Influence of stress history on the strength parameters of an unsaturated statically compacted soil

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Abstract: Unsaturated soils are generally near the ground surface and are commonly overconsolidated due to environmental effects. The stress state variables for an unsaturated, in situ profile consist of the net total stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$, where σ is the total stress (in three directions), u_a is the pore-air pressure, and u_w is the pore-water pressure. These stress state variables control the behavior of the unsaturated soil. A total stress ratio, TSR, was used in this study as a measure of the stress history. The total stress ratio is defined as the ratio of the compaction pressure to the current confining pressure. Shear tests were conducted using a modified direct shear apparatus on a statically compacted unsaturated soil subjected to various total stress ratios with controlled matric suction. The shear strength parameters (i.e., ϕ', ϕ^b, and c') for an unsaturated soil were measured using the modified direct shear apparatus. The total stress ratio influences the shear strength parameter ϕ^b of a compacted soil. The shear strength parameter ϕ^b decreases with matric suction regardless of the loading history. For a compacted soil with a total stress ratio of 1.0, ϕ^b was higher than that for the soil tested at a total stress ratio greater than 1.0, regardless of increase in matric suction, and was shown to be influenced by loading history.

Key words: unsaturated soil, shear strength, stress history, compacted soil, direct shear test, matric suction.

Résumé : Les sols non saturés se situent généralement près de la surface du terrain et sont communément surconsolidés à cause des effets environnementaux. Les variables de l'état des contraintes pour un profil non saturé in situ consiste en une contrainte totale nette, $(\sigma - u_a)$, et une succion matricielle, $(u_a - u_w)$, où σ est la contrainte totale (en trois dimensions), u_a la pression d'air dans les pores, et u_w la pression interstitielle. Ces variables de l'état des contraintes contrôlent le comportement du sol saturé. Un rapport de contraintes totales, TSR, a été utilisé dans cette étude comme une mesure de l'histoire des contraintes. Le rapport des contraintes totales est défini comme un rapport de la pression de compactage sur la pression de confinement. Des essais de cisaillement ont été réalisés au moyen d'un appareil de cisaillement direct sur un sol non saturé compacté de façon statique et soumis à divers rapports de contraintes totales en contrôlant la succion matricielle. Les paramètres de résistance au cisaillement (i.e., ϕ', ϕ^b, et c') pour un sol non saturé ont été mesurés au moyen de l'appareil de cisaillement direct modifié. Le rapport de contraintes totales influence le paramètre de résistance au cisaillement ϕ^b d'un sol compacté. Le paramètre de résistance au cisaillement ϕ^b décroît avec la succion matricielle indépendamment de l'histoire des contraintes. Le paramètre de résistance au cisaillement ϕ^b pour un sol compacté avec un rapport de contraintes totales de 1.0 était plus élevé que celui du sol testé sous un rapport de contraintes totales plus grand que 1.0, indépendamment de l'accroissement de la succion matricielle. Le paramètre de résistance au cisaillement ϕ^b s'est révélé être influencé par l'histoire des contraintes.

Mots clés : sol non saturé, résistance au cisaillement, histoire des contraintes, sol compacté, essai de cisaillement direct, succion matricielle.

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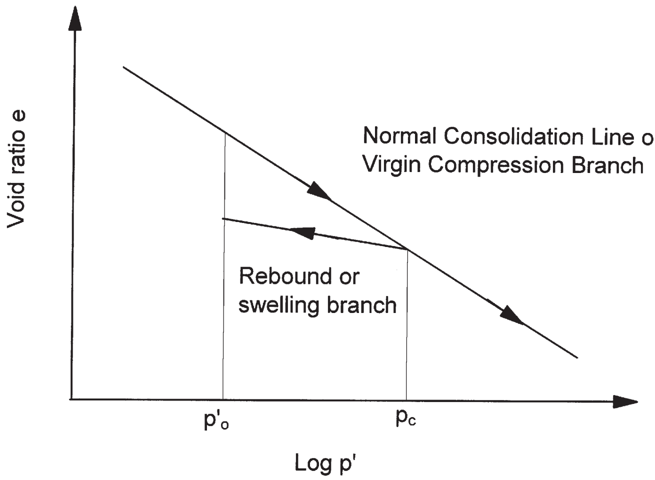
Fig. 1. The relationship between effective stress p' and void ratio e for a saturated soil.



Introduction

In situ soils commonly have a stress history that renders the soil anisotropic. The total vertical stress at a particular depth is due primarily to the weight of the overlying soil. A change in vertical stress can occur over time as a result of geological deposition, erosion, and man-made construction. A change in the climatic environment changes the matric suction and results in a continuously changing stress state, or stress history, in the soil. Stress history is not only of relevance to natural soils but is also of interest to artificially compacted soils.

The prediction of volume change and the evaluation of shear strength require information on the present in situ stress state in a soil mass and possible future changes to the stress state. The stress history of a soil is commonly determined using laboratory tests, generally a one-dimensional oedometer test. The oedometer test is used to translate the in situ overburden pressure and the matric suction stress onto the net total stress plane.

In situ, unsaturated soils with negative pore-water pressures have generally been subjected to repeated climatic environmental changes and the soil takes on the character of being overconsolidated (Brooker and Ireland 1965). Compacted embankments are also unsaturated soils with negative pore-water pressures. The matric suction in a soil (i.e., $(u_a–u_w)$, where u_a is the pore-air pressure and u_w is the pore-water pressure) changes in response to imposed environmental changes (i.e., drying and wetting). The matric suction in a soil profile can vary widely, whereas the net total stress state remains entirely constant. The matric suction in the soil increases during dry seasons and decreases during wet seasons.

Measures of stress history

The overconsolidation ratio, OCR, has been used in geotechnical engineering as an expression of stress history for saturated soils (Fig. 1). The vertical stress versus void ratio relationship for a saturated soil is approximately linear on a logarithmic stress scale when the soil is normally consolidated (i.e., virgin compression line). The state of the unloaded soil can be anywhere below and to the left of the virgin compression line produced by the initial loading. The stress state cannot reach the region above and to the right of the virgin compression line. Any stress state inside the boundary surface gives rise to an overconsolidated soil and the overconsolidation ratio for a saturated soil is given by the following equation:

$$[1] \qquad \mathrm{OCR} = \frac{p_c}{p_0'}$$

where
OCR is the overconsolidation ratio for a saturated soil;
p_0' is the current overburden effective stress; and
p_c is the preconsolidation pressure.

The preconsolidation pressure, p_c, can be approximated as the stress at the intersection of the swelling (or recompression) line and the virgin compression line defined by one-dimensional loading.

An overconsolidation ratio for unsaturated, compacted soils and unsaturated natural soils has not been clearly established. One definition has been suggested by Fredlund and Rahardjo (1993) wherein the present in situ state of stress in an unsaturated soil is translated onto the total stress plane and is called the swelling pressure. The swelling pressure should be “corrected” for sampling disturbance using a modified Casagrande type of construction (Fredlund et al. 1980; Fredlund 1983). Fredlund and Rahardjo (1993) suggested that the overconsolidation ratio, OCR, of an unsaturated and (or) swelling soil be defined as follows:

$$[2] \qquad \mathrm{OCR} = \frac{p_c}{p_s'}$$

where p_s' is the corrected swelling pressure.

The in situ matric suction, translated onto the total stress plane, is called the matric suction equivalent (Yoshida et al. 1983). The matric suction equivalent combined with the overburden stress constitute the swelling pressure of the soil. The preconsolidation pressure, p_c, refers to the maximum applied stress to which the soil has come to equilibrium in its history. The magnitude of the matric suction equivalent will be equal to or lower than the in situ matric suction. The difference between the in situ matric suction and the matric suction equivalent is primarily a function of the degree of saturation of the soil (Fredlund and Rahardjo 1993).

There is need for a more in-depth study of procedures that can be used to define the overconsolidation ratio of compacted soils and unsaturated natural soils. A rigorous procedure should take into consideration the independent effects of confining pressure and matric suction.

In this study, a total stress ratio, TSR, is defined to represent the loading history of a compacted soil:

$$[3] \qquad \mathrm{TSR} = \frac{p_{\mathrm{comp}}}{(\sigma_v - u_a)}$$

where
$(\sigma_v - u_a)$ is the current confining pressure;
p_{comp} is the static compaction pressure; and
σ_v is the total stress.

Table 1. Physical properties of the soil for the test programs.

Specific gravity	2.65
Plasticity index	Nonplastic
Maximum particle size	0.1 mm
Sand (%)	0
Silt (%)	92
Clay (%)	8

The total stress ratio is written in terms of the applied total stresses, and no attempt is made to represent the pore-water pressures. Even if the pore-water pressure were known during the compaction process and during the testing process, it is not clear how an overconsolidation ratio can be defined when there are two independent stress state variables. For this study, the total stress ratio and the matric suction will be used independently when interpreting the test results. When the compaction pressure is equal to the current net vertical confining pressure, the total stress ratio is one. The total stress ratio simply provides a ratio of the total vertical stresses applied to the soil since it was remolded.

Purpose of this study

This study focuses on the relationship between the loading history of an unsaturated, compacted soil and its shear strength. The loading history of the compacted soil is represented using the compaction pressure, the vertical pressure, and the matric suction. Shear tests on a compacted soil were conducted using a modified direct shear apparatus. The total stress ratio and the matric suction are used in the interpretation of both the shear stress versus horizontal displacement curve and the vertical displacement versus horizontal displacement curve, obtained from the direct shear tests. The influence of loading history on the shear strength parameters (i.e., the effective angle of internal friction with respect to confining pressure ϕ', the angle of internal friction with respect to matric suction ϕ^b, and the effective cohesion intercept c') for a compacted soil is presented and discussed.

Testing program

The testing program is divided into two parts. Test program 1 focuses on defining the shear strength of compacted specimens when the total stress ratio is 1, and test program 2 focuses on defining the shear strength of compacted specimens when various total stress ratios are used.

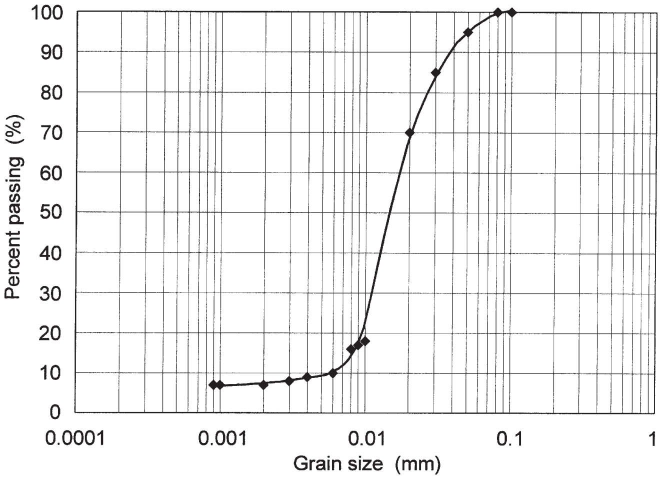
Description of the soil

The physical properties of the silty soil used in this study are shown in Table 1. The soil is a nonplastic silt with a grain-size distribution curve as shown in Fig. 2. The silty soil has a relatively uniform grain-size distribution with a median grain size D_{50} of approximately 0.02 mm. The compacted soil specimens used in the study had a diameter of 60 mm and a height of 51.3 mm. All soil specimens were prepared at an initial water content of 13%.

Testing equipment

The general features of the direct shear apparatus used in the testing program are shown in Fig. 3. The apparatus is similar in design to those used by Escario (1980), Gan and Fredlund (1988), and Campos and Carrillo (1995). However, the soil specimens in this study were circular in shape.

Fig. 2. Grain-size distribution curve for the soil used in the testing programs.



The cylindrical chamber was constructed of acrylic. The direct shear box was completely enclosed in a pressure chamber to elevate the ambient air pressure during the test. The shear box was built of stainless steel and divided into an upper shear box and a lower shear box.

An innovative adaption to the direct shear apparatus involved the use of five thin ring spacers that were placed between the upper shear box and the lower shear box. It was found that the use of the five thin spacers reduced the friction associated with the relative displacement of the shear box. The soil specimen in the shear box was enclosed with a rubber membrane. The tension in the membrane due to the shear displacement of the box was insignificant.

Shearing forces were induced by displacing the lower portion of the shear box and were measured using a load cell installed on the lateral surface of the upper portion of the shear box.

The independent control of both the pore-air pressure and the pore-water pressure required the use of a high air-entry ceramic disk for the water phase and a coarse disk for the air phase. The air-entry value of the ceramic disk on the bottom portion of the shear box was 500 kPa. The ceramic disk was 5 mm in thickness and was epoxyed in place, around its perimeter.

Test procedures

The test program involved a study of the relationship between loading history and the shear strength of a compacted soil. A one-dimensional, static compaction stress was applied to prepare the soil specimens at a constant water content. The soil was compacted into the direct shear ring. Pore-air pressure, pore-water pressure, and normal stress were applied to the soil specimens for a period of 24 h to allow sufficient time for the applied stresses to reach equilibrium. Each specimen, therefore, had a constant net vertical stress and a constant matric suction throughout the test. The pore-air pressure was applied to the upper surface of the soil specimen. The pore-water pressure was maintained at atmo-

Fig. 3. The modified direct shear apparatus used for the testing program.

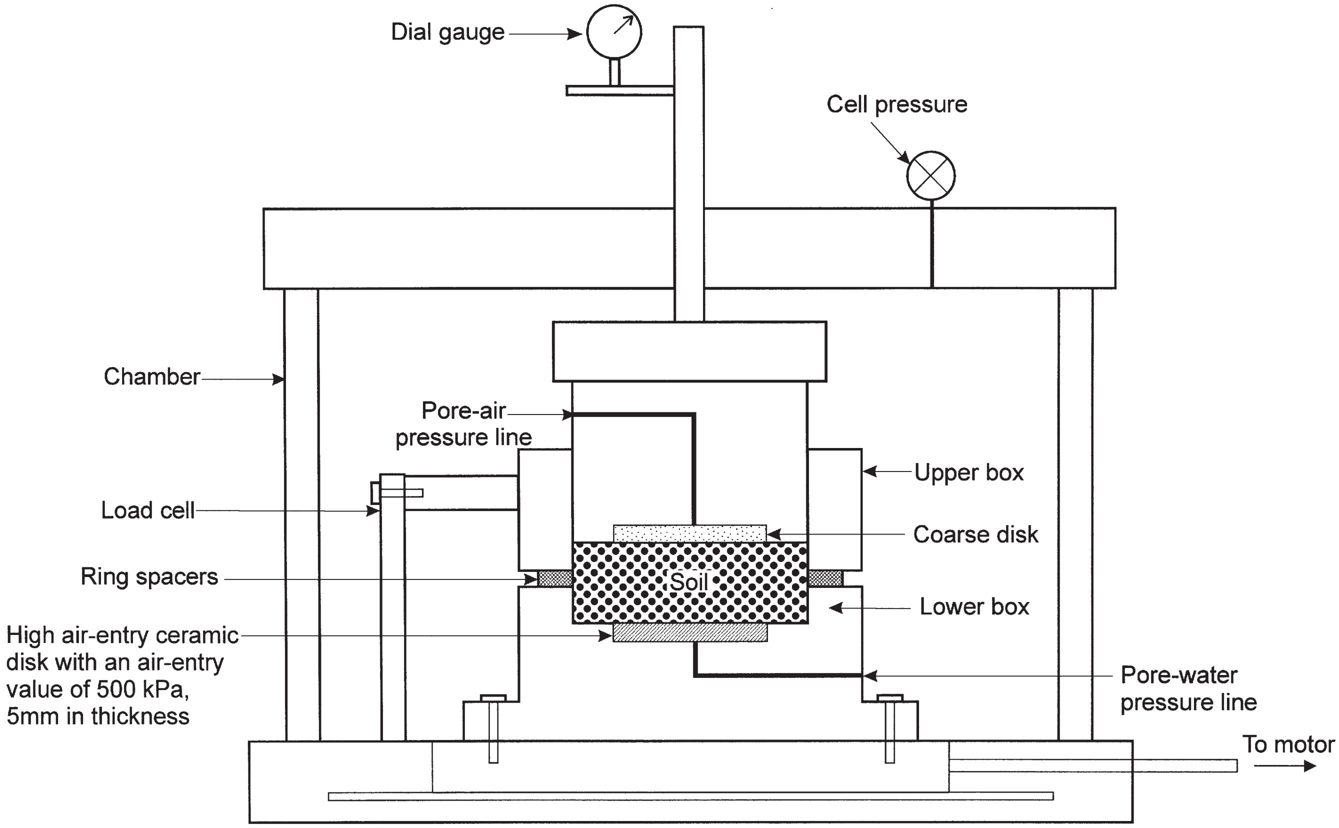
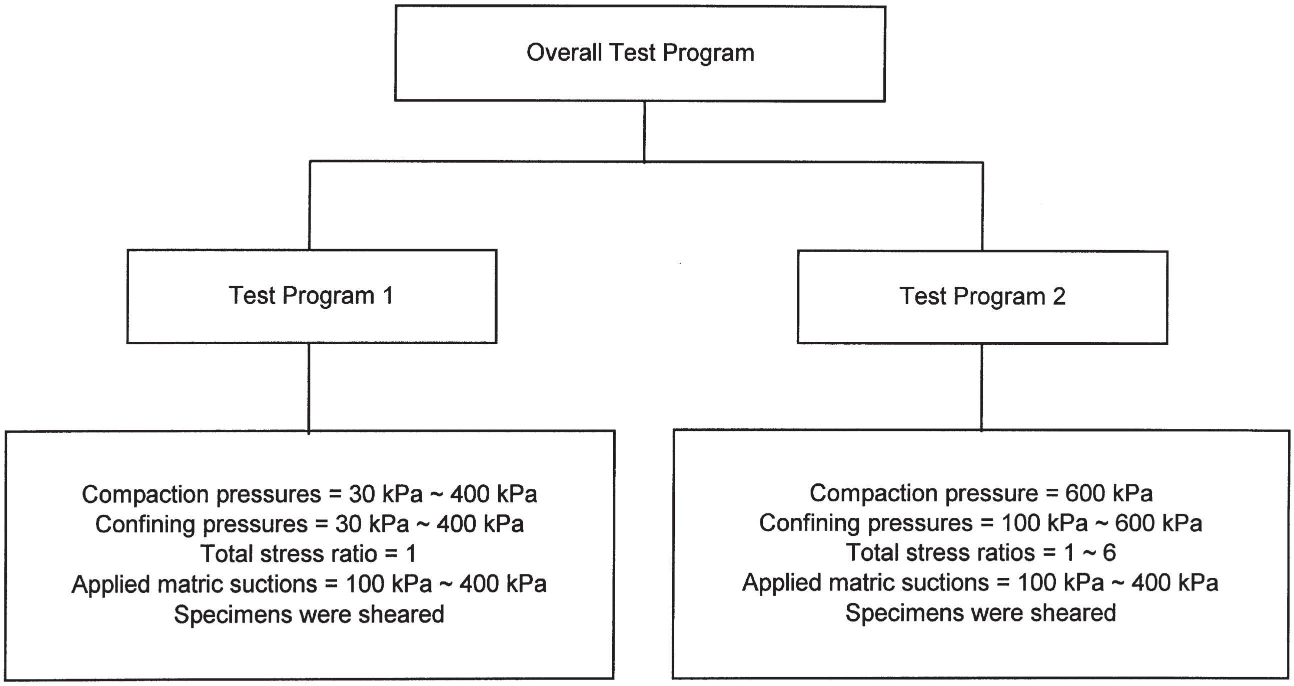


Fig. 4. Layout of the testing programs.



spheric conditions through the ceramic base plate. The pore water was allowed to drain, or enter the specimen, as desired.

During shearing of the specimens, the pore-air pressure, pore-water pressure, and vertical stress were maintained constant. These test procedures were used for test programs 1 and 2 as shown in Fig. 4. The general stress paths followed by the soil specimens in test program 1 are illustrated on a three-dimensional plot that includes void ratio (Fig. 5). The compaction pressure, total vertical pressure, and matric suc-

Fig. 5. Loading history associated with test program 1.

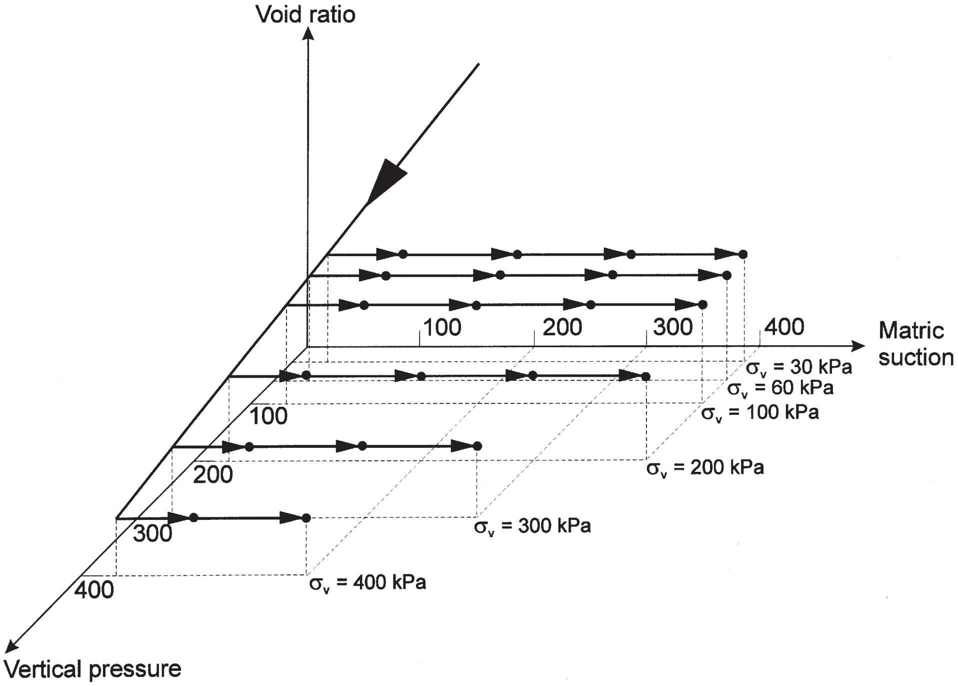


Table 2. Direct shear tests for normally consolidated soils.

Compaction pressure (kPa)	Vertical pressure (kPa)	Measured matric suction at applied compaction pressure (kPa)	Applied matric suction (kPa)
30	30	27.1	100
30	30	27.1	200
30	30	27.1	300
30	30	27.1	400
60	60	28.9	100
60	60	28.9	200
60	60	28.9	300
60	60	28.9	400
100	100	30.1	100
100	100	30.1	200
100	100	30.1	300
100	100	30.1	400
200	200	31.5	100
200	200	31.5	200
200	200	31.5	300
200	200	31.5	400
300	300	32.1	100
300	300	32.1	200
300	300	32.1	300
400	400	32.7	100
400	400	32.7	200

tion associated with each test as part of test program 1 are shown in Table 2. The compaction pressure ranged from 30 to 400 kPa. A vertical stress equal to compaction pressure (i.e., total stress ratio of one) was applied to each specimen. The matric suction in the compacted soil was measured during compaction of the specimen (i.e., the suction was measured with the compaction stress applied) (see Table 2). A designated matric suction was then applied to the compacted soil prior to the application of a shear force under drained conditions. The applied matric suction was always larger than the measured matric suction and, as a result, some water drained from the specimen as equilibrium was attained.

The general stress paths for the soil specimens in test program 2 are shown in Fig. 6. The stress values associated

Fig. 6. Loading history associated with test program 2.

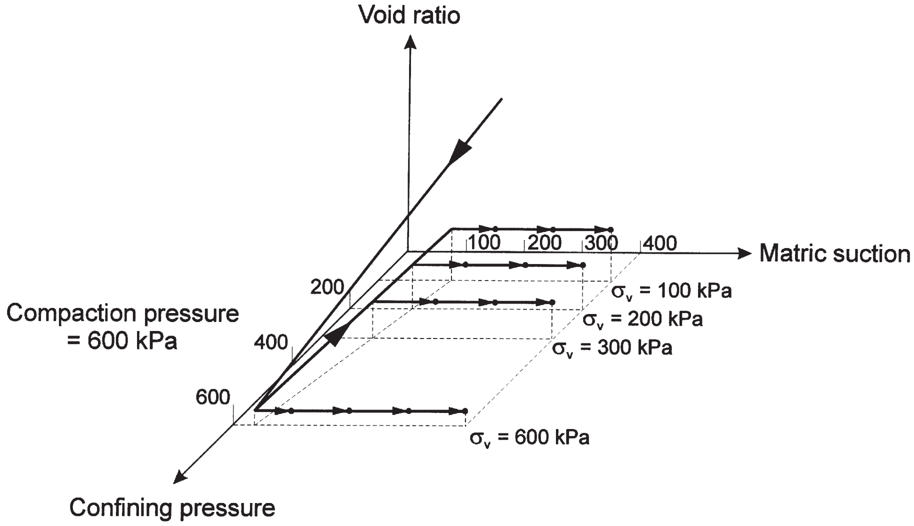


Table 3. Direct shear tests for overconsolidated soils.

Compaction pressure (kPa)	Vertical pressure (kPa)	Total stress ratio	Matric suction applied compaction pressure (kPa)	Applied matric suction (kPa)	Computed matric suction after unloading (kPa)		
					$B_w = 0$	$B_w = 0.1$	$B_w = 0.2$
600	100	6	33.1	100	33.1, drying	83.1, drying	133.1, swelling
600	100	6	33.1	200	33.1, drying	83.1, drying	133.1, drying
600	100	6	33.1	300	33.1, drying	83.1, drying	133.1, drying
600	100	6	33.1	400	33.1, drying	83.1, drying	133.1, drying
600	200	3	33.1	100	33.1, drying	73.1, drying	113.1, swelling
600	200	3	33.1	200	33.1, drying	73.1, drying	113.1, drying
600	200	3	33.1	300	33.1, drying	73.1, drying	113.1, drying
600	200	3	33.1	400	33.1, drying	73.1, drying	113.1, drying
600	300	2	33.1	100	33.1, drying	63.1, drying	93.1, drying
600	300	2	33.1	200	33.1, drying	63.1, drying	93.1, drying
600	300	2	33.1	300	33.1, drying	63.1, drying	93.1, drying
600	300	2	33.1	400	33.1, drying	63.1, drying	93.1, drying
600	600	1	33.1	100	33.1, drying	33.1, drying	33.1, drying
600	600	1	33.1	200	33.1, drying	33.1, drying	33.1, drying
600	600	1	33.1	300	33.1, drying	33.1, drying	33.1, drying
600	600	1	33.1	400	33.1, drying	33.1, drying	33.1, drying

Note: Drying indicates that water moved out of the soil specimen during testing, and swelling indicates that water moved into the soil specimen during testing. Matric suctions are the measured values when the compaction pressure and the applied vertical pressure are 600 kPa.

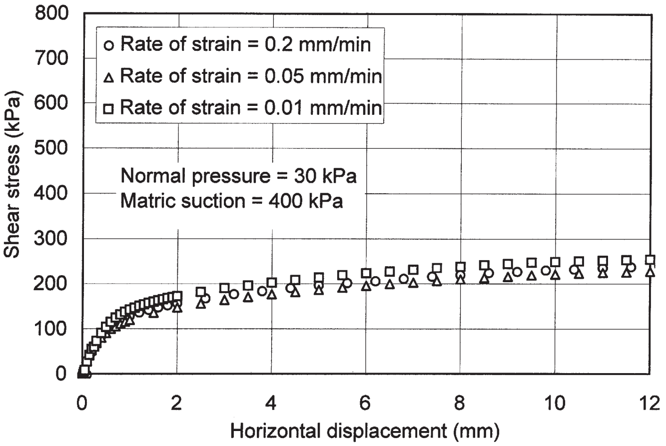
with each soil specimen in test program 2 are presented in Table 3. The compaction pressure for all specimens in test program 2 was 600 kPa. The average measured matric suction at the time of compaction for all specimens was 33.1 kPa when the soil was compacted at 600 kPa. The applied confining pressures were 100, 200, 300, and 600 kPa, resulting in the total stress ratios from 1 to 6. Since the matric suction was not measured when the vertical pressure was lowered from 600 kPa, the matric suction of each compacted specimen was computed using a pore pressure coefficient, B_w, which was estimated to be between 0 and 0.2, since the initial degree of saturation was approximately 30% (Campbell 1973; Skempton and Bishop 1954).

The computed matric suctions using three pore pressure coefficients, B_w, are indicated in Table 3. The soil specimens underwent drying or swelling depending upon the relationship between the computed matric suction and the applied matric suction.

Determination of the rate of shear

Procedures for determining strain rates (and displacement rates) have been suggested by Bishop et al. (1960), Ruddock (1966), Lumb (1966), Satija and Gulhati (1979), and Ho and Fredlund (1982*a*). Bishop et al. suggested that the strain rate for saturated soils is related to the coefficient of consolidation, c_v. Ruddock suggested using a strain rate that produced a failure envelope without a cohesion intercept for unsaturated soils. However, this may not always be feasible due to the overconsolidated nature of the soil. Lumb suggested that the methods developed for determining the rate of strain for

Fig. 7. Influence of the rate of strain on the maximum shear stress.



saturated soils can also be used for unsaturated soils and showed that the shear strength parameters for unsaturated soils were unaffected when the strain rate was smaller than that indicated for saturated soils. Satija and Gulhati conducted a series of tests to assess the effect of the rate of axial strain during the triaxial testing of unsaturated soils. A low rate of strain was used for shearing the unsaturated soil specimens to ensure complete dissipation of the pore-water and pore-air pressures during shear. The deviator stress was found to be relatively insensitive to strain rate used and suggested that the change in water content for drained tests should be used to determine the strain rate for testing of unsaturated soils. Ho and Fredlund presented a theoretical model to estimate the rate of strain required when determining the strength of an unsaturated soil. The equalization time required for an undrained strength test where the pore-water pressure is measured was found to be slightly less than that required for a drained test, since the high air-entry disk controls pore pressure equalization within the soil specimen.

In this study, preliminary pilot tests were performed to determine an appropriate strain rate. Figure 7 shows shear stress versus horizontal displacement curves for various rates of shear displacement at a normal pressure of 30 kPa and a matric suction of 400 kPa. Specimens with the highest suction were selected because of their low coefficient of permeability. The results of the three rates of strain on different specimens showed peak shear strength values varying by ±5%. The results do not indicate a trend with displacement rate. A strain rate of 0.05 mm/min was selected for the entire test program.

After each specimen was in equilibrium with the applied stresses, it was sheared at a constant strain rate of 0.05 mm/min until a horizontal displacement of 12.0 mm was approached.

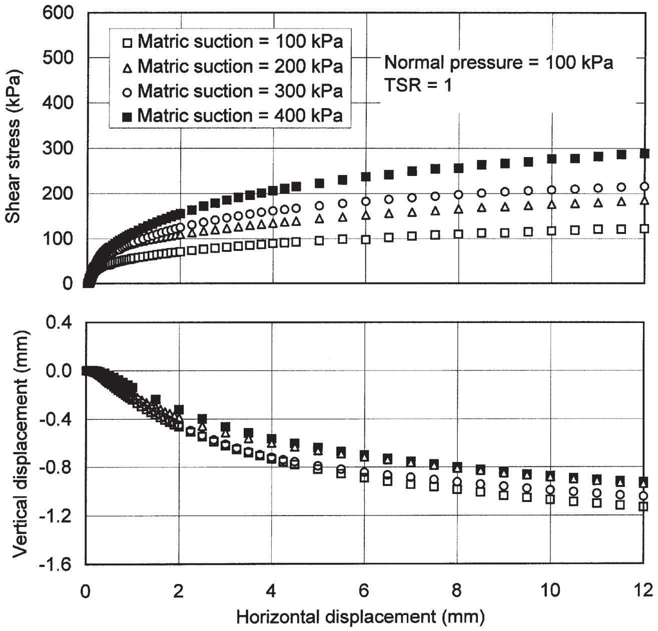
Direct shear test results

The direct shear test results from test programs 1 and 2 are presented separately and described in the following sections.

Shear strength results for compacted specimens with a total stress ratio of unity (test program 1)

The maximum or peak shear stress was used as the failure criterion. If the shear stress versus horizontal shear displacement curves did not exhibit a peak stress, the shear stress at a set arbitrary horizontal shear displacement value (e.g., 12.0 mm) was selected. Figure 8 shows shear stress versus horizontal shear displacement curves for compacted soils at a *constant confining pressure* of 100 kPa. The results show that the shear stress increased gradually with horizontal shear displacement; however, a peak shear stress could not be obtained for these compacted soils. The shear strength of the compacted specimens showed an increase in strength due to an increase in the matric suction at a constant confining pressure.

Fig. 8. Shear stress and vertical displacement versus horizontal displacement curves for compacted specimens at a constant normal pressure of 100 kPa in test program 1.



Changes in vertical displacement versus horizontal shear displacement are also shown in Fig. 8 for specimens at a constant confining pressure of 100 kPa. Negative values for the vertical displacements were observed, indicating a reduction in volume (i.e., contraction) of the soil specimens. The negative volume change during direct shear results in a gradual increase in the shear resistance of the soil.

The shear stress and vertical displacement versus horizontal displacement corresponding to a *constant matric suction* value of 100 kPa for the direct shear specimens are shown in Fig. 9. The confining pressures applied to the soil specimens ranged from 30 to 400 kPa. The compacted soils with a total stress ratio of 1 did not exhibit a peak shear stress. The shear strength of the compacted specimens at a constant matric suction increases with confining pressure.

Shear strength results for compacted specimens tested at various total stress ratios (test program 2)

Figure 10 shows the shear stress versus displacement curves corresponding to a constant matric suction of 100 kPa for various total stress ratios. The applied confining pressures ranged from 100 to 600 kPa, and TSR varied from 1 to 6. The shear stress increased with confining pressure. Since the compaction pressure applied to all soil specimens

Fig. 9. Shear stress and vertical displacement versus horizontal displacement for compacted specimens at a constant matric suction of 100 kPa in test program 1.

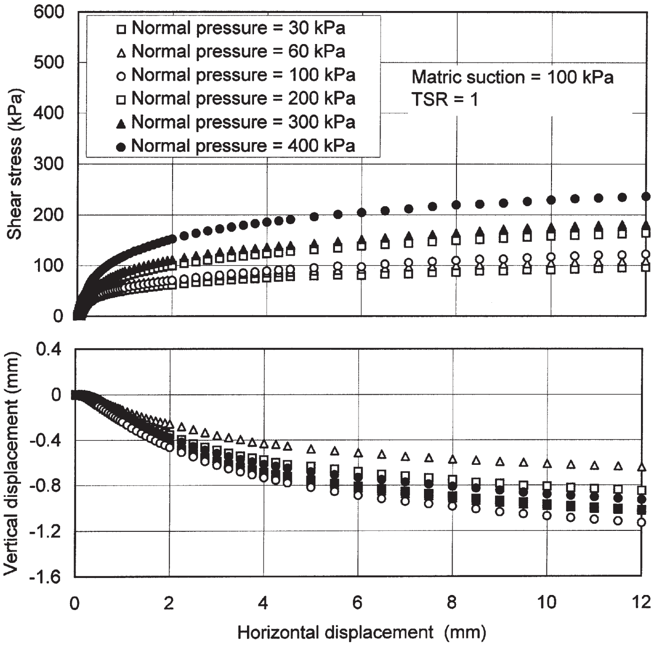
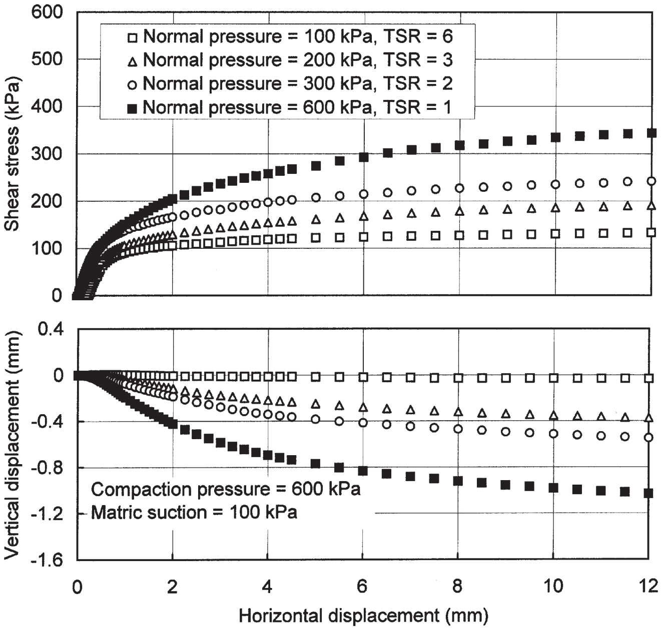


Fig. 10. Shear stress and vertical displacement versus horizontal displacement for compacted specimens with various total stress ratios in test program 2.



was constant, an increase in the confining pressure is similar to a decrease in TSR. Figure 10 shows that the shear strength of the unsaturated soil increases with a decreasing TSR. The shape of the shear stress versus horizontal displacement curve at confining pressures of 600 kPa (i.e., TSR equal to 1) is different from the shear stress versus horizontal displacement curve at a confining pressure of 100 kPa (i.e., TSR equal to 6). The stress–strain curve at a confining pressure of 600 kPa (i.e., TSR equal to 1) shows a strain-hardening type of behavior. The results indicate that stress history has an influence on the shear stress versus horizontal shear displacement relationship.

Changes in vertical displacement versus horizontal shear displacement are also shown in Fig. 10 for specimens with various total stress ratios. Vertical displacements of the compacted specimens show increasing volume decrease with an increasing vertical pressure. The vertical displacement for a specimen with a TSR equal to six was very small.

Figure 11 shows the shear stress and vertical displacement versus horizontal displacement for compacted specimens at various matric suction values. All specimens were subjected to a compaction pressure of 600 kPa. When the confining pressure was 100 kPa, TSR was equal to six. The shape of the shear stress versus horizontal shear displacement curve at a matric suction of 100 kPa indicated a strain-hardening behavior similar to that of overconsolidated saturated soils. The shape of the stress–strain curve for the compacted soil with a TSR of six shows an increase in strength with an increase in matric suction.

Discussion on the shear strength parameters

A linear form of the shear strength equation for unsaturated soils was presented by Fredlund et al. (1978):

$$[4] \qquad \tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

where

τ is the shear strength;

c' is the effective cohesion intercept;

σ_n is the total normal stress;

ϕ' is the effective angle of internal friction with respect to confining pressure;

ϕ^b is the angle of internal friction with respect to matric suction; and

$(\sigma_n - u_a)$ is the confining pressure.

Equation [4] shows that two independent stress state variables are required to describe the shear strength for an unsaturated soil. Figure 12 shows the relationship between confining pressure and shear strength at various matric suction values for the specimens compacted at a total stress ratio of 1.0. Figure 13 shows the relationship between confining pressure and shear strength for specimens compacted at various total stress ratios. The specimens subjected to confining pressures of 600 kPa have a total stress ratio of 1.0. The total stress ratios of the other specimens are greater than one. The relationship between confining pressure and shear strength presented in Figs. 12 and 13 shows the influence of loading history on shear strength. The influence of the varying loading histories is slight.

The effective angle of internal friction with respect to confining pressure can be determined from Figs. 12 and 13. It is the tangent of a straight line relating the net normal stress to shear strength. The effective angle of internal friction with respect to confining pressure at a constant matric suction and various total stress ratios is compared in Fig. 14. The angle of internal friction increases slightly with an increase in the total stress ratio at a constant matric suction. The angle of internal friction of the compacted soil appears to be essentially constant with matric suction. The shear

Fig. 11. Shear stress and vertical displacement versus horizontal displacement for compacted specimens at various matric suctions in test program 2.

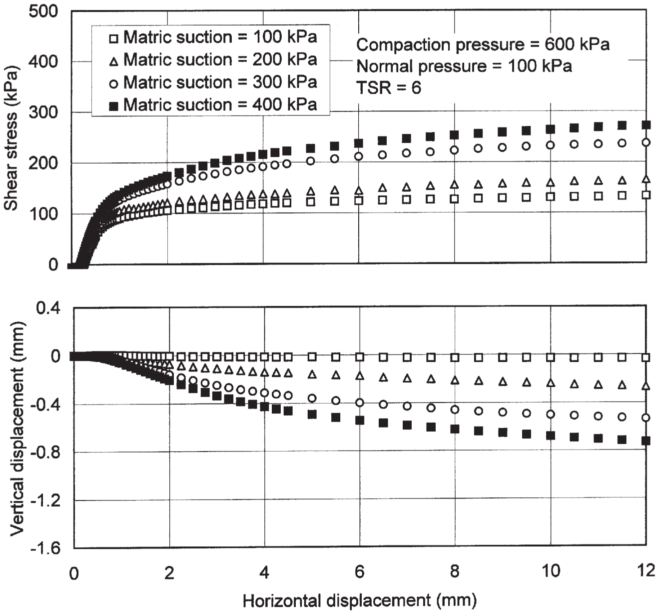
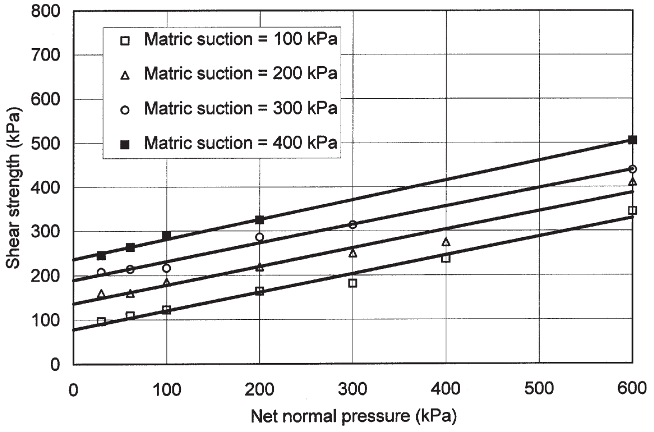


Fig. 12. Relationship between normal pressure and shear strength for compacted specimens with a total stress ratio of 1.



strength parameters of the unsaturated soil with respect to confining pressure show no change due to loading history.

The total cohesion, *c*, can be computed as the intersection of the failure surface with the shear strength axis for various matric suction values (Figs. 12, 13). The total cohesion, *c*, plotted versus matric suction is shown in Fig. 15. The relationship between matric suction and total cohesion is nonlinear, since the increments of total cohesion decrease with an increasing matric suction. The above-mentioned behavior is independent of the stress history of the compacted soil. The total cohesion versus matric suction curve for a total stress ratio of one appears to be coincident with that for a total stress ratio greater than one. Total cohesion, *c*, becomes equal to effective cohesion, c', when the matric suction is equal to zero. The estimated effective cohesion, c', from the total stress versus matric suction curve approaches zero; however, it should be noted that no tests were run with matric suctions less than 100 kPa.

Fig. 13. Relationship between normal pressure and shear strength for compacted specimens at various total stress ratios (test program 2).

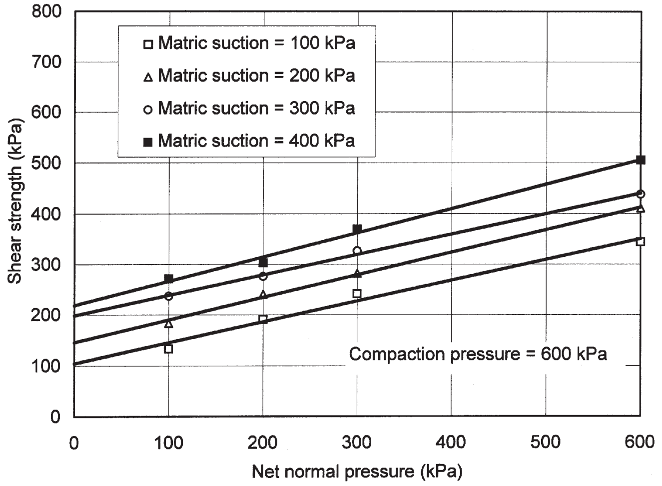


Fig. 14. Relationship between matric suction and angle of internal friction, ϕ'.

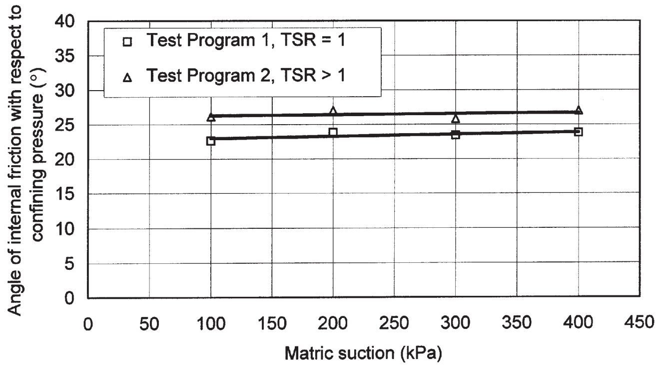
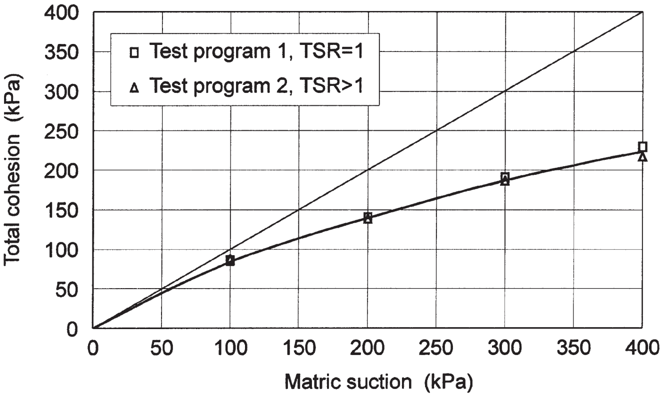


Fig. 15. Relationship between matric suction and total cohesion.



The relationship between matric suction and shear strength for compacted soils at various total stress ratios is shown in Figs. 16 and 17. The plot of shear strength versus matric suction shows slight nonlinearity regardless of the loading history of the compacted soil. Increments of shear strength change decrease slightly with increasing matric suction. Ho and Fredlund (1982*b*) stated that the shear strength equation proposed by Fredlund et al. (1978) produces a pla-

Fig. 16. Relationship between matric suction and shear strength for compacted specimens with a total stress ratio of 1.

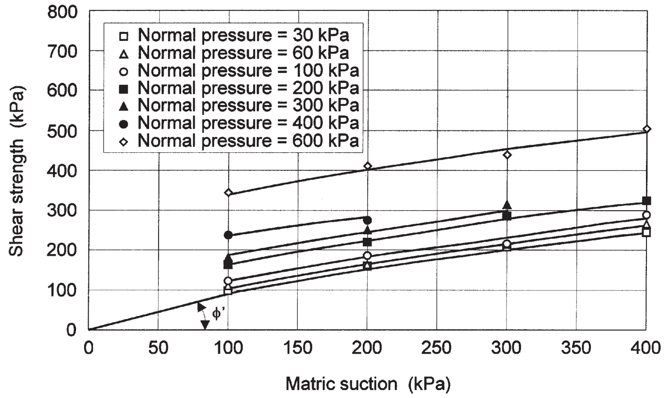


Fig. 17. Relationship between matric suction and shear strength for compacted specimens tested at various total stress ratios (test program 2).

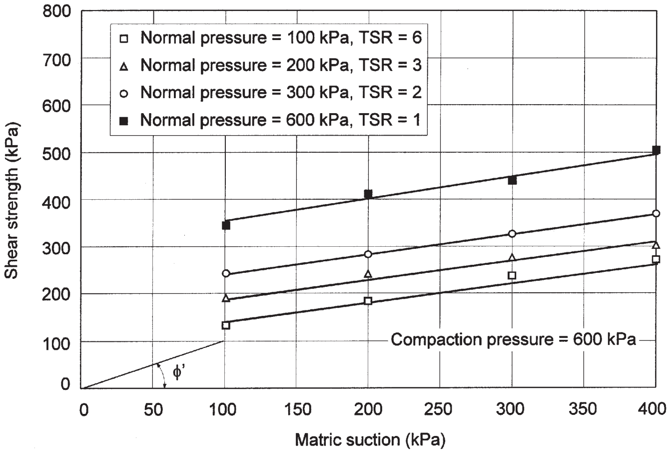


Fig. 18. Change in shear strength parameter with respect to matric suction, ϕ^b, for various loading histories.

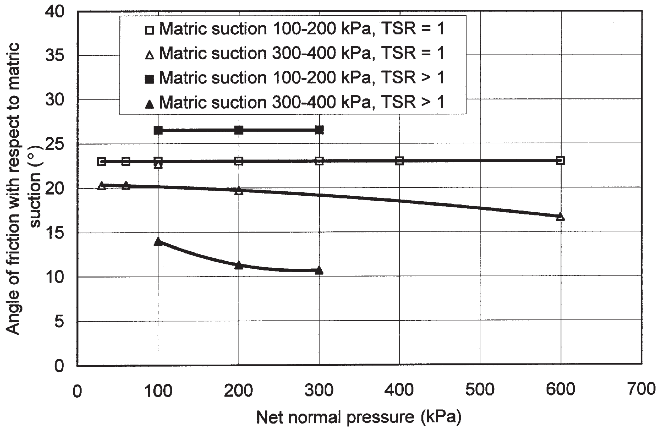
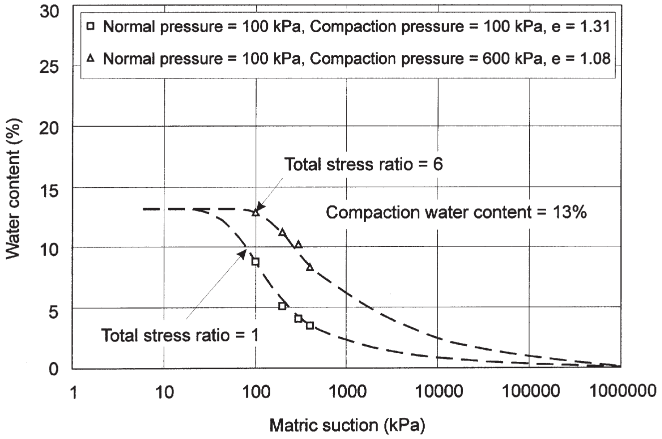


Fig. 19. Soil-water characteristic curves for compacted soil specimens.



nar failure envelope that can generally be applied over a limited range of matric suction. Gan and Fredlund (1988) observed nonlinearity in the shear strength versus matric suction relationship from direct shear tests performed over a higher range of matric suctions. Similarly, Escario and Saez (1986) and Campos and Carrillo (1995) showed nonlinearity in the shear strength versus matric suction relationship. Results obtained from these testing programs appear to show a slight nonlinearity in the failure envelope.

The angle defining the change in shear strength with respect to matric suction, ϕ^b, in eq. [4], can be evaluated as a strength parameter for the compacted soil. Gan et al. (1988) stated that the angle ϕ^b can be viewed as being a part of either the frictional component of shear strength or the cohesional component of shear strength. The computed shear strength parameter ϕ^b is plotted against the confining pressure for different values of matric suction in Fig. 18. The ϕ^b angles were graphically estimated from the best-fit lines in Figs. 16 and 17. The shear strength parameter ϕ^b appears to decrease slightly at high matric suctions (i.e., 300–400 kPa), regardless of the loading history, and changes with an increase in confining pressure in the range of matric suctions from 300 to 400 kPa. Even if the confining pressure applied to the compacted soil is maintained constant, ϕ^b for the compacted soil increases with an increase in the total stress ratio for matric suctions in the range from 100 to 200 kPa. In the matric suction range from 300 to 400 kPa, ϕ^b decreases with total stress ratio, and thus is affected by loading history.

The direct shear tests conducted in this study were fully drained, therefore water was allowed to enter or leave the specimen as desired under the applied stresses. The water content of the soil specimens changed due to differing matric suctions being applied. Soil-water characteristic curves for the compacted soils were computed from the direct shear tests and are shown in Fig. 19. The soil-water characteristic curve can also be used to estimate the unsaturated soil parameters or the shear strength function (Fredlund et al. 1996). The loading history is shown to influence the shape of the soil-water characteristic curve.

The soil-water characteristics curves in Fig. 19 are desorption curves corresponding to total stress ratios of 1 and 6. The confining pressure used in defining the soil-water characteristics curves is 100 kPa. Water contents for compacted specimens with a total stress ratio of one are lower than those with a total stress ratio greater than one, at any matric suction. The void ratio of the compacted specimens results in a change in the soil-water characteristics curves. A total stress ratio greater than one corresponds to the use of a high compaction pressure and produces a decrease in the void ratio of a compacted soil. The results indicate that loading history has an influence on the strength parameter ϕ^b for compacted soils. The influence of stress history is associated with differences in the soil-water characteristics curve under differing compaction conditions.

Conclusions

This study defined total stress ratio, TSR, with regard to a compacted soil as the ratio of the compaction pressure to the net normal pressure used when testing a specimen. The total stress ratio appears to influence the shear strength parameter ϕ^b of a compacted soil. Direct shear tests were performed on compacted soil specimens subjected to various loading history conditions. Shear stress versus horizontal shear displacement and specimen volume change during direct shear were measured for the compacted soil specimens.

A peak shear stress could not be obtained on the stress versus displacement curves for the compacted soil subjected to a total stress ratio of 1.0. The stress–strain curve showed an apparent strain-hardening type behavior. Negative volume changes (i.e., contraction) were associated with an increase in shear resistance.

In the case of a total stress ratio greater than one, the stress–strain curve for the compacted soil reached a peak shear strength value. The stress–strain curves changed with an increasing matric suction. Volume changes associated with a total stress ratio of 1.0 were lower than those associated with a total stress ratio greater than 1. Volume decrease due to direct shear became greater with increasing matric suctions. The shear stress versus horizontal shear displacement relationship was influenced by the loading history of the compacted soil.

The effective angle of internal friction, ϕ', with respect to confining pressure for the compacted soil at a total stress ratio greater than 1.0 is slightly higher than when the total stress ratio was 1.0, regardless of the matric suction. The relationship between matric suction and total cohesion is nonlinear regardless of loading history. The increase in total cohesion is a function of matric suction. The computed shear strength parameter ϕ^b decreases with matric suction, regardless of the loading history, and is higher for a compacted soil with a total stress ratio of 1.0 than for the soil tested at a total stress ratio greater than 1.0, regardless of the increase in matric suction. The shear strength parameter ϕ^b was also shown to be influenced by loading history.

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