SWELLING AND COMPRESSIBILITY CHARACTERISTICS OF SOIL – BENTONITE MIXTURES

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ABSTRACT

Understanding characteristics of soil mixtures lead to increasing the confidence level before applying such materials in the field. The outcomes of this study can provide insight into the swelling and the compressibility behavior of soil – bentonite mixtures, between non-swelling materials and swelling materials. A simple swell and compression laboratory test has been conducted for the purposes of this study. The result of this study indicated that the existence of bentonite in the soil mixtures influence the swelling behavior, which follows a hyperbolic curve model. Amount and size of non-swelling fraction affected the swelling and compressibility.

Keywords: bentonite, soil mixtures, swelling, swelling pressure, compressibility.

INTRODUCTION

The swelling behavior of expansive soils often causes unfavorable problems, such as differential settlement and ground heaving. Recently, expansive soils are attracting greater attention. The soil is often designed as soil mixtures requiring among others low shrinkage and swelling properties, low hydraulic conductivity, and high strength. There are various applications where the soils have to be engineered to suit the desired behavior as back-filling (buffer) materials for high-level nuclear waste [1], and soils barrier for landfill liner [2, 3].

Many attempts have been performed in the past to understand the properties, indices and geotechnical properties, of the soil mixtures. Previous researchers have concentrated on the swelling behavior of expansive clays but with little attention given to the compressibility characteristics. The soil mixtures are commonly a blend of swelling soils (montmorillonite) with non-swelling soils (kaolinite, and/or sand) [2, 4]. The engineering properties of clay soils, such as the plastic limit and liquid limit, depend upon the moisture content of the clays which in turn is attributable to the amount of clays with high cation exchange capacity and to the type of interlayer cations. The plasticity index, i.e. the liquid limit minus the plastic limit, is a common indicator of an expansive soil. At liquid limit, Na-montmorillonite may have water films between 100Å and 200Å thick and Ca-montmorillonite may have water films between 15Å and 19Å thick [5]. Shrink and swelling behaviour of montmorillonite soils make unstable slopes and cause building foundation problems. Swelling or uplift pressures generated by montmorillonite may approach values as high as 981 kPa [6].

The solution to some of these engineering problems may be resolved by understanding the behaviour of clays composed of single and/or mixtures of clay minerals. This paper presents the result of a study in the volume change and compressibility of soil – bentonite mixtures. An experiment is carried out to study swell – deformation characteristics of bentonite mixed with different amount and types of non-swelling soil such as coarser fraction (sand) and finer fractions (silt).

LABORATORY EXPERIMENTS

Materials

The soils used in this study are commercial bentonite clay, kaolin, and fine sand. The particle size distributions of the soils are shown in Fig. 1, and the basic properties are listed in Table 1. The percentage of bentonite by weight is varied between 5% and 100%. The plasticity and potential expansiveness of soil – bentonite mixtures are illustrated in Fig. 2.

Table 1. Physical properties of the soil used.

Soils description	Sand %	Silt %	Clay %	D_{50} μm	Liquid Limit	Plastic Limit	Linear shrinkage	Activity, PI/CF
Bentonite [a]	5.4	2.4	73.2	0.62	307.3%	45.4%	17.4%	3.6
Kaolin	4.3	75.6	19.9	4.1	72.3%	39.8%	6.6%	1.6
Sand [b]	71.5	4.0	0.0	820	NP	-	-	-

Note: [a] Wyoming bentonite, [b] Mining sand (24.5% Gravel), NP = non-plastic, PI = plasticity Index, CF = Clay fraction
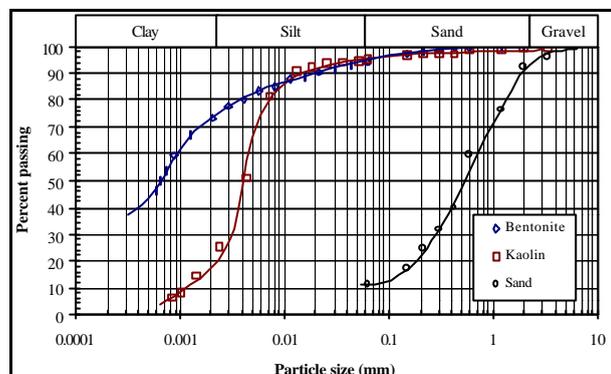

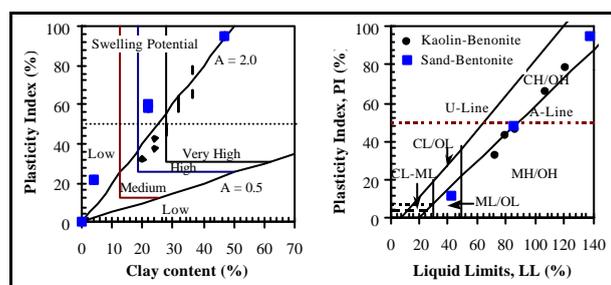Figure 1. Particle size distribution of soils.

Figure 2. Potential expansiveness and plasticity chart of soil-bentonite mixtures

The kaolin comprised predominantly silt (75.6%), whereas 73.2% of the bentonite is clay. The sand comprised 35.6% coarse, 23.6% medium, and 12.3% fine size. Uniformity coefficient (Cu) and coefficient of curvature (Cc) are 9.08 and 1.19 respectively. Further, the sand can be classified into well-graded sand with gravel (SW).

Tests Scheme

A conventional oedometer apparatus was used for determination of the swelling and compressibility of soil mixtures. The calculated quantities of soil mixtures, at optimum moisture content (OMC), were transferred to consolidation ring of 50 mm internal diameter and 20 mm height. All the soil mixtures were compacted statically in the specially constructed mould (Fig. 3) to their maximum dry density (MDD) using the hydraulic jack. The compressive force was applied to the upper plug until the flange is in contact with the barrel of

the mould. The moisture content and dry density of the specimens after moulded was determined as a control to their OMC and MDD. The results are presented in Table 2.

The specimen was positioned in the loading frame with a seating load of 3.89 kPa. The soil samples were then inundated with distilled water and allowed to swell until they reached equilibrium values of swelling. At this point a standard consolidation test is conducted by applying incremental loads starting with 14 kPa and ending with 1600 kPa. The pressure required to revert the specimen to its initial height was determined as the swelling pressure.
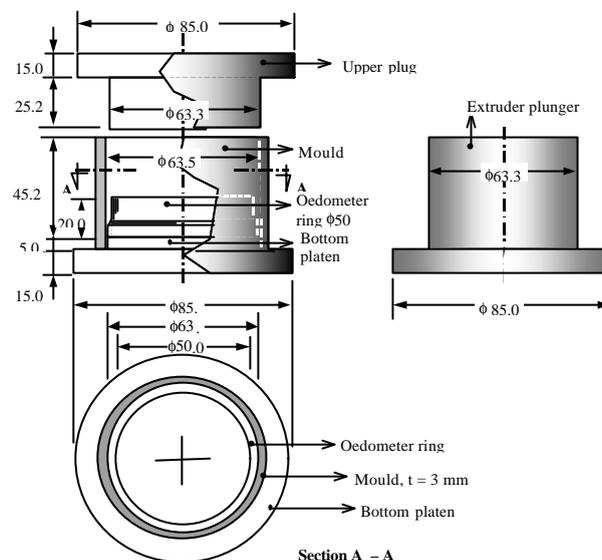

Figure 3. Static compaction mould for swelling specimens.

Table 2. Compaction Properties Soil Mixtures.

Soil Code	KB1	KB2	KB3	KB4	SB1	SB2	SB3
OMC (%)	32.4	30.6	30.7	31.5	18.2	17.9	16.5
Moisture *(%)	32.43	30.20	31.03	31.24	18.53	18.10	16.64
Variability (%)	0.09	1.30	1.07	0.82	1.80	1.11	0.84
MDD (Mg/m³)	1.28	1.29	1.30	1.31	1.72	1.67	1.60
Dry density *(Mg/m³)	1.275	1.294	1.308	1.314	1.719	1.662	1.610
Variability (%)	0.39	0.31	0.61	0.30	0.05	0.47	0.62

Note: *After molded; OMC : optimum moisture content; MDD: maximum dry density

Clay mineralogy

The clay minerals have been determined by X-ray diffraction test as shown in Fig. 4. The kaolin consists of mainly kaolinite minerals which is obviously at peak 12.7 Å, 24 Å, and 38.43 Å. The other mineral, illite was also detected interlayer with montmorillonite and kaolinite at 5.01 Å, 4.46 Å and 4.37 Å. The mica-

like clay minerals, phlogopite (brown mica) was observed at 8.89º. The montmorillonite mineral was found strongly in bentonite at basalt spacing of 5.75 Å, 17.25 Å, and 19.98 Å. Quartz and illite mineral was strongly appeared at basalt spacing of 3.36 Å and 3.19 Å respectively. The quartz was also found at 4.28 Å, 2.46 Å, and 2.29 Å in the low intensities. Mixed layer between illite and montmorillonite was found at 4.52 Å of basalt spacing.[4].
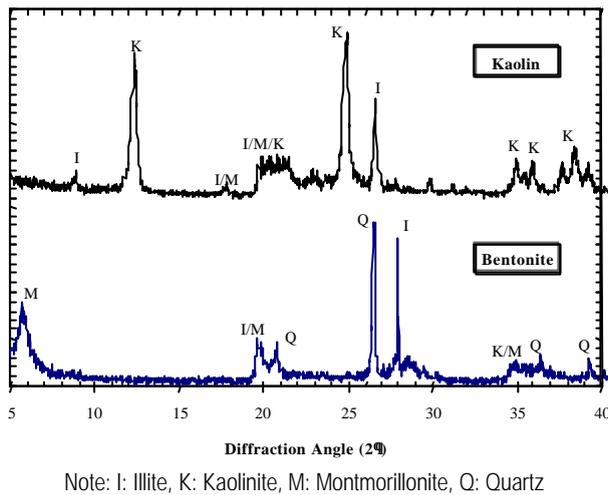

Note: I: Illite, K: Kaolinite, M: Montmorillonite, Q: Quartz

Figure 4. X-Ray diffraction of kaolin and bentonite soils.

RESULT AND DISCUSSION

Swelling Characteristics

The swell potential was defined as the percentage swell of a laterally confined sample, which has soaked under a surcharge pressure of 3.89 kPa after being compacted to maximum density at optimum moisture content according to the compaction test. The results obtained are presented in Fig. 5 in the form of percentage of swell versus time with varying percentage of bentonite content. The swell is expressed as a percentage increase in sample height.

It has been observed that for all the mixtures, increase in swelling with log time is slow initially, increases steeply, and then reaches an asymptotic value. The time required to reach an asymptotic value varies considerably, depending upon the percentage of bentonite and the type and amount of non-swelling fraction. The maximum amount of swelling generally increases with increasing bentonite content. Fig. 5 depict, even at the same percentage of bentonite, that considerable differences exist in

the nature of time-swell relationship. At low bentonite content, the rate of swelling is very slow with sand but increases gradually with decrease in the particle size of the non-swelling fraction.

Fig. 6 replots the time-swell relationship as percentage of the maximum swell. Here, the percent swell at a particular time is calculated as the ratio of amount of swell of the mixture at that time to the total swell and is denoted as a percentage. This is observed that for sand – bentonite mixtures, the rate of swelling is very slow and follow a similar swell path. In other hand, it was observed that the swelling almost completed within 1440 min (±24 hrs) for kaolin mixtures for all percentage of bentonite.
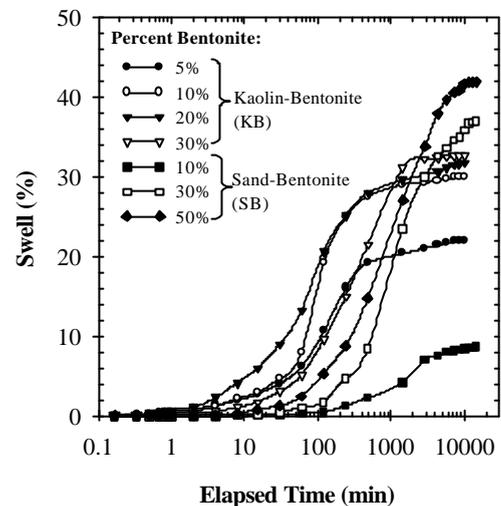

Figure 5. Swelling behaviour (as percent of initial height) of soil-bentonite mixtures
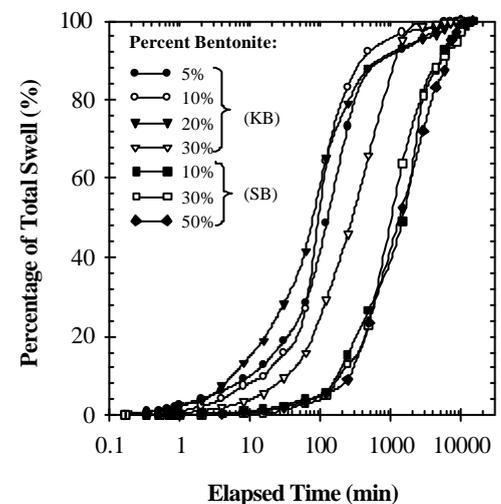

Figure 6. Swelling behaviour (as percent of total swell) of soil-bentonite mixtures

There is very limited reference about the rate of swelling. However, the rate of swelling may be approached as similar as in the coefficient of consolidation determination as given in Equation 1a.

$$c_V = \frac{T_v \cdot \left(\frac{H_{avg}}{2} \right)^2}{t_{50}} \qquad (1a)$$

If T_v and H_{avg} are taken as constants and c_v is symbolized with c_s, then the equation can be expressed as follows:

$$c_s \approx \frac{1}{t_{50}} \qquad (1b)$$

The t_{50} is the time required to achieve 50% of swell. For all mixtures 50% of swell are achieved within 100 min (±1 hr, 40 min) and 1000 min (±16 hrs, 40 min) for kaolin and sand mixtures respectively.

Dakshanamurthy [8] noticed two stages of swelling. In the first stage of hydration of dry clay particles, water is adsorbed in successive monolayers on the surface of montmorillonite clay apart which referred to as interlayer or intercrystalline swelling. The second phase of swelling is due to double-layer repulsion. Large volume changes accompany this stage of swelling. These occurrences can be approached closer as illustrated in Fig. 7, which the curve can be divided into three phases. Initial swelling is generally less than 10% of the total swelling. This is essentially due to swelling of the bentonite clay particles within the voids of the coarser non-swelling fraction.
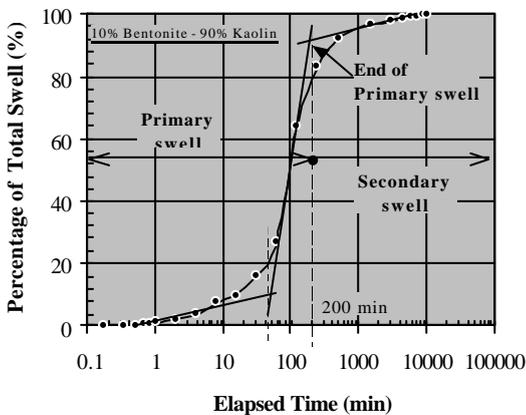

Figure 7. Typical time-percent swell of total swell curve

Primary swelling develops when the void can no longer accommodate further clay particle swelling. It occurs at a faster rate. After the primary swelling was completed, slow continued swelling occurs. It is observed that the end of primary swelling of kaolin-bentonite mixtures are varies within 200 – 1000 minutes. In general, the time needed for completion the primary swelling increase associated with increase in bentonite content. But, this is not appeared in the sand-bentonite mixtures.

Furthermore, the swelling mechanism of compacted expansive clay can be illustrated by the model as given in Fig. 8. The volume of swelling clay particles such as montmorillonite increase by absorbing water into the interlayers of montmorillonite, and the void in the compacted expansive clay are filled by this volume.
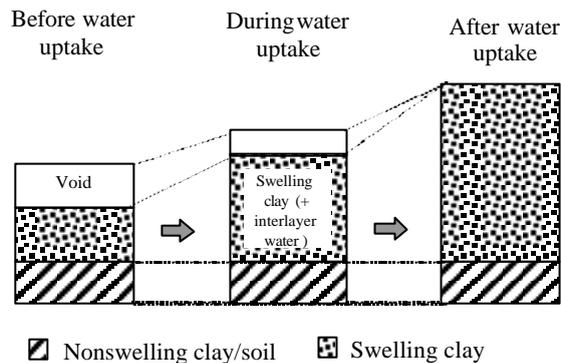

Figure 8. The model of the swelling deformation of compacted expansive clay

After water uptake, the compacted expansive clay can swell at a constant vertical pressure as in the swelling deformation test. The volume of compacted clay increases as the volume of swelling clay particles increases until the swelling pressure of the clay particles equals the vertical pressure (see Fig. 8).

Maximum Swelling

The maximum swelling can be predicted using hyperbolic model (Eq. 2) and calculated by Eq. 3 [9, 10].

$$S_v(t) = \frac{dh(t)}{h_o} = \frac{t}{(a+bt)} \qquad (2)$$

$$S_{v\,max} = \lim_{t \to \infty} e_v(t) = \lim_{t \to \infty} \left(\frac{1}{\frac{a}{t} + b} \right) = \frac{1}{b} \qquad (3)$$

where t is time from the start of water inundation, $S_v(t)$ is vertical swelling at time (t), and a and b are constants determined by fitting procedures. The calculated maximum swelling is presented in Table 3 and the curves of the hyperbolic are also shown in Fig. 9. This is observed that the swelling take longer time to reach the maximum swelling.

Table 3. Swelling, swelling pressure and compressibility index

Soil Mix	Percent Bentonite	SP (%)	Hyperbolic constants (Eq. 3)		Max. Swell (%)[a]	Ps (kPa)	Cs$_v$ (10^2)
			a	b			
Kaolin:	5	21.92	4.475	0.0449982	22.22	114	26.99
	10	29.96	3.199	0.0324435	30.82	325	25.58
	20	31.75	2.194	0.0316716	31.57	356	29.14
	30	32.65	8.299	0.0293099	34.37	420	39.36
Fine Sand	10	8.68	167.25	0.1007024	9.93	165	7.50
	30	36.96	31.815	0.0244295	40.93	580	32.38
	50	41.96	37.675	0.0205627	48.63	660	31.48

Note: SP: swelling potential (measured for 10 days observation), Ps: swelling pressure. [a] Predicted using Eq. 3, Cs$_v$: Coefficient of Compressibility (after swell)
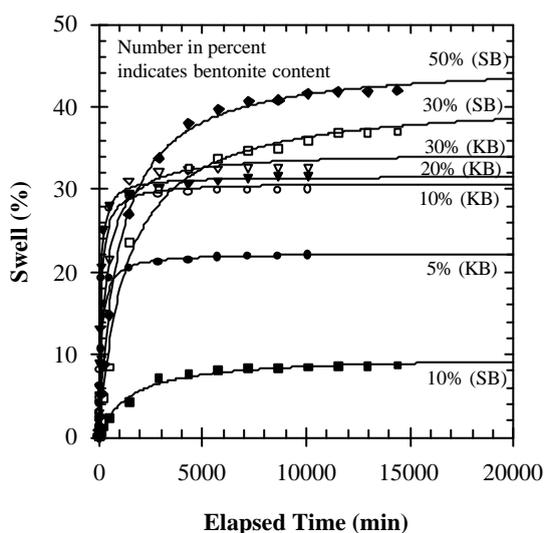

Figure 9. Time-swell hyperbolic relationship for estimation of maximum swelling

Swelling Pressure

Swell pressure is defined here as the pressure required to compress the specimen, that has been soaked and completed the swell under 3.89 kPa pressure, back into its original configuration (before swell). The swell pressure was measured by the pre-swelled method for simplicity; however, there is experimental evidence that different methods gave similar results [11, 12] especially at high density.

Figure 10 shows the change in sample height (%) and pressure (kPa) curves for soil – bentonite mixtures, which is determined from oedometer test. At least two essential values can be attracted from this results i.e. compressibility and swelling pressure of compacted soil.
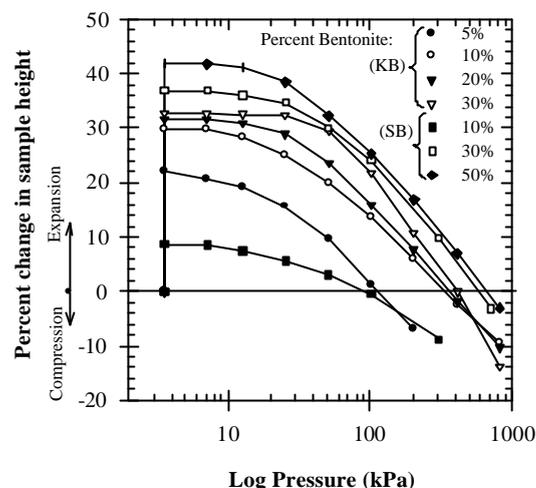

Figure 10. Percent change in sample height versus loading applied pressure

The figure shows that the swell pressure increase with increasing bentonite content. Sand – bentonite mixtures exhibit greater swelling pressure than other mixtures. It is perhaps caused by the greater initial dry density and lower water content when the specimen was compacted. This is in agreement with El-Sohby and Rabba [12].

Mathew and Rao [13] indicated that by increasing the valence of exchangeable cations in homoionized clay, the overall compression in the system is reduced and the pre-consolidation pressure (p_c) is increased. The equilibrium void ratio at any applied pressure is a direct function of the repulsive forces arising from the interaction of adjacent diffuse double layers and pore fluid. As the valence of exchangeable cations in the clay increased, there is a reduction in the diffuse double –layer thickness and in the magnitude of the repulsive forces. These finally result in a lower equilibrium void ratio at any given pressure until higher pressures are reached [14].

Compressibility Characteristics

The virgin compressibility is defined as the linear part of the volumetric strain (e_v) vs. log pressure (p) curve under virgin loading path. The curves of soil-bentonite mixtures (Fig. 10) show that the virgin compressibility characteristics are not evident up to a vertical pressure of 25 and 50 kPa. Moreover, the coefficient of compressibility (C s_v) is defined as the slope of

linear portion of the virgin loading curve after the specimen was allowed to swell, as given in Equation 4.

$$Cs_v = \frac{\Delta S_v}{\Delta log(p)} \qquad (4)$$

It is observed that the compressibility of soil increase with increase in swelling and percent of bentonite. The higher swollen soil compress rapidly subjected to applied load. It can be affected by absorbing water during swell, which caused reducing the strength.

CONCLUSION

Based on the study undertaken thus far it can be concluded that:
1. The swelling, swelling pressure, and compressibility of bentonite mixed kaolinite and sand, generally, increases associated with bentonite percentage. Apart of the mineralogical and clay content, the amount and size of the non-swelling fraction play role in governing the swelling and compression behavior
2. In general, the swelling behavior occurred in two distinct stages i.e. primary swelling and secondary swelling. Secondary swelling occurred after primary swelling completed.
3. The swell behavior was time dependent, which follows a hyperbolic relationship during the stages and hence can be used to predict the magnitude of maximum swelling.

Acknowledgement

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