SOME BLACK COTTON SOILS OF GHANA; A POTENTIAL FOR USE IN GEOSYNTHETIC CLAY LINERS

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ABSTRACT

Black cotton soils contain the clay mineral montmorillonite which is the property of bentonite that makes it useful in geosynthetic clay liners. These soils occur in large quantities in Ghana. Importation of geosynthetic clay liners which contain bentonite as the major barrier material is expensive and a local alternative will have positive economic repercussions. The hydraulic conductivity of black cotton soils from Dowhenya, Prampram, and Tsopoli all in the Accra plains of Ghana were sandwiched between two geotextiles, tested, and compared to commercial bentonite. The results of the swell index test were 7.0mL/2g, 7.0mL/2g, 5.0mL/2g, and 30mL/2g for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. The water content results obtained were 12.20%, 10.13%, 10.83%, and 17.48% for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. The particle size distribution test results indicated that clay fractions are 83.4%, 71.3%, 72.9%, and 95.0% for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. pH results determined are 7.86, 7.82, 7.90, and 10.24 for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. The permeability of Dowhenya, Prampram, and Tsopoli black cotton soils was determined to be 1.03 X 10^{-9}cm/s, 7.61 X 10^{-9}cm/s, 2.04 X 10^{-9}cm/s and these compare well to the commercial bentonite permeability value of 2.08 X 10^{-9}cm/s tested under the same conditions. Based on the results, black cotton soils from these areas can be used as a potential substitute for commercial bentonite in geosynthetic clay liners.

Keywords: black cotton soil, geosynthetic clay liner, montmorillonite, and permeability.

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1. INTRODUCTION

Geosynthetic Clay Liners (GCLs) are fast becoming a worldwide phenomenon whereby they are preferred over the traditional compacted clay liners for lining containment facilities. This is due to the superior performance of the Geosynthetic clay liners over the compacted clay liners in terms of protecting groundwater and soil against pollution. According to Bouazza *et al.* (2013), the hydraulic performance of GCLs depends in most cases on the hydraulic conductivity of bentonite and the only exceptions are GCLs containing a geomembrane.
Bentonite is any clay, which is composed dominantly of a smectite clay mineral whose physical properties are dictated by this clay mineral. For industrial purposes, two main classes of bentonite exist Sodium and Calcium bentonite. Smectite clay mineral in bentonite is what gives bentonite the unique properties that make it useful in geosynthetic clay liners. This clay mineral is also reported to be the dominant mineral in black cotton soils occurring in Ghana (Gidigasu, 2012).

Black Cotton soils are known to be potentially expansive soils that are black or greyish black or in their eroded phase greyish white in colour, heavy loam or clay (usually 50%), with predominant clay mineral of the smectite group. There are vast deposits of Black Cotton Soils in Ghana; they cover over 168,000 hectares 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 parts of the Volta Region (B.R.R.I, 1985).

The primary functional component of a geosynthetic clay liner is its internal bentonite layer. The properties of bentonite are largely controlled by its mineralogy, and most notably by that of its smectite component. It is essential, therefore, to understand smectite mineralogy, and how this mineralogy influences water sorption, swelling, and corresponding engineering behavior (Bouazza and Bowders, 2010).

The objective of this study is to evaluate the chemical, mineralogical, and engineering properties of black cotton soils from the Accra Plains as a substitute for commercial bentonite in geosynthetic clay liners. Subsequently, prospective clays that qualify as substitutes for commercial bentonite could be identified and recommended. This study may enable the performance of Ghanaian clay to be benchmarked against imported commercial bentonite.

A variety of techniques may be employed for evaluating the composition, properties, and quality of commercial bentonite. Many of these techniques are applicable for evaluating commercial bentonite in general, while others are applicable for more specifically evaluating the quality of commercial bentonite for use in GCL applications (Bouazza and Bowders, 2010). The mineral composition of clayey materials is most commonly determined using X-ray diffraction (XRD) (Bouazza and Bowders, 2010). This was done to determine the main minerals within Ghanaian black cotton

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soils. The cation exchange capacity (CEC) is mostly determined and along with other properties helps to distinguish between sodium and calcium bentonite (Murray, 2007).

High-quality commercial bentonite is comprised of 70% to 90% particles less than 2 µm (clay fraction). The aggregate particle size of a commercial bentonite product may impact its initial hydration. Particle size distribution including the hydrometer test is used to determine the particle size composition of which the clay fraction is of importance (Bouazza and Bowders, 2010).

The water content of GCL bentonite is an important quality control parameter because of its role in governing mass per unit area. Water content is expressed gravimetrically

$$w\% = \frac{m_w}{m_s} \times 100\%, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where *mw =mass of water and ms =mass of soil solids* and may be determined by oven drying to constant mass following ASTM D2216. The water content of GCLs in the "dry" or non-prehydrated state typically ranges from about 10%–18% (Koerner, 1998). This suggests that non-prehydrated GCLs generally fall within the stable one-layer or two-layer hydrate states of the crystalline swelling regime.

The result of a free swell test is an index value (Swell Index) that may be used to assess commercial bentonite swell potential as an indirect measure of its effectiveness as a hydraulic barrier. ASTM Standard D5890 describes procedures for conducting the free swell test for commercial bentonite quality control. Ca^{2+}-bentonites typically exhibit swell indices on the order of 5 to 10 mL/2g. Na^{+}- bentonites may exhibit swell indices of 25–35 mL/2 g. Most GCLs contain commercial bentonite with swell indices of at least 24 mL/2 g (Trauger, 1994). Soil pH plays an important role in ion mobility, precipitation and dissolution phenomena, and oxidation-reduction equilibria. The pH of a Na^{+}- bentonite suspension usually ranges from 8.5 to 10.5, whereas the pH of Ca^{2+}- bentonite will usually be lower than 7.0 to 8.5 (Trauger, 1994).

2. METHODOLOGY

2.1 Soil Sampling

Three sites were selected for preliminary studies and the subsequent detailed investigation. The locations which are Tsopoli, Dowhenya, and Prampram (Figure-1) were explored using test pitting and auguring. These soils are formed over the ancient igneous rocks composed mainly of felsic and mafic Dahomeyan gneisses and schists (Ghana Geological Survey, 2009). Test pits were excavated using a pick axe and shovel down to a depth of 2 meters and then augered using a hand-operated auger to 3 meters. The dimension of the test pit was 1-meter length by 1.5 meter breadth by 3 meters depth. Disturbed samples were taken from within 0.3m-3.0m at all locations, bagged, labelled, and sent to the laboratory for testing. (Umar-Farouk *et al*. 2019)

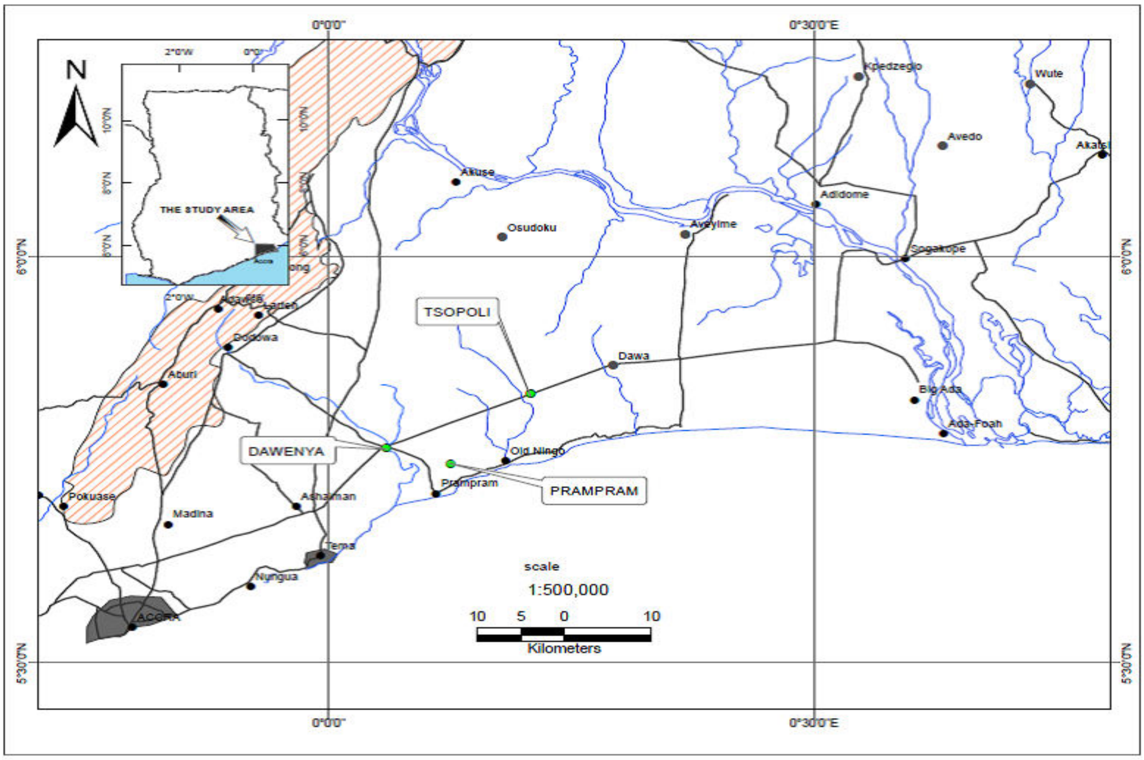

Figure-1. Map of Accra Plains showing sampling locations.

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2.2 Chemical and Mineralogical Analysis

Major oxides and minor elements were analyzed using the X-Ray Fluorescence Spectrometer method. Some samples were also analyzed for their mineralogical composition using the X-Ray diffraction method. The cation exchange capacity (CEC) of clayey soils was determined using the ammonium displacement method (Burrafato and Miano, 1993).

2.3 Particle Size Distribution

Wet sieve analysis and hydrometer test were conducted for the black cotton soils and only hydrometer test was for the commercial bentonite as it was only fined. Sodium Hexametaphosphate was used as the deflocculating agent. The specific gravity was determined using the pycnometer method (BS 1377-1990). (Umar-Farouk *et al.* 2019)

2.4 Swell Characteristics

ASTM Standard D5890 describes procedures for conducting the free swell test for commercial bentonite quality control. The result of a free swell test is an index value (Swell Index) that may be used to assess commercial bentonite swell potential as an indirect measure of its effectiveness as a hydraulic barrier.

2.5 pH

The pH of the black cotton soils was determined at the Laboratory of the Building Materials Development Division of the Building and Road Research Institute, Kumasi using a glass electrode (Thomas, 1996).

2.6 Permeability

Samples were air-dried, crushed, and sieved through the 0.425mm and 0.072mm sieves. The material passing the 0.425mm sieve was collected and tested for the coefficient of permeability within two geotextiles. The same was done for the material passing the 0.075mm sieve to ascertain the effect of particle size on the coefficient of permeability. The soil obtained from the sieving was placed on geotextiles cut into disc shapes with a diameter of 100mm till 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 by the ASTM D5887-99. The permeability was now computed using the relation

$$K = \frac{QL}{Ath} \qquad \text{.......................................} (2)$$

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 the flow rate in cm^3/sec and L is the thickness of the composite in cm.

For each soil represented by the name of the sampling location, three tests were conducted and the average of the permeabilities was computed. Figure-2 shows the composite of geotextiles and black cotton soil.

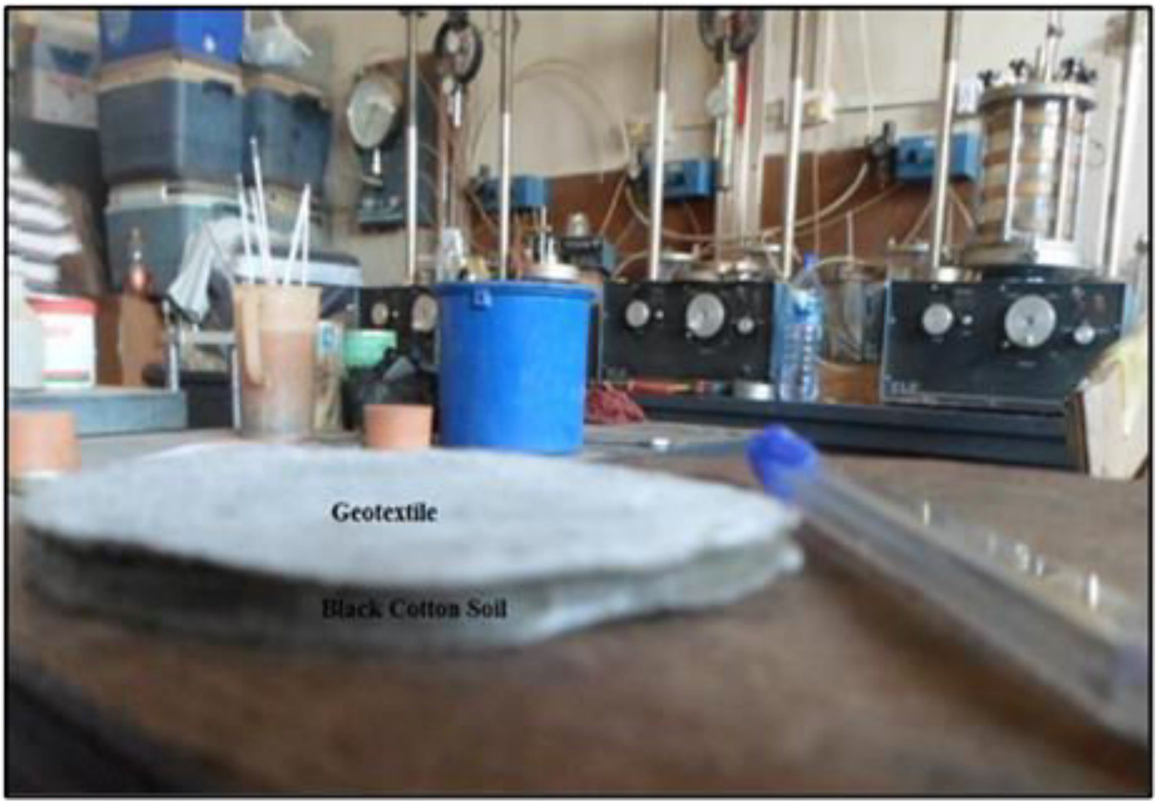

Figure-2. Composite of geotextiles and black cotton soil after the flux test.

3. RESULTS AND DISCUSSIONS

3.1 Chemical and Mineralogical Analysis

3.1.1 Chemistry

Table-1 shows the chemical composition of the black cotton soils and commercial bentonite. It is observed that Al_2O_3, Fe_2O_3, and SiO_2 constitute 81.05%, 87.20%, 88.96%, and 87.07% for commercial bentonite, Dowhenya, Prampram, and Tsopoli respectively.

The ratio of sodium oxide and calcium oxide for commercial bentonite is greater than one while that of black cotton soils is less than one. This is an indication that the sodium content is higher than the calcium content in the commercial bentonite while the opposite is true for the black cotton soils. This suggests that commercial bentonite is sodium bentonite. Among the black cotton soils, sodium oxide is higher in the Dowhenya sample than in Prampram and Tsopoli. This could be the reason why the Dowhenya sample has a higher swell index.

Table-1. Chemical composition of soils (Umar-Farouk et al. 2019).

Oxides	CONCENTRATION (W %)			
	Commercial Bentonite	Dowhenya	Prampram	Tsopoli
SiO_2	55.98	63.89	71.07	63.21
Al_2O_3	18.29	13.97	11.04	14.78
Fe_2O_3	6.78	9.34	6.85	9.08
TiO_2	0.35	1.26	0.87	1.2
CaO	1.88	1.58	1.27	1.18
Na_2O	3.38	0.91	0.87	0.52
K_2O	0.55	0.19	0.22	0.14
MgO	4.28	1.7	1.32	1.52
P_2O_5	0.08	0.06	0.04	0.04
MnO	0.05	0.25	0.14	0.19
SO_3	0.05	0.11	0.11	0.08

3.2 Mineralogy

The diffractograms obtained from the XRD test analysis of all the soils show similar phases. All three soils are also similar to the commercial bentonite indicating that the soils have similar mineralogy. The predominant minerals were quartz and montmorillonite. Figure-3 shows the diffractograms obtained from the XRD tests.

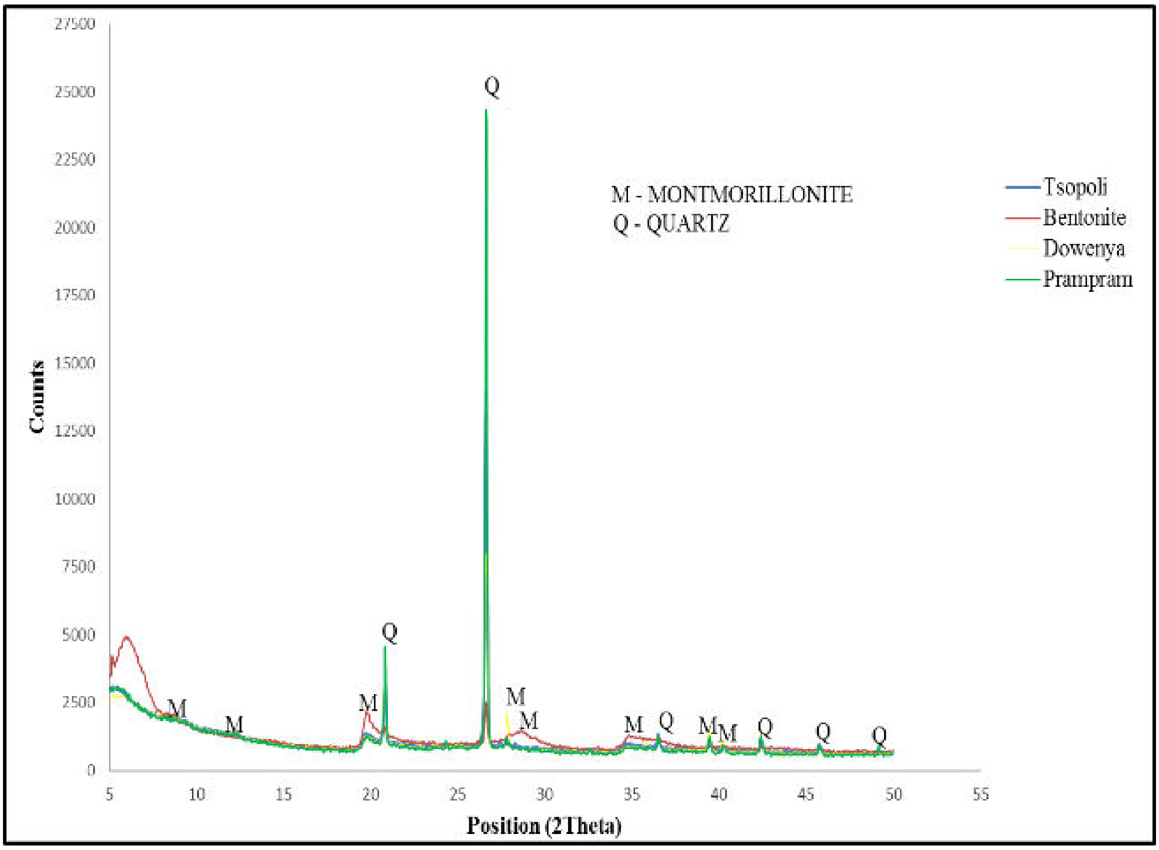

Figure-3. Diffractograms of the three soils and commercial bentonite (Umar-Farouk *et al*. 2019).

3.3 Cation Exchange Capacity

The CEC values of the black cotton soils were found to be 51.02 for Dowhenya soil, 46.99 for Prampram soils, 38.94 for Tsopoli soils, and 80.41 for commercial bentonite. It is noticed that the most abundant cations in the soils are calcium, magnesium, and potassium cations. According to Murray (2007), sodium montmorillonite and hectorite have high Base Exchange capacities, generally ranging between 80 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. From the results of the X-ray diffractometry and the Cation Exchange Capacity (CEC), it can be concluded that the soil from Dowhenya, Prampram, and Tsopoli has calcium montmorillonite as the dominant clay mineral.

3.4 pH

The pH values were determined to be 7.86, 7.82, 7.90, and 10.24 for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. All the soils fall within the 7.0-8.5 indicated by Trauger's (1994) pH range for calcium bentonite.

Table-2 gives a summary of the exchangeable cations, cation exchange capacity, dominant clay mineral, and pH.

Table-2. Summary of exchangeable cations, cation exchange capacity, and dominant clay mineral (Umar-Farouk *et al.* 2019).

ID	Exchangeable cations (meq/100g)					C.E.C (meq/100g)	Dominant clay mineral	pH
	Na	K	Mg	Ca	H+	Calculated		
Dow	0.08	0.16	21.36	29.4	0.05	51.02	Ca-montmorillonite	7.86
Pra	0.08	0.14	19.49	27.2	0.05	46.99	Ca-montmorillonite	7.82
Tso	0.06	0.12	17.62	21.1	0.05	38.94	Ca-montmorillonite	7.90
CB	29.4	0.90	22.01	28.0	0.05	80.41	Na-montmorillonite	10.2

Dow- Dowhenya, Pra- Prampram, Tso- Tsopoli, CB- Commercial Bentonite

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3.4 Particle Size Distribution

The Dowhenya 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 Dowhenya, Prampram, and Tsopoli respectively. The commercial bentonite consisted of 95% clay size and 5% silt size particles and therefore classify as Clay. The clay size fraction in all three soils is within the 70% to 90% indicated by Bouazza and Bowders (2010) as the typical range of clay fraction of bentonite Umar-Farouk *et al*. (2019). Figure 4 gives the grading curves obtained from the particle size distribution test for the three soils.

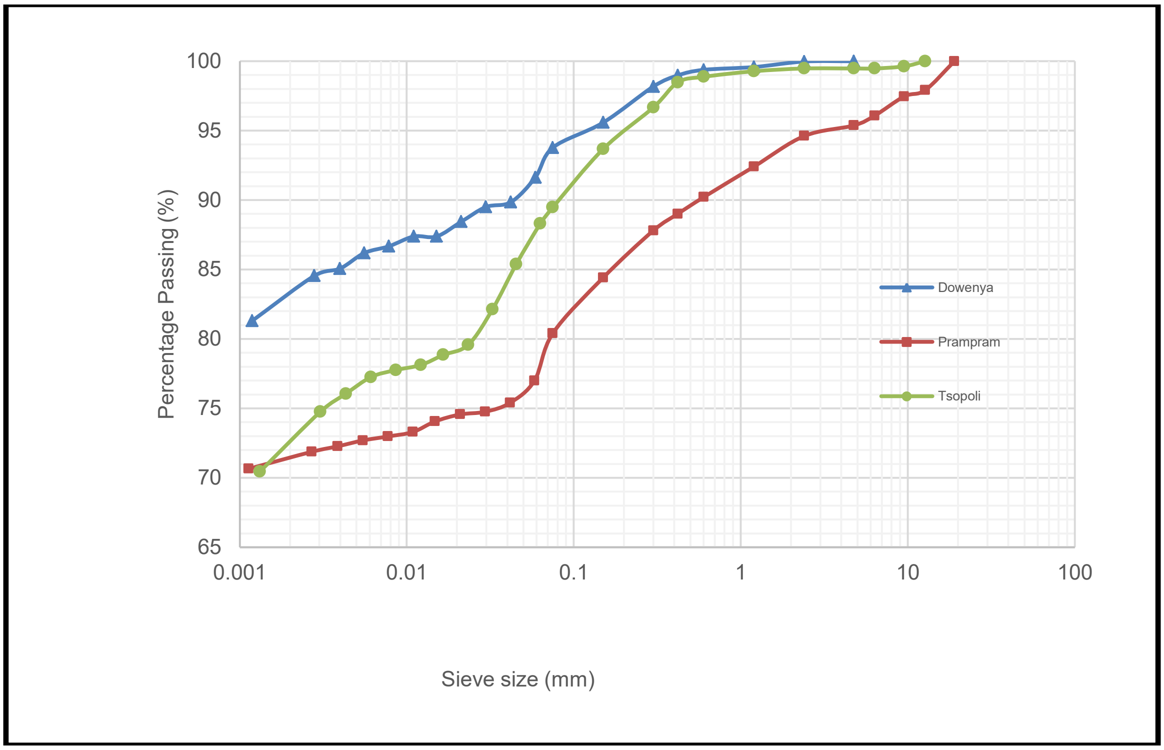

Figure-4. Particle size distribution curves for the three soils.

3.5 Water Content

The water content was determined by ASTM D2216 and was 12.20%, 10.13%, 10.83%, and 17.48% for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. The water contents for the black cotton soils are generally lower than that of commercial bentonite but fall within the range of 10% - 18% indicated by Koerner (1998) as the water content range for calcium bentonite.

3.6 Swell Index

The swell index for the soils was determined using the procedure detailed in ASTM D5890. The commercial bentonite was found to have a higher swell index of 30mL/2g than the black cotton soils which had swell indices of 7.0mL/2g, 7.0mL/2g, and 5.0mL/2g for Dowhenya, Tsopoli, and Prampram respectively all at a temperature of 21^{o}C. The swell indices for the black cotton soils fall within the range of 5 - 10 mL/2g for Ca^{2+}-commercial bentonite given by Trauger (1994).

3.7 Permeability

The results of the permeability for Dowhenya, Prampram, Tsopoli, and commercial bentonite are presented in Table-3. The permeability test results of the black cotton soils were in the order of 10^{-9}cm/s and compares excellently 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 while the United States of America environmental protection agency gave a permeability of the order 10^{-9}cm/s. The permeability of all the black cotton soils falls within the LI 2182 and the USA environmental protection agency standards.

Table-3. Summary of permeability test results for the three soils pass 0.075mm sieve.

ID	THICKNESS (mm)	PERMEABILITY (cm/s)	Min.com. LI 2182 STANDARD	USA EPA
CB	5	2.08 X 10^{-9}	10^{-6}	10^{-9}
DOW	5	1.03 X 10^{-9}		
PRA	5	7.61 X 10^{-9}		
TSO	5	2.04 X 10^{-9}		

4. CONCLUSIONS

The results of the swell index test were 7.0mL/2g, 7.0mL/2g, 5.0mL/2g, and 30.0mL/2g for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. The results of the black cotton soils are within the 5-10mL/2g range indicated to be typical of calcium bentonite.

The water content results obtained were 12.20%, 10.13%, 10.83%, and 17.48% for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively. The particle size distribution test results indicated that the clay fractions are 83.4%, 71.3%, 72.9%, and 95.0% for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively.

pH results determined are 7.86, 7.82, 7.90, and 10.24 for Dowhenya, Prampram, Tsopoli, and commercial bentonite respectively while the results of the cation ion exchange capacity are 51.02meq/100g, 46.99 meq/100g, 38.94 meq/100g and 80.41 meq/100g for Dowhenya, Prampram, Tsopoli and commercial bentonite respectively.

The permeability of Dowhenya, Prampram, and Tsopoli black cotton soils was determined to be 1.03 X 10^{-9}cm/s, 7.61 X 10^{-9}cm/s, 2.04 X 10^{-9}cm/s and these compare well to the commercial bentonite permeability value of 2.08 X 10^{-9}cm/s tested under the same conditions.

Based on the results, black cotton soils from these areas can be used as substitutes for commercial bentonite in geosynthetic clay liners.

SYMBOLS & ABBREVIATIONS

K coefficient of Permeability in cm/sec
h head difference in cm
A area of flow
t the time of flow in seconds
Q flow rate in cm^3/sec and
L thickness of the composite in cm
Dow Dowhenya
Pra Prampram
Tso Tsopoli
Mont Montmorillonite
CB Commercial Bentonite
Ca Calcium
Na Sodium

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