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THE RELATIONSHIP BETWEEN THE SOIL-WATER CHARACTERISTIC CURVE AND THE UNSATURATED SHEAR STRENGTH OF A COMPACTED GLACIAL TILL

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The Relationship Between the Soil-Water Characteristic Curve and the Unsaturated Shear Strength of a Compacted Glacial Till

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ABSTRACT: Soils compacted at various "initial" water contents and to various densities should be considered as "different" soils from a soil mechanics behavioral standpoint even though their mineralogy, plasticity, and texture are the same. The engineering behavioral change from one specimen to another will vary due to differences in soil structure or aggregation. The shear strength of an unsaturated soil and the soil-water characteristic curve are dependent on soil structure or the aggregation, which in turn is dependent on the "initial" water content and the method of compaction. The laboratory preparation of specimens must, therefore, closely represent the physical conditions and the stress state conditions likely to occur in the field if a proper assessment of the shear strength parameters is to be achieved. This paper is primarily concerned with the study of the relationship between the shear strength of an unsaturated soil and its soil-water characteristic curve.

Consolidated drained direct shear tests were conducted on statically compacted glacial till specimens, both under saturated and unsaturated conditions, representing three "initial" water contents and densities. The "initial" water contents and densities of the specimens were selected to represent the dry, optimum, and wet of optimum water content conditions with reference to the compaction curve. Multistage, unsaturated, direct shear tests were conducted under three different net normal stresses with varying matric suction values for each case. The soil-water characteristic curves were also developed on specimens with "initial" conditions similar to those used for the unsaturated shear strength tests.

The shear strength variation with respect to matric suction was found to be nonlinear for all the tests. The rate of increase in the shear strength contribution due to matric suction, however, was found to be related to the rate of desaturation of the soil. The desaturation characteristics are a function of the "initial" water content of the compacted specimens. For any particular net normal stress and matric suction, specimens compacted wet of optimum water content offered more resistance to desaturation and exhibited a higher shear strength when compared to specimens compacted at dry of optimum or at optimum water content conditions. Under similar "initial" conditions, the soil-water characteristic curve bears a close relationship to the unsaturated shear strength behavior of the soil.

KEYWORDS: unsaturated soils, shear strength, stress state, soil-water characteristic curve, suction, soil structure

The constitutive equations for volume change, shear strength, and flow for unsaturated soil are becoming generally accepted in geotechnical engineering (Fredlund and Rahardjo 1993). The measurement of soil parameters for the unsaturated soil constitutive models, however, remains a demanding laboratory process. Empirical procedures to estimate the unsaturated soil properties would be valuable. Observing the similarities in their behavior, several investigators have proposed equations for defining the soil-water characteristic curve and use them to predict the variation of unsaturated coefficient of permeability with respect to suction (Brooks and Corey 1964; McKee and Bumb 1984; van Genuchten 1980; Fredlund and Xing 1994; Fredlund, Xing, and Huang 1994). Laboratory studies reporting the similarities in shear strength behavior of an unsaturated soil and the soil-water characteristic curve are, however, lacking.

A rational approach for characterizing the shear strength of an unsaturated soil in terms of stress state variables was put forward by Fredlund et al. (1978). Elastic-plastic and critical state soil mechanics theories have also been extended through the use of the stress state variables (Karube 1988; Toll 1990; Wheeler and Sivakumar 1992).

The shear strength variation with respect to matric suction has been well established as being nonlinear (Gan et al. 1988; Escario and Juca 1989; Abramento and Carvalho 1989). The nonlinear increase in shear strength can be attributed to the desaturation of a soil as the matric suction is increased. The rate of desaturation of a soil with respect to the applied suction is dependent on the "aggregation" or the "structure" of the soil. In this paper, the influence of "aggregation" on the desaturation characteristics and unsaturated shear strength behavior of the soil with respect to matric suction is presented and discussed. The close relationship of the shear strength of unsaturated soils to the soil-water characteristic curve under similar "initial" conditions is highlighted. The influence of "initial" water content on the saturated shear strength parameters is also presented.

Background

A linear equation for the shear strength of an unsaturated soil was proposed by Fredlund et al. (1978):

$$\tau_f = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \qquad (1)$$

where

τ_f = shear strength of an unsaturated soil,
c' = effective cohesion of the soil,
ϕ' = effective angle of shearing resistance for a saturated soil,

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ϕ^b = angle of shearing resistance relative to an increase in matric suction,
σ_n = normal stress,
u_a = pore-air pressure,
u_w = pore-water pressure,
$(\sigma_n - u_a)$ = net normal stress on the failure plane at failure, and
$(u_a - u_w)$ = matric suction at the point of failure.

Experimental results by Gan and Fredlund (1988), Escario and Juca (1989), Abramento and Carvalho (1989), and Wheeler and Sivakumar (1992) show a nonlinear variation of shear strength with respect to suction when tested over a wide-range matric suction. When the matric suction is lower than the air-entry value, the soil is essentially saturated and the applied matric suction acts directly to increase the effective stress in contributing to the shear strength. In terms of stress state variables, a matric suction increase is essentially equivalent to an increase in net normal stress up to the air-entry value, $(u_a - u_w)_b$, of the soil. Under these circumstances, ϕ^b is equal to ϕ'. With an increase in matric suction beyond the air-entry value, the specimen starts to desaturate and the area of water across which the matric suction acts also decreases (Vanapalli 1994). At this point, the shear strength envelope becomes nonlinear, as matric suction is less effective than the net normal stress in increasing the shear strength (i.e., ϕ^b decreases with an increase in matric suction). The nonlinear nature of the shear strength envelope depends on the desaturation characteristics of the soil. The desaturation characteristics of a soil can be different due to the soil structure and the soil aggregation. These factors are dependent upon the "initial" water content and the compaction effort used on the soil.

A fine-grained soil will, in general, have two levels of soil structure: a macro structure and a micro structure. These structures are present in both natural and compacted soils. The macro and micro structures of the soil are a function of the type of soil, initial water content, compaction procedures, and the applied stresses. The micro structure is the arrangement of the elementary particle associations within the soil aggregates, whereas the macro structure is the arrangement of soil aggregates (Mitchell 1976).

The desaturation characteristics of a soil with changing matric suctions can vary for different "initial" water contents. Soil molded dry of optimum has an *open* structure with large interconnected pores. Specimens compacted dry of optimum have interclod pores that make the soil take on the appearance of a coarse soil. Soils compacted dry of optimum contain relatively large interconnected pore spaces located between the clods of clay rather than the microscopic pore spaces among soil particles within the clods. These large pores offer little resistance to drainage under an applied matric suction. As a result, the macro structure controls the initial desaturation process in compacted specimens, particularly when the "initial" water contents are dry of optimum.

In contrast to soils compacted dry of optimum, it is generally recognized that the pore spaces are in a more *occluded* state in a cohesive soil compacted wet of optimum. The specimens having higher "initial" water contents often exhibit no visible interclod pores and offer more resistance to desaturation under an applied suction in comparison to specimens compacted dry of optimum. As a result, the micro structure in specimens compacted wet of optimum controls the desaturation characteristics of the soil rather than the macro structure. The threshold for the *occluded* and *open* states is believed to be approximately at optimum water content conditions (Marsall 1979).

The shear strength of unsaturated soils is primarily controlled by the shearing resistance mobilized along the interaggregate contacts (Barbour and Yang 1992). In saturated soils, the angle of shearing resistance, ϕ', is dependent mainly on the friction developed due to the interlocking of aggregates. In unsaturated soils, the structure or aggregation is supported by the suction, which may be maintained even under the application of compressive stresses (Toll 1990). As a stress state variable, suction contributes to the increase in shear strength of an unsaturated soil through the wet-surface, interaggregate contact points.

The "initial" molding water content of the soil influences the structure or the aggregation and hence the desaturation characteristics and wet surface interaggregate contact points at a particular suction. Thus, the unsaturated shear strength of a soil can differ due to varying desaturation characteristics that are dependent upon the "initial" water content of the soil. The laboratory testing of soils must therefore closely represent the physical properties and the stress state conditions likely to occur in the field if a proper assessment of the shear strength parameters is to be achieved.

The influence of "aggregation" on the shear strength behavior of a glacial till in saturated and unsaturated conditions arising from the use of different "initial" water contents is presented and discussed in this paper. The relationship between the soil-water characteristic curve and the unsaturated shear strength behavior is also studied.

Test Program

A glacial till obtained from Indian Head, Saskatchewan was used for the study. The soil was air-dried for several days, pulverized using a rubber mallet, and passed through a 2-mm sieve. The liquid limit, ω_L, and the plastic limit, ω_P, are 36 and 17%, respectively. The percentages of sand, silt, and clay were 28, 42, and 30, respectively. The AASHTO standard compacted density was 1.80 Mg/m^3 with an optimum water content of 16.3%. The specific gravity of soil was 2.73. The soil is classified as a sandy clay, CL, and the clay fraction is predominately a calcium montmorillonite.

The required quantity of soil thoroughly mixed with water was placed into a constant volume mold 100 mm in diameter and statically compacted. Specimens 100 mm in diameter and 21 mm in height were prepared. The specimens for conducting direct shear tests (i.e., 51 by 51 by 20 mm) were trimmed from the 100-mm-diameter specimen. A comprehensive experimental program was conducted using the statically compacted specimens in saturated and unsaturated conditions. Three initial water contents were selected representing dry of optimum water content conditions (i.e., initial water content of 13% and a γ_d equal to 1.73 Mg/m^3) at optimum water content (i.e., initial water content of 16.3% and a γ_d equal to 1.80 Mg/m^3) and wet of optimum water content (i.e., initial water content of 19.2% and a γ_d equal to 1.77 Mg/m^3).

Saturated Shear Strength Parameters

Effective shear strength parameters were determined both under single-stage testing and the residual shear strength testing using a conventional direct shear apparatus. To attain saturation, soil specimens in the direct shear box were allowed to imbibe water for a period of 24 h under a nominal surcharge (i.e., porous disk and loading cap). The specimen was then fully consolidated under a specified load. A period of 24 h was observed to be sufficient to consolidate the specimens. Multistage direct shear tests under saturated conditions were also conducted to obtain the effective shear strength parameters for analysis. The study showed that the multistage test was suitable for use with the modified direct shear apparatus.

Single-Stage Direct Shear Tests

The measured shear strength parameters in the single-stage direct shear, performed at different "initial" water contents and densities, were essentially the same (i.e., effective cohesion, c', was equal to 15 kPa, and the angle of shearing resistance, ϕ', was equal to 23°). Lee and Haley (1968) and Gibbs and Hilf (1953) reached similar conclusions from their tests on compacted specimens with different "initial" water content conditions. The principal reason stated by Lee and Haley (1968) was that after saturation and consolidation to the same effective stresses, the strength of specimens with different "initial" water contents resulted in different changes in water content for a given structure. Changes in strength resulting from these changes in water content tend to compensate for the strength differences due to the structure.

Residual and Multistage Direct Shear Tests

One series of tests (i.e., specimens with an optimum water content of 16.3% and γ_d of 1.80 Mg/m^3) was conducted to obtain the residual shear strength parameters since the analysis of the single-stage tests showed that different "initial" water content conditions for the soil did not significantly influence the saturated shear strength parameters if the dry density varied by a small amount. The dry densities for the tests conducted varied between 1.73 to 1.80 Mg/m^3. The specimens were sheared along precut planes (i.e., at the interface of the top and bottom halves of the direct shear box) after consolidation. Based on experience of previous studies on the same soil, a horizontal displacement of 5 mm travel was selected for studying the shear strength mobilization for five cycles. The results obtained from the residual shear testing showed that there was essentially no drop in strength once the soil attained a peak strength value. Under continued reversals of the shear box, approximately the same maximum stress was observed. This procedure confirmed the suitability of the soil for multistage testing.

Multistage testing using the direct shear testing equipment (i.e., equipment modified to determine the shear strength on unsaturated soil) with the same initial conditions adopted for the residual testing was selected. From all three types of tests conducted, there was little variation in the angle of shearing resistance, ϕ', as observed in Table 1 and Fig. 1. The shear strength parameters along with the displacement rates for the different types of direct shear tests conducted are summarized in Table 1.

The variation in the cohesion from 15 kPa in single-stage testing to 4 kPa in the multistage testing can be attributed to the variation in strain rate, different pieces of direct shear equipment used, type of testing procedures, and the possible variation in soil properties.

TABLE 1—*Strength parameters of saturated till from different types of direct shear tests.*

Type of Direct Shear Test	c', kPa	ϕ', degrees	Displacement Rate mm/day
Single-stage	15	22.5	18
Residual	8	23	18
Multistage	4	23	2.7

Ruddock (1966) postulated that failure to achieve complete equalization of pore-water pressures in multistage testing will be reflected in an increase in the measured cohesion. However, the angle of shearing resistance, ϕ', would not be significantly affected. Schmertman and Osterberg (1960) showed that larger strains are required for the complete mobilization of the frictional component of strength compared to the cohesive component of strength in multistage testing. It is possible that by the time the frictional component of strength is fully mobilized, the cohesion present upon further shear may be small. Gan (1986) used the same glacial till in his research and showed that once the peak shear strength was mobilized, the effective cohesion component was negligible.

The unsaturated shear strength tests for this research program were conducted using drained conditions in multistage testing. Therefore, the average shear strength parameters of ϕ' equals 23° and c' equal to 0 kPa can be considered to be reasonable.

Unsaturated Shear Strength Tests

The unsaturated shear strength of the statically compacted specimens was determined in multistage testing by using modified direct shear equipment designed by Gan and Fredlund (1988). Multistage testing overcomes two main problems generally encountered in testing unsaturated soils. Firstly, the time required for testing is reduced, making it feasible to test unsaturated soils of low permeability. Secondly, the same specimen can be tested under a fairly large range of matric suctions. This procedure helps to avoid the variability caused from the nonuniformity of different specimens. Design details of modified direct shear equipment are available in Gan and Fredlund (1988).

Before placing the trimmed unsaturated specimen in the shear box, the high air-entry disk was saturated with de-aired water by flooding the base of the shear box. The disk was placed in this condition overnight. Through the application of a small air pressure, the water was flushed out from below the ceramic disk in order to ensure the removal of any diffused or entrapped air in the system. This was done several times to ensure complete saturation of the high air-entry disk. The unsaturated soil specimen was then placed carefully into the shear box. The specimen was flooded with water (i.e., a small head of reservoir was created) for a period of 24 h to ensure saturation of the specimen. Vacuum grease was applied at the interface of shear surfaces to ensure that the water did not leak out. Care was taken not to contaminate the high air-entry porous disk with vacuum grease and to ensure there were no air leaks in the ceramic disk.

A predetermined normal stress and the desired matric suction was applied to the specimen by maintaining a constant air pressure in the pressure chamber keeping the high air entry disk saturated. Under an applied net normal stress, the specimen consolidates and the water collects at the top of the specimen. Since the coefficient of permeability of the air-entry disk is generally lower than the permeability of the soil, drainage under the net normal stress is upwards and thus some water is likely to be collected at the top of the specimen. The specimen gradually desaturates under the applied matric suction and comes to equilibrium with the applied stress state variables. During the process of equilibration, readings were taken of the vertical deflection and the water movement from the specimen with time. The applied stress state variables act on the specimen only after achieving total equilibration. Several trial studies were performed before deciding on the time for equilibration under each applied matric suction (Vanapalli 1994). A time period of five to six days for equilibrating the specimen and a

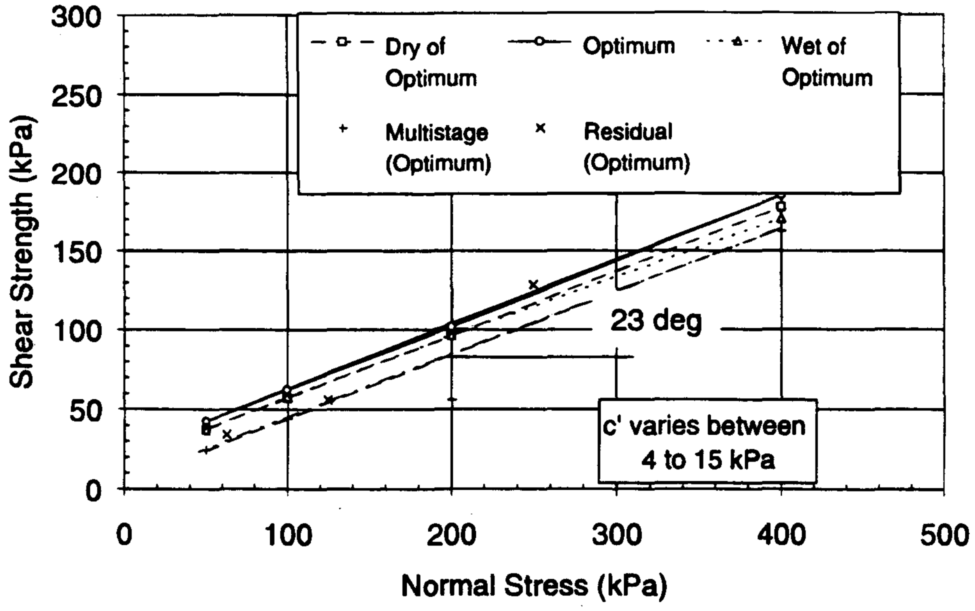

FIG. 1—*Results of saturated shear strength tests under different procedures.*

displacement rate of 2.7 mm/day were found to be satisfactory to achieve consolidated drained testing conditions. Five-stage multistage shear tests were conducted. The matric suction ranges selected were between 50 to 500 kPa. At each stage of loading, the specimen was sheared to obtain its peak strength and the shear load was then released by reversing the direction of horizontal shear displacement. The specimen was left in this condition overnight and a new matric suction was applied while maintaining the same net normal stress. The test process was repeated again under the new matric suction value. The peak load was attained after a movement of 1.2 to 2 mm under an applied matric suction. A five-stage multistage testing was possible within a displacement of 6 to 8 mm. Any diffused air collected at the bottom of the high air-entry disk was removed at regular intervals. The unsaturated shear strength behavior of the glacial till specimens was studied for different initial conditions and is summarized in Table 2.

The variation of shear strength with matric suction for the specimens tested with the initial conditions representing dry of optimum conditions under net normal stresses of 25, 75, and 200 kPa (i.e., results of Series D, E, F1, and F2) are shown in Fig. 2. All the experimental points are shown using symbols. The best-fit nonlinear envelopes are shown as continuous lines. The ordinate values represent the saturated shear strength values for the respective net normal stresses (i.e., $c' + (\sigma_n - u_a)\tan\phi'$). The straight lines drawn with a slope of 23° represent the saturated shear strength envelopes. The nonlinear nature of the shear strength envelope with respect to suction can be observed through comparison to the saturated shear strength envelopes. The nonlinear behavior can be observed for all the strength envelopes.

The shear strength envelopes are linear up to a particular matric suction value. The matric suction value at which the nonlinearity commences appears to coincide with the air-entry value of the soil. Air-entry value is the suction at which the specimen starts to desaturate. Below the air entry value, an increase in matric suction is equivalent to an increase in the net normal stress and the shear strength contribution due to matric suction is similar to the applied net normal stress. Hence ϕ^b is equal to ϕ' up to the air-entry value of the soil. In other words, Terzaghi's effective stress equation is valid for shear strength conditions up to the air-entry value of the soil.

With an increase in the matric suction, the specimen starts to desaturate. Desaturation starts through large size pores first, and the smaller sizes follow later. The area of water available for transmitting shear strength decreases with desaturation (i.e., the water area available along the interaggregates over which the matric suction acts decreases with increasing matric suction). Thus,

TABLE 2—*Multistage unsaturated shear strength tests in direct shear*

Series	Water Content Relative to Optimum	Initial Degree of Saturation, %	Initial Water Content, %	Dry Density, (Mg/m^3), γ_d	$(\sigma_n - u_a)$, kPa	Final Water Content, %
A1	Optimum	86.3	16.6	1.79	75	13.69
A2	Optimum	86.1	16.3	1.80	75	13.41
B	Optimum	86.1	16.3	1.81	200	13.39
C	Optimum	86.0	16.0	1.78	25	13.51
D	Dry of Optimum	61.4	13.0	1.73	25	13.60
E	Dry of Optimum	62.8	13.3	1.73	100	14.05
F1	Dry of Optimum	61.4	12.8	1.74	200	14.05
F2	Dry of Optimum	61.4	13.0	1.73	200	14.60
G	Wet of Optimum	94.6	18.8	1.77	25	17.07
H	Wet of Optimum	94.6	19.1	1.76	100	14.72
I	Wet of Optimum	98.2	19.2	1.78	200	13.67

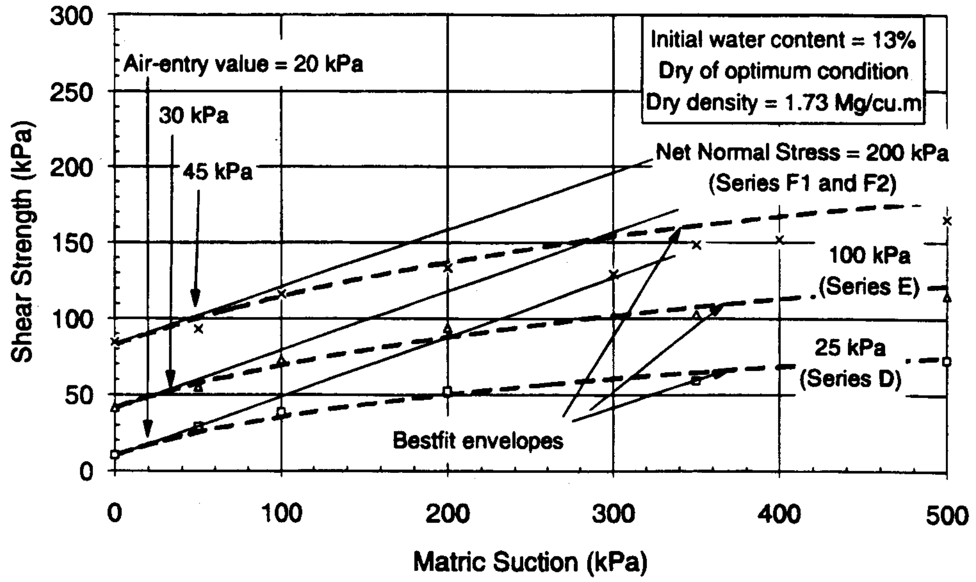

FIG. 2—*Variation of shear strength with matric suction under different net normal stresses with initial water content at dry of optimum conditions.*

the angle of shearing resistance due to matric suction, ϕ^b, decreases with increasing matric suction. Hence, the variation in shear strength with respect to matric suction is nonlinear beyond the air-entry value of the soil.

Figure 2 also indicates that the air-entry value of the soil is dependent on the applied net normal stress. The air-entry value of the soil increases with an increasing applied stress. The void ratio along with the coefficient of permeability of the specimen decreases with an increase in the applied net normal stress. Thus, the desaturation of the specimen starts at a higher matric suction value when the applied net normal stress is increased. The rate of desaturation is lower for specimens subjected to higher net normal stresses compared to specimens subjected to lower net normal stresses. The shear strength envelopes obtained from the results of Series A1, A2, B, and C representing optimum conditions (see Table 2) and Series G, H, and I representing the wet of optimum initial conditions also show similar trends.

The variation of shear strength with net normal stress at different matric suction values for Series D, E, F1, and F2 are plotted in Fig. 3. It should be noted that the envelopes are plotted for each value of matric suction using a different series of test results conducted on different specimens. Small variations would be expected because the analysis is conducted using different specimens. Also, there were small differences in the initial conditions (i.e., densities and initial water contents) of the specimens tested (see Table 2). These envelopes are essentially "congruent" within the limits of experimental error. The slope angle is approximately equal to angle of internal friction, ϕ', of 23°. For all practical purposes, it can be inferred from these results that the angle of internal friction, ϕ', is independent of the applied matric suction.

Escario and Juca (1989) observed that ϕ' was independent of the matric suction for Madrid clayey sand (i.e., ω_L = 32%, Ip = 15%, clay content = 17%, silt content = 31%, and sand content = 46%) but not for Guadalix red clay (i.e., ω_L = 33%, Ip =

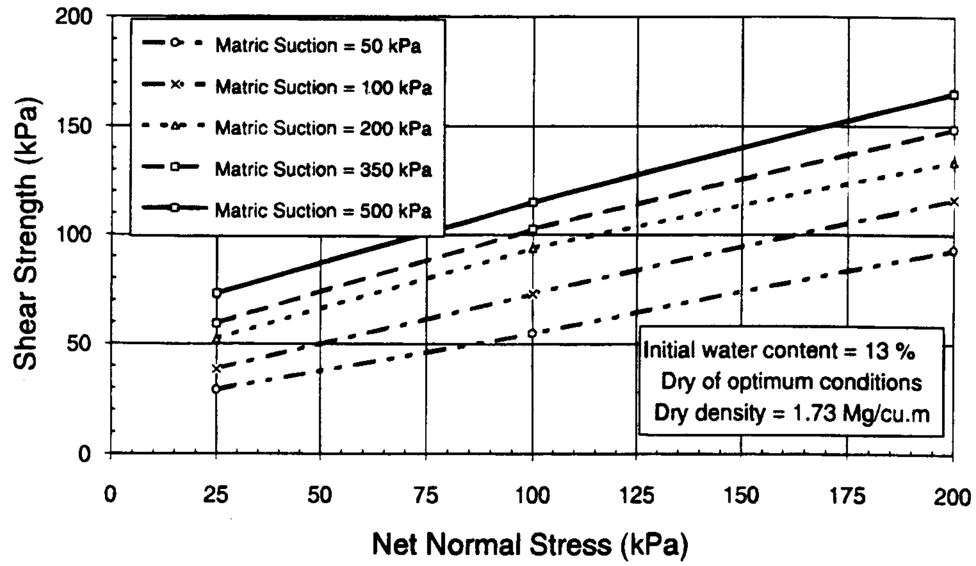

FIG. 3—*Variation of shear strength with net normal stress under different matric suctions for specimens with initial water content at dry of optimum conditions.*

13.6%, clay content = 86%, silt content = 11%, and sand content = 3%). Drumright (1990) reported that ϕ' was slightly influenced by matric suction and suggested the use of a bilinear variation of ϕ'. Karube (1988) stated that there was a variation in ϕ' due to the influence of matric suction if a dilation correction was not applied. However, ϕ' is independent of the matric suction if a dilation correction is taken into account.

Observations similar to Series D, E, F1, and F2 (see Fig. 3) were made for the results of Series A1, A2, B, and C at optimum initial water content conditions and Series G, H, and I results at wet of optimum water content conditions.

Soil-Water Characteristic Curves

A soil-water characteristic curve is defined as the variation of water content (i.e., either gravimetric or volumetric water) or degree of saturation with suction. The soil-water characteristic curves were developed using a pressure plate apparatus for the suction range from 0 to 1500 kPa and osmotic desiccators for the range of 3500 to 300 000 kPa. Similar to specimens used for conducting direct shear tests, specimens 63.5 mm in diameter were trimmed using stainless steel consolidation rings. These specimens were preconsolidated to the stresses similar to the net normal stresses ($\sigma_n - u_a$) used for testing unsaturated shear strength as shown in Table 2. An indirect procedure was used to allow a known level of stress to be applied on the specimens. First, the compression index, C_c, and the swelling index, C_s, were determined using conventional one-dimensional consolidation tests. Once the C_c and C_s values were known, specimens were preconsolidated by an amount equal to the net normal stresses used for direct shear testing the unsaturated soil. Thus, the required initial stress state and the initial void ratio conditions could be induced in the specimens used for developing soil-water characteristic curves. More details on preparing "preconsolidated" specimens are detailed in Vanapalli (1994).

Pressure Plate Tests

The soil-water characteristic curves developed using a pressure plate apparatus and osmotic desiccators for the suction range of 0 to 300 000 kPa are shown in Fig. 4. The soil-water characteristic curves for this research program were developed on preconsolidated specimens 63.5 mm in diameter. A 5-N load was applied on the specimen to ensure good contact between the specimens and the ceramic disk. The airtight chamber of the pressure plate was then pressurized to a desired suction. The ceramic disk of the pressure plate apparatus was saturated before subjecting the specimens to suction. Equilibrium was assumed when water no longer discharged from the pressure plate. Approximately six to seven days were required to attain equilibration under each applied matric suction for the soil used in the study. After equilibrium was attained, the test assembly was dismantled and each test specimen was weighed. This procedure was repeated for each applied suction.

The soil-water characteristic curves were determined for suction ranges of 0 to 1500 kPa using pressure plate apparatus. The change in weight of each specimen at each matric suction was measured. The water content of the specimen at a matric suction of 1500 kPa was measured using half of the specimen. The water contents at various matric suction values were determined from back calculations. The degree of saturation of each specimen was computed from the volume-mass relationships. The initial void ratio of the specimen was used in these calculations since statically compacted specimens are relatively resistant to shrinkage. The change in void ratio with respect to suction was not considered to be significant.

To attain the soil-water characteristic relationship beyond 1500 kPa, osmotic desiccators were used. The salt solutions in the glass desiccators control the relative humidity in the specimen. Five selected aqueous solutions that cover the suction values of 3500 to 300 000 kPa were used. Small chunks of specimens (i.e., about 3 to 5 g) obtained from the specimen remaining after completing the pressure plate tests were used to complete the soil-water characteristic curves by placing them (i.e., the specimens) in a glass desiccator with salt solution.

Figure 4 presents soil-water characteristic curves in terms of the variation in the degrees of saturation of the specimens with applied suctions. These specimens were not subjected to any preconsolidation pressures. The variation in the degree of saturation on a linear scale is plotted as the ordinate, and the matric suction is plotted on a logarithmic scale as abscissa. The macro pore

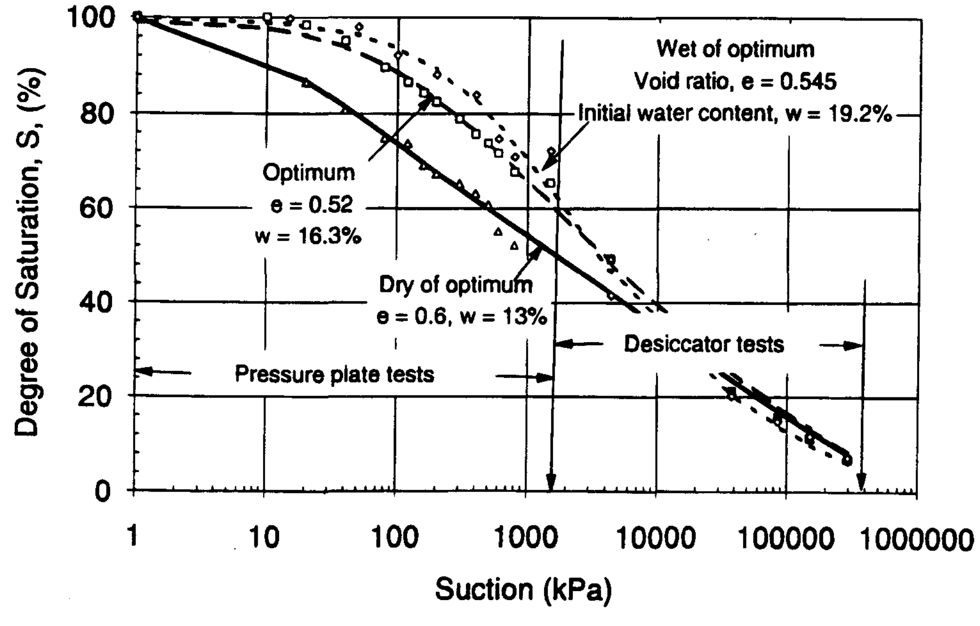

FIG. 4—*Soil-water characteristics of specimens with different initial water contents.*

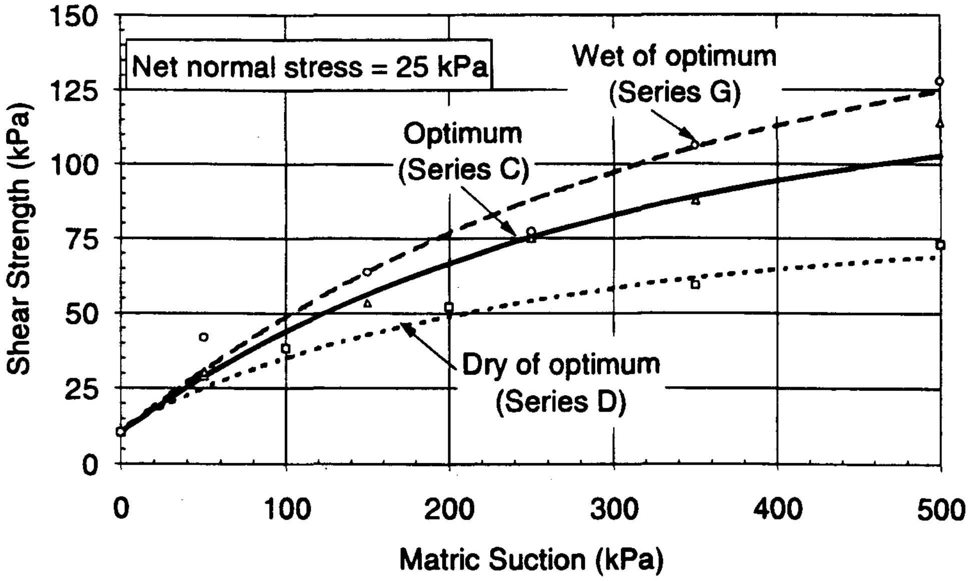

FIG. 5—*Variation of shear strength with matric suction under 25 kPa net normal stress for specimens tested with different initial water contents.*

structure is more predominant for specimens compacted dry of optimum. This pore structure facilitates easier drainage of water (i.e., desaturation) under an applied matric suction. Thus, dry of optimum specimens desaturate without offering much resistance to flow, particularly at small values of matric suction. This observation is in concurrence with those of Elsbury et al. (1990), who stated that "the interclod structure of dry of optimum specimens looked more like gravel." A wet of optimum water content specimen can be assumed to be relatively homogeneous, with virtually no visible evidence of interclod pores (Elsbury et al. 1990). In contrast to the dry of optimum specimens, the pore channels in the wetter specimens are generally disconnected and offer greater resistance to the water flow. The soil in such a condition is more impervious since the micro structure dominates and provides resistance to the desaturation process. The slope of the soil-water characteristic curve is much flatter in comparison to the dry of optimum water content specimens. The specimen prepared at optimum water content conditions lies in between these two curves. However, it can be noticed that the behavior is more like that of a soil compacted wet of optimum.

Unsaturated Shear Strength and Its Relation to the Soil Structure or Aggregation

The variation of shear strength with respect to matric suction for unsaturated soil specimens tested with the initial water content conditions near optimum (Series C), dry of optimum (Series D), and wet of optimum (Series G) subjected to a net normal stress of 25 kPa are shown in Fig. 5. At any particular matric suction value, the specimens tested at dry of optimum water content condi-

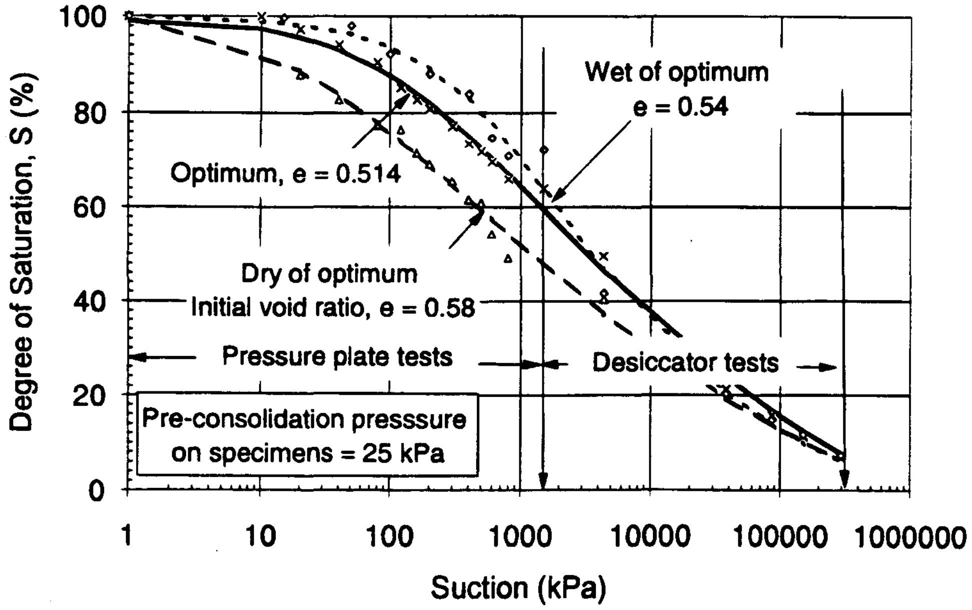

FIG. 6—*Soil-water characteristics of specimens with 25 kPa preconsolidation pressure.*

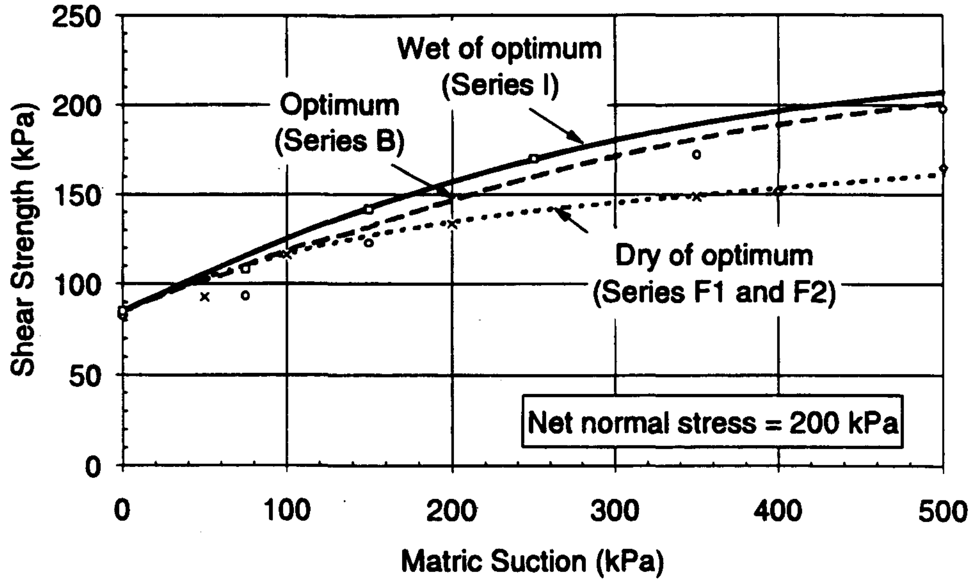

FIG. 7—*Variation of shear strength with matric suction under 200 kPa net normal stress for specimens tested with different initial water contents.*

tions have the lowest shear strengths. Specimens tested at wet of optimum water content conditions have the highest strengths as more interaggregate contact area points are wetted. For this case, matric suction serves as the stress state variable, which is more effective in contributing to the shear strength. The dry of optimum water content specimens have a lower storage capacity at any particular matric suction compared to the optimum and wet of optimum water content specimens. This is due to its interaggregation, which allows the dry of optimum water content specimens to desaturate rapidly. Therefore, at any particular matric suction, the water content (or the degree of saturation) of the dry of optimum water content specimen is lower when compared to the optimum and wet of optimum water content specimens. Hence, the contribution to shear strength due to matric suction is lower. The variation in dry density from 1.73 to 1.80 Mg/m^3 (i.e., void ratio variation of 0.58 to 0.52) is considered to be small and assumed to have no marked influence on the unsaturated shear strength behavior.

Figure 6 shows the soil-water characteristic curves of specimens preconsolidated to 25 kPa. The void ratios of the specimens are also shown. It can be seen that the soil-water characteristic curves from dry of optimum water content conditions is well below the soil-water characteristic curves of specimens with water contents at optimum and wet of optimum conditions. The degree of saturation for any given value of suction is lower for dry of optimum water content specimens in comparison to specimens of water contents at optimum and wet of optimum conditions. Similar behavior is observed for the unsaturated shear strength of the soils. Similar behavior is, therefore, expected for the coefficient of permeability of the unsaturated soil. This behavior could be attributed to the resulting aggregation and pore structures induced

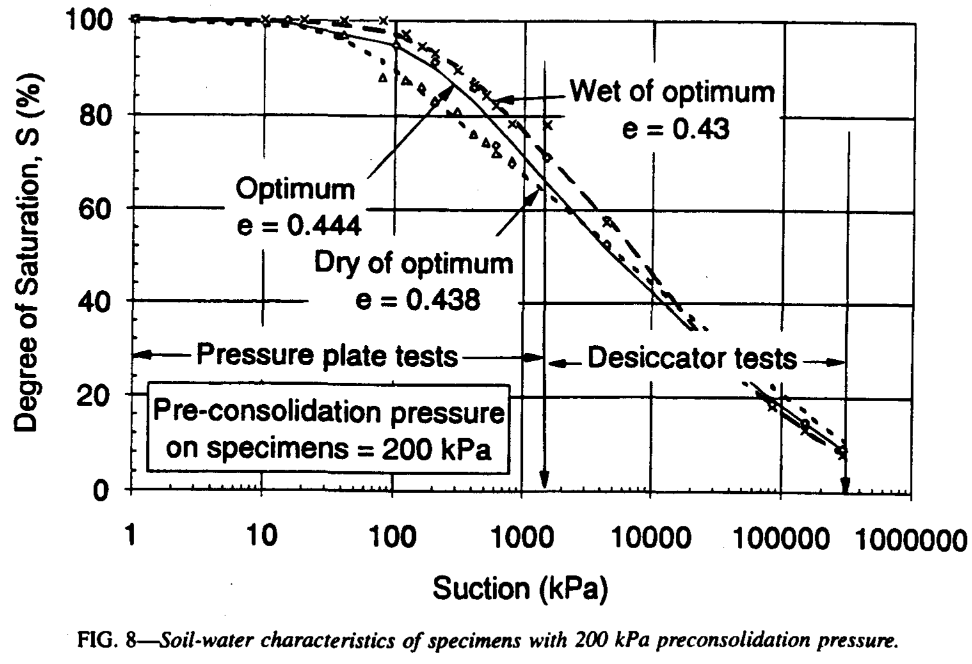

FIG. 8—*Soil-water characteristics of specimens with 200 kPa preconsolidation pressure.*

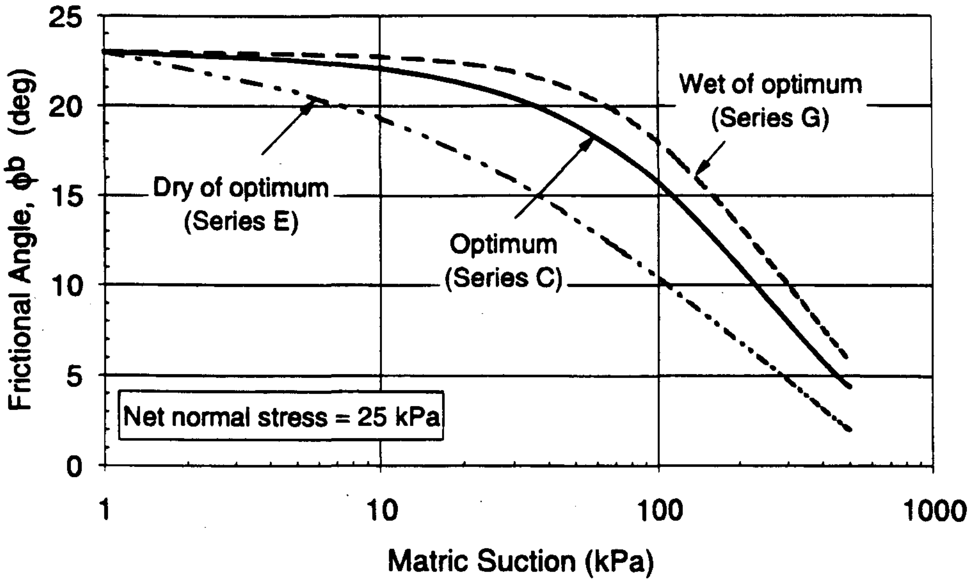

FIG. 9—*Variation of frictional angle due to matric suction under 25 kPa net normal stress for specimens tested with different initial conditions.*

in the specimens due to their "initial" molding water contents and the stress state.

Figure 7 shows the variation of shear strength with respect to matric suction when specimens are subjected to a net normal stress of 200 kPa at different "initial" water content conditions. The observations made for Fig. 5 are equally valid for Fig. 7. However, at a high net normal stress, the differences in shear strength for the specimens with water contents at optimum and wet of optimum conditions are not significant. It appears that the soil structure for optimum or wet of optimum conditions when subjected to higher stresses is similar. Similarly, significant differences in the soil-water characteristic curves are not observed for specimens tested with water contents at optimum and wet of optimum water content conditions (Fig. 8).

For all "initial" conditions of water contents (i.e., dry of optimum, optimum, and wet of optimum) and various preconsolidation pressures, the soil-water characteristic curve behavior is similar at higher suctions (i.e., 20 000 to 300 000 kPa) in all the specimens (Figs. 4, 6, and 8). The interaggregate structure appears to be essentially the same for all specimens prepared at different "initial" conditions (i.e., at higher values of suctions).

The variation of ϕ^b versus matric suction is shown using the "best-fit" envelopes for net normal stresses of 25 and 200 kPa in Figs. 9 and 10. The discussions provided for Figs. 4 to 8 are also valid for this situation. From these studies, it may be noted that the shear strength behavior of an unsaturated soil bears a close relationship to the soil-water characteristic curve behavior under similar "initial" conditions.

Summary and Conclusions

The variation of shear strength with respect to matric suction is nonlinear for all the specimens tested. The rate of increase in

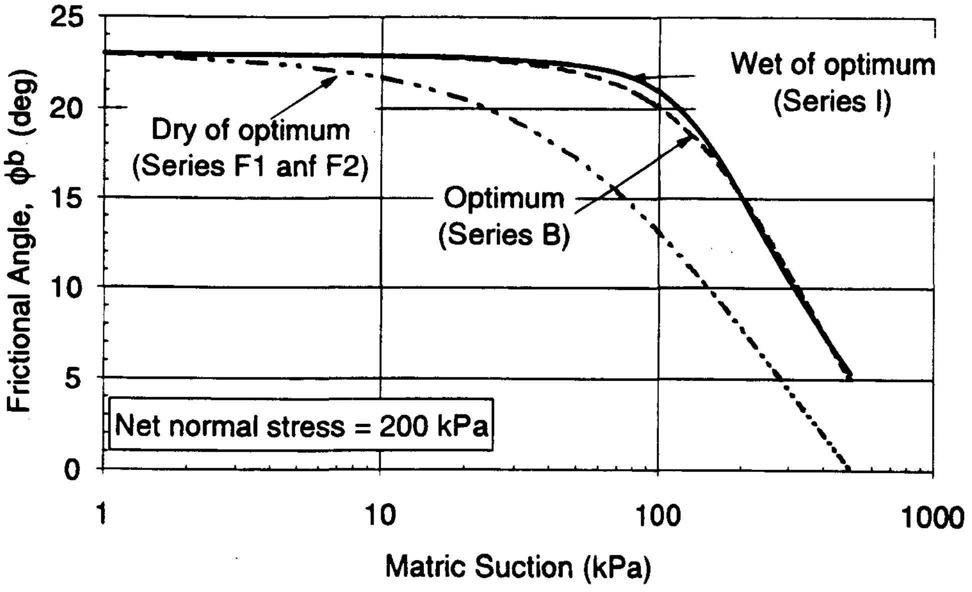

FIG. 10—*Variation of frictional angle due to matric suction under 200 kPa net normal stress for specimens tested with different initial conditions.*

the shear strength contribution due to matric suction is, however, related to the rate of desaturation characteristics of the soil, which is dependent on the "initial" water content conditions. The resulting structure or aggregation formed under a particular "initial" water content governs the flow and water storage characteristics with a changing suction. The structure or aggregation also influences the unsaturated shear strength behavior.

At a particular level of net normal stress and matric suction, a specimen compacted wet of optimum water content has more area of water at interaggregate contacts to communicate suction. As a result, specimens compacted at or wet of optimum water content develop higher shear strength in comparison to specimens compacted at dry of optimum. Also, specimens compacted wet of optimum start to desaturate at higher suctions when compared to specimens compacted at optimum and dry of optimum. The unsaturated shear strength behavior bears a close relationship to the soil-water characteristic curve behavior under similar "initial" conditions.

The "initial" water content and "aggregation" showed no influence on the effective shear strength parameters, c' and ϕ', in single-stage direct shear. The angle of shearing resistance, ϕ', appears to be unique for the different displacement rates and test procedures of direct shear used in this testing program. The resulting "aggregation" at failure in saturated specimens appears to be independent of the "initial" water contents for the range of void ratios tested.

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