A LABORATORY TECHNIQUE FOR ESTIMATING THE RESILIENT MODULUS OF UNSATURATED SOIL SPECIMENS FROM CBR AND UNCONFINED COMPRESSION TESTS

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ABSTRACT: In the research study presented in this paper, a modified test procedure is proposed to interpret the California Bearing Ratio (CBR) test results taking into account the influence of unsaturated conditions in terms of degree of saturation. Specimens compacted in the CBR mold at nearly saturated conditions were allowed to dry for varying time periods in order to achieve different values of degree of saturation (i.e., unsaturated conditions). Unconfined compression strengths (UCS) were also determined on specimens that were prepared in a similar manner as the CBR test specimens. The unconfined compression tests were chosen in this study because it is a quicker and simpler test to perform in comparison to the CBR tests. The focus of the present study was to understand the influence of degree of saturation on the CBR values and the unconfined compressive strength behaviour and propose a simple laboratory testing technique to estimate the resilient modulus (Mr) from these tests.

RÉSUMÉ: Dans l'étude de recherche présentée dans ce papier, un Test de Direction de Californie modifié (CBR) le test est proposé d'interpréter les résultats tenant compte de l'influence du degré de saturation. Compacts de spécimens dans CBR mold aux conditions presque saturées a été permis de sécher pour varier de périodes dans l'ordre pour atteindre des valeurs différentes de degrés de saturation (c.-à-d., les conditions d'unsaturated). Les forces de compression de Unconfined ont été aussi déterminées sur les spécimens qui ont été préparés dans une façon similaire comme les spécimens de CBR. Les tests de compression de unconfined ont été choisis dans cette étude parce que c'est un test plus rapide et plus simple pour exécuter. Le focus de l'étude actuelle était de comprendre l'influence de degré de saturation sur les valeurs de CBR et le unconfined le comportement de force compressif et propose une technique simple pour estimer le modulus élastique des tests de compression de unconfined.

1. INTRODUCTION

Pavements are typically constructed using compacted soils that are in a state of unsaturated condition (with degrees of saturation between 75 to 90% and negative pore-water pressures in the order of many atmospheres). The negative pore-water pressure, or matric suction, \((u_a - u_p)\) is defined as the difference between the \(u_a\), the pore-air pressure, and \(u_p\), the pore-water pressure. The matric suction of a soil varies considerably and thus has a significant effect on the strength of the pavement. Several design and maintenance measures are usually undertaken to maintain unsaturated conditions of the pavement to achieve favourable engineering properties of soil (i.e., an appropriate coefficient of permeability and high shear strength). However, the conventional procedures for pavement design are often an oversimplification of in-situ conditions and are based on empirical procedures that do not take into consideration the principles of unsaturated soil mechanics. Limited numbers of studies are available in the literature for the design of pavements extending the principles of unsaturated soil mechanics.

Three procedures are commonly used by the department of transportation agencies in Canada and the U.S.A. towards the design of pavements. The first procedure is based on test results of the California Bearing Ratio Tests (CBR Test). In this test procedure, a compacted, soaked soil specimen is loaded at a constant rate until a defined deformation is reached. This test provides an indirect measure of the shear strength of a soil, which is used in the design of pavements. Some investigators have reservations in using the CBR test procedure, as it does not properly simulate the shearing forces imposed on sub-soils that underlie a pavement structure (Garber and Hoel, 1997). The second procedure is based on the resistance test or R-Value test, which was first formulated in 1930’s and used to determine the stability of field and laboratory samples of bituminous pavements. Later, it was modified to determine the resistance of sub-grade materials and used in the design of pavements. More recently, pavement design procedures have been based on the third method, which is a mechanistic-empirical design method using resilient modulus \((M_r)\) values (Chadbourn et al. 2002). The resilient modulus value is determined through the cyclic triaxial loading while measuring the recoverable axial strain. The resilient modulus value is widely accepted as the mechanistic property of a pavement’s sub-soil under vertical loading conditions (Barksdale et al. 1997). It is based on a realistic interpretation as pavements are loaded in a cyclic manner. However, the determination of resilient modulus values is expensive, time consuming and requires extensive laboratory facilities.
In the above design procedures, the thicknesses of the various layers of a pavement structure are determined based on traffic volumes, loads, and material characterization test results. The influence of matric suction is not considered in all the above three methods in the design of pavements. This is one of the key limitations, as matric suction has a significant influence on the engineering behavioural characteristics of pavements; related to the volume change, the coefficient of permeability and shear strength of pavements. A rational approach pavement design should be based on the principles of unsaturated soil methods.

This paper presents a methodology for understanding the influence of unsaturated conditions (in terms of degree of saturation) on a compacted soil that is used as a sub-grade material using a modified CBR test. Specimens compacted in CBR molds at nearly saturated conditions were allowed to dry for varying time periods in order to achieve different values of degrees of saturation (i.e., unsaturated conditions). Unconfined compression strengths (UCS) were also determined on specimens that were prepared in a similar manner as the CBR test specimens. The unconfined compression tests were chosen in this study because it is a quicker and simpler test to perform. The focus of the study presented in the paper was to understand the relationship between the modified CBR and the unconfined compressive strength (UCS) behaviour and propose a simple technique to indirectly estimate resilient modulus ($M_r$) values from these tests. The results of the research study presented in this paper are promising and encouraging as they promote simplistic methods of laboratory testing that can be used in the design of pavements using the principles of unsaturated soil mechanics.

A more widely used recent test method on which pavement designs are based is the resilient modulus, $M_r$ value. The resilient modulus is defined as the ratio between repeated deviator stress, $(\sigma_1 - \sigma_3)$ and resilient strain, $\varepsilon_a$ and can be calculated using Eq.[1]

$$M_r = \frac{(\sigma_1 - \sigma_3)}{\varepsilon_a} \quad [1]$$

where:

$(\sigma_1 - \sigma_3)$ is the maximum repeated axial stress and;


\( e_{la} \) is the maximum recoverable resilient axial strain

The laboratory testing procedures for determining the resilient modulus \( (M_r) \) values is time consuming and needs expensive equipment and highly trained personnel (AASHTO T292-91).

The design of pavements can also be based on index properties of the soil. Testing of index properties is relatively simple and inexpensive. Correlation of the index properties of a soil to more mechanistic property such as resilient modulus has the potential to provide a reasonable and cost effective means of pavement design (Zeghal, 2001).

2.2 Bearing Capacity Design and Unsaturated Soils

An alternate method of pavement design can be based on extending bearing capacity theory using principles of unsaturated soil mechanics. The bearing capacity of roadway systems depends on the strength of the soils beneath the surface layer. The required soil properties for determining the bearing capacity include the saturated shear strength parameters \( (c', \phi) \) and frictional angle indicating the rate of increase in shear strength with respect to matric suction, \( (\phi^b) \).

Two modes of failure are considered in the bearing capacity design approach for roadway systems. The first failure criteria are based on the limit equilibrium method. This method assumes that the base layer acts as an elastic material to distribute load to the sub-grade (Broms, 1963, 1964; Bender and Barenburg, 1978; Giroud and Noiray, 1981; Milligan et. al. 1989; Sattler et al. 1989; Szafron, 1991). Complex factors such as pore water pressure and soil layering can be modelled in a simpler form using this method (Fredlund et al. 1997). The second mode of failure is based on extending the general shear failure criteria for all the pavement layers (McLeod, 1953). This method is realistic; however, it involves a complex and tedious series of calculations. Also, incorporation of matric suction and pore water pressures into this failure mode criteria is difficult and complex (Fredlund et al. 1997). Due to these reasons, it is not the preferred method of determining the bearing capacity of a layered soil system

Design loads in bearing capacity design are estimated using the Equivalent Single Wheel Load (ESWL). The load calculation procedure is similar to the ESAL estimation as per AASHTO’s Guide for the Design of Pavement Structures. The basis of the ESWL is the pressure a tire places on a roadway system over an assumed rectangular area. Portland Cement Association (PCA, 1984) assists in the calculation of these design loads.

The estimation of the bearing capacity of a layered system is determined by the following equation:

\[
q_n = c'_{1}N_c + \frac{1}{2}B\gamma_{r}N_{\gamma}
\]  

where:

- \( q_n \) is the bearing capacity of a pavement system;
- \( c'_{1} \) is the cohesion of the top soil layer;
- \( B \) is the width of the foundation;
- \( \gamma_{r} \) is the unit weight of the top soil layer;
- \( N_c \) is the cohesion bearing capacity factor and;
- \( N_{\gamma} \) is the surcharge bearing capacity factor.

The cohesion value is modified to determine the contribution of matric suction in the bearing capacity equation. Fredlund et al. 1997 suggested the use of the following equations to incorporate the influence of matric suction into a two layered soil system as modified cohesion values.

\[
c_1 = c_1' + (u_a - u_w)_{1}\tan\phi^b
\]

\[
c_2 = c_2' + (u_a - u_w)_{2}\tan\phi^b
\]

where:

- \( c_1' \) is the total cohesion of the base layer;
- \( c_1 \) is the effective cohesion of the base layer;
- \( c_2' \) is the total cohesion of the sub-base layer;
- \( c_2 \) is the effective cohesion of the sub-base layer;
- \( (u_a - u_w)_{1} \) is the matric suction in the base layer;
- \( (u_a - u_w)_{2} \) is the matric suction in the sub-base layer;
- \( \tan\phi^b \) is the friction angle related with the matric suction in the base layer and;
- \( \tan\phi_{b}^b \) is the internal friction angle related with the matric suction in the sub-base.

The ultimate bearing capacity of a pavement structure, including the effects of matric suction, can be calculated using the following equation (Fredlund, Ollo and Gan, 1997):

\[
q_n = c'_{1}N_c + \frac{1}{2}B\gamma_{r}N_{\gamma}
\]

where:

- \( B_{e} \) is the equivalent contact width

2.3 Pavement Design Using the Principles of Unsaturated Soil Mechanics

Some studies were undertaken extending the principles of unsaturated soil mechanics to better understand engineering behaviour of pavements (Edil et al. 1979, Barbour et al. 1992, Lytton et al. Fredlund et al. 1997). The moisture distribution that occurs beneath pavements has been the research focus of several investigators (Birgisson and Roberson 1999, Roberson and Siekmeier, 2002). Saturated-unsaturated flow modelling techniques were used to provide a more detailed insight of moisture distribution in soil layers (Wallace, 1977, Lytton et al. 1990 and Barbour et al. 1992). The saturated coefficient of permeability and the soil-water characteristic curve
were used to predict the moisture distribution in soil layers.

Several other modelling studies were undertaken to determine matric suction variation under a pavement structure or soil layers based on moisture distributions (Richards and Chan 1971, Lytton et al. 1990, Wilson, 1990 and Joshi, 1993). More recently, Alonso et al. 2002 studies have shown the moisture transfer in pavement structures control the mechanical performance of its base, sub-base, and sub-grade layers.

Richards and Peter (1987) investigations show that resilient modulus values depend on suction values along with several other properties. Lytton (1996) suggested an empirical equation for estimating the resilient modulus for a dry granular soil:

\[ E = k_1 p_a \left( \frac{I_1}{p_a} \right)^{k_2} \left( \frac{\tau_{oct}}{p_a} \right)^{k_3} \]  \[ \text{[6]} \]

where:

- \( I_1 \) is the sum of all principal mechanical stresses;
- \( \tau_{oct} \) is the octahedral shear stress;
- \( p_a \) is the atmospheric pressure in the same units as the resilient modulus and;
- \( k_1, k_2, k_3 \) are material properties of the dry granular soil.

When the soil is in a state of unsaturated condition, the effect of soil suction is incorporated into Eq. [6]. Equation [6] takes the form as given below after inclusion of suction parameter:

\[ E = k_1 p_a \left( \frac{I_1 - 3\theta h_m}{p_a} \right)^{k_2} \left( \frac{\tau_{oct}}{p_a} \right)^{k_3} \]  \[ \text{[7]} \]

where:

- \( \theta h_m \) is the lower bound term from Lamborn’s theory and;
- \( f \) is the function of volumetric water content.

3. UNCONFINED COMPRESSION TESTING OF UNSATURATED SOILS

The native or borrowed soil is compacted to form the sub-grade of the pavement. The compacted soil is typically in a state of unsaturated condition. The soil has a negative pore-water pressure, \( u_w \), and the pore-air pressure, \( u_a \), is typically equal to atmospheric pressure conditions. In other words, the matric suction, \( (u_a - u_w) \), is equal to the negative pore-water pressure. The shear strength of unsaturated soils can be interpreted using unconfined compression test results extending shear strength equation for unsaturated soils proposed by Fredlund et al. 1978 (Vanapalli et al. 1999).

The pore-air and the pore-water pressures are not measured in a conventional unconfined compression test during the shearing stage. The shear strength of the soil can be interpreted in terms of initial matric suction values (Vanapalli et al. 1999). The matric suction of the soil specimen can decrease, increase, or remain relatively constant during the shearing stage of the specimen. However, matric suction is likely to decrease in field compacted soils as the pore-air pressure, \( u_a \), slightly increases due to compression without significant changes in the pore-water pressures. In other words, the matric suction in soil specimens at failure conditions in the unconfined compression tests will be slightly less than the initial matric suction. Due to this reason, it is quite probable that the determined shear strength will be a conservative value from the unconfined compression test results.

Kawai et al. 2002 described the relationship between matric suction and the unconfined compressive strength of a dynamically compacted specimen by the following relationship:

\[ q_u = 8.09 (u_a - u_w) \]  \[ \text{[8]} \]

where:

- \( q_u \) is the unconfined compression strength and;
- \( (u_a - u_w) \) is the suction strength at failure.

4. TEST PROGRAM

The test program was undertaken on a soil that has been used as a sub-grade material by the Minnesota Department of Transportation at a full-scale pavement test facility located adjacent to Interstate 94 in Otsego, Wright County, Minnesota, U.S.A.

Figure 2 shows the grain size analysis data of two representative soil samples collected from the test site. The soil can be described as silty sand (SM) according to the Unified Soil Classification System (USCS). The soil consists of about 50% coarse particles (i.e., sand) and 50% fines (i.e., silt and clay). The specific gravity of the soil was equal to 2.7. The optimum water content and dry unit weight of the soil from modified Proctor’s test were determined to be 13% and 18.6 kN/m\(^3\) respectively.

The CBR test was conducted in the laboratory on this soil using conventional ASTM standard test method (ASTM D 1883-1999). The initial water content density and values’ were chosen such that the specimens prepared for CBR tests were initially in a state of saturated condition. The water content and dry density used to achieve this initial condition were 16% and 18.6 kN/m\(^3\) respectively. This procedure deviates from the conventional CBR testing procedure in which the tests are conducted only at optimum moisture content.
The compacted samples in the CBR molds were subjected to drying beneath two 40-watt light bulbs for varying time increments in order to achieve different degrees of saturation. Discolouration and some shrinkage cracks were observed in a few specimens after drying when the drying for time periods greater than 12 hours. The CBR molds were then wrapped in plastic and placed in a moisture-controlled room for a period of a week in order to achieve equilibrium moisture content conditions in the sample. Soil samples were collected at three different heights after drying from the CBR mold in companion specimens to determine the degrees of saturation from mass-volume properties. The sample preparation procedures described here facilitated the preparation and testing of CBR samples to understand the influence of unsaturated conditions in terms of degree of saturation on the CBR values.

The soil specimens of 33 mm diameter and 70 mm height were prepared to determine the unconfined compressive strength of the soils using the procedure proposed by Subbarao (1972). In this procedure, a soil specimen in a Harvard mini-mold was subjected to a defined constant load for a defined time period. More details of sample preparation procedure are available in Fry (1977). This procedure was useful to achieve compaction energies in the Harvard mini-mold similar to those applied in the CBR mold during compaction. After compaction, samples were extruded from the mini-Harvard molds. The specimens were then wrapped in a moisture control room for a period of 24 to 48 hours in order to achieve uniform moisture content conditions in the specimens.

The prepared soil specimens were placed in the unconfined compression apparatus after examination to make sure no visible cracks or defects were seen. The soil specimens were then manually, axially loaded at a strain rate of 1.2 mm/min until failure load was observed. Loads were recorded regularly at 0.5 mm intervals of soil compression. Sudden and violent failure was observed in certain cases in soil specimens with low degrees of saturation.
5. INTERPRETATION OF TEST RESULTS

Figure 3 shows the variation of axial stress with respect to axial strain from unconfined compression tests. The results show a regular trend of increase in shear strength of the soil specimens with a decrease in the degree of saturation. The reduction in the degree of saturation is associated with an increase in matric suction values. Similar to earlier studies by other investigators, the experimental data suggests there is a nonlinear increase in the shear strength from the tests (Gan et al. 1988; Vanapalli et al. 1996).

However, some scatter was observed, particularly in the soil specimens with low degrees of saturation (i.e., high suction). Vanapalli et al. (2000) reported similar observations from unconfined compression test results undertaken on a silty soil for the entire suction range (i.e., 0 to 1,000,000 kPa). The scatter at lower degrees of saturation can be attributed to large changes in suction values even with small changes in water content values of the soil specimens. No scatter was observed in the results in specimens with higher degrees of saturation (i.e., 55 to 100%).

Figures 4 and 5 show the variation of normalized CBR and unconfined compressive strength (UCS) values with respect to the degree of saturation values respectively. The normalized CBR value is defined as the ratio of the CBR value at saturated conditions to CBR values at unsaturated conditions. Similarly, normalized UCS value is the ratio of unconfined compression strength at saturated conditions to unconfined compression values at unsaturated conditions. The degree of saturation was determined from three sets of data of soil specimens taken along the length of CBR and unconfined compression specimens. The variation in degree of saturation of these specimens taken along the length at three different heights was less than ±2% for unconfined compression test specimens. However, the variation in degree of saturation along the length of the CBR specimen was higher than 2% and in certain cases was around 4%.

The normalized CBR values decreased with a decrease in the degree of saturation. However, the trend is rather weak for CBR specimens (Figure 4) in comparison to trends unconfined compression test results (Figure 5). A best-fit curve is drawn through the data in both figures (Figures 4 and 5).

There are several possible reasons for the scatter observed in test results shown in Figure 4. Some shrinkage was observed in the compacted soil specimen within the CBR molds particularly for specimens at low degrees of saturation. This shrinkage resulted in a few millimetres gap that was extending approximately 1 to 3 mm length along a part of the CBR mold perimeter. Due to this reason, there was a reduction in the lateral confining pressure at certain portions particularly at the top of the specimen in the CBR mold during the loading. Also, the scatter in degree of saturation values within the CBR mold along the length of the specimen was higher. The scatter in the degree of saturation values may be attributed to the larger size of CBR specimen and faster rate of drying to achieve lower degrees of saturation. It is also likely the time period used for achieving equilibration water content (or degree of saturation) by placing the dried specimen in moisture control room for one week may not be sufficient due to the large size of the specimen.

The time period of placing the unconfined compression test specimens for 24 to 48 hours after drying has resulted in less scatter in the degree of saturation values along the length of the specimens. This could be attributed to smaller size of the specimen.
The data shown in Figures 4 and 5 respectively are plotted in Figure 6 as the variation of relative CBR and unconfined compressive strength (UCS) values for comparison purposes. The theoretical saturated value obtained from interpolation of the data was utilized to calculate relative values for each set of results. The relative values were determined by dividing the unsaturated values with the theoretical saturated value (Figure 6). It is of interest to note that the CBR and unconfined compression strength (UCS) test results follow a unique trend line.

Relationships have been developed earlier in the literature to indirectly estimate the resilient modulus ($M_r$) from CBR tests and R-values as shown below:

$$M_r (MPa) = 10.342 \times CBR \quad [8.1]$$

$$M_r (MPa) = 8.0 + 3.8 R \quad [8.2]$$

Relationships similar to Equations 8.1 and 8.2 can be developed from simple and unconfined compression strength test results using the principles of unsaturated soil mechanics. Investigations are in progress to propose such relationships.

6. CONCLUSIONS

Pavement design procedures are commonly based on CBR tests, R-values or resilient modulus ($M_r$) values. More recently, the use of $M_r$ values is widely accepted in the design of pavements. However, determination of $M_r$ values is time consuming and requires extensive testing procedures. Due to this reason, this is an expensive technique.

The influence of one of key parameters, soil suction, is not taken into consideration in the determination of $M_r$ values. In this paper, a modified test procedure is proposed to interpret the California Bearing Ratio (CBR) test results taking into account the influence of unsaturated conditions in terms of degree of saturation. Along similar lines, unconfined compression strengths were also determined on unsaturated soil specimens. The test results show similar trends of CBR tests and unconfined compression test results. These results are encouraging as they not only provide a valid framework to understand the influence of soil suction on the engineering behaviour of pavements; but also are helpful to develop simple relationships to estimate $M_r$ values from conventional unconfined compression tests.

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8. REFERENCES


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