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ORIGINAL PAPER

Influence of Mineral Montmorillonite on Soil Suction Modeling Parameters of Natural Expansive Clays

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Abstract Expansive soils exhibit swell/shrink behavior with fluctuating moisture conditions arising from seasonal changes. Pore-water interactions occurring at the micro scale level of the soil specimen during swelling are mainly caused due to adsorptive forces and diffuse double layer charges on the clay particles. This chemical behavior is mainly attributed due to the presence of clay minerals such as Montmorillonite and is hypothesized that there is a strong correlation between soil water–suction relationship and percent clay mineral Montmorillonite. In the present research, an attempt is made to establish this relationship by studying natural compacted expansive clays and studying their respective soil water characteristic curve (SWCC). Four high plasticity expansive clays are selected and studied for mineralogy, expansive behavior and unsaturated properties. Soil water characteristic curves of these soils are determined from pressure cell technique and filter paper method. SWCC data was fitted against Van Genuchten and Fredlund and Xing models and the obtained model parameters are compared with the percent clay mineral in the soil. Test results from this research reemphasized the fact that that clayey soils with higher percentages of Montmorillonite content exhibited higher swelling behavior. Test results also showed that there is inconsistency with pore distribution SWCC modeling parameters with varying mineral content. Addressing the relationship between the percent Montmorillonite in a soil to SWCC modeling parameters is the main outcome.

Keywords Expansive soil · Montmorillonite · SWCC · Modeling parameters for SWCC

Introduction

Expansive soils are quite unstable and cause damage to the structures overlying them due to their volume change behavior. The swell shrink behavior of expansive soils causes damages to structures that are much higher than the damages caused by other natural disasters like earthquakes and floods [9, 12]. The behavior of these fine grained soils is better understood with their type of constituent mineral and unsaturated behavior arising from seasonal moisture variation of the field [12]. Previous studies show that the soil–water interaction induced by the climatic changes is very complex, and involves the coupled effects among the changes in water content, suction, stress, deformation and shear strength [13, 18].

The moisture absorption characteristic of a soil is mainly dependent on the pore size distribution, suction and mineralogy of a soil [11]. This expansive behavior of the clays is mainly attributed to the water absorption characteristic of minerals like Montmorillonite (MM) [11]. Hence, it is important to study both unsaturated soil response and clay mineralogy in better understanding the soil behavior. Soil suction concept and prediction procedures provide a better characterization of the behavior of expansive soils and a more reliable estimate of anticipated volume change for selected conditions based on comparisons with measured field behavior [15].

The soil water characteristic curve (SWCC) is a fundamental property governing soil–water interaction and is the relationship between matric suction (ψ) and water

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content. The matric suction corresponding to the sudden drop in the curve is referred to as air entry suction (ψ_a). The water content corresponding to the bend in the curve at low degrees of saturation is known as the residual water content (θ_r). Both these parameters define the shape of the curve along with the type of soil. Soils with smaller pores have high ψ_a. Soils with very large pore sizes exhibit greater changes in water content with matric suction [6]. Table 1 presents the two most commonly used SWCC models for expansive soils available in the literature. These models showed reliable fitting when tested for expansive soils and are being adopted in the present research.

Many researchers including Bernier et al. [2], Alonso et al. [1] and Delage et al. [4] studied the relationship between matric suction and swelling behavior of expansive clays. Leong et al. [10] conducted suction measurements using the WP4 Dew-point Potentiameter and measured total suction for two expansive clays. It was found that there was a close match between the total suction measured when compared with filter paper technique. Hoyos et al. [8] conducted SWCC tests on stabilized expansive clays and analyzed using Fredlund and Xing's [7] SWCC model equation. SWCC test and modeling results show a relatively minor influence of cement dosage on the soil's entry values and SWCC model parameters.

Pedarla et al. [14] conducted suction studies on two expansive clays with different mineralogy and found that mineralogy plays an important role in the swell-shrink and suction characteristics of the clay. Also, soil with higher percentage Montmorillonite (MM) showed higher swell-shrink characteristic. In a study conducted by Villar and Lloret [17] on sand bentonite mixtures, it was found out that the swelling of bentonite is directly related to the vertical pressure applied during saturation. The current study examines the influence of Montmorillonite (MM) presence in natural expansive clays. Soil water characteristic curve modeling parameters are also studied for the effect of MM presence.

Table 1 Soil water characteristic curve (SWCC) models

	Model	Parameters
Van Genuchten [16]	$\frac{\theta-\theta_r}{\theta_s-\theta_r} = \left(\frac{1}{(1+(a\psi)^n)}\right)^m$	a, n and m—soil parameters $m = 1 - \frac{1}{n}$
Fredlund and Xing [7]	$\theta = \theta_r + \frac{\theta_s-\theta_r}{\left(\ln\left(e+\left(\frac{\psi}{a}\right)^n\right)\right)^m}$	a_1, n_1 and m_1—soil parameters θ_s—saturated water content θ_r—residual water content

Experimental Study

Four high plasticity expansive clays were selected for the present research study. These surficial disturbed soils were collected from the different regions across United States having different geological formations and distinct behavior. Standard laboratory tests were conducted on both the soil specimens in order to identify their behavior. The optimum moisture content and dry density properties were determined using Standard Proctor Test and these results are summarized in Table 2.

In this research, clay mineralogy and individual mineral constituents are identified from the Chittoori and Puppala's [3] technique. Chittoori and Puppala [3] used basic soil properties like total potassium (TP), specific surface area (SSA) and cation exchange capacity (CEC) to predict the expansive clay mineral contents in a soil. This method has been adopted in the current study to evaluate the mineralogy of the clays. Based on the USCS soil classification system all the soils were classified as high plasticity clays (CH). Grayson soil exhibited the maximum plasticity index value compared to the other soils. Also, the Montmorillonite content of the soil is high compared to the other soils.

Swell Behavioral Studies

One dimensional swell strain and swell pressure tests were performed in a conventional consolidometer setup following ASTM D-4546 method. After the compacted soil specimen was placed in the consolidometer an initial seating load of 7 kPa was applied. Once proper loading contact was achieved, the test setup was inundated with water and the specimen was allowed to undergo swelling in the vertical direction. The soil specimens were allowed to

Table 2 Basic soil characterization

Property	Burleson soil	Grayson soil	Colorado soil	San Antonio soil
Liquid limit, w_L (%)	55	75	63	67
Plasticity index, w_P (%)	37	49	42	43
USCS classification	CH	CH	CH	CH
% passing US Sieve No. 200	90	92	85	86
Specific gravity, G_s	2.72	2.73	2.70	2.79
% Montmorillonite fraction	34	42	36	38
% Illite fraction	20	25	34	30
Maximum dry density, MDD (kg/m^3)	1633	1457	1649	1608
Optimum moisture content, OMC (%)	19	24	19	22

swell for a period of 24 h or until the swell readings reached plateau conditions. Swell deformation measurements were taken at regular time intervals and used to determine vertical swell strains. Load back swell pressure test is conducted on all soils. The total load applied to the specimen to bring back to its original position was then used to calculate its swell pressure. Appliance correction factors were applied to each of the swell pressure tests for the determination of actual swell pressure as suggested in [5]. Figure 1 presents the 1-D swell strains exhibited by Colorado soil specimen at two different compaction dry densities, maximum dry density (MDD) and 95 % of maximum dry density (95 % MDD). The specimen exhibited a maximum swell of 12 % at maximum dry density (MDD) and 8.2 % swell at 95 % MDD. Figures 2 and 3 present the load-back swell pressures obtained from Colorado soil at two different densities. Soil specimen at 95 % MDD exhibited a swell pressure of 137.7 kPa (20 ψ) and 194 kPa (28 ψ) at MDD condition. The particle and mineral density was very high in case of MDD condition which resulted in higher swelling behavior.

Specimens compacted at lower dry unit weight had experienced lower swell strains and exhibited lower swelling pressures. This reduction in swell strains were expected as compaction void ratio is larger at low dry unit weight condition and hence this void space accommodates a partial amount of swelling in the soil specimen. Table 3 below presents the 1-D swell strains and load back swell pressure result summary for all the selected soils.

Test results showed that the soil exhibiting the maximum swell strains was Grayson soil. The soils presented in Table 3 are in the order of their maximum swell strains exhibited in the present swell testing. Chemical activity derived from clay mineralogy influences the swell behavior of expansive clays. The soils exhibiting maximum swell strains (Grayson) also showed a higher swell pressure due to the presence of high amounts of Montmorillonite content present in this soil when compared to the same of the remaining soils. Soils compacted at maximum dry density (MDD) condition showed higher swell strains and swell pressures due to the presence of more soil and mineral content than at 95 % MDD.

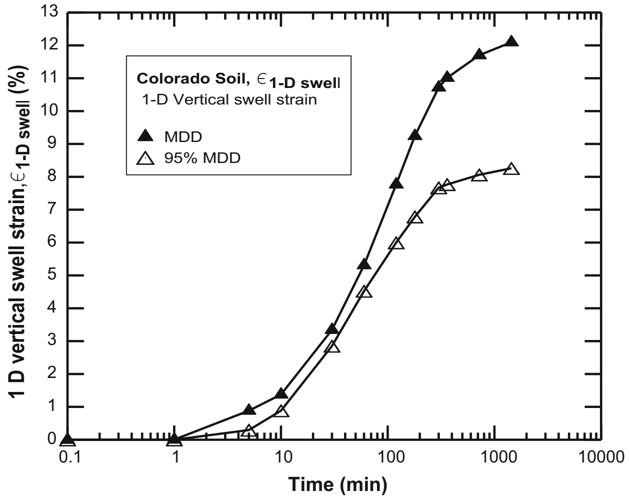

Fig. 1 One dimensional swell strains for Colorado soil

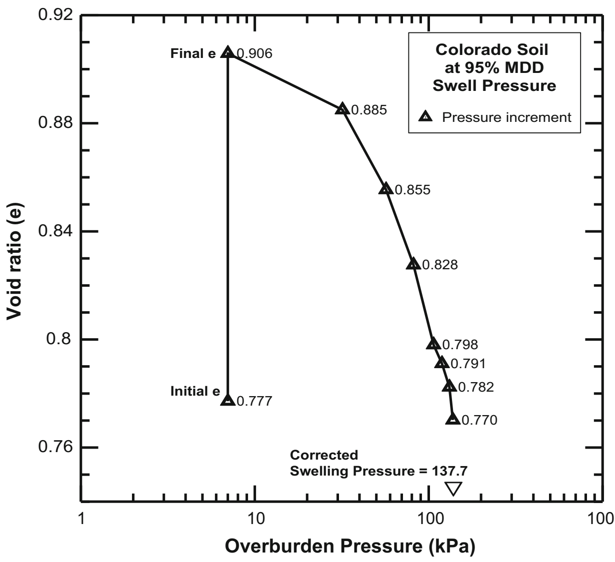

Fig. 2 Load-back swell pressure test on Colorado soil at 95 % MDD

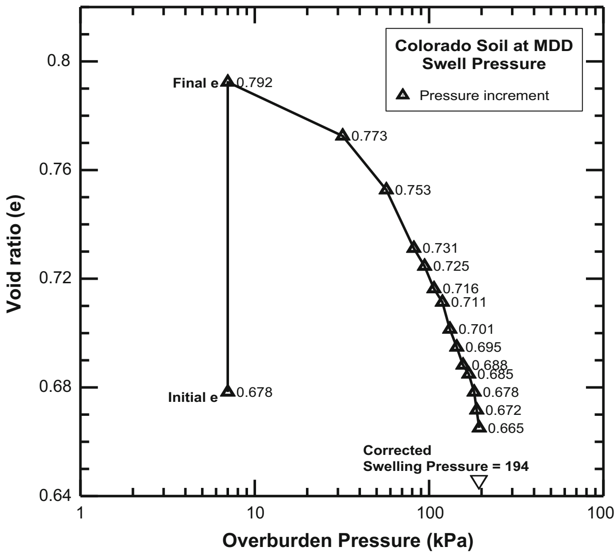

Fig. 3 Load-back swell pressure test on Colorado soil at MDD

Influence of Mineral Montmorillonite on swell behavior

Montmorillonite mineral due to its high cation exchange capacity and large specific surface area, plays an

Table 3 Summary of the 1-D swell strains and swell pressure test results

Ranking	1-D Swell strain (%)			Swell Pressure (kPa)	
Soil	PI	MDD	95 % MDD	MDD	95 % MDD
Grayson	49	14.2	9.8	243.5	156.4
Colorado	42	12.0	8.2	194.0	137.7
San Antonio	43	10.2	7.3	231.1	137.7
Burleson	37	8.8	5.5	183.4	112.8

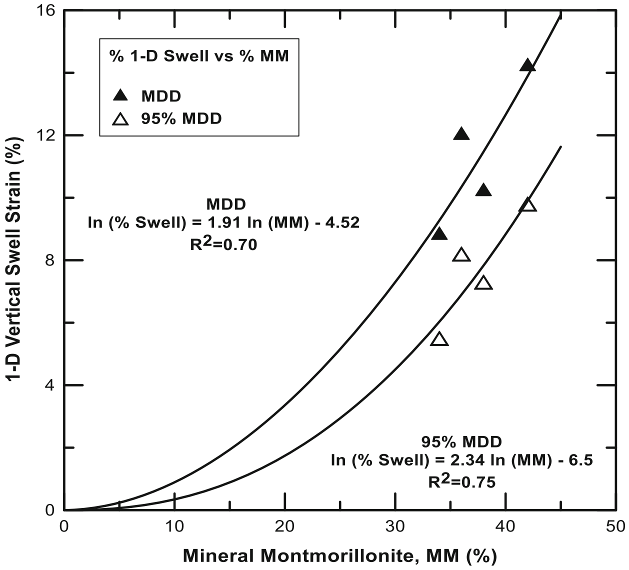

Fig. 4 Variation of 1-D Vertical Swell with Montmorillonite content for expansive clays

important role in the swell behavior of expansive clays. The presence of this mineral allows the clay to have higher swelling/shrinking capabilities. Figure 4 shown above presents the variation of 1 Dimensional swell (1-D swell) with Montmorillonite content. From the test results on four expansive clays it was observed that, with an increase in Montmorillonite content the soils exhibited more 1-D swell strains. Fitting models were plotted both for MDD and 95 % MDD condition. These fitting models were based on the test soils exhibit a coefficient of determination (R^2) around 0.8. These models can be used to predict the one dimensional swell strains from the pre-determined mineral Montmorillonite content in a soil.

Figure shown below presents the variation of swell pressures of expansive clays with percent Montmorillonite content in a soil. The load back swell pressure tests were conducted on soil specimens compacted at MDD and 95 % MDD. From the test results it was observed that, with an increase in Montmorillonite content the soils exhibited more swell pressures (Fig. 5).

These fitting models were based on four soils and represent a coefficient of determination (R^2) value around 0.9. From the above figures it can be noticed that the variation of swelling strains and swelling pressures are proportional to the percent Montmorillonite (%MM) content in soil. The curves are assumed to start from origin as the degree of expansion reduces tremendously with no %MM content in soil. However, Illite and Kaoline minerals minimally contribute towards soil swell behavior and are currently neglected.

Unsaturated Soil Behavior

Soil–water characteristic curves (SWCC) were measured using a pressure cell apparatus at low matric suction range and filter paper technique at high matric suction range. The pressure cell apparatus with a 500 kPa ceramic plate was used for measuring the SWCC following the drying path in the suction range of 0–500 kPa (ASTM D6836-02). The filter paper technique (ASTM D5298-10) was adopted for the matric suction for a range of 500–10,000 kPa. Samples were air dried to attain target moisture levels and once equilibrated and tested using filter paper technique. Figures 6, 7, 8 and 9, present the SWCCs measured for the suction range of 0–10,000 kPa. At select suction cycles, the specimen dimensions were measured. The volumetric change measured was then estimated and applied to the calculations of volumetric water contents corresponding to the respective values of suction pressures. Two models, Van Genuchten [16] and Fredlund and Xing [7] were used to fit the experimental data. The change in volume is predominant in expansive clays during application of suction conditions which alters the volumetric water content in the compacted soil specimens. Hence forth, care is taken to measure the volumetric changes during SWCC studies.

All the high plasticity clayey specimens were statically compacted to 95 % MDD as it represents a near field compaction state. The variation of volumetric moisture content with matric suction for Burleson, Colorado, Grayson and San Antonio soil specimens are presented in Figs. 6, 7, 8 and 9, respectively. As stated in literature, experimental data fitted with standard Van Genuchten [16] and Fredlund and Xing [7] models and are presented along test results.

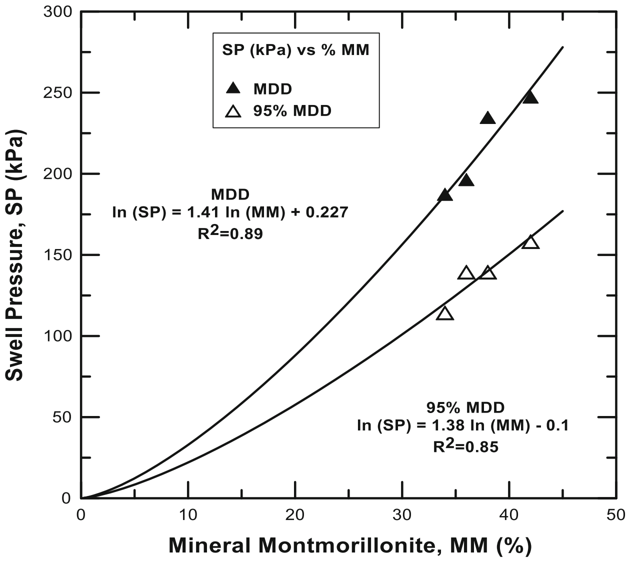

Fig. 5 Variation of swell pressures with Montmorillonite content for expansive clays

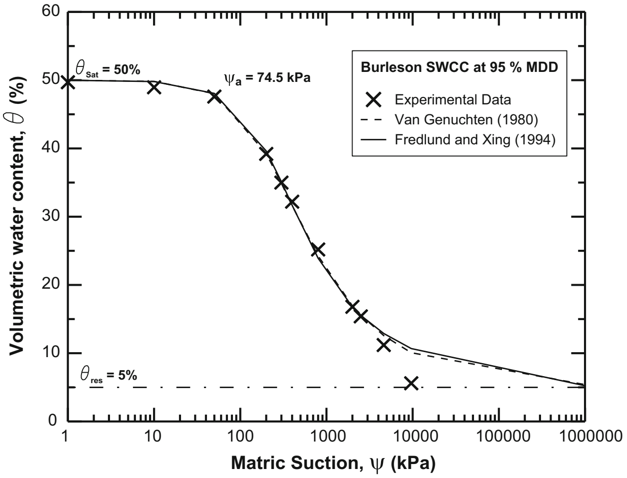

Fig. 6 Soil water characteristic curve of Burleson soil

Burleson soil absorbed maximum saturated volumetric moisture content (θ_{sat}) of 50 % and showed an air entry value (ψ_a) of 74.5 kPa (10.8 ψ). The residual moisture content retained in the specimen (θ_{res}) was 5 %. Similar results were observed for the rest of high plasticity soils selected for this research. Unique soil suction parameters obtained from the measured soil water characteristic curves are presented in Table 4. The experimental SWCC data obtained from the laboratory measurements were plotted against the commonly used curve fitting models.

Table 5 presents the curve fitting parameters obtained from the Van Genuchten [16] and Fredlund and Xing [7] models plotted against all the four soils. The coefficient of determination (R^2) for all the models are greater than or equal

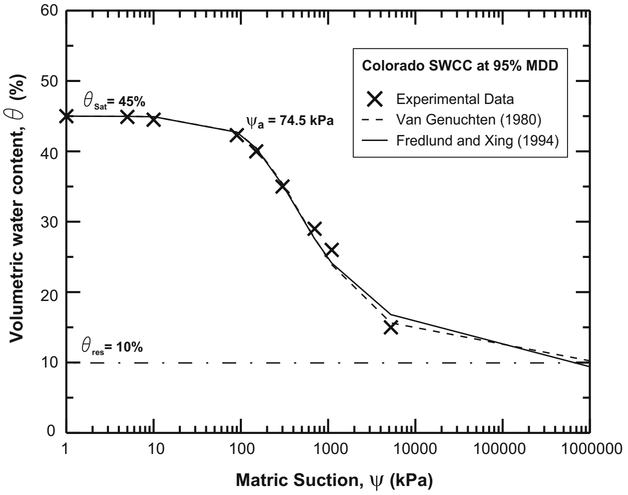

Fig. 7 Soil water characteristic curve of Colorado soil

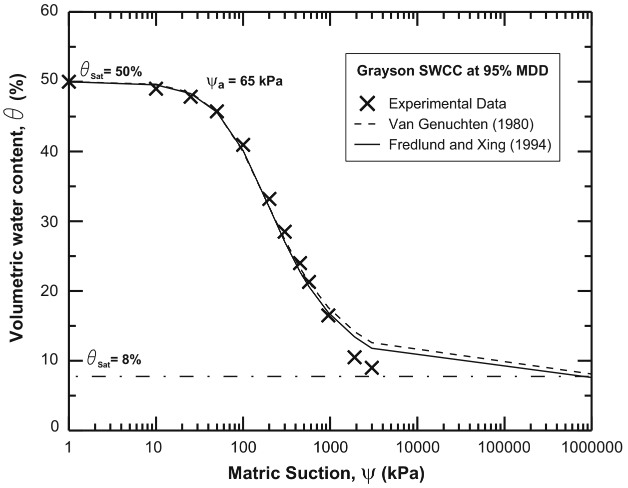

Fig. 8 Soil water characteristic curve of Grayson soil

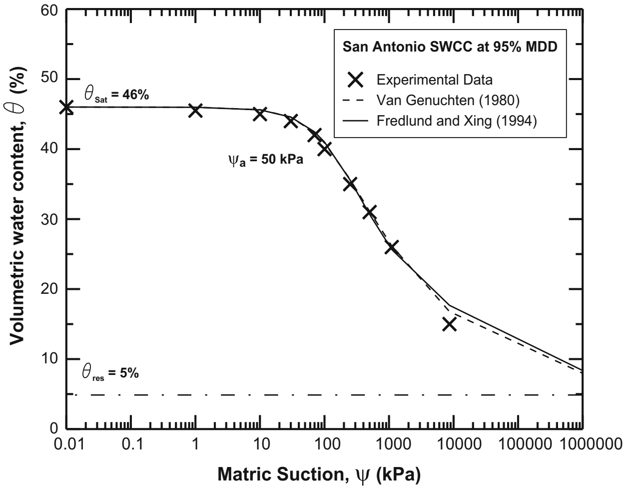

Fig. 9 Soil water characteristic curve of San Antonio soil

to 0.97. These models have proven to be reliable in modeling the soil water characteristic curves of present soils.

Analysis of Modeling Parameters

SWCC model parameters represent the inherent characteristics of the soil specimen. The ‘a’ parameter from Van Genuchten and ‘a_1’ from Fredlund and Xing models represent the air entry head or pressure of a soil. Parameters ‘n’ and ‘n_1’ govern the pore size distribution and ‘m’ and ‘m_1’ represent the overall symmetry of the curve. Hence, for the four soils in the present research, variation of air entry head and pore distribution are studied.

Table 4 Soil suction parameters obtained from measured SWCCs

Soil	Saturated volumetric moisture content (θ_{sat}) (%)	Residual volumetric moisture content (θ_{res}) (%)	Air entry value (ψ_a) (kPa)
Burleson	50.0	5	74.5
Colorado	45.0	10	74.5
Grayson	50.1	8	65.0
San Antonio	46.0	5	50.0

Figures 10 and 11 present the variation of ‘a’ and ‘a_1’ parameters with swell strain. ‘a’ and ‘a_1’ experimental results were fitted with best fit models and a coefficient of determination (R^2) is obtained for these models.

The ‘a’ and ‘a_1’ parameters showed a consistent trend with expansive mineral content of the soil. Grayson soil exhibited the highest ‘a’ parameter from Van Genuchten model whereas Burleson soil has the least value. Parameters ‘n’ and ‘m’ from Van Genuchten model were inconsistent with percent mineral Montmorillonite. For the Fredlund and Xing fitting model, ‘a_1’ parameter was highest for Burleson and least for Grayson soil. This inverse relationship with mineral content is due to the fact that ‘a_1’ is an inverse function of pore size distribution for a soil.

Table 5 Curve fitting parameters for SWCC models

Soil	Van Genuchten Model (1980)				Fredlund and Xing Model (1994)			
	a	n	m	R^2	a_1	n_1	m_1	R^2
Burleson	0.005	1.55	0.35	0.98	210	1.45	0.90	0.99
Colorado	0.004	1.60	0.37	0.97	210	1.60	0.60	0.98
Grayson	0.010	1.65	0.39	0.98	110	1.50	0.90	0.99
San Antonio	0.008	1.29	0.22	0.98	145	1.20	0.60	0.98

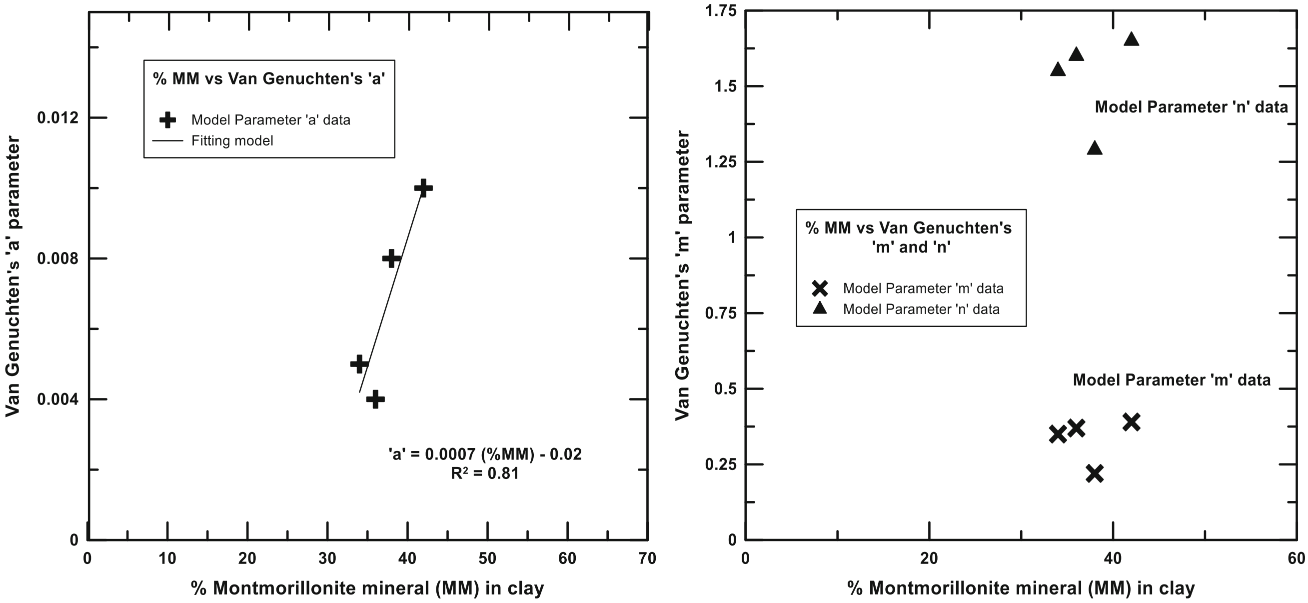

Fig. 10 Variation of Van Genuchten’s SWCC modeling parameters with percent mineral Montmorillonite

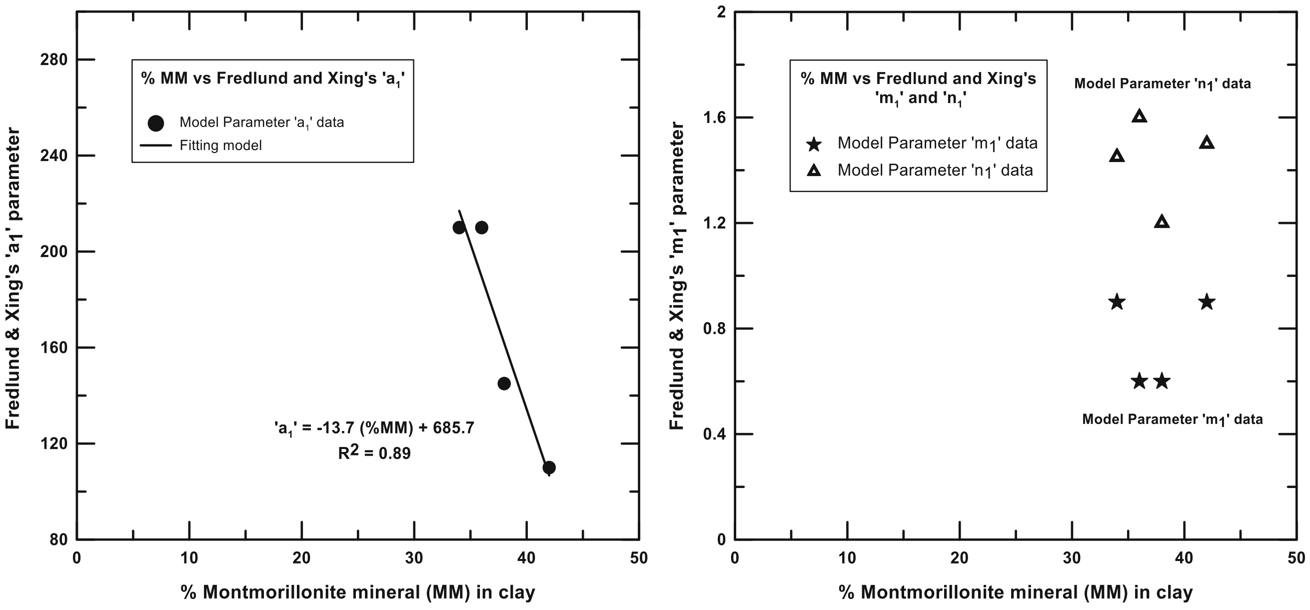

Fig. 11 Variation of Fredlund and Xing's SWCC modeling parameters with percent mineral Montmorillonite

From the above plots, it was concluded that the fitting parameters 'n, m, n_1, m_1' from both the models did not show a consistent trend in variation with expansive behavior of soils. Parameters 'n, m, n_1, m_1' did not exhibit any variation with change in clay fraction or percent mineral Montmorillonite. This could be due to the dependency of SWCC parameters solely on grain size distribution. Hence, it is premature at this point to draw conclusive trend between soil mineralogy parameters with the corresponding SWCC model parameters 'n, m, n_1, m_1'.

Summary

Four natural expansive clays were selected for the present study and studied for basic soil characterization. Statically compacted soil specimens were tested for swelling strains and swelling pressure tests to understand their response to moisture imbibition. Grayson soil with dominant mineral Montmorillonite exhibited high swelling strains and swelling pressure compared with other soils. Swelling strains and swelling pressure results determined in the laboratory were proportional to the %MM (Montmorillonite) present in the soils. This re-emphasizes the dependency of swelling behavior on mineral Montmorillonite. However, swelling behavior caused from Illite fraction of the clay content is currently neglected in this study.

It is found that, air entry values and the residual moisture contents determined from SWCC are independent of the degree of expansiveness of a soil. From the analysis of SWCC modeling parameters, it is observed that the air entry or pressure head parameters showed direct relationship with %MM. Pore size distribution and gradation parameters n, m, n_1, m_1 did not exhibit any variation with change in clay fraction or percent mineral Montmorillonite. This could be due to the dependency of SWCC on grain size distribution, rather than the degree of expansion of a soil or the presence of mineral Montmorillonite. Future studies are needed on diverse soil types to develop trends with more than one soil composition related parameter.

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References

1. Alonso EE, Gens A, Josa A (1990) A constitutive model for partially saturated soils. Géotechnique 40:405–430
2. Bernier F, Volckaert G, Alonso E, Villar M (1997) Suction-controlled experiments on Boom clay. Eng Geol 47:325–338
3. Chittoori BCS, Puppala AJ (2011) Quantitative estimation of clay mineralogy in fine-grained soils. J Geotech Geoenviron Eng 137(11):997–1008
4. Delage P, Howat MD, Cui YJ (1998) The relationship between suction and swelling properties in a heavily compacted unsaturated clay. Eng Geol 50:31–48
5. Fredlund, D. (1969) Consolidometer test procedural factors affecting swell properties. In: Proceedings, 2nd international conference on expansive clay soils, College Station, TX, pp 435–456
6. Fredlund D, Rahardjo H (1993) Soil mechanics for unsaturated soils. Wiley, New York

7. Fredlund DG, Xing A (1994) Equations for the soil-water characteristic curve. Can Geotech J 31(4):521–532
8. Hoyos LR, Thudi HR, Puppala AJ (2007) Soil-water retention properties of cement treated clay. In: Problematic soils and rocks and in situ characterization, GSP 162, Geo-Institute of ASCE, CD-Rom Proceedings of Geo-Denver 2007, Denver, Colorado
9. Jones DE, Holtz WJ (1973) Expansive soils: the hidden disaster, vol 430. Civil Engineering, New York, pp 49–51
10. Leong EC, Tripathy S, Rahardjo H (2003) Total suction measurement of unsaturated soils with a device using the chilled-mirror dew-point technique. Geotechnique 53(2):173–182
11. Mitchell JK (1993) Fundamentals of soil behavior. Wiley, New York
12. Nelson D, Miller DJ (1992) Expansive soils problems and practice in foundation and pavement engineering. Wiley, New York
13. Ng CWW, Zhan LT, Bao CG, Fredlund DG, Gong BW (2003) Performance of an unsaturated expansive soil slope subjected to arti-ficial rainfall infiltration. Géotechnique 53(2):143–157
14. Pedarla A, Puppala AJ, Hoyos LR, Zapata CE, Chittoori B (2014) Study of SWCC Modeling parameters with variation in swell behavior and mineralogy of four compacted expansive clays. In: Unsaturated soils: research and applications, UNSAT 2014, Australia, vol 2, pp 951–957
15. Snethen DR, Johnson LD (1980) Evaluation of soil suction from filter paper. In: Geotech. Lab., US Army Eng. Waterway Exp. Sta., Vicksburg, Mississippi, Misc. Paper No. 6L-80-4
16. Van Genuchten M (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898
17. Villar MV, Lloret A (2004) Influence of temperature on the hydro-mechanical behaviour of a compacted bentonite. Appl Clay Sci 26(1–4):337–350
18. Zhan L, Chen P, Ng CWW (2007) Effect of suction change on water content and total volume, of an expansive clay. J Zhejiang Univ Sci A 8(5):699–706