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Test Study on Soil-Water Characteristic Curve (SWCC) of Sandy Soil-Cement-Bentonite Mixtures

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Abstract

The soil-water characteristic curve (SWCC) of unsaturated soils is considerably important in the analysis of geotechnical engineering and geo-environmental engineering problems involving soils that remain under partially saturated conditions. The SWCC reflects the behavior of unsaturated soils with regards to its hydraulic conductivity, shear strength, volume change behavior, and modeling of pollutant migration. In this paper, test studies on SWCC of sandy soil, which was improved by the mixing of Portland cement and bentonite, are presented. A miniature KU tensiometer was used to measure the suction of soil, soil-cement and soil-cement-bentonite samples. Two types of soil were used to represent samples of sandy soils in Thailand and were collected from Chonburi and Huahin. The mixed proportions are as follows: cement content of 220 kg/m^3, water cement ratio of 2 and bentonite water ratio of 0.05. Results show that the influence of grain size distribution of soil and additives affects the SWCC. The SWCCs obtained from suction test can be used to estimate permeability function (k-function) curves. Moreover, the capillary parameters and relative permeability parameters for the soil and soil cement are determined from SWCC and k-function, respectively. These parameters are the model parameters for simulating the pollutant migration.

Keywords: Sandy soil; soil water characteristic curve; permeability function curve; model parameters; pollutant migration

1. Introduction

Many geotechnical engineering and geoenvironmental engineering problems frequently occur in the soil above groundwater level which is called unsaturated soil. These problems are slope failure in rainy season, foundation behavior in wetting area, and contaminant migration in the vadose zone, for example. Moreover, the compacted soil in road construction is always in a condition of unsaturated soil. In particular, Thailand locates in a tropical climate area where the soil is generally unsaturated at most time of the year, and the pore pressure is negative (i.e., soil suction). The behavior of the unsaturated soil can be described from soil water characteristic curve

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(SWCC). SWCC explains the water holding capacity in the soil under different matrix suction levels. The water content can be defined as the amount of the water contained within the pores of the soil. In geotechnical engineering, the gravimetric water content is commonly used; it is a ratio of the mass of water to the mass of solids and pore air pressure and is defined as equal to zero. However, in soil science, the volumetric water content is commonly used; it is the ratio of the volume of water to the total volume of soil, and the soil pore pressure of unsaturated soil is always negative (less than atmospheric pressure). SWCC can be used to derive the unsaturated soil property functions for the coefficient of permeability, shear strength and volume change (Barbour [1], Fledlund ed al. [2]). The typical SWCC of unsaturated soil can be divided into three stages which are capillary saturation, desaturation or funicular zone and residual saturation zone (Vanapalli et al. [3], Sillers et al. [4]). Tuller and Or [5] described the SWCC as an important hydraulic property that has a significant effect on soil texture and soil structure as well as other constituents, including organic matter. The solute and contaminant transport in the environment must be predicted to determine the SWCC. They show typical SWCCs for soils with different textures to demonstrate the effect of porosity (saturated water content) and the varied slopes of the relationships resulting from variable pore-size distributions. In addition, Zhou and Yu [6] found that water content and stress state have a greater influence on the SWCC than other effects, but their influence tends to decrease when suction increases.

According to the importance of SWCC in the engineering problems, this paper focuses on the SWCC determination of sandy soil-cement-bentonite samples by suction test. The aim of this study is to investigate the effect of the grain size distribution and the additive on SWCC including the application of the results for the simulating of the pollutant migration.

2. Experimental Conditions

2.1 Experimental Materials

Two types of soil were used to represent samples of sandy soils in Thailand and were collected from the provinces of Chonburi and Huahin. Chonburi soil is artificial foundry sand; i.e., AFS35. AFS (American Foundrymen's Society Average Fineness Number) was used to denote the relative grading of sand, and it was calculated using the old BS mesh numbering system for sieves. Huahin soil was the natural sandy soil from Rajamangala University of Technology Rattanakosin Wangklaikangwon. The characteristics of both soils, including soil-cement and soil-cement-bentonite, are shown in Table 1. The mixed proportion of soil-cement-bentonite samples are as follows: cement content of 220 kg/m^3, water cement ratio of 2 and bentonite water ratio of 0.05 (Nicholson et al. [7]).

Table 1. The characteristics and basic properties of the experiment materials

Properties	Sandy Soil		Soil-Cement		Soil-Cement-Bentonite	
	Chonburi	Huahin	Chonburi	Huahin	Chonburi	Huahin
D10, mm	0.222	0.063	-	-	-	-
D60, mm	0.562	0.376	-	-	-	-
Cu	2.53	5.29	-	-	-	-
USCS	SP	SM	-	-	-	-
Specific gravity	2.69	2.62	2.65	2.67	2.60	2.68
Porosity	0.41	0.37	0.44	0.45	0.42	0.44
Dry density, g/cm^3	1.60	1.64	1.45	1.46	1.51	1.52

2.2 SWCC Determination

The suction of soil and soil cement samples were measured by KU (Kasetsart University) tensiometer which can measure the values of suction from 0 to 100 kPa (Jotisankasa et al. [8]). Fig. 1 shows the set up for suction-monitoring on soil and soil cement samples. The point-wise measurement was used to be the method in this study that Tapparnich [9] proposes the process of testing as follows: (1) takes specimen into PVC ring to prevent water evaporation from the samples as shown in Fig. 2 and soak it for about four days (2) after that, measure the dimension and weigh the specimen (3) install the tensiometer at the top of the specimen for measuring the suction including measuring and weighing it after measurement is finished, (4) reduce the weight of the specimen about 2 or 3 grams and cover and cure it for 24 hours (5) perform stage 3 and 4 again until water content is close to zero or the suction is close to 100 kPa and (6) dry in an oven to determine the final water content. After the experiment, the test data were used to construct soil water characteristic curve (SWCC) by using a Van Genuchten [10] formula as shown in eq (1).

$$\theta = \left[\frac{1}{1+(\alpha h)^n} \right]^m (\theta_s - \theta_r) + \theta_r \tag{1}$$

where θ = volumetric water content (vwc); θ_s = saturated vwc; θ_r = residual vwc; h = suction head; α and n = curve fitting parameters; m = 1-1/n

Fig. 1. Experimental set up for suction-monitoring

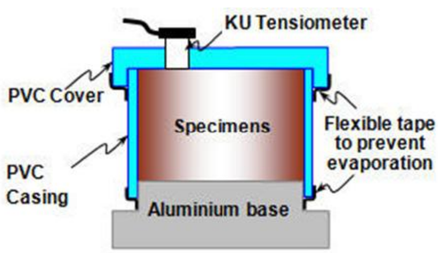

Fig. 2. Sample preparation

3. Experimental Results Analysis

3.1 SWCCs of Sandy Soil-Cement-Bentonite Mixtures

According to suction test, the SWCC fits of sandy soil, soil-cement and soil-cement-bentonite samples using the mathematics models proposed by van Genuchten are shown in Fig 3. The van Genuchten parameters for fitting SWCC are determined by using Solver program. As a result, soil type and particle size of soil affect the soil suction. If the particle size of soil is smaller, the suction is higher. The suction of soil in drying process is greater than the wetting process because when the water is drained out in the drying process, the water content decreases and the suction increases; while when the water infiltrates the soil in wetting process, the water content increases and the suction decreases. SWCC of soil cement samples is more slope than sandy soil. It shows if the soil pore is smaller, the suction is higher; and it is corresponding to previous researches.

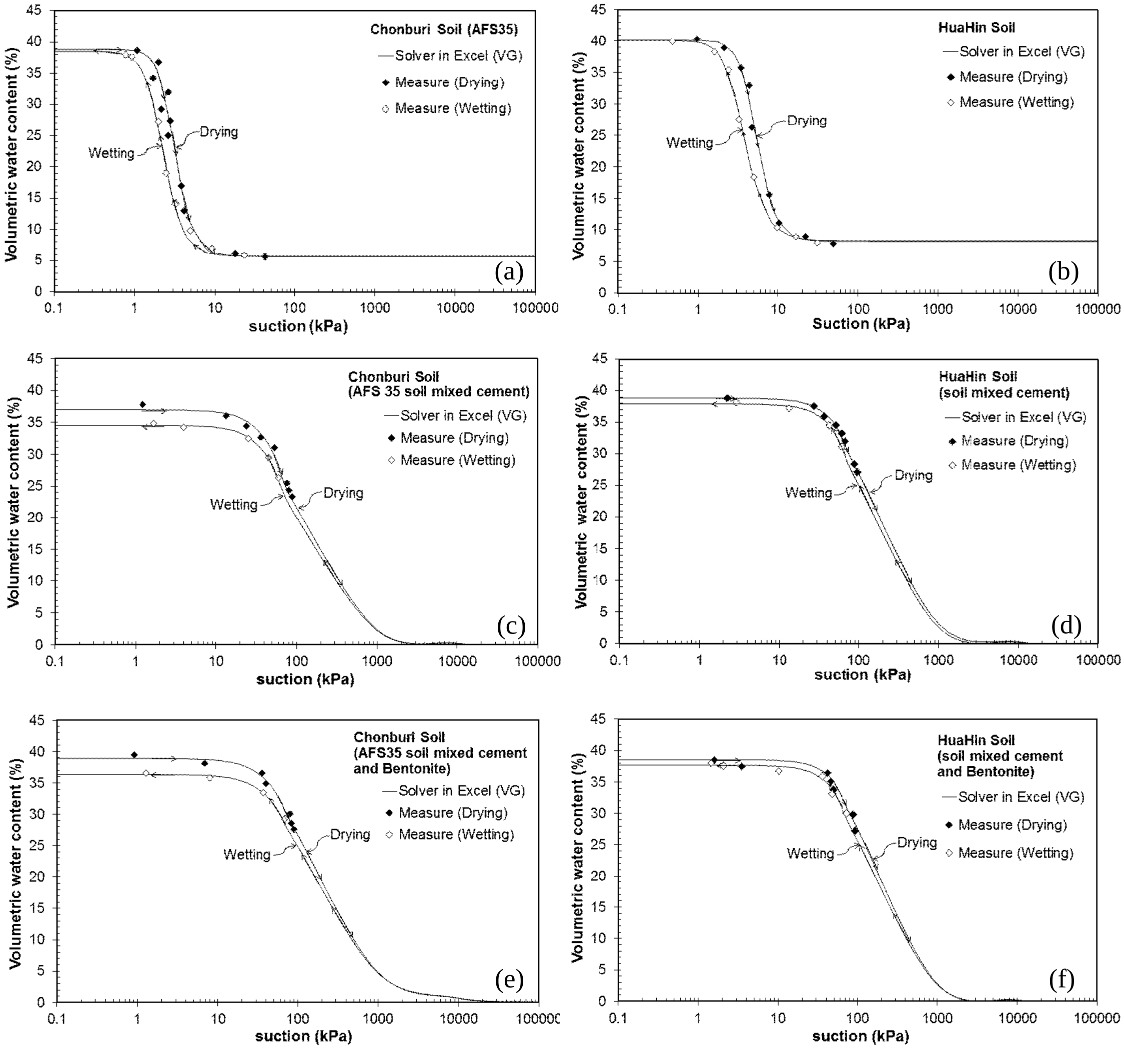

Fig. 3. Soil water characteristic curves of sandy soil, soil-cement and soil-cement-bentonite samples

3.2 Determination of Permeability Function using SWCC

The SWCC can be used to estimate the permeability function (k-function) using the Jackson [11] formula as shown in eq (2). The k-function curves for sandy soil and soil-cement samples are shown in Fig. 4. For soil-cement-bentonite, the k-function curves are not shown because the saturated hydraulic conductivity is not determined.

$$K_i = K_s \left(\frac{\theta_i}{\theta_s} \right)^c \frac{\sum_{j=1}^{m} \left[(2j + 1 - 2i) \psi_j^{-2} \right]}{\sum_{j=1}^{m} \left[(2j - 1) \psi_j^{-2} \right]} \tag{2}$$

where K_i = hydraulic conductivity at volumetric water content; K_s = saturated hydraulic conductivity; m = number of increment of volumetric water content; ψ = suction head at midpoint of each volumetric water content increment; i and j = summation indices; c = 1

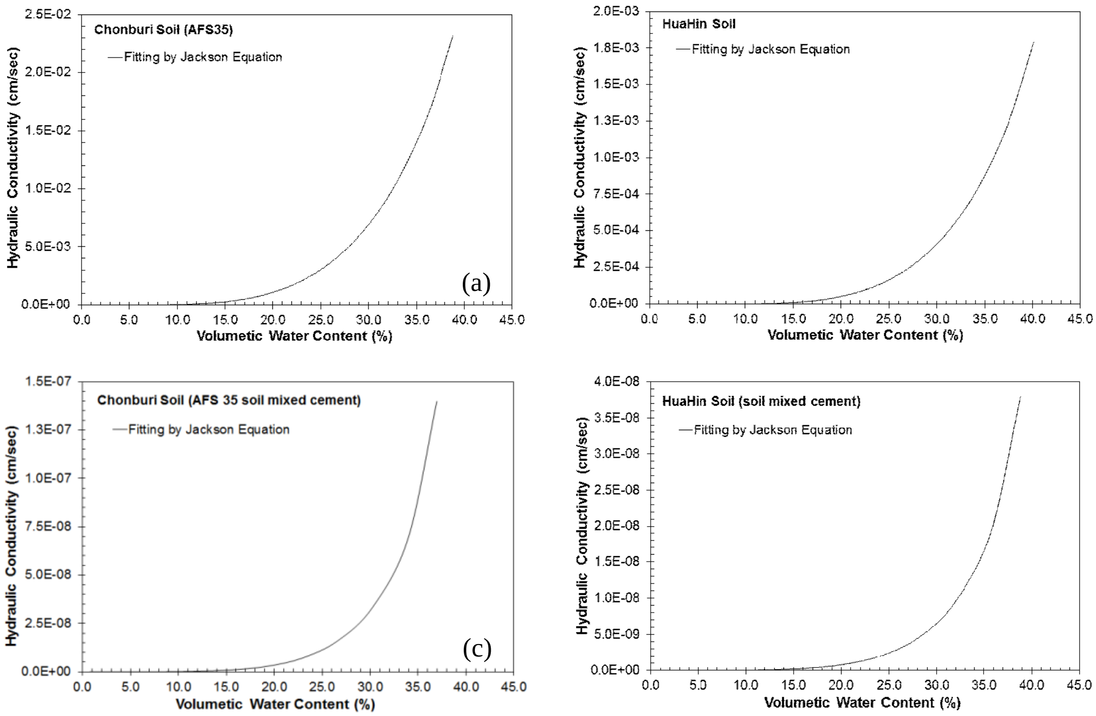

Fig. 4. Permeability function curves of sandy soil and soil cement

4. Numerical Simulation Results

A case study of pollutant migration is simulated to show how to use the results from SWCC determination to engineering problems. The numerical simulator utilized in this study is TMVOC, which was used within PetraSim. The TMVOC simulator is based on the code of TOUGH2, which was developed by Pruess and Battistelli [12].

4.1 Determination of Model Parameters for Simulating Pollutant Migration

In this study, Chonburi soil and Chonburi soil mixed cement are used as the materials in simulation. The input parameters required for the numerical simulation are grouped into three sets as described below:

1. Properties of Chonburi soil and Chonburi soil mixed cement, which are the particle density, the porosity and the hydraulic conductivity were the same as the properties of experimental materials used in centrifuge test as described previously.
2. The static two-phase S-P relationships of the soil and soil cement (NAPL-water and air-NAPL) were estimated from the SWCCs (air-water) using a scaling factor method proposed by Leverett [13] and Parker et al. [14], as shown in Fig. 5. The capillary pressure parameters were determined using SWCCs for the hree-phase system. The relative permeability parameters were estimated using the permeability function (k-S). These model parameters for the soil and soil cement were determined using the van Genuchten model (1980) and the Parker model (1987) as reported in Table 2.
3. Typical chemical properties of the pollutant were found in Reid et al. [15]. In this study, liquid paraffin was used as the pollutant.

Table 2. Model parameters for tested sandy soil and soil cement

Description	Chonburi soil	Chonburi Soil mixed cement
Relative permeability parameters for the Parker's model (1987)		
Limiting saturation S_m	0.345(F1)	0.345(F1)
Fitting parameter, n	3(A)	3(A)
Capillary pressure parameters for the van Genuchten's model (1980)		
$\lambda = m = 1\text{-}1/n$	0.770(C1)	
Residual water saturation, S_{lr}	0.147(F2)	
$1/P_0 = \alpha/\rho_w g$ ($1/Pa^{-1}$)	$3.406x10^{-4}$ (C1)	
Maximum value for capillary pressure, P_{max} (Pa)	$4.215x10^{-4}$ (M)	
Satiated water saturation, S_{ls}	1(F2)	
Capillary pressure parameters for the Parker's model (1987)		
Limiting saturation, S_m		0(F2)
Fitting parameter, n		2.045(F2)
Strength parameter for air-NAPL, $\alpha_{an}= \alpha\times\beta_{an}$		0.336(C2)
Strength parameter for NAPL-water, $\alpha_{nw} = \alpha\times\beta_{nw}$		0.221(C2)

Strength parameter is the parameter describing the shape of the saturation-capillary head curve.

α is a curve fitting parameter; β_{an} (= σ_{aw}/σ_{an}) is scaling factor for air-NAPL; β_{nw} (= $1/(1-1/\beta_{an})$) is scaling factor for NAPL-water; **F1** is a curve fitting parameter of k-function curve; **F**2 is a curve fitting parameter of S-P curve; **A** is recommended by Rasmusson; **C1** is calculated from van Genuchten curve fitting parameter (n); **M** is measured from a suction test; **C2** is calculated from a fitting parameter multiply by a scaling factor (Rasmusson)

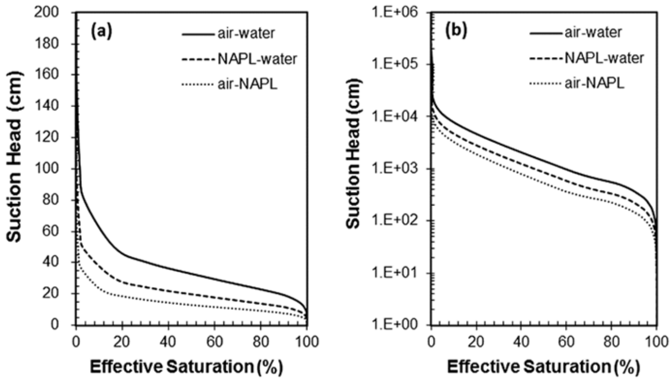

Fig. 5. Three two-phase the scaled saturation-capillary head (S-P) relations for (a) sandy soil and (b) soil cement

4.2 Description of Problem

The two-dimensional sections of the numerical models were generated as the cross sections of 26.30 m. long by 8.00 m. deep. The groundwater levels located at 4.05 m. deep from ground surface. The grid spacing of the numerical models, in the vertical and the horizontal directions, was based on the groundwater levels and the thickness of the wall as shown in Fig 6. Simulations were performed under isothermal conditions. The atmospheric boundary condition was fixed at the grid top and specified as the constant absolute pressure of 1.013×10^5 Pa. A soil grain specific heat of 50,000 J/kg °C and a porosity of 0.999 were assumed for the atmospheric grid blocks because effects of the inner domain on the atmospheric boundary are negligible due to the volume of the atmospheric boundary (Rasmusson [16]). The walls were modelled as the Chonburi soil-cement material. The simulated pore pressure distributions were applied to the boundary condition and the model was run to reach the steady-state condition before introduction of the pollutant.

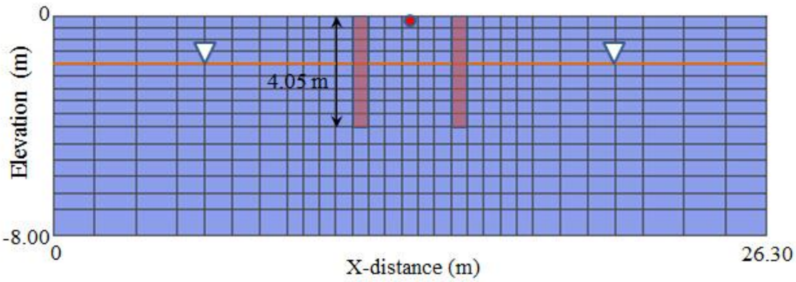

Fig. 6. The two-dimensional sections of the numerical models

4.3 Plume Migration Distribution

The computed pollutant saturation contour of plume migration is shown in Fig. 7. The numerical models simulated observed effects of the wall on the plume migration distribution for the condition of no groundwater flow. The pollutant plume can penetrate below the groundwater level; however, the amount of the pollutant near the wall tip was minimal. A large amount of LNAPL was retained above the groundwater level, and some LNAPL was trapped in the unsaturated zone. The plume migration distribution was symmetrical. The plume migration distribution in the numerical simulation depends on the capillary and the relative permeability parameters, including some of the chemical properties of the LNAPL. Overall, the result from the numerical simulations confirms the effective performance of the soil cement wall as a containment barrier.

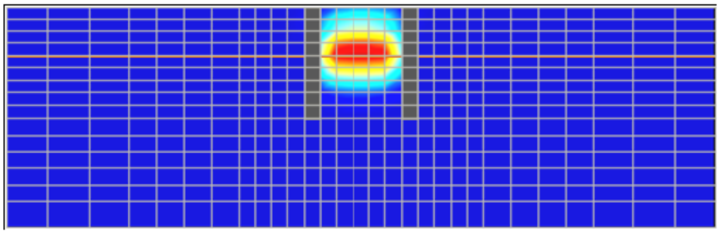

Fig. 7. Pollutant plume migration

5. Conclusion

Utilizing the KU-tensiometer apparatus, the SWCCs of sandy soil-cement-bentonite sample between the degrees of saturation versus suction are determine and analyzed. The effect of different sandy soils and different additives are investigated. Results show that grain size distribution of soil and additive affect the SWCCs. If the particle size of the soil is smaller, the suction is higher. When the water content increases, the suction decreases. For sandy soil-cement mixtures, the capillary height is greater than that of sandy soil without cement mixture while the permeability decreased. For sandy soil-cement-bentonite mixtures, the capillary height is greater than that of sandy soil-cement mixture, and the permeability is more decreased. Results confirm that greater cement content and bentonite content leads to greater relative filling ratio of pores, which needs a more effective method to measure the suction. Moreover, the SWCCs can be used for estimating the model parameters to investigate the behavior of the pollutant migration. The result from numerical simulation shows the pollutant did not migrate through the soil-cement wall, indicating that the walls were effective as a containment barrier.

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