The Role of Micro-scale Properties in the Study of Expansive Soils

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ABSTRACT

A comprehensive study of expansive soil behavior includes understanding the surface phenomena of clay particles or aggregates within the soil matrix. This research focuses on six micro-scale properties of four natural expansive soils including matric suction at OMC, specific surface area (SSA), cation exchange capacity (CEC), pH, surface conductance and mineralogy, in order to better understand the microscopic behavior of expansive soils. An approach to approximate surface conductance is proposed. The role of each micro-scale property in the assessment of macroscopic expansive soil behavior as swell potential is discussed. Among these six properties, matric suction at OMC is found to be the most accurate predictor of soil swelling given that the soil samples under tests were also compacted at OMC.

INTRODUCTION

Expansive soil is the type of clayey soil that experiences significant volume change when water comes in or out. The macroscopic behavior of expansive soils is difficult to predict because the individual clay particles are mostly controlled by surface electro-physico-chemical forces other than mechanical forces because of their infinitesimal size and the diffuse double layer formed around each clay particle (or aggregate). As a result, an approach to fully understand expansive soil behavior lies in understanding the surface phenomena of individual clay particles within the soil matrix and the interaction of contacting particles caused by surface forces.

The conventional studies of expansive soil characteristics mainly focus on plasticity and soil heave measurement (Nelson and Miller, 1992). The most commonly studied properties are plasticity index and activity (Skempton 1953; Raman 1967; Chen 1988). However, plasticity is mostly a phenomenological parameter. On the other hand, the results of oedometer tests are also phenomenological and limited by various boundary and environmental conditions.

Before soil expansion takes place, an expansive soil is unsaturated. Therefore the soil behavior is highly affected by surface tension forces especially matric suction (Nelson and Miller 1992; Fredlund and Rahardjo 1993). At the same time, SSA and CEC have also been recognized as important factors controlling many physical and chemical properties of fine-grained soils (Peterson et. al 1996; Mitchell 1976). Combined with the study of CEC is the study of pH, as it indicates the degree of cation exchanges within soil minerals (Mitchell 1976). X-ray diffraction (XRD) provides an excellent way to study the mineralogical composition of expansive soils (Al-Rawas 1999). The properties of matric suction, SSA, CEC, pH and XRD diffraction pattern are considered micro-scale properties because they reveal the nature of the diffuse double layer and mineralogy, which in combination determines the expansive soil behavior. In this study, six micro-scale properties of four expansive soils were obtained from lab testing. Percent of swell and swell pressure were also achieved from traditional oedometer tests. The role of each micro-scale property in reflecting the degree of swell percent and swell pressure is evaluated.

TESTED MATERIALS AND SOIL PROPERTIES

Four expansive soils named Hollywood, Carnisaw, Heiden and Eagle Ford were selected as the test materials. The first three were sampled from Oklahoma and the last from North Texas.

Common geotechnical properties

Common geotechnical lab tests were performed following ASTM standards (ASTM 1999) and the obtained soil information is given in Table 1 below.

Table 1. Some geotechnical properties of the samples tested. *LL*, liquid limit; *PL*, plastic limit; *SL*, shrinkage limit; I_p, plasticity index; *CF*, clay fraction (<2μm); *A*, activity; *Gs*, specific gravity; and USC=Unified soil classification

Test sample	LL (%)	PL (%)	SL (%)	PI (%)	CF (%)	A	G_s	USC
Carnisaw	59	32	20	27	51	0.5	2.68	MH
Hollywood	54	20	16	34	62	0.6	2.78	CH
Heiden	70	21	19	48	50	1.0	2.77	CH
Eagle Ford	92	35	25	57	66	0.9	2.71	CH

Soil suction and swell potential

Matric suction of each soil sample at optimum moisture content (OMC) was measured following the filter paper method (ASTM-D5298 1999). The swell potential was assessed by performing the standard test method for one-dimensional swell test of cohesive soils (ASTM-D4546 1999). Compacted samples at OMC were submerged in de-ionized water in an oedometer and allowed to swell under a seating load of 1kPa. After full expansion, the samples were consolidated to their original height so that the swell pressure was retrieved. The test results are given in Table 2.

Table 2. Summary of the suction and the swell test results. *OMC*, optimum moisture content; γ_d, maximum dry unit weight; $(u_a-u_w)_{OMC}$, matric suction at OMC; *S*, swell percent; *SP*, swell pressure

Test sample	OMC	γ_d (kN/m^3)	$(u_a-u_w)_{OMC}$ (kPa)	S (%)	SP (kPa)	Swell potential*
Carnisaw	26.2	16.2	410	2.3	75	Medium
Hollywood	20.6	16.7	565	5.7	141	Medium
Heiden	24.2	15.5	771	9.3	230	High
Eagle Ford	27.1	14.2	1040	12.7	263	Very high

*Based on Chen (1988) classification scheme.

SSA and CEC tests

The total specific surface area values given in Table 3 were obtained following the EGME surface area determination method proposed by Cerato and Lutenegger (2002). The cation exchange capacity and the pH of each soil were determined by Harris Laboratory, Inc., Lincoln, Nebraska using a 1N ammonium acetate extraction method (Rhoades 1982).

Table 3. Some physical and electro-chemical properties of the samples tested. *SSA*, specific surface area (total); *CEC*, cation exchange capacity; and λ_s, surface conductance

Test sample	SSA (m^2/g)	CEC (meq/100g)	pH	K %	Mg %	Ca %	Na %	H %	λ_s ($\times 10^{-8}$ S)
Carnisaw	107.5	27.3	4.4	0.9	9.1	1.8	0.2	88	8.27
Hollywood	145.5	26.4	7.2	1.3	4.6	93.2	1.0	0	1.12
Heiden	229.0	50.7	8.7	0.8	11.0	82.2	6.0	0	1.34
Eagle Ford	213.5	49.6	7.7	1.5	13.2	77.8	7.5	0	1.41

In Table 3, surface conductance λ_s was obtained from the other measured properties in combination with the mobility of counterions, u_{cat} (m^{2}V^{-1}s^{-1}), following an approximate equation (Santamarina 2001; Ning 2007) defined as:

$$\lambda_s \approx u_{cat} \frac{CEC}{SSA} \qquad (1)$$

Considering the counterions as cations, the mobility for each cation of K, Mg, Ca, Na and H in each soil is 7.6, 5.5, 6.2, 5.2, 36.2 ($\times 10^{-8}$ m^{2}V^{-1}s^{-1}), respectively; according to the mobility chart of cations given by Santamarina (2001). Electron mobility is an ion property determining the drift velocity of electrons it can mobilize given an applied electrical field. A weighted conductance based on the percentage of each cation can be written as:

$$\lambda_s = \frac{\sum u_i P_i CEC}{SSA} \qquad (2)$$

Where u_i is the mobility of each cation and the percentage, P_i, is based on the count and not the mass of each cation.

MINERALOGICAL STUDIES

The samples were prepared following the conventional methods of analyzing clay mineral composition. Soil suspension was prepared for each soil sample. The soil suspensions were then centrifuged to separate out the >2μm size fraction. The clear liquid was removed and the remaining slurry was spread on a glass slide to prepare the XRD sample. Untreated, glycolated and heated sample slides were tested and the corresponding diffraction patterns of each soil are given in Figures 1~4.

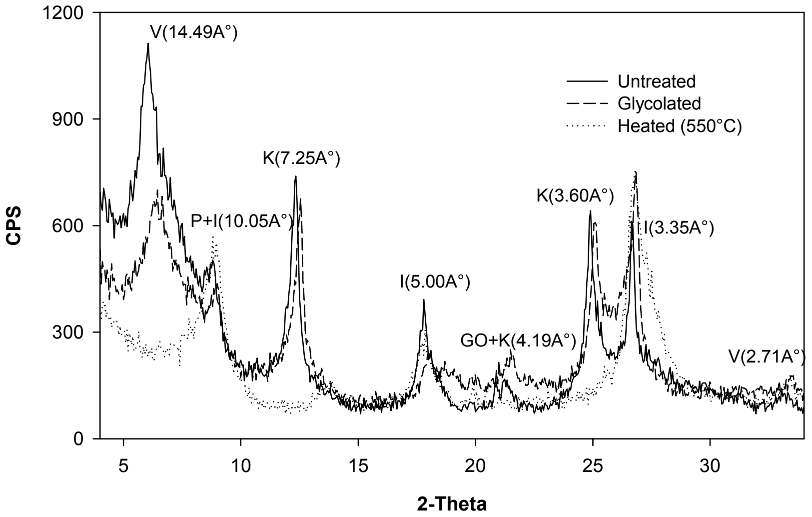

Figure 1. X-ray diffraction pattern of the Carnisaw soil

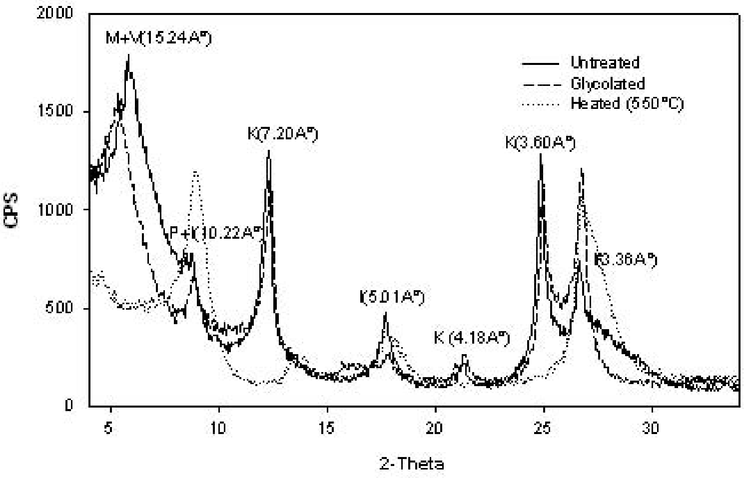

Figure 2. X-ray diffraction pattern of the Hollywood soil

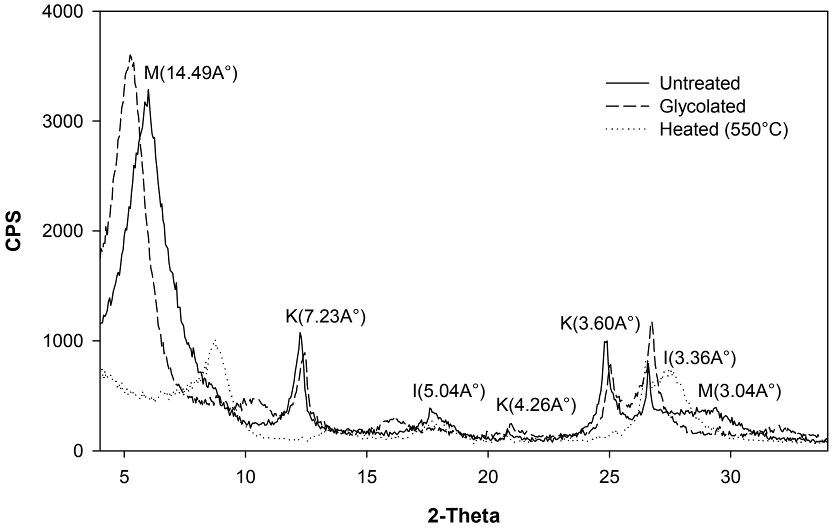

Figure 3. X-ray diffraction pattern of the Heiden soil

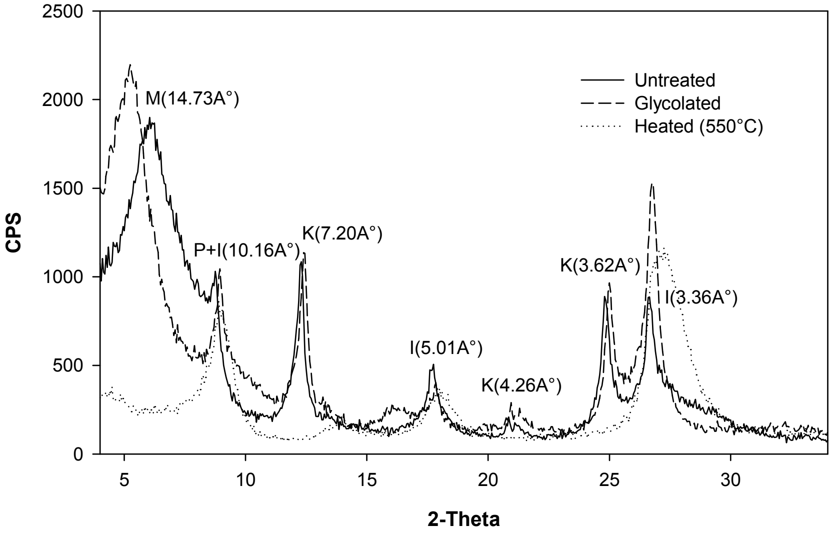

Figure 4. X-ray diffraction pattern of the Eagle Ford soil

Analysis of XRD results

A summary of the results and observations from the XRD tests is given in Table 4 together with the geological classification and the geotechnical description. The percentages of cations, which were determined from the CEC tests, are also presented in Table 4. The percentages of montmorillonite, vermiculite, illite and kaolinite were determined following the semi-quantitative analysis method provided by USGS open file report (2001), and represent the approximate percentage values within the clay portion of the soils.

Table 4. Summary of the geological, geotechnical, mineralogical and chemical results. M, montmorillonite; KA, kaolinite; I, illite; V, vermiculite; Na, sodium; Ca, calcium; Mg, magnesium; K, potassium; and H, hydrogen

Test sample	Geological classification	Geotechnical description	Clay minerals* (%)	Cations (%)
Carnisaw	Residuum weathered from shale of Pennsylvanian age	Red brown silty clay	V (24), I (48), KA (28)	Na (0.2), Ca (1.8), Mg (9.1), K (0.9), H (88.0)
Hollywood	Clayey colluvial sediments over limestone of Cretacious age	Yellowish olive fat clay with trace of light grey limestone	M+V (37), I(34), KA (29)	Na (1.0), Ca (93.2), Mg (4.6), K (1.3),
Heiden	Clayey shale of Cretacious age	Olive grey highly plastic fat clay with trace of organic root	M (73), I (10), KA (17)	Na (6.0), Ca (82.2), Mg (11.0), K (0.8),
Eagle Ford	Fossiliferous clayey shale with sandy shale lenses	Yellowish tan highly plastic pure clay	M (42), I (41), KA (17)	Na (7.5), Ca (77.8), Mg (13.2), K (1.5),

*Mineral percentages of only the clay portion of the soils

DISCUSSION OF RESULTS

Expansive soil behavior is mostly determined by electrical, chemical and physical forces that are exerted on the surface of soil particles or aggregates. These surface forces come from the interaction between the diffuse double layers of adjacent particles and the interaction between diffuse double layer and bulk fluid or air. However, these forces are difficult to identify and quantify. Instead, the six proposed micro-scale properties were investigated from direct lab measurements. Among these six properties, matric suction determines how the particles are bounded together by the surface tension force as well as the degree of development of diffuse double layer. The pH is derived from the acidity of the soil and is indicative of the type of bonding of hydrogen on the soil mineralogical unit and thus affects the development of diffuse double layer. Surface conductance is a comprehensive electrical property combing SSA, CEC and counterion mobility. It is believed to be a more direct illustration of the effect of electrical forces. Mineralogy is used to describe the influence of expansive minerals within the clay portion on soil heave. Plastic index or activity is not considered a micro-scale property because both of them are determined from an empirical specification for plasticity (e.g., blow number) and not directly from an underlying physical-mechanical mechanism.

From Table 2, it is observed that the ranking with respect to the percent of swell is: Carnisaw < Hollywood < Heiden < Eagle Ford and the ranking concerning the swell pressure is the same. These are consistent with the ranking of swell potential based on plasticity (Chen 1988). The matric suction values at OMC shows a good correlation with the measured swell percent, which means as matric suction increases, the soil swell becomes more significant. Table 3 shows none of the individual properties of SSA, CEC, pH and the comprehensive electrical property, surface conductance, alone exhibit a satisfactory correlation with the swell measurements. However, except for the Carnisaw soil, which has low pH and high hydrogen content, surface conductance does show a good correlation with the swell measurements. The underlying mechanism is uncertain yet. Similarly, there is not a well-developed correlation observed from the summary of XRD test results in Table 4.

Soil swell is a complex process involving the interaction of many microscopic mechanisms brought by various types of surface forces. In this case, matric suction plays a more significant role than other micro-scale properties in reflecting the swell potential. The reason may be that the matric suction values were measured from soil specimens compacted at OMC, and the corresponding measured swell percent and pressure were also of specimens compacted at OMC. It is expected that the other micro-scale properties may play an important role if samples are prepared differently, e.g., compacted from slurry and dried to reach different moisture content than OMC, or stabilized using chemicals. Quantitative prediction of soil heave based on these micro-scale properties is expected to be established in future research.

CONCLUSIONS

In this study six micro-scale properties are studied in order to assess their roles in determining soil swell. An approach to approximate surface conductance of expansive soils is proposed. These properties reveal the intrinsic microscopic behavior of expansive soils. Plasticity is not considered a micro-scale property because it is defined from phenomenological observations. Moreover, it can hardly reflect the development of diffuse double layer which is the prominent determinant of fine-grained soil behavior.

Matric suction at OMC is found to provide a most accurate assessment of soil heave because the samples were also tested under OMC in the oedometer tests. Although the other micro-scale properties did not show significance in this study, they are believed to do so if the sample preparation methods or the test conditions are modified. More micro-scale properties, like dielectric permittivity and microstructure, will be investigated in future research. In conclusion, the macroscopic soil behavior in terms of heave is determined by the overall function of various surface forces which derive from the intrinsic micro-scale properties.

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