Proceeding of the Second International Conference on
Unsaturated Soils
Beijing, China, August 27 – 30, 1998
Volume 1, pp. 143 - 148

THE SOIL–WATER CHARACTERISTICS OF SAND-BENTONITE MIXTURES USED FOR LINERS AND COVERS

J. T. Stoicescu, M. D. Haug, and D. G. Fredlund

THE SOIL-WATER CHARACTERISTICS OF SAND-BENTONITE MIXTURES USED FOR LINERS AND COVERS

Jeffrey T. Stoicescu
(M.D. Haug & Associates Ltd., Saskatoon, SK, Canada, S7N 3R2)
Moir D. Haug and Delwyn G. Fredlund
(University of Saskatchewan, Saskatoon, SK, Canada, S7N 5A9)

Abstract

This paper describes the results of a laboratory research program designed to establish the soil-water characteristic curves for compacted sand-bentonite. In many parts of the world, covers and liners for waste containment facilities exist above the water table. This unsaturated condition either exists for the design life of the facility or significantly affects the design of the cover or liner. In order to successfully model moisture and oxygen transfer through the unsaturated portion of these barriers, it is necessary to know the soil-water characteristic curve for the material. Compacted sand-bentonite has gained increased popularity as a cover material due to its low hydraulic conductivity and its high storage potential. However, little information is available regarding the adsorption and desorption characteristics of this material. In order to address this need, a laboratory program was designed to determine the soil-water characteristic curves for compacted sand-bentonite mixtures, and to determine the most suitable techniques for measuring this relationship. In this research program, four sets of soil specimens were prepared. Series 1 specimens consisted of ASTM C-109 sand compacted at optimum water content using standard Proctor compaction. Series 2 specimens were prepared by mixing 8% bentonite with 92% ASTM C-109 sand, moisture conditioned to optimum water content, and compacted using standard Proctor effort. Series 3 and 4 specimens were prepared with the same material composition as series 2 specimens, but the molding water contents were 2% dry of optimum and 2% wet of optimum, respectively. The test results showed that a small addition of bentonite to a sandy soil caused a significant increase in the storage potential of the mixture. The addition of bentonite changed the soil-water characteristic curve from a typical "S-shaped" curve to a bimodal curve. Changes in molding water content also influenced the shape of the soil-water characteristic curve. The results of this research indicate the good potential for sand-bentonite mixtures to be used for construction of soil liners or covers subjected to negative pore-water pressures during the design life of the facility.

Introduction

The design of soil barriers used for waste containment facilities has traditionally focused on the saturated parameters such as the saturated hydraulic conductivity. In many parts of the world, unsaturated soil conditions are prevalent and control the structure and hydraulic nature of the soils in the region. These areas of the world cannot rely on saturated parameters alone in the design and construction of soil barriers for waste containment facilities. The soil-water characteristic curve can be used to determine the soil-water content or degree of saturation within a soil mass subjected to different soil suctions. This relationship can be used within saturated-unsaturated computer modelling programs such as SEEP/W [1] and SoilCover [2] to model the flux rates through a soil barrier and the time for infiltration to proceed through the barrier system. Therefore, the soil-water characteristic curve is one component required to assess the performance of a soil cover or liner subjected to negative pore-water pressures during the design life of the facility.

Many geo-environmental engineers are noting that soil mixtures consisting of sand and bentonite provide good performance characteristics for use as a soil liner or cover. Research has shown that sand-bentonite mixtures possess low saturated hydraulic conductivities under various conditions of initial molding water content and dry density [3]. However, limited published information exists regarding the unsaturated properties of sand-bentonite mixtures such as soil-water characteristic curves, air entry values, and residual water contents. For this reason, a laboratory research program was established to measure the soil-water characteristics of sand-bentonite mixtures. The first phase of the research program was designed to study the effects of bentonite addition on the shape of the soil-water characteristic curve of a sandy soil. The second phase of the research program was designed to determine the effects of molding water content on the shape of the soil-water characteristic curve for a sand-bentonite mixture. The results of the first phase of the test program shows that the addition of bentonite to a sandy soil results in a soil-water characteristic curve with a significant increase in the air entry value and storage potential. The test results from the second phase shows that changes in molding water content affected the shape of the soil-water characteristic curve for a sand-bentonite mixture.

Theory

Volume-mass relationships such as volumetric water content, degree of saturation, and dry density are important components when assessing the unsaturated characteristics of a soil mixture. In this section, the formulas required for the calculation of the volume-mass properties used in the soil-water characteristic curve are derived. Fig. 1 shows a typical sand-bentonite mixture separated into its basic components of air, water, bentonite, and soil. To simplify the formulation of the volume-mass relationships, the total volume (V_t) is assumed to represent a unity volume. That is, V_t is assumed to be 1 for all calculations. This assumption allows all volume relationships (V_a, V_w, V_b, V_s) to be some portion of the total volume.

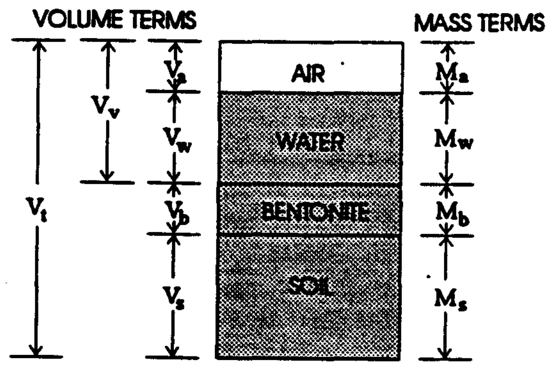

Fig. 1 Volume-mass components of a sand-bentonite mixture

1. Formulation for Mass Properties

The dry density formulation can be defined as:

$$\rho_d = \frac{Total\ Soil\ Mass}{Total\ Volume} = \frac{(M_s + M_b)}{V_t} \quad (1)$$

Since Vt is equal to 1, the dry density formulation can be defined as:

$$\rho_d = M_s + M_b \quad (2)$$

The gravimetric water content formulation can be modified so that the mass of water in the soil structure can be calculated by using the water content (w) and the dry density.

$$\text{Gravimetric water content} = w = \frac{Water\ Mass}{Total\ Soil\ Mass} = \frac{M_w}{(M_s + M_b)} \quad (3)$$

By substituting Eq. 2 into Eq. 3, the mass of water can be simplified into the following formulation:

$$M_w = (w)\,\rho_d \quad (4)$$

The mass of bentonite within the entire soil mass is a function of the total soil mass and the bentonite content. The bentonite content (c) is the percentage of bentonite based on the total dry soil mass of the mixture.

$$M_b = (c)\,(\text{total dry mass of soil}) = (c)\,(M_s + M_b) = (c)\,(\rho_d) \quad (5)$$

The mass of sand within the entire soil mass is a function of the total soil mass and the bentonite mass.

$$M_s = (1 - c)\,(\text{total dry mass of soil}) = (1 - c)\,(M_s + M_b) = (1 - c)\,(\rho_d) \quad (6)$$

2. Formulation for Specific Gravity

The specific gravity of a soil particle is defined as the ratio of the density of a particular soil particle to the density of water at a temperature of 4°C under atmospheric pressure conditions (101.3 kPa) [4]. The specific gravity for bentonite particles and sand particles are as follows:

$$G_s = \frac{\rho_s}{\rho_w} \quad \text{(specific gravity for sand particles)} \quad (7)$$

$$G_b = \frac{\rho_b}{\rho_w} \quad \text{(specific gravity for bentonite particles)} \quad (8)$$

3. Formulation for Volume Properties

The volume of the bentonite particles can be defined as:

$$V_b = \frac{M_b}{\rho_b} \quad (9)$$

By substituting Eqs. 8 and 5 into Eq. 9, the volume of the bentonite fraction shown in Fig. 1 can be defined as:

$$V_b = \frac{(c)(\rho_d)}{(G_b)(\rho_w)} \quad (10)$$

The volume of the sand particles can be derived similar to that of bentonite particles to yield the following formulation:

$$V_s = \frac{M_s}{\rho_s} = \frac{(1-c)(\rho_d)}{(G_s)(\rho_w)} \quad (11)$$

The volume of water can be expressed in terms of gravimetric water content and dry density of a soil mass by combining Eq. 4 and the density equation for water.

$$V_w = \frac{M_w}{\rho_w} = \frac{(w)(\rho_d)}{\rho_w} \quad (12)$$

4. Formulation for the Degree of Saturation of Sand-Bentonite Mixtures

The degree of saturation of a soil mixture is defined as the ratio of the volume of water within a sôil structure to the total volume of voids.

$$\text{Degree of Saturation} = S = \frac{V_w}{V_v} = \frac{V_w}{(1 - V_b - V_s)} \quad (13)$$

By substituting Eqs. 10, 11, and 12 into Eq. 13, the degree of saturation can be expressed in terms of bentonite content, dry density of the soil mixture, specific gravity of bentonite, and specific gravity of sand.

$$S = \frac{V_w}{V_v} = \frac{\dfrac{(w)(\rho_d)}{\rho_w}}{1 - \dfrac{(c)(\rho_d)}{(G_b)(\rho_w)} - \dfrac{(1-c)(\rho_d)}{(G_s)(\rho_w)}} \quad (14)$$

5. Formulation for the Volumetric Water Content of Sand-Bentonite Mixtures

The volumetric water content is an important unsaturated parameter that is utilized in the soil-water characteristic curve. The volumetric water content gives an indication of the storage capacity of a soil mixture. The volumetric water content is defined as the ratio of the volume of water within the total volume of a soil mixture.

$$\text{Volumetric Water Content} = \theta = \frac{V_w}{V_t} = \frac{(w)(\rho_d)}{\rho_w} \tag{15}$$

Laboratory Test Program

Four series of test specimens were prepared in this test program. Series 1 specimens consisted of 100% ASTM C-109 sand which was moisture conditioned to the optimum water content of 8% and compacted using standard Proctor effort to a maximum dry density of 1.65 Mg/m^3. Series 2 specimens consisted of 92% ASTM C-109 sand mixed with 8% BARAKADE-90 bentonite (based on dry soil mass). Series 2 specimens were moisture conditioned to the optimum water content of 15% and compacted using standard Proctor effort to a maximum dry density of 1.78 Mg/m^3. Series 3 and 4 specimens were prepared with the same mixture ratio and compactive effort as series 2 specimens, but the molding water contents were 2% dry of optimum and 2% wet of optimum, respectively. Series 3 specimens were moisture conditioned to a water content of 13% and compacted using standard Proctor effort to a dry density of 1.77 Mg/m^3. Series 4 specimens were moisture conditioned to a water content of 17% and compacted using standard Proctor effort to a dry density of 1.73 Mg/m^3. The same specimens were trimmed into specimen rings (50 mm diameter : 12 mm height) and saturated in a one-dimensional oedometer to ensure constant volume during the saturation process.

The soil-water characteristic curve for each of the specimens was measured using three apparatuses. Table 1 summarizes these apparatuses and the suction range that each were used in determining the soil-water characteristic curve for each specimen. To ensure testing reproducibility, the soil-water characteristic curves were completed at least six times for each series of test specimens. To ensure testing reliability, the soil-water characteristic curve was measured over the same range of suctions for both the Tempe cell and Pressure Plate to ensure that the results from these two separate apparatuses were comparable.

Table 1. Summary of the laboratory equipment used to measure the soil-water characteristic curve

Laboratory Equipment	Range of Soil Suctions Tested (kPa)
Tempe Cell	0 - 125
Pressure Plate	125 - 1500
Vapor Extractor	4000 - 300000

The Tempe cell and Pressure Plate apply suction to soil specimens utilizing the axis-translation technique [4], [5]. The Tempe cell is designed to test the soil-water characteristic curve using a single specimen for the suction range listed in Table 1. The Pressure Plate uses multiple samples to measure the soil-water characteristic curve. The components and procedures associated with measuring the soil-water characteristic curves for sand-bentonite mixtures using the Tempe cell and the Pressure Plate tests are described by Stoicescu [5]. The vapor extractor method utilizes a series of sealed chambers containing saturated salt solutions to control the relative humidity within the chamber [5]. The relative humidity within each chamber provides an osmotic suction to the soil specimen placed above the salt solution. The sand-bentonite specimens required eight weeks to equilibrate in the vapor extractors.

The specific gravity for ASTM C-109 sand and BARAKADE-90 bentonite were measured in this research program. The specific gravity of each material was used in combination with the formulas presented in the theory section of this paper and the laboratory results from the soil moisture testing equipment, to calculate the soil-water characteristic curve for each of the soil specimens.

Test Results

The specific gravity for ASTM C-109 sand and BARAKADE-90 bentonite were measured to be 2.65 and 2.83, respectively. The sample preparation and testing methodology used to measure the specific gravity of ASTM C-109 sand was similar to the procedures recommended by ASTM test designation D854-92. The specific gravity of the bentonite soil was measured by using a modified version of ASTM test designation D854 [5].

The soil-water characteristic curves for series 1 and 2 specimens are shown on Fig. 2. The air entry value for the ASTM C-109 sand (series 1) and the bentonite modified sand (series 2) were determined to be 1.74 kPa and 12 kPa, respectively. The test results show that the addition of bentonite to a sandy soil caused the pore-water to remain within the soil mass until higher soil suctions were applied. These results suggest that the storage potential of a sandy soil can be significantly increased with a relatively small addition of bentonite.

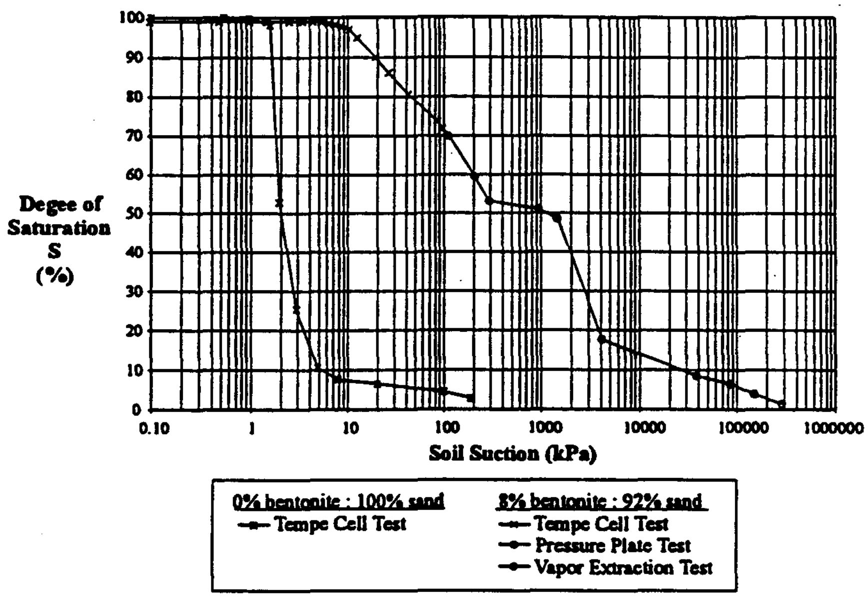

Fig. 2 Soil-water characteristic curves for ASTM C-109 sand and a sand-bentonite mixture

The soil-water characteristic curves for the sand-bentonite mixtures exhibited a bimodal or double-humped shape. The first consideration in analyzing the shape of the curves was to ensure that use of multiple apparatuses in measuring the soil-water characteristic curve was not responsible for the bimodal shape. To address this concern, the soil-water characteristic curves for 12 sand-bentonite specimens (series 2) were measured using the Tempe cell and the Pressure Plate. The results showed that the two apparatuses produced almost identical results and confirmed the presence of one hump and the start of a second hump [5], [6]. The second drop in the soil-water characteristic curve, beyond 1600 kPa, was only measured using the vapor extraction technique, due to the lack of commercially available laboratory equipment which can apply matric suctions to a soil specimen beyond 1500 kPa.

The soil-water characteristic curves shown in this research provide evidence that pore size distribution controls the shape of the soil-water characteristic curve. The grain size distribution of the ASTM C-109 sand exhibited a D_{10} of 0.180 mm, with a coefficient of uniformity and coefficient of curvature of 2.17 and 1.33, respectively. These results indicate a relatively uniform material. As a result, the pore sizes within the soil mass would be uniform, causing the pore-water to be released over a narrow range of soil suctions, which was shown in Fig. 2. For the sand-bentonite specimens, the soil-water characteristic curve exhibited a gradual sloping curve in the low suction range (0.1 to 500 kPa) and a sharp dropping curve in the high suction range (beyond 500 kPa). Once again, the pore sizes within the soil mass can be used to describe this moisture release. In the sand-bentonite sample, it can be theorized that pore-water was trapped in inter-aggregate pores and intra-aggregate pores. The inter-aggregate pores are a mixture of pores that exist between the sand particles and bentonite platelets. In a sand-bentonite specimen, there would be a wide range of inter-aggregate pore sizes. The wide gradual shape of the soil-water characteristic curve in the low suction range indicates this wide range of inter-aggregate pore sizes. The intra-aggregate pores consist of the pore spaces within the orientated bentonite platelets. Since these pores are much smaller, higher applied suctions were required to remove the pore-water. The sharp steep nature of the curve points to the uniform nature of the pore sizes.

The soil-water characteristic curves for the sand-bentonite specimens prepared with various molding water contents are shown in Fig. 3. These test results show that changes in the molding water content influenced the shape of the soil-water characteristic curve in a sand-bentonite mixture. For soil suctions ranging from 50 kpa to 3000 kPa, the sand-bentonite mixture prepared wet of optimum exhibited greater saturation than the soil specimens prepared to optimum and dry of optimum water content. Beyond 4000 kPa, the molding water content had little influence on the shape of the soil-water characteristic curve.

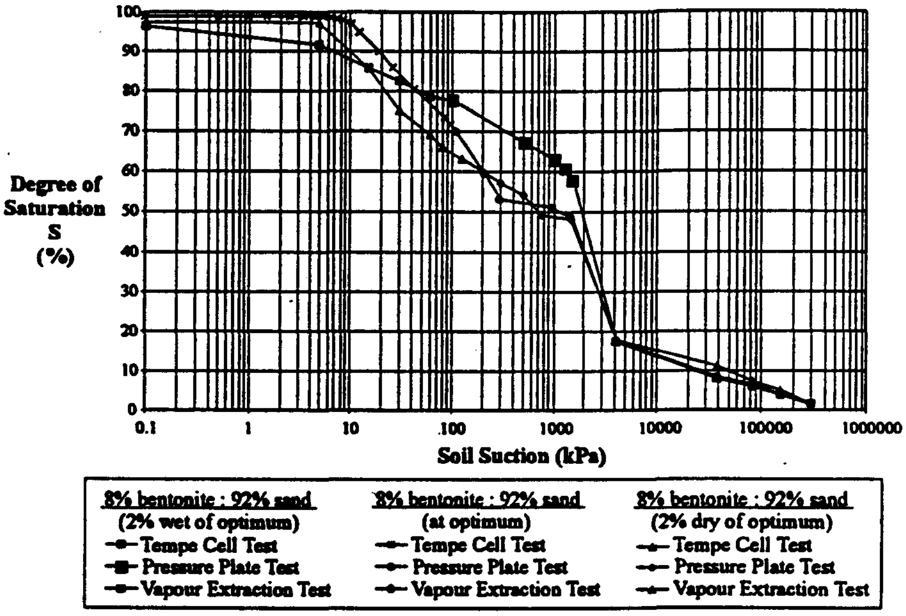

Fig. 3 Soil-water characteristic curves for sand-bentonite mixtures prepared with varying molding water contents

In the field, physicochemical and biological interactions will also contribute to moisture retention. However, the capillary model provides a good fundamental basis for understanding the general shape of a soil-water characteristic curves including the fundamental shape difference between curves for sand, silt, and clay-sized specimens.

Conclusions and Recommendations

The soil-water characteristic curves measured in this research indicated that sand-bentonite mixtures may provide a high degree of saturation even when a soil mixture is exposed to high soil suctions in the field. These findings may have significant economic implications for soil barriers designed in an area with minimal sources of native clay soils. It also suggests that it may be advantageous at some locations to purchase and transport small quantities of bentonite to the proposed waste containment site in order to improve the on-site soils, rather than performing a geotechnical program to find and transport marginal quality clay-based native soils from a nearby site.

References

[1] Geo-Slope International. *SEEP/W Version 4.05 User's Manual, finite element software for 2-D saturated-unsaturated seepage modelling*, Calgary, Alberta, Canada, (1997).

[2] MEND. *SoilCover User's Manual, Version 2.0.* MEND Report 1.25.1, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, (1996).

[3] Haug M.D. and Wong L.C. Impact of molding water content on the hydraulic conductivity of compacted sand-bentonite liner material. *Canadian Geotechnical Journal*, 29 (1992), 253-262.

[4] Fredlund D.G. and Rahardjo H. *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons Inc., New York, (1993), 517 pp.

[5] Stoicescu J.T. *Properties of Unsaturated Sand-Bentonite Mixtures used for Liners and Covers.* M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Canada, (1997), 244 pp.

[6] Stoicescu J.T., Haug M.D., and Fredlund D.G. The Soil-Water Characteristics and Pore Size Distribution of a Sand-Bentonite Mixture. *Proceedings of the 49th Canadian Geotechnical Conference*, St. John's, Newfoundland, Canada, Vol. 2 (1996), 721-728.