Recent Advancements in Predicting the Behaviour of Unsaturated and Expansive Soils

Aritra Banerjee [1[0000-0001-5522-1730]], Anand J. Puppala[2[0000-0003-0435-6285]], Surya S. C. Congress [3[0000-0001-5921-9582]], Sayantan Chakraborty[4[0000-0002-6809-5953]] and Aravind Pedarla [5]

[1]Research Scientist, AIS Division, The University of Texas at Arlington Research Institute, Fort Worth, Texas, USA
aritra@uta.edu
[2]A.P. and Florence Wiley Chair Professor, Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, Texas, USA
anandp@tamu.edu
[3]Associate Research Scientist, Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, Texas, USA
congress@tamu.edu
[4]Associate Transportation Researcher, Texas A&M Transportation Institute
The Texas A&M University System, College Station, Texas, USA
sayantan@tamu.edu
[5]Geotechnical Engineer, TSIT, Fort Worth, Texas, USA
apedarla@tsitservices.com

Abstract. This keynote paper focuses on the advancements of characterization of unsaturated expansive soils which would allow better prediction of its swelling and mechanical behaviours. The paper has been divided into three parts. Firstly, a novel model is developed by considering two micro-soil parameters, soil-specific surface area and internal pore size distribution, to predict the natural swelling in expansive clayey soils. The model was validated by comparing the predictions with experimental results for eight soils. Secondly, the paper deals with the diffuse-double-layer (DDL) theory–related electrostatic forces from individual clay minerals of expansive soils and their influence on soil swelling. A DDL-based model was also developed, which was validated for swell prediction for fourteen expansive soils. A good correlation was observed for both models when the results were compared with experimental results. Finally, the paper demonstrated the use of vapour pressure technique to control suction beyond 5 MPa for performing suction-controlled repeated load triaxial (RLT) test at high suction state. This novel technique mitigates the limitation of axis-translation technique for maintaining suction till the air-entry-value (AEV) of the ceramic disk. These new models and unsaturated laboratory testing techniques would aid in better characterization of expansive soils in their unsaturated state. This would also provide accurate prediction of swell and stiffness behaviours of soils, thereby reducing the uncertainties in the design of civil infrastructure built on expansive soils.

Keywords: Unsaturated Soils, Swelling, Expansive Soils, Resilient Modulus, High-suction State.

1 Introduction

Expansive Soils are known to be problematic for supporting civil infrastructure, such as low-height residential structures, pavements and others, due to the tendency of such soils to undergo significant volume changes with considerable moisture content fluctuations. These moisture fluctuations are commonly caused due to seasonal and daily variations in temperature and precipitation. However, due to the growth in population and associated urbanization, expansive soils are often used as foundation soils and construction still takes place on top of expansive soils (Puppala and Cerato 2009). Several cases of severe distress had been observed for such constructed structures and pavements due to the swell-and-shrink–related movements of these soils (Katti et al. 1984; Puppala et al. 2013). These damages had been reported to be greater than those observed for the damages caused by floods, hurricanes, tornadoes, and earthquakes (Jones and Holtz 1973; Puppala et al. 2011).

Many parts of the world lie within the arid and semi-arid regions, where precipitation is lower than the rate of evaporation. Hence, during most of the year the soil in such regions, especially at shallow depths are in unsaturated state, wherein theories of classical soil mechanics and geotechnical engineering of either dry or fully saturated soils doesn’t apply. The study of unsaturated soil involves the principles of mechanics, hydraulics, thermodynamics, and interfacial physics. Because of the complexity of the material properties and the requirement of sophisticated equipment to characterize the behaviour of unsaturated soils, limited research has been conducted, resulting in a lack of knowledge.

The negligence or oversimplification of the relations, required to accurately study the behaviour of unsaturated soils, has resulted in incorrect predictions of strength and volume changes of soil when it is subjected to various kinds of loads, such as structural and climatic loads (Banerjee et al. 2018a). This is especially true for expansive soils. Since the volume changes of expansive soils create severe distress to civil infrastructure, the study of the behaviour of expansive soils had motivated the unsaturated soil research (Jones and Holtz 1973; Lu and Likos 2004).

Additionally, the problems due to expansive soils might have risen due to the lack of consideration for soil mineralogy (Puppala et al. 2004; Chittoori and Puppala 2011). Most of the previous correlations for predicting the behaviour of expansive soil adopted a PI-based methodology to propose simplistic relationships that were utilized to predict the swelling potential of clayey soils, which may be an erroneous approach (Puppala et al. 2004, 2011). In this study, an attempt was made to improve the understanding of the behaviour of expansive soil by identifying the parameters that affect the swelling characterization of clayey soils and also demonstrate the need for advanced setups to determine the resilient modulus-suction relationship in expansive soils. In the past, studies have been conducted to identify various micro soil parameters such as clay mineralogy, surface area, matric suction, and pore distribution, and their effect on behaviour of soils (Katti et al. 1984; Puppala et al. 2013; Chakraborty and Nair 2017, 2018; He et al. 2018).

The first part of research data presented in this keynote paper focuses on correlating two micro-soil parameters, soil-specific surface area and internal pore size distribution, with the swell behaviour of expansive clay. These two parameters account for the swell potential of clay minerals in soil and internal moisture distribution that provides moisture access to the clay minerals present in soils. The second part of this paper deals with the diffuse-double-layer (DDL) theory–related electrostatic forces from individual clay minerals of an expansive soil and their influence on soil swelling and a DDL-based model was developed and validated for swell prediction for expansive soils. Finally, the use of vapour pressure technique to control suction beyond 5 MPa was demonstrated for performing suction-controlled repeated load triaxial test at high suction state. This novel technique mitigates the limitation of axis-translation technique for maintaining suction till the air-entry-value (AEV) of the ceramic disk. This was performed to reduce the variation of resilient modulus for each loading sequence.

Some of the advancements presented in this keynote paper showcased improved characterization of expansive soils and mechanical characterization studies on unsaturated soils at field moisture conditions corresponding to high suctions. These studies, though requires additional studies and tests, will provide better and comprehensive characterization and assessments of soil behaviour that will lead to better infrastructure designs on these soils.

2 Swell Prediction Methods

The swelling potential of soils is mostly based on the clay minerology. Previous studies had demonstrated that by using parameters such as specific surface area, cation exchange capacity, and total potassium, the clay minerology of various clayey soils could be predicted (Chittoori and Puppala 2011). Specific Surface Area (SSA) of the clay particles is the property of the material and is defined as the total surface area of the solid particles per unit of mass. This property represents the reactivity of clay minerals, which often translates to rate of moisture adsorption for clayey soils, which results in swelling (Pedarla 2013). There are a few methods to determine the value of SSA, among which the ethylene glycol monoethyl ether (EGME) method was used in this study. Previously, Carter et al. (1986) and Cerato and Lutenegger (2002) had used this method and concluded that the test results were repeatable. Pedarla (2013) had noted that SSA aids in indirectly quantifying the amount of expansive clay minerals, such as montmorillonite and illite, which are commonly found in soils.

Researchers had suggested that the moisture distribution and its access to clay minerals within soil could be estimated by determining the internal pore structure and pore distribution (Likos and Wayllace 2010). Mercury intrusion porosimetry (MIP) technique is used to evaluate the pore size distribution in a soil specimen. In MIP technique a non-wetting liquid, i.e. mercury, is forced into the accessible pores within the soil specimen. From the MIP data, the average pore diameter and the pore void distribution of the soil were determined due to the ink bottle effect (Pedarla 2013). Researchers have attempted to study the effect of pore distribution and pore connectivity on the behaviour of expansive soil (Zhou et al. 2011; and Cui and Tang 2011). These studies have concluded that the MIP technique is successful way to determine the pores and the structure of clayey soils. Pedarla (2013) had selected different soils from various parts of the United States to study their swelling behaviour. A synopsis of these test results are shown in Table 1.

Two types of swell characterization studies were used by Pedarla (2013). One-dimensional swell tests were conducted on soil specimens of 2.54 cm height and 6.35 cm diameter. These tests were conducted in an oedometer in accordance to ASTM D4546 (2014). Additionally, three-dimensional swell strain tests were conducted on larger soil specimens with 10.16 cm height and 5.08 cm diameter. Figure 1 presents the schematic and illustrations of the 3D swell test setup used by Pedarla (2013). The details of the test setup and operating principles are discussed in Pedarla (2013). The volume change of soil specimen in the lateral direction was quantified from the changes in the water chamber volume readings. The soil specimen encased in the chamber was submerged in the water tub and then allowed to swell in all directions. Strains in both directions were measured and used to determine the volumetric strains of these soils at different moisture content levels.

Table 1. Basic Properties of the Test Soils

	Liquid limit (LL)	Plasticity index (Pl)	USCS classification	Clay fraction (%)	MDUW (kN/m^3)	OMC (%)	SSA (m^2/g)
Grayson	75	49	CH	55	14.3	24	223.0
San Antonio	67	43	CH	52	15.8	22	192.4
Colorado	63	42	CH	46	16.2	19	185.0
Burleson	*55*	37	CH	52	16.0	19	132.4
San Diego	42	28	CL	23	17.0	17	92.6
Anaheim	48	27	CL	32	16.9	18	118.5
Oklahoma	41	21	CL	30	15.6	24	76 .3
Keller	25	11	CL	34	18.5	14	115.0

Note: MDUW = maximum dry unit weight; OMC = optimum moisture content; SSA = specific surface area; USCS = unified soil classification system.

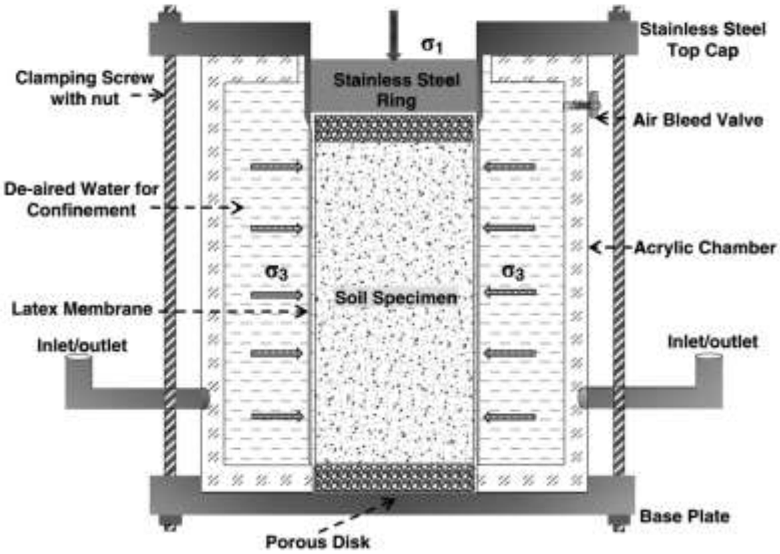

Fig. 1. Schematic of 3D swell strain test setup designed for the study

Table 2 summarizes the volumetric swell strains for all eight soils when subjected to full saturation under different confining pressures. It was observed that Grayson soil swelled the most, while San Diego soil swelled the least. In general, soil specimens were observed to swell less with increasing confining pressures, which may be because the confining pressure resists the repulsive pressure induced due to hydration of diffused double layer systems of the clay particles.

As mentioned earlier, the surface area of clay minerals in soils plays a significant part in determining the amount of swelling in expansive soils. The minerals such as montmorillonite have a very high surface area when compared with minerals such as kaolinite and illite (Mitchell and Soga 2005). The soil specimens which have higher percentages of montmorillonite and illite minerals have a tendency to have more reactive surface area per unit of mass of soil, which results in higher affinity for moisture and such soils mostly experience larger amounts of swelling. Hence, specific surface area of clay minerals was attempted to be determined by Pedarla (2013) to study the swelling behaviour of clayey soils.

The ethylene glycol monoethyl ether (EGME) method was used to determine the value of SSA, which has been used in agronomy circles (Carter et al. 1986), and was later validated for geotechnical applications by Cerato and Lutenegger (2002). Cerato and Lutenegger (2002) had identified the potential of this method for a wide range of clay mineralogy in soils, where SSA ranges from 15 to 800 m^2/g.

Table 2. Volumetric swell strains obtained from experimental studies for different soil specimens at 95% MDUW at different confining pressures

	Volumetric swell strain, ε_{vol} (%)		
Soil	7 (kPa)	50 (kPa)	100 (kPa)
Grayson	11.65	8.76	7.67
Colorado	9.29	7.55	6.30
San Antonio	9.13	7.4	5.74
Burleson	8.03	6.45	4.69
Keller	6.84	5.73	3.71
Anthem	4.80	4.30	2.87
Oklahoma	5.03	3.69	2.69
San Diego	4.52	3.43	2.13

Table 3 shows a summary of MIP test results for eight clayey soils. In MIP technique, the amount of mercury injected into a soil specimen at various pressure points is measured, and these data were used with the theory of cylindrical pore model to determine the pore size distributions and various related porosity parameters (Pedarla 2013). The distribution of pore-volumes is also shown in Table 3.

Table 3. The distribution of pore volumes for different soils as obtained from MIP technique

Soil	Cumulative volume of mercury intrusion (mL/g)	Micro-pores (%)	Medium-pores (%)	Macro-pores (%)
Anthem	0.16	18	5	32
Burleson	0.18	15	55	30
Colorado	0.23	10	50	40
Grayson	0.25	23	37	40
Keller	0.13	20	48	32
Oklahoma	0.21	26	54	24
San Antonio	0.16	20	53	27
San Diego	0.16	7	46	47

2.1 Swell Strain Modelling

The primary objective of the research by Pedarla (2013) was to propose a new conceptual model that accounts for soil mineralogy and pore size distribution as these properties are known to influence the swell behaviours of test soils. The details regarding the procedure and the assumptions involved are presented by Pedarla (2013).

A new hypothetical parameter termed as the Total Surface Area Ratio (TSAR) which governs the effects of surface area from clay mineralogy and pore area in a compacted soil specimen is hence formulated in this modelling. Total Surface Area

Ratio (TSAR) is defined as the ratio of total surface area calculated from the clay mineralogy in a soil specimen to the total pore surface area calculated from MIP tests of the same soil specimen. (Pedarla 2013). TSAR of a soil represents the fraction of clay minerals that can be exposed to moisture from the interconnected pores within the same soil specimen. TSAR of a soil specimen is mathematically determined from the following equation:

$$TSAR = \frac{TSA_{CF}}{TSA_{MIP}} \tag{1}$$

where TSAR is the total surface area ratio; TSA_{CF} is the total surface area of clay mineral present in the soil; and TPA_{MIP} is the total pore area of finer fraction determined from MIP studies. The summary of TSAR values determined at 95% MDUW for different soils is presented in Table 4.

Table 4. Summary of TSAR values for soil samples compacted at 95% MDUW

Soil	1D swell	3D swell
Anthem	1.887	1.872
Burleson	3.613	3.861
Colorado	5.638	6.030
Grayson	5.817	5.770
Keller	2.312	2.292
Oklahoma	0.775	0.768
San Antonio	4.110	4.076
San Diego	1.066	1.057

Figure 2 shows the variations of volumetric swell strains at 95% MDUW condition. It was determined that the swell strain is directly proportional to the value of TSAR. The following swell prediction model was postulated by Pedarla (2013) by using the boundary conditions of the test conditions:

$$\varepsilon_{\mathrm{swell(1D,3D)}} = a(TSAR) + b \tag{2}$$

where a and b are modelling parameters and are dependent on the test-related boundary conditions.

Three TSAR correlations were developed for three individual confining pressure conditions for these tests. The development of additional experimental databases in the future would aid development of more generalized TSAR vs. swell strain correlations that account for compaction and test confining conditions. In summary, this study demonstrated a fundamental method using soil internal information that would provide more accurate predictions of the complex swelling behaviour of soils.

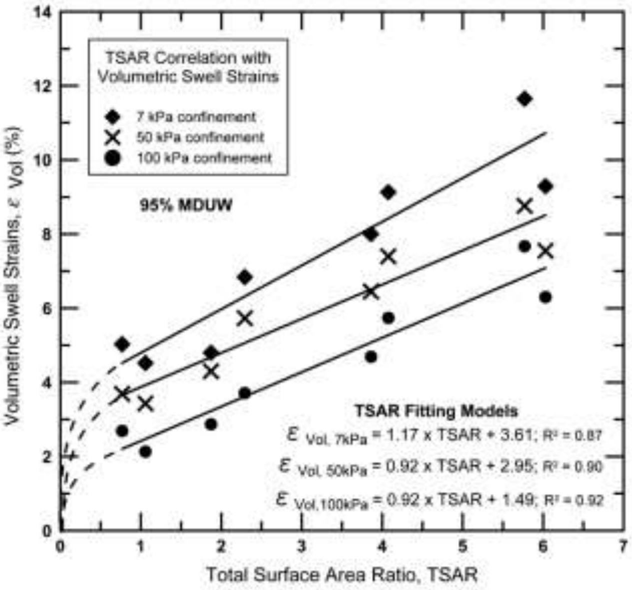

Fig. 2. *TSAR* correlation with volumetric swell strain for sample compacted at 95% MDUW

3 Diffused Double-Layer Swell Prediction Model

Diffuse-double-layer (DDL) theory, as proposed by Chapman (1913), provides a strong basis for the understanding of swell behaviour of a clay specimen. When clay comes in close contact with water, the negative charged clay particles tend to attract the water molecules. The water molecules distribute over the surface area of the clay particles thereby increasing the particle size. The extent to which the clay particles have attraction forces on the water molecules can be termed as diffused double layer water. Lu and Likos (2004) specified that crystalline swelling or Type 1 swelling which is caused by interlayer absorption of water particles was followed by electrical double layer attraction forces which is also known as Type 2 swelling. These long-range double layer attraction forces are the primary concern for the present research and are hence considered and used in the swell prediction model. Researchers have made efforts to develop correlations based on the DDL theory, which have accurately predicted the swelling pressure of bentonite (Schanz and Tripathy 2009). When the complexities of naturally available expansive clays and the wide distribution of expansive minerals is considered, such a theory was used by Puppala et al. (2017), wherein many assumptions were made to address the soil matrix swelling from the fundamental diffuse-double-layer influence.

Puppala et al. (2017) had selected fourteen naturally available expansive soils for this study (Table 5). The properties such as, specific surface area, cation exchange capacity, and total potassium of these soils were also determined using methods proposed by Chittoori and Puppala (2011). These experimental results were used to interpret three dominant clay minerals; viz., montmorillonite (MM), illite (I), and kaolinite (K). One-dimensional (1D) swell strain and swell pressure tests were conducted in an oedometer, in accordance to ASTM D4546 (2008). A summary of these test results is presented in Table 6. It is apparent from these tests that there is no direct correlation between plasticity property, plasticity index (PI), and 1D swell strain or swell pressure potentials of the tested soils. This confirms the myths in the PI-based swell characterization methods. Soil swell properties were observed to be dependent on the presence of clay minerals that predominantly attract and hold water molecules. Therefore, a deeper understanding of diffused double layer and its potential thicknesses was expected to provide deeper understanding of the soil swelling behaviour (Puppala et al. 2017).

Table 5. Soil characterization and mineralogy tests results

Soil	LL	PI	OMC	CEC	SSA	MM (%)	I (%)	K (%)	Classification
Anthem	48	27	18	118.5	71.7	25.3	24.5	50.8	CL
Burleson	55	37	19	132.4	100.1	33.8	19.6	46.6	CH
Cleburne	38	21	15	105.8	57.1	20.4	6.3	73.2	CL
Colorado	63	42	19	185.0	91.6	35.8	35.0	29.3	CH
Denton	55	30	19	156.5	41.2	20.4	8.7	71.0	CH
Grapevine	46	26	19	156.5	34.3	18.6	11.5	69.9	CL
Grayson	75	49	24	223.0	116.1	43.0	23.7	33.3	CH
Keller	25	11	14	115.0	60.0	22.0	18.3	59.7	CL
Mansfield	67	38	26	176.4	121.4	42,8	22.1	35.1	CH
Oklahoma	41	21	24	76.3	63.3	19.7	70.0	10.3	CL
Plano	24	12	27	229.3	54.4	29.6	37.7	32.7	CL
San Antonio	67	43	22	192.4	97.4	37.9	30.9	31.2	CH
San Diego	42	28	17	92.60	87.2	26.9	25.3	47.8	CL
Waco	58	34	28	250.1	126.7	50.1	18.8	31. 2	CH

Table 6. Summary of the 1D swell strains and swell pressure test results at 95% MDUW

Soil	Notation	PI	1D swell strain (%)	Swell pressure (kPa)
Anthem	AN	27	4.5	94.2
Burleson	BU	37	5.8	112.8
Cleburne	CL	21	3.2	81.1
Colorado	CO	42	8.2	137.7
Denton	DE	30	1.5	65.3
Grapevine	GV	26	1.3	82.7
Grayson	GR	49	9.8	168.4
Keller	KE	11	5.6	98.0
Mansfield	MA	38	3.4	113.6
Oklahoma	OK	21	3.8	63.0
Plano	PL	12	4.7	116.5
San Antonio	SA	43	7.3	137.7
San Diego	SD	28	3.4	50.5
Waco	WA	34	2.2	79.9

3.1 Diffuse-Double-Layer Swell Prediction Model

The model is based on the double layer water attraction capacity of individual clay minerals. Pedarla (2013) used this concept to develop the diffuse-double-layer swell prediction model (DDLSPM). The assumptions for the formulation and development of the DDLSPM model was described in detail by Pedarla (2013). As discussed earlier, upon contact with moisture, the clay minerals in soils undergo expansion with increase in their double layer water thickness. Hence, the clay minerals are assumed to be stacked in a uniform chain pattern. The compacted soil specimen comprises of soil solids and voids. Among the soil solids the clay portions contribute to the swelling behaviour. The determination of volume of clay minerals in a soil specimen was determined by dividing the clay portion. Once the number of mineral layer stacks for all three clay minerals are determined, the total diffused double layer thickness or expansion or swell displacement for a given expansive soil is given by Eq. (3).

$$TDDLT = \sum_{i=1}^{n} N_i \text{ x } DDLT_i \tag{3}$$

where TDDLT is the total diffused double layer induced swell thickness or displacement, *n* is the number of clay minerals (i.e. 3) in the soil, N_i is the number of crystal layers pertaining to individual mineral, $DDLT_i$ is the diffused double layer thickness of an individual mineral. The value of *TDDLT* represents the cumulative thicknesses of DDLs of all the three minerals, and this indirectly represents soil swelling without including internal crystalline swelling. Once the total diffuse-double-layer thickness of the soil was determined, it was used to estimate the DDL-induced swell strains of the soil specimens, as noted in the following Eq. (4).

$$\varepsilon_{DDL}\ (\%) = \frac{TDDLT}{h} \text{ x } 100 \tag{4}$$

where ε_{DDL} is the strain caused by the formation of diffuse-double-layer thickness during saturation; and *h* is the initial specimen height. Table 7 shows the *TDDLT* values and DDL swell strains for all fourteen expansive clays at 95% MDUW conditions. Table 7 presents the total double layer water induced strain by each of the soil specimens. The compacted soil specimen has an initial height of 2.54 cm. During the saturation phase of the specimen, the minerals attract the moisture molecules and form a diffused Double water layer. The specimen strains are calculated based on the initial specimen height and the total double layer formed due to the mineral attraction forces between clay mineral and water molecules. It was evident that Grayson soil formed the largest double layer water thickness.

Table 7. Swell strain estimated from DDLSPM at 95% MDUW condition

Soil	Notation	TDDLT (m)	ε_{DDL} (%)
Anthem	AN	0.0427	168
Burleson	BU	0.0897	353
Cleburne	CL	0.0190	75
Colorado	CO	0.0849	334

Denton	DE	0.0285	112
Grapevine	GV	0.0300	118
Grayson	GR	0.1191	469
Keller	KE	0.0397	156
Mansfield	MA	0.0690	272
Oklahoma	OK	0.0350	138
Plano	PL	0.0493	194
San Antonio	SA	0.1009	397
San Diego	SD	0.0325	128
Waco	WA	0.0370	146

3.2 DDLSPM Correlation with Swell Properties

An attempt was made by Puppala et al. (2017) to correlate DDLSPM-based swell strains with those measured from the swell tests. Correlations with the measured 1D swell strains of all soils are presented in Fig. 3a, which correspond to 95% MDUW condition. Figure 3b present the correlations with measured swell pressure at 95% MDUW condition. From Fig. 3, it is evident that swell potential of a soil is directly proportional to its respective DDL thicknesses and strains. This confirms that the present DDLSPM approach is sound and shows a good correlation between them. The correlation trend in both figures shows a nonlinear trend between DDLSPM swell strains and measured swell characteristics and hence a nonlinear formulation is formulated and used in the present analysis. This formulation is presented in the following Eq. (5):

$$\varepsilon_i \; or \; SP = a \text{ x } \varepsilon_{DDL}^{b} \tag{5}$$

where ε_i is the swell strain measured at initial compaction condition; SP is the swell pressure of an expansive clay; ε^{b}_{DDL} is the diffuse-double-layer-induced swell strain; and a and b are the formulation constants or correction factors. The constants a and b are dependent on many independent soil and test parameters like particle arrangement during compaction, moisture access to the clay particles and direction of particle swelling. a and b are not unique, and they are dependent on the swell property that is correlated with ε_{DDL}. These constants are regarded as potential indicators of the reduction factors of total DDL-based swell strains to measured corresponding swell characteristics. The trends in Fig. 3 show that swell strain and DDL strain show a certain degree of correlation between both parameters. This indicates that the potential use of the DDL theory and the DDL-based swell strain estimation could provide a more fundamental approach to estimate swell properties of compacted clayey soil specimens (Puppala et al. 2017).

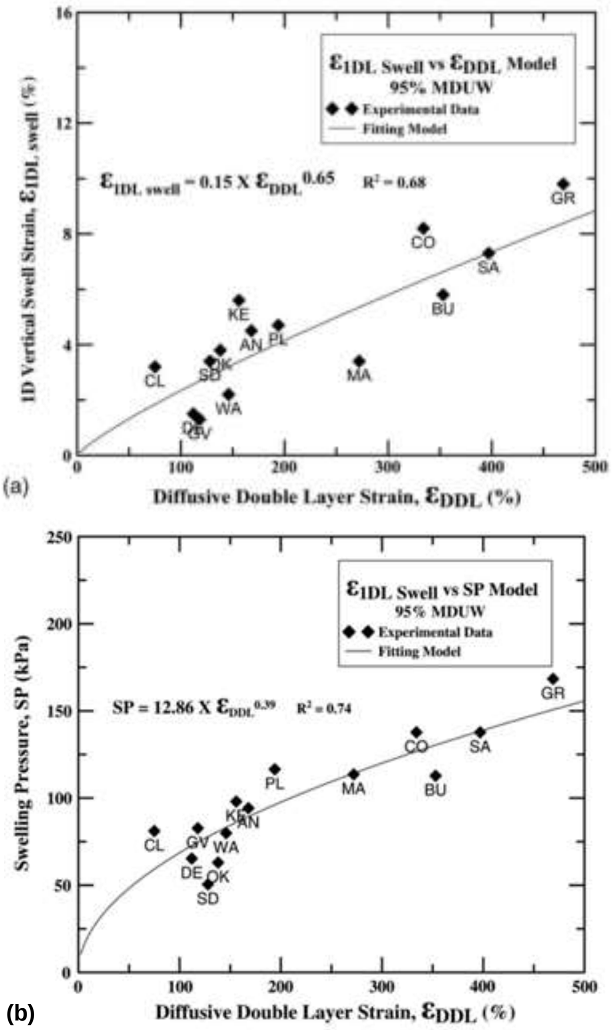

Fig. 3. DDL swell model for (a) 1D swell strains; (b) swell pressure at 95% MDUW

4 Resilient Modulus measurements at high-suction state

The design of pavement sections built over high-plasticity subgrade soils requires the knowledge of resilient modulus over a wide range of suction to consider the variations in resilient modulus with seasonal and diurnal variation of moisture. An experimental setup adept at performing suction-controlled repeated load triaxial (RLT) tests at high suction (5 to 600 MPa) has been developed by integrating an automated relative humidity apparatus within a cyclic triaxial setup. Previously, several researchers had examined the fundamental effects of matric suction (s) on M_R of various pavement materials (Ng et al. 2013; Ruttanaporamakul et al. 2014; Salour and Erlingsson 2015; Han and Vanapalli 2016). However, most of these studies had been performed by indirectly measuring suction of tested soil specimens in post-test conditions by utilizing filter paper techniques, which have been reported to be quite user-dependent and unreliable (Ng and Menzies 2014). In the past, only a limited number of studies have been conducted by performing tests under suction-controlled condition using the axis-translation technique, where low to moderate suction levels were maintained throughout the specimen. However, due to the limitations of the axis-translation technique, which include limitations of ceramic disks and air diffusion, high values of suction cannot be applied, which hinders the applicability of such approaches for a different soil types, most notably fine-grained materials.

Other researchers had documented the performance issues for pavements constructed over high-plasticity expansive soils (Petry and Little 2002; Puppala et al. 2011, 2019; Das et al. 2018). In-spite of the requirement of advanced setup which is capable of simulating the in-situ conditions during extreme climatic conditions and determining the value of M_R in such conditions, such facilities are available (Puppala 2008; Salour et al. 2014). The characterization of expansive soil behaviour is particularly crucial at high values of suction beyond 1 MPa and up to 700 MPa (Likos and Lu 2003). During the dry season when there is high temperature and low moisture content for long durations high values of suction are induced, which may be well beyond the test range of the conventionally adopted axis-translation technique. To date, suction-controlled RLT tests have not been conducted at high-suction states and corresponding influences of shrinkage and desiccation cracking on M_R have not been effectively analysed.

A novel testing setup has been developed by integrating a cyclic triaxial testing setup with an automated relative humidity system to conduct RLT tests at suction ranging from 5 to 100 MPa. Figure 4 shows the schematic layout of the RLT test setup. The details regarding the triaxial setup are provided by Banerjee and Puppala (2015) and Banerjee et al. (2018b, 2018c). The auto-RH apparatus used in study is capable of applying a constant relative humidity (RH) throughout the specimen gas phase, which induces total suction in the range of 5 to 600 MPa and beyond.

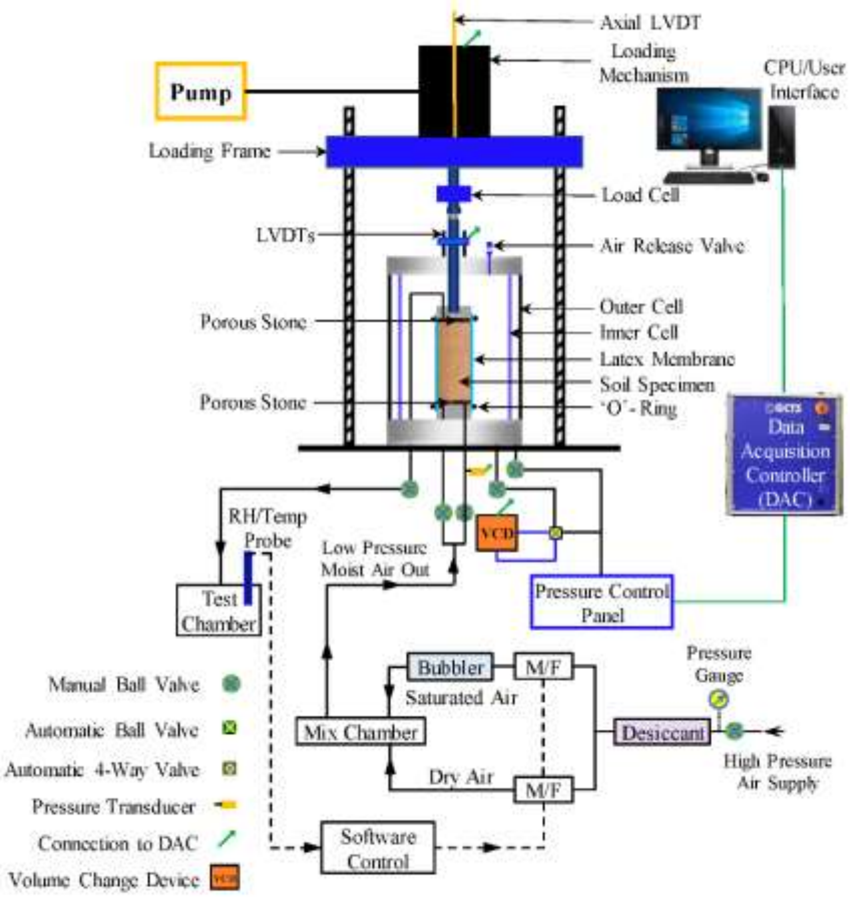

Fig. 4. Schematic layout of the setup for conducting suction-controlled RLT tests on soils under high total suction using auto-RH apparatus

4.1 Auto-Relative Humidity Apparatus and suction-controlled RLT testing

Vapour pressure control is used to induce high-suction states within the soil specimen. An automated relative humidity apparatus was utilized to induce high-suction states. A similar automated RH control unit was used by Likos and Lu (2003) to determine total suction characteristic curves of non-expansive and expansive clays. The study by Banerjee et al. (2019) demonstrated the first attempt to integrate an RLT test setup with the automated RH control unit. The auto-RH apparatus comprises of an auto-RH control unit, a desiccating chamber, a gas bubbler, and an RH and temperature probe, along with peripherals such as connecting pipes and read-outs. The aim of this apparatus is to supply a steady stream of moist air at the target RH to control the desired total suction within the soil specimen. Therefore, a steady stream of low-pressure humid air having the target RH is generated by mixing of water vapour saturated air ("wet") and dry air in different proportions in an environmentally sealed mixing chamber. The details of the working principle are provided by Banerjee (2017).

After the pre-conditioning stage, wherein the sample is subjected to the target RH stream of air outside the triaxial cell, the soil specimen is removed and enclosed within the triaxial cell. Humid air at the required RH is routed through the base pedestal of the triaxial cell, which is fitted with a porous stone. The humid air is forced to pass through or around the specimen. The exhaust air from the soil sample is routed out of the triaxial cell via a porous stone housed within the top cap and a semi-rigid pipe to a small cylindrical test chamber. This chamber houses the humidity/temperature probe, which allows direct measurement of the RH and temperature of the exhaust air. The small cylindrical test chamber has a small opening to allow the exhaust air is gradually flow out, thereby providing a continuous flow of air through the system, for a quicker equilibration process.

The feedback from the RH/temperature probe allows the auto RH-control unit to automatically regulate the volumes of dry and wet air streams by using the mass-flow (M/F) valves. The signal form the RH/temperature probe is utilized to compute the induced total suction in the soil specimen which is determined using the Kelvin's equation (Eq. 6, Sposito 1981).

$$\psi = -\frac{RT}{v_{wo}\,\omega_v}\ \ln\left(\frac{u_v}{u_{vo}}\right) = -\frac{RT}{v_{wo}\,\omega_v}\ln(RH) \tag{6}$$

where ψ = total suction (kPa), T = absolute temperature (K), R = universal gas constant (J mol^{-1} K^{-1}), v_{wo} = specific volume of water (m^3/kg), ω_v = molecular mass of water vapour (kg/kmol), u_v = partial pressure of pore-water vapour (kPa), and u_{vo} = saturation pressure of pure water vapour (kPa).

In this study, an expansive clayey soil was used to illustrate the performance and utility of the novel integrated triaxial setup at performing the suction-controlled RLT tests at high-suction state. The expansive clayey soil is a mixture of a locally available sandy clay and commercially available sodium bentonite clay comprising the clay mineral montmorillonite. The clayey soil mixture is classified as high-plasticity clay (CH), according to the Unified Soil Classification System (USCS) with a plasticity index of 92%. The clayey soil (CH) specimens were compacted at target dry density of 1.47 g/cm^3 and moisture content of 24%.

A series of suction-controlled repeated load triaxial (RLT) tests were conducted on clayey soil specimens at high-suction state by Banerjee et al. (2019). Suction-controlled RLT tests were performed at different values of total suction. In order to avoid the influence of Soil Water Characteristic Curve (SWCC) hysteresis, all the soil specimens were prepared at a specific target density and water content and subsequently saturated and then air dried by applying an alternating 12 hour drying and suction equilibration cycles. The auto-RH apparatus was used to equilibrate the suction within the soil specimens, before the specimens were subjected to loading sequences of the RLT test. The equilibrated soil specimens were taken out from the acrylic chamber and were carefully transferred to the triaxial cell. A major advantage of suction control using vapour pressure technique is that since externally air pressure is not applied, net or effective confining pressure is same as the applied cell pressure Thereby, the same confining pressure is applied by the pressure control panel as recommended by AASHTO T307 (2012), which have been listed by Banerjee (2017).

A series of suction-controlled RLT tests were conducted at different suction levels of 5, 30, and 100 MPa on soil specimens in suction-controlled conditions using an auto-RH apparatus. M_R was determined for each loading sequence as the average of M_R over the last five cycles (96th to 100th cycles). Figure 5 shows the variation of M_R with deviator stress and confining pressure for specimen subjected to 5 MPa total suction. Figure 5a depicts the variation of M_R with a change in values of cyclic deviator stress for different confining pressures at total suction of 5 MPa, whereas Fig. 5b shows the variation of M_R with a change in confining pressure for different values of cyclic deviator stress at total suction of 5 MPa. It was noted that the M_R decreased with an increase in the values of cyclic deviator stress for all confining pressure subjected to 5 MPa suction. Similar trends were observed at lower suction state by Ng et al. (2013); Ruttanaporamakul et al. (2014) and Banerjee (2017).

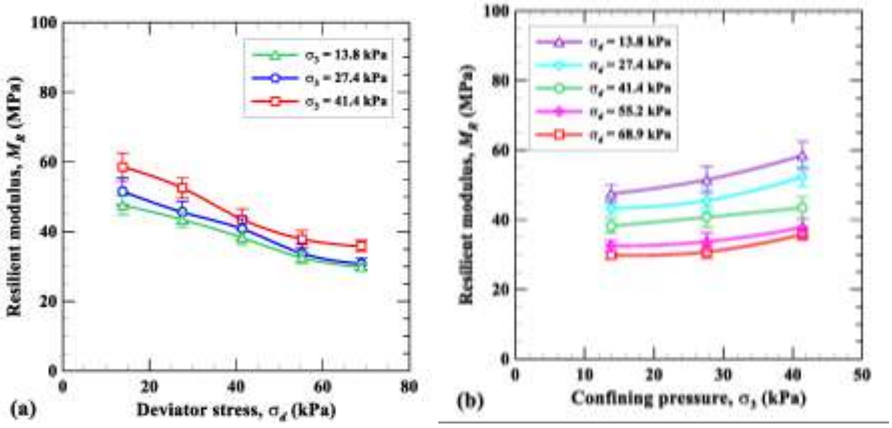

Fig. 5. Variation of M_R with (a) deviator stress, and (b) confining pressure of clayey soil specimen at a total suction of 5 MPa.

The coefficients of variation (CV) for each sequence for 5, 10, and 30 MPa total suction values were computed. The maximum and average CV for all the suction levels was observed to be around 7.7% and 5.2%, respectively. Since for each of these sequences, the average values of CV were less than 6% and the maximum value of CV was less than 10%, these values are deemed to be within acceptable range, considering the poor repeatability of traditional RLT tests.

5 Summary and Conclusions

Several essential findings were obtained from the research studies conducted related to unsaturated and expansive soils. These findings have been discussed in this section.

Research into unsaturated soil has witnessed many advancements primarily due to the abilities to better understand micro and chemico behaviours that can be linked with macro behaviours. In one of studies presented the Swell characterization studies of different clayey soils were conducted at different confining stress conditions. A new analysis method was utilized to determine the pore surface area of clayey particles in soils using MIP data. A new parameter termed as TSAR was defined. A semi-linear relationship between the TSAR value and the swelling behaviour was observed when compared to experimental test results. In future other soils need to be tested and the model presented needs to be validated in order to generalize the swell behaviour of clayey soils.

The development of a novel swell prediction model based on the diffuse-double layer (DDL) theory for expansive soils was also introduced. The model is based on the diffused double layer water induced soil swell theory which emphasizes on the attraction of water molecules adhering to the surface of the clay minerals thus resulting in the swelling of soil mass. DDL theory provides a strong foundation for the swell prediction model and shows a good fit of measured swell data for all the eight soils studied in the present research. Two correction factors or constants a and b are introduced in this model which governs the behaviour of the model. The constants available from this model are dependent on many independent parameters like particle arrangement during compaction, moisture access to the clay particles and direction of particle swelling. The model was validated by comparing the predictions with the experimental soil swell test results. It was observed that some soils with high PI values experienced low swelling, whereas soils with low PIs, experienced higher swelling. This confirms the misconceptions in the PI-based swell characterization methods. In future, the correction factors a and b from DDL model may be standardized by comprehensively studying them at different compaction levels and moisture access theories for different soils.

A fully automated relative humidity apparatus was integrated with a cyclic triaxial setup to conduct repeated load triaxial tests under suction-controlled conditions to compute the M_R at high-suction state. The application of suction using vapour pressure technique and conducting RLT tests at high suction states is the novelty of the study. This integrated setup is applicable for various types of fine-grained soils at different degree of saturation. The results from the series of suction-controlled RLT tests at different high-suction conditions demonstrated the ability of the integrated setup to determine M_R values with high reliability, due to low values of CV. These results along with additional data from other experimental tests on expansive soils can be used for the development and calibration of elaborate prediction models for variation of M_R over wide range of suction for various types of silty and clayey soils, especially for expansive soils.

The advanced models and characterization methods would assist in better prediction of performance of essential civil infrastructures over varying diurnal and seasonal climatic and ground conditions. Thereby, increasing the confidence on the design developed and minimizing the maintenance required during its service life due to better designs.

Acknowledgements

The experimental work described in this paper was part of various research projects funded by the National Science Foundation (NSF), including funding from Award # 1031214 (Program Director Dr. Richard J. Fragaszy), Major Research Instrumentation Program (Program Manager: Dr. Joanne D. Culbertson; Award # 1039956) and National Science Foundation Industry-University Cooperative Research Center (I/UCRC) program funded 'Center for the Integration of Composites into Infrastructure (CICI)' site (NSF PD: Andre Marshall; Award # 1464489) and their support is gratefully acknowledged. Any findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We also acknowledge the support of Texas Department of Transportation's Research and Technology Implementation (RTI) for their past funding on research performed at UTA.

References

1. AASHTO. AASHTO T-307: Determining the Resilient Modulus of Soils and Aggregate Materials. American Association of State Highway and Transportation Officials, Washington, D.C. (2012).
2. Abduljauwad, S. N.: Study on the performance of calcareous expansive clay. Bull. Assoc. Eng. Geol., 30(4), 481–498(1993).
3. Banerjee, A.: Response of Unsaturated Soils under Monotonic and Dynamic Loading over moderate Suction States. Doctoral Dissertation, Dept. of Civil Engineering, University of Texas at Arlington, Arlington, Texas (2017).
4. Banerjee, A., and Puppala, A. J.: Influence of Rate of Shearing on Strength Characteristics of Saturated and Unsaturated Silty Soil. In Proc. 50th Indian Geotechnical Conference, Pune, India (2015).
5. Banerjee, A., Patil, U. D., Puppala, A. J., and Hoyos, L. R.: Evaluation of Liquefaction Resistance in Silty Sand via Suction Controlled Cyclic Triaxial Tests. PanAm Unsaturated Soils 2017, American Society of Civil Engineers, Reston, VA, 543–552(2018b).
6. Banerjee, A., Patil, Ujwalkumar D, Puppala, A. J., and Hoyos, L. R.: Suction-controlled repeated load triaxial test of subgrade soil at high suction states, in Unsaturated Soils. Proceeding of Seventh International Conference on Unsaturated Soils, Hong Kong, pp. 667–672(2018a).
7. Banerjee, A., Puppala, A. J., Hoyos, L. R., Likos, W. J., and Patil, U. D.: Resilient Modulus of Expansive Soils at High Suction Using Vapor Pressure Control. Geotechnical Testing Journal, 43(3), (In Press) (2019).
8. Banerjee, A., Puppala, A. J., Patil, U. D., Hoyos, L. R., and Bhaskar, P.: A Simplified Approach to Determine the Response of Unsaturated Soils Using Multistage Triaxial Test. IFCEE 2018: Advances in Geomaterial Modeling and Site Characterization, GSP 295, 332–342(2018c).
9. Carter, D. L., Mortland, M. M., and Kemper, W. D.: Specific surface. Methods of soil analysis. 2nd Ed., A. Klute, ed., ASA and SSSA, Madison, WI, 413–423 (1986).
10. Cerato, A. B., and Lutenegger, A. J.: Determination of surface area of fine grained soils by the ethylene (EGME) method. Geotech. Test. J., 25(3), 315–321 (2002).

11. Chakraborty, S., and Nair, S.: Impact of Curing Time on Moisture-Induced Damage in Lime-Treated Soils. International Journal of Pavement Engineering, pp. 1–13 (2018a).
12. Chakraborty, S., and Nair, S.: Impact of Different Hydrated Cementitious Phases on Moisture-Induced Damage in Lime-Stabilised Subgrade Soils. Road Materials and Pavement Design (19:6), pp. 1389–1405 (2018b).
13. Chapman, L. A.: Contribution to the theory of electrocapillarity. Philos. Mag., 25(148), 475–481 (1913).
14. Chittoori, B. C. S., and Puppala, A. J.: Quantitative estimation of clay mineralogy in fine-grained soils. J. Geotech. Geoenviron. Eng., 997–1008 (2011).
15. Cui, Z. D., and Tang, Y.: Microstructures of different soil layers caused by the high-rise building group in Shanghai. Environ. Earth Sci., 63(1), 109–119 (2011).
16. Das, J. T., Banerjee, A., Chakraborty, S., and Puppala, A. J.: A Framework for Assessment of Sustainability and Resilience in Subgrade Stabilization for a High-Volume Road." Transportation Research Board, 97th Annual Meeting, Washington, D.C. (2018).
17. Han, Z., and Vanapalli, S. K.: Relationship between resilient modulus and suction for compacted subgrade soils. Engineering Geology, Elsevier B.V., 211, 85–97 (2016).
18. He, S., Yu, X., Banerjee, A., and Puppala, A. J.: Expansive Soil Treatment with Ionic Soil Stabilizer. Transportation Research Record: Journal of the Transportation Research Board (2018).
19. Jones, D.E., and Holtz, W.G.: Expansive Soils – The Hidden Disaster. Civil Engineering, American Society of Civil Engineers, New York, 139-153 (1973).
20. Katti, R. K., Moza, K. K., and Katti, D. R.: Unconventional behavior of expansive soils. Proc., 16th Budapest Conf. on Soil Mechanics and Foundation Engineering, 137–146 (1984).
21. Likos, W. J., and Wayllace, A.: Porosity evolution of free and confined bentonites during interlayer hydration. Clays Clay Miner., 58(3), 399–414 (2010).
22. Likos, W., and Lu, N.: Automated Humidity System for Measuring Total Suction Characteristics of Clay. Geotechnical Testing Journal, 26(2) (2003).
23. Lu, N., and Likos, W. J.: Unsaturated Soil Mechanics. J. Wiley, Hoboken, N.J. (2004).
24. Mitchell, J. K., and Soga, K.: Fundamentals of soil behavior. 3rd Ed., Wiley, Hoboken, NJ. (2005).
25. Ng, C. W. W., and Menzies, B.: Advanced Unsaturated Soil Mechanics and Engineering. CRC Press (2014).
26. Ng, C. W. W., Zhou, C., Yuan, Q., and Xu, J.: Resilient modulus of unsaturated subgrade soil: experimental and theoretical investigations. Canadian Geotechnical Journal, 50(2), 223–232 (2013).
27. Pedarla, A.: SWCC and clay mineralogy-based models for realistic simulation of swell behavior of expansive soils. Doctoral Dissertation, Dept. of Civil Engineering, Univ. of Texas at Arlington, Arlington, Texas (2013).
28. Pedarla, A., Puppala, A. J., Hoyos, L. R., and Chittoori, B.: Evaluation of Swell Behavior of Expansive Clays from Internal Specific Surface and Pore Size Distribution. Journal of Geotechnical and Geoenvironmental Engineering, 142(2) (2016).
29. Petry, T. M., and Little, D. N.: Review of Stabilization of Clays and Expansive Soils in Pavements and Lightly Loaded Structures—History, Practice, and Future. Journal of Materials in Civil Engineering, 14(6), 447–460 (2002).
30. Puppala, A. J.: Estimating Stiffness of Subgrade and Unbound Materials for Pavement Design. NCHRP Synthesis 382, Transportation Research Board, Washington, D.C. (2008).

31. Puppala, A. J., Congress, S. S. C., and Banerjee, A.: Research Advancements in Expansive Soil Characterization, Stabilization and Geoinfrastructure Monitoring. Frontiers in Geotechnical Engineering, G. M. Latha, ed., 15–29 (2019).
32. Puppala, A. J., Katha, B., and Hoyos, L. R.: Volumetric shrinkage strain measurements in expansive soils using digital imaging technology. Geotech. Test. J., 27(6), 547–556 (2004).
33. Puppala, A. J., Manosuthikij, T., and Chittoori, B. C. S.: Swell and shrinkage characterizations of unsaturated expansive clays from Texas. Eng. Geol., 164, 187–194 (2013).
34. Puppala, A. J., Manosuthkij, T., Nazarian, S., and Hoyos, L. R.: Threshold moisture content and matric suction potentials in expansive clays “prior to initiation of cracking in pavements. Canadian Geotechnical Journal, 48(4), 519–531 (2011).
35. Puppala, A. J., Pedarla, A., Pino, A., and Hoyos, L. R.: Diffused Double-Layer Swell Prediction Model to Better Characterize Natural Expansive Clays. Journal of Engineering Mechanics, 143(9) (2017).
36. Ruttanaporamakul, P., Rout, R. K., Puppala, A. J., and Pedarla, A.: Resilient Behaviors of Compacted and Unsaturated Subgrade Materials. Geo-Congress 2014 Technical Papers: Geo-Characterization and Modeling for Sustainability, 1396–1405 (2014).
37. Salour, F., and Erlingsson, S.: Resilient modulus modelling of unsaturated subgrade soils: laboratory investigation of silty sand subgrade. Road Materials and Pavement Design, 16(3), 553–568 (2015).
38. Salour, F., Erlingsson, S., and Zapata, C. E.: Modelling resilient modulus seasonal variation of silty sand subgrade soils with matric suction control. Canadian Geotechnical Journal, 51(12), 1413–1422 (2014).
39. Schanz, T., and Tripathy, S. (2009). “Swelling pressure of a divalent-rich bentonite: Diffuse double-layer theory revisited.” Water Resour. Res., 45(5).
40. Sposito, G. (1981). The thermodynamics of soil solutions. Oxford University Press, New York.
41. Zhou, H., Fang, Y.-G., Gu, R.-G., and Zeng, C. (2011). “Microscopic analysis of saturated soft clay in Pearl River Delta.” J. Cent. South Univ. Technol., 18(2), 504–510.