Volume Change and Hydraulic Conductivity of Soil-Bentonite Mixture

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ABSTRACT

The aim of this study was to estimate volume change and hydraulic conductivity and to collect suction data for UKM (University Kebangsaan Malaysia) soil - bentonite mixture. This mixture is proposed as a barrier material in waste containment systems. Tests were performed on UKM soil mixed with different bentonite contents (0%, 5%, 10% and 20%). It was found that with the addition of bentonite, both shrinkage and swelling strains increased. Insignificant cracks appeared at 0% and 5% bentonite content. However, significant cracks appeared in UKM soil after mixing with 10% and 20% bentonite contents. The results also showed that bentonite decreases the hydraulic conductivity of UKM soil significantly. The results from tested samples after 1 to 4 drying cycles showed that the largest rise in soil hydraulic conductivity occurred at first or second drying. Soil water characteristic curves (SWCC) were developed for compacted soil samples (with and without bentonite) using pressure membrane apparatus. The relative locations of SWCC plots were higher for the soil samples mixed with bentonite.

KEYWORDS: Volume change, Bentonite, UKM soil, Soil suction, Hydraulic conductivity, Cyclic hydraulic conductivity.

INTRODUCTION

At a landfill, the garbage is compacted and covered at the end of every day with several inches of soil to reduce odor and litter as well as control rodents and pests. The landfill plays a vital role in the whole waste treatment/disposal process. The most suited soil type for landfilling to satisfy the Environmental Protection Agency (EPA) standards is fine grained soil with high clay content which has low permeability (Bagchi, 2004; Datta, 2012; Gray, 1989; McBean et al., 1995). Clayey soils pose many problems to geotechnical engineering structures due to their large-scale volume changes and poor shear strength. Moreover, clayey soils have more ability to swell than other soils (Kalkan and Yarbasi, 2013). Soils with high swell potential are called ‘expansive soils’. The expansive soil is a soil that changes in size as a result of a change in water content. Normally, expansive soils grow in size and swell when they absorb water and reduce in size and shrink when they become dry. Volume change in soil leads to distortions in the form of settlement due to contraction as a result of dryness or in the form of expansion due to swelling as a result of the absorption of water and increased humidity. Swelling of the soil leads to cracks and structural collapses which include swelling in the sidewalks, cracks in the walls and floor and distortions in the door frames. These distortions may be mild, medium or large depending on the amount of swelling. Swelling soils are distributed in

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many parts of the world like Saudi Arabia, Jordan, Egypt, Sudan, Africa, Ghana, Australia, China, Canada and the United States (Dhowian et al., 1990). Moreover, cracks allow contamination to pass through the soil and can affect the geotechnical properties of the soil. The presence of soil contaminants has different effects on the physical, chemical and mechanical properties of the soil. Furthermore, soils tend to shrink when they lose moisture. In particular, fine-grained soils are susceptible to shrinkage and its resulting volume change. Shrinkage can cause cracking in soils, and this may have an adverse impact on the engineering properties and behavior of the soils. These adverse effects include decreased strength of the cracked soils and increased flow through the soils (Li and Zhang, 2011). Cracks create paths for the transfer of fluids. Broken soils can increase by the infiltration of surface water in the containment system or leakage of fluids into the surrounding soil and groundwater. Soils may suffer volume changes due to changes in their water content rather than external loads. All soils will undergo a reduction in total volume when exposed to drying condition (Jong and Warkentin, 1965). On the other hand, clayey soils may suffer swell by increasing their water content. Expansive soils swell and shrink regularly when subjected to moisture changes. The term expansive soils does not only mean the ability to increase in volume (swell) when water is allowed to access freely, but also to decrease in volume or shrink after water is withdrawn. Clayey soils are widespread worldwide. The damage caused by expansive soils is very significant because of their high volume change which comes from swell-shrink behavior, especially in the regions of the world where there is a large seasonal variation in moisture and rainfall, exposing the structures to periodic swelling and shrinkage cycles (Basma et al., 1996). Formation of cracks is enhanced by the availability of clay (Holtz and Kovacs, 1981). At high plasticity index, the probability of shrinkage and swelling increases, while the extent of reduction in size drops to a minimum. However, shrinkage and cracking can be brought to the minimal level by fortifying clay soil with coarse-grained materials (Kleppe and Olson, 1985), while for the construction of a liner in arid sites, Daniel and Wu (1993) suggested the use of clayey sand with low hydraulic conductivity and low shrinkage values. Hydraulic conductivity is a widely used criterion in testing of soil liner materials for facility design and construction quality assurance. Hydraulic conductivity is an expression of the rate at which a liquid passes through the porous matrix (Fetter, 2001). One of the most important factors that increase hydraulic conductivity is the cracks in soil. The cracks in clayey soils, as previously mentioned, come from volume changes which occur during desiccation and lead to an increase of water flow (Daniel and Wu, 1993). However, hydraulic conductivity can be enhanced by mixing with a higher content of bentonite powder (Pal and Ghosh, 2013; Takai et al., 2013). But soils with higher bentonite content exhibited higher crack porosities regardless of other parameters (Gebrenegus et al., 2011). In addition, water molecules hold more tightly to the fine particles of a clayey soil than to coarser particles of a sandy soil, so clays generally retain more water (Leeper and Uren, 1993). Conversely, sands provide easier passage or transmission of water through the profile (Singh and Sharma, 2014). Clay type, organic content and soil structure also influence soil water retention (Charman and Murphy, 2007). Fredlund and Xing (1994) described the suction in soil by plotting soil water characteristic curve (SWCC). The soil water characteristic curve (SWCC) is a graphical representation of the mathematical relationship between the matric suction of a soil (defined as the difference between the pore air pressure and the pore water pressure) and either its water content (gravimetric or volumetric) or degree of saturation. Matric suction may be considered as an important variable in defining the state of stress in an unsaturated soil. Therefore, it is necessary to control or measure matric suction in laboratory studies. The most common method to measure the SWCC of a soil is by a pressure plate extractor in which no external stress is applied, and volume change of the soil specimen is assumed to be zero (Ng and Menzies, 2007). SWCC is also used to predict the soil water storage. The soil with high water storage has high volume change. The lower SWCC means lower water storage, thus lower volume change (Amarasinghe and Anandarajah, 2011; Lu and Likos, 2006; Oh et al., 2012; Stoltz et al., 2012; Walsh et al., 2000). However, some soils show that the water holding capacity increases with the addition of lime, especially when increasing the curing time up to 150 days (Al-Taie and Khattab, 2006). For dredged soils, cement-based solidification/stabilization can be used. Air-entry value of water retention curve increases and the amount of the shrinkage decreases with increasing cement content, but with increasing the initial water content, a weak bond occurs leading to decrease the air-entry value and increase the amount of shrinkage (Chiu et al., 2013).

The aim of this study was to evaluate the influence of various bentonite contents on the volume change, hydraulic conductivity and suction of UKM soil.

MATERIALS AND METHODS

Materials

Bentonite

Bentonite used in the present investigation is a high-swell sodium bentonite containing sodium montmorillonite. Its properties are listed in Table 1. In general, it has a specific gravity of 2.66, a plasticity index of 394.6 and a cation exchange capacity of 90 meq/100g.

Table 1. Properties of bentonite

Property	Value
Specific gravity	2.66
Liquid limit	464.6
Plastic limit	70.0
Plasticity index	394.6
Cation exchange capacity	90.0 meq/100 g of dry soil
Chemical composition	
Formula	Concentration (%)
SiO_2	60.85
Al_2O_3	14.82
Fe_2O_3	4.38
CaO	3.67
Na_2O	3.13
MgO	3.09
K_2O	0.79
TiO_2	0.61
Other	0.44
Heat loss	8.22

UKM soil

Initially, the natural soil is a residual soil taken from the University Kebangsaan Malaysia (UKM) campus in Bangi, Selangor, Malaysia. This soil is termed as UKM soil. The soil was sampled from 0.5 to 1 m below the ground surface. The UKM soil samples were mixed after sampling all the qantity in order to get a homogeneous soil. Then, the UKM soil was mixed with different ratios of bentonite (0% bentonite, 5% bentonite, 10% bentonite and 20% bentonite) to produce four types of soil samples with different plasticity index and different clay content.

According to the unified classification system, the UKM soil is sandy with low plasticity index clay (CL).

After adding 5% bentonite, the classification remains the same (CL). However, when bentonite was increased to 10% and 20%, respectively, the soil changed to high plasticity index clay (CH). Sieve analyses for all types of soils are shown in Fig. 1. The physical and chemical properties of UKM soil and other types of mixed soil samples are listed in Table 2.

Table 2. Physical and chemical characteristics of UKM soil with different bentonite contents

Characteristics	Bentonite content			
	0%	**5%**	**10%**	**20%**
Specific gravity	2.607	2.609	2.612	2.617
Liquid limit (%)	36.16	47.31	53.88	87.21
Plasticity index (%)	16.96	28.25	36.18	69.01
Linear shrinkage (%)	8.2	12.86	15.9	23.57
Passing no. 200 sieve (%)	47.16	49.80	52.44	57.73
Clay content (< 2 µm) (%)	18	22.9	28.5	38.5
Unified Soil Classification System (USCS)	CL	CL	CH	CH
pH	4.0	6.81	9.05	9.83
Compaction properties				
Optimum water content (%)	14.29	16.01	18.63	20.3
Maximum dry unit weight (kN/m^3)	18.05	17.69	16.93	16.12
Chemical composition				
SiO_2 (%)	62.07	62.86	55.96	54.62
Al_2O_3 (%)	29.46	25.81	21.46	23.06
Fe_2O_3 (%)	5.70	5.48	5.21	5.18
MgO (%)	0.58	1.45	1.51	1.11
CaO (%)	0.03	1.23	1.54	1.00
TiO_2 (%)	1.17	1.04	0.96	0.94
Na_2O (%)	-	1.01	1.17	0.77
K_2O (%)	0.76	0.78	0.74	0.67
Other	0.05	0.14	0.37	0.30
Heat loss	0.18	0.2	11.08	12.35

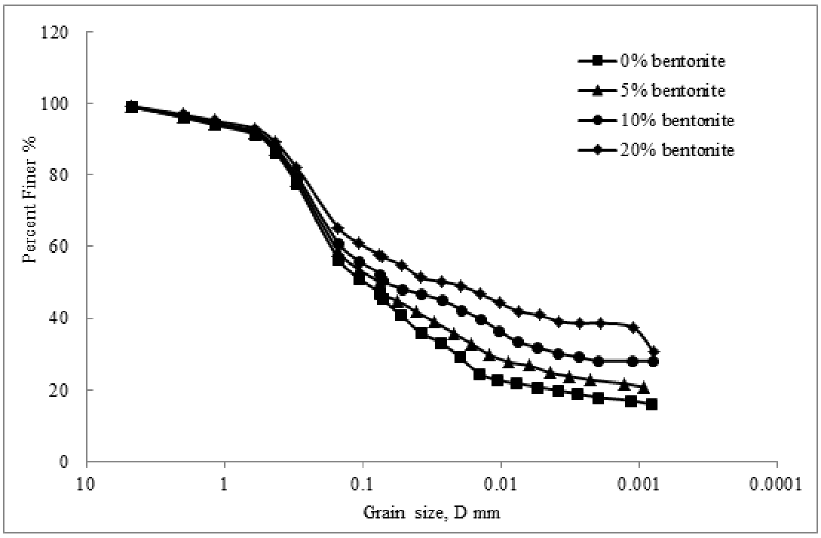

Figure (1): Grain size distribution

Figure (2): Sample preparation procedure for hydraulic conductivity test

Testing Procedure

The experimental procedure involved determining compaction behavior of UKM soil mixed with 0%, 5%, 10% and 20% bentonite contents. The compaction behavior curves were determined according to the standard test method (ASTM D698). The soil used for compaction was dried in an oven and crushed with a rubber hammer until it passed the U.S. No. 4 sieve. The soils were moistened with tap water using a spray bottle, and stirred with a trowel during mixing to ensure an even distribution of water. Then, the soils were sealed in plastic bags and allowed to hydrate for at least 24 h prior to compaction. Standard compaction mould was used with 102 mm diameter and 116 mm height which holds 943 cubic centimetres of soil. Compaction of three separate lifts of soil using 25 blows by a 2.49 kg hammer falling from 304.8 mm was used in compaction tests. Compacted samples were used for shrinkage strain, expansive strain, soil suction and hydraulic conductivity tests. Volume change measurements were made to evaluate shrinkage and expansive behavior. For hydraulic conductivity tests, the specimens were either immediately placed in permeameters for saturation or wrapped in plastic to prevent drying until they could be saturated. After compaction, the soil samples were divided into two groups. The first group was saturated with water to measure expansive strain and the second group was left to dry to measure shrinkage strain. Standard compaction mould (102 mm in diameter and 116 mm in height) was used to prepare samples at maximum dry density and optimum water content following the standard test method (ASTM D698) for expansive strain test. Initially, saturation was conducted by soaking the specimens in flexible-wall permeameter using a hydraulic gradient of 10 and an average effective stress of 10.5 kPa following ASTM D 5084. The specimens were permeated with tap water until the ratio of inflow to outflow was about 1, and the hydraulic conductivity was steady. This procedure resulted in specimens saturated close to field condition. When the specimen was removed from the permeameter, measurements were made of its height, diameter and weight. The volumetric expansive strain is defined as the increase in volume (ΔV_e) to the original volume of the soil specimens before saturation (which is normally equal to the volume of standard mould, V), expressed by (Albrecht and Benson, 2001; Puljan, 2010):

$$Expansive\ strain\ = \frac{\Delta V_e}{V} \times 100\%.$$

Similar to expansive strain test, soil specimens were prepared at maximum dry density and optimum water content following the standard test method (ASTM D698) for the volumetric shrinkage strain test. After compaction, the drying process was conducted using an oven at a temperature of approximately 34 ± 2^o C for a period of more than 10 days depending on the sample type. The weight, height and diameter of each specimen were then measured. The volume change was used to determine the volumetric shrinkage strain of the soil specimens. The volumetric shrinkage strain is defined as the reduction in volume (ΔV_s) to the original volume of the soil specimens (V) (%), expressed by (Albrecht and Benson, 2001):

$$Volumetric\ shrinkage\ strain\ = \frac{\Delta V_s}{V} \times 100\%.$$

For the desiccation crack test, soil specimens were prepared at maximum dry density and optimum water content using a 6 inch (152.4 mm) cylindrical mould 116.43 mm in height compacted in three layers with 56 blows for each layer following the standard test method (ASTM D698). The drying process was conducted for a period of more than 10 days depending on the sample type using an oven at a temperature of approximately 34 ± 2^o C. The surficial dimensions of cracks were measured by gauge wires in order to find the crack intensity factor (CIF) to evaluate the magnitude of desiccation cracks developed in the soils, expressed by (Harianto et al., 2008; Kleppe and Olson, 1985; Peng et al., 2006):

$$CIF = \frac{A_c}{A_t};$$

where A_c is the desiccation crack area and A_t is the total surface area of the soil sample. For hydraulic conductivity test, the soil was compacted according to the standard test method (ASTM D698). After compaction, cylindrical specimens with a diameter of 70 mm and a height of 35 mm were prepared from the mixtures compacted by standard compaction energy at optimum water content. Then, hydraulic conductivity was determined following ASTM D5084; i.e., using flexible membrane apparatus as shown in Figure 2. Porous stones and filter paper were placed against the ends of the samples to distribute the permeate de-aired water across the entire end area of the sample. Once the sample has been prepared in the test cell, the cell is filled with water and the specimen is saturated by applying pressures gradually step by step in two directions back pressuring from bottom and cell pressuring surrounding the sample to force water enter the sample for saturation until the back pressure reaches 215 kPa, giving the degree of saturation of more than 98% (Black and Lee, 1973; Head, 1998). After saturation was completed, readings of inlet and outlet burette were taken until the measured hydraulic conductivity reached a relatively steady-state condition.

To determine hydraulic conductivity increase due to cracking, samples were subjected to hydraulic conductivity testing after each dry cycle. After the first hydraulic conductivity test, samples were desiccated in the oven at 34°C ± 2°C for a period of approximately 5-10 days depending on the sample type. At the end of the drying period, each sample was weighed and the diameter and height were measured. The samples were then put back inside the flexible-wall membrane and permeated with water until saturation was achieved. Each sample was saturated at least four times (including the initial saturation) and dried at least three times (Albrecht and Benson, 2001).

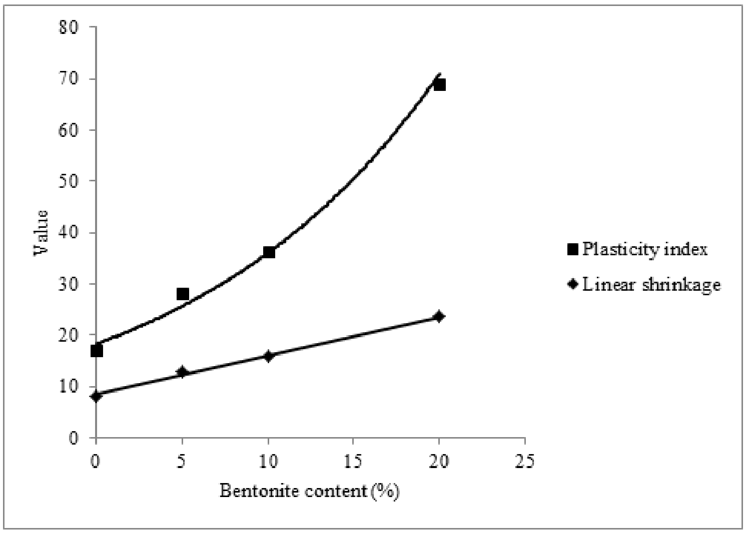

Figure (3): The relation between linear shrinkage, plasticity index and bentonite content

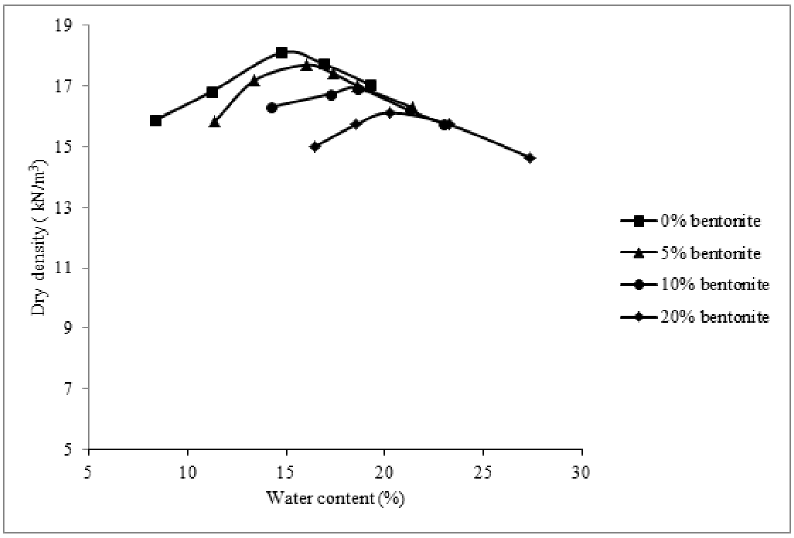

Figure (4): Water content – dry density relationship

An accurate knowledge of soil volume changes induced by suction changes without any external mechanical loading is of major importance for soil drying measurements. Actually, this is done through the measurement of the Soil Water Characteristics Curves (SWCC), which define the relationship between gravimetric or volumetric water content and soil suction (Barbour, 1998). Thus, determination of soil water characteristic curves was carried out according to ASTM D 6836-02 standard method using Pressure Extractor Chamber apparatus. The Pressure Extractor Chamber (PEC) apparatus consists of a saturated porous ceramic plate inside a pressure chamber. Similar to hydraulic conductivity test, soil samples were compacted to optimum water content and maximum dry density following the standard compaction test method (ASTM D698), then cylindrical specimens with a diameter of 50 mm and a height of 50 mm were prepared from the compacted samples. The soil specimens were saturated by inundation in a saturation tray. The specimen was held within the retaining ring during saturation to prevent distortion or sloughing. In addition, it was placed in the saturation tray on top of a porous material (filter paper) without the accompanying ceramic plate. Saturation was continued for at least 24 hours and until no gas bubbles were visible. After saturation in a saturation tray, the specimen was weighed to ensure that the degree of saturation is not greater than 97 %. Saturated soil samples were placed on top of the plate during testing. Suction was imposed on the soil samples by controlling both pore air pressure and pore water pressure, and the difference between the two pressures is the matric suction. It is the most commonly used method for determining soil water characteristic curves. The maximum differential pressure, which can be applied across the plate before cavitation, is constrained by the air entry value of the plate. Suctions of 10, 50, 100, 300, 500, 1000 and 1500 kPa were used to define the SWCC.

RESULTS AND DISCUSSION

Effect of Bentonite on the Physical Properties of UKM Soil

As mentioned previously, the natural soil (UKM soil) was classified as low plasticity clay (CL). After adding 5% bentonite, the classification remained the same (CL). After adding 10% bentonite and 20% bentonite, the soil classification changed to high plasticity index clay (CH). As shown in Table 1, the specific gravity of bentonite is 2.66 while the specific gravity of the natural soil is 2.607 (Table 2). It was also found that the increase in the plasticity index and linear shrinkage was very high after bentonite addition as shown in Figure 3. The increases in the plasticity index was not linear and changed the soil classification to high plasticity clay. The increases in soil plasticity index were about 11, 19 and 47 after the addition of 5%, 10% and 20% of bentonite, respectively. At the same time, the increases in linear shrinkage were approximately 5, 8 and 15.5 after adding 5%, 10% and 20% of bentonite, respectively.

Effect of Bentonite on the Compaction Condition of UKM Soil

From Figure 4, it is obvious that the maximum dry density for natural soil (UKM soil) is 18.05 kN/m^3. After adding 5%, 10% and 20% bentonite to the natural soil, the maximum dry density dropped down to 17.7 kN/m^3, 16.93 kN/m^3 and 16.12 kN/m^3, respectively, due to the increase in clay content (bentonite content). Furthermore, the optimum water content for natural soil (UKM soil) is 14.3% and increased to 16.01%, 18.63% and 20.3% as the bentonite contents were increased to 5%, 10% and 20%, respectively. Generally, adding bentonite to UKM soil increases optimum water content and decreases maximum dry density. This behavior was also noted by Amadi and Eberemu (2013) in which they found that after adding 2.5%, 5%, 7.5% and 10% of bentonite to the natural reddish brown lateritic soil, the maximum dry density decreased from 18.91 kN/m^3 for 0% bentonite to 17.98 kN/m^3 for mixtures with 10% bentonite content, while the optimum water contents were 11.65% for 0% bentonite and 13.88% for 10% bentonite content. The reduction in maximum dry density with increasing bentonite content was due to the high swelling characteristics of bentonite that forms a gel around the particles causing an increase in the effective size of the aggregate, resulting in an increase in the volume of voids and thus in a decrease in dry density (Baik et al., 2007; Le Bell and Stenius, 1980). The increase in optimum moisture content with increasing bentonite content is related to the increasing request to more moisture for hydration reaction that comes from the increased fine content (Amadi and Eberemu, 2013; Dueck et al., 2008; Warr and Berger, 2007).

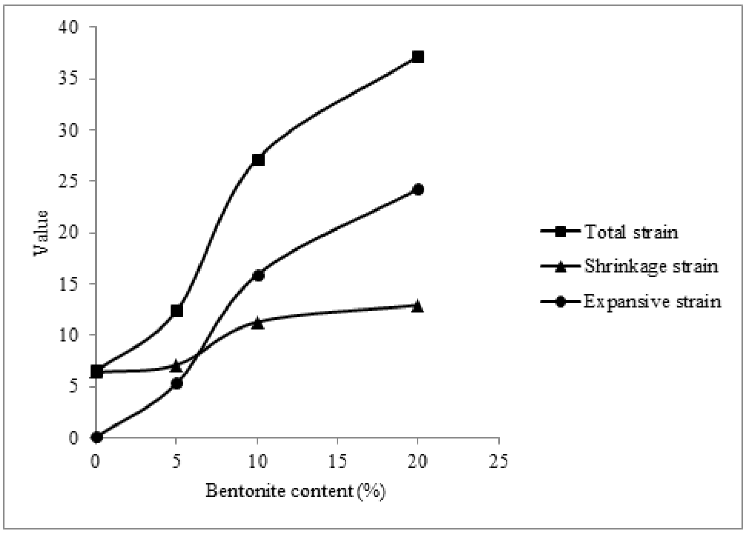

Figure (5): Effect of bentonite content on soil volume change

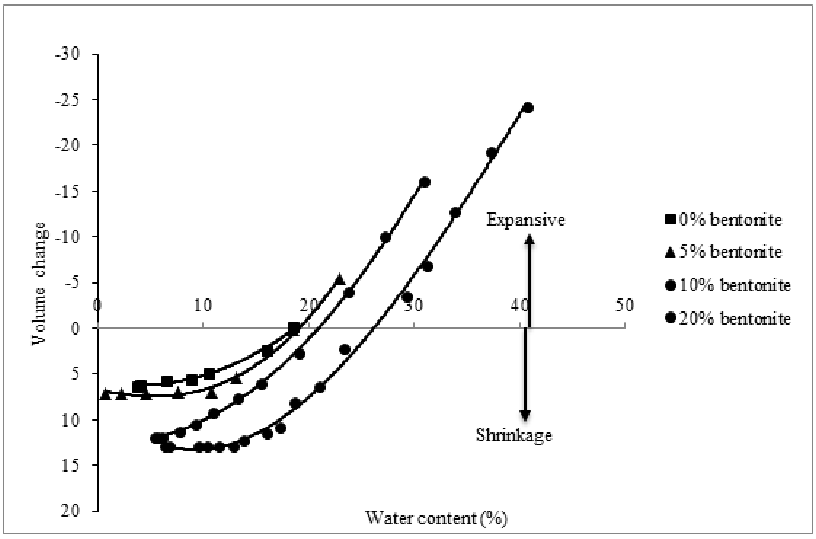

Figure (6): Water content *vs.* soil volume change

Effect of Bentonite on the Shrinkage and Expansive Strains of UKM Soil

In regard to soil volume changes, soils were compacted at maximum dry density and optimum water content. The shrinkage and expansive strains increase as the bentonite content is increased (Fig. 5). At zero bentonite content, the soil does not have significant expansive strain, while the shrinkage strain was around 6.4%. Adding 5% bentonite to the UKM soil results in almost equal shrinkage and expansive strains of the soil. However, adding 10% and 20% bentonite increases the expansive strains in UKM soil more than shrinkage strains due to the high plasticity index of bentonite. However, the total volume change or total strain increases as the bentonite content is increased. The total strain is the sum of shrinkage strain and expansive strain. It can be seen that the increment in shrinkage strains after adding 0% and 5% bentonite to UKM soil is more than the increment in expansive strain. In addition, the increment in the shrinkage strains after adding 10% and 20% bentonite to UKM soil is less than the increment in expansive strain. The ability of soil to absorb water increases as the clay content (bentonite) is increased as shown in Figure 6. Therefore, a higher volume change occurs in UKM soil mixed with 20% of bentonite.

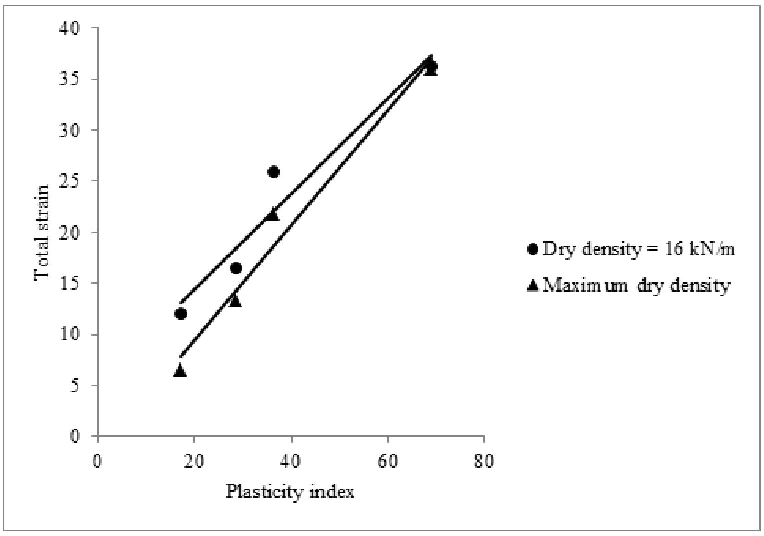

Figure (7): Total volumetric shrinkage strains *vs.* plasticity index

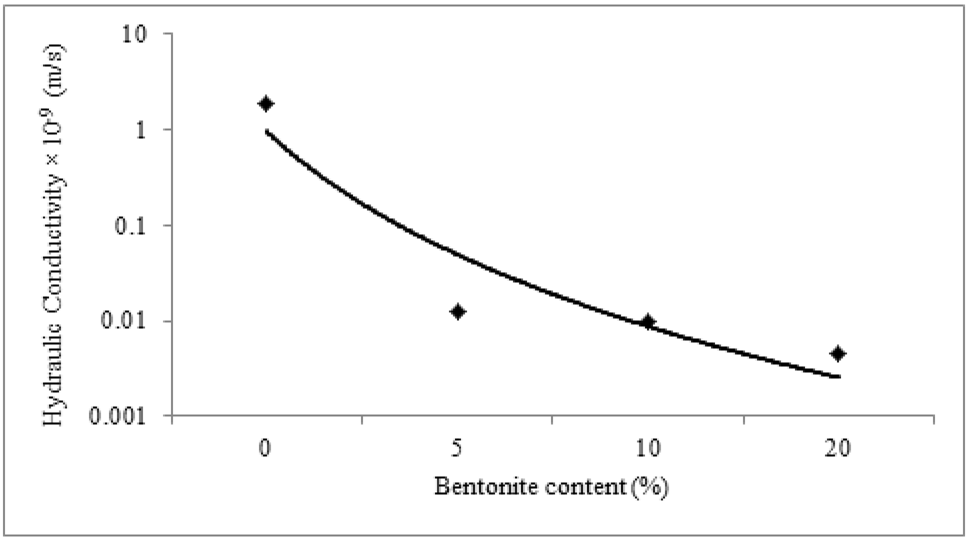

Figure (8): Bentonite content *vs.* hydraulic conductivity

In order to evaluate the effect of plasticity and clay content (bentonite) on the soil volume change, two samples from each soil type were taken. One was compacted at maximum dry density (standard compaction energy) and the other was compacted at the wet side at approximately 21% water content to obtain a dry density of about 16 kN/m^3 (less compaction energy was adopted, total compactive effort equal to 528 kN-m/m^3 for 0% bentonite, 552 kN-m/m^3 for 5% bentonite, 576 kN-m/m^3 for 10% bentonite and 600 kN-m/m^3 for 20% bentonite). Then, the total strain was measured for each sample, and the results were drawn with respect to the soil plasticity index as shown in Figure 7. The total strain for samples that have same dry density and water content (dry density= 16 kN/m^3, water content= 21%) increases as the plasticity index or bentonite content is increased. Furthermore, the sample that was compacted at maximum dry density has less total strain due to the increase in dry density. However, Figure 7 shows that the plasticity index effect on the volume change is more than those of dry density and water content. Thus, the plasticity index has the largest effect on soil volume change.

Comparing to the previous studies, the swelling potential and compressibility of bentonite mixed with sand, generally, increases as bentonite percentage increases. At low bentonite content, small swelling occurs with sand but increases gradually with the increase in bentonite content due to the decrease in the particle size of the non-swelling fraction causing increased expansive strains and high volume change in soil samples (Muntohar, 2003). However, upon air-drying, all the soil samples exhibited desiccation cracking with the amount of shrinkage increasing as moisture content increases during compaction. At any initial moisture content, soil samples containing 20% bentonite shrank more than those containing 10% bentonite (Tay et al., 2001). With reducing bentonite content ratio, the swelling pressure and swelling strain underwent very significant decreases. Furthermore, it was found that the swelling pressure was influenced more strongly than the swelling strain by changing the bentonite content ratios (Cui et al., 2012).

Effect of Bentonite on the Hydraulic Conductivity Suction of UKM Soil

From the discussion above, it was found that the increment in the amount of bentonite in the soil has many negative side effects on UKM soil through increased shrinkage and expansive strains. However, the increase in bentonite content decreases the soil hydraulic conductivity significantly as shown in Figure 8. Insignificant cracks appeared in UKM soil with and without 5% bentonite. However, significant cracks appeared in UKM soil after mixing with 10% and 20% bentonite as shown in Figure 9. The size, shape and distribution of cracks for UKM soil with 10% and 20% bentonite content are clear and greater than in UKM soil with 0% and 5% bentonite content.

In order to evaluate the effect of bentonite content on soil hydraulic conductivity, the hydraulic conductivity ratio (Kr), was used. The hydraulic conductivity ratio (Kr) is the ratio between the hydraulic conductivity of soil at first, second and third cycles to the zero cycle hydraulic conductivity, respectively. This parameter can be used to explain two criteria: low cracking potential and high self-healing potential. When Kr is close to unity, the soil has low crack potential.

From Figure 10, the hydraulic conductivity ratio (Kr) value increases up to 5.64, 4.88, 6.74 and 11.15 for 0%, 5%, 10% and 20% bentonite content, respectively. Moreover, maximum Kr value was observed at cycle 2 for low bentonite contents (0% and 5%), and at cycle 1 for higher bentonite contents (10%, and 20%). In Figure 11, the time required for saturation increased as the amount of bentonite increased. However, the required time for saturation decreased very significantly after first cycle for 10% and 20% bentonite contents due to the desiccation cracks in soil samples. However, the hydraulic conductivity decreased with an increase in saturation time, especially in soils with high plasticity index, possibly due to self-healing of the soil.

Previous studies found that the hydraulic conductivities of soils which had been allowed to dry (drying-wetting cycles ≥ 1) were greater than for those which were not allowed to dry prior to measurement (drying-wetting cycles = 0), and largest increases in hydraulic conductivity occurred at first or second cycles of desiccation. Also, the time required to reach a steady outflow volume decreased as the amount of desiccation increased due to cracks in the soil mass. Self-healing of the soil likely affected the hydraulic conductivity of the specimens (Omidi et al., 1996; Rayhani et al., 2007).

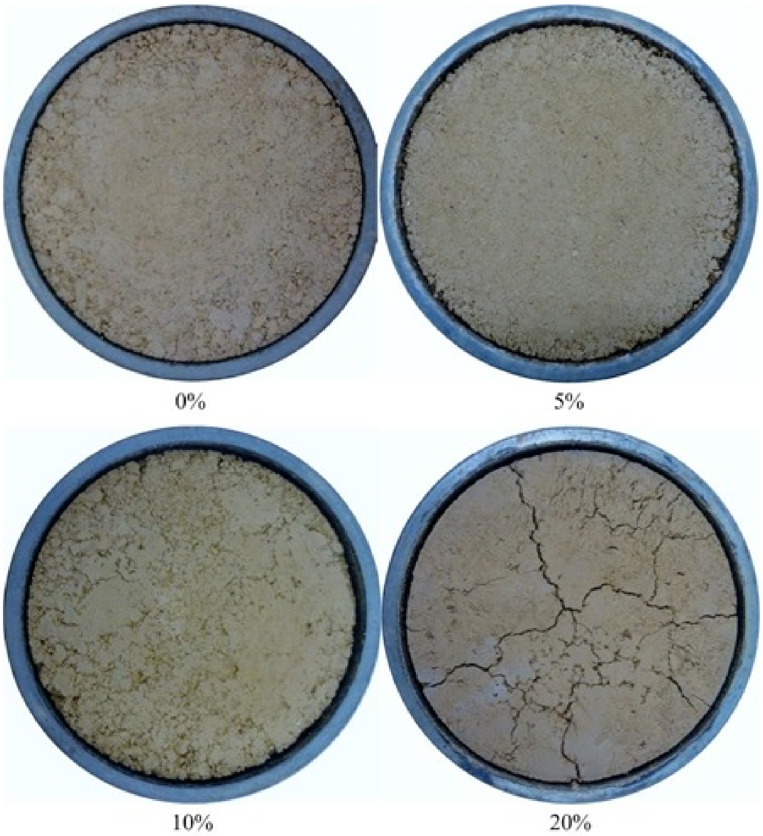

Figure (9): Cracks in UKM soil mixed with 0%, 5%, 10% and 20% bentonite

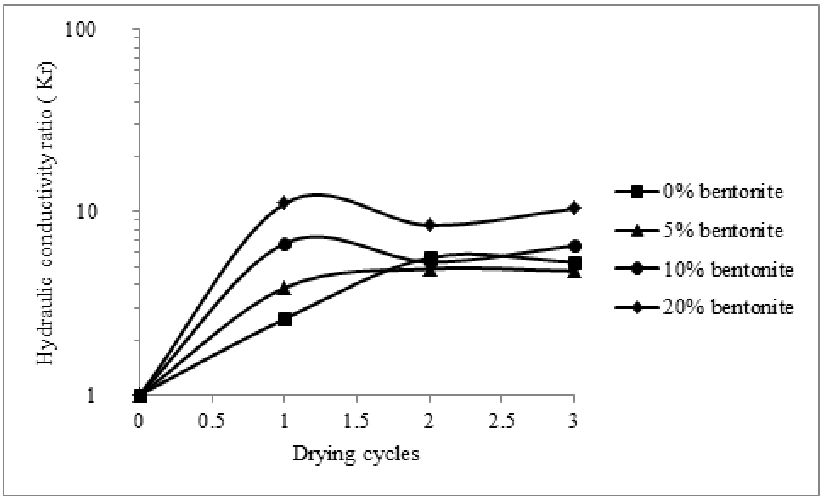

Figure (10): Hydraulic conductivity ratios *vs.* drying cycles

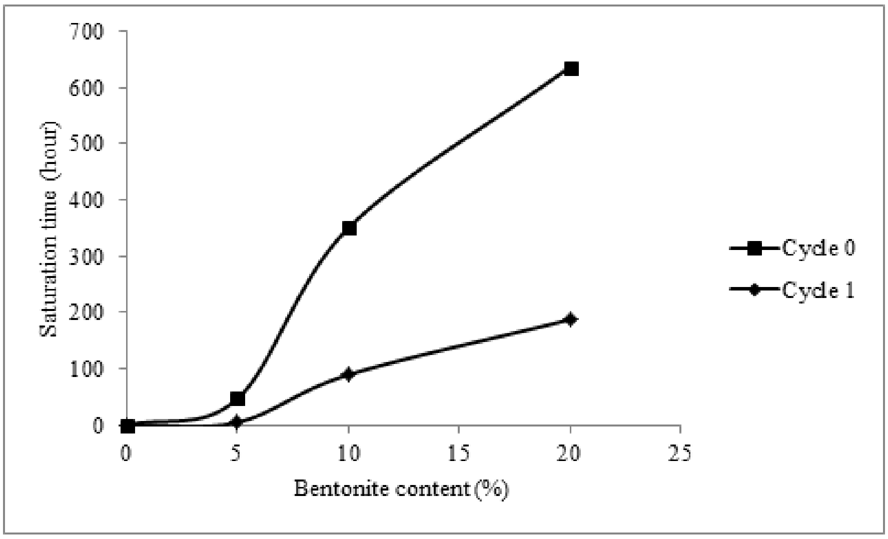

Figure (11): Saturation time *vs.* bentonite content

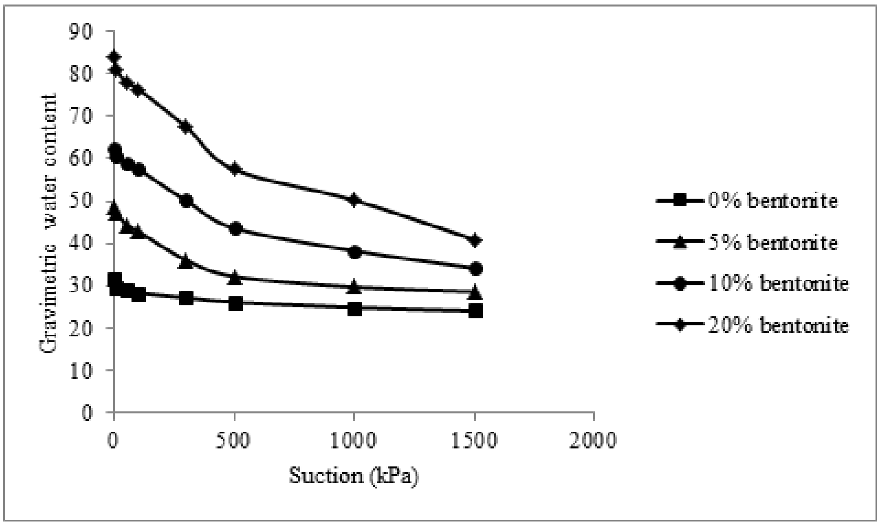

Figure (12): Effect of bentonite content on the suction of UKM soil

The soil water characteristics curves are shown in Fig. 12. The results show that the gravimetric water content increases after mixing the soil with bentonite. This rise in water content indicates that the amount of water required for saturation also increases, thus increasing the suction in soil samples. Generally, the gravimetric water content increased with higher bentonite content. This was expected, since that the mixing of bentonite with UKM soil increased the plasticity of the mixtures, and therefore more water was retained at any given matric suction. Similar result was obtained by Osinubi and Amadi (2010).

CONCLUSIONS

The shrinkage and expansive strains increase as bentonite content increases due to the high plasticity index of bentonite. In addition, the plasticity index parameter has greater influence on the shrinkage and expansive strains than dry density and optimum moisture content parameters. Moreover, significant cracks appeared in UKM soil (natural soil, S1) after mixing with bentonite, especially at 20% bentonite content. On the other hand, the increase in bentonite content decreases the soil hydraulic conductivity significantly. The hydraulic conductivity ratio (Kr) value increases up to 11.15 for 20% bentonite content due to cracking in the soil sample. However, maximum Kr value was observed at cycle 1 and cycle 2. Thus, two cycles are enough to damage the soil sample. The results also show that the gravimetric water content increases significantly after mixing the soil with bentonite due to increasing the plasticity of the mixture.

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