Influence of matric suction on the compressibility behaviour of a compacted unsaturated fine-grained soil

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ABSTRACT

The compressibility characteristics of compacted unsaturated fine-grained soils are influenced by several parameters such as: initial compaction water content, soil structure, compaction energy, applied loading, and clay mineralogy. The stress state variable; matric suction, which is conventionally used in the interpretation of the engineering behaviour of unsaturated soils is also influenced by all these parameters. Therefore, an experimental investigation was undertaken to understand the influence of matric suction on the compressibility characteristics of a statically compacted glacial till from Indian Head, Saskatchewan. In the present research program, the compressibility characteristics were determined for specimens compacted with initial water contents between 14 and 19% prepared using two different compaction energies; namely, 70 kJ/m^3 and 140 kJ/m^3. All studies were conducted using conventional oedometer equipment under an applied stress range of 15 to 800 kPa. In addition, compressibility characteristics were also studied on identical saturated specimens. The study shows that the compressibility behaviour of the test specimens under unsaturated conditions is significantly different from the saturated conditions. The key objective of this paper is to highlight the importance of taking matric suction into account in the compressibility characteristics of compacted unsaturated soils in engineering practice applications.

RÉSUMÉ

Les caractéristiques de compressibilité de sols à grains fins compactés sont influencées par plusieurs paramètres tels que: la teneur en eau au compactage initial, la structure du sol, l'énergie de compactage, le chargement appliqué, et la minéralogie de l'argile. La variable d'état de contrainte; la succion matricielle, qui est traditionnellement utilisé dans l'interprétation du comportement des sols non saturés est également influencée par tous ces paramètres. Par conséquent, une étude expérimentale a été entreprise pour comprendre l'influence de la succion matricielle sur les caractéristiques de compression statique d'un till glaciaire compacté de Indian Head, en Saskatchewan. Dans le présent programme de recherche, les caractéristiques de compressibilité ont été déterminés pour les spécimens compactés avec une teneur en eau initiale entre 14% et 19% préparés sous deux différentes énergies de compactage, à savoir 70 kJ/m^3 et 140 kJ/m^3. Toutes les études ont été réalisées en utilisant un appareil oedométrique conventionnel sous une gamme de contraintes s'étalant de 15 à 800 kPa. En outre, les caractéristiques de compression ont également été étudiées sur des spécimens identiques saturés. L'étude montre qu'il existe une différence marquée entre le comportement en compression des échantillons sous des conditions non saturées et saturées. Le principal objectif de cet article est de mettre en évidence l'importance de tenir compte de la succion dans les caractéristiques de compression des sols compactés non saturés dans plusieurs applications pratiques d'ingénierie.

1 INTRODUCTION

Significant progress has been made during the last fifty years towards understanding the engineering behaviour of unsaturated soils (Bishop 1959, Bishop and Donald 1961, Matyas and Radhakrishna 1968, Barden et al. 1969, Fredlund and Morgenstern 1977, Toll 1990, Vanapalli et al. 1996, Barbour 1998, Tarantino and Tombalato 2005). Several researchers during the last three decades have proposed frameworks for rational interpretation of the engineering behaviour of unsaturated soils using two or more independent stress state variables (Fredlund and Morgenstern 1977, Alonso et al. 1990 and Wheeler and Sivakumar 1995). In all these frameworks, matric suction, $(u_a - u_w)$ which is defined as the difference between the pore-air pressure, u_a and pore-water pressure, u_w of an unsaturated soil is one of the stress state variables. The pore-air pressure, u_a in soil structures is typically equal to atmospheric pressure and the pore-water pressure, u_w with respect the atmospheric pressure is the matric suction, $(u_a - u_w)$.

Research focus since the first international conference on unsaturated soils held in 1995 in Paris, has been towards implementing the mechanics of unsaturated soils into engineering practice. In spite of significant advancements made with respect to our understanding of flow and shear strength behaviour of unsaturated soils in recent years; limited studies are reported in the literature about the settlement behaviour of compacted fine-grained unsaturated soils.

More recently, an approach was proposed for predicting the settlement behaviour of coarse-grained unsaturated soils using the modulus of elasticity of coarse-grained soils under saturated conditions and the soil-water characteristic curve (SWCC) by Vanapalli et al. (2008). In this technique, the modulus of elasticity of the soil under saturated conditions and Poisson's ratio are used in estimating the settlement of sandy soils. The proposed technique in estimating the settlement was similar to the procedures used in conventional engineering practice (Poulos and Davis 1980). The results of this study show that the settlement behaviour of coarse-grained saturated soils is significantly different from unsaturated soils. The differences associated with the settlement behaviour of saturated and unsaturated coarse-grained soils were attributed to the influence of matric suction, $(u_a - u_w)$.

The conventional procedure for the determination of settlement behaviour of saturated fine-grained soils is derived from consolidation test results using the relationship between void ratio and effective stress (Casagrande 1936). In this scenario, the change in void ratio is proportional to the change in water content as the soil is always in a state of saturated condition (i.e., settlement associated with drainage of water phase). Some studies are available in the literature to interpret consolidation behaviour of unsaturated soils (Fredlund and Hasan 1979, Ho et al. 1992, Fredlund and Rahardjo, 1993 and Estabragh et al. 2004). These studies can be extended to interpret the settlement behaviour of unsaturated soils which are initially in a state of saturated condition. These studies are useful in estimating the settlement in unsaturated soils associated with the changes in water content as the soil desaturates in terms of two stress state variables; namely, the net normal stress, $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$. There are no procedures available in the literature to estimate the settlement behaviour of fine-grained compacted soils associated with changes in the expulsion of air in soils (i.e., drainage of the air phase) due to applied loading taking account of the influence of matric suction, $(u_a - u_w)$.

Several parameters are likely to influence the settlement behaviour of compacted fine-grained soils. Some of the key parameters are the inital compaction water content, soil structure, compaction energy, applied loading, and clay mineralogy. The initial compaction water content and compaction energy significantly influence the soil structure of compacted soils. The soil structure is defined as the arrangement of soil particles within a soil matrix (Mitchell, 1993). Compacted fine-grained soils exhibit a flocculated (i.e. open structure) if the initial water content used for compaction is on the dry side of the optimum water content. The soil structure is dispersed (i.e. orientated) if the initial water content used for compaction is on the wet side of the optimum water content (Lambe 1958, Barden 1965, Barden and Sides 1971, Benson and Daniel 1990, and Elsbury et al. 1990). Studies by Vanapalli et al. (1999) demonstrate that there is a strong relationship between the various parameters that influence the compacted fine-grained soils such as soil structure and initial compaction water content and the stress state variable, matric suction, $(u_a - u_w)$.

Compacted fine-grained soils are commonly used in the construction of pavements, embankments, soil covers, soil liners and other geotechnical structures. These soils are likely to be in a state of unsaturated condition during their entire design life. Settlement of such compacted soil structures are also analysed using the principles of saturated soil mechanics. This approach leads to erroneous estimates in the settlement behaviour as the influence of matric suction is ignored. An approach to estimate the settlement drainage of air phase without any change in water content due to loading of compacted soils in terms of stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$ is not available.

In this paper, results of a testing program undertaken on a compacted fine-grained soil (i.e., glacial till) are presented to show the differences in compressibility characteristics in saturated and unsaturated conditions using conventional consolidation equipment. The test specimens with different initial compaction water contents ranging from 14 to 19% were subjected to an applied stress range of 15 to 800 kPa. The water content range was chosen such that the soil specimens would have varying soil structures from the wet and dry side of optimum water content conditions representing both dispersed and flocculated structures. The key objective of this research program is to understand how various parameters including matric suction, $(u_a - u_w)$, influence the compressibility characteristics of compacted fine-grained soils associated with the drainage of the air phase.

2 TESTING PROGRAM

The following section outlines the properties of the soil tested and the procedures used for two different series of oedometer testing programs in the present research program. The first series of tests were performed to determine the conventional compressibility characteristics using compacted saturated till specimens. The second series of tests were conducted to determine the compressibility characteristics of compacted unsaturated till specimens using modified conventional oedometer test equipment.

2.1 Soil Tested

The soil used in this research project was a glacial till obtained from Indian Head, Saskatchewan. Table 1 summarizes the properties of the tested soil (Power et al. 2007). The soil is classified as CL, which is clay of low plasticity as per the USCS Classification System.

Table 1: Index Properties of Indian Head Till

Index Property	Value
Liquid Limit, w_l (%)	32.5
Plastic Limit, w_p (%)	17.0
Plasticity Index, I_p (%)	15.5
Specific Gravity, G_s	2.72
Percent Sand Size Particles, (%)	23
Percent Silt and Clay Size Particles, (%)	77
Water Content Range, w (%)	14 to 19

The test specimens were prepared using six different initial compaction water contents and two different initial compaction energies in order to understand the influence of compaction energy and soil structure on the compressibility characteristics of the glacial till. The 70 kJ/m^3 stress was designated as the low compaction energy (LE) while 140 kJ/m^3 stress was considered as the high compaction energy (HE). Figure 1 shows the compaction curves for the low and high compaction energies used in this testing program in comparison to the Standard Proctor Curve of Indian Head till.

Identical initial conditions were used for the two different testing procedures (i.e., for testing saturated and unsaturated specimens). The test specimens were prepared in 50 mm diameter rings with a height equal to 18 mm.

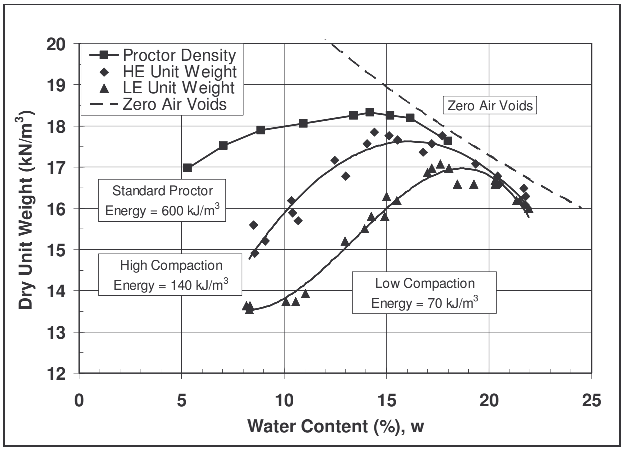

Figure 1: Comparison of high and low energy static compaction curves to the standard Proctor curve.

2.2 Oedometer Tests on Saturated Soil Specimens

Specially designed water-tight acrylic chambers were used to house the compacted test specimens (see Figure 2). A 10 mm high head of water was maintained in these chambers during the entire period of testing. The compacted unsaturated specimens were allowed to imbibe water following the ASTM Standard D4546-03 Method C (i.e. constant volume conditions) entitled, "Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils". This technique was followed for saturating the soil specimen by gradually increasing the degree of saturation through inundation. The initial matric suction of the compacted unsaturated test specimen gradually dissipates as the degree of saturation increases. Test specimens prepared in this fashion were designated as "*inundated*" test specimens.

The specimens tend to swell as the degree of saturation increases. The swelling characteristics of a soil are dependent on the percentage of clay and its clay mineralogy. In order to ensure that the initial conditions of the specimen (i.e. void ratio, *e*, and height) remains constant during inundation, the specimen was gradually loaded to counter the swelling tendency. The applied stress was increased in 2.5 kPa increments until there was no tendency for the specimen to swell. Extreme care was taken to ensure that the stress applied did not compress the specimen beyond its initial height.

Conventional oedometer testing procedures were followed to determine the compressibility characteristics of the saturated soil specimens in the stress range of 15 to 800 kPa (i.e., e vs. σ' relationship). Figure 2 shows the equipment and accessories used for determining the *e* vs. σ' relationship of the compacted saturated soil specimens. Conventional fixed-ring, Wykeham Farrance oedometer cells were modified to determine this relationship. A loading system consisting of a steel loading frame, and lead shot for dead load was used to apply the stress to the specimens. Deformation of the specimens was measured using 50 mm dial gauges.

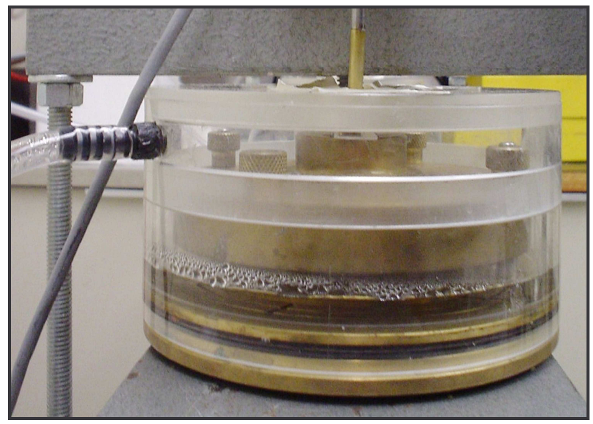

Figure 2: Specially designed acrylic chamber for testing specimens under inundated conditions.

2.3 Oedometer Tests on Unsaturated Soil Specimens

Specially designed acrylic chambers were used to house the compacted unsaturated soil specimens during testing (see Figure 3). In order to ensure that outside environmental conditions (i.e. temperature or humidity level fluctuations) did not alter the test results obtained in this research, the laboratory environment was kept at a constant temperature of 22°C ±0.5°C and a humidity level of 40% ±10%. In addition, to maintain the initial compaction water content of the test specimens, a 100% humid air stream was pumped into the acrylic chambers for the entire duration of the testing period. The relative humidity conditions within the chambers were measured using an RH meter which was monitored throughout the duration of the test. The test specimens were placed inside the acrylic chambers once the humidity level inside the chambers reached 100%. The soil specimens were then loaded and unloaded following conventional oedometer testing procedures. As discussed earlier, the settlement in saturated soil specimens is mostly associated with the drainage of water from the soil specimen and perhaps to a small extent to the compression of entrapped air; however, the change in settlement of compacted specimens in non-inundated conditions is associated with the expulsion of air (i.e. drainage of the air-phase).

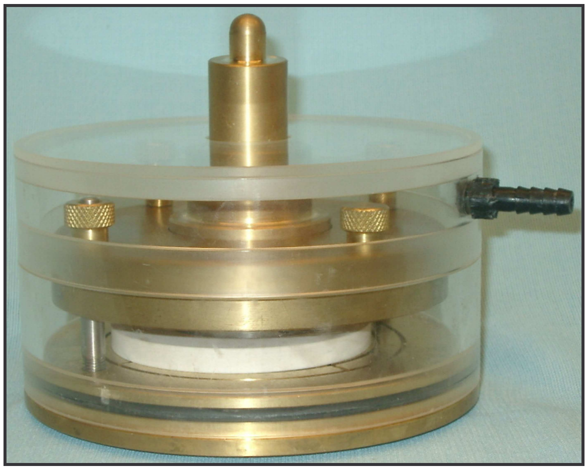

Figure 3: Specially designed acrylic chambers with inlet for 100% humidity stream during testing specimens under non-inundated conditions.

3 COMPRESSIBILITY CHARACTERISTICS OF SATURATED SOIL SPECIMENS

The volume change behaviour of a saturated test specimen during loading depends on the applied stress range, initial water content and density (i.e. initial void ratio, *e*). One of the key parameters influencing the compressibility characteristics is the coefficient of permeability of the soil.

The saturated coefficient of permeability of a fine-grained soil specimen compacted dry of optimum conditions is typically two to three orders greater than the coefficient of permeability of specimens initially compacted with a water content that is wet of optimum conditions (Lambe and Whitman 1971, Haug et al. 1992 and Benson and Daniel 1990). The Elsbury et al. (1990) investigation on the failure of compacted clay liners demonstrate that large soil clods are formed when a fine-grained soil is compacted with water content on the dry side of optimum. In other words, initial compaction under dry of optimum conditions will impart an open structure to the fine-grained soil and hence will have a higher coefficient of permeability under saturated conditions.

The parameters that influence the volume change or the settlement behaviour of fine-grained saturated soils also have an impact on the behaviour of unsaturated soils. In addition, matric suction has a significant influence on the compressibility characteristics of compacted soils that are in a state of unsaturated condition. The research presented in this paper makes an attempt to understand how various variables influence the compressibility characteristics under two different conditions; namely inundated and non-inundated conditions.

4 RELATIONSHIP BETWEEN THE VOID RATIO, *e* VS. APPLIED STRESS, σ'_V

The relationship between void ratio, *e* vs. applied stress, σ'_v in the range of 15 to 800 kPa was determined for both saturated and unsaturated test specimens prepared using both low and high compaction energies. The term σ'_v is conventionally used for describing the effective stress in saturated soils but is typically not used in the characterisation of the engineering behaviour unsaturated soils; however, the term is used in the present research to allow comparisons between the commonly used compressibility parameters of both *inundated* and *non-inundated* test results. In both cases σ'_v is designated as the total applied stress.

A series of *e vs.* σ'_v relationships were determined for six different initial compaction water contents. For brevity, only the *e vs.* σ'_v relationships for two of the water contents used in this research, namely 14% (dry of optimum water content) and 17% (wet of optimum water content) are detailed in the following sections. The initial conditions (i.e. void ratio, degree of saturation, matric suction and soil structure) of both the saturated and unsaturated tests were “identical”.

The *e vs.* σ'_v relationships are presented for both the saturated and unsaturated test specimens to compare and understand the differences in the compressibility characteristics. The results of saturated specimens are shown with solid continuous lines and that of unsaturated specimens with discontinuous or dashed lines in Figures 4 to 7. Table 2 summarizes some of the key results of the studies.

4.1 Compressibility of specimens compacted with low initial water contents

Figure 4 and Figure 5 show the *e vs.* σ'_v relationship for specimens prepared with an initial water content of 14% (dry of optimum conditions) using low and high compaction energies respectively. The initial matric suction values of these specimens measured using the axis-translation technique were 280 and 290 kPa respectively (Power et al. 2007). These results suggest that the matric suction values of compacted specimens are more dependent on the initial compaction water content rather than the density or compaction energy. Similar observations were reported by other investigators (Olson and Langfelder 1965, Krahn, and Fredlund 1972, and Vanapalli et al. 1999). The small differences in the measured matric suction values of the order of 3.5% in the present results may be attributed to errors associated with the instrumentation or other unforeseen errors.

The test specimens that are in a state of unsaturated condition (i.e., non-inundated) initially offer a higher resistance to the applied stress. Due to this reason, there is relatively small decrease in void ratio compared to the specimens that are in a state of saturated (i.e., inundated) condition. This resistance can be attributed to the contribution of matric suction in the test specimens. Several investigators studies show that the increase in shear strength and relatively low volume change of unsaturated specimens can be attributed to the aggregation between particles that are held together by suction (Toll, 1990; Oh et al. 2008). Alternatively, this behaviour can be explained in terms of degree of saturation. Table 2 summarizes the volume-mass relationships along with other properties derived from the test results undertaken in this study.

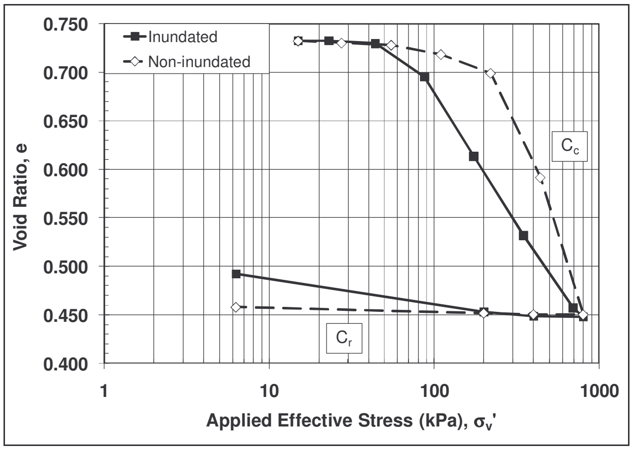

Figure 4: Comparison of *e-log* σ_v' relationship for inundated and non-inundated specimens prepared using low compaction energy with an initial compaction water content equal to 14%.

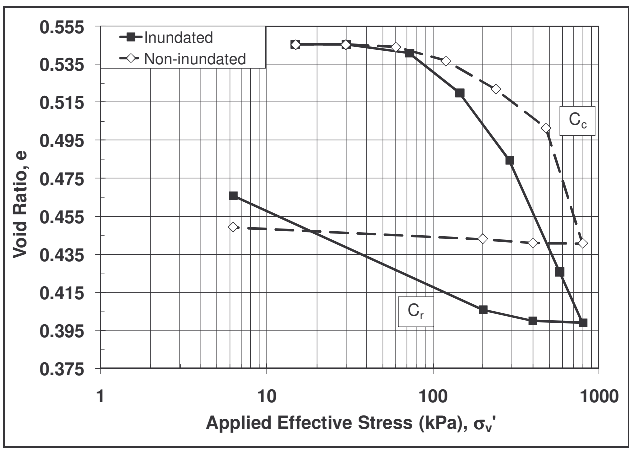

Figure 5: Comparison of *e-log*σ_v' relationship for inundated and non-inundated specimens prepared using high compaction energy with an initial compaction water content equal to 14%.

The degree of saturation in the specimen gradually increases due to a reduction in void ratio upon an increase in the applied stress. An increase in the degree of saturation, *S* is associated with an increase in compression of the test specimen and decrease in the matric suction. The test specimens with an initially low degree of saturation will have a higher matric suction value than those with a high degree of saturation (see Table 2). The matric suction of an unsaturated test specimen offers resistance to deformation in spite of an increase in the applied stress.

The initial void ratio, *e* for the specimens prepared using low and high compaction energies was 0.732 and 0.545 respectively. The reduction in void ratio for unsaturated test specimens for both low (i.e. 0.7) and high (i.e. 0.525) compaction energies for the stress range up to 200 kPa is small. Settlement associated with the stress range up to 200 kPa is due to the expulsion of pore-air from the non-inundated test specimens.

However, for the same stress range (i.e. 200 kPa) there is a significant drop in void ratio, *e* compared to the initial conditions for both the low (i.e. 0.6) and high (0.5) compaction energies for saturated soil specimens. This difference in the magnitude of the deformation can be attributed to the influence of the matric suction component of the unsaturated test specimens.

As the degree of saturation, *S* of the unsaturated soil specimen increases due to an increase in the applied stress, its behaviour begins to resemble that of the initially saturated test specimens. The *e vs.* σ_v' relationship for both the saturated and unsaturated test specimens show similar slopes for the virgin compression part of the curve (i.e. compression index C_c). At this point the degree of saturation of the initially unsaturated soil specimen is approaching 100%.

Table 2: Mass volume relationships for specimens prepared with high and low compaction energies

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Note 1: C_r refers to the slope of the *e vs.* σ_v' curve during the unloading phase of the consolidation tests see Figures 4 to 7.

4.2 Compressibility of compacted specimens with high initial water contents

The matric suction influence on the compressibility characteristics of the unsaturated soil specimens is significantly reduced for specimens prepared with initial water contents greater than 17% (i.e., wet of optimum specimens). The *e vs.* σ'_v relationships for specimens prepared with an initial water content of 17%, using low and high compaction energies are shown in Figure 6 and Figure 7 respectively. The initial matric suction values of these specimens measured using the axis-translation technique were 80 and 95 kPa respectively (Power et al. 2007). The difference in matric suction values for wet of optimum specimens is close to 15%. These differences may be associated to the influence of occluded water bubbles in the specimens compacted at wet of optimum conditions.

In spite of initial resistance to the applied stress offered by the matric suction for the unsaturated specimens prepared using low compaction energy and water content equal to 17%, its influence is negligible for specimens prepared using the high compaction energy. The degree of saturation of the unsaturated specimens prepared with water contents greater than 16% quickly approach 100% as the applied stress is increased. This means that the matric suction value is tending towards zero, if not zero, and therefore cannot offer the same resistance as with specimens initially prepared with lower water contents (see Table 2).

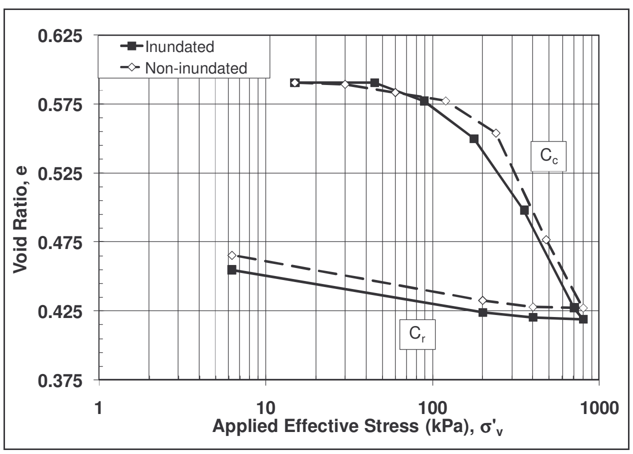

Figure 6: Comparison of *e-log*σ_v' graphs for inundated and non-inundated specimens prepared using low compaction energy with an initial compaction water content equal to 17%.

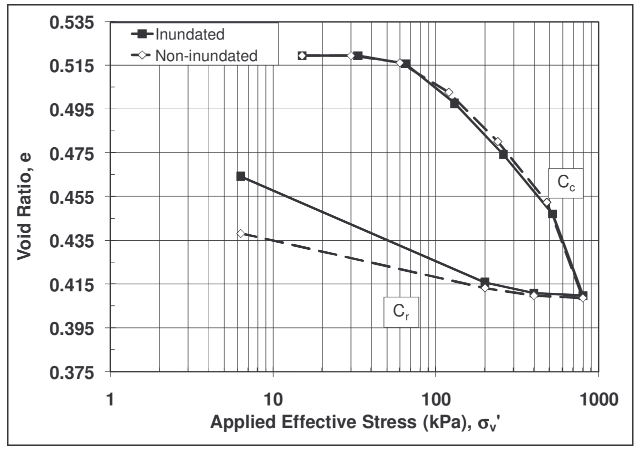

Figure 7: Comparison of *e-log*σ_v' relationship for inundated and non-inundated specimens prepared using high compaction energy with an initial compaction water content equal to 17%.

5 INFLUENCE OF INITIAL MATRIC SUCTION ON THE COMPRESSION INDEX, C_C

Figure 8 illustrates the relationship between the compression index, C_c and initial compaction water content, w for both inundated and non-inundated test specimens compacted using low and high compaction energies. For non-inundated specimens prepared using the low compaction energy, and initial water content (i.e. w < 16%) the effect of structure is clearly evident. For these specimens, as mentioned earlier, an open structure is achieved that would offer less resistance upon saturation and increased loading, leading to a relatively higher compression index, C_c than their inundated counterpart specimens. Prior to reaching the virgin compression portion of the *e vs.* σ_v' curve, these specimens would offer more resistance to deformation due to the influence of matric suction, (u_a - u_w). This behaviour can also be explained in terms of the saturated coefficient of permeability. The saturated coefficient of permeability will be relatively high in specimens with open structure which contributes to higher rate deformation (i.e., change in void ratio, *e*) as shown in Figure 4 and Figure 7.

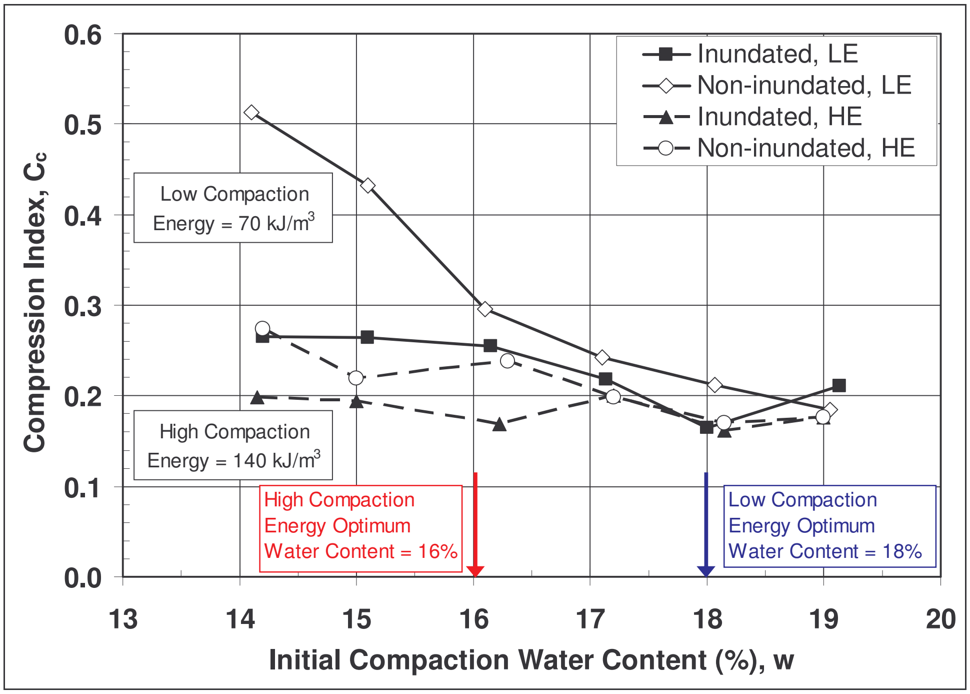

Figure 8: Compression index vs. initial soil water content for specimens prepared using both low and high compaction energies.

Figure 8 shows that the difference in the value of the compression index, C_c between the inundated and non-inundated test specimens, prepared using the high compaction energy reduces to a value approximately equal to 0.2 regardless of the initial compaction water content for specimens prepared on the wet side of optimum water content conditions. For these specimens the effect of structure is less pronounced than those prepared using low compaction energy and water content between 14 and 17%.

6 SUMMARY AND CONCLUSIONS

Several parameters which include initial compaction water content, soil structure, compaction energy, and the degree of saturation influence the compressibility characteristics of fine-grained compacted unsaturated soil specimens. It is the interplay of all these parameters that affects the deformation behaviour of the soil due to an applied stress. The matric suction, $(u_a - u_w)$ can be used as a key parameter in explaining the composite influence of all the parameters.

The effect of initial compaction energy on the compressibility characteristics of the glacial till investigated in this paper is mainly observed when the energy used for compaction is relatively large. The effect of soil structure is clearly evident in specimens prepared using low compaction energy and low initial water contents (i.e., dry of optimum conditions). These specimens have a higher void ratio and undergo large compression even under relatively low applied stresses. The effect of soil structure on the compressibility characteristics diminishes in the high stress range.

The influence of matric suction on the compressibility characteristics of the unsaturated specimens investigated in this paper is significantly reduced for specimens prepared with initial water contents greater than 16% as their initial degree of saturation, S is relatively high and tends towards 100% quickly with an increase in the applied stress. Such a behaviour can be attributed to the dispersed structure imparted to these specimens and low matric suction values achieved at wet of optimum water content conditions. The limited contribution from matric suction reduces as the degree of saturation increases with an increase in applied stress. This behaviour can be observed from the results shown in Figures 6 and 7. There is little difference between the e vs. σ_v' curves for both the inundated and non-inundated conditions.

In engineering practice the compressibility index, C_c is used to calculate settlement assuming that the soil is in a saturated state. However, using the saturated compressibility index in estimating settlements of an unsaturated soil will lead to erroneous results. The methods and equipment presented in this paper allow for the determination of an unsaturated compressibility index using simple modifications to the conventional oedometer testing equipment. Reliable estimates of the compressibility index, C_c for unsaturated soils will lead to more precise estimates of settlements for engineering practice applications.

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