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ABSTRACT

A laboratory test program was conducted to evaluate the soil water characteristics of sand-bentonite specimens. Two sets of test specimens were prepared. Series 1 specimens consisted of ASTM C-109 sand prepared to optimum dry density using standard proctor compaction. Series 2 specimens were prepared by mixing 8% bentonite with C-109 sand, moisture conditioned, and compacted to optimum standard proctor density. The complete soil water characteristic curves were measured for the soil specimens using the tempe cell, pressure plate, and vapor extractors. The results of this test program showed that the addition of bentonite to a sandy soil caused a dramatic increase in moisture retention. In addition, the soil water characteristic curve for the sand-bentonite mixture displayed a bimodal shape. The soil water characteristic curves were modelled to determine the pore size distribution of the soil specimens. Series 1 specimens exhibited a single pore size distribution while series 2 specimens revealed a dual pore size distribution.

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INTRODUCTION

The soil water characteristic curves and pore size distributions for sand and sand-bentonite soils were evaluated in a laboratory test program. Previous research has shown that sand-bentonite mixtures provide good performance characteristics in saturated conditions (Haug and Wong, 1992). In many parts of the world, covers and liners exist in unsaturated conditions for nearly the entire duration of its design life. Therefore, the soil water characteristic curve for sand-bentonite mixtures would allow for improved modelling of barriers designed in an unsaturated environment. For this reason, a laboratory test program was established to assess the effects of bentonite addition on the moisture retention of a sandy soil. In addition, the relationships between the soil water characteristic curve and the pore size distribution were studied. The test program involved the measurement of soil water characteristics for two series of soil specimens prepared to optimum dry density using standard proctor compaction. Series 1 specimens consisted of ASTM C-109 sand while, series 2 specimens were comprised of 8% bentonite mixed with ASTM C-109 sand. The pore size distribution for each soil specimen were calculated from the soil water characteristic curve. The results of this test program show that the addition of bentonite to a sandy soil results in a dramatic increase in moisture retention. In addition, the pore size distribution for a soil mass can be used to approximate the air entry value and the general shape of a soil water characteristic curve.

THEORY

Many researchers have proposed theoretical and empirical equations to model the soil water characteristic curve. The most recent and noted of these models have been proposed by van Genuchten (1980), Ross and Smettem (1993), Zhang et al (1994), and Fredlund and Xing (1994). The theoretical basis of the soil water characteristic curve is developed based on an assumed pore size distribution. Most models that are developed to model the moisture retention curve assume that pore sizes within a soil mass can be described as a set of interconnected pores that are randomly distributed.

Fredlund and Xing (1994) presented empirical formulation used to model typical unimodal (S-shaped) soil water characteristic curves for soils. The model was developed based on empirical fits with a wide range of soils including clays, tills, silts, sands, and even mine tailings. Fredlund and Xing (1994) showed that the experimental results were in excellent agreement with the predicted moisture retention for all of these soil types. The formulation proposed by Fredlund and Xing (1994) relating the volumetric water content to soil suction is as follows:

$$\theta = \theta_s * \left[\frac{1}{ln[\, e + (\psi / a)^{n} \,]} \right]^{m} \qquad [1]$$

where

θ = volumetric water content

θs = saturated volumetric water content

e = 2.71828...

ψ = soil suction

a, n, m = fitting parameters

Fredlund and Xing (1994) developed a curve fitting program, CFVIEW, which uses eq. 1 along with the soil moisture lab data to provide a best-fit soil water characteristic curve for suctions ranging from 0 to 10^6 kPa. The program varies the curve fitting parameters a, n, and m along with a least-squared adjustment calculation to obtain the best-fit curve for the lab data.

The pore size distribution for a soil can be determined by calculating the derivative of the formulation used to describe the shape of the soil water characteristic curve. The derivative of eq. 1 yields the following distribution:

$$f(\psi) = \frac{m * n * (\psi / a)^{n-1}}{a * [\, e + (\psi / a)^{n} \,] * (\, log[\, e + (\psi / a)^{n} \,] \,)^{m+1}} \qquad [2]$$

where

$f(\psi)$ = probability of pore water to be released from a soil mass at a particular suction.

By using the capillarity theory, it is possible to relate the pore size within a soil mass to the suction applied to the soil mass. Equation 3 shows the relationship between matric suction, (u_a-u_w), and pore radius, r.

$$(u_a - u_w) = \frac{2 * Ts}{r} \qquad [3]$$

where

(u_a-u_w) = matric suction

Ts = surface tension of water = 0.07275 N/m at 20°C

r = pore radius

All soils do not possess a unimodal soil water characteristic curve. Durner (1994), Zhang and van Genuchten (1994), Ross and Smettem (1993), Othmer et al (1991) suggested that dual-porosity soil specimens exhibit a bimodal soil water characteristic curve. Durner (1994) suggested the bimodal shape is due to the following:

1) the two pore size distributions are emptying at their equivalent capillary pressure,
2) some water loss in the high suction range may be associated with thinning of the water films on the soil matrix surfaces and at particle contact points.

Models developed by Othmer et al (1991), Ross and Smettem (1993), and Durner (1994) were based on superposition of unimodal curves to produce a bimodal curve.

LABORATORY TEST PROGRAM

Two series of test specimens were prepared in this test program. Series 1 specimens consisted of ASTM C-109 sand moisture conditioned to an optimum water content of 8% and compacted using standard proctor compaction to an optimum dry density of 1.65 Mg/m^3. Series 2 specimens consisted of ASTM C-109 sand mixed with 8% BARAKADE-90 bentonite (based on total dry mass) produced by the Bentonite Corporation. Series 2 specimens were moisture conditioned to optimum water content of 15% and compacted using standard proctor compaction to an optimum dry density of 1.78 Mg/m^3. Series 1 and 2 specimens were saturated in an oedometer to ensure constant volume during the saturation process. The saturated soil specimens were placed into three separate apparatuses, shown in table 1, to measure the relationship between volumetric water content and soil suction. To ensure testing reproducibility, the soil water characteristic curves for series 1 and 2 were completed six times.

Table 1. The equipment used to measure the soil water characteristics of a soil

Equipment Type	Range of Suctions Tested (kPa)
Tempe Cell	0 - 300
Pressure Plate	300 - 1500
Vapor Extractor	4000 - 300000

Fredlund and Rahardjo (1993) provides a description of the components and testing procedures for the tempe cell and pressure plate. The vapor extractor method utilizes a series of sealed chambers containing saturated salt solutions to control the relative humidity within the chamber. The relative humidity in the chamber provides an osmotic suction to the soil specimens positioned above the salt solution. The sand-bentonite specimens required 8 weeks to equilibrate in the vapor extractors.

TEST RESULTS

The soil water characteristic curves for ASTM C-109 sand and the bentonite modified sand are shown in figures 1 and 2, respectively. These figures show the relationship between the volumetric water content and the soil suction applied to the soil mass. The test results show that the addition of bentonite to the sandy soil caused a dramatic increase in moisture retention of the soil, especially in the high suction range (beyond 500 kPa).

During the laboratory testing program, the time required for equilibrium to be established between the pore-water within the soil mass and the applied suction varied for the two soils tested. The ASTM C-109 sand required only a few hours to equilibrate at each suction interval tested. As a result, the entire soil water characteristic curve shown in figure 1 required only 2 days to complete. Conversely, the bentonite modified sand required up to four days to equilibrate at each suction range. Thus, the entire soil water characteristic curve shown in figure 2 required nearly 8 weeks to complete.

These results suggest that major improvement in the long-term moisture retention of sandy soils can be obtained with the addition of bentonite to the soil mass.

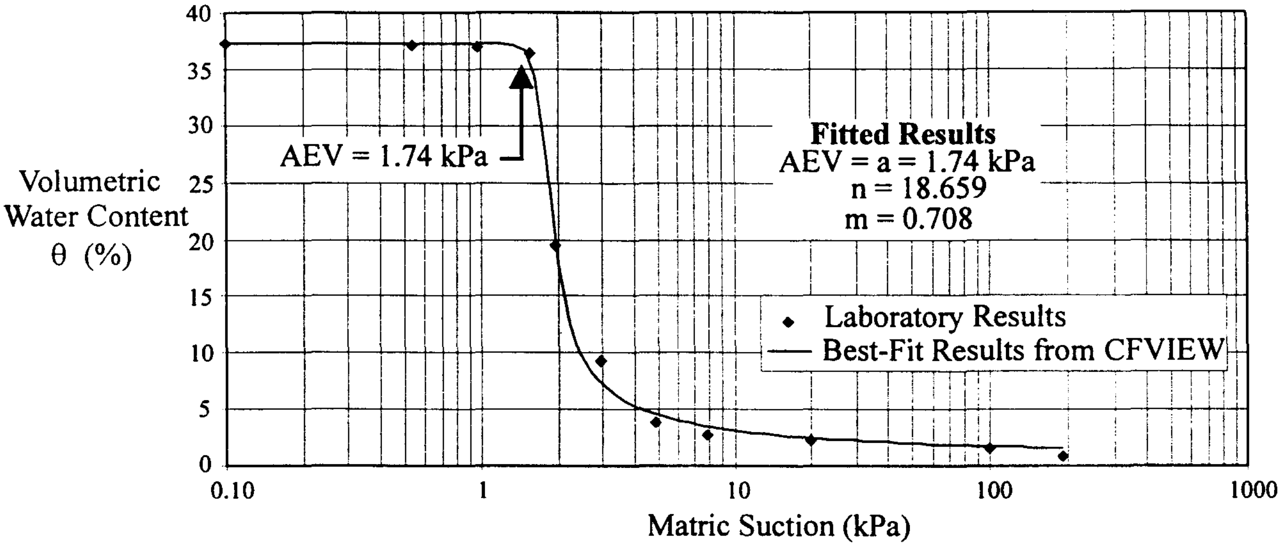

FIGURE 1. The soil water characteristic curve for ASTM C-109 sand prepared to optimum dry density using standard proctor compaction.

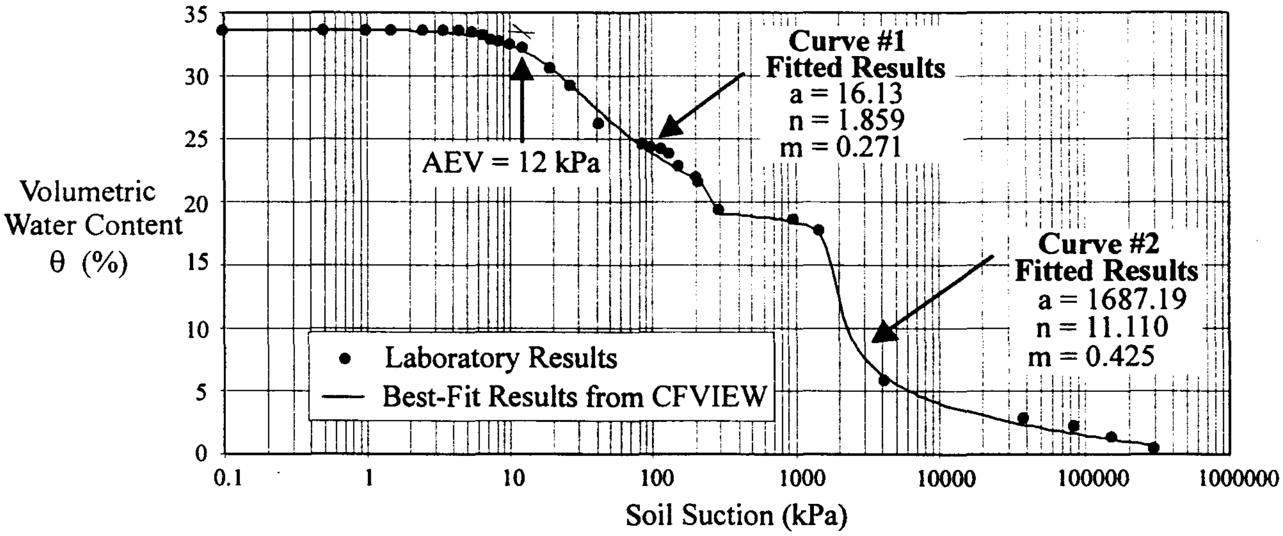

FIGURE 2. The soil water characteristic curve for ASTM C-109 sand modified with 8% bentonite prepared to optimum dry density using standard proctor compaction.

A best-fit analysis was performed on the soil water characteristic curves using eq. 1. The computer program CFVIEW was used in conjunction with the laboratory data to assess the fitting parameters a, n, and m associated with the best-fit curve. For ASTM C-109 sand, the fitting parameters modelled from the soil moisture lab data were: a = 1.74, n = 18.66, and m = 0.71.

The soil water characteristic curve for the mixture of ASTM C-109 sand with 8% bentonite exhibited a bimodal shape. The first step in modelling the laboratory data involved separating the curve into two distinct unimodal (S-shaped) curves as shown in figure 2. Each unimodal soil water characteristic curve was modelled separately using eq. 1. As a result, two sets of curve fitting parameters (a, n, and m) exist. One set of parameters were used to fit the soil water characteristic curve in the low suction range, while another set of parameters were used for the curve in the high suction range. The two soil water characteristic curves were superimposed to provide a complete bimodal fit of the measured data. The fitting parameters for the bentonite modified sand are summarized in figure 2.

The air entry values for the ASTM C-109 sand and the bentonite modified sand were determined to be 1.74 kPa and 12 kPa, respectively. For the ASTM C-109 sand, the a parameter was equivalent to the air entry value of the sand. However, the a parameter for the bentonite modified sand was slightly larger than the air entry value of the soil. Since the a parameter is defined as the inflection point of the soil water characteristic curve, poorly graded soils exhibiting a sharp drop in the soil water characteristic curve will possess an air entry value approximately equal to the a parameter. For soils exhibiting a gradual drop in soil moisture, the a parameter will be slightly larger than the air entry value of the soil.

The pore size distributions for the ASTM C-109 sand and the bentonite modified sand are shown in figures 3 and 4, respectively. The pore size distribution was calculated by utilizing the curve fitting parameters (a, n, and m) and eq. 2. The pore size distribution for ASTM C-109 sand exhibited a sharp rise with a maximum frequency occurring at the air entry value, 1.74 kPa. The sharp nature of the curve suggests a soil mass with a uniform gradation. The predominant pore size in the soil structure was determined to be 80 μm. The sharp drop in the soil water characteristic curve for the ASTM C-109 sand occurred over the same range of suctions as the sharp rise in the pore size distribution. These results show that the pore size distribution is related to the soil water characteristic curve. Furthermore, the pore size distribution can be used to approximate the air entry value and the general shape of a soil water characteristic curve.

The bentonite modified sand displayed a dual pore size distribution as shown in figure 4. The predominant pore sizes within the soil mass were 10 μm and 0.8 μm. The maximum frequencies associated with distributions 1 and 2 were 12 kPa and 1800 kPa, respectively. The shape of the pore size distribution corresponded to the shape of the soil water characteristic curve for the bentonite modified sand. In figure 4, pore size distribution 1 is a wide gradual curve extending over a large range of pore sizes. This finding suggests that distribution 1 consists of a mixture of sand and bentonite pores that exhibit moisture retention over a wide range of suctions. The shape of the soil water characteristic curve for distribution 1 is also wide and gradual which provides further evidence of a mixture sand and bentonite pores. Conversely, pore size distribution 2 is a sharp curve extending over a narrow range in suctions. This result suggest that distribution 2 consists of small uniformly-sized bentonite pores exhibiting capillaric moisture retention of approximately 1800 kPa. The soil water characteristic curve in the high suction range supports this finding due to its sharp drop between 1800 kPa and 2000 kPa. Overall, these results further reinforce the fact the pore size distribution can be used to approximate the air entry value of a soil mass and explain the general shape of the soil water characteristic curve.

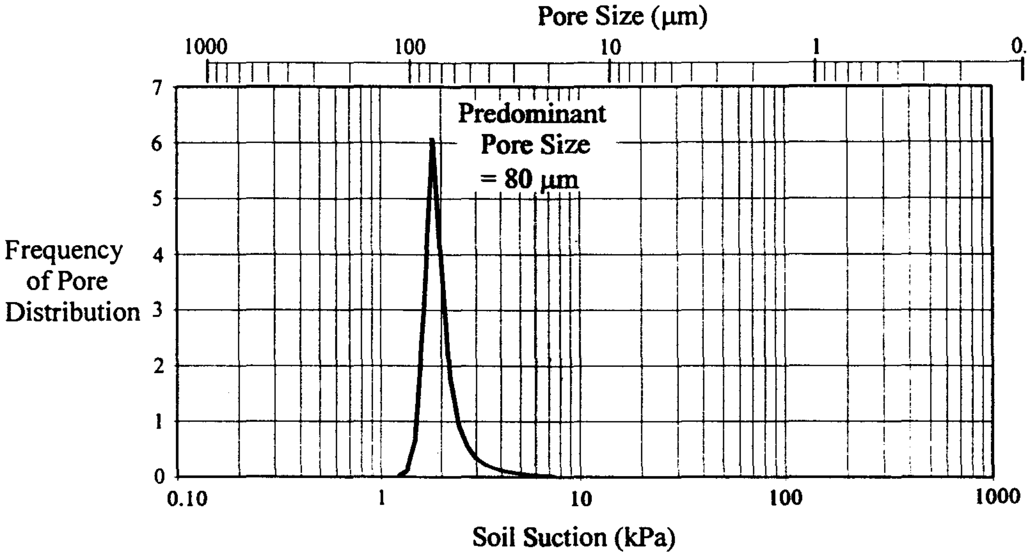

FIGURE 3. The pore size distribution for ASTM C-109 sand.

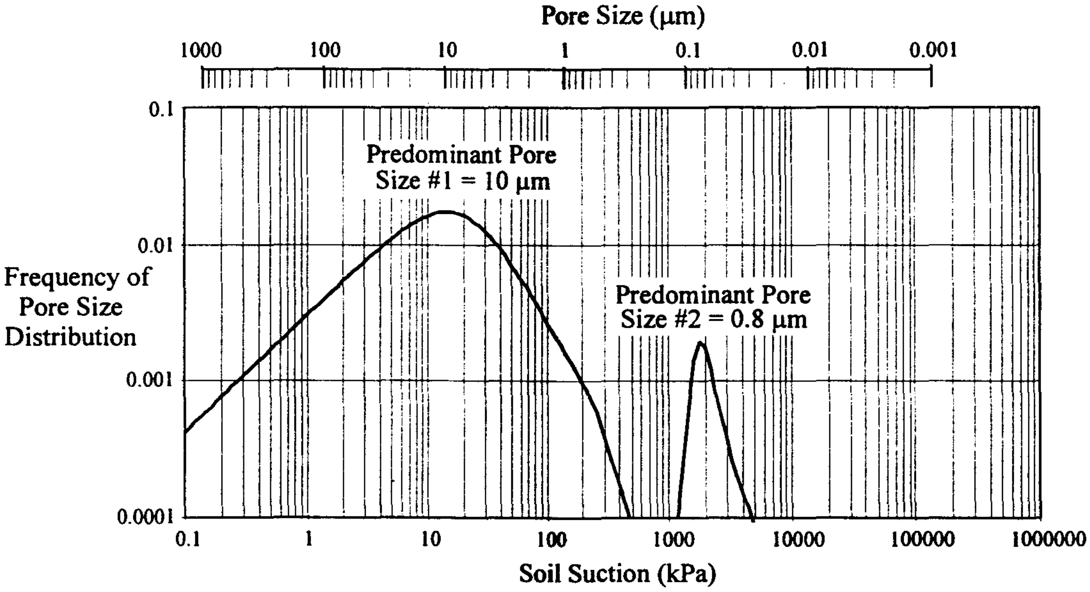

FIGURE 4. The pore size distribution for ASTM C-109 sand modified with 8% BARAKADE-90 bentonite.

SUMMARY AND CONCLUSIONS

In this research, it was determined that the addition of bentonite to a sandy soil results in a dramatic increase in soil moisture retention. The importance of this finding can be related to the construction of a cover or liner in a sandy environment. A barrier constructed with soil possessing good moisture retention will exhibit excellent flexibility and long term performance under unsaturated field conditions. In addition, it may be more economical to construct the barrier with commercial bentonite and on-site sand than to construct the barrier using a large amount of fine-grained soil transported from a separate site.

Another finding in this research is that the pore size distribution of a soil mass can be used to approximate the shape of the soil water characteristic curve for the soil. A steep and narrow pore size distribution would indicate a uniform pore size within the soil mass resulting in a soil water characteristic curve with a sharp drop at the air entry value. A wide gradual pore size distribution would indicate a well-graded mixture of pore sizes within the soil mass resulting in a soil water characteristic curve with a gradual drop in water content after the air entry value.

An engineer could use the pore size distribution to determine at which suctions a soil would lose most of its capillary pore water. Another advantage of the pore size distribution is that it would allow the engineer to approximate the shape of the soil water characteristic curve for a particular soil. Since measuring the pore size distribution is less time-consuming than measuring the soil water characteristics of a soil, it becomes obvious as to the advantages of using the pore size distribution in a design program. For example, the pore size distribution could be used to assess many types of soil mixtures for use as a cover or liner. An engineer could use the results from the pore size distribution test to rule out soil mixtures which would not provide adequate moisture retention under field suctions. Based on the recommendations from the engineer, the soil water characteristic curves could be measured for the most desirable soil mixtures for modelling purposes.

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