Investigation of the Effect of Lime Treatment on the Soil Water Characteristics Curve of Expansive Soils

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ABSTRACT

The engineering behavior of natural untreated and compacted lime-treated expansive soils, which typically exist in a state of unsaturated condition, can be better-explained using concepts from unsaturated soil mechanics. The soil water characteristics curve (SWCC) is the key unsaturated soil property for obtaining unsaturated soil property functions (USPFs). However, there are limited studies on the effect of lime on the SWCC of lime-treated expansive soils. This study investigated the effect of lime on the SWCC of lime-treated expansive soils. The drying portion of SWCCs for untreated natural soil and lime - treated soil samples with three different lime contents (3 %, 6 % and 9 %) with 7 days of curing were studied. The SWCCs were determined by using pressure plate apparatus in the suction range of 0 – 1400 kPa. The shrinkage curve (SC) was also determined to evaluate the change in volume of the different soil samples. The experimental results indicate that SWCC is affected by lime treatment and there is a change in the SWCC parameters and in the shape and position of SWCC as the percentage of lime is changed. The SWCC of the lime-treated soil samples show a higher rate of desaturation as the lime content increases. The Air Entry Value (AEV) and residual water content of lime-treated soil decreases with increase in percentage of lime and the SWCC shifts towards the left side as the AEV decreases. The differences in AEV obtained from gravimetric- water-content-based SWCC (w-SWCC) and degree-of-saturation-based SWCC (S-SWCC) for the lime-treated soil samples were small when compared to the untreated natural soil sample.

Keywords: Air-entry value, Expansive soil, Lime treatment, Shrinkage curve, Soil–water characteristic curve, Unsaturated soil,

1. INTRODUCTION

Expansive soils experience large volumetric changes when subjected to change in moisture content. Infrastructures, particularly light-weight structures are severely damaged by these volumetric changes. This problem of expansive soils can be addressed by applying chemical treatment, such as lime treatment for stabilization of the soil.

Researchers have investigated the swell-shrink response of expansive soils using index properties and other soil laboratory tests. However, the engineering behavior of compacted expansive soils that are typically in a state of unsaturated condition can be better-interpreted if the influence of matric suction is considered [1]. In order to establish the relationship between unsaturated soil theory and engineering problems related to expansive soils, which exist at unsaturated state, the use of SWCC of expansive soils is investigated. The SWCC constitutes the primary soil information required for the analysis of seepage, shear strength, volume change, air flow, and heat flow problems involving unsaturated soils. The SWCC is relatively easy to measure and has become the key unsaturated soil property for obtaining USPFs.

Following the development of unsaturated soil mechanics, many researches were carried out in measuring the SWCC of soils [2, 3, 4, and 5]. Most of these studies were mainly on either non-expansive soils or on untreated natural expansive soils. However, very limited experimental data have been reported in literature on the SWCC of chemically treated expansive soils [6], especially on the impact of lime on the SWCC of expansive soils and hence on the USPFs of expansive soils.

The effects of lime treatment on the physicochemical properties of expansive soils can be attributed to a number of chemical reactions altering the soil nature and structure. The main two chemical reactions are [6, 7] are: (i) an immediate ion exchange reaction between exchangeable clay ions and calcium ions provided by the lime. Flocculation and agglomeration of the soil particles occur, transforming the plastic soil to a more granular and less plastic material [6, 8]. As a result of this reaction, the soil generally acquires an aggregated, more porous and less deformable structure [6, 9, 10]. In the context of SWCC studies, this would be expected to affect water retention. (ii) long-term pozzolanic reactions which promote dissolution of siliceous and aluminous compounds from the clay mineral lattice, reacting with calcium ions in the pore water to form calcium silicate hydrates, calcium aluminate hydrates and hydrated calcium aluminosilicates. This can potentially change soil pore connectivity as well as pore size distribution [10, 11].A simplified qualitative view of typical soil-lime reactions [7] is as follows:

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^- \quad (1)$$

$$Ca^{2+} + 2(OH)^- + SiO_2(\text{clay silica}) \rightarrow C-S-H \quad (2)$$

$$Ca^{2+} + 2(OH)^- + Al_2O_3\ (\text{clay alumina}) \rightarrow C-A-H \quad (3)$$

Where, $C = CaO$, $A = Al_2O_3$, and $H = H_2O$

Although it is clear that lime treatment, as indicated above, can potentially affect the water retention of the lime-treated soil, research on the SWCC of lime-treated expansive soils is relatively limited [6, 12]. In this study, hydrated lime with different contents was added into expansive soil. The optimum water contents and maximum dry density of the soil samples were determined by standard compaction method. The drying SWCC tests were carried out by using pressure plate apparatus. The Shrinkage Curve (SC) were determined for both untreated and lime-treated soil samples using ring method to account for the volume change behavior of expansive soils upon drying. The SC was combined with gravimetric-water-content-based SWCC (w-SWCC) to determine the degree-of-saturation-based SWCC (S-SWCC). The effect of lime treatment on the SWCC parameters of expansive soil was investigated using the w-SWCC and S-SWCC.

2. MARERIALS AND METHODS

Soil samples were collected from a test pit located at Ayer- Tena area in Bahirdar, Ethiopia, from a depth of 1.5m. Soil samples were prepared according to [13]. Tests were conducted to determine the index properties of the soil samples using ASTM standards. The index properties of the natural untreated soil are presented in Table 1.

Table 1 Properties of expansive soil used in this study

Clay (%)	85.9
Sand (%)	3.8
Silt (%)	9.8
Liquid Limit (%)	108.1
Plastic Limit (%)	38.0
Plasticity Index (%)	70.1
Free Swell (%)	135
Specific gravity Gs	2.73
pH	7.5
USCS Soil Classification	CH

The chemical composition of hydrated lime used in this investigation was studied by using X-Ray Fluorescence analysis [14] and is presented in Table 2.

Table 2 Chemical composition of hydrated lime used in this study

Constituent	Percentage by weight (%)
SiO_2	6.21
Al_2O_3	2.18
Fe_2O_3	3.57
CaO	59.47
MgO	3.91
Na_2O	0.61
K_2O	0.79
TiO_2	0.33
P_2O_5	0.21
MnO	0.28
SO_3	0.58

The minimum necessary percentage of lime to treat this soil was determined using pH test as per the procedure outlined in [15]. According to this test, the lime percentage needed for soil stabilization was found to be 6 %. The lime requirement determined by a pH test (6 %), as well as additional two different lime content values below and above 6 % (i.e., 3 % and 9 %) were applied to evaluate the effect of lime treatment on the SWCC. After mixing thoroughly the dry powders of the soil and lime, water was carefully added in small increments, and the wet paste was mixed thoroughly. The soil samples were allowed to cure by covering them with impermeable plastic bag. Lime-treated soil samples were compacted with their respective Maximum Dry Density (MDD) and Optimal Moisture Content (OMC) values and covered with impermeable plastic bag and then cured for 7 days.

The SWCCs were determined for untreated natural soil and lime-treated soil samples with lime content of 3 %, 6 %, and 9 % for 7-day curing periods following the drying path as per [16] using pressure plate apparatus. The pressure plate apparatus is a reliable and widely used method of measuring SWCC [17]. The measurement capacity of the pressure plate apparatus is governed by the air-entry value of the ceramic disc which is typically limited to 1500 kPa [6]. This study has applied suction ranges of 0 – 1400 kPa to measure SWCC, since the air entry value of the available ceramic disc was 1500 kPa. The soil samples are initially saturated for the SWCC and SC tests. SC of untreated natural soil and lime-treated samples with 3 %, 6 %, and 9 % for 7-days of curing were measured with a digital micrometer.

3. RESULTS AND DISCUSSION

3.1 Moisture – Density Relationships

The soil samples were prepared by compacting in the Standard Proctor Test using a 2.5 kg hammer falling 308 mm into a soil-filled mold. The mold was filled with three equal layers of soil. Each soil-filled mold received 25 drops of hammer. The dry density vs. moisture content curve was then plotted to determine the MDD and OMC. Untreated natural and lime-treated soil samples yielded the typical bell-shaped compaction curves as shown in Figure 1. The MDD decreased and the OMC increased as percentage of lime increases. MDD for an untreated natural soil was 1.26 g/cm^3 and reduced to 1.24 g/cm^3, 1.21 g/cm^3 and 1.18 g/cm^3 with the addition of 3 %, 6 % and 9 % lime, respectively. The OMC for an untreated natural soil was 33.8 % and increased to 35.6 %, 40.3 % and 41.2 % with the addition of 3 %, 6 % and 9 % lime, respectively. This is due to the fact that hydrated lime is finer than soil, which increases surface area, as well as flocculation and agglomeration, which cements soil particles and creates greater pore structure [6]. Wetting the fine lime's large surface area necessitates the addition of extra water. As a result, the MDD is reduced while the OMC is increased.

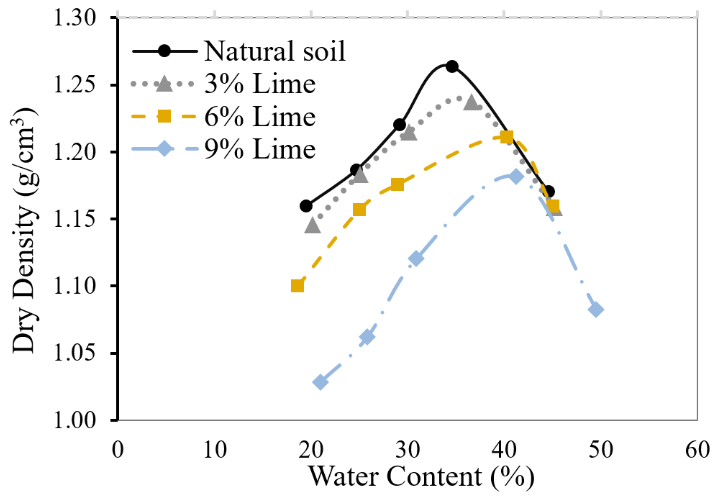

Figure 1 Compaction curves for untreated natural and lime-treated soil sample

3.2 SWCC and SC: Curve Fitting and Analysis

3.2.1 The fitting of SC

Even though several equations for fitting SCs have been suggested by different researchers, the hyperbolic equation [1], Eq. (4), provides the best match for the curves, while w-SWCC is combined with the SC test [18] and the fitting parameters are obtained using the EXCEL Solver function.

$$e(\omega) = a_{sh}\left(\left(\frac{\omega}{b_{sh}}\right)^{c_{sh}} + 1\right)^{\frac{1}{c_{sh}}} \tag{4}$$

where a_{sh} = minimum void ratio upon complete drying (i.e., ranging from 0.4 to 1.0), b_{sh} = variable related to the slope of the drying curve calculated as: $b_{sh} = (a_{sh} \times S_o)/G_s$
and c_{sh} = variable related to the sharpness of curvature as the soil desaturates, and S_o = initial degree of saturation.

3.2.2 The fitting of w-SWCC and S-SWCC

In order to analyze the effect of lime addition on the SWCC parameters of expansive soils, the model by Fredlund and Xing [19] was used to fit the curves. The fitting formula for w-SWCC is expressed in Eq. (5) and the fitting parameters were obtained using the EXCEL Solver function [8].

$$\omega(\psi) = c(\psi)\frac{\omega_s}{\left\{\ln\left[e + (\psi/a)^n\right]\right\}^m} \tag{5}$$

Where:

$\omega(\psi)$= gravimetric water content at any soil suction, ψ, e = constant equal to 2.71828, ω_s = saturated gravimetric water content, a = fitting parameter indicating the inflection point that bears a relationship to the air-entry value, n= fitting parameter related to the rate of desaturation, m = fitting parameter related to the curvature near residual conditions and $C(\psi)$= correction factor directing the SWCC to 10^6 kPa at zero water content, and given by Eq. (6):

$$C(\psi) = 1 - \frac{\ln(1+\psi/\psi_r)}{\ln\left[1+(10^6/\psi_r)\right]} \tag{6}$$

The w - SWCC paired with SC was used to determine S-SWCC, which was employed to identify the true AEV. The void ratio and water content provided by the SC can be used to calculate the degree of saturation, which can then be used to convert the w-SWCC to the S-SWCC [20]. The fitting formula for S-SWCC is expressed as Eq. (7) and the fitting parameters were obtained using the EXCEL Solver function.

$$S(\psi) = c(\psi)\frac{S_o}{\left\{\ln\left[e+\left(\psi/a\right)^n\right]\right\}^m} \qquad (7)$$

Where S_o is the initial degree of saturation, $S(\psi)$ is degree of saturation at any suction calculated as: $S(\psi) = \frac{G_s\omega(\psi)}{e(\omega(\psi))}$, with G_s is specific gravity, $\omega(\psi)$ is measured gravimetric water content determined using pressure plate test and $e(\omega(\psi))$ is calculated void ratio using Equation 1 and the other parameters are described in Eq. (5).

3.3 Analysis of Soil Water Characteristic Curves

3.3.1 Analysis of w-SWCCs

Curing periods of 7-day and 14-day were initially investigated. The results indicated that the SWCCs for 7-day curing and 14-day curing are almost the same as presented in Table 3. Hence, further investigation was carried out using 7-day curing period. The effect of lime addition on w-SWCC of soil samples cured for 7-days is presented in Table 3 and Figure 2. The impact of lime addition on expansive soils was investigated by observing changes to Fredlund and Xing [19] SWCC curve fitting parameters. The results indicate that the SWCC curve fitting parameters were affected by the addition of lime. The addition of lime changed the shape and position of the w-SWCCs significantly. The value of "a" and AEV increased at first, but as the percentage of lime increased, the value of "a" and AEV decreased. The AEV first increased from the natural-untreated value of 75 kPa to 130 kPa at a lime content of 3 %, it then decreased to 115 kPa and 80 kPa at lime contents of 6 % and 9 %, respectively. The "n" value of a lime-treated soil sample first decreased, but then began to increase as the percentage of lime content increased.

Table 3 w-SWCC fitting parameters of Fredlund and Xing model [19]

Parameters	Natural	7-day curing period			14-day curing period		
		3%	6%	9%	3%	6%	9%
ω_s (%)	45.36	42.36	41.02	40.56	42.29	40.96	40.51
a	133.75	295.88	235.37	115.98	295.88	235.37	115.98
n	1.78	1.49	1.72	2.56	1.49	1.72	2.56
m	0.31	0.60	0.51	0.40	0.60	0.51	0.40
ψ_r (kPa)	1780	1449	1449	1402	1449	1449	1402
R^2	0.999	0.999	0.999	0.999	0.999	0.999	0.999
AEV(kPa)	75	130	115	80	130	115	80
ω_r (%)	25.08	21.32	20.11	17.33	21.25	20.05	17.28

The w-SWCC of the lime-treated soil samples shows a higher rate of desaturation as the lime content increases, compared to the untreated natural soil sample, implying that the water from the pores was easily drained in lime-treated soils when suction increased, compared to the untreated soil sample. The "m" value of a lime-treated soil sample first increased, but then decreased as the proportion of lime content increased. Both saturated and residual water contents decreased as the lime content increased.

3.3.2 Analysis of SCs

The effect of lime addition on SC of natural soil and lime-treated soil samples cured for 7 days is presented in Figure 3 and Table 4. The results indicate that the curve fitting parameters are affected by lime treatment.

When comparing the SCs of the lime-treated soil sample to the SCs of the untreated natural soil sample, it was noted that the SCs of the lime-treated soil sample shifted upward. This is due to the addition of lime, which resulted in a larger void ratio in the lime-treated soil sample. The "a_{sh}", "b_{sh}", and "c_{sh}" value increased up to 7-day curing period for all lime-treated soil samples at the percentage lime considered in this study. For lime-treated soil samples, "c_{sh}" value was higher and considered as low compressible soils, which essentially produced a horizontal line from the initial void ratio to completely dry void ratio. On the other hand, untreated natural soil sample produced a gradual curve that immediately started to curve from the completely dry void ratio and gradually moved towards saturation line, which would have much higher compressibility (or undergo considerable volume change) up-on drying.

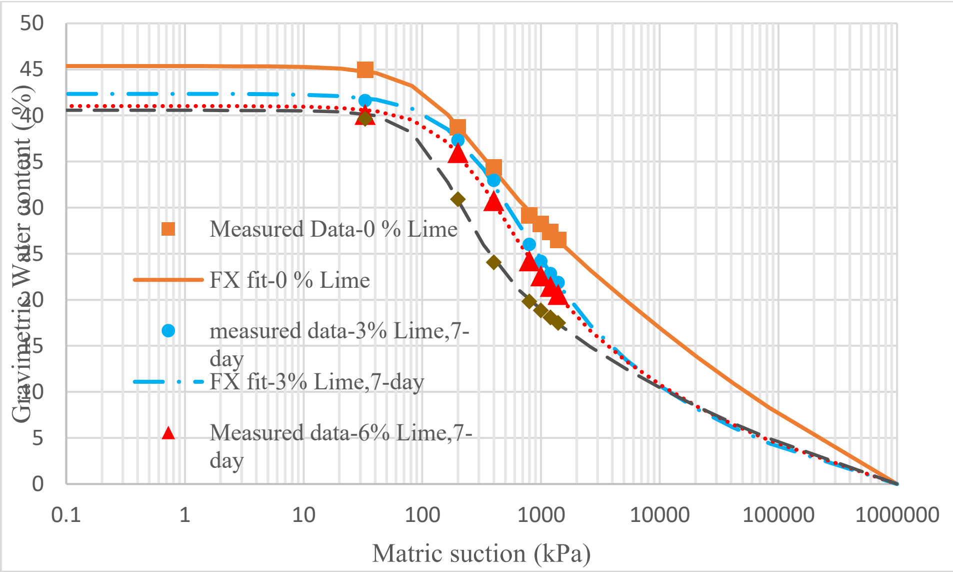

Figure 2 w-SWCC for untreated natural soil sample and lime-treated soil sample with 7-day of curing period.

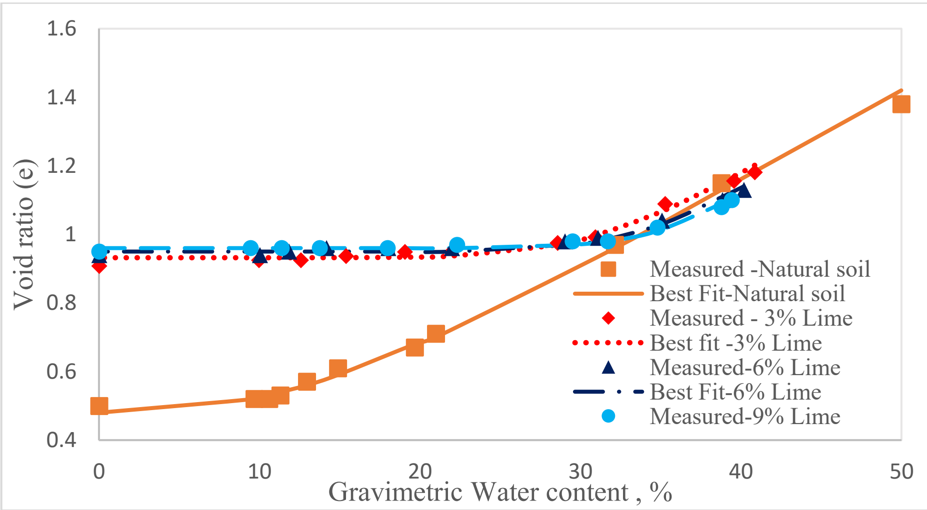

Figure 3 SC for untreated natural soil sample and lime- treated soil sample with 7-day of curing

Table 4 SC fitting parameters for untreated and lime-treated soil samples

Parameters	Natural	7-day curing period		
		3%	6%	9%
ω_s (%)	49.99	41.63	40.17	39.43
a_{sh}	0.48	0.93	0.95	0.96
b_{sh}	0.17	0.32	0.34	0.34
C_{sh}	2.56	8.04	10.74	14.69
R^2	0.997	0.980	0.983	0.985

3.3.3 Analysis of S-SWCCs

For soils that do not experience considerable volume change when soil suction increases, the AEV determined using w-SWCC and S-SWCC is the same. However, for a soil that undergoes significant volume change as soil suction increases, the AEV depends on the w-SWCC and SC test results. In such soils, the AEV is underestimated by the w-SWCC test result. In such circumstances, SWCC paired with SC should be employed to identify the true AEV [18]. Table 5 and Figure 4 present the S-SWCC results for the soil samples.

Table 5 S-SWCC fitting parameters of Fredlund and Xing model [19]

Parameters	Natural	7-day curing period		
		3%	**6%**	**9%**
S_o (%)	95.70	89.19	87.66	86.63
a	1200.00	524.85	430.22	213.59
n	0.18	3.69	4.20	4.63
m	0.17	0.19	0.20	0.22
ψ_r (kPa)	3358	1598	1213	1100
R^2	0.994	0.999	0.999	0.999
AEV (kPa)	1200	245	210	150
S_r (%)	79.61	60.80	58.46	49.46

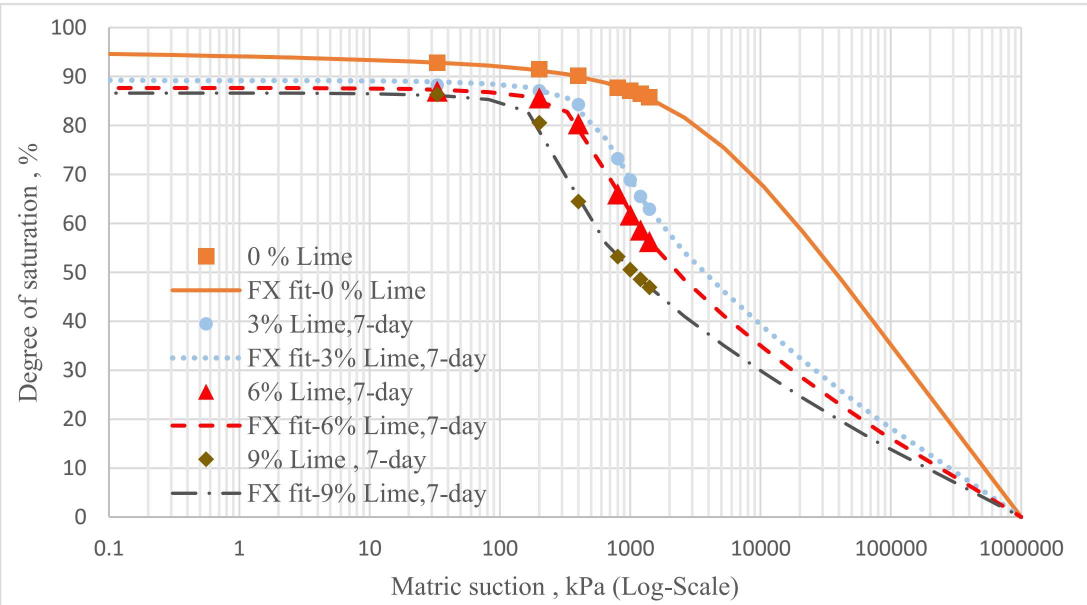

Figure 4 S-SWCC for untreated natural soil sample and lime- treated soil sample with 7-day of curing period.

The shape and position of the S-SWCCs changed significantly as a result of the addition of lime, as shown in Figure 4. The S-SWCC of untreated natural soil has a smooth desaturation slope across the suction range, whereas the S-SWCC of lime-treated soils exhibits a steep desaturation slope between the AEV and residual suction. The impact of lime addition on expansive soils was investigated by observing changes to Fredlund and Xing [19] SWCC model parameters. The results indicate that the SWCC curve fitting parameters were affected by the addition of lime. The value of "a" decreased as percentage of lime increased. Similarly, the AEV decreased as percentage of lime increased. It decreased from 1200 kPa at natural-untreated value to 245 kPa, 210 kPa and 150 kPa, at lime contents of 3 %, 6 %, and 9%, respectively, for seven days of curing. A reduced AEV in lime-treated soil samples is related to a lower water retention at low suctions. This is a result of the immediate ion exchange reaction between exchangeable clay ions and calcium ions provided by the lime, which results in flocculation and agglomeration of the soil particles that transform the plastic soil to a more granular and a more porous microstructure [6]. This indicates that the lime treatment has produced a more open microstructure with larger void ratio and hence a lower AEV. The "n" value of a lime-treated soil sample increases as the percentage of lime increases, meaning that the addition of lime results in a more uniform pore size distribution [21] and a faster rate of desaturation than a natural soil sample that has not been treated. The effects of lime treatment on the values of "m" were found to be insignificant. The residual suction (ψ_r) value decreased as the percentage of lime increased. It decreased from 3368 kPa at natural-untreated value to 245 kPa, 210 kPa and 110 kPa, at lime contents of 3 %, 6 %, and 9 %, respectively. Both initial and residual degree of saturation decreased as the lime content increased. This is due to the fact that lime-treated soils absorb less water than untreated natural soils at saturation stage. However, as the suction increases, the rate of desaturation increases, and water from the pores is expelled faster due to more open structures generated by the addition of lime [6].

4. CONCLUSIONS

The results in this study indicate that SWCC was affected by lime treatment and there were changes in the SWCC parameters, the shape and position of SWCC, as the percentage of lime changed. The AEV of lime-treated soil decreased with increase in percentage of lime. This is due to flocculation, agglomeration into larger particles and chemical bonding, as a result of addition of lime, which create an open structure, resulting in larger void ratio The SWCC parameter "n", which is an approximate indicator of the pore size distribution and rate of desaturation, increases as the percentage of lime increases, indicating that lime-treated soils exhibit higher rate of desaturation than untreated natural soil.

Based on the results obtained in this study, it is recommended to carry out further research to investigate the potential of the use of S-SWCC to evaluate the improvement effect of stabilizers on expansive soils since S-SWCC is very effective in showing volume change effect. Such an approach may result in a better understanding of the optimum amount of lime content required for stabilization of expansive soils. Investigations on other factors influencing the SWCC function of treated soils such as initial water content, initial dry density, compaction effort, suction measuring methods, and hysteresis effects are also recommended.

CONFLICT OF INTEREST

The authors report there are no competing interests to declare.

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