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The influence of soil structure and stress history on the soil–water characteristics of a compacted till

S. K. VANAPALLI,* D. G. FREDLUND* AND D. E. PUFAHL*

The soil–water characteristic defines the relationship between the soil suction and gravimetric water content, *w*, or the volumetric water content, *θ*, or the degree of saturation, *S*. Theoretical and empirical relationships are available to model the unsaturated soil properties such as the coefficient of permeability and shear strength using the soil–water characteristic and the conventional saturated soil properties. These procedures are attractive to engineering practitioners because rigorous laboratory tests on unsaturated soil are difficult and time-consuming and, therefore, costly. Various investigators generally have used the soil–water characteristic over a limited suction range (usually 0 to about 1500 kPa) to model the unsaturated soil behaviour. Soils, however, change from a saturated to a dry condition over a range of suctions from 0 to 1 000 000 kPa. A rationale for extending the soil–water characteristic up to 1 000 000 kPa is provided in this paper, and a method for estimating the residual state of saturation is presented. Soil–water characteristics were developed for the entire range of suctions from 0 to 1 000 000 kPa on statically compacted clayey till specimens prepared at three different initial water contents. The influence of initial water content, soil structure and stress history, as it relates to the soil–water characteristic, has been studied and is reported in this paper. The initial water contents selected for this study represent the dry of optimum, optimum and wet of optimum conditions with corresponding densities determined from the standard AASHTO test. The results indicate that initial moulding water content has considerable influence on the resulting structure (and aggregation), which in turn influences the soil–water characteristics. In the low suction range (i.e. 0–1500 kPa), macrostructure governs the soil–water characteristics for specimens compacted with dry of optimum initial water contents and they exhibit a steeper slope. However, for the specimens compacted at wet of optimum, microstructure governs the soil–water characteristic behaviour. The soil–water characteristic of the specimens compacted at dry of optimum are influenced by the stress history; however, stress history appears to have no significant influence on the soil–water characteristics of the specimens compacted with wet

Il existe plusieurs relations théoriques et empiriques permettant de faire une maquette des propriétés d'un sol non saturé en utilisant la courbe caractéristique sol-eau et les propriétés conventionnelles des sols saturés. Ces procédures sont intéressantes pour les praticiens industriels car il est difficile, long et coûteux de réaliser des tests rigoureux en laboratoire sur sols non saturés. Divers investigateurs utilisent normalement une courbe caractéristique sol-eau sur une gamme de succions limitée, allant habituellement de 0 à environ 1500 kPa, pour faire une maquette du comportement du sol non saturé. Les sols, cependant, passent d'un état saturé à un état sec dans une gamme de succions allant de 0 à 1 000 000 kPa. Nous justifions l'extension de la courbe caractéristique sol-eau jusqu'à 1 000 000 kPa et nous donnons une méthode permettant d'évaluer l'état de saturation résiduelle à partir de la courbe étendue. Plusieurs facteurs exercent une influence sur le comportement de la courbe caractéristique sol-eau. Pour utiliser avec succés la courbe caractéristique sol-eau afin de prédire les propriétés du sol non saturé, il est important de bien comprendre les facteurs qui influencent les prises de mesure. Il est également important de simuler autant que possible les conditions in situ qui sont susceptibles de se produire sur le terrain pendant les essais en laboratoire. Des courbes caractéristiques sol-eau ont été développées pour toute la gamme de succions de 0 à 1 000 000 kPa sur des spécimens d'argile à moraines compactés de manière statique avec trois teneurs initiales en eau. Nous montrons dans cet exposé l'influence de la structure du sol (et de l'agrégation) et de l'état de contrainte sur la courbe caractéristique sol-eau. Les teneurs en eau initiales choisies pour cette étude représentent les conditions sèches de la valeur optimum, la valeur optimum et les conditions humides de la valeur optimum, avec des densités correspondantes déterminées par le test AASHTO. Les résultats montrent que la teneur en eau de moulage initiale a une influence considérable sur la structure du sol (et l'agrégation) qui en résultent.

of optimum conditions. The soil–water characteristic behaviour of specimens compacted with optimum initial water contents lies in between those of specimens compacted with water contents that are dry and wet of optimum. It appears that soil–water characteristics are not significantly influenced either by the soil structure (aggregation) or the stress history for the high suction ranges (i.e. 20 000–1 000 000 kPa).

KEYWORDS: fabric/structure of soils; soil–water characteristic; stress history; suction; unsaturated soils.

INTRODUCTION

A theoretical framework for unsaturated soil mechanics, which closely parallels that of saturated soil mechanics, has been developed and firmly entrenched over the past 15 years. The constitutive equations for volume change, shear strength, and flow through unsaturated soil are receiving general acceptance in geotechnical engineering applications (Fredlund & Rahardjo, 1993). Because experimental studies on unsaturated soils are time-consuming and costly, relationships between the soil–water characteristic and saturated soil properties are now being developed to predict/model the engineering behaviour of unsaturated soils.

The soil–water characteristic defines the relationship between the soil suction and either the gravimetric water content, w, or the volumetric water content, θ, or the degree of saturation, S. Geotechnical engineers are generally more conversant with the term degree of saturation, S, than with volumetric water content, θ. Therefore, the soil–water characteristic relationship should have greater meaning if it is presented using degree of saturation versus suction. The soil–water characteristic can be described as a measure of the water-holding capacity (i.e. storage capacity) of the soil as the water content changes when subjected to various values of suction.

The soil–water characteristic is a conceptual and interpretative tool by which the behaviour of unsaturated soils can be understood. As the soil moves from a saturated state to drier conditions, the distribution of the soil, water, and air phases changes as the stress state changes. The relationships between these phases take on different forms and influence the engineering behaviour of unsaturated soils. For example, in some cases the behaviour may be primarily related to the volume of the separate phases (e.g. water content), or the continuity and tortuosity of the liquid phase (e.g. coefficient of permeability, molecular diffusion) or the air phase (e.g. coefficient of vapour or oxygen diffusion). In other cases it is the nature of the interphase contact area controlling stress transfers (e.g. shear strength, volume change) or interphase mass transfers (e.g. chemical adsorption, volatilization) which controls behaviour (Barbour, 1999). These interphase relationships can be derived using the soil–water characteristic data and can then be used for estimating unsaturated soil properties.

The soil–water characteristic and the saturated coefficient of permeability have been used in predicting the relationship between suction and the coefficient of permeability (Brooks & Corey, 1964; van Genuchten, 1980; Mualem, 1986; Fredlund *et al.*, 1994). It has also been shown that the soil–water characteristic and the saturated shear strength parameters can be used to predict the variation in shear strength with respect to suction (Vanapalli *et al.*, 1996; Fredlund *et al.*, 1996).

This paper provides an explanation of the different phase relationships from a saturated condition to a dry condition (i.e. for a suction range of 0–1 000 000 kPa) using the soil–water characteristic. A construction procedure is also presented to define the residual state of saturation in an unsaturated soil using the entire soil–water characteristic.

The distinguishing features of the soil–water characteristic depend on several factors such as soil structure (and aggregation), initial moulding water content, void ratio, type of soil, texture, mineralogy, stress history, and method of compaction. Of the factors stated above, the stress history and initial moulding water content seemingly have the most influence on the soil structure (and aggregation), which in turn dominates the nature of the soil–water characteristic for fine-grained soils. Specimens of a particular soil, in spite of having the same texture and mineralogy, can exhibit different soil–water characteristics if they are prepared at

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different initial moulding water contents and possess different stress histories. As a result, the engineering behaviours of the specimens will also differ.

Soil–water characteristics are commonly developed in the laboratory using pressure plate equipment that is not capable of applying a confining pressure or significant vertical stresses to the specimen, whereas in the field the soil usually has a complex stress history. To obtain a reliable soil–water characteristic, the soil structure and stress history, which may occur in the field, should be reasonably simulated in the laboratory. In this paper, a method for developing the soil–water characteristic for fine-grained soils under differing stress histories is proposed. The influences of stress history and initial moulding water content on the soil–water characteristics of statically compacted till specimens have been evaluated. This evaluation has been accomplished by loading and unloading specimens in a conventional oedometer and then using a pressure plate apparatus and vacuum desiccators to determine the suction–water content relationship from 0 to 1 000 000 kPa. The influence of initial moulding water content on the structure (and aggregation) is evaluated by comparing the soil–water characteristic data with data obtained from individually compacted specimens. The matrix suction of the individually compacted specimens was determined using the axis-translation technique on a null pressure plate apparatus.

KEY FEATURES OF SOIL–WATER CHARACTERISTIC

Soil–water characteristics are plotted on an arithmetic scale if the suction range used for testing is small (i.e. 0–1000 kPa). However, it is also common to plot the soil–water characteristic behaviour on a semi-logarithmic plot if the suction range used for testing is large. While many engineering applications are concerned with the lower end of the suction range (i.e. less than 500 kPa), other applications such as soil covers and soil liners may require consideration of rather large values of suction (i.e. in excess of 3000 kPa).

A typical soil–water characteristic is illustrated in Fig. 1 for the entire range of suction values (i.e. 0–1 000 000 kPa). The key features of the soil–water characteristic are explained using this figure.

Air-entry value of the soil

Conceptually, the air-entry value represents the differential pressure between the air and water that is required to cause desaturation of the largest pores (i.e. 'air entry'). The air-entry value of the soil is obtained by extending the constant slope portion of the soil–water characteristic to intersect the suction axis at 100% saturation (Fig. 1). The corresponding value of suction is taken as the air-entry suction value of the soil. If the ordinate in Fig. 1 is plotted as volumetric water content, the slope of the portion of the curve up to the air-entry value is equivalent to the coefficient of volume compressibility, m_v.

Identifiable stages

There are three identifiable stages of desaturation (Fig. 1): namely, the boundary effect stage, the transition stage (i.e. primary and secondary) and the residual stage of unsaturation (Vanapalli, 1994). Figure 1 also illustrates the variation in the wetted

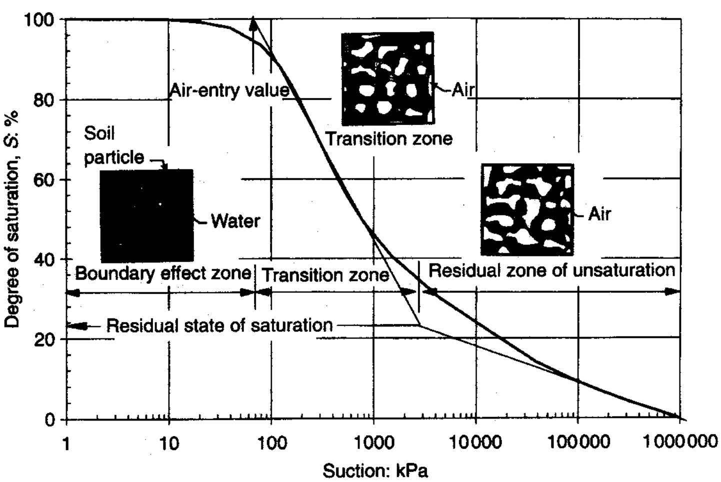

Fig. 1. Typical soil–water characteristic showing zones of desaturation

area of contact for the different stages of the soil–water characteristic. In the boundary effect stage, almost all of the soil pores are filled with water. The soil desaturates at the air-entry value in the transition stage. In this stage, the flow of water is in the liquid phase as the applied suction increases and the soil dries rapidly with increasing suction. The connectivity of the water in the voids or pores continues to reduce with increased values of suction, and eventually large increases in suction lead to relatively small changes in the degree of saturation.

Residual state of saturation

The residual state of saturation can be considered to be the degree of saturation at which the liquid phase becomes discontinuous. Consequently, the residual state of saturation represents the degree of saturation value beyond which it becomes increasingly difficult to remove water from a specimen by drainage. The point at which residual state of saturation is reached is not always clearly defined.

Traditionally, soil–water characteristic has been defined over a range of suctions that is limited from 0 to 1500 kPa. A suction value of 1500 kPa has taken on significance as 'residual suction' because it corresponds to the wilting point for many plants (van Genuchten, 1980). However, this arbitrary value may not actually correspond to a residual state of saturation condition. Some authors have shown suction to increase asymptotically to infinity along the soil–water characteristic as the degree of saturation approaches the residual state (i.e. approximately a constant value) (Nitao & Bear, 1996).

It is often necessary to define the residual state of saturation condition in order to obtain the fitting parameters in numerical models for predicting permeability (Brooks & Corey, 1964; van Genuchten, 1980) or shear strength (Vanapalli *et al.*, 1996; Fredlund *et al.*, 1996). Such equations offer computational advantages and are useful in developing closed form solutions. Several empirical procedures are available to define the residual state of saturation using the soil–water characteristic (Brooks & Corey, 1964; White *et al.*, 1970). These procedures typically do not use the soil–water characteristic data for the entire range of suction (i.e. 0–1 000 000 kPa). A graphical procedure can be used to define the residual state of saturation when the entire suction range is used (Fig. 1). This procedure is similar to the Casagrande construction for finding the point of 100% consolidation on a deflection versus log time relationship. The procedure involves first drawing a tangent line through the inflection point on the straight line portion of the soil–water characteristic. The residual state of saturation can be defined as the point where the line extending from 1 000 000 kPa along the curve intersects the previous tangent line (Fig. 1).

High values of suction

Models based on soil–water characteristics that were developed for a limited range of suction (i.e. 0–1500 kPa) may not be suitable for the prediction of unsaturated flow properties at low water contents and high suctions. For example, in the prediction of performance of soil covers for waste disposal sites, estimates of actual evaporation are required. These predictions require that the soil–water characteristic be defined at suctions exceeding 3000 kPa (Wilson *et al.*, 1994). While the matrix suction, $(u_a - u_w)$, component largely governs the engineering behaviour of unsaturated soils which are in excess of a metre or so below the ground surface, the surface phenomenon of evaporation is controlled by total suction (Wilson *et al.*, 1994). Total suction, ψ, is composed of matrix suction, $(u_a - u_w)$, and osmotic suction, ψ_o. There appears to be a common value of total suction at which all soils approach zero water content. This suction value corresponding to zero water content is approximately 1 000 000 kPa (Croney *et al.*, 1958; Russam, 1958; Fredlund, 1964; Vanapalli, 1994). These observations are also supported by thermodynamic principles (Richards, 1965). Thus, it is useful and meaningful to use the soil–water characteristic for the entire range of suction values (i.e. 0–1 000 000 kPa) in the prediction of unsaturated soil properties.

The data for the soil–water characteristic are generally obtained from a pressure plate apparatus at low to moderate suctions (0–1500 kPa) and an osmotic desiccator for the higher suction range (i.e. 3500–300 000 kPa or higher). Luckner *et al.* (1991) expressed some concerns about using a soil–water characteristic defined over the entire range of suctions based on pressure plate and desiccator tests, since these techniques are based on different modes of water movement (i.e. liquid flow versus vapour migration). However, if the soil–water characteristic is viewed from a phenomenological point of view, the total suction represents the total energy deficiency in the water phase. Whether equilibrium with the applied energy state is obtained by liquid flow or by equilibration with the vapour phase is not of concern for the definition of the soil–water characteristic.

Typical soil–water characteristics for various soils

Typical soil–water characteristics for various soils over the entire range of suctions are shown in Fig. 2. The gradation and plasticity properties of these soils are provided in Table 1.

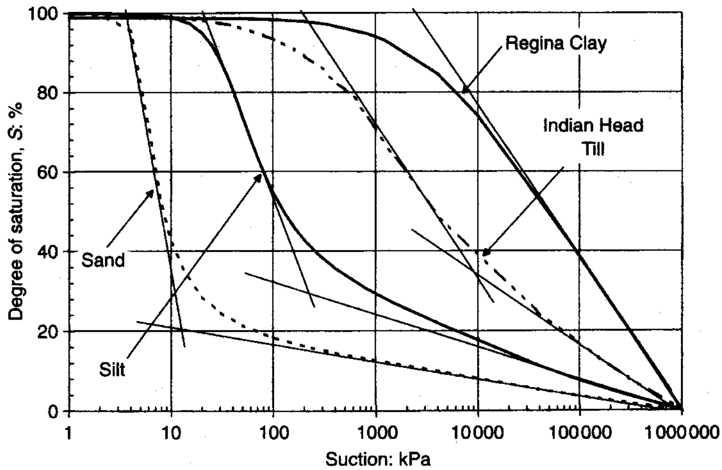

Fig. 2. Typical soil–water characteristic for four Canadian soils

Table 1. Summary of the soil properties

Soil type	Sand: %	Silt: %	Clay: %	ω_L: %	ω_P: %	Reference
Sand	98	2	–	–	–	Unpublished data, University of Saskatchewan Laboratory (1994)
Silt	52·5	37·5	10	22	16·6	Huang (1994)
Indian Head Till	28	42	30	35·5	16·8	Vanapalli (1994)
Regina Clay	8	41	51	75·5	24·9	Fredlund (1964)

These curves illustrate that the key features of the soil–water characteristic (such as the air-entry value and the residual state of saturation) are well defined for most of the soils. A coarse-grained soil such as a gravel or sand has large interconnected pores and shows a tendency to change in degree of saturation at a fast rate as values of suction increase. The rate of drying decreases with an increase of fines. The water storage capacity of a soil that corrresponds to a particular value of suction is higher for a soil with a higher percentage of fines. The air-entry value is also higher for soils which have more fines. Similarly, the residual state of saturation also increases with the increase in fines. The construction procedure for defining the residual state of saturation appears to be suitable for most soils except for very fine-grained soils, such as expansive soils and slurried soils (e.g. Regina Clay), which desaturate continuously without exhibiting a distinct break (Fig. 2).

SOIL AND TESTING PROGRAMME

A sandy clay till obtained from Indian Head, Saskatchewan, Canada was used in this testing programme. This soil is classified as a CL according to the Unified Classification System. The liquid limit and plastic limit and grading properties are given in Table 1. The clay fraction is predominantly a calcium montmorillonite. The AASHTO standard compacted maximum density is 1·80 Mg/m^3 at an optimum water content of 16·3%. The relative density of the soil solids is 2·73.

The soil was air-dried for several days, pulverized using a rubber mallet and passed through a 2 mm sieve. A prescribed amount of distilled water was sprayed on the air-dried soil in several layers and left overnight in tightly covered plastic bags in a humidity-controlled room. The soil was then thoroughly hand-mixed. To help prevent the formation of soil–water clods, the mixed soil was again passed through a 2 mm sieve. The mixed soil was placed in plastic bags and kept in a humidity-controlled room for at least 48 h.

All samples for the testing programmes were statically compacted to 100 mm in diameter and 21 mm in height. The samples were prepared in a single layer using a constant volume mould to obtain the required initial conditions of water content and density. A specimen 63·5 mm in diameter was cut from the 100 mm dia. sample using stainless steel sharpened consolidation rings. These specimens were then used to obtain data for the soil–water characteristic from a pressure plate apparatus. In a pressure plate apparatus, the prepared specimen sits on a high air-entry ceramic disk in a sealed air pressure chamber. Water in a compartment beneath the disk is maintained at zero water pressure while an applied air pressure induces a matrix suction under which the specimen is allowed to come to equilibrium.

Testing programme, section 1 (soil–water characteristics)

The testing programme was performed in two sections. Tests on specimens in section 1 were used to obtain data for the soil–water characteristics. Four specimens with different stress histories (i.e. with equivalent pressures 0, 25, 100 and 200 kPa) and different 'initial' water contents were prepared for testing. The meaning of the term equivalent pressure is detailed in the next section.

Saturated specimens with 0 kPa equivalent pressure

Compacted specimens 63·5 mm in diameter and 21 mm in height, having been prepared with the required initial water content and density, were sandwiched between filter paper and porous stones in consolidation rings and were loaded to 3·5 kPa in a conventional oedometer. These specimens were submerged in distilled water, allowing access to drainage at top and bottom for about 36 h. The degree of saturation of these specimens was checked using waxed trial samples which were weighted in air and water. The degrees of saturation of specimens were greater than 99% for all the samples. Volume changes were not measured for these specimens. These specimens were removed from the oedometers and placed in the pressure plate apparatus. These specimens are referred to as specimens with 0 kPa equivalent pressure in the paper.

Saturated specimens with simulated stress history

A conventional pressure plate apparatus does not allow specimens to be loaded externally during testing. Nevertheless, it remains of interest to assess the importance of applied stress and stress history for the features of the soil–water characteristic. Therefore, it was decided to use specimens which had a stress history (i.e. the specimens had a known equivalent pressure). The void ratio versus stress relationship (both in loading and unloading conditions) was determined through conventional odeometer testing.

The procedure used for inducing a predetermined equivalent pressure is explained using Fig. 3. This gives the void ratio versus stress relationship for a specimen with a water content equal to 16·3% (i.e. representing optimum water content conditions). This compacted specimen was placed in an oedometer, saturated under constant volume conditions and then loaded to 200 kPa (point A). The specimen was then allowed to swell under a nominal pressure of 3·5 kPa (point B). While the specimen had experienced a maximum prestress pressure of 200 kPa, it had a void ratio corresponding to 100 kPa on the initial compression branch after swelling under the applied pressure of 3·5 kPa (point C). The equivalent pressure for this specimen is equal to 100 kPa.

Using a similar procedure, specimens of differing equivalent pressures as shown in Fig. 4 were

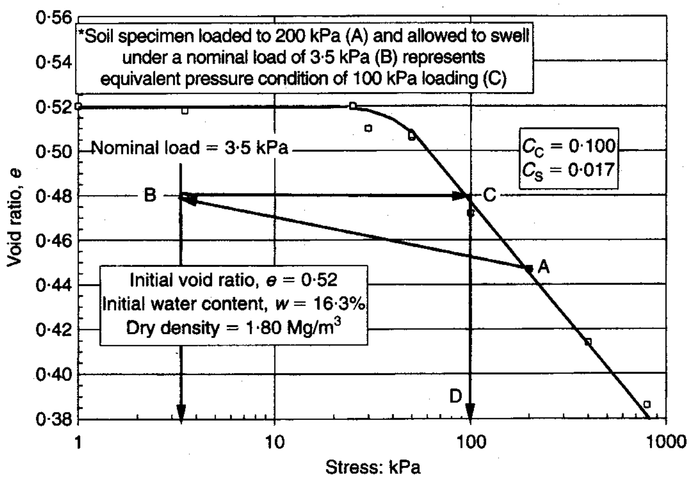

Fig. 3. Void ratio versus the applied stress for an initial void ratio of 0·52

Dry of optimum	Optimum	Wet of optimum
$\gamma_d = 1{\cdot}73\ \mathrm{Mg/m^3}$	$\gamma_d = 1{\cdot}80\ \mathrm{Mg/m^3}$	$\gamma_d = 1{\cdot}77\ \mathrm{Mg/m^3}$
$w = 13\%$	$w = 16{\cdot}3\%$	$w = 19{\cdot}2\%$
Equivalent pressure (kPa)	Equivalent pressure (kPa)	Equivalent pressure (kPa)
1. 0 kPa	1. 0 kPa	1. 0 kPa
2. 25 kPa (40 kPa)	2. 25 kPa (25 kPa)	2. 25 kPa (25 kPa)
3. 100 kPa (160 kPa)	3. 100 kPa (200 kPa)	3. 100 kPa (210 kPa)
4. 200 kPa (320 kPa)	4. 200 kPa (400 kPa)	4. 200 kPa (420 kPa)

Note: The values in parentheses are prestress pressures.

Fig. 4. Testing programme for soil–water characteristics (section 1)

prepared and used for testing. The prestress pressures are also shown in parentheses. To use this procedure, the compression index, C_c, and the swelling index, C_s, values have to be known. These values were measured from a separate laboratory test programme for the three different initial water content conditions and are summarized in Table 2.

Saturated specimens with 25 kPa equivalent pressure

The procedure described earlier would not be suitable for preparing optimum and wet of optimum initial water content specimens with an equivalent pressure of 25 kPa, because these specimens are in a state of constant volume conditions at these pressures (see Fig. 3, for example). Hence, the specimens were loaded to 25 kPa in stages and were allowed to remain for a period of 36 h and were used for testing.

Pressure plate tests for all specimens

The specimens prepared using conventional oedometer testing were kept in their consolidation rings and set on the ceramic disk of the pressure plate. A mass of 500 g was placed on top of the specimens to ensure that good contact was maintained between the ceramic disk and the soil specimen. This applied mass resulted in a vertical pressure of 1·6 kPa on the specimen. It was impractical to apply pressures as large as 3·5 kPa because of space limitations in the pressure plate apparatus.

The chamber above the soil specimens was pressurized to the desired value of suction. The water from the specimen discharged under the influence of the suction. The volume of water that was discharged under these conditions was estimated from the known initial mass of the specimen. Equilibrium was assumed when water no longer discharged from the pressure plate. Six to seven days were typically required for the specimens to reach equilibrium with the applied suctions. At this point, the specimens were removed and weighed to determine their water content. This procedure was repeated at each desired value of suction. Soil–water characteristics were determined for suctions ranging from 0 to 1500 kPa using pressure plate apparatus. More details of the test procedure are available in ASTM (1993).

When the tests on each specimen were terminated at a suction of 1500 kPa, the specimen was removed and approximately half of it was used as a final check of the water content. A small sample of the remainder of the specimen, about 4–5 g, was used in the osmotic desiccator apparatus to determine total suction which is described later in this section.

The calculations of degree of saturation in this study were made with reference to the void ratio of the specimen at the equivalent pressure (i.e. no allowance was made for subsequent volume change). The changes in void ratio with respect to suction were calculated for a series of tests and were not found to be significant for the sandy clay till used in this project (Vanapalli, 1994). Statically

Table 2. Compression and swelling indices values for different initial conditions

Initial condition	C_c	C_s
Dry of optimum ($w = 13\%$, $\gamma_d = 1{\cdot}73\ \mathrm{Mg/m^3}$)	0·16	0·016
Optimum ($w = 16{\cdot}3\%$, $\gamma_d = 1{\cdot}80\ \mathrm{Mg/m^3}$)	0·10	0·017
Wet of optimum ($w = 19{\cdot}2\%$, $\gamma_d = 1{\cdot}77\ \mathrm{Mg/m^3}$)	0·08	0·010

compacted specimens of this material are relatively stiff and resistant to volume change with respect to changes in suction. Results from Sridharan *et al.* (1971) also support this behaviour. However, for soils of high plasticity such as expansive clays, the variation of void ratio with respect to suction may be significant.

Osmotic desiccator tests

An osmotic desiccator was used to complete the soil–water characteristic for ranges of suction greater than 1500 kPa. Salt solutions in glass desiccators control the relative humidity and vapour pressure in the specimen. In this study, five aqueous solutions were selected, producing a range of suction values from 3500 to 300 000 kPa (*CRC Handbook of Chemistry and Physics*, 1995). The salts used in this study and their associated relative humidities and suction values at a temperature of 23°C are summarized in Table 3. A maximum value of 300 000 kPa of total suction was considered adequate to define the soil–water characteristic.

Each sub-specimen taken from the pressure plate tests was placed in one of the glass desiccators containing a liquid of specific salt concentration corresponding to a known value of total suction. This testing programme was undertaken in a room where the temperature was controlled. The mass was measured using a sensitive electronic balance (i.e. 0·001 g). After the specimen had reached equilibrium with the atmosphere in the desiccator, the water content was determined. In this way, a complete soil–water characteristic for the entire range of suctions was determined for the soil specimen associated with an initial water content and predetermined stress history.

While the pressure plate apparatus measures matrix suction only, the osmotic desiccator measures total suction. Since the osmotic component of suction should only be weakly dependent on water content, and since the matrix component increases exponentially with decreasing water content, the difference between total suction and matrix suction should become increasingly small at high suctions.

Table 3. Summary of salt solutions, humidities and equivalent total suction used in osmotic desiccator tests

Salt	Relative humidity: %	Equivalent total suction: MPa
Lithium chloride $LiCl.H_2O$	11·3	297·6
Magnesium chloride $MgCl_2.6H_2O$	32·9	151·7
Magnesium nitrate $Mg(NO_3)_2.6H_2O$	53·4	85·6
Sodium chloride $NaCl$	75·7	38
Potassium sulphate K_2SO_4	96·8	4·4

Testing programme, section 2 (individually compacted specimens)

Section 2 comprises three sets of tests to determine the matrix suction of individually compacted specimens of 100 mm in diameter and 21 mm in height. These tests were used to evaluate the role that soil structure or aggregation plays in determining soil suction. The specimens were prepared based on the water content and density associated with the AASHTO standard compaction tests. The matrix suction for the individually compacted specimens was determined with a null pressure plate using the axis-translation technique (Hilf, 1956). Each set of individually compacted specimens was prepared at the same dry density (i.e. constant void ratio with varying initial water contents). Three such sets were prepared and the results of these tests are summarized in Table 4.

Specimens were prepared with initial water contents ranging from 12·5% to 19·2%. Matrix suction measurements for specimens with water contents lower than 12·5% could not be made due to the limitations of the air-entry value of the porous stone in the null pressure plate (i.e. 500 kPa). It was difficult to prepare the specimens with water contents greater than 19·5% because the specimens were very soft and difficult to handle. In some cases a film of water developed on the surface of the specimen, suggesting that positive pore water pressures might have been developing in the specimens at these higher water contents. Therefore, it was decided to restrict the study of matrix suction measurements for individually compacted specimens to a water content range of 12·5% to 19·2%.

RESULTS AND DISCUSSION

Properties influencing the desaturation characteristics of fine-grained soils

Soil–water characteristics with different initial water contents and densities are shown in Fig. 5 (equivalent pressure 0 kPa). The drying characteristics with respect to soil suction vary with the initial moulding water contents. Fine-grained soils, such as this sandy clay till, typically have two levels of structure: a macro-level structure and a micro-level structure. The soil microstructure is described as the elementary particle associations within the soil, whereas the arrangement of the soil aggregates is referred to as the macrostructure (Mitchell, 1976). Typically, both the macro- and micro-levels of structure are present in natural and compacted clayey soils. The resulting macrostruc-

Table 4. Variation of degree of saturation (water content) versus matrix suction for individually compacted specimens (section 2)

Matrix suction: kPa	Dry density 1·73 Mg/m³ Void ratio, $e = 0{\cdot}58$	Dry density 1·80 Mg/m³ Void ratio, $e = 0{\cdot}52$	Dry density 1·77 Mg/m³ Void ratio, $e = 0{\cdot}545$
74	87·2 (*18·5*)		
92	84·7 (*18·0*)		
138	79·8 (*16·9*)		
148	78·7 (*16·7*)		
186	76·8 (*16·3*)		
228	68·1 (*14·5*)		
232	67·8 (*14·5*)		
258	66·5 (*14·1*)		
368	61·0 (*12·9*)		
372	60·5 (*12·1*)		
39		98·5 (*18·76*)	
62		92·4 (*17·60*)	
140		86·2 (*16·41*)	
160		86·3 (*16·44*)	
220		78·6 (*14·97*)	
300		71·0 (*13·52*)	
82			90·4 (*18·04*)
126			85·3 (*17·02*)
246			78·2 (*15·61*)
283			72·6 (*14·49*)
376			65·2 (*13·01*)

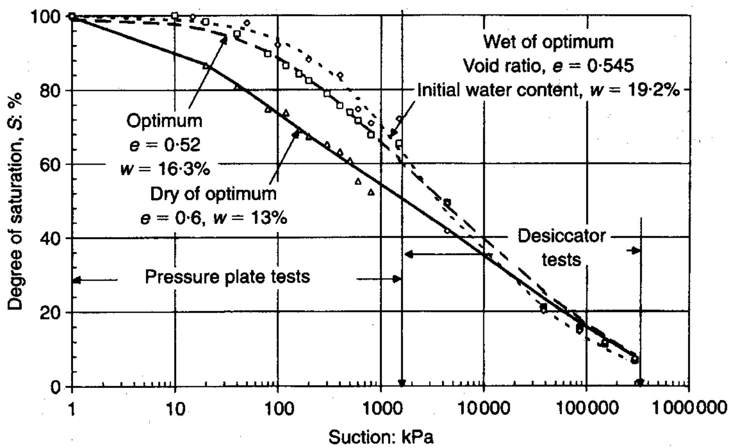

Fig. 5. Soil–water characteristics for specimens compacted at different initial water contents

ture of specimens prepared at different initial water contents is different in spite of their identical mineralogy, texture and method of preparation.

The resistance to water discharge (i.e. desaturation) is relatively low in the dry of optimum specimens in comparison to optimum and wet of optimum specimens (Fig. 5). The specimens with initial water content dry of optimum contain relatively large pore spaces which are located between the clods of soil as compared to the pore spaces within the clods. The relatively low suction values associated with removing water from the large pores are significantly different from the large suctions required to remove water from the microscopic pore spaces between soil particles within the clods of clay. As a result, the macrostructure controls the initial desaturation of compacted clayey specimens with initial water contents, which are dry of optimum.

The pore spaces in a clayey soil compacted at an initial water content wet of optimum are not generally interconnected or are in an occluded state. These soils are more homogeneous and have a higher storage capacity due to their different structure. They have no visible interclod pores and offer more resistance to desaturation under an applied suction in comparison to those specimens compacted dry of optimum. In contrast to the specimens compacted dry of optimum, the microstructure in the specimens compacted wet of optimum controls and resists the desaturation (drying) characteristics of the soil. Hence, the slope of the soil–water characteristic is relatively flatter for the wet of optimum specimen in comparison to the dry of optimum initial water content specimen in the lower suction range where the desaturation was attained by the liquid-phase drainage (i.e. 0–1500 kPa). The boundary between the occluded pore space and the open pore conditions occurs at water contents approximately equal to the optimum water content (Marshall, 1979), and, hence, the specimen prepared at optimum water content condition lies between these two.

The soil–water characteristics developed for the specimens compacted dry of optimum and with equivalent pressures of 0, 25, 100 and 200 kPa are shown in Fig. 6. It is apparent that the air-entry value of the specimens increases with increasing equivalent pressure. In general, beyond the air-entry value of suction, the specimens subjected to higher equivalent pressures have higher degrees of saturation. The macrostructure appears to dominate the soil–water characteristic features of the specimens prepared dry of optimum in spite of the increase in the equivalent pressures.

Figures 7 and 8 show the variation of degree of saturation with respect to suction for specimens at optimum and wet of optimum with different equivalent pressures. In spite of the different equivalent pressures, the soil–water characteristics of specimens with wet of optimum initial water content conditions appear to be the same (i.e. the soil–water characteristics appear to be independent of the stress history; Fig. 8). The drying characteristics are governed by the microstructure for wet of optimum water content specimens for the entire suction range. The soil–water characteristic behaviour of the specimens compacted at optimum water content condition lies between those of specimens tested with dry and wet of optimum initial conditions (Fig. 7). The air-entry value increases with both an increase in the initial moulding water content and the equivalent pressures for all the specimens tested.

The variation of air-entry pressure with the initial void ratio for all the specimens tested with different initial water contents is shown in Fig. 9. The figure shows that for any particular void ratio, the air-entry values of the specimens tested dry of optimum are always lower than those of the specimens tested at optimum and wet of optimum. Thus, the soil structure (and aggregation), which is a function of the initial moulding water content, governs the air-entry value. The air-entry values of specimens wet of optimum do not appear to be strongly dependent on the applied stress history.

Soil–water characteristic behaviour in the high suction range

For all the initial conditions of water content (i.e. dry of optimum, optimum and wet of opti-

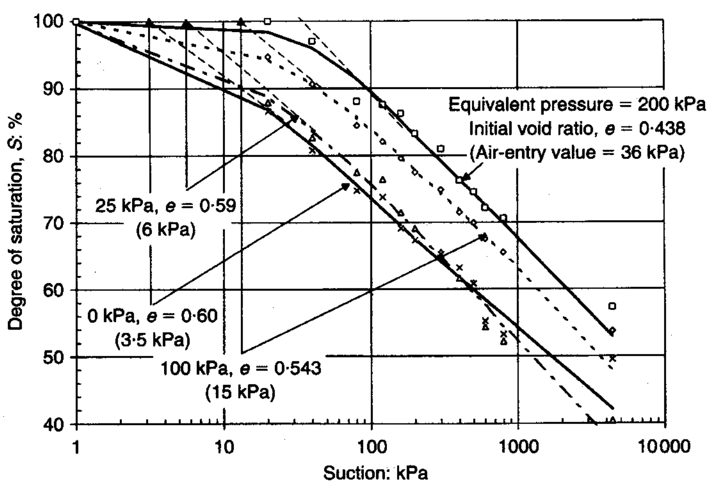

Fig. 6. Soil–water characteristics for specimens compacted dry of optimum water content

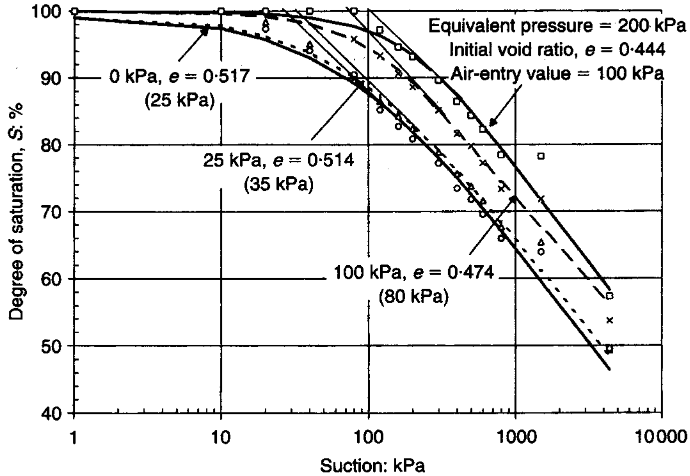

Fig. 7. Soil–water characteristics for specimens compacted at optimum water content

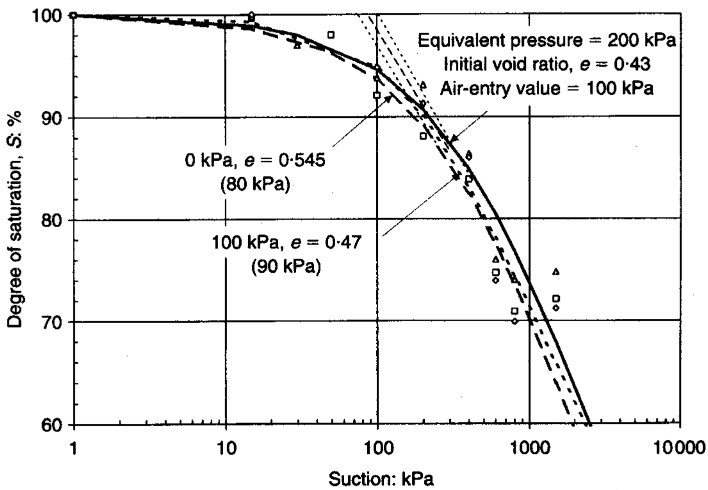

Fig. 8. Soil–water characteristics for specimens compacted wet of optimum water content

mum) and stress history, the soil–water characteristic behaviour appears to be similar at higher suctions (i.e. 20 000–300 000 kPa) (Figs 10–12). In other words, the inter-aggregate structure appears to be the same for all the specimens at these higher suctions. Presumably, the water films at these suctions are so thin that all the water is within the range of influence of the osmotic and adsorptive fields.

The soil–water characteristic (testing programme – section 1) and statically compacted individual specimens (testing programme – section 2)

The data from section 2 of the testing programme (Table 4) are used to explain the influence of initial water content on the soil structure (and aggregation), and thereby on the suction in the soil. The soil–water characteristics (testing programme, section 1) described in the previous section are

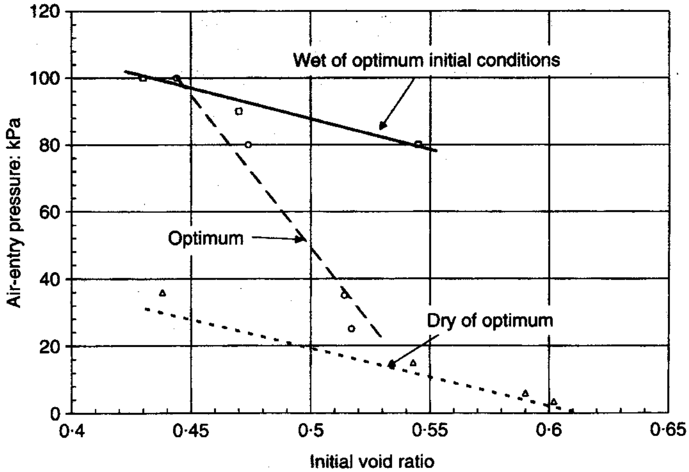

Fig. 9. Air-entry value versus initial void ratio from the soil–water characteristics

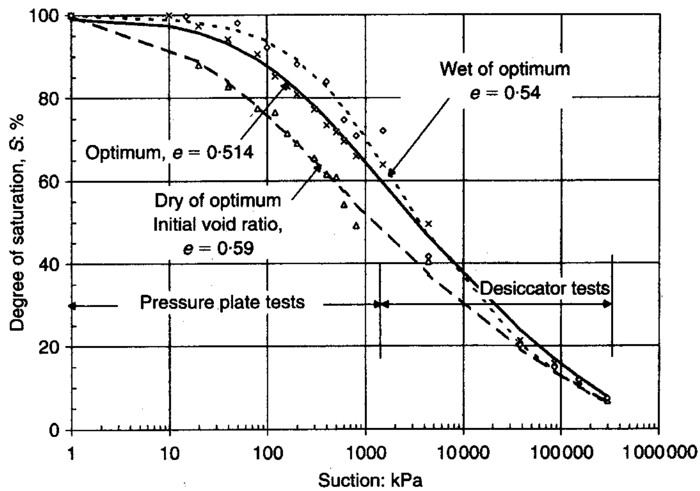

Fig. 10. Soil–water characteristics for specimens with an equivalent pressure of 25 kPa

compared with the matrix suction versus degree of saturation results of individually compacted specimens. The relationship between the degree of saturation and matrix suction obtained from individually compacted specimens is different from the soil–water characteristic, which is the variation of degree of saturation with suction for a single specimen. Moreover, the resulting soil structure (and aggregation) of the individually compacted specimens at various initial water contents will be different from that of specimens with a corresponding water content on the soil–water characteristic.

Dry of optimum initial water content conditions

Figure 13 shows the best-fit soil–water characteristic for a specimen with dry of optimum initial water content conditions with an equivalent pressure of 0 kPa. The degree of saturation versus matrix suction results of individually compacted specimens are also shown. The initial void ratios for all specimens are the same. Matrix suction and corresponding degrees of saturation greater than 75% for individually compacted specimens lie above the best-fit soil–water characteristic. These specimens with degrees of saturation greater than

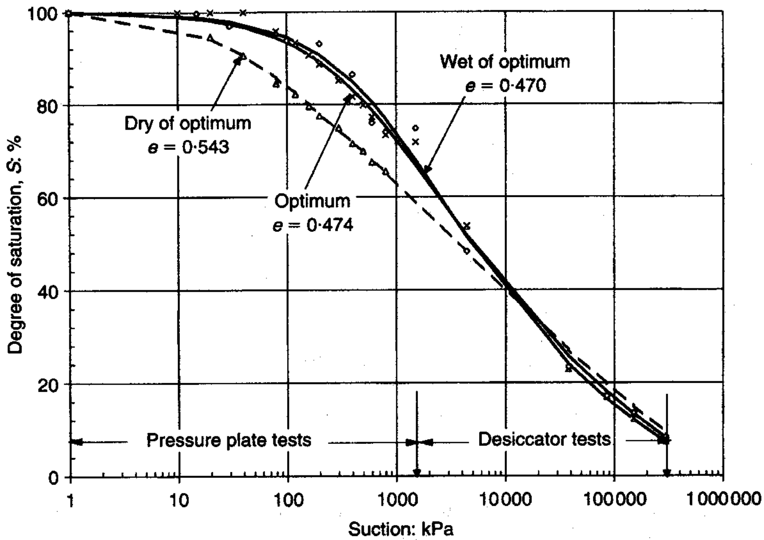

Fig. 11. Soil–water characteristics for specimens with an equivalent pressure of 100 kPa

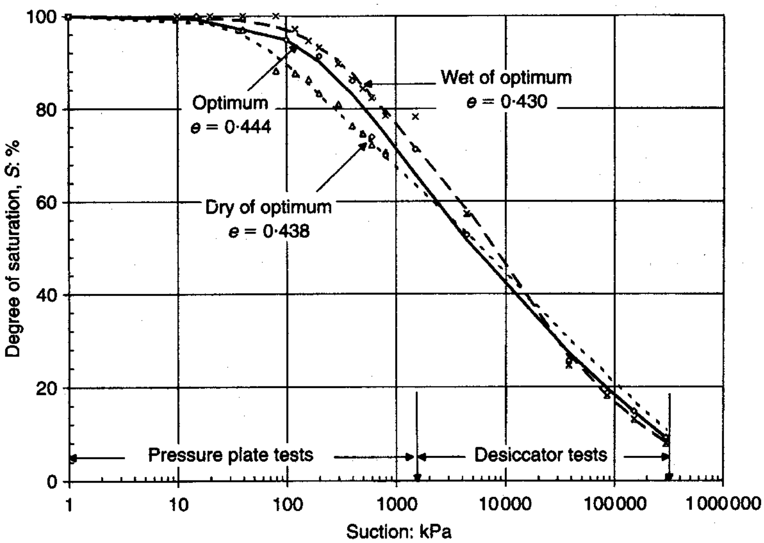

Fig. 12. Soil–water characteristics for specimens with an equivalent pressure of 200 kPa

75% have water contents above 16%. The resulting soil structure (and aggregation) at this water content and higher should be similar to that of the specimens at optimum and wet of optimum conditions.

The matrix suction values of the individually compacted specimens with degrees of saturation less than 68% and corresponding water content of 14·5% are comparable to the values of suction and degree of saturation of the specimens used to determine the soil–water characteristic. At these water contents of approximately 14·5%, the individually compacted specimens and the specimen used for the soil–water characteristic can be considered to be 'identical' due to their 'similar' soil structure (and aggregation).

It is apparent that the behaviour of the individually compacted specimens at higher saturations is

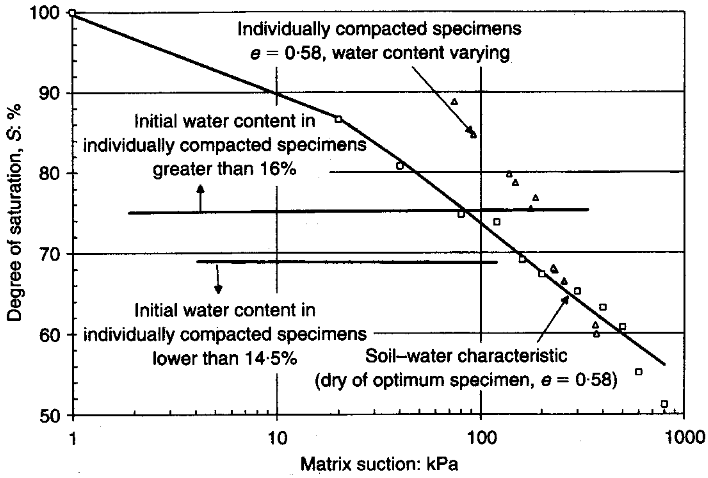

Fig. 13. Comparison of soil–water characteristics for specimens compacted dry of optimum water content and compacted at the same initial void ratio

different from the soil–water characteristic behaviour. In these cases, the initial water contents of the specimens are different, and the resulting soil structure (and aggregation) is different. Over the selected range of water contents (i.e. from 12·5% to 19·2%), the degrees of saturation of the individually compacted specimens varied from 58·8% to 90·3%. These specimens are different from one another because they have different soil structures (resulting from the interparticle aggregations) based on their initial water content.

Optimum initial water content conditions

Figure 14 shows the best-fit soil–water characteristic with optimum initial water content conditions (void ratio equal to 0·52 and initial water content of 16·3%) and an equivalent pressure of zero. The degree of saturation versus matrix suction of individually compacted specimens is also shown for comparison. The soil–water characteristic lies below the results of individually compacted specimens in the region of 0–150 kPa matrix suction. The initial water content in individually com-

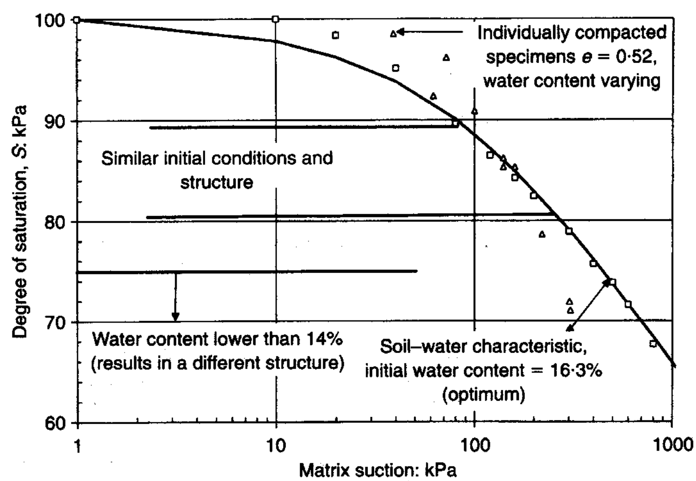

Fig. 14. Comparison of soil–water characteristics for specimens compacted at optimum water content and those compacted at the same initial void ratio

pacted specimens for this range of matrix suction is higher than 16·3% (i.e. degree of saturation greater than 86%). With the increased water content in the compacted specimens, the soil aggregations differ and result in a different soil structure. As the water content in the individually compacted specimens decreases, the values of matrix suction fall below the soil–water characteristic. This discrepancy is expected because the specimens with lower water contents exhibit a different soil structure based on their aggregation, which in turn depends on the water content. The resulting structure (or aggregation) is similar to the soil structure expected for specimens with dry of optimum conditions. At a degree of saturation around 86% (i.e. at 16·3% water content), both the individually compacted specimens and the specimen used for the soil–water characteristic show similar matrix suction values. This correspondence is possible as both the structure and density in the two specimens are approximately the same and they behave as 'identical' specimens.

Wet of optimum initial water content conditions

Figure 15 gives the comparisons of soil–water characteristics obtained using wet of optimum initial conditions (i.e. initial water content equal to 19·2%) and an equivalent pressure of zero with those of individually compacted specimens. The individually compacted specimen results fall below the soil–water characteristic. The individually compacted specimens were tested with water contents in the range of 13–19·2%. It can be seen that, as initial water contents in the individually compacted specimen increase, the agreement with the soil–water characteristic also increases.

Figure 16 shows the degree of saturation versus matrix suction for all of the individually compacted specimens with different initial water contents for the three void ratios (i.e. dry densities) tested. The figure shows that the results fall within a narrow band. The same data, when plotted as gravimetric water content versus matrix suction, show a clearer relationship (Fig. 17). Olson & Langfelder (1965) and Krahn & Fredlund (1972) reported similar observations for a wider range of void ratios (i.e. dry densities). Thus, for the void ratios used in this study (i.e. 0·52–0·58), it is the initial water content which governs the matrix suction of individually compacted specimens, and not the initial void ratio.

SUMMARY AND CONCLUSIONS

Several empirical and theoretical procedures are available in the literature to model unsaturated soil properties using the soil–water characteristic. The literature indicates that the range of suction from saturation to the dry condition in a soil varies from 0 to 1 000 000 kPa irrespective of the type of soil. Two key features of the soil–water characteristic are the air-entry value and the residual state of saturation. Residual state of saturation is used as one of the parameters in several models. A graphical procedure is proposed in this paper to define the residual state of saturation using the entire soil–water characteristic. Models that use the entire soil–water characteristic have a definite advantage for predicting unsaturated soil properties over the entire range of suction and water contents.

The initial moulding water content has a consid-

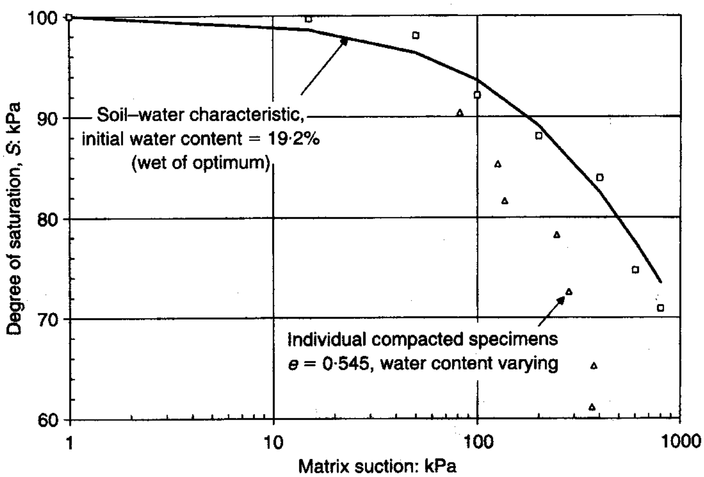

Fig. 15. Comparison of soil–water characteristics for specimens compacted wet of optimum initial water content and compacted at the same initial void ratio

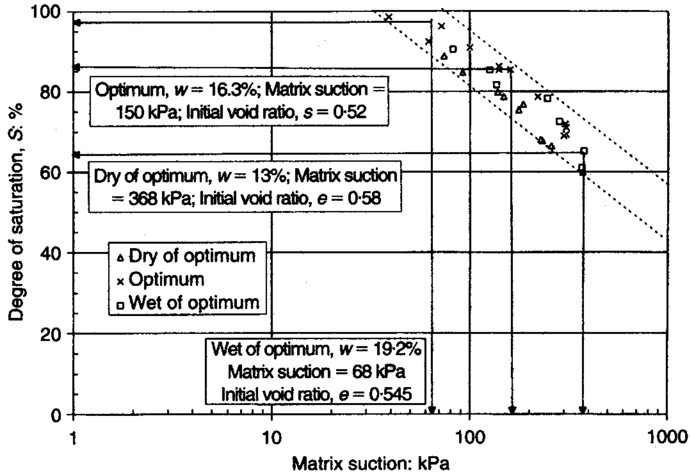

Fig. 16. Degree of saturation versus matrix suction values for compacted specimens

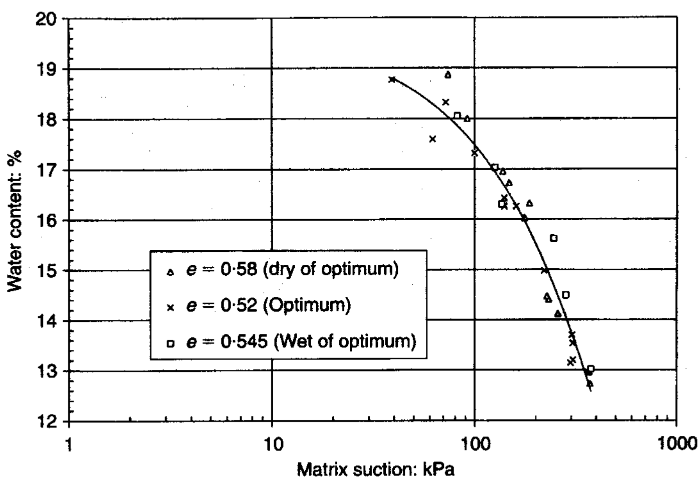

Fig. 17. Gravimetric water content versus matrix suction for compacted specimens

erable influence on the resulting structure (and aggregation) of fine-grained soils such as the sandy clay till used in this research programme. The soil–water characteristic of fine-grained soils is dependent mainly on the structure (and aggregation) and the stress history, rather than the initial void ratio.

Macrostructure governs the soil–water characteristic behaviour for specimens compacted with initial water contents dry of optimum, particularly in the low range of suction values. These specimens exhibit a steeper soil–water characteristic when compared with specimens compacted at optimum and wet of optimum water contents. The dry of optimum specimens act more like a coarse-grained soil because of their highly aggregated macrostructure. The air-entry value and the residual state of saturation of the soil increase with the equivalent pressure for specimens with dry of optimum initial water content conditions.

Microstructure apparently governs the soil–water characteristic behaviour of specimens compacted wet of optimum. The soil–water characteristic behaviour is not significantly influenced by the equivalent pressure or the stress history in this study (i.e. 0–200 kPa). Specimens wet of optimum have higher air-entry values and higher values of residual state of saturation than those compacted at optimum or dry of optimum water contents.

The soil–water characteristics appear to be approximately the same over suction ranging from

20 000 to 1 000 000 kPa (desiccator tests) for specimens tested with different initial water content conditions. The soil structure (and aggregation) appears to have no influence on the soil–water characteristic behaviour in this range of suctions.

The matrix suctions of individually compacted specimens determined from null pressure plates were dependent on the initial water content rather than the initial void ratio. At 'identical' conditions (i.e. at similar densities, water contents and stress state conditions), the matrix suctions corresponding to a particular degree of saturation were observed to be the same as those given by the soil–water characteristic. The conclusions of this study should be valid for all fine-grained soils.

More fundamental research, however, is recommended to fully understand the soil–water characteristic, particularly because it relates to the development of methods for estimating the properties of unsaturated soils. Additional experimental work will be required on various soils throughout the world to add credence to the results presented here.

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