

Unconfined compression strength as consistency index for compacted clay in construction – a statistical approach

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ABSTRACT

In this paper, unconfined compression strength (UCS) as obtained from an unconsolidated-undrained test is used as a consistency index for classification of natural clay. For saturated clay, the UCS or undrained shear strength is independent of the confining pressure and is an indicator of consistency in stiffness. However, the structure of compacted clay varies as a function of compaction effort and water content and as such is more heterogeneous than that of natural clay. This study investigates whether UCS can be used as a consistency index for compacted clay. Two different types of clay, Calgary till and Regina clay, were used with clay contents of about 15 and 45%, respectively. Compacted clay specimens were prepared at varying water contents using the standard Proctor method. Computer X-ray scanning technique and filter paper method were used to quantify the variation of bulk density and matric suction along the specimen's height, respectively followed by UCS determination. Empirical correlations among bulk density, matric suction and UCS were developed. In addition, these data were analyzed using a statistical approach. The results provide confidence levels for the use of UCS as a consistency index for compacted clay used in construction.

RÉSUMÉ

Dans cet article, la résistance en compression simple (UCS) obtenue à partir d'un test non consolidé-non drainé est utilisée comme indice de consistance pour la classification de l'argile naturelle. Pour l'argile saturée, la résistance UCS ou au cisaillement non-drainé est indépendante de la pression de confinement et constitue un indicateur de la consistance de la rigidité. Cependant, la structure de l'argile compactée varie en fonction de l'effort de compactage et de la teneur en eau et, en tant que telle, est plus hétérogène que celle de l'argile naturelle. Cette étude examine si UCS peut être utilisé comme indice de consistance pour l'argile compactée. Deux types d'argiles, le till de Calgary et l'argile de Regina, ont été utilisés avec une teneur en argile d'environ 15 et 45%, respectivement. Des échantillons d'argile compactée ont été préparés à différentes teneurs en eau en utilisant la méthode standard de Proctor. La technique de balayage aux rayons X par ordinateur et la méthode du papier filtre ont été utilisées pour quantifier la variation de la densité apparente et la succion matricielle le long de la hauteur de l'échantillon, suivies d'une détermination UCS. Des corrélations empiriques entre densité apparente, succion matricielle et UCS ont été développées. De plus, ces données ont été analysées en utilisant une approche statistique. Les résultats fournissent des niveaux de confiance pour l'utilisation de l'UCS en tant qu'indice de consistance pour l'argile compactée utilisée dans la construction.

1 INTRODUCTION

Compaction is especially important when soil is used as an engineering material in engineered earth structures such as shallow foundations, backfills for retaining structures and buried pipes, railroad and highway embankment and fills, earth dams, retaining wall backfills, and levees along rivers. The Proctor compaction test is a laboratory method of experimentally determining the physical characteristics or the compaction curve of a compacted soil. One of the important characteristics determined is the optimal water content at which for a given soil type will be in its densest state (at maximum dry density). The compaction curve is a function of four variables: dry density, water content, soil type and compaction effort. For standard Proctor test, the compaction effort in terms of the hammer weight, drop height and number of layers of soil placed into the mold is specified, and is supposed to be fairly constant. Thus, for a given soil type, the unconfined compressive strength of the compacted specimen depends on the former two variables: dry density and water content. For a given compaction effort, these two variables are uniquely

defined by the compaction curve. Therefore, it is postulated that the unconfined compressive strength of compacted soil could be used as a consistency index for quality assurance and control in construction of engineered earth structures.

In this study, compacted specimens were prepared using standard Proctor tests from two fine-grained soils. Computed X-ray tomography (CT) was used to map the spatial distribution of bulk density within the compacted specimens. Filter paper method was used to measure matric suction along the specimen height. Then, unconfined compression tests were conducted to determine the strength and deformation properties of the compacted clay specimens. The first part of this paper describes soil types used, testing procedures and test data. The second part deals with correlation among variables and statistical analysis of the test data, along with concluding remarks.

2 TESTING PROGRAM

2.1 Materials

One of the materials used is Regina clay, a dark brown highly expansive clay. The clay was obtained from an excavation site near Mosaic Stadium in Regina, Saskatchewan, Canada. The soil was oven-dried, crushed and sieved through a 2-mm sieve prior to any testing. Compaction test results show that Regina clay has an optimum water content of 28.5% with a dry density of 1.5 Mg/m³. The clay content, plastic and liquid limits are 50, 25 and 80%, respectively. The clay fraction comprises approximately 20-75% montmorillonite, 15-45% illite, and 10% kaolinite by mineralogy.

Another material used is Calgary till, a light brown expansive glacial till deposit. The till was obtained from an excavation site in the Sage Hill neighborhood in the northwest part of Calgary, Alberta, Canada. Likewise, with the Regina clay, the soil was also oven-dried, crushed and sieved through a 2-mm sieve prior to any testing. Compaction test results show that Calgary till has an optimum water content of 11% with a dry density of 1.8 Mg/m³. The clay content, plastic and liquid limits are 25, 25 and 35%, respectively.

2.2 Proctor Compaction Test

The Proctor compaction test is a laboratory-scale test conducted to determine the maximum dry density and the corresponding optimum water content of a particular soil when compacted. Under the standard, ASTM D698, the main equipment required to conduct a compaction test include a Proctor hammer (a mass of 2.5 kg and a free fall height of 305 mm) and a Proctor compaction mold (height of 116.4 mm, 101.6 mm in diameter) and collar setup.

Oven-dried and crushed soil was mixed throughout with water at a desired water content, and placed inside an air-tight plastic bag for 48 hours to allow equilibrated hydration. Then, the moist soil was placed into the mold in three equal layers with 25 blows being impacted per soil layer. Once the mold was filled, the final wet mass of the compacted specimen was measured to determine the corresponding density. The specimen was extruded for other tests such as CT tomography, matric suction measurement, unconfined compression tests and water content measurement.

2.3 Computed X-ray Tomography

Computed X-ray tomography (CT) is an advanced imaging method employing tomography created by computer processing. Digital geometry processing is used to generate a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images taken around a single axis of rotation. CT imaging has been used to quantify the physical uniformity and local deformation features of soil samples (e.g., Desrues et al. 1996; Wong 2003). The principles and equipment details of a CT scanner can be found in the above mentioned references. Only a brief description will be presented herein. The CT scanner used in this study is General

Electric Model Hi Speed CT/i. The settings were: 120 kV (KVP), 150 mA (X-ray tube current), 0.8 sec full rotation scan, and 25 cm FOV (field of view). The resolution of each pixel (picture element) was 0.19 mm by 0.19 mm by 1 mm. The compacted specimen sealed inside a food saver bag was positioned inside a motorized aluminum tube which slides along the axis of the scanning ring in the CT unit. During the CT scanning process, an X-ray source and an array of detectors rotate in synchrony around the longitudinal axis of the specimen. A multiple set of data is generated from a number of views around a section of the specimen forming a cross-sectional matrix or a scan. More precisely, the X-ray attenuation obtained from different angular positions are combined to generate the pixels (picture element) of the matrix. Each individual pixel represents a specific CT number or a specific X-ray attenuation coefficient normalized with respect to water. Typical CT numbers for the scanned specimens fall in the range of 900 to 1800. The higher the CT number, the denser the material is. Presence of air reduces the CT values. Therefore, the CT number reflects the composition of the pixel containing air, water and soil particles.

2.4 Matric Suction Measurement

The objective of this test series is to determine the matric suction distribution along the specimen height of compacted Regina clay specimens. Filter paper method which has been developed primarily in soil science and agronomy was used in this study. This method is classified as an "indirect method" of measuring soil suction. When a piece of filter paper is in direct contact with a moist soil specimen, moisture exchange takes place between the soil specimen and the filter paper until an equilibration state is attained. The moisture content of the filter paper at the equilibration state corresponds to the matric suction of the soil. Calibration curves of filter paper water content versus matric suction have been developed for different filter paper types (Fawcett and Collis-George 1967; McQueen and Miller 1968).

In this study, Whatman No. 42 filter paper as per ASTM standard specification E832 was used with minor modifications. Circular filter pieces of 55 in diameters and strips of 20 by 100 mm were used to measure the matric suction at both ends and along the specimen height of the compacted cylindrical specimens, respectively. These pieces were soaked with a 2% formaldehyde solution and placed in an oven for 24 hours. This was done to prevent mold from developing on the filter paper during the test.

A stack of three filter papers consisting a piece of pretreated filter paper with a diameter of 55 mm sandwiched between two pieces of protective pretreated filter paper with a diameter of 60 mm, was mounted at both ends of the compacted soil specimen using aluminum foil pieces. Two outer filter paper pieces were used to prevent soil contamination, and the middle one was used for moisture measurement. Similarly, five stacks of three pretreated filter paper strips were mounted circumferentially at 5 locations along the specimen height in a staggered manner to avoid the connectivity between each stack. Then, the soil specimen was covered with an aluminum foil piece, and inserted in an air-tight food-saver

plastic bag. Vacuum pressure was applied to the food-saver bag so that the filter paper stack was tightly held in contact with the soil. The whole assembly was placed inside an air-tight glass container in a closed thermostat box at 21°C to allow the specimen to reach its equilibration state which took about 8-10 days. Upon equilibration, the specimen was CT scanned first, and then was removed from the food-saver bag. The moist filter paper pieces were oven-dried and weighed to obtain their respective water contents. The soil matric suction was determined using the calibration curves (Leong et al. 2002; Fredlund et al. 2012):

$$\log(\text{matric suction in kPa}) = 4.945 - 0.0673 w \quad [1]$$

(for $w < 47\%$)

$$\log(\text{matric suction in kPa}) = 2.909 - 0.0229 w \quad [2]$$

(for $w > 47\%$)

where w = water content in %.

2.5 Unconfined Compression Test

The objective of this test series is to determine the unconfined compressive strength (UCS) of the compacted soil specimen. Cylindrical specimens of 100 mm in diameter and 115 mm in height were prepared at a desired water content using a standard compaction mold and proctor in three layers according to ASTM D 5080. Extruded specimens were sealed in air-tight plastic bags for 24 hours. Then, the specimen was mounted on an ELE load frame of 10 kN capacity, and a constant displacement rate of 1 mm per min was applied to shear the specimen. The axial load, axial and radial displacements were monitored using a load cell and external LVDTs, respectively. The duration of each compression test was about 10-15 minutes. The portion of the failed specimen was oven-dried to determine its water content.

3 TEST RESULTS

Figure 1 illustrates the compaction curve for Regina clay. It shows an optimum water content of 28.5% at a maximum dry density of 1500 kg/m³.

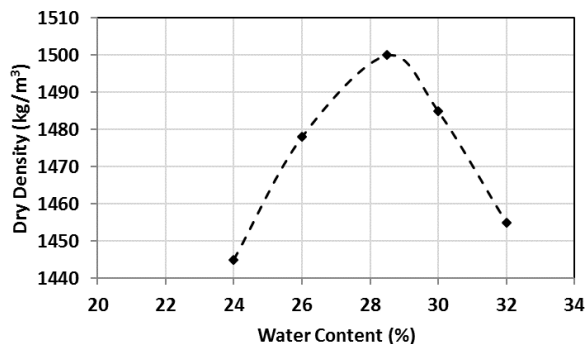


Figure 1. Proctor compaction test results - compaction curve of Regina clay

Figures 2 to 4 show the typical CT scans (slices) of three compacted Regina clay specimens compacted at

water contents of 25, 28 and 31%, respectively. Each scan (slice) is 1.0 mm in thickness. The total number of scans used in this study is about 112 which is close to the compacted sample height. These images were converted from the CT numbers using a graphic software. The darker and lighter areas represent looser and denser matrices with lower and higher bulk densities, respectively. Circular dents made by the hammer were observed at the first and second compaction layers in specimens with water contents of 25 and 28%.

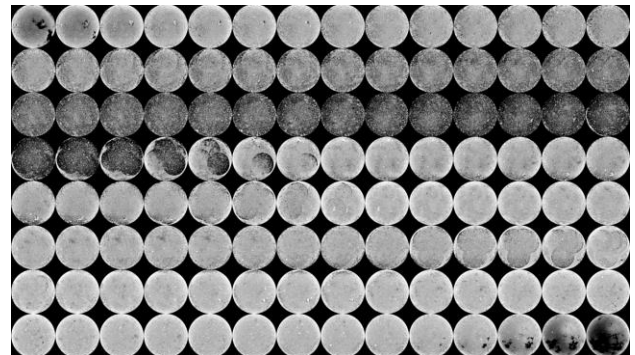


Figure 2. CT scans for compacted Regina clay specimen with 25% water content

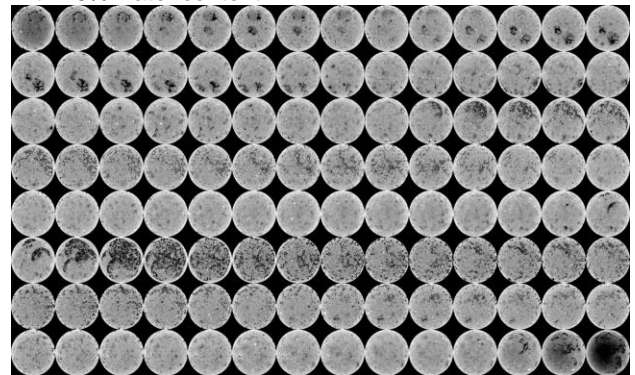


Figure 3. CT scans for compacted Regina clay specimen with 28% water content

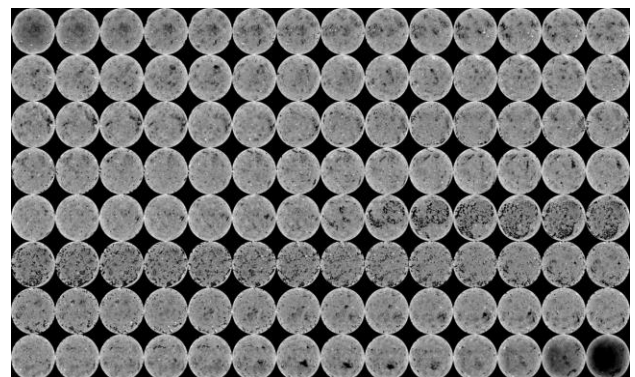


Figure 4. CT scans for compacted Regina clay specimen with 31% water content

To investigate the variations of CT numbers and therefore variations of bulk density along the specimen height, the average CT numbers of each scan (slice) was determined and calibrated to a bulk density value. Figures

5 to 7 show the histogram for the CT sliced bulk density of compacted Regina clay specimens with water contents of 25, 28 and 31%, respectively. It is clearly shown that the specimen with water content of 25%, on the dry side is more heterogeneous than those at the optimum and wet side. The spatial distribution of CT slice bulk density is displayed in Figure 8 of slice bulk versus specimen height. Three compaction layers were clearly detected which are consistent with the CT images shown in Figures 2 to 4. The bulk density was much reduced at the interfaces between two layers.

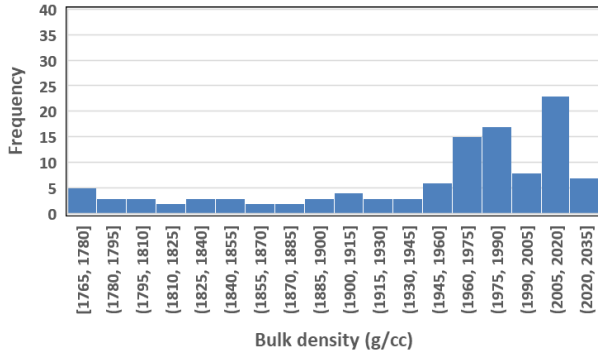


Figure 5. CT slice bulk density histogram for compacted Regina clay specimen with water content of 25%

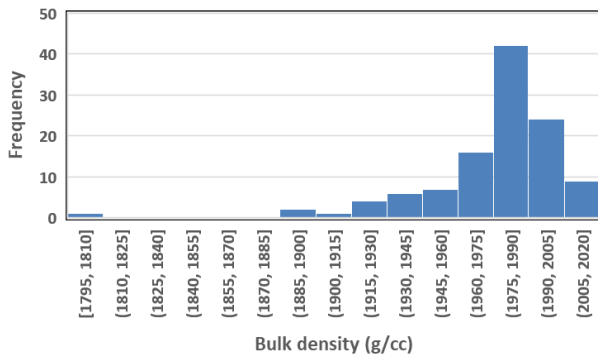


Figure 6. CT slice bulk density histogram for compacted Regina clay specimen with water content of 28%

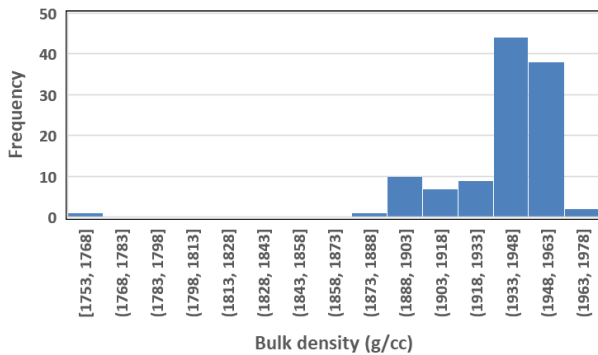


Figure 7. CT slice bulk density histogram for compacted Regina clay specimen with water content of 31%

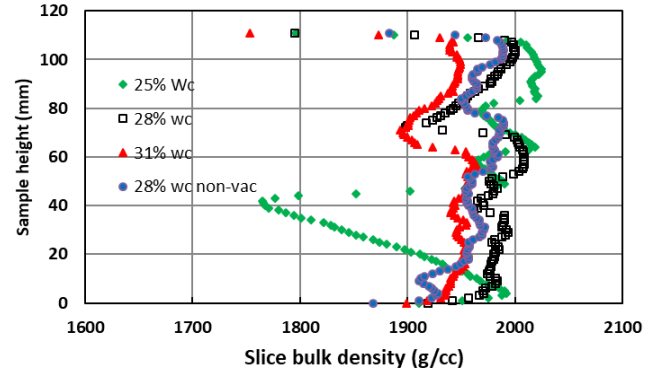


Figure 8. CT slice bulk density versus specimen height for compacted Regina clay specimens with water contents of 25, 28 and 31%

Figure 9 presents the spatial distribution of measured matric suction versus specimen height for compacted Regina clay specimens with water contents of 25, 28 and 31%. The measured values are comparable to those shown in Figure 10 measured by Chowdhury (2013) and Wong (2017). However, there is significant variation of measured matric suction within each compacted specimen. This implies that the water phase contributing to the matric suction is not continuous in compacted soil. It is interesting to notice that the variation in measured matric suction decreases with increasing water content used in the compaction. The compacted specimen with water content on the wet side (31%) yields the lowest variation due to low measured matric suction, which again consistent with the results of the CT slice bulk density. The compacted specimen with water content on the dry side (25%) exhibits significant variation in measured CT slice bulk density and matric suction.

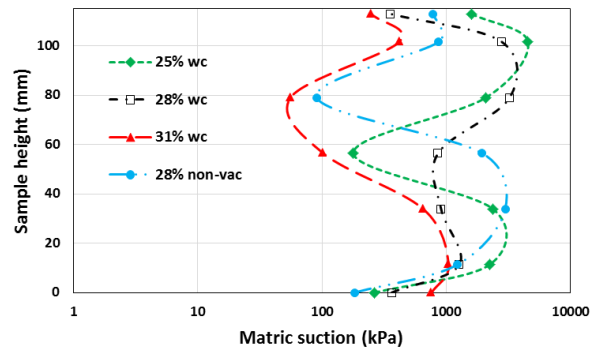


Figure 9. Measured matric suction versus specimen height for compacted Regina clay specimens with water contents of 25, 28 and 31%

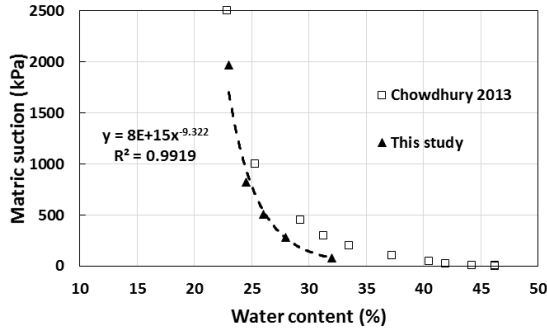


Figure 10. Soil-water characteristic curve of compacted Regina clay

Results of measured unconfined compressive strength and deformation modulus were determined from the unconfined compression tests on compacted Regina clay specimens and plotted in Figures 11 and 12, respectively. Both geotechnical properties decrease with increasing water content which are mainly attributed to reduction in matric suction with increasing water content. Again, the variation in these two properties is reduced as the soil specimens were compacted on the wet side of the compaction curve. This is probably due to the fact that on the dry site, the water added is more difficult to be homogenized within the dry soil particles. Figures 13 and 14 are histograms illustrating the frequencies of measured unconfined compressive strength and deformation modulus for compacted Regina clay specimens. Log-normal distributions are observed in both figures. Such distributions are commonly encountered in geotechnical characterization of in situ properties of natural soils and rocks such as residual friction angle of mudstone and unconfined compressive strengths of sandstone (Becker et al. 1998) and pile resistances in clay and sand (Zhang et al. 2001).

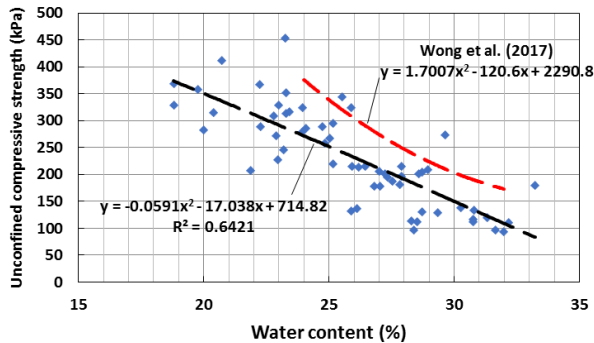


Figure 11. Unconfined compressive strength versus water content for compacted Regina clay specimens

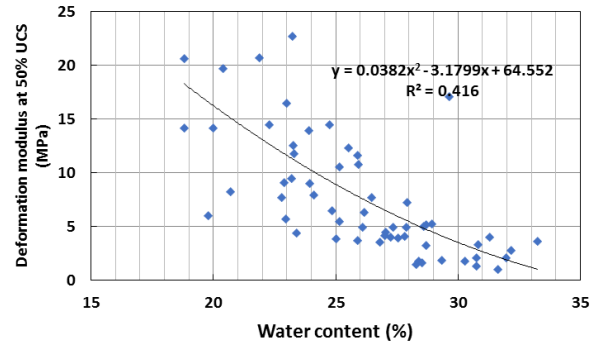


Figure 12. Deformation modulus versus water content for compacted Regina clay

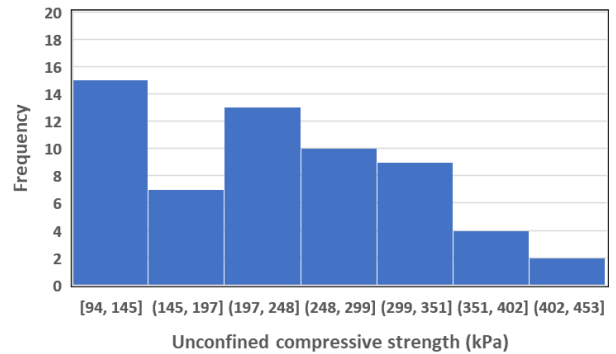


Figure 13. Unconfined compressive strength histogram for compacted Regina clay specimens

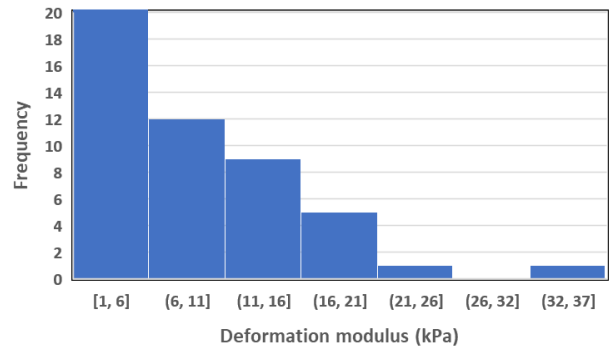


Figure 14. Deformation modulus histogram for compacted Regina clay specimens

Figures 15 to 18 depict the test results of compacted Calgary till specimens. The material shows the behavioural trends similar to those observed in compacted Regina clay specimens. In general, the unconfined compressive strength and deformation modulus of Calgary till are lower than those of Regina clay. The clay content of Calgary till is lower than that of Regina clay, and the water content retained in Calgary till is lower as well as the matric suction.

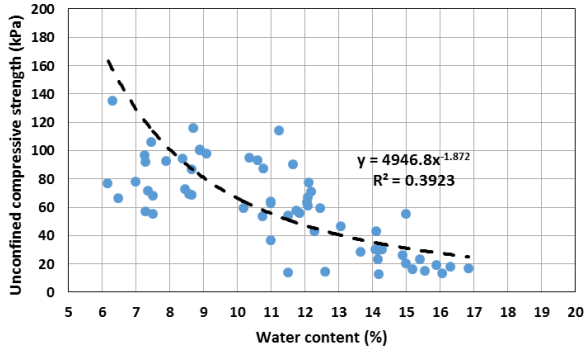


Figure 15. Unconfined compressive strength versus water content for compacted Calgary till specimens – power curve-fitting better

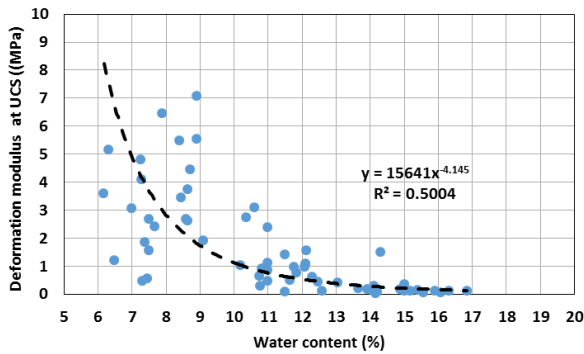


Figure 16. Deformation modulus versus water content for compacted Calgary till specimens

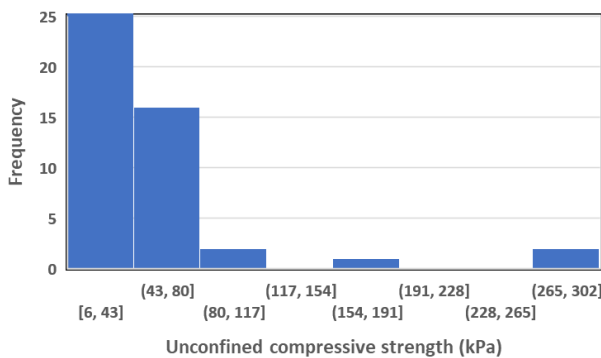


Figure 17. Unconfined compressive strength histogram for compacted Calgary till specimens

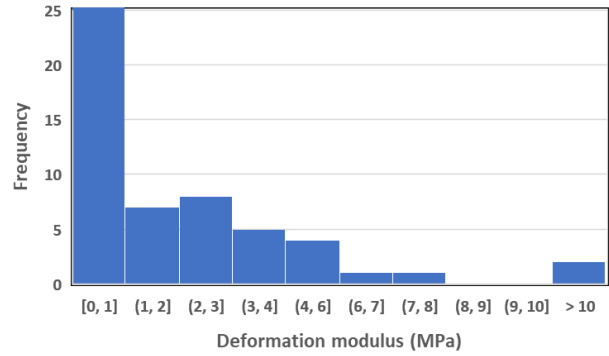


Figure 18. Deformation modulus histogram for compacted Calgary till specimens

4 CONCLUDING REMARKS

The use of the unconfined compression strength (UCS) as a consistency index for compacted clay has been validated using the standard Proctor method, Computer X-ray tomography (CT) scans, and unconfined compression tests on Regina clay and Calgary till samples. The CT scan images illustrate the general trend of decreasing bulk density with increasing sample water content. More heterogeneity was observed in samples with water contents lower than optimum. The higher homogeneity degree in the dry side leads to a significant variation in matric suction measurements, which in turn, causes significant variations in the unconfined compression strength and deformation modulus measurements in the unconfined compression tests. Thus, greater care and attention must be taken in selecting appropriate design values in construction with compacted clay. The variability in the unconfined compressive strength and deformation modulus for compacted clay were found to follow log-normal distributions, which is acceptable with respect to geologic materials.

5 ACKNOWLEDGEMENT

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