Nigerian Journal of Technology (NIJOTECH)
Vol. 32, No. 1, March, 2013, pp. 93–100.

ISSN 1115-8443

CHARACTERIZATION OF GEOTECHNICAL PROPERTIES OF LATERITIC SOIL-BENTONITE MIXTURES RELEVANT TO THEIR USE AS BARRIER IN ENGINEERED WASTE LANDFILLS

A.A. Amadi[a], **A.O. Eberemu**[b]

[a]Department of Civil Engineering, Federal University of Technology, Minna, Nigeria.
Email: agapitusahamefule4@yahoo.com
[b]Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria. ***Email:*** aeberemu@yahoo.com

Abstract

The purpose of this study was to characterize lateritic soil bentonite mixtures intended for use as low-permeability barrier in municipal waste disposal landfill. Characterization of the soil mixtures included measurement of Atterberg limits, compaction properties, hydraulic conductivity, shear strength, and desiccation shrinkage potential. Accordingly, laboratory tests involving soil mixtures with 0, 2.5, 5, 7.5 and 10% bentonite contents, prepared at varying compaction states (2% dry of optimum, optimum and 2% wet of optimum) and compacted using West African standard (WAS) compactive effort were carried out. Results show that mixtures with bentonite are adjudged to be suitable materials for liners because they met the statutory hydraulic conductivity requirement (i.e., $k \leq 1.0 \times 10^{-9}$ m/s). Acceptable volumetric shrinkage strain of ≤4% (a maximum allowable volumetric shrinkage found in literature and adopted by most regulatory agencies for barrier material) was maintained by most soil mixtures. Although, slight reduction in shear strength was established, unconfined compressive strength (UCS) values for all soil mixtures met or exceeded the general specification i.e., UCS $\geq$ 200 kN/m^2 required for performance in waste repositories.

Keywords: barrier, bentonite, hydraulic structures, lateritic soil, waste landfill

1. Introduction

To provide long term containment and isolation of wastes from the environment required in engineered landfills, the design of waste cells in waste disposal facilities should ensure minimum fluid flow through or into the repository systems over the designed lifetime and prevent leachate migration out of the repository. Such designs typically consist of a compacted clay layer, geomembrane, geosynthetic clay layer, and/or a combination of these in a multi barrier system [1, 2].

Unlike in most earthworks where the strength and degree of compaction are the controlling factors in the suitability assessment, low permeability and desiccation shrinkage requirement along with their capacities of attenuation of contaminants presents additional criteria in the selection and emplacement of materials in the construction of clay liners for landfill projects. Specifically, low permeability (k) is considered the key parameter for evaluating the suitability of construction materials in the aforementioned structures [3, 4, 5, 6].

When compared with active clay soils, lateritic soils presents attractive option because of its greater shear strength properties, chemical resistance, better workability and availability within economic haul distance in tropical latitudes where they occur in abundance [7, 8, 9, 10, 11]. In addition, positive and extensive experience of using lateritic soil in several geotechnical structures such as highway embankments, road bases, airport runways, earth dams etc for several decades has encouraged research in the use of the soil as material for soil liners. However, the soil has high hydraulic conductivity apparently due to the predominance of inactive and non expanding 1:1 kaolinite clay mineral in the soil [12, 13].

In the laterization processes, sesquioxides of iron and aluminum are absorbed onto the surfaces of the

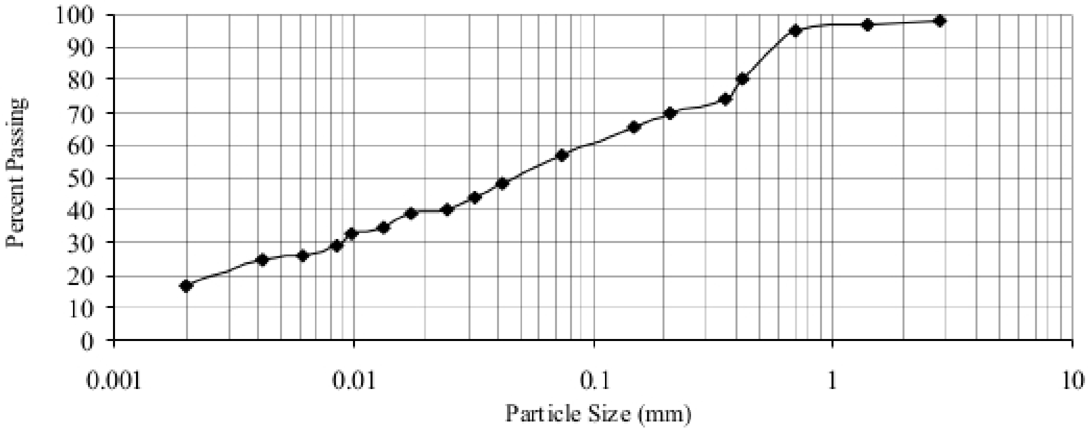

Figure 1: Particle Size Distribution Curve of Lateritic Soil.

clayey constituents through the interaction of the positively charged sesquioxides and the negatively charged clay particles. The sesquioxides cause a physical cementation of fine particles into coarser aggregations resulting in a granular structure [14]. The consequences of these processes on the engineering characteristics of lateritic soils include low plasticity, high permeability, low swelling potential etc. Therefore, for lateritic soil to satisfy the hydraulic requirements and self sealing function, an enhancement scheme with bentonite is necessary.

Bentonite is a highly plastic and swelling clay containing small quantities of inert mineral grains with relatively high specific surface (i.e., 100–800 m^2/g) and high net negative charge as reflected by cation exchange capacities that range from 80 meq/100 g to 150 meq/100 g [15, 16, 17]. In the resulting mixture, bentonite controls the hydraulic conductivity, swelling and physico-chemical functions, lateritic soils on the other hand provides greater chemical and desiccation shrinkage resistance as well as better workability [5, 6, 18, 19, 20, 21].

The objective of this study therefore was to characterize some important geotechnical properties of the resulting lateritic soil-bentonite mixtures with special reference to their use as barrier in engineered waste landfills.

2. Materials and Testing Procedures

Soil: The soil used in this study is a natural reddish brown lateritic soil collected from a lateritic soil formation in Shika, Zaria, Nigeria (Latitude 11°15 N and Longitude 7°45 E) at depths of between 1.5m to 2.0m.

Bentonite: The bentonite used in this study is processed in powdered form and was obtained from a major supplier in Lagos, Nigeria. It is a representative of typical bentonite available for construction purposes.

2.1. Index properties and compaction tests

The index properties and compaction tests were conducted in accordance with BS 1377 [22] on soil mixtures with the relevant quantities of bentonite.

2.1.1. Preparation of specimens

The soil was air dried and pulverized sufficiently to run through the BS No. 4 (4.76 mm aperture) sieve. For samples containing bentonite, the relevant quantities of dry soil and bentonite (0, 2.5, 5, 7.5, and 10%) were mixed. The required percentage of tap water based on dry weight (2% dry of optimum, optimum and 2% wet of optimum) was added to obtain the desired water content and thoroughly mixed until a uniform consistency was achieved. Specimens were compacted with West African Standard (WAS) compactive efforts, an intermediate effort derived from 4.5 kg rammer falling through 450 mm onto five layers in a British Standard mould, each receiving ten (10) blows [23, 24].

2.2. Hydraulic conductivity test

The hydraulic conductivity of compacted mixtures were evaluated using the rigid wall permeameter under falling head condition after soaking for 24 hours in accordance with procedures outlined in BS 1377 [22]. Processed soils were compacted and soaked for at least 24 hours in de-aired tap water before the commencement of permeation. The permeant liquid was tap water and permeation was terminated after a steady flow was established (i.e., when there was no statistically significant trend in hydraulic conductivity over time in agreement with [25, 26].

2.3. Volumetric shrinkage test

Specimens were prepared by compacting processed soils as in above. The volumetric shrinkage upon desiccation was measured by extruding compacted cylin-

Table 1: Summary of index properties of soil.

Property	Quantity
Natural moisture content (%)	19.60
Liquid Limit (%)	42.20
Plasticity Index (%)	22.22
Linear shrinkage (%)	5.56
USCS Classification	CL
Specific gravity	2.60
pH	6.67
Activity	0.92
Color	Reddish- brown
Dominant Clay Mineral	Kaolinite

Table 2: Properties of bentonite used in the study.

Property	Quantity
Liquid Limit (%)	250
Plasticity Index (%)	205
Percent Passing # 200 Sieve	92
Specific Gravity	2.38
Swelling Potential	High

drical specimens from the compaction moulds and allowing the specimens to dry on a laboratory table [27]. Shrinkage was monitored for 28 days by taking the circumferential diameter and height to compute volume, hence the volumetric shrinkage strains.

2.4. Strength test

The test was conducted on specimens prepared as in above. Testing was performed on cylindrical specimens having a diameter and length of 38mm and 76mm respectively, which were trimmed from the larger compacted cylinders. The samples were tested in triaxial compression test machine without applying cell pressure [22].

3. Results and Discussion

3.1. Characterization of study soil and bentonite

Particle size distribution of the study soil (Fig. 1) showed that it comprised of about 12% sand content (0.063–2mm), 57% fines content (percentage passing no. 200 sieve) and 17% clay sized particles (percentage smaller than 2m). The oxide composition presented in Table 3 indicate that silica and sesquioxide of iron and aluminum constitute about 87% of the oxides present while mineralogical composition determined by X-ray diffraction (XRD) showed that kaolinite constitute the dominant clay fraction (Table 1).

Similarly, sieve analysis of the air dry bentonite showed that the percentage passing No. 200 sieve is

Table 3: Oxide composition of lateritic soil and bentonite oxide.

	Concentration (%)	
	Lateritic soil	Bentonite
CaO	0.28	0.86
SiO2	35.60	58.14
Al2O3	27.40	21.73
Fe2O3	2.40	2.46
MgO	0.22	2.42
SO3	0.85	-
Mn2O3	2.00	-
K2O	ND	0.52
TiO2	-	1.86
Na2O	-	2.08
Loss on ignition	14.60	13.28

92%. Some properties of the bentonite are shown in Table 2 while the oxide composition is reported in Table 3. The plasticity Index (PI) of the bentonite indicates that it is a highly plastic material and has a high swelling potential.

The soil-bentonite mixtures demonstrated substantial increases in liquid limit (LL), plasticity index (PI) and only a slight increase in linear shrinkage with the stepped introduction of bentonite into the natural soil (see Fig. 2). Higher liquid limit and plasticity index are associated with soils having a greater quantity of clay particles [16] which in turn manipulates the hydraulic conductivity.

On the basis of data developed from Atterberg limit tests and particle size distribution parameters, mixtures containing 0-5% bentonite were classified as inorganic clay of low plasticity (CL), while mixtures with 7.5-10% bentonite are classified as clay soils of high plasticity (CH) under the Unified Soil Classification System (USCS). From the requirements for liner materials, i.e., liquid limit > 20 and plasticity index > 7 [28, 29], the soil mixtures are found to be suitable as liner material.

3.2. Compaction characteristics

The traditional compaction curves of dry unit weight versus moisture content corresponding to WAS compactive effort for the various soil mixtures (0, 2.5, 5, 7.5 and 10% bentonite content) are reported in Fig. 3. The curves for the treated specimens are similar to the curve for untreated specimen. The addition of bentonite resulted in decreased maximum dry unit weight but the optimum water content increased slightly with higher bentonite content.

The maximum dry unit weight decreased from 18.91 for the natural soil to 17.98 kN/m^3 for mixtures with

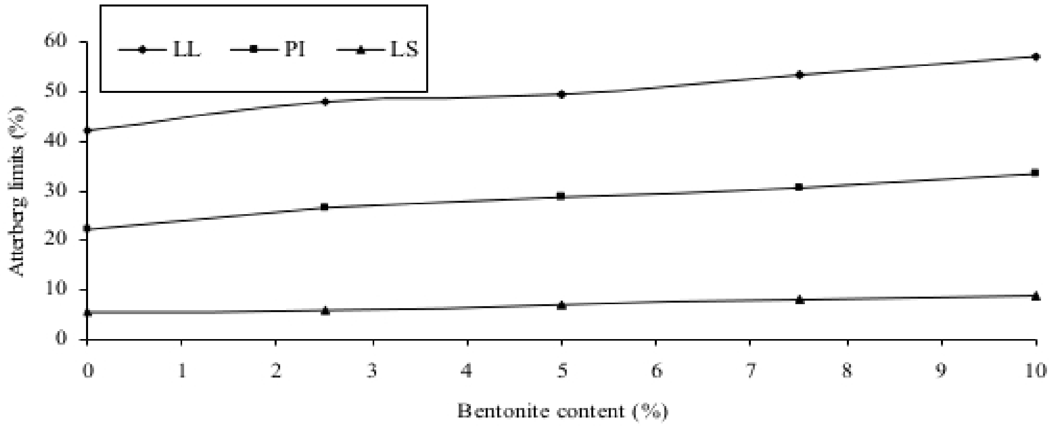

Figure 2: Variation of Atterberg limits with bentonite content.

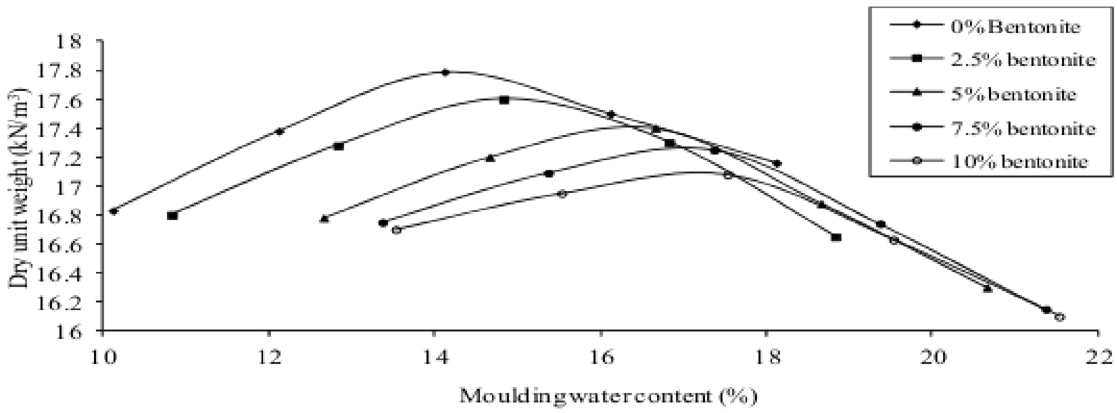

Figure 3: Compaction curves for soil mixtures containing 0, 2.5, 5, 7.5 and 10% bentonite.

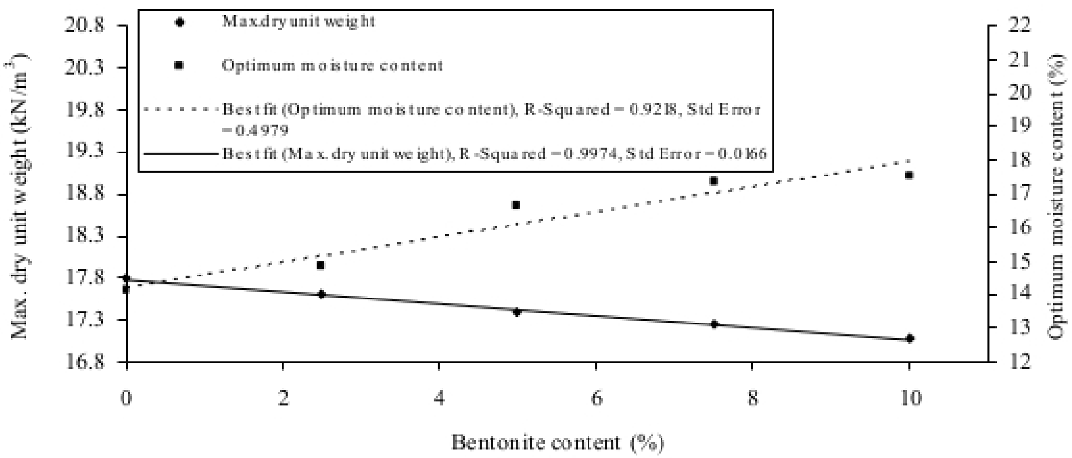

Figure 4: Variation of maximum dry unit weight and optimum moisture content with bentonite content.

10% bentonite content while the optimum water content were 11.65 for 0% bentonite and 13.88% for 10% bentonite content. The variation of maximum dry unit weight and optimum water content with bentonite content is illustrated in Fig. 4.

The decrease in maximum dry unit weight with increase in bentonite content may be as a result of high swelling characteristics of bentonite that could form a gel around the soil particles. When gel forms around the soil particles, their effective size increases, which causes increase in void volume, and thus decreased dry unit weight. The increase in optimum moisture content with higher bentonite content is connected with the increasing demand for more moisture for hydration reaction arising from the increased fines content with larger surface area.

3.3. Variation of hydraulic conductivity with bentonite content

Variation of logarithm of hydraulic conductivity with bentonite content for the various compaction states is illustrated by data in Fig. 5. The figure indicates that hydraulic conductivity decreased exponentially with increase in bentonite content. Soil mixture with the highest bentonite content of 10% recorded an average hydraulic conductivity of 1.49 $\times 10^{-11}$ m/s compared to 7.91 $\times 10^{-9}$ m/s for natural soil (i.e., 0% bentonite content). This shows that addition of 10% bentonite reduced the hydraulic conductivity by up to two orders of magnitude. Although the general requirement for an isolation material such as compacted clay liner is that the hydraulic conductivity should not exceed 1 $\times 10^{-9}$ m/s, soil mixtures at the different compaction states achieved much lower hydraulic conductivities.

The decrease in hydraulic conductivity with increase in the amount of bentonite may be explained by the very high specific surface of bentonite particles. The high specific surface of bentonite particles allow them to retain a portion of water (double layer water) that may not be able to flow as freely as the remaining water in the pore space. In addition, saturated bentonite can absorb water up to 5 times its own mass to form a gel up to 15 times its own dry volume [30]. Therefore, the decrease in hydraulic conductivity due to the addition of bentonite is probably because bentonite forms a gel or paste that fills most of the voids [16, 17, 31]. Similar results have been reported by a number of researchers [4, 32] for sand and other soil bentonite mixtures.

3.4. Variation of volumetric shrinkage with bentonite content

The effect of bentonite content on volumetric shrinkage is reported in Fig. 6. An increasing trend in shrinkage strain with higher bentonite content was observed for specimens prepared at the various compaction states. Notably, specimens compacted wet of optimum moisture content yielded higher shrinkage values. The highest strain value of 4.34% was observed in specimen containing 10% bentonite. The increase in volumetric shrinkage resulting from higher bentonite content was due to increase in plasticity index, hence a greater affinity for water. Thus, specimens with higher bentonite content or plasticity index had greater quantity of water to be removed during drying [27, 33, 34, 35]. Soils with higher clay content and higher plasticity index retain a greater volume of water and thus are more prone to large volumetric shrinkage strains during drying. Generally, most specimens met threshold requirement for performance namely $V_{sh} \leq 4\%$ found in literature and adopted by most regulatory agencies. Compacted samples for all levels of bentonite content exhibited no visible desiccation cracking.

3.5. Variation of unconfined compression strength with bentonite content

The variation of unconfined compressive strength (UCS) with bentonite content at various compaction water contents is shown in Fig. 7. UCS of compacted samples generally decreased with higher bentonite contents. The reduction in shear strength is partly attributed to the increase in clay size particles (bentonite) that filled voids between soil particles, which lowered the frictional resistance between the soil particles at their contact points. However, the recorded values of the various soil mixtures met or exceeded the general specification i.e., UCS $\geq$ 200 kN/m^2 required for performance in waste repositories [36, 37]. The stated minimum UCS value is required to maintain the integrity of the liner against the overburden stress imposed by the waste material above it and to make the liner stable when employed on slopes as well as to maintain the trafficability of construction equipment during the construction phase [37].

4. Conclusions

In this study, preliminary evaluation of index and geotechnical properties of lateritic soil-bentonite mixtures for their suitability as barrier material in waste repositories was carried out. Analysis of data obtained from the study indicate that the geotechnical properties investigated namely: the Atterberg limits (liquid limit, plastic limit and plasticity index), hydraulic conductivity, volumetric shrinkage potential and strength of the natural soil were substantially influenced by the introduction of bentonite. Expectedly, soil mixtures developed higher Atterberg limits as well as shrinkage potential but exhibited lower hydraulic conductivities and reduced strength with higher bentonite contents.

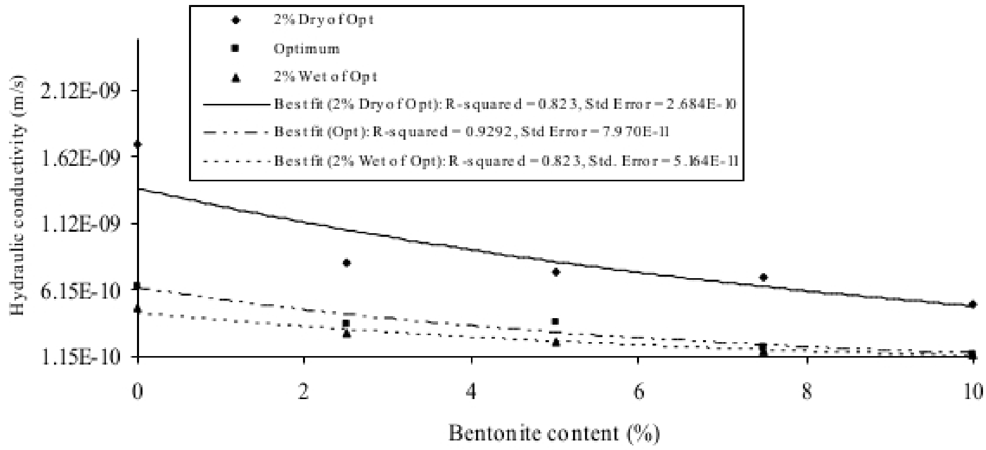

Figure 5: Variation of hydraulic conductivity with bentonite content.

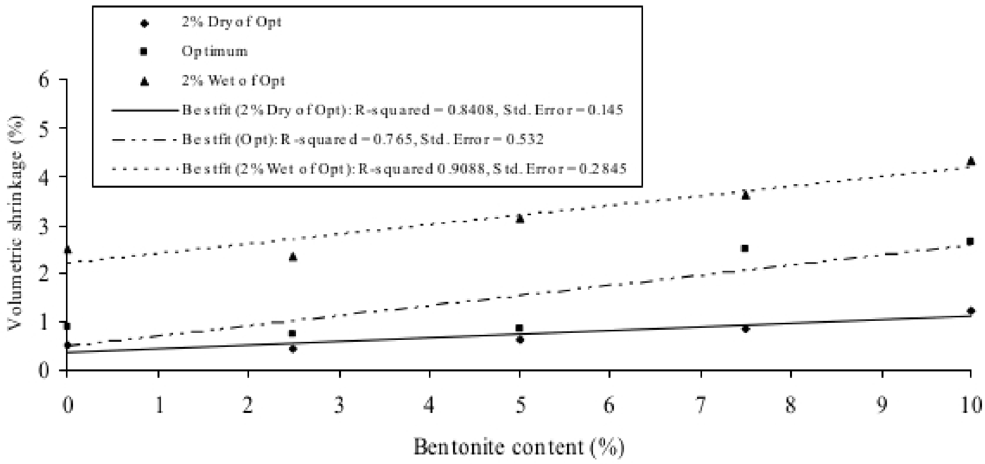

Figure 6: Variation of volumetric shrinkage strain with bentonite content.

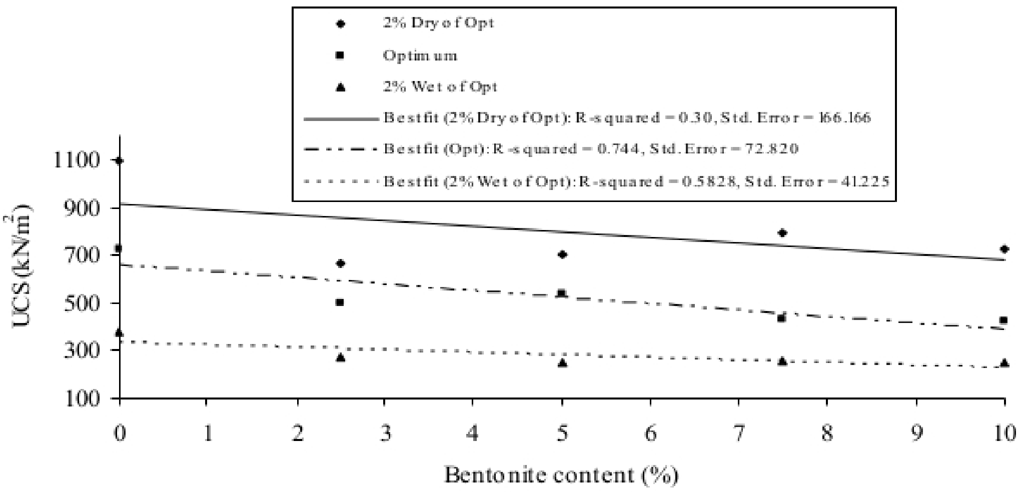

Figure 7: Variation of unconfined compressive strength with bentonite content.

Overall, bentonite treatment of the study soil resulted in favourable and superior geotechnical properties relevant to its application as barrier in hydraulic structures. In view of the preliminary nature of this study, more work is therefore required especially on their capabilities for attenuation and retention of contaminants.

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