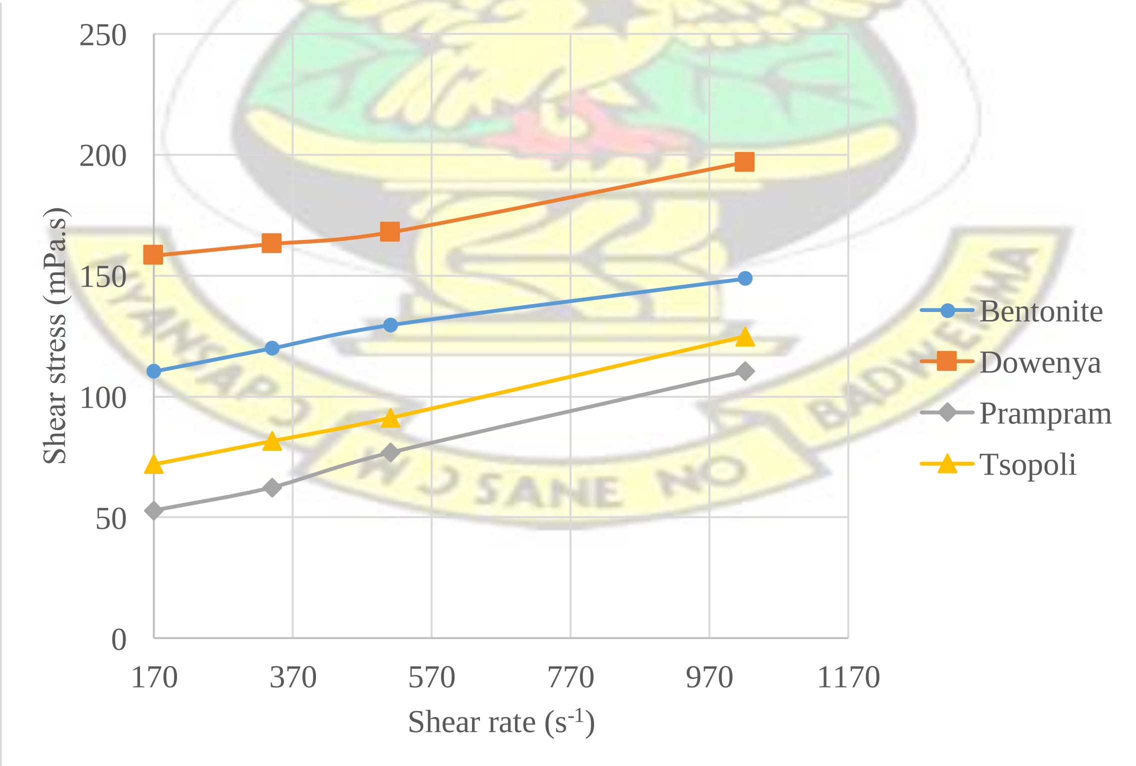
Sample ID	**Percentage of sodium carbonate by weight**				
	0%	**6%**	**8%**	**10%**	**12%**
Dawhenya	150	185	207	290	277

Prampram	115	130	174	190	190
Tsopoli	164	179	193	210	204

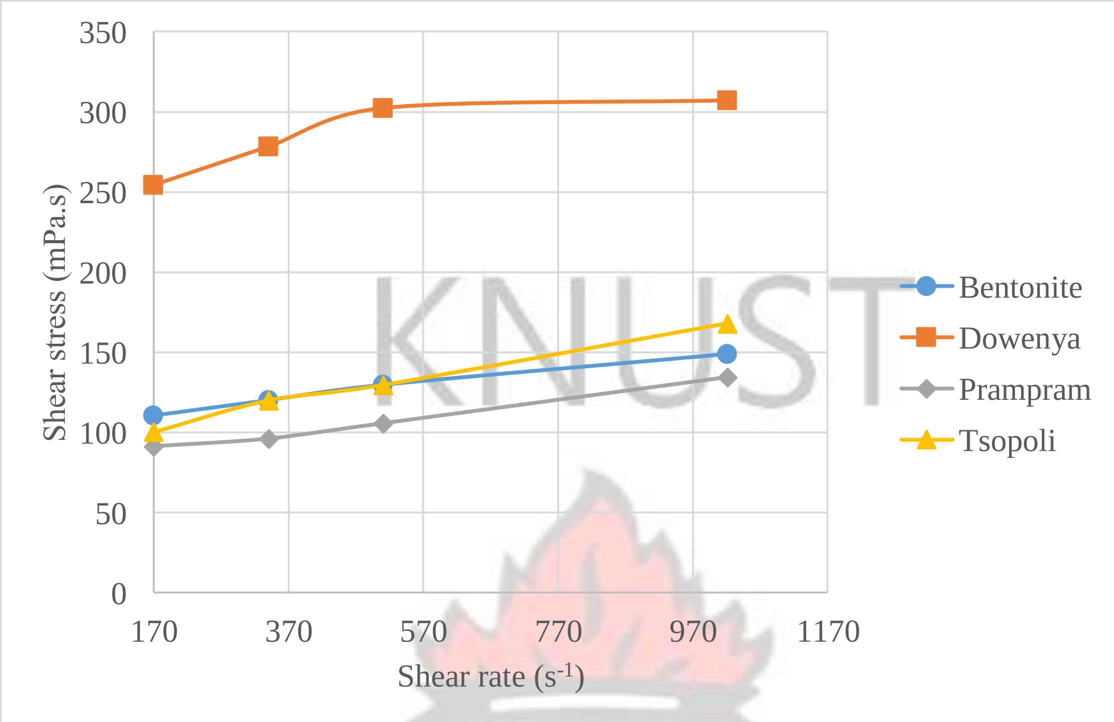
Percentage variation of sodium chloride by mass with black cotton soils

Sample ID	**Percentage of sodium chloride by weight**			
	0%	**6%**	**8%**	**10%**
Dawhenya	150	101	83	46
Prampram	115	96	70	50
Tsopoli	164	125	100	75

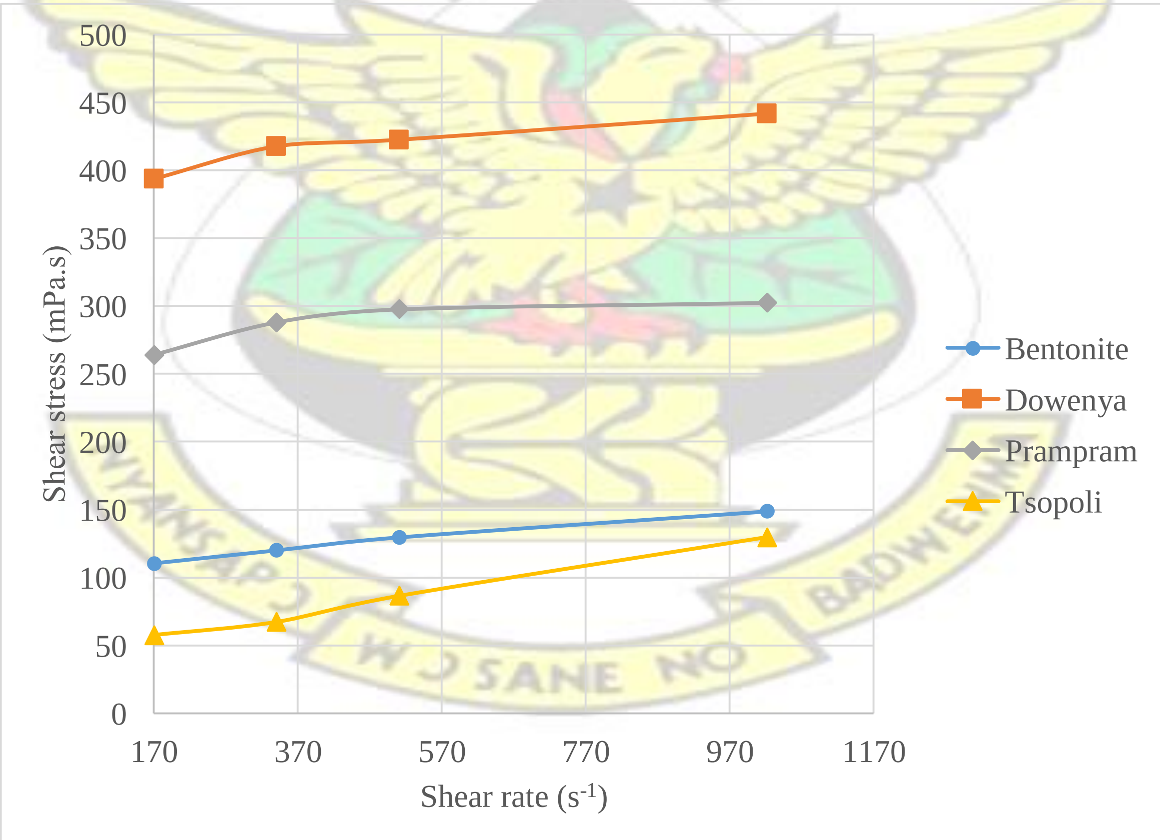
APPENDIX B



Rheological behavior of beneficiated samples at a concentration of 42.5g/350ml



Rheological behavior of beneficiated samples at a concentration of 52.5g/350ml



Rheological behavior of beneficiated samples at a concentration of 62.5g/350ml

APPENDIX C

Cost of using commercial bentonite, cost of producing black cotton soil and the percentage cost saving for a geosynthetic clay liner of dimensions 500m x 200m x 0.005m as the minimum order.

Material	Volume (m^3)	Cost ($)	Cost savings (%)
Commercial bentonite	500	3,014.71	0
Black cotton soil	500	176.38	94.15