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Engineering properties of a vertisolic expansive soil deposit

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ABSTRACT

Vertisolic expansive soils are characterized by unique morphological features and extensive volume changes of swelling clay minerals. The engineering properties of such a soil deposit in Regina, Canada, were investigated under in situ conditions. Results indicated a bi-modal SWCC composing of a fissure AEV (10 kPa) and a matrix AEV (300 kPa based on water content and 6000 kPa based on degree of saturation). The latter value matched the field water content and the plastic limit, of which both occurred at $S_{ave} \approx 80\%$. The swell-shrink path was found to be S-shaped and included a low structural shrinkage ($S_{ave} = 100\%$ to $S_{ave} = 80\%$ at w_p) followed by a sharp decline during normal shrinkage ($S_{ave} = 80\%$ to $S_{ave} = 60\%$ at w_s) and then by a low decrease during residual shrinkage ($S_{ave} = 60\%$ to $S_{ave} = 0\%$). An equilibrium soil microstructure for the undisturbed samples mean that for the field conditions (up to the matrix AEV), the soil aggregates remain fully saturated whereas drainage and volume changes primarily occur through the fissures.

1. Introduction

Vertisolic expansive soils are characterized by unique morphological features and extensive volume changes of swelling clay minerals (Brierley et al., 2011). A typical example of such deposits is the Regina clay (Saskatchewan, Canada) that 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, illite, and chlorite) and exhibits high water adsorbing and water retention capabilities. The surface layer of the clay has extensive fissuring that is derived from moderate over-consolidation as well as alternate swell-shrink and freeze–thaw cycles (Ito and Azam, 2010). Stress induced particle rearrangement has resulted in localized wedge-shaped aggregates bounded by slickensides. The hairline discontinuities especially influence heaving and subsidence in the top stratum of the deposit where most of the construction occurs. Being in contact with the atmosphere, volume changes in this layer are governed by seasonal weather variations, that is, by periodic saturation and desaturation.

Alternate swelling and shrinkage in Regina clay has 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). Damages to 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 associated repair cost 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. To ensure an uninterrupted infrastructure utility, there is a need to understand the volume change behavior of the indigenous deposit.

The main objective of this paper was to investigate the engineering properties of Regina clay under in situ conditions. First, the geotechnical index properties were determined for preliminary soil assessment. Second, the soil water characteristics curve (SWCC) was determined to understand the water retention capacity of the soil. Third, the swell-shrink test was conducted to study soil volume changes during saturation–desaturation. Finally, scanning electron microscopy was conducted for selected samples to correlate soil microstructure with engineering behavior.

2. Geologic evolution of the deposit

The Quaternary period in southern Saskatchewan was governed by a series of glacial events that, in turn, were responsible for erosion of the Cretaceous and Tertiary rocks and their subsequent deposition to form the indigenous glacial drift. The drift consists of the following three groups from older to younger (Christiansen and Saure, 2002): Empress (gravel and sand), Sutherland (till and stratified deposits), and Saskatoon (till, gravel, sand, silt, and clay). Alternate scraping, deposition, overburdening, and reworking of materials by up to seven glacial advances and retreats resulted in extensive particle disintegration. The present-day surface soils in the Regina area formed during the last glaciation known as the Wisconsinan (23,000 years B.P. to 17,000 years B.P) that covered the entire province. The ice sheet started to retreat in the northeastwardly direction around 17,000 years B.P. The rate of ice meltdown was initially about 60 m/year and gradually increased to 275 m/year in the final stages. According to Mollard et al.

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(1998), this process was completed around 8000 years B.P. when the essential features of the present landform emerged including moraines (a raised ground covering of unsorted till) and eskers (a long winding ridge of sorted sands and gravel). These ground features bounded the proglacial Regina Lake where fine-grained soils gradually settled at the basin floor during the Wisconsinan to develop a homogeneous clay deposit of up to 12 m depth. Subsequent wet–dry and freeze–thaw cycles, alluvial and fluvial transportation processes and the presence of salt-forming ions further modified the deposit during the postglacial period. Overall, the soil preserved the pre-existing expansive clay minerals such as smectite, illite and chlorite due to restrained leaching in the Lake and the prevalent aridity in the area (Ito and Azam, 2009).

The indigenous clay deposit has a spatially variable stress distribution because of the following reasons: (i) geologic rebound of the deposit due to removal of up to 1000 m thick glacial cover; (ii) swelling and shrinkage of clay minerals due to water hydration and dehydration in spring and summer; and (iii) heave and subsidence of the soil layers due to ice lens formation and decay in winter and spring. Ito and Azam (2009) reported that the average vertical swelling pressure in the surface layer (1.2 m deep and a vertical overburden pressure of 20 kPa) of the clay is 120 kPa. Since this soil layer is laterally confined, the lateral earth pressure is expected to be higher than the vertical overburden pressure (Hong, 2008). Whereas no data is available for the local soil deposit, in situ measurements by Brackley and Sanders (1992) indicated that the lateral pressure in surficial expansive clays (2 m deep) is up to four times the vertical pressure. Such passive conditions imply localized shearing failure during alternate volume changes due to seasonal weather variations. The internal movement occurs in multiple directions (20° to 60° with the horizontal) thereby developing a network of intersecting shear planes. These slickensides form the boundaries of wedge-shaped aggregates with a central low and a circumferential high because of material oozing outwards and upwards along the weak boundaries (Brierly et al., 2011). Successive swell-shrink cycles render these soil features quite permanent and conspicuous particularly in the surface layer. This is the case with the local clay deposit that exhibits extensive soil fissuring (up to 2 mm wide) with inconsistent lateral spacing and variable dip angles in the top 1.5 m depth.

The stress related morphology in vertisolic expansive soils is initiated at the microstructural level and is governed by the clay mineral type and the amount of clays and non-clays such as silts, salts, carbonates, and organics (Ahmad and Mermut, 1996). The overall soil matrix is characterized by a random arrangement of plasma (clay particles generally finer than 0.002 mm) usually forming a sepic fabric (anisotropic domains of clay particle booklets) with several striated interference patterns (Douglas, 1990). The primary conspicuous morphological features in such soils include the following (Fitzpatrick, 1993): (i) vosepic zones of plasma separation along the larger voids with striations largely parallel to the walls of the voids; (ii) skelsepic zones of plasma accumulation near the surface of coarse skeletal grains eventually forming galaxies or comet tails; and (iii) masepic zones of elongated striations within the plasma as a precursor to a vosepic zone. In addition to these stress induced features, the plasma fabric undergoes periodic changes due to wet–dry cycles. According to Cui et al. (2006), the sepic fabric during swelling is characterized by a face-to-edge particle arrangement due to water hydration of the negatively charged surfaces of expansive clay minerals. This microstructure collapses during shrinkage due to water removal between adjacent clay surfaces and results in a predominantly face-to-face particle arrangement.

3. Research methodology

Undisturbed samples were obtained using the ASTM Standard Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes (D1587-08) from a depth of 0.6 m to 1.2 m. Individual specimens were plastic-wrapped and wax-coated and the entire collection was transferred and stored at the University of Regina as per the ASTM Standard Practice for Preserving and Transporting Rock Core Samples (D5079-08).

3.1. Geotechnical index properties

The geotechnical index properties were determined for preliminary soil assessment and for use in subsequent laboratory investigations according to the ASTM test methods as follows: (i) field water content (w) by the Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D2216-05); (ii) field dry unit weight (γ_d) by the Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method (D2937-10); (iii) specific gravity (G_s) by the Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (D854-10); (iv) 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); (v) shrinkage limit (w_s) by the Standard Test Method for Shrinkage Factors of Soils by the Wax Method (D4943-08); and (vi) grain size distribution by the Standard Test Method for Particle-Size Analysis of Soils (D422-63(2007)).

3.2. Soil water characteristic curve

The SWCC was determined according to 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) using about 10 mm thick specimens obtained from the undisturbed core samples. Predetermined suction values were applied using pressure plate/membrane extractors manufactured by Soil Moisture Equipment Inc. These included the following: (i) a 5 bar pressure plate extractor (Model 1600) along with a 0.5 bar porous plate (0675 Series) for 30 kPa suction and a 3 bar porous plate (0675 Series) for 100 kPa and 200 kPa suction; (ii) 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 (iii) a 100 bar pressure membrane extractor (Model 1020) and a cellulose membrane (1041D21) for 2000 kPa and 6000 kPa suction. The porous plates and the cellulose membranes were submerged in distilled and de-aired water for 24 h to expel air bubbles. 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 extractor. For each suction value, the expelled water from the samples was monitored in a graduated burette. When two consecutive readings nearly matched over a 24 hour period, the test was terminated and the sample water content was determined.

The dew point potentiameter (WP4-T) was used for suction measurement at low water content. The sampling cup was half filled with soil to ensure accurate suction measurement (Leong et al., 2003) by using about 5 mg of material with a known water amount. The unsaturated sample was forwarded to the head space of the sealed measurement chamber, set at 25 °C temperature, through a sample drawer and was allowed to equilibrate with the surrounding air. Equilibration was usually achieved in 10 min to 20 min, as detected by condensation on a mirror and measured by a photoelectric cell. From knowledge of the universal gas constant, R (8.3145 J/mol°K), sample temperature, T (°K), water molecular mass, X (18.01 kg/kmol), and the chamber relative humidity, p/p_o, soil suction was calculated ($\psi = RT/X\, ln(p/p_o)$) and displayed on the potentiameter screen. The water content of the soil was measured as described earlier.