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Soil water characteristic curve and improvement in lime treated expansive soil

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Abstract. Methods commonly used to evaluate the improvement of lime-treated expansive soil include swelling characteristics and unconfined compressive strength. In the field, lime-treated expansive soils are in compacted unsaturated state. Soil water characteristic curves (SWCCs) represent a key parameter to interpret and describe the behavior of unsaturated expansive soil. This paper investigates the use of SWCC as a technique to evaluate improvements acquired by expansive soil after lime treatment. Three different lime contents were considered 2%, 4% and 6% by dry weight of clay. Series of tests were performed to determine the SWCC for the different lime content under curing periods of 7 and 28 day. Correlations between key features of the soil water characteristic curves of lime treated expansive soils and basic engineering behavior such as swelling characteristics and unconfined compression strength were established. Test results revealed that initial slope (S_1), saturated water content (w_{sat}), and air entry value (AEV) play an important role in reflecting improvement in engineering behavior achieved by lime treatment.

Keywords: unsaturated soil; expansive soil; lime treatment; soil water characteristic curves

1. Introduction

Expansive clays undergo significant volume changes (whether swell or shrinkage) with change in water content. These volume changes cause severe damages to engineering systems constructed above expansive formations. Several studies were performed to investigate the effectiveness of chemical treatment on the arresttnig the swelling behavior of expansive soils. Chemical additives considered included lime, cement and fly ash or their combinations (Puppala *et al*. 2006, Al Zubaidi *et al*. 2013, Calik and Sadoglu 2014, Voottipruex and Jamsawang 2014). Chemical treatment using lime is considered one of the widely used technique for the mitigation of expansive clays (Al-Mukhtar *et al*. 2010, Siddique and Hossain 2013). When lime is added to the soil, cation exchange reaction causes flocculation of samples and reduces the plasticity of soil. Furthermore, the addition of lime leads to the formation of cementitious compounds through

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pozzolanic reactions that bind soil particles together. Both reactions improve the workability and mechanical behavior of compacted lime-soil mixture. Typical criteria for assessing the degree of improvement of lime-treated expansive soils include unconfined compression strength, plasticity, swelling characteristics and compressibility (Alper *et al.* 2006, Nalbantoglu 2006, Khattab *et al.* 2007, Ramadas *et al.* 2011).

Field application of lime treatment to expansive soils includes mixing and compaction which render a soil unsaturated. Unsaturated soils behavior is governed by two stress variables; namely, soil suction and net stress which control the behavior of unsaturated expansive soil; therefore, their behavior can be best interpreted using unsaturated soil mechanics. Soil water characteristic curve (SWCC) emerged as a fundamental constitutive relation used in describing the unsaturated behavior of soil. SWCC defines the relationship between amount of water designated as gravimetric water content or degree of saturation and soil suction as shown in Fig. 1. The importance of the SWCC is stemmed from two main experimental observations. First, changes in unsaturated soil properties are associated with the amount of water in the soil pores or soil suction; therefore, it is evident that relationship exists between SWCC and unsaturated soil properties (Vanapalli *et al.* 1996, Fredlund *et al.* 1996). Many models were proposed to predict unsaturated behavior of soil such as hydraulic conductivity, shear strength, and volume change from SWCC (Leong and Rahardjo 1997, Barbour 1998). Second, SWCC is closely related to the pore size distribution of soil. Several experimental investigations confirmed the dependence of SWCC shape on grain structure and pore-size distribution (Amaral *et al.* 2013, Cuisinier *et al.* 2011, Arroyo *et al.* 2013). Examples of practical uses of SWCC include the design, modeling and analysis of unsaturated slope (Ng and Pang 2000, Zhan 2007), design of unsaturated pavement subgrade (Mechanistic Empirical pavement design, Zapata *et al.* 2007, Zapata 2009). In addition, SWCCs are used for the estimation of in situ soil suction based on water content measurements (Fredlund *et al.* 2011a).

Soil improvement can be traced back to significant changes in soil microstructure due to lime addition (Russo 2005, Cuisinier *et al.* 2008, 2011). Therefore, SWCC can provide insight on modifications caused by lime at the microstructural level (Russo 2005). Recently, experimental studies were performed to evaluate the effectiveness of chemical treatment on the unsaturated expansive soils using soil-water characteristic curve. Puppala *et al.* (2006) reported that SWCC is considered as a useful tool in understanding the chemical stabilization effects on expansive soil. Yang *et al.* (2011) analyzed the improvement of expansive soil acquired by addition of lime and fly ash using main features of SWCC.

Main features of the SWCC include air-entry value (AEV), residual water content (w_r), initial slope (S_1), de-saturation slope (S_2), and saturation water content (w_{sat}) as shown in Fig. 1. The air-entry value is defined as the suction beyond which air begins to enter the soil pores starting with the largest pore. The residual water content (w_r) is defined as the amount of water that is tightly attached to soil particles and any increase in suction results in insignificant change in water content. The initial slope (S_1) is the slope of the SWCC portion at suction levels less than AEV, while the de-saturation slope (S_2) refers to the slope of the curve between the AEV and residual water content.

$$S_1 \text{ or } S_2 = \Delta w / \log(\Psi_2 / \Psi_1) \tag{1}$$

Where; Δw = difference in gravimetric water content.
Ψ_2/Ψ_1 = values of suction at two points along the slope.

These features are strongly related to soil structure and pore size distribution (Miao *et al.* 2006,

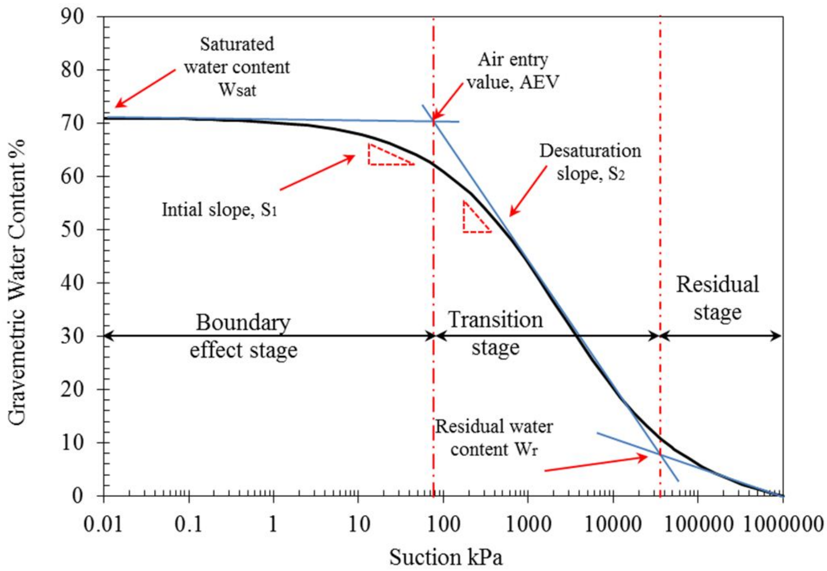


Fig. 1 Typical soil water characteristic curve

Chao *et al* 2008). As such, the SWCC can be used to provide insight on the modifications caused by lime on the microstructure level based on the magnitude of change in key features of the SWCC.

The aim of this study is to introduce SWCC as a tool to assess the effectiveness of lime treatment on expansive soils. SWCCs of lime-treated expansive clay were evaluated to interpret changes in key features of SWCC. Different variables considered included lime content (2%, 4% and 6% by dry weight of clay) and curing period (7 and 28 days). A series of tests were performed to evaluate the swelling characteristics and unconfined compression strength of lime-treated expansive soil under similar lime content and curing period. Correlations between changes in SWCC features (i.e., saturated water content, curve slope, air-entry value and residual water content) and observed behavior with respect to swelling characteristics (swelling potential and pressure) and unconfined shear strength were inferred.

2. Materials used

Key contributors to the formation of expansive soils include arid climate conditions, geological history and sedimentation environment, all of which are present in Saudi Arabia. Fig. 2 delineates areas in Saudi Arabia where expansive soils were identified. Detailed information regarding expansive soil distribution in Saudi Arabia, their geological origin, and swelling characteristics has been well documented in the technical literature (Erol and Dhowian 1990, Azam *et al*. 2003, Sabtan 2005, Aiban 2006). Case studies on damages of light buildings and pavements due to expansive soils were also documented in the technical literature (Al-Mhaidib 1999, Shamrani *et al*. 2010, Dafalla and Al-Shamarani 2012). It is estimated that the economic losses from expansive soil damages in Saudi Arabia during the period 1977-1987 totaled approximately 300 million US dollars. This cost was attributed to building and pavements damages (Al-Muhaidib 2003, Ruwaih

Table 1 Summary of soil characterization data for Al-Qatif Soil

Value	Test
Color	Greenish brown
Specific gravity, G_s	2.71
Liquid limit, w_L (%)	160-170
Plastic limit, w_P (%)	60
Classification	Clay of high plasticity (CH)
Unified soil swelling potential (ASTM D4546-03)	22-30%
Swelling pressure (ASTM D4546-03)	450-600 kPa
% fines pass #200	95
Clay percentage (%)	60-75%

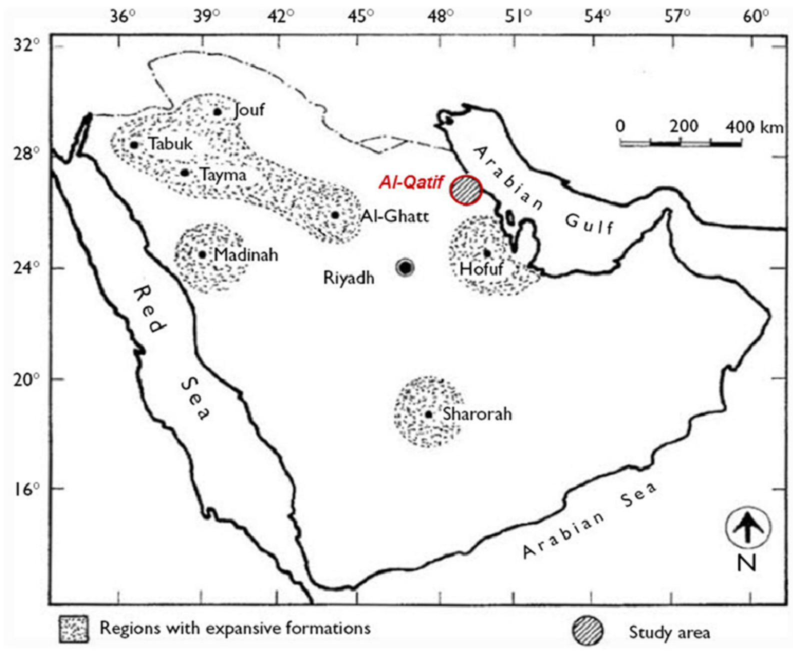


Fig. 2 Map of distribution of the expansive formations area in Saudi Arabia (adapted from Ruwaih 1987, Dhowian *et al*. 1985)

1987).

The expansive clay used in this study were obtained from the city of Al-Qatif located along the shoreline of the Arabian Gulf in the eastern province of Saudi Arabia as shown in Fig. 2 (approximate latitude 26°56′N and longitude 50°01′E). This city is about 20 km north of Dammam, the main port city of the Kingdom along the Gulf Coast. Several characterization studies performed on expansive clays in this region revealed the expansive soil exhibit high plasticity and possess moderate to highly expansive potential (Hameed 1991, Abduljauwad 1994). This was also substantiated by mineralogical analysis that confirmed the presence of expansive clay minerals such as montimorillonite (Rafi 1988). In-situ sampling of Al-Qatif clay was performed using a test pit excavated to a depth 2.0-2.5 m below ground surface. The location of the test pit was selected to be near areas were structural damages were observed. Samples are stored in plastic bags and transported to the laboratory for full geotechnical characterization. Table 1 provides a summary of soil characterization results of Al-Qatif soil.

Lime used in this study is a commercial grade calcium hydroxide (assay 90%) supplied by Winlab Chemicals, UK. Estimation of the optimum lime content value for lime-clay mixtures was evaluated using ASTM D6276 – 99a originally proposed by Eades and Grim (1996). The optimum lime content defines the lime content beyond which further increase in lime content will have negligible effect on improvement of soil. According to ASTM standard, the lowest percentage of lime that results in a soil-lime pH of 12.4 is considered the optimum lime content. Results of test performed on soil indicated that 4% to be optimum lime content. Two additional lime contents equivalent to ± 2% of optimum lime content were considered in this study.

3. Sample preparation and mixture characterization

Samples obtained from the field were air dried, pulverized by Los Angeles apparatus, and sieved using sieve No. 40. For soil samples treated with lime, the oven dried soil was mixed with lime followed by the addition of target amount of water and thoroughly mixed again. All mixtures are stored in plastic bags in a humid environment for a period of 24 hours to homogenize. Specimens were statically compacted to maximum dry density (MDD) evaluated using standard compaction effort (i.e., 12,400 ft-lbf/ft^3 (600 kN-m/m^3) (ASTM D698 2000). Compaction curves of lime treated soils as function of lime content are shown in Fig. 3. Compacted specimens were plastic wrapped, and were stored in a humidity room for a curing period of 7 or 28 days.

A series of tests were performed to evaluate Atterberg limits (i.e., liquid and plastic limit) and shrinkage limit of lime-expansive clay mixtures with different lime contents. Fig. 4 shows the variation of Atterberg limits and shrinkage limit with lime content. From Fig. 4, it is apparent that,

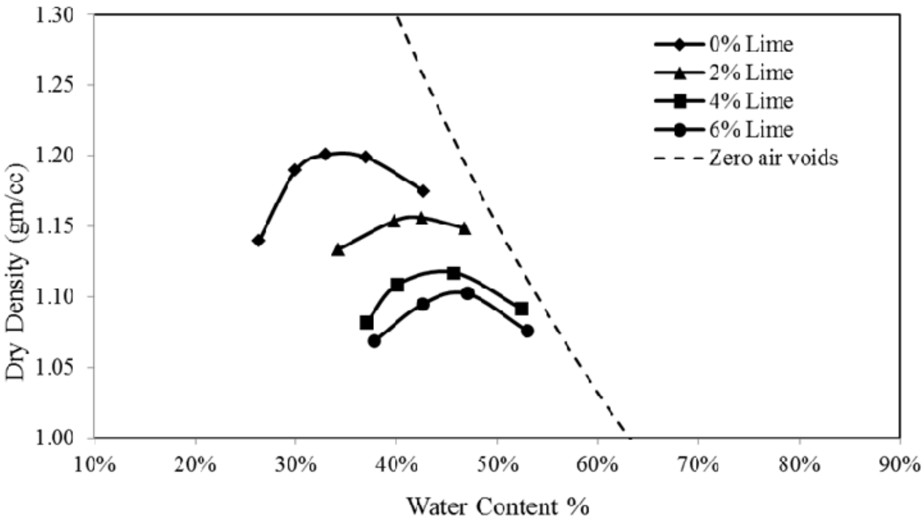


Fig. 3 Compaction curves of lime-treated expansive clay for different lime contents

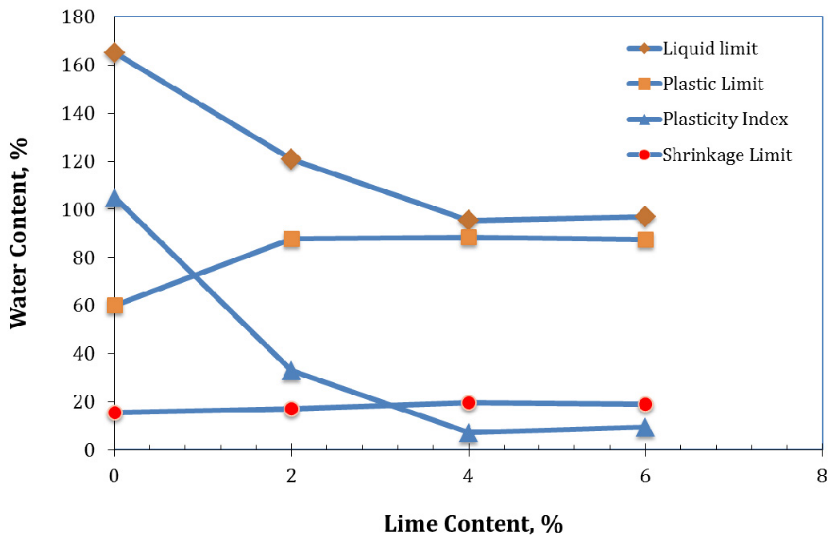


Fig. 4 Variation of Atterberg limits with lime contents

up to 4%, lime addition had a significant on Atterberg limits and shrinkage limit. Beyond 4% lime content, negligible change was observed.

4. Experimental procedures

4.1 Soil water characteristic curve

Soil water characteristic curve SWCCs of untreated and lime-treated expansive soils were evaluated using axis translation technique and filter paper method to cover a wide suction range. Axis translation technique was applied using Fredlund SWC-150 device shown in Fig. 5. A schematic diagram of the Fredlund SWCC device is illustrated in Fig. 6. The device primarily comprise of stainless steel pressure chamber, pressure panel and loading system. The base plate is manufactured with a special recess to accommodate a high entry value ceramic disc and provide a water filled compartment below the disc. The water in the compartment below the ceramic disc is connected to two graduated burettes fixed on both sides of the pressure panel to measure the flow of water in and out of the sample. These burettes are used for periodic flushing of air bubbles that may accumulate below the ceramic disc. Further details about device components were provided by Pham *et al*. (2004), Padilla *et al*. (2005), Elkady and Al-Mahbashi (2012).

Samples were statically compacted in stainless steel rings to dimensions of 50 mm in diameter and 16 mm thick. Prior to suction application, samples were saturated for at least 24 hours in the oedometer cell under a vertical stress of 7 kPa. After saturation, suction was increased incrementally up to 1,500 kPa (using a ceramic disc with air entry value of 15 bar). Samples were allowed to equilibrate under each suction increment. Equilibrium was attained when water level in burettes did not change within 24 hours. After equilibrium, amount of water expelled from specimen were recorded based on changes in burette water level. At the end of the test, water content at each suction level was back-calculated based on the cumulative loss in water content

Fig. 5 Fredlund SWC-150 device

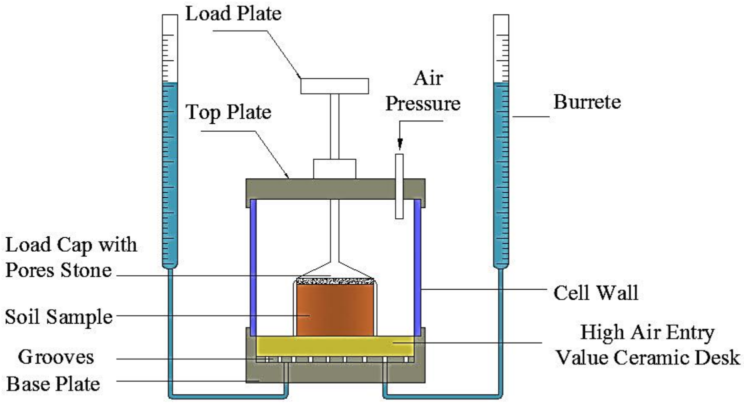


Fig. 6 Sketch of the pressure cell in Fredlund SWC-150 device

measured at each stage.

The filter paper method was used to determine the soil water characteristic curves of the lime-treated expansive clays for suction levels greater than 1,500 kPa. Matric suction was measured using contact filter paper technique as described in ASTM D 5298-(2003). Testing procedure involved using a Whatman No. 42 filter paper disc (55 mm in diameter) sandwiched between two identical statically compacted samples of 70 mm in diameter and 20 mm high.

To determine the drying SWCC for suctions greater than 1,500 kPa, compacted samples were allowed to dry under laboratory controlled conditions to different target water contents. All target water contents were less than the minimum water content obtained using the axis translation technique. To ensure, uniform distribution of moisture content in the dried specimen, the drying process was performed with a slow rate (at least 48 hours). The dry rate was controlled using glass jar with a perforated plastic film sealed. When the targeted water content was reached, the sample's weight and volume were recorded and the specimen was wrapped in thin plastic film and stored in a humidity room for 24 hours to homogenize. The two sample pieces and filter paper were wrapped using electrical tape and transferred to the tight-able glass jar. To ensure good contact between the specimen and the filter papers, a small load equivalent to vertical stress of 7 kPa was placed on top of specimen inside the glass jar. All samples (placed in glass jars) were stored in temperature controlled environment for a period about 21 days to equilibrate. Fig. 7 shows the setup of the filter paper test. At the end of equilibration period, water content of filter

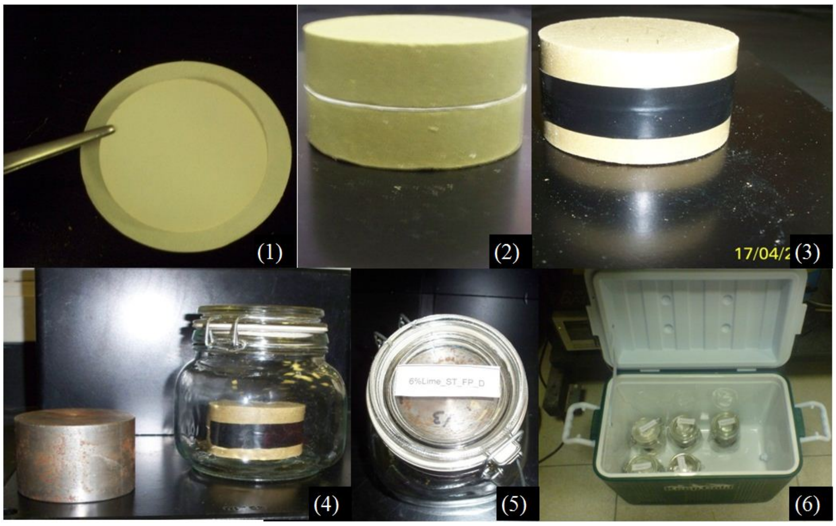


Fig. 7 Prepared sample for filter paper technique

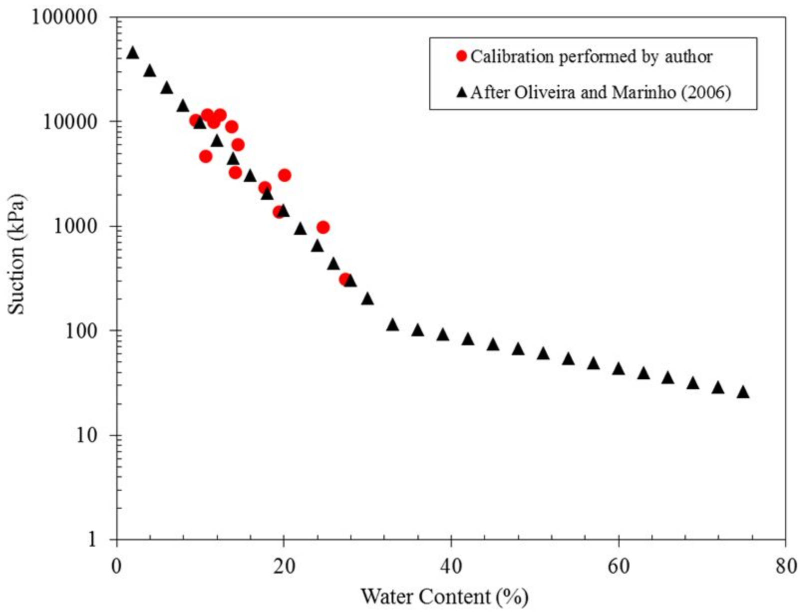


Fig. 8 Verification of filter paper calibration curve

paper was determined using gravimetric techniques and using a balance with resolution of 0.0001 g. Values of matric suction corresponding to measured water content of filter paper were obtained from the calibration curve developed by Oliveira and Marinho (2006) and verified by author as shown in Fig. 8.

4.2 Swelling characteristics and unconfined compression strength

The swelling characteristics (i.e., swelling potential and swelling pressure) of expansive clay before and after lime treatment (considering 2%, 4% and 6% of lime content with 7 and 28 days curing periods) were evaluated using a series of one-dimensional consolidometer tests in accordance with ASTM D4546-(2003). The swelling potential was defined as vertical strain occurring due to the wetting of samples under a vertical stress of 7 kPa. After reaching final swelling strain, the vertical stress was increased incrementally. The pressure required to return the specimen back to its initial height (or void ratio) is termed swelling pressure.

Unconfined compressive strength (UCS) of untreated and lime-treated expansive clays were assessed according to ASTM D2166-(2000). Untreated and lime-treated specimens were remolded with final dimensions of 38 mm in diameter and 76 mm high. For lime-treated specimens, curing was conducted for 7 or 28 days. The water content of UCS specimens at the end of curing should correspond to initial water content used in sample preparation. This was confirmed by weighing specimens immediately after curing and observing negligible change in UCS specimens' weight. Based on specimen water content, the matric suction in UCS specimens was estimated from SWCCs presented in Fig. 10. Matric suction in test specimens ranged between 500 and 2500 kPa. All specimens were loaded to failure with a strain rate of 0.3 mm/min.

5. Results and discussion

5.1 Variation of SWCC features with lime content

All SWCC data obtained from the experimental program were fitted using an equation proposed by Pham and Fredlund (2008). This equation was originally proposed for soils exhibiting significant volume change and has non-sigmoid shaped SWCC as shown in Fig. 9. Furthermore, the curve-fitting parameters used in the equation have physical relationships to unsaturated soil properties (i.e., air entry value, saturated water content, initial slope, residual water content). This equation is defined as follows

$$\begin{aligned} w(\psi) &= w_{\text{sat}}(M_1 + M_3) + S_1[1 - \log(\psi_{\text{ae}})(M_1 + M_3) - M_2] \\ &+ S_2\left[-M_1 \log\left(\frac{10^6}{\psi_{ae}}\right) - \log\left(\frac{10^6}{\psi_{ae}}\right) M_3 + M_2 \right] \end{aligned} \tag{2}$$

Where

$w(\psi)$ is gravimetric water content as a function of suction;

w_{sat} is water content at 1 kPa suction

ψ_{ae} is air entry suction

ψ_r is the residual soil suction

S_1 is the slope of the SWCC of the portion less than the air entry

S_2 is the slope of the SWCC of the portion between air entry value and the residual suction.

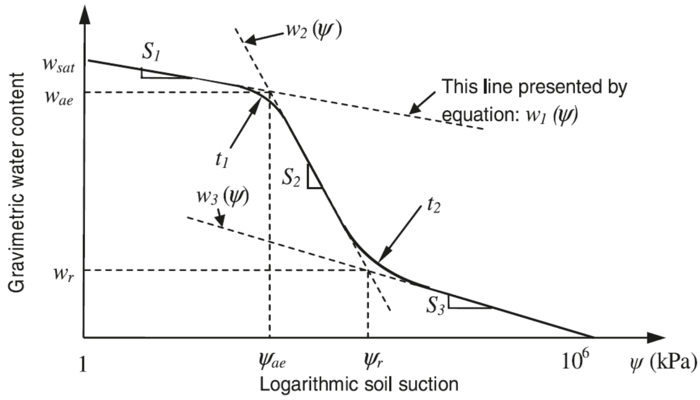
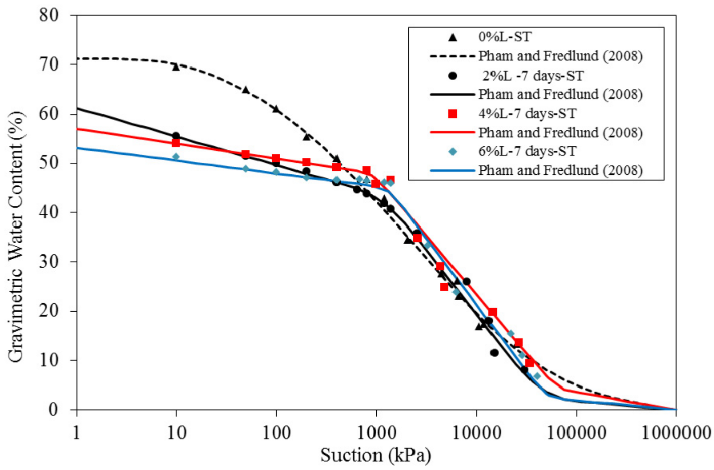
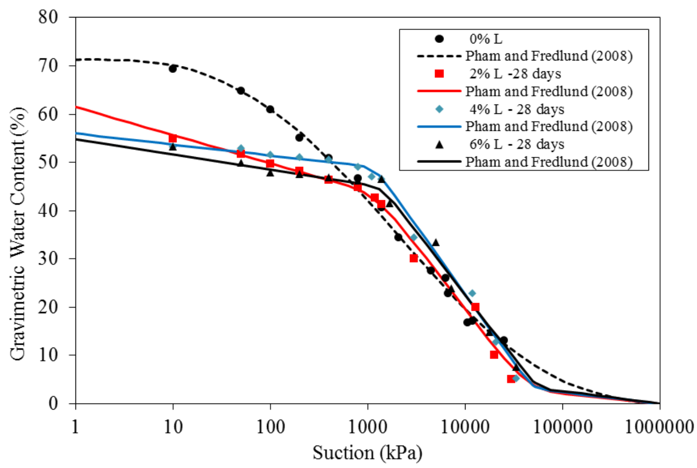


Fig. 9 Variables included in SWCC fitting equation proposed by (Pham and Fredlund 2008)



(a)



(b)

Fig. 10 Effect of Lime Content on SWCCs at: (a) 7-Day Curing Period; (b) 28-Day curing period

$$M_1(\psi)=\frac{\left[\log\left(\frac{\psi}{\psi_r}\right)-\frac{\ln(10)}{2t_2}\left(1-\frac{\psi_r^{t_2}}{\psi_r^{t_2}-\psi^{t_2}}\right)\right]\frac{\psi_r^{t_2}}{\psi_r^{t_2}-\psi^{t_2}}}{\log\left(\frac{10^6}{\psi_r}\right)} \tag{3}$$

$$M_2(\psi)=\left[\log\left(\frac{\psi}{\psi_r}\right)-\frac{\ln(10)}{2t_2}\left(1-\frac{\psi_r^{t_2}}{\psi_r^{t_2}-\psi^{t_2}}\right)\right]\frac{\psi_{ae}^{t_1}\psi_r^{t_2}}{(\psi_{ae}^{t_1}-\psi^{t_1})(\psi_r^{t_2}-\psi^{t_2})} \tag{4}$$

$$M_3(\psi)=\frac{\log(10)-\log(\psi)}{\log(10)-\log(\psi_r)} \tag{5}$$

Where t_1 and t_2 are parameters that control the transition between different portions of the SWCC.

Figs. 10(a) and (b) illustrate the drying SWCCs of lime-treated expansive clay as a function of lime content and curing period. From these curves, improvements in the behavior of expansive clay as a result of lime treatment was assessed based on changes in main features of SWCC including air entry value (AEV), residual water content (w_r), saturation water content (w_{sat}), initial slope (S_1), de-saturation slope (S_2). Variation of SWCC features with lime content are depicted in Figs. 11 through 13 and summarized in Table 2.

Visual examinations of SWCCs in Fig. 10(a) and (b) revealed a significant reduction in the initial slope (S_1) of SWCC of the lime treated expansive clay. This indicates a reduction in de-saturation rate. Quantification of changes in initial slope (S_1) indicates a significant decrease by more than 70% with addition of lime content up to 4% as shown in Fig. 11. Further addition of lime to 6% causes a far less significant change in S_1. Furthermore, the air-entry value increased

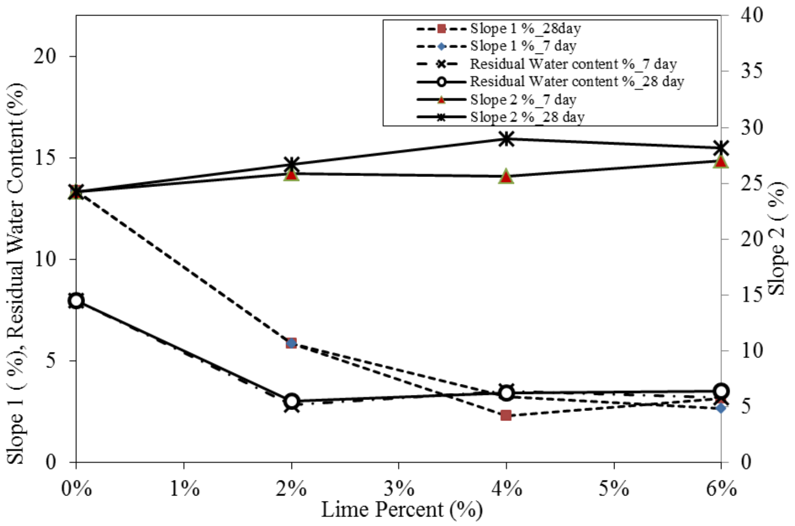


Fig. 11 Variations on initial slope (S_1), residual water content (w_r) and slope (S_2) of lime-treated expansive soils

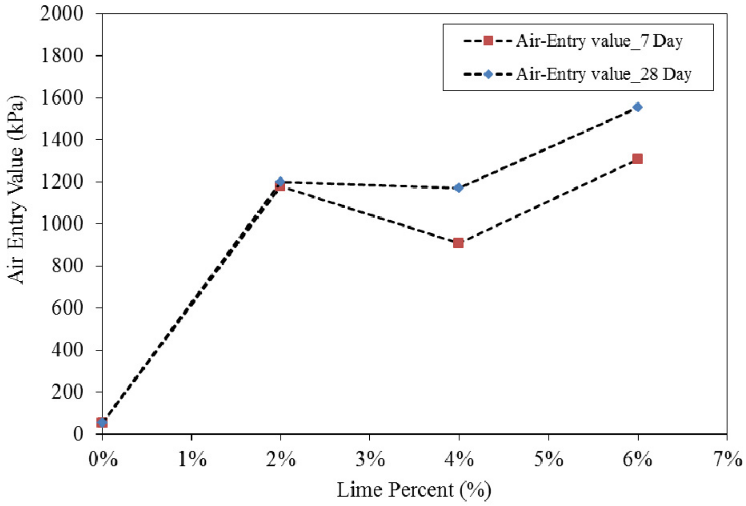


Fig. 12 Effect of lime content on AEV of lime-treated expansive soils

with increase in lime content. This indicates that significant changes in pore distribution of lime-treated soils did not occur due to the further increase in lime to 6%. On the other hand, the AEV was observed to increase with increase in lime content; however, on a limited scale. Increase in AEV values corresponding to 4% lime content were estimated to be between 1593% and 2077% after 7 and 28 days curing periods; respectively. At 6% lime content, the AEV increased by 2330% and 2790% at 7 day and 28 days of curing; respectively (Fig. 12). It should be noted that the initial slope and air entry value are primarily controlled by the size of the large pore (macro-pores) in the soil. Similar conclusions were reported by Arroyo *et al*. (2013) for unsaturated silty sand stabilized with different cement content. Therefore, the decrease in S_1 and increase in AEV are indicative of reduction in macro-pores resulting in an increase in retention capacity of samples. Plausible explanations for these changes are attributed to soil fabric change due flocculation, blockage of macro-pores with cementitious products and unreacted lime filling the pores.

On the other hand, the saturated water content decreased by 19.7% and 21.1% with increase of lime content up to 4% for 7 and 28 days; respectively (Fig. 13). This decrease in saturated water content is attributed to volume change characteristics of untreated and lime-treated expansive clay. When lime is added to expansive soils, the swelling (volume change) potential of the soil is reduced causing decrease in the water storage volume and, in turn, decrease in saturated water content.

Visual examination of Fig. 10 also revealed that, beyond the AEV, the SWCC for untreated and lime-treated soils tend to converge to a single curve. Hence, the de-saturation slope (S_2) was insignificantly affected by lime content as shown in Fig. 11. This is attributed to the fact that de-saturation slope is effected by the small pores sizes (micro-pores) in the soil revealing that lime addition had a minor impact on microstructure of samples. From Fig. 11, the addition of lime caused a significant reduction in residual water content (w_r). However, further increase in lime content showed no specific trend for the variation of residual water content with lime content.

Curing period up to 28 days (which considered in this study) had a less significant effect on the features of SWCC, except for AEV which showed a significant increase with increasing of curing period along with increase in lime content.

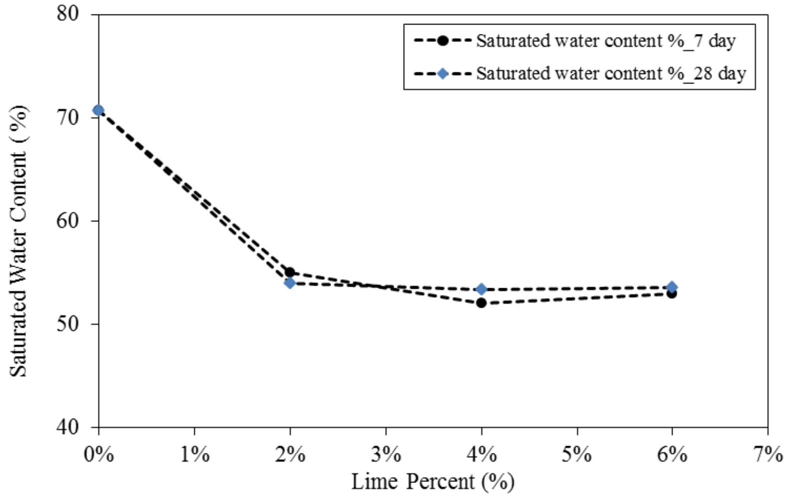


Fig. 13 Effect of lime content on saturated water content (w_{sat}) of lime-treated expansive soils

Table 2 Fitting Parameters of SWCC

Lime content	0%	2%		4%		6%	
Curing period (days)	-----	7	28	7	28	7	28
Air-Entry Value (AEV, kPa)	53.75	1181.71	1200.00	910.35	1170.27	1308.21	1555.60
Residual water content (w_r, %)	7.95	2.85	3.00	3.50	3.40	3.20	3.50
Saturated water content (w_{sat}, %)	70.65	55.00	53.99	52.00	53.40	53.00	53.6
Initial slope (S_1, %)	13.39	5.83	5.83	3.25	2.28	2.63	3.16
Desaturation slope (S_2, %)	22.80	25.82	25.82	23.67	28.18	26.78	26.06

5.2 Effect of lime content on the swelling characteristics and unconfined compressive strength

Baseline information on the engineering behavior of lime-treated expansive soils in terms of typical evaluation criteria; namely, swelling potential, swelling pressure and unconfined compression strength was presented. Trends for the variation of swelling potential, swelling pressure, and unconfined compression strength are provided in Figs. 14 and 15.

Fig. 14 indicated that percentage of reduction in swell potential was about 80 % with the addition of 2% lime and increased to 98% when lime content increased to 4%. Beyond 4% lime content, minimal reduction in swell potential was observed. Similar observations were noted for the effect of lime content on swelling pressure as shown in Fig. 14. Furthermore, curing period up to 28 days had a minimal effect on the swelling strain of lime treated expansive soils; however, had a more significant effect on swelling pressure.

On the other hand, unconfined compression strength increased with increase in lime content for both curing periods (i.e., 7 and 28 day) as shown in Fig. 15. In contrary to swelling characteristics (Fig. 14), curing period up to 28 days was observed to have a significant effect on the unconfined compression strength. This is attributed to the development of cementitious compounds via

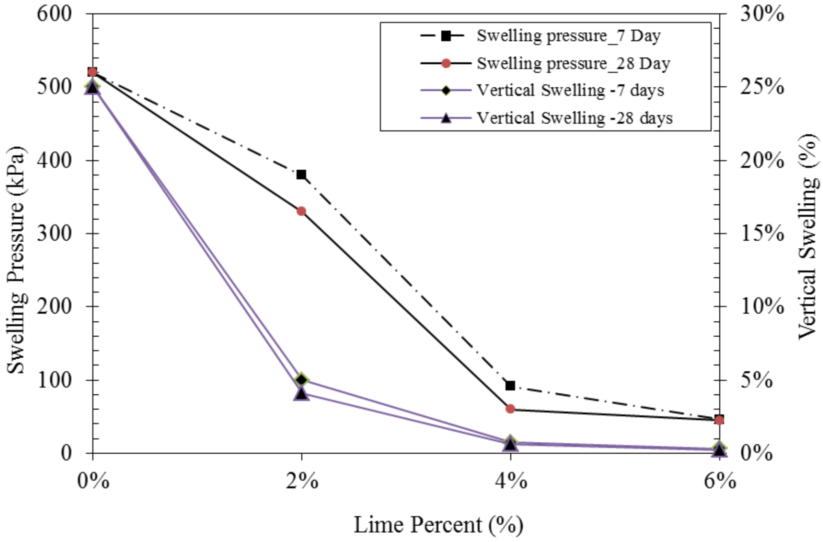


Fig. 14 Effect of lime content and curing period on the swelling characteristics

time-dependent pozzolanic reactions causing increase in strength of lime treated-soils.

From the above observations, it can be established that 4% is considered as the optimum lime content corresponding to minimum values of swelling potential and swelling pressure and significant increase in unconfined compression strength. Increasing the percentage of lime to greater than 4% does not provide additional benefits from the perspective of swelling characteristics.

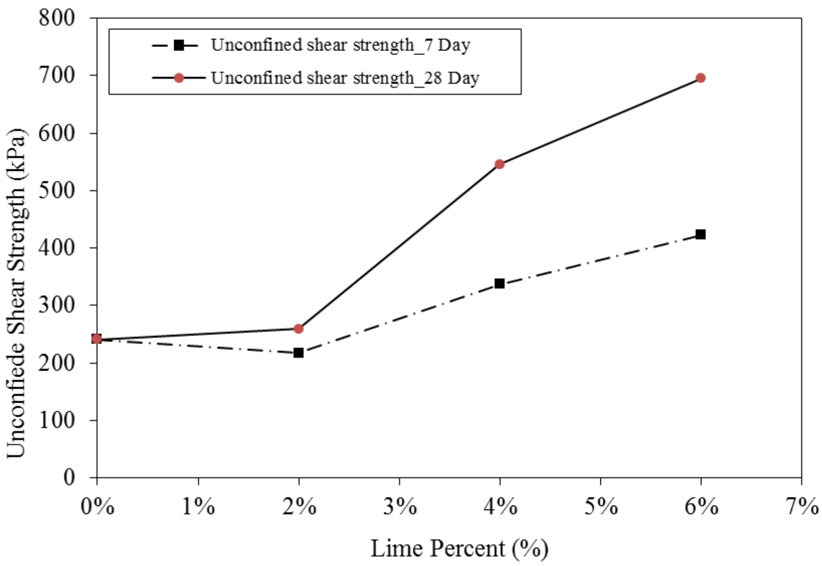


Fig. 15 Effect of lime content and curing period on unconfined shear strength

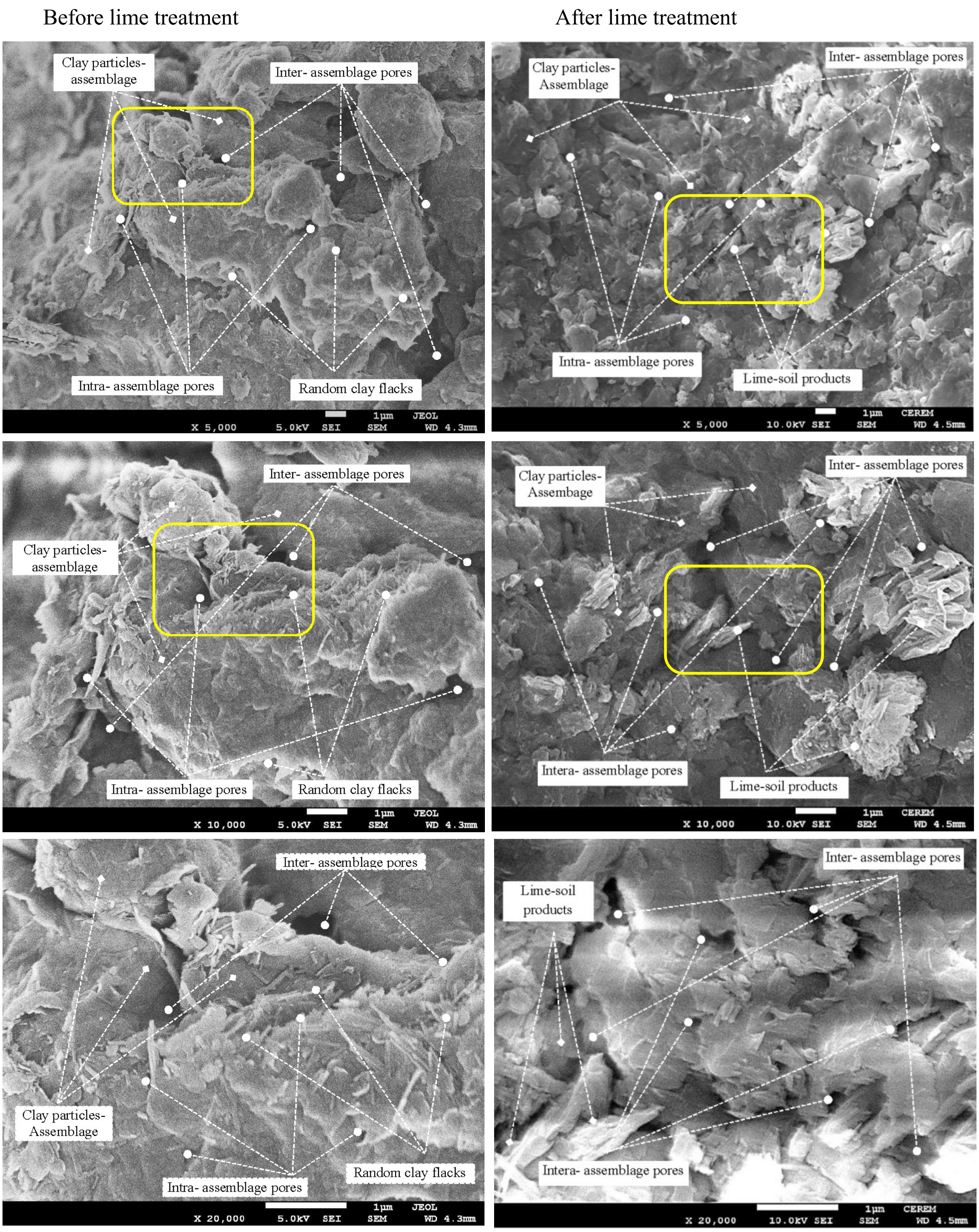


Fig. 16 Scanning electron microscope of Al-Qatif expansive clay before and after lime (4%) treatment

6. Discussion

The effect of lime content on swelling potential, swelling pressure and unconfined compressive strength of the lime-treated soil cured for periods of 7 and 28 days represents a clear evidence of the improvements in the engineering behavior of expansive soil. All treated samples showed significant improvements summarized in the Figs. 14 and 15.

Similarly, SWCC showed significant changes to key features that can be well correlated to the observed improvement of engineering behavior. Main features of SWCC that can be used to evaluate improvements in engineering behavior of expansive soils due to lime treatment are air entry value, initial slope and saturated water content.

The decrease in the initial slope (S_1) and saturated water content (w_{sat}) correlate well with swelling characteristics under various lime content. Specifically, at 4% lime content, the average reduction in saturated water content (w_{sat}) was about 26% and decrease in initial slope (S_1) was about 75% correspond to a reduction of swelling potential and swelling pressure by 98% and 82.4%; respectively.

Table 3 Critical values of key parameters of SWCC used in the analysis

Parameter	Saturated gravimetric water content (w_{sat}, %)	Air -entry value (AEV, kPa)	Initial slope (S_1, %)
Expansive soil	> 53.0	≤ 900.0	> 3.5
Non expansive soil	≤ 53.0	> 900.0	≤ 3.5

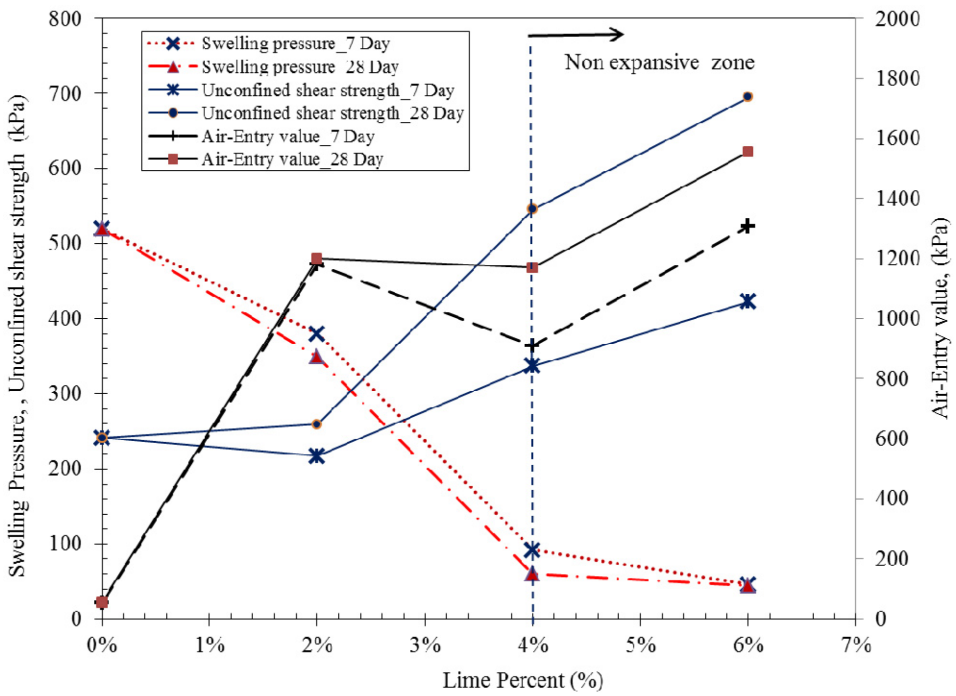


Fig. 17 Correlation between AEV and unconfined compression strength of lime-treated expansive soils

Fredlund *et al.* (2011b) suggested that there is a correlation between shrinkage limit and residual water content as well as air-entry value and plastic limit. To investigate whether similar correlation exists, trends for the variation of shrinkage limit, plastic limit, residual water content and air-entry value with lime content were examined (Fig. 4, 11 and 12). From these trends, it is observed that shrinkage limit and residual water content show similar trends of negligible change in value with change in lime content. On the other hand, plastic limit and air-entry value are partial correlated with increase in value accompanied by increase in lime content up to 4%.

As stated previously, AEV is closely related to the microstructure and fabric of lime-treated soils. Increase in AEV signifies a decrease in pore size as well as increase in inter-particle contacts due to the formation of cementitious material. To identify these changes in fabric, the specimens were dried using freeze-drying technique and scanned in field emission scanning electron microscope with 5 to 10 KV. Results from scanning electron microscope (SEM) indicated change in the fabric after lime treatment as shown in Fig. 16. From Fig. 16, the fabric of lime-treated clay was observed to be denser with low inter-assemblage pores and more interparticles contact. This increase in inter-particle contacts will result an increase in shear strength. As shown in Fig. 17, the increase of AEV about 1600% and 2077% correspond to increase in shear strength by about 40% and 126% for 4% lime content and 7, 28 days curing period; respectively.

Based on general trends of AEV, w_{sat}, and S_1 shown in Figs. 11 through 13, key features of SWCC can be considered as critical limits or boundary state limits identifying expansive and non-expansive states for this soil. These limits are confirmed by test results of typical tests for evaluating the swelling characteristics and unconfined compression strength (Fig. 17). These critical values can be used as indicators for the improvement achieved in Al-Qatif expansive soil after lime treatment. A summary of proposed limits are presented in Table 3. It is worth noting that both requirements of w_{sat} and S_1 should meet the requirements for non-expansive soils.

7. Conclusions

From the results obtained in this study, several conclusions could be driven as:

- Addition of lime had a significant improvement in the hydro-mechanical properties (i.e., swelling characteristics and SWCC) of expansive soil.
- The improvement in lime-treated expansive soil can be assessed based on main features of SWCC. Increase in air-entry value (AEV) reflects an improvement in unconfined compression strength. Reduction of saturated water content w_{sat} and desaturation slope S_1 also are indicative of improvement in the volume stability (swelling characteristics) of lime-treated expansive soil.
- S_2 had an insignificant effect on evaluating the improvement due to lime treatment. This indicates that lime treatment had a minimal effect on the microstructure level of soil.
- Improvements on lime-treated expansive soil that were analyzed by the main features of SWCC showed good agreement with results obtained from typical evaluation criteria swelling characteristics and unconfined shear strength for expansive clay tested (Al-Qatif highly expansive soil).
- Both values of w_{sat} and S_1 should be satisfied to meet the requirements for non-expansive soils.
- The authors recommend similar studies to be performed on different expansive soils treated with lime.

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