Unsaturated soil properties of a fissured expansive clay

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ABSTRACT
The engineering properties of expansive Regina clay were investigated under in situ conditions to understand the influence of geologically induced fissuring and environmentally caused saturation. Results indicated a bi-modal SWCC comprising of a fissure AEV (10 kPa) and a matrix AEV (300 kPa). The latter value matched the field water content and the plastic limit, of which both occurred at S = 80%. The swell-shrink path was found to be S-shaped and included an initial low structural shrinkage (S = 100% to S = 80% at w_p) followed by a sharp decline during normal shrinkage (S = 80% to S = 60% at w_s) and then by a low decrease during residual shrinkage (S = 60% to S = 0%).

RÉSUMÉ
Les propriétés mécaniques de l'argile expansible de Regina ont été étudiées dans des conditions in situ pour comprendre l'influence de la saturation causée par l'environnement, et la fissuration causée par le mouvement géologique. Les résultats montrent la présence d 'une SWCC bimodale comprenant une fissure AEV (10 kPa) et une matrice de AEV (300 kPa). Cette dernière valeur correspond à la teneur en eau sur le terrain et la limite de plasticité, toutes deux survenues à S = 80%. Le cycle d'expansion et rétrécissement a été trouvé en forme de S et inclus un rétrécissement initial structurel (S = 100% à S = 80% w_p à) suivi d'une forte baisse au cours du rétrécissement normal (S = 80% à S = 60% à w_s) et ensuite par une diminution faible lors du rétrécissement résiduel (S = 60% à S = 0%).

1 INTRODUCTION

Expansive clays constitute a distinct class of problematic soils that is characterized by extensive changes in volume. Commonly found in arid and semi-arid regions of the globe, these fine-grained sedimentary soils experience a net water deficit most of the year. Consequently, these materials tend to swell when exposed to seasonal precipitation or anthropogenic activity like lawn watering. If the deformations are prevented, such as by structural loads, pressure is exerted that results in distress and eventual damage of engineered facilities. In North America alone, the estimated cost associated with the design, construction, and maintenance of engineered facilities built in, on, or with expansive soils is greater than the combined cost of all other natural hazards (Jones and Holtz 1973).

The Regina clay deposit in southern Saskatchewan is a typical example of expansive soils. It evolved due to geologic weathering of glacio-lacustrine sediments under restrained leaching in a semi-arid climate (Christiansen and Saure 2002). The soil is primarily composed of expansive clay minerals (such as smectite, hydrous mica, and chlorite) and exhibits high water adsorbing and water retention capabilities. Equally important is the presence of fissures, which are derived from moderate over-consolidation, physical and chemical weathering and numerous swell-shrink cycles in the surface layer of the clay (Ito and Azam 2010). These vertical hairline discontinuities govern the extent of volume changes in the top layer (where most of the civil infrastructure resides) of the local expansive clay deposit. Being in contact with the atmosphere, volume changes in this layer are governed by seasonal climatic variations, that is, by periodic saturation and desaturation.

Alternate volume changes in Regina clay has markedly impaired civil infrastructure such as transportation networks (Kelly et al. 1995), residential, industrial, and commercial facilities (Azam and Ito 2007), and water supply and sewage collection systems (Hu and Hubble 2005). The damages to these engineered facilities are clearly manifested in the form of differential heave in roadways and sidewalks, inclined cracking in slab-on-grade basements and masonry walls, and fatigue and breakage in underground storage tanks and buried pipelines. The related cost of repair and maintenance is usually quite enormous. For example, the breakage rate in the 850 km long water supply network in the city has now reached a 30-year maximum of 0.27 breaks/km/year, costing more than $2 million in annual maintenance. Furthermore, the city is undergoing a period huge economic activity along with infrastructure development. Some of the mega-projects include the Global Transportation Hub, the 55000-seat Covered Stadium, the 26-storey Capital Pointe Hotel and Condominiums building, and the 18-storey Mosaic Potash Tower. To ensure an uninterrupted use of existing infrastructure and to assist in the initial design of new facilities, there is an exigent need to understand the volume change behavior of expansive Regina clay.

The main objective of this paper was to investigate the unsaturated soil properties of the expansive Regina clay under in situ conditions. Geotechnical index properties were determined for preliminary soil assessment. The effects of geologically induced fissuring and environmentally caused saturation were evaluated using undisturbed field samples. The water retention capacity was studied in conjunction with soil volume change using the soil water characteristics curve (SWCC) and the swell-shrink paths, respectively.

2 RESEARCH METHODOLOGY

2.1 Site Conditions

The soil represented an extensive deposit of the glacio-lacustrine clay in Regina. At the sampling site, the surface layer appeared desiccated in the month of September when the soil is usually unsaturated due to the preceding summer. A visual survey of the exposed cutting showed the presence of fissures with dimensions of 1 mm to 2 mm width and 50 mm to 100 mm height. With inconsistent lateral spacing, these soil discontinuities were more numerous at the top and gradually reduced over the 1.5 m cut depth. Further, the fissures were primarily vertical in nature but exhibited some variation in the dip angles with respect to the horizontal.

2.2 Sample Collection

High quality undisturbed samples were obtained using the ASTM Standard Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes (D1587-08). To preserve the field water saturation, the samples were wrapped with plastic sheets and coated with molten wax in accordance with the ASTM Standard Practice for Preserving and Transporting Rock Core Samples (D5079-08). All of the samples were carefully transported to the Geotechnical Testing Laboratory at the University of Regina and stored at 24°C in a humidity chamber (RH ≈ 95%).

2.3 Geotechnical Index Properties

The geotechnical index properties were determined for preliminary soil assessment according to the ASTM test methods as follows: (a) field water content (w) by the Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D2216-05); (b) field dry unit weight (γ_d) by the Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method (D2937-10); (c) specific gravity (G_s) by the Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (D854-10); (d) liquid limit (w_l), plastic limit (w_p) and plasticity index (I_p) by the Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (D4318-10); (e) shrinkage limit (w_s) by the Standard Test Method for Shrinkage Factors of Soils by the Wax Method (D4943-08); and (f) clay size fraction (material finer than 0.002 mm) by the Standard Test Method for Particle-Size Analysis of Soils (D422-63(2007)).

2.4 Soil Water Characteristic Curve

The SWCC was determined in accordance with the ASTM Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge (D6836-02(2008)e2). The undisturbed core sample (from 0.6 m to 1.2 m depth) was sliced to about 10 mm thickness to obtain duplicate specimens and their initial gravimetric water content was determined. Predetermined suction values (10 kPa, 30 kPa, 100 kPa, 200 kPa, 300 kPa, 400 kPa, 500 kPa, 2000 kPa, and 6000 kPa) were applied using pressure plate/membrane extractors manufactured by Soil Moisture Equipment Corp. These included the following: (a) a 5 bar pressure plate extractor (Model 1600) along with a 0.5 bar porous plate (0675 Series) for 10 kPa and 30 kPa suction, a 3 bar porous plate (0675 Series) for 100 kPa and 200 kPa suction; (b) a 15 bar pressure plate extractor (Model 1500F1) and a 5 bar porous plate (0675 Series) for 300 kPa, 400 kPa, and 500 kPa suction; and (c) a 100 bar pressure membrane extractor (Model 1020) and a cellulose membrane (1041D21) for 2000 kPa and 6000 kPa suction. The porous plates were gradually submerged in a tray filled with distilled and de-aired water for 24 hours to ensure that no gas bubbles appear in the plates. Likewise, the cellulose membranes were saturated with the same quality water in the pressure extractor vessel for 24 hours. Thereafter, the specimens along with the retaining ring were placed on their respective porous plate or cellulose membrane and allowed to saturate in water. Next, the excess water was removed and each porous plate or membrane was placed in the designated pressure plate extractors. For each suction value, the expelled water from the samples was periodically monitored in a graduated burette. When two consecutive readings over a 24 hour period were found to be close, the application of suction was terminated and the water content of the samples was immediately determined. The volumetric water content ($\theta = w\,\gamma_d / \gamma_w$) was plotted as a function of the applied suction to obtain the SWCC.

2.5 Swell-shrink Path

The swell-shrink test was conducted in accordance with the ASTM Standard Test Method for Shrinkage Factors of Soils by the Wax Method (D4943-08). To obtain the void ratio, the volume of soil specimens was determined using the water displacement method. Each specimen was coated with molten microcrystalline wax (G_s = 0.91) and allowed to cool down at room temperature. After wax solidification, the sample was submerged in a 250 ml graduated cylinder that was filled with distilled water. The water height in the cylinder was carefully recorded using a Vernier caliper before and after sample submersion in the cylinder. A graduated syringe was used to remove the increased amount of water displaced by the sample thereby bringing the water height back to the initial reading. The displaced water mass was determined by weighing the graduated syringe before and after water filling and recording the difference. This quantity was readily converted to water volume representing the volume of the wax-coated soil. The volume of soil was obtained from the difference of volume of the wax coated sample and the volume of wax (mass/0.91). A 7.4% correction was applied to account for the underestimation due to air entrapment at soil-wax interface in this method, as suggested by Prakash et al. (2008). The mass of the sample was also determined to estimate the bulk unit weight of the soil. Using basic phase relationships, the void ratio was determined from a knowledge of the bulk unit weight of the soil.

3 RESULTS AND DISCUSSIONS

3.1 Geotechnical Index Properties

Table 1 summarizes the geotechnical index properties of the fissured expansive clay. The gravimetric field water content (w_f) and the dry unit weight (γ_d) were found to be 31.2% and 13.4 kN/m^3, respectively. From the measured specific gravity (G_s = 2.75) and the degree of saturation (S_f = 84%), the field void ratio (e_f) was calculated to be 1.0. The surface layer of the soil is highly affected by seasonal variations in water availability (snow melt in spring and precipitation in summer) and water deficiency (low rainfall and freezing in fall and winter). In the month of September when the samples were collected, indigenous soils generally experience a net water deficit given the semi-arid climate prevalent in the region. The high liquid limit (w_l = 83%) and plastic limit (w_p = 30%) along with a low shrinkage limit (w_s = 15%) suggest the high water absorbing and retaining capabilities of the clay. These features are attributed to the geologic origin of the soil that is primarily composed of expansive clay minerals such as smectite, illite, and chlorite (Ito and Azam 2009).

Table 1. Summary of geotechnical index properties

Property	Value
Field Water Content, w_f (%)	31.2
Field Dry Unit Weight, γ_d (kN/m^2)	13.4
Specific Gravity, G_s	2.75
Field Void Ratio, e_f*	1.0
Field Degree of Saturation, S_f (%)†	84
Liquid Limit, w_l (%)	82.8
Plastic Limit, w_p (%)	30.1
Plasticity Index, I_p (%)	52.7
Shrinkage Limit, w_s (%)	15
-0.002 mm, C (%)	66
Activity, A= I_p /C	0.8

* $e = (Gs\ \gamma_w / \gamma_d) - 1$

† $S = w\ Gs / e$

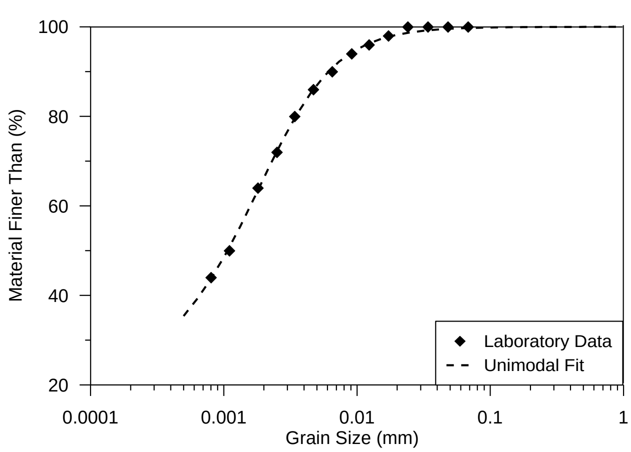

Figure 1. Grain size distribution curve

Figure 1 gives the grain size distribution (GSD) curve for the expansive clay using combined sieve and hydrometer analyses. About 99% of the grains were found to be smaller than 0.075 mm and the clay size fraction (material finer than 0.002 mm) measured 66%. Using the plasticity index (I_p = 53%), the activity (A) of the soil was found to be 0.8, a value associated with moderate swelling capability. Based on the Unified Soil Classification System (USCS), the fine-grained soil was classified as CH (clay with high plasticity).

3.2 Soil Water Characteristic Curve

The soil water characteristic curve is defined as the relationship between volumetric water content (θ) and matric suction. This curve describes important features of soils when their saturation state is altered. Soils can remain fully saturated despite an increasing suction. The air entry value (ψ_a) is defined as the suction value at which the intrusion of air into bigger pore spaces commences under the action of capillarity. After passing the air entry value, soils continuously lose the capillary water with increasing suction until they reach the residual state. The remaining adsorbed water (that is electrochemically attached to the clay particles) is difficult to force out by the application of suction. The suction required to completely desiccate a soil equals 1,000,000 kPa. The entire curve can be considered to comprise of three straight-line parts: a horizontal line from saturation to the air entry value; a steep downward slope from the air entry value to the residual state; and a flat downward slop from the residual state to completely dry state. The shape of the curve is primarily affected by the following soil properties: (a) grain size distribution that influences pore connectivity and tortuousity; (b) dry unit weight that is related to the total void space in a soil; (c) clay mineral types and amounts that dictate the amount of adsorbed water; and (d) soil microstructure that governs pore characteristics especially in clays.

Figure 2 gives the SWCC of the investigated expansive clay. The estimated curve was obtained using the geotechnical index properties (w, G_s, and γ_d) along with the best fit of the measured grain size distribution data (Fredlund et al. 2002). The measured grain size distribution data were fitted according to the unimodal equation given by Fredlund et al. (2000). The computer software of SoilVision Systems Inc. was used for SWCC estimation. Based on a physico-empirical approach, the software divided the GSD into uniform particle sizes, each size assigned an individual SWCC from the database of measured SWCC, and all summed to develop the entire curve.

The estimated SWCC followed the typical theoretical trend described above. The full saturation volumetric water content equalling 0.52 remained constant up to the air entry value of 300 kPa. Desaturation occurred at an increased rate between the air entry value and the residual suction of 70000 kPa (at a volumetric water content of 0.1). The curve finally joined the abscissa at 1,000,000 kPa under completely dry soil conditions. The slope of the final portion of the estimated SWCC was found to be much flatter than the middle part.

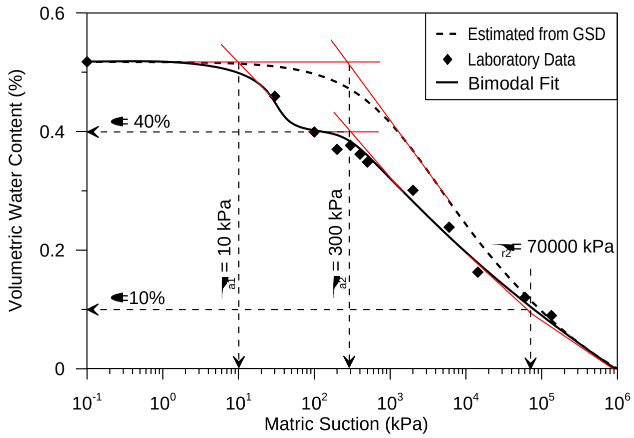

Figure 2. Soil water characteristic curve

The laboratory data for the expansive clay exhibited deviations from the estimated SWCC. The data generally shifted downward because of variations in pore size distribution. The undisturbed geological sample was primarily flocculated in contrast to a dispersed sample for grain size distribution: dispersion was ensured using sodium hexametaphosphate. The corresponding larger pores for the former sample were easy to dewater because of reduced capillarity. This resulted in a higher reduction in volumetric water content at the same matric suction. More importantly, the data fitted quite well to a bimodal distribution with two air entry values: a lower value (10 kPa) corresponding to drainage through fissures followed by a higher value (300 kPa) associated with seepage through the soil matrix. Fissures in the local expansive clay are derived from over-consolidation, weathering and swell-shrink cycles (Ito and Azam 2010). When the undisturbed samples were gradually desatuarted, air first entered into the fissures at low suction. Azam and Wilson (2006) reported that upon wetting fissures in expansive soils are generally filled because of lateral swelling. However, periodic swelling and shrinkage render these discontinuities to have much lower tensile strengths than the soil aggregates. This led to a quick drainage through these paths of least resistance to water flow. Subsequent application of suction also affected the soil aggregates and eventually forced air to enter into the pore system of the soil matrix. This matrix AEV is similar to that obtained from GSD estimation because water movement through an aggregate is affected by the arrangement of individual particles.

Whereas the observed SWCC data could be fitted as a unimodal curve, the bimodal fit was found to better capture the observed soil fissuring in the undisturbed field samples of the clay. As mentioned before, fissures in the local expansive clay are derived from over-consolidation, geologic weathering and swell-shrink cycles. Similarly as stated earlier, the hairline discontinuities were found to be more numerous at the ground surface where the low confining pressures allowed the soils to crack at relatively low suction values and gradually closed with depth due to an increasing confining pressure.

3.3 Swell-shrink Path

Figure 3 shows the swell-shrink path for the investigated expansive clay. Theoretical lines representing various saturation degrees were obtained from basic phase relationship and using G_s = 2.75. Field samples were first wetted to achieve complete saturation from an initially unsaturated state and subsequently desatuarted by applying different suction values in a pressure plate extractor. The void ratio and water content of each sample was determined as described earlier in this paper.

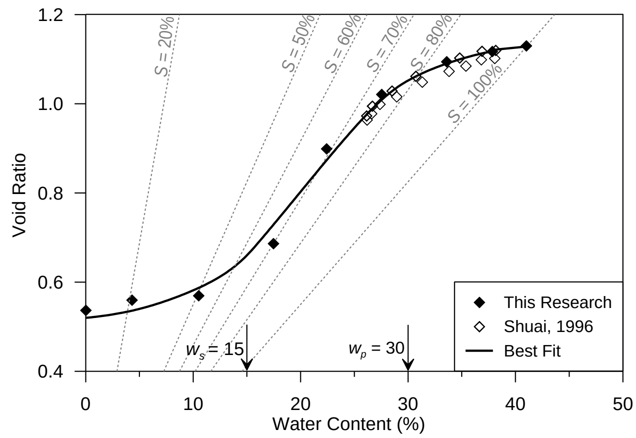

Figure 3. Swell-shrink path

The data depicted in Figure 3 indicate an S-shaped curve representing the progressive drying (from e = 1.13 to e = 0.53) of the undisturbed soil. The curve comprises of an initial low structural shrinkage followed by a sharp decline during normal shrinkage and then by a low decrease during residual shrinkage (Haines 1923). During structural shrinkage, some of the larger and relatively stable voids (fissures) are emptied such that the decrease in soil volume is less than the volume of water lost. Volume decrease in soil is equal to the volume of water lost during normal shrinkage thereby leading to a 45^o straight line parallel to the 100% saturation line and suggesting that drainage is through the soil matrix. During residual shrinkage, air enters the pores close to the shrinkage limit and pulls the particles together due to suction. This leads to a further decrease in soil volume albeit lower than the volume of water lost. The structural shrinkage portion of the curve correlated well with Shuai (1996) data who used compacted Regina clay samples with similar initial conditions (w = 26% and e = 0.97).

Studying the swell-shrink path (Figure 3) in conjunction with Table 1 indicated that the various shrinkage stages correlate well with the consistency limits as follows: (i) structural shrinkage from the S = 100% line to the plastic limit; (ii) normal shrinkage from the plastic limit to the shrinkage limit; and (iii) residual shrinkage from the shrinkage limit to complete desiccation. The central linear portion of the swell-shrink curve representing only 20% change in saturation (S = 80% to S = 60%) is associated with bulk of volume changes in the investigated clay.

The swell-shrink path is reversible once the sample reaches an equilibrium condition. Tripathy et al. (2002) reported that this stage is usually attained after about four cycles in compacted soils. For the undisturbed samples of the investigated expansive clay having undergone numerous swell-shrink cycles since deposition, an equilibrium condition is considered to have been attained. Ito and Azam (2010) confirmed this through the closely matching photomicrographs highlighting the presence of fissures in field samples at various degrees of saturation.

Theoretically, the swell-shrink path comprises of two straight lines: a sloped line closely following the S = 100% line that joins a horizontal line at a void ratio associated with the shrinkage limit of the soil. This means that soils essentially remain saturated up to the shrinkage limit. Due to the presence of fissures, the investigated expansive clay exhibited deviations from this theoretical behavior. Only the point corresponding to the fissure AEV is expected to be close to the S = 100% line on Figure 3. The field water content and the plastic limit were found to occur at S ≈ 80% up to which structural shrinkage (including drainage through fissures) was found to dominate soil volume change. This also means that the matrix AEV (Figure 2) does not occur at S = 100% (as suggested by the GSD estimated SWCC) but at a lower saturation of 80% (as depicted by the laboratory data).

4 SUMMARY AND CONCLUSIONS

Knowledge of the unsaturated soil properties is paramount for civil infrastructure construction in, on, or with expansive soils located in arid/semi-arid regions of the globe. Geologically induced fissuring and environmentally caused saturation govern the engineering properties of the expansive Regina clay. Laboratory investigations on undisturbed samples were conducted to develop a clear understanding of the geotechnical behavior of this local soil. The main conclusions of this research are summarised as follows:

- The high liquid limit (w_l = 83%) and plastic limit (w_p = 30%) along with a low shrinkage limit (w_s = 15%) indicated the high water absorbing and retaining capabilities of the clay. These data correlated well with soil composition and observed volume change tribulations.
- The laboratory measured soil water characteristic curve was found to follow a bimodal function comprising of a low fissure AEV (10 kPa) and a high matrix AEV (300 kPa). The latter value closely matched with the field water content and the plastic limit, of which both occurred at S = 80%.
- The swell-shrink path was found to be S-shaped and included an initial low structural shrinkage (S = 100% to S = 80% at w_p) followed by a sharp decline during normal shrinkage (S = 80% to S = 60% at w_s) and then by a low decrease during residual shrinkage (S = 60% to S = 0%).

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