An estimation of the soil water characteristics curves of Trinidad's expansive clays

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Abstract. Volume change behaviour of expansive clays has been one of the leading causes of damage to civil infrastructures worldwide. Contributing factors that lead to failures relate to changes in water content within the soil. Variations of water content can vary significantly based on an area's climate regime. Trinidad has two seasons, the dry season (January to June) and the wet season (July to December). This variation leads to volume changes of expansive clay, where they exist mainly within the central and south regions of Trinidad. These areas are densely populated by residential and commercial buildings, which can be susceptible to damages from unsaturated expansive clays. The Soil Water Characteristic Curve (SWCC) for expansive clays is critical to estimate their unsaturated properties for the analysis of water flow movement. This study investigates the SWCCs for two expansive clay soil types in Trinidad. A WP4-T (Water Potential Measurement) is used to measure soil suction. The shrinkage curve (SC) test is conducted to consider the volume change of soil. The Fredlund and Xing (1994) SWCC equation and Fredlund and Zhang (2013) SC equation are used to fit the measured data. The SWCCs in terms of gravimetric and volumetric water contents and degree of saturation are compared. It is found that the normalised degree of saturation SWCC can provide a better display of the SWCC and estimation of the air-entry value.

1 Introduction

Expansive soils are widely distributed in many arid and semi-arid areas throughout the world. The dramatic volume change behaviour (swell/shrink) of expansive soils associated with environmental or manmade changes contribute to damages to civil infrastructures, for example, significant failures to buildings on shallow foundations, retaining structures and naturally sloping landmasses. In the central and southern regions of Trinidad, expansive clays are predominant with varying degrees of high to low plasticity [1-2]. Since Trinidad has two seasons, such as the dry season (January to June) and the wet season (July to December), these changes in climate conditions cause moisture change within expansive clays and consequently changes in volume.

The Soil Water Characteristics Curve (SWCC), defining the amount of water in soil for different values of soil suction, has been used for the estimation of unsaturated soil property functions in geotechnical engineering practice. Typically, the SWCC is determined with the assumption that the soil does not significantly change volume as soil suction is changed [3-4]. However, expansive clays undergo considerable volume change with changes in soil suction. Several researchers recently recognised that the volume change in expansive soils has a considerable influence on the measured SWCC represented in terms of volumetric water content or degree of saturation. Therefore, caution is exerted in

selecting the measured data with a volume change correction [5-12].

This paper investigates the SWCC for two expansive clay soil types in Trinidad. A WP4-T (Water Potential Measurement) was used to measure soil suction and the corresponding gravimetric water content was obtained. The shrinkage curve (SC) test was conducted to obtain the relationship between the gravimetric water content and the instantaneous void of the soil. The Fredlund and Xing [3] SWCC equation and Fredlund and Zhang [11] SC equation are used to obtain the SWCCs in terms of gravimetric and volumetric water contents, and degree of saturation.

2 Methodology

2.1 Test soils

The soils tested in this study are Ecclesville clay and Brasso clay located in central Trinidad. The basic properties of these soils are shown in Table 1. The soils are classified as CH, based on USCS (Unified Soil Classification System), with plasticity index (PI) of 36 and liquid limit of 60. Both soils have an overall high percentage of fines (silt and clay) as compared to sand and gravel. The soils were chosen for their known volume change in response to changes in soil suction.

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Table 1. Basic properties of the soils investigated in this study.

Soil	Ecclesville clay	Brasso clay
USCS classification	CH	CH
Sand (%)	7	0
Silt (%)	68	64
Clay (%)	24	36
Liquid limit (%)	60	61
PI (%)	36	36
Dry unit weight (kN/m ³)	21.2	21.0
Specific gravity	2.61	2.56

2.2 Gravimetric water content and soil suction

In this study, the WP4-T (Water Potential Measurement) was used to measure soil suction for the expansive clays. Soil samples were initially dried, crushed and sieved through the No. 40 sieve, and then mixed with water near to their liquid limit. Mixed soil samples were pasted into the measuring sample cup of the WP4-T and readings were taken between the sample conditions being wet to air-dry. The corresponding gravimetric water content was also measured. Fig. 1 shows the WP4-T equipment with a typical soil sample.

Fig. 1. Soil samples tested using the WP4-T.

The Fredlund and Xing [3] equation (Equation 1) was used to fit best the data points obtained from test results,

$$w(\psi) = w_s \left[1 + \frac{\ln \left(1 + \frac{\psi}{h_r} \right)}{\ln \left(1 + \frac{10^6}{h_r} \right)} \right] \left[\frac{1}{\ln \left[\exp(1) + \left(\frac{\psi}{a_f} \right)^{n_f} \right] \right]^{m_f}} \right] \quad (1)$$

where $w(\psi)$ = gravimetric water content at any specified suction, ψ ; w_s = saturated gravimetric water content; h_r = residual soil suction; and a_f , n_f , and m_f = curve-fitting parameters. The fitting parameters (a_f , n_f , and m_f) were determined using the MATLAB's curve fitting module [13]. The value of a_f represents the air-entry value (AEV -kPa) from this SWCC.

2.3 Shrinkage curve test

Volume changes of the test soils during suction change were measured and taken into account for establishing the SWCCs. Soil samples near the liquid limit, similarly prepared for the gravimetric water content SWCC test, were also used. The shrinkage curves were obtained experimentally from measuring the volume of initially wet soil to air-dry. The wet soil samples, as shown in Fig. 2, were placed into stainless steel rings of known dimensions, which has an approximate diameter of 40 mm and height of 20 mm. As the soil within the ring dries, the water content is calculated from measuring the water loss and the corresponding volume change from measurements of diameters and heights using a micrometer gauge.

Fig. 2. Soil samples prepared for the shrinkage test.

The Fredlund and Zhang [11] equation (Equation 2) was used to best fit the data points obtained from the SC test,

$$e(w) = a_{sh} \left[\frac{w^{c_{sh}}}{b_{sh}^{c_{sh}}} + 1 \right] \left(\frac{1}{c_{sh}} \right) \quad (2)$$

where e = void ratio; a_{sh} = the minimum void ratio (e_{min}); b_{sh} = slope of the line of tangency; and c_{sh} = curvature of the shrinkage curve. The fitting parameters (a_{sh} , b_{sh} , and c_{sh}) were determined using the MATLAB's curve fitting module [13].

2.4 SWCCs

Using equations (1) and (2), the SWCCs in terms of the volumetric water content SWCC and degree of saturation can be obtained as

$$\theta(\psi) = \frac{w(\psi)G_s}{1 + e(w)} \quad (3)$$

$$S(\psi) = \frac{w(\psi)G_s}{e(w)} \quad (4)$$

where G_s = specific gravity; θ = volumetric water content; and S = degree of saturation.

The degree of saturation SWCC (Equation 4) is then normalised by the initial degree of saturation at 1kPa (S_o).

3 Results and Discussion

Table 2 presents the Fredlund and Xing fitting parameters for the gravimetric water content SWCC. Fig. 3 shows the plots of gravimetric water content versus soil suction for both measured data and curve-fitting estimate. High R^2 values of 0.995 and 0.993 indicate the curves are well fitted with the measured data. It is noted that the initial gravimetric water contents are near 79% and 55% for Ecclesville clay and Brasso clay, respectively. The initial gravimetric water content is dependent on the initial moisture condition of the soil sample. The AEV values for Ecclesville clay is 337.6 kPa, lower than Brasso clay AEV of 388.2 kPa.

Table 2. Gravimetric water content SWCC fitting parameters for soil samples.

Soil Series	a_f (kPa)	n_f	m_f	h_r (kPa)	w_s	R^2
Ecclesville clay	337.6	5.164	0.585	6483	0.79	0.995
Brasso clay	388.2	5.680	0.520	2000	0.55	0.993

Fig. 3. Gravimetric water content SWCC.

The Fredlund and Zhang fitting parameters for the SC are presented in Table 3. Fig. 4 shows the void ratio versus gravimetric water content plots for both measured data and curve-fitting estimate. High R^2 values of 0.994 and 0.995 again indicate that the fitting parameters correlate highly with the experimental data. The volume of soil samples decreases as water is removed through evaporation. The material begins to desaturate near the plastic limit.

By using Equation 3, the volumetric water content SWCC is obtained. Table 4 presents the Fredlund and Xing fitting parameters for the volumetric water content SWCC. Fig. 5 shows the plots of volumetric water content versus soil suction for both measured data and curve-fitting estimate. High R^2 values and plots again indicate that the curves are well fitted with measured data. The initial volumetric water contents are near 70%

and 58% for Ecclesville clay and Brasso clay, respectively. The AEV values for Ecclesville clay is 403 kPa, lower than Brasso clay AEV of 430 kPa. For both clay samples, the AEVs of the volumetric water content SWCC are higher than those of the gravimetric water content SWCC.

Table 3. SC fitting parameters for soil samples.

Soil Series	a_{sh}	b_{sh}	c_{sh}	R^2
Ecclesville clay	0.508	0.211	2.251	0.994
Brasso clay	0.403	0.160	3.038	0.995

Fig. 4. SC for both Ecclesville clay and Brasso clay.

Table 4. Volumetric water content SWCC fitting parameters for soil samples.

Soil Series	a_f (kPa)	n_f	m_f	h_r (kPa)	w_s (%)	R^2
Ecclesville clay	403	4.577	0.359	2935	0.7	0.995
Brasso clay	430	4.398	0.361	2467	0.58	0.999

Fig. 5. Volumetric water content SWCC.

By using Equation 4, the degree of saturation SWCC is obtained and then the saturation values are normalised using the initial degree of saturation calculated at 1kPa (S_0). Fig. 6 shows the normalised degree of saturation SWCC plot for Ecclesville clay. This normalisation was made to better display the degree of saturation SWCC for the soil samples. The estimated AEV values from the normalised degree of saturation SWCC are summarised in Table 5, together with those of gravimetric and volumetric water content SWCCs.

Table 5. Comparison of the air-entry values.

Soil	Ecclesville clay	Brasso clay
Gravimetric water content SWCC AEV (kPa)	337.6	388.2
Volumetric water content SWCC AEV (kPa)	403	430.3
Degree of saturation SWCC AEV (kPa)	390	570

Fig. 6. Normalised degree of saturation SWCC for Ecclesville clay.

For Ecclesville clay, the differences of the normalised degree of saturation SWCC AEV to the gravimetric and volumetric water content SWCC AEVs are 13% and 3% respectively. However, for Brasso clay, those differences are 32% and 25%. While the Brasso clay has lower initial water content than that of the Ecclesville clay, the difference in AEVs is more significant.

While two soils used in this study have almost identical plasticity index, there is a difference in the percentage of fines. This may cause the differences in SWCC, AEV, and shrinkage curve for two soils. Zapata et al. [14] presented the prediction model for the SWCC by using the weighted plasticity index, which contains both the percentage of weight passing the No. 200 US sieve and PI.

4 Conclusion

The SWCCs for two expansive clay soil types in Trinidad have been investigated in this study. The SWCCs in terms of gravimetric and volumetric water contents and degree of saturation were estimated and compared. The results of this study show that the variation of AEVs among the SWCCs are significantly large for expansive clays of high plasticity. The normalised degree of saturation SWCC provides a better display of the SWCC and estimation of the AEV.

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