Geotechnical Evaluation of a Ghanaian Black Cotton Soil for use as Clay Liner in Tailings Dam Construction*

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Abstract

The purpose of tailings impoundment is to contain tailings produced from mineral processing. Chemicals used in mineral extraction processes are usually hazardous to biota and fauna and their presence in tailings may pollute the environment. To prevent the flow of such contaminants from tailing dams into the environment, low permeability membranes or seals are used in the basin of the tailings dam as barrier layer. Geomembranes and natural clay liners are typical examples. The use of naturally occurring clay materials provides the most economical liner for tailings dam construction. Lateritic clay and weathered shale have been evaluated for use as liner. Black cotton soils occur in substantial quantities in parts of Ghana but their potential use as a clay liner has not been evaluated. This study presents laboratory evaluation of a typical black cotton soil from the Accra plains of Ghana as potential clay liner for tailings dam construction. Results of the study indicate that the hydraulic conductivity or permeability, plasticity index, fines content and cation exchange capacity of the black cotton soils met the specification of typical clay liner systems. The soil however failed the specific gravity and liquid limit requirements marginally and hence, the soils may be used as clay lining system in tailings dams.

1 Introduction

In Ghana, million of tonnes of rock are mined, crushed, milled, and processed to recover desired metal and millions of tonnes of tailings are also generated. Mine tailings are composed of fine grained rock materials and may also contain toxic chemicals which are potentially hazardous to the environment if not properly disposed off or contained.

Safe tailings disposal has therefore become a major environmental concern and hence, mining companies are compelled to impound tailings behind specially designed tailings dams that incorporate basin liner systems. Liner systems are used primarily to prevent the flow of pollutants from tailings into the environment and, therefore, protect the soil and ground water from pollution.

Commonly used liners include geosynthetics liners and natural clay soils. Slimes are also sometimes used as low permeability barriers (U.S. Environmental Protection Agency, 1994). These major liner systems have their peculiar advantages and limitations. The main benefits of geosynthetic liners (e.g. geomembranes) include superior performance in terms of hydraulic conductivity, ease of installation and increased landfill airspace due to the relative thickness of a geosynthetic liner compared with an equivalent clay liner, however, the high cost of these geomembranes is a disadvantage. Others such as panel shrinkage, desiccation cracking, chemical incompatibility, cation exchange and lack of hydration in geomembrane have been identified by Legg and McLennan, (2011) as some problems associated with the use of geosynthetic barrier systems which adversely affect the hydraulic conductivity performance of the barrier. Clay liners on the other hand are naturally occurring materials which provide the most economical liners for tailings dam construction. Rowe (2005) identified that both clay liners and geosynthetic liners are susceptible to desiccation and may develop cracks. However, clay liners have self healing properties.

Many naturally occurring geo-materials have been evaluated for use as clay liner, for instance, compacted lateritic soil have been used as liners and cover in waste containment application (Liman, 2009; Osinubi and Nwaiwu, 2005, Eberemu, 2007). Weathered shales have also been evaluated for use as liner (Obrike *et al.*, 2009). However, some special clay soils commonly referred to as black cotton soils and defined as "dark grey to black soils with high content of clay usually over 50%, in which montmorillonite is the principal clay mineral and are commonly expansive" (USAID/BRRI, 1971) which occur in substantial quantities in parts of Ghana have not been evaluated for use as liner systems. Studies on these black cotton soils reveal that they are unsuitable for earthworks and road construction (e.g. Ola, 1978; Osinubi, 2006). However, very little is known about its potential use as a clay liner. This study therefore attempts to evaluate the geotechnical characteristics of a typical black cotton soil from

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Tsopoli in the Accra plains of Ghana for possible use as lining material in tailings dam construction.

1,1 Characteristics of Typical Clay Liners

To evaluate the suitability of a potential source for clay lining the following suite of tests are recommended (O'Sullivan and Quigley, 2002): natural moisture content, Atterberg limit (liquid/plastic limits), particle size grading, organic content, compaction curves (dry density/ optimum moisture content relationship), moisture condition value (MCV) and permeability The cations exchange capacity (CEC), specific surface area (SSA), clay mineralogy, pH, and electrical conductivity have also been mentioned by some researchers (e.g. Marcos and Pejon, 2006; Yong et al. 1999) as suitability criteria for assessment of clay liners.

According to Marcos and Pejon (2006) a clay liner should possesses among other characteristics; low hydraulic conductivity ($<10^{-9}$ m/s), minimum of 10% clay content and plasticity index (PI) between 12% and 65%. United Kingdom (U.K.) Environmental Agency (2009) specified that a clay liner material should comply with the minimum requirements shown in Table 1.

Rowe *et al.*, (1995) stated that the specifications for clay liners often include:

i) A minimum cation exchange capacity of 10 meq/100 g of soil.
ii) Compaction or cementation to high densities and effective porosities that are low enough to minimize the flow of contaminants through them; the maximum hydraulic conductivity allowable is about 10^{-7} cm/s (10^{-9}m/s).
iii)The liner should be compatible with the leachates to be retained, such that the hydraulic conductivity shall not increase significantly on exposure to leachate.
iv)A chemical flux point of 10^{-8} cm/s or less is preferable since diffusion often becomes the dominant migration mechanism and
v) Should plug the pore space in natural soil such that large channels for contaminant transport are effectively eliminated.

Natural clay liners should generally possess (U.K. Environmental Agency, 2009): low hydraulic conductivity, adequate shear strength, and minimal shrinkage upon reduction of moisture content. The plasticity, workability, low frost susceptibility, adequate chemical resistance, low dispersivity and adequate attenuation/retardation capacity of the material are also very important.

Table 1 Requirements of a Clay Liner

Property	**Minimum requirement based on BS 1377; 1990 test specifications**
Permeability	Characteristic permeability of all samples tested in the laboratory shall be ≤ $5x10^{-10}$ m/sec
Remoulded undrained shear strength	Typically ≥50kN/m^2
Plasticity index (Ip)	10%≤ Ip ≤65%
Liquid limit (LL)	≤ 90%
Percentage fines <0.063mm	≥ 20% but with a minimum clay content (particle<2um) of 8%
Percentage gravels >5mm	≤ 30%
Maximum particle size	2/3rd compacted layer thickness. Typically 125mm but must not prejudice the liner, for instance by larger particles sticking together to form larger lumps

Source: U.K. Environmental Agency, (2009)

2 Materials and Method

The soil used in the study was collected from a depth between 0.3 m and 1.4 m below ground level from Tsopoli in the Accra Plains of Ghana. The geographical location of the test pit was N 05°53'55.0"; E 00°01'05.40". Studies by Gidigasu (2012) reveal that the material classifies as black cotton soil. The site is known to be underlain by the garnetiferous hornblende gneiss of the Dahomeyan formation (Gidigasu and Appiagyei, 1980). A typical soil profile consists of a topsoil which is underlain by a dark grey to black clay soil. Underneath this layer is a grey to brown clay soil with calcium carbonates concretions scattered through the horizon but tending to be more at the base and this is underlain by weathered and fresh rock. The clay mineralogy of the soils has been reported as 40%-60% montmorillonite and less than 20% kaolinite (Cobbina, 1988).

The soils were air-dried and pulverized before use. The soil samples were then subjected to chemical, index and engineering property tests. The chemical composition of the soil was determined using X-ray florescence analysis at the Ghana Geological Survey. The physico-chemical characteristics of the soil were determined at the Soil Science Section of the Department of Agriculture, KNUST. Index properties determined include particle size distribution, specific gravity of the solids, Atterberg limits and linear shrinkage. These tests were carried out according to testing procedures stipulated in the BS, 1377 (1990). Compaction test was performed using the Standard Proctor Specifications (BS 1377, 1990). The permeability of the soil was determined using consolidation test (BS 1377, 1990) on samples compacted at optimum moisture content (OMC) using the standard proctor specification.

The coefficient of permeability was calculated from the relation:

$$k = M_v \times C_v \times \gamma_w \quad (1)$$

where k is the coefficient of permeability, C_v is the coefficient of consolidation and γ_w is the unit weight of water.

3 Results and Discussion

3.1 Chemistry of the soil

The chemical composition of the soil is presented in Table 2. The dominant oxides in the soil are silica, alumina and iron which constitute about 87% of total oxides. The others occur in small concentration and make up only about 13%. The heavy metals concentration in the soil occur within tolerable limits with the exception of nickel whose concentration is elevated (127ppm).

Typical physico-chemical characteristics of the soil are shown Table 3. The significant exchangeable ions identified were Ca=30 meq/100g, Mg =13 meq/100g, K= 0.58 meq/100 g, Na= 5.47 meq/100g, Al= 0.20meq/100g and H = 0.40 meq/100g. The cation exchange capacity (defined as the total/amount of exchangeable cations a soil is capable of adsorbing, expressed in milliequivalents per 100 grams of soil) is 49.65.

The pH of the soil is 6.94 and it indicates that the soil forming medium is almost neutral and organic matter content of 2.9 %. The loss on ignition at $1000^{o}C$ is 6.2%.

The cation exchange capacity (CEC) of the soil 49.65 meq/100g is found to be greater than the minimum (10 meq/100g) suggested by Rowe *et al.*, (1995).

Table 2 Chemical Composition of the Soil

Major Oxides	Concentrations (% weight)
SiO_2	62.18
Al_2O_3	18.23
Fe_2O_3	6.7
Na_2O	2.07
MgO	2.45
K_2O	0.11
CaO	0.7
P_2O_5	0.05
MnO	0.07
TiO_2	1.09
SO_3	0.1
Heavy Metals	**Concentration (ppm)**
Ni	32.6
Cr	127
Mo	18.4
Pb	11.5

Table 3 Physico-Chemical Characteristics of the Soil

Parameter	Concentration (meq/100g)
Calcium	30.00
Magnesium	13.00
potassium	0.58
Sodium	5.47
Aluminum	0.20
Hydrogen	0.40
pH	6.94
Organic matter content	2.97%
Loss On Ignition	6.2%

3.2 Geotechnical characteristics

The geotechnical properties determined on the soil are presented in Table 4 and are discussed in this section.

Specific Gravity

The specific gravity of the solid particles in the soil is 2.37 which is below the 2.5 minimum recommended in the ONORM S 2074 (1990) and United State Environmental Protection Agency (1982).

Table 4 Geotechnical characteristics of the soil

Parameter	Concentration (meq/100g)
Calcium	30.00
Magnesium	13.00
potassium	0.58
Sodium	5.47
Aluminum	0.20
Hydrogen	0.40
pH	6.94
Organic matter content	2.97%
Loss On Ignition	6.2%

Particle Size Distribution and Textural Classification

The particle size distribution curve of the soil is shown in Fig. 1. The soil classifies as clay on the United State Engineers Textural Classification chart. Gravel size is absent in the soil but has sand size content of 19.70%, silt size content of 18.00% and clay size content of 63.30%. The fines content (<0.063 mm) of the soil is 81.30%, a value greater than those reported for typical clay liners which should contain at least 20% of silt or clay sized material (U. K. Environmental Agency, 2009).

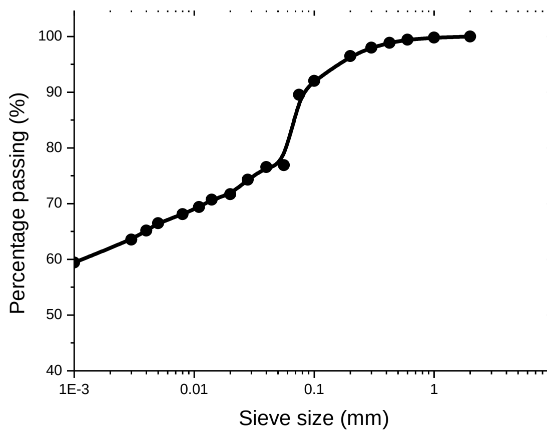

Fig. 1 Particle size Distribution of the Soil

Atterberg Limits and Plasticity Characteristics

The liquid limit (LL) and plastic limit (PL) of the soil is 91.72% and 29.60% respectively. The plasticity index is 62.12%. The liquid limits of the soil that is 91.72% is slightly greater than the U. K. Environmental Agency (2009) and Seymour and Peacock (1994) requirement which must be less than or equal to 90%. The standard also requires that the plasticity index of the clay liner ranges between 10% and 65% (U. K. Environmental Agency, 2009) and/or 12% to 65% (Marcos and Pejon, 2006). The soil satisfies the requirement for plasticity index. Linear shrinkage of the soil is 24.22% and has shrinkage limit of 19.06%.

Kayadelen (2008) mentioned that soils that classify as inorganic clay of low plasticity (CL) and inorganic clay of high plasticity (CH) on the Unified Soil Classification System are most commonly used for the construction of compacted clay liners. The black cotton soil studied classified as inorganic clay of high plasticity (CH) and hence could be used as clay liner.

Compaction characteristics

The compaction characteristic of the soil is shown in Fig. 2. It is noted that the Maximum Dry Density (MDD) of the black cotton soil is 1.61Mg/m^3 and the corresponding Optimum Moisture Content (OMC) of 23.98% was obtained.

Permeability

The coefficient of permeability of the soil estimated from consolidation characteristics on samples compacted at OMC using the proctor standard was of the order of x10^{-10} m/sec (x10^{-9} cm/sec). The permeability passes the requirement of a minimum x10^{-9} m/sec (Marcos and Pejon, 2006; Rowe *et al.*, 1995) and 5 x 10^{-10} m/sec (U. K. Environmental Agency, 2009). Typical variation of coefficient of permeability with increasing load pressure is presented in Figure 3. It is noted that the permeability (k) reduces exponentially with load pressure (x) by the relation k=1.88+27.63exp(-x/82.76) with R^2=0.96. From the graph the minimum load pressure required to reduce the permeability of the compacted black cotton soil to its minimum (approximately 3 x 10^{-10} m/s) is about 143 kPa.

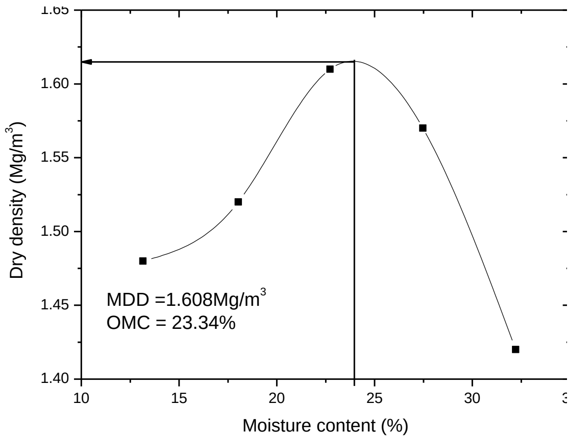

Fig. 2 The Compaction Characteristics of the Soil

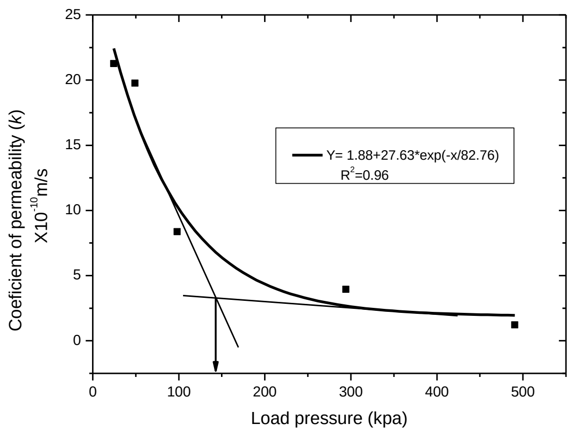

Fig. 3 Variation of Coefficient of Permeability with Loading Pressure

4 Conclusions

The study evaluated the suitability of black cotton soils from Tsopoli in the Accra plains of Ghana for use as clay liners in tailings dam construction. From laboratory studies the black cotton soil passed the requirement of a typical clay liner. Some of the requirements that were met include: the hydraulic conductivity or permeability, plasticity index, liquid limit, percentage fine content and cation exchange capacity. The authors are of the view that the high value of the liquid limit obtained as compared with U.K. Environmental Agency (2009) standard should not be used as a basis to reject the material for use as clay liner since the difference is insignificant.

Considering the main characteristics of typical clay liner systems, the black cotton soil has a potential for use as natural clay liner. However, the following precautions must be taken during the design and construction using the material. The presence of montmorillonite clay in the soil suggests that it is prone to shrink/swell phenomena with change in moisture regime, which could influence the effectiveness of the clay liner and therefore a blanket of waste rock, sand or gravelly materials (minimum load pressure of 143kPa) could be placed on top of the compacted black cotton liner. But if deposition of tailings would be immediately after construction the self weight of the tailings would counterbalance the effect of swell through consolidation and thereby reducing the permeability to its barest minimum.

The use of this black cotton soil in tailings dam containment would be most beneficial, if the mines are situated within economic haulage distance from the soil deposits. Prior to their being used, cost-benefit analysis should be conducted.

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