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K_o-Volume Change Characteristics of an Unsaturated Soil with Respect to Various Loading Paths

ABSTRACT: The volume change behavior of an unsaturated soil is a function of the stress state variables; namely, net normal stress and matric suction. The total and water volume changes during drained and constant water content loadings are investigated, and their behavior is described with respect to changes in the stress state variables. Volume changes are also presented in terms of void ratio and water content changes. The differing characteristics of volume change during drained and constant water content loadings are reflected clearly through the void ratio and water content changes. The significance of the highest, past matric suction is shown to be similar to the preconsolidation pressure influence on a saturated soil. The laboratory test results show that the water coefficient of volume change changes significantly from the reloading curve to the virgin compression curve. The effect of preconsolidating the soil was also shown to influence significantly the measured soil-water characteristic curve.

KEYWORDS: Volume change, unsaturated soil, matric suction, consolidation, K_o-loading

Introduction

Many geotechnical problems involving unsaturated soils require an understanding of the volume change behavior of the soil under various loading conditions (or stress paths). The loading can be applied by changing one or both of the two independent stress state variables of unsaturated soil, namely, net normal stress and matric suction. The loading can be applied under drained or undrained conditions. Under undrained loading conditions, the total stress is applied to a soil while keeping the pore-air and pore-water under undrained conditions, resulting in excess pore-air and pore-water pressures. Under constant water content loading, only the pore-water is maintained in an undrained condition (or water content is maintained constant) during the loading, while the pore-air is allowed to drain. As a result, only the excess pore-water pressure will develop during the constant water content loading.

In the drained condition, the pore-air and pore-water pressures are allowed to drain during the application of the load. An example of drained loading would be the increase in matric suction caused by lowering the water pressure below the high air entry disk. Consequently, the pore-water drains out from the soil and the pore-air volume of the soil increases. In this case, the pore-water pressure is lowered to a minimum pressure. At the same time, the matric suction is increased to a maximum value that the soil has ever experienced. Another example of drained loading would be the dissipation of excess pore-water pressures (or consolidation) following the constant water content loading. During the consolidation process, both pore-air and pore-water are allowed to drain from the soil. The dissipation of excess pore-water pressure during a consolidation process causes the pore-water pressure or the matric suction to return to its original magnitude prior to the constant water content loading. In other words, the pore-water pressure (or the matric suction) follows a reloading process.

The total and water volume changes during constant water content loading, increasing matric suction, and consolidation tests are different as explained by Alonso, Gens and Hight (1987), Rahardjo (1990), and Rahardjo and Fredlund (1995).

The objective of this paper is to illustrate and describe the differences in total and water volume changes of an unsaturated soil through several series of experiments. In each series of experiments, the soil is subjected to an alternating series of loading, namely: loading by increasing matric suction, constant water content loading, and consolidation loading. The differing volume change behavior of the unsaturated soil under these loading conditions has a direct effect on the coefficient of compressibility of the soil. The coefficient of compressibility, in turn, affects the rate of the transient process.

Constitutive Surfaces and Equations at a Point for an Unsaturated Soil

In *drained loading*, air and water are allowed to drain from an unsaturated soil during the application of a net normal stress or a matric suction increment. Volume change can be expressed as a function of the stress state variables for unsaturated soils, $(\sigma - u_a)$ and $(u_a - u_w)$, where: σ = total stress, u_a = pore-air pressure, and u_w = pore-water pressure, as shown in Fig. 1*a*. The volume change constitutive equation can be written as an incremental, linear equation (Fredlund and Morgenstern 1976):

$$dV_v/V_o = m_1^s\, d(\sigma - u_a) + m_2^s\, d(u_a - u_w) \quad [1]$$

where:

V_v = volume of soil voids
V_o = initial total volume of the soil
m_1^s = coefficient of soil volume change with respect to a change in net normal stress (dependent on the stress state)

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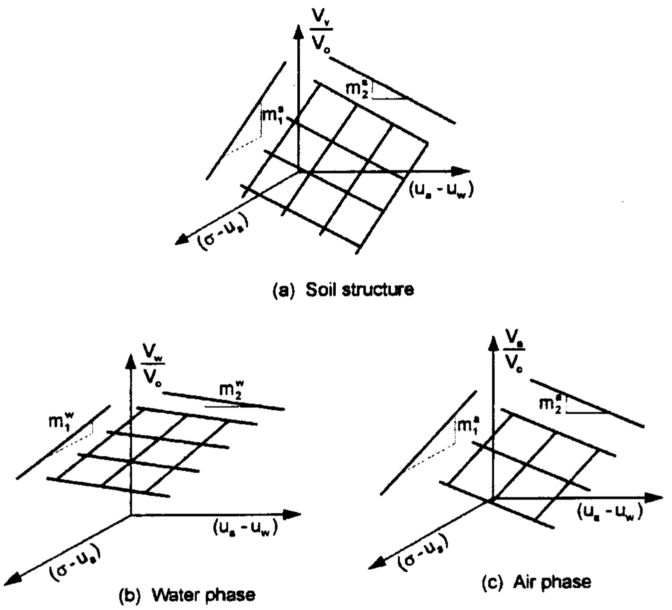

FIG. 1—*Linearized portion of constitutive relations at a point during a one-dimensional, drained compression.*

m_2^s = coefficient of soil volume change with respect to a change in matric suction (dependent on the stress state)

The change in the volume of water in an unsaturated soil is illustrated in Fig. 1*b* and can be expressed as an incremental, linear relation:

$$dV_w/V_o = m_1^w\, d(\sigma - u_a) + m_2^w\, d(u_a - u_w) \qquad [2]$$

where:

V_w = volume of water
m_1^w = coefficient of water volume change with respect to a change in net normal stress (dependent on the stress state)
m_2^w = coefficient of water volume change with respect to a change in matric suction (dependent on the stress state)

The total and water volume changes are commonly measured in the laboratory tests, while the air volume change is computed as the difference between the total and water volume changes on the basis of the continuity requirement. Figure 1*c* illustrates the air volume change where m_1^a is the coefficient of air volume change with respect to a change in net normal stress, while m_2^a is the coefficient of air volume change with respect to a change in matric suction.

In *undrained loading*, air and water are not allowed to drain from the unsaturated soil during the application of a total stress increment. As a result, the pore-air and pore-water pressures increase and the soil volume decreases due to the compression of the pore fluid, as shown by stress path AB in Fig. 2. The net volume change, $(dV_v/V_o)_o$, at B is the sum of the volume changes due to a change in net normal stress $(dV_v/V_o)_1$, from point A to C, and due to a change in matric suction $(dV_v/V_o)_2$, from point C to B. The magnitudes of $(dV_v/V_o)_1$ and $(dV_v/V_o)_2$ can be computed using Eq 1.

K_o-cylinder with Pore-air and Pore-water Pressure Measurements for Testing Unsaturated Soil

A special K_o-cylinder was built for testing unsaturated soils under undrained and drained loading conditions, as shown in Fig. 3. The details of the K_o-cylinder are described by Rahardjo and Fredlund (1997). The soil specimen has an internal diameter of 102 mm and a height of approximately 200 mm. The pore-air pressure, u_a, is controlled through the coarse bronze disk at top of the specimen, while the pore-water pressure, u_w, is controlled through the high air entry ceramic disk at the bottom of the specimen. Matric suction in the soil specimen is equal to the difference between the controlled pore-air and pore-water pressures under equilibrium conditions. The total stress, σ_y, is applied through a loading cap using a loading frame.

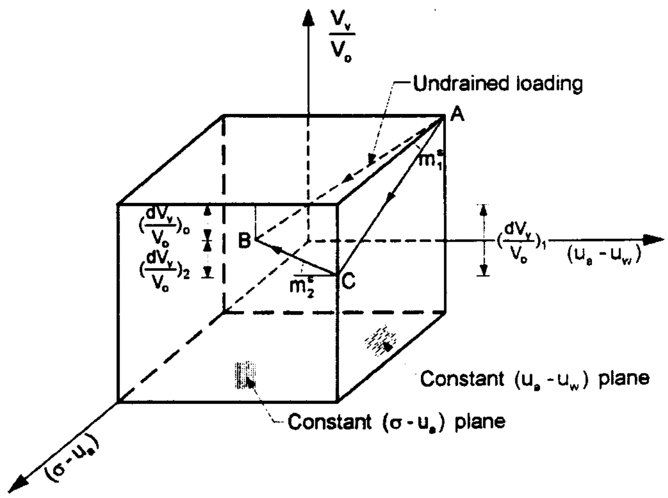

FIG. 2—*Three-dimensional plot of volume change during undrained loading of an unsaturated soil.*

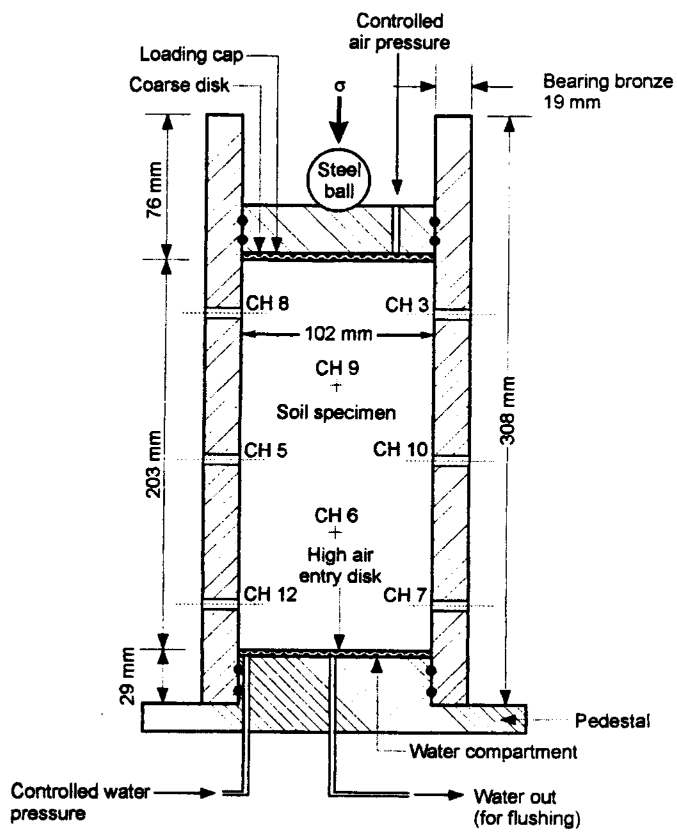

FIG. 3—*K_o-cylinder for undrained loading and consolidation tests.*

Pore-air and pore-water pressure measuring ports are provided 'ong the height of the cylinder. Coarse bronze disks and high air .try disks are used for the pore-air and pore-water pressure measuring ports, respectively. The measurement system provides continuous measurements of pore pressures along the soil specimen throughout the test. In addition, the vertical deflection of the soil specimen and the water volume change are measured to give independent measurements of total and water volume changes in the specimen.

Soil Properties

A silty sand with soil properties shown in Table 1 was used in this study. The soil was initially slurried and formed into specimens to ensure homogeneity of the soil. The soil-water characteristic curves for the soil are shown in Fig. 4 in terms of (V_w/V_o) and gravimetric water content, w. In addition, the degrees of saturation at various matric suctions were computed indicating that the soil desaturates around 5 to 10 kPa matric suction (i.e., air entry value). The desaturation point of the soil corresponds to a gravimetric water content around 20–22%, as indicated by the shrinkage curve of the soil shown in Fig. 5.

The saturated coefficient of permeability with respect to water was found to vary with void ratio, as shown in Fig. 6. Initially, slurried specimens were consolidated to various void ratios prior to conducting the permeability tests (Rahardjo 1990). The unsaturated permeability functions were computed using the soil-water characteristic curves in terms of (V_w/V_o) and various saturated coefficients of permeability following the procedure described by Fredlund and Rahardjo (1993). The permeability functions are ilrated in Fig. 7.

TABLE 1—*Index properties of the silty sand used in the study.*

Properties	Silty Sand
Grain size distribution	
Sand	52.5 %
Silt	37.5 %
Clay	10.0 %
Atterberg limits	
Liquid limit, LL	22.20
Plastic limit, PL	16.60
Specific gravity, G_s	2.68

Testing Program

Several series of experiments were conducted on initially slurried specimens of the silty sand, using the K_o-cylinder. The series of experiments consisted of *Increasing Matric Suction* (M) tests, *Constant Water Content* (CW) loading, and *Consolidation* (C) tests. Figure 8 illustrates the stress paths followed by the series of experiments on the S_3 specimen. The specimen was first brought to an initial net normal stress and matric suction (Point F in Fig. 8). Successive experiments followed the order M, CW, and C tests, and were carried out using a progressive series of cycles. For example, consider intermediate paths OP, PQ3, Q3R, and RS in Fig. 8. An *Increasing Matric Suction* test was performed on the specimen following the stress path OP. The matric suction was increased by lowering the pore-water pressure, u_w, while maintaining the pore-air pressure, u_a, and the net normal stress, $(\sigma_y - u_a)$, constant.

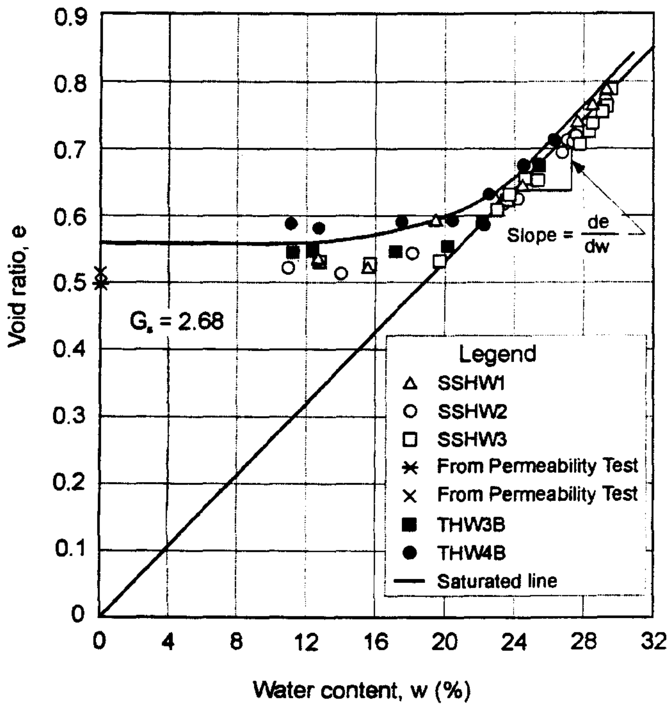

FIG. 5—*Shrinkage relationship for the silty sand.*

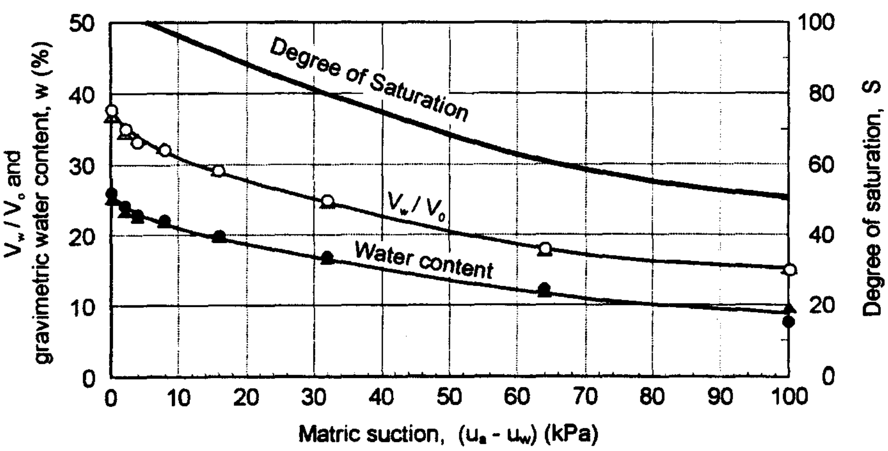

FIG. 4—*Soil-water characteristic curves for the silty sand measured.*

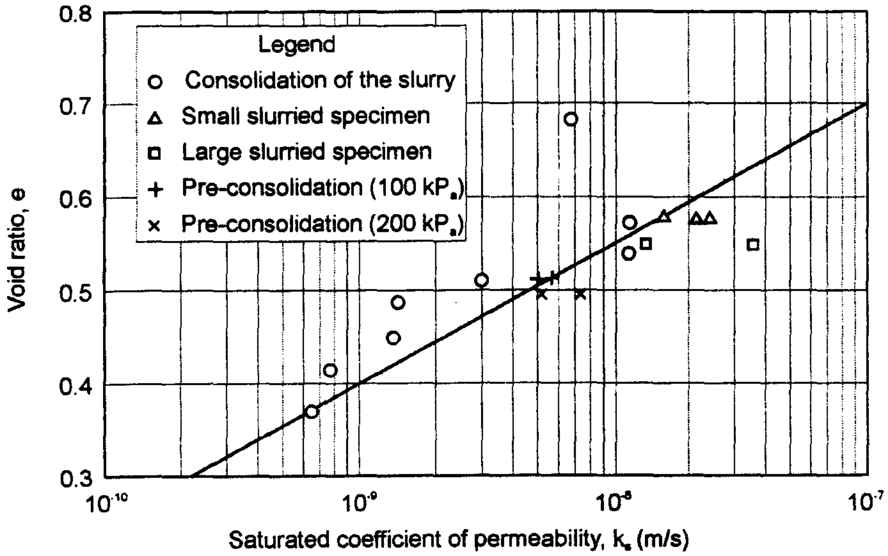

FIG. 6—*Variation in the coefficient of permeability at saturation with respect to void ratio for the silty sand.*

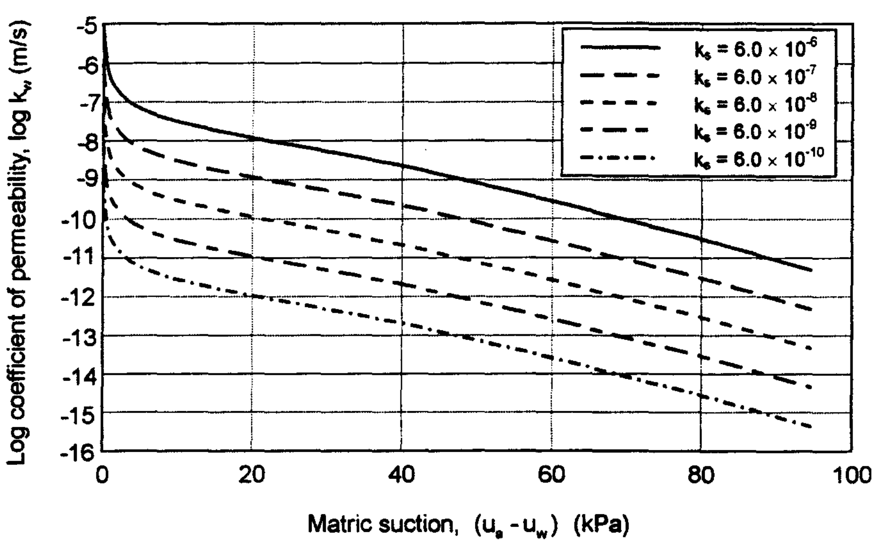

FIG. 7—*Unsaturated permeability functions for the silty sand.*

During the test, the total and water volumes decreased, as shown in Figs. 9 and 10, in terms of (V_v/V_o) and (V_w/V_o), respectively. Both (V_v/V_o) and (V_w/V_o) are plotted against the net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$.

After applying the higher matric suction value at Point P, the specimen was subjected to a stepwise increase in the total stress, $d\sigma_y$, under a *Constant Water Content* (CW) loading condition along the PQ1, Q1Q2, and Q2Q3 paths shown in Fig. 8. The CW test was conducted by allowing air to drain from the side of the loading cap while the top of the cylinder was enclosed in an air chamber that was pressurized to the same pressure as the controlled pore-air pressure. Details of the air chamber are given in Rahardjo and Fredlund (1997). In this case, the pore-air pressure, u_a, remained constant during the CW loading. On the other hand, water was not allowed to drain and the result was an increase in the pore-water pressure, u_w, throughout the specimen.

As a result of the CW test, the net normal stress increased to a higher magnitude and the matric suction decreased as indicated by Point Q3 in Fig. 8. The total and water volume changes during the CW test are shown in Figs. 9 and 10, respectively. Figure 10 shows that the water volume remained constant along the CW loading paths PQ1, Q1Q2, and Q2Q3, while the total volume decreased (Fig. 9).

A *Consolidation* (C) test was carried out along the Q3R path in Fig. 8, by allowing the excess pore-water pressures to dissipate. The pore-water pressures returned to the original magnitudes before the CW loading. In the end (i.e., Point R), the matric suction returned to its original value as shown at Point P. The total stress, together with the increase in total stress from the CW loading, $(\sigma_y + d\sigma_y)$, remained constant during the consolidation test. The total and water volume changes during the *Consolidation* tests are illustrated in Figs. 9 and 10. The total and water volume changes dur-

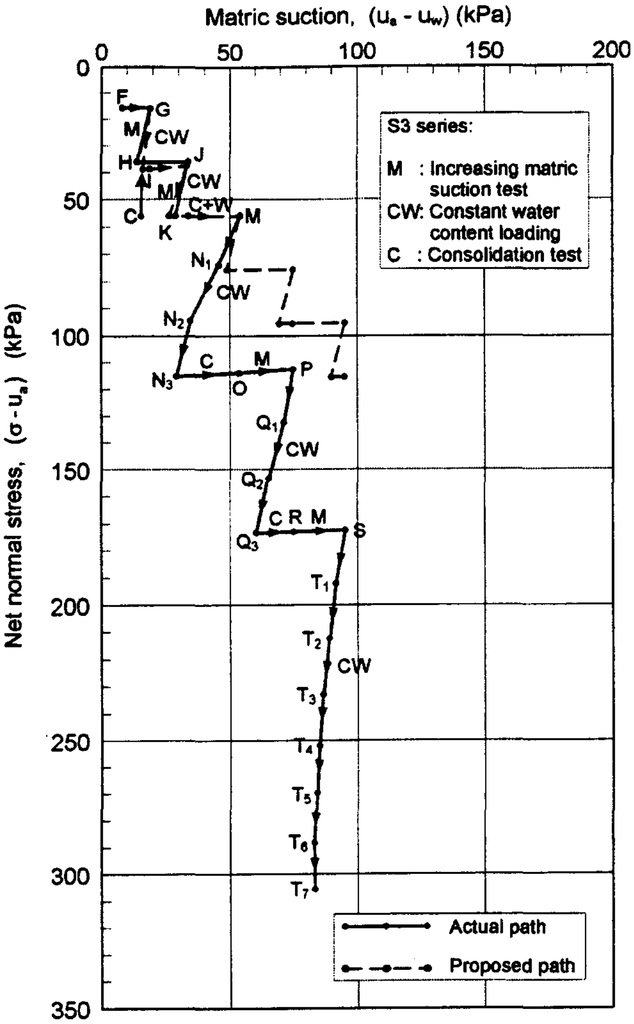

FIG. 8—*Actual stress state path for the Series 3 experiments.*

ing *Consolidation* test (Q3R path) are not as high as those associated with the *Increasing Matric Suction* test (OP path).

The total and water volume changes during the tests can also be expressed using void ratio, *e*, and gravimetric water content, *w*. The plots of void ratio and gravimetric water content associated with the S_3 series of experiments are shown in Figs. 11 and 12, respectively. Similar results from another series of experiments, the S_4 series, are presented in Figs. 13–15. Tables 2 and 3 illustrate the volumetric properties of soil specimen during the S_3 and S_4 series of tests.

Volume Change Behavior in the Silty Sand Specimens

A comparison of the change in volume, (V_v/V_o) plots, from both series of experiments, S_3 and S_4, indicates that the total volume changes associated with the various tests performed, M, CW, and C on an unsaturated soil specimen were smaller than the water volume changes associated with the same tests. For the entire series of tests, the maximum variation in overall volume change (V_v/V_o) was in the range of 0.025 (see Figs. 9 and 14) as compared to the maximum variation in water volume change (V_w/V_o) of 0.1 (see Figs. 10 and 15). This comparison indicates that there is an increasing stiffness in the soil structure as the soil becomes unsaturated. Much of the water volume change in the soil occurred during the *Increasing Matric Suction* tests. The total volume change during the *Constant Water Content* loading is generally small, as illustrated in Fig. 2.

There was a distinct difference in the water volume change (V_w/V_o) versus $(u_a - u_w)$ relationships from the *Consolidation* and *Increasing Matric Suction* tests in the S_3 and S_4 test series (see Figs. 10 and 15). The water volume changes during the Consolidation tests were considerably smaller than the water volume changes during the *Increasing Matric Suction* tests. This difference can be illustrated by comparing the gravimetric water content change during the *Consolidation* tests (i.e., N3O and Q3R paths in Fig. 12) with the gravimetric water content change during the *Increasing Matric Suction* tests (i.e., OP and RS paths in Fig. 12). The slopes

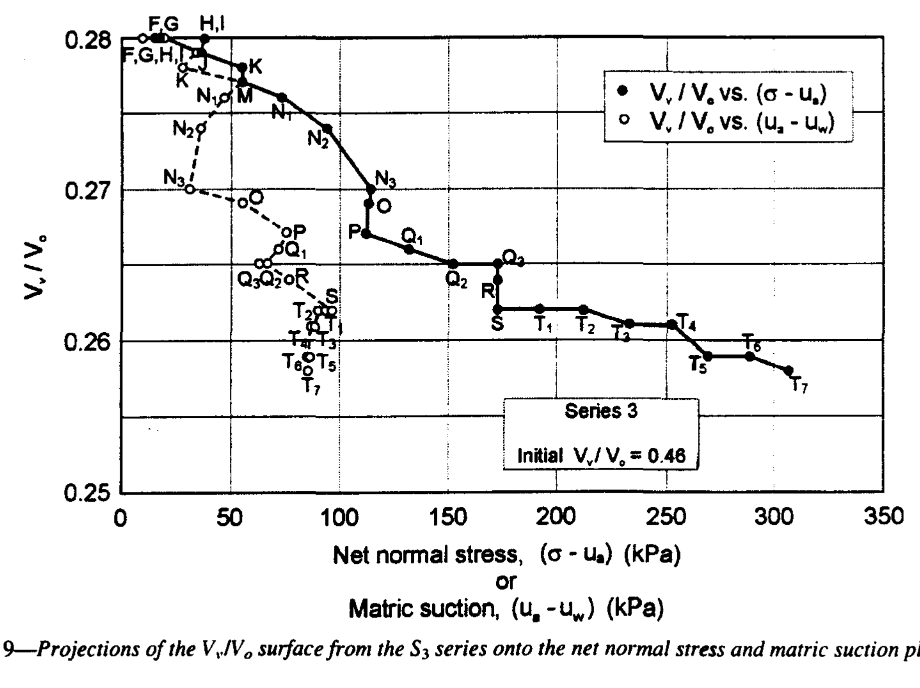

FIG. 9—*Projections of the V_v/V_o surface from the S_3 series onto the net normal stress and matric suction planes.*

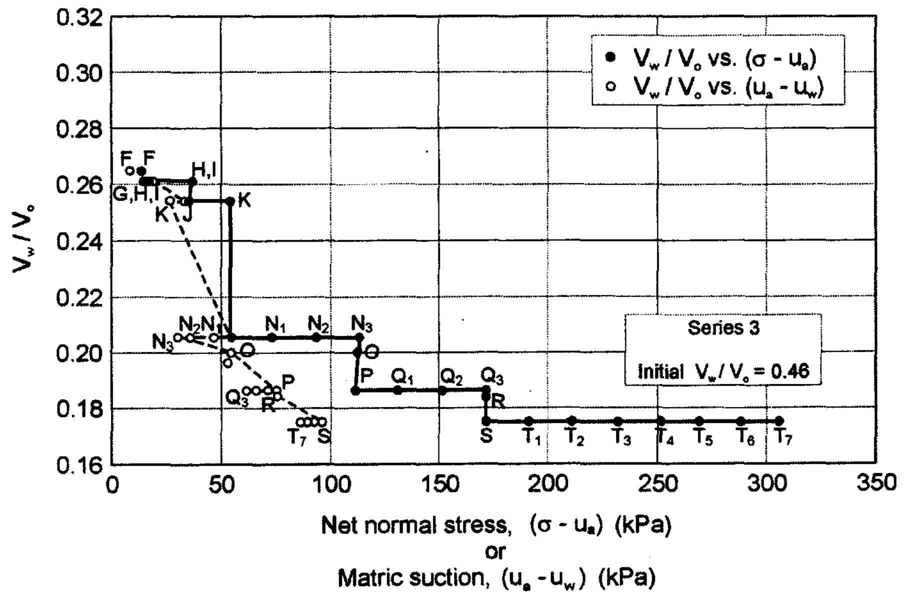

FIG. 10—*Projections of the V_w/V_o surface from the S_3 series onto the net normal stress and matric suction planes.*

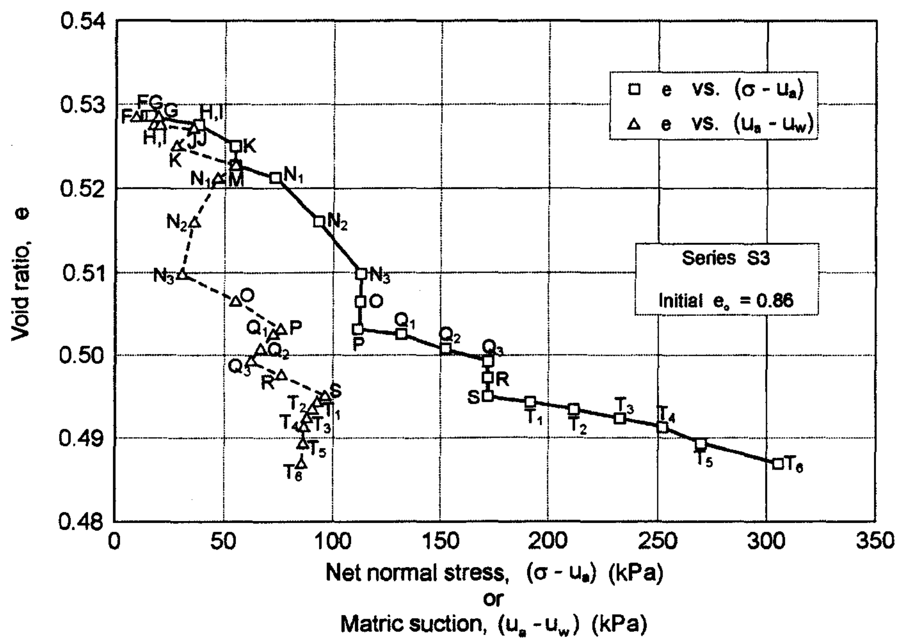

FIG. 11—*Projections of the void ratio surface from the S_3 series onto the net normal stress and matric suction planes.*

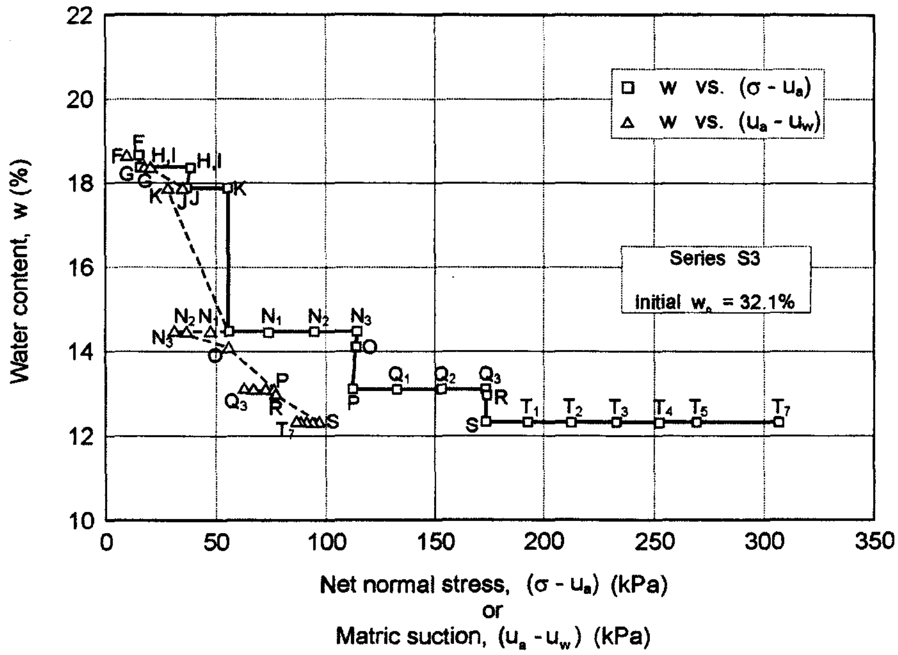

FIG. 12—*Projection of gravimetric water content surface from S_3 series onto the net normal stress and matric suction planes.*

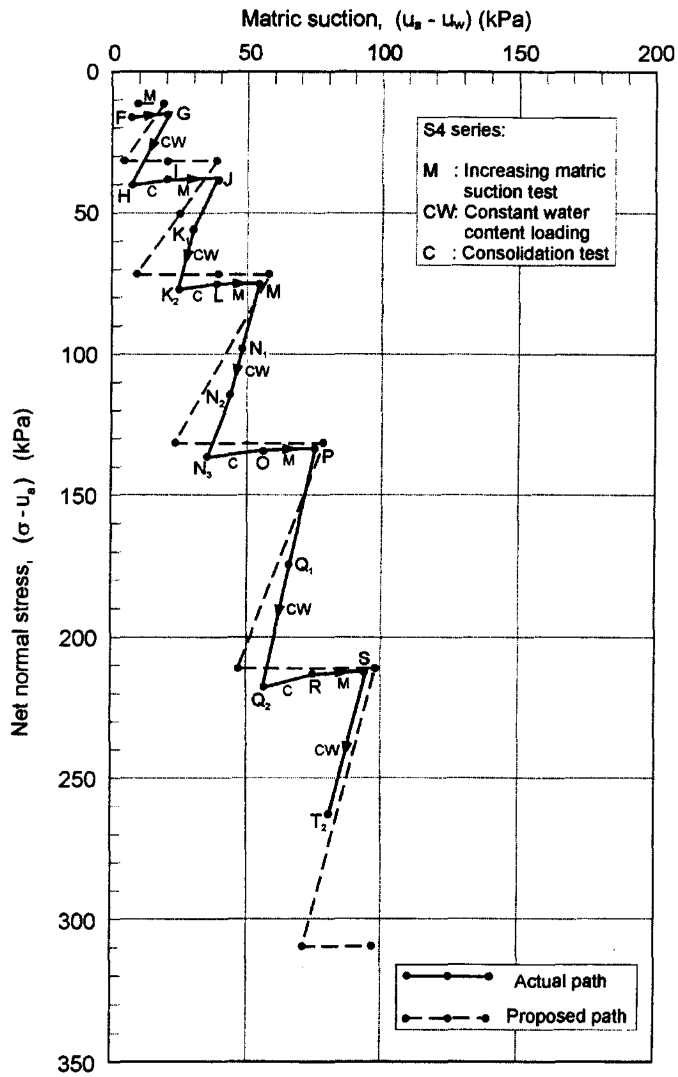

FIG. 13—*Actual stress state path for the Series 4 experiments.*

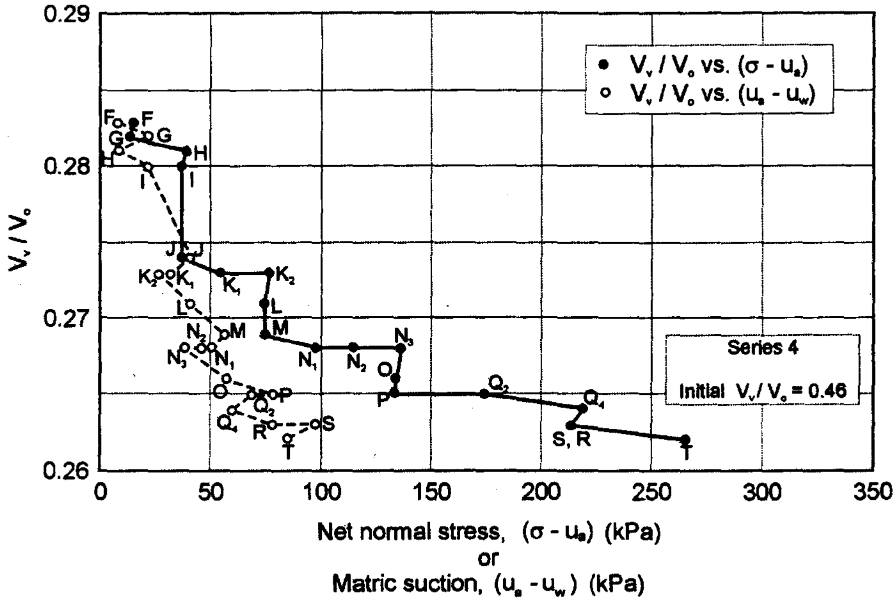

FIG. 14—*Projections of the V_v/V_o surface from the S_4 series onto the net normal stress and matric suction planes.*

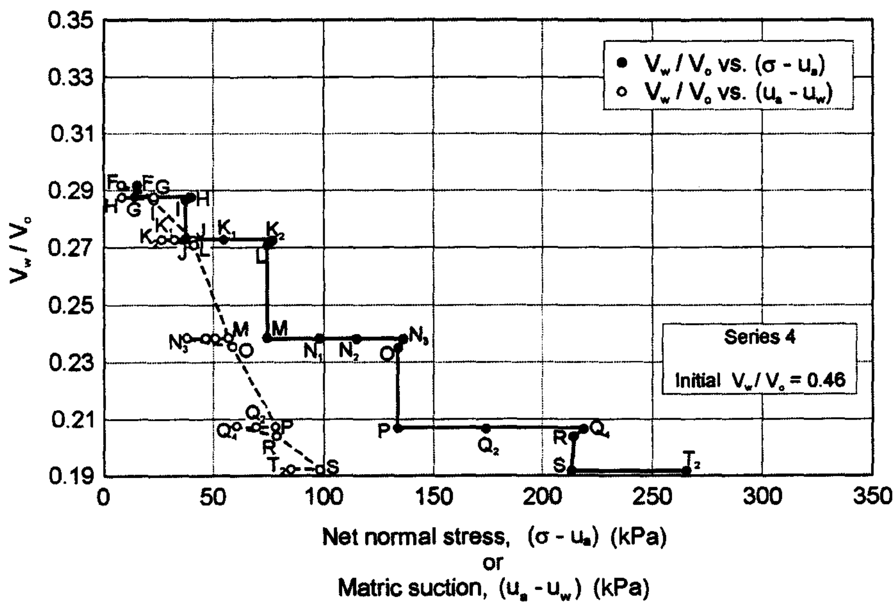

FIG. 15—*Projections of the V_w/V_o surface from the S_4 series onto the net normal stress and matric suction planes.*

TABLE 2—*Volumetric properties of soil specimen during the S_3 series of experiments.*

ocess	V_f (cm³)	V_{wf} (cm³)	e_f	w_f (%)	S_f (%)
A–F	1631.77	534.38	0.5286	0.1867	94.67
F–G	1631.77	526.32	0.5286	0.1839	93.26
G–H	1630.77	526.32	0.5277	0.1839	93.43
H–I	1630.73	526.17	0.5276	0.1839	93.41
I–J	1630.16	512.05	0.5271	0.1789	90.99
J–K	1628.06	512.05	0.5251	0.1789	91.34
K–M	1625.67	414.78	0.5229	0.1449	74.30
M–N1	1624.05	414.78	0.5214	0.1449	74.52
N1–N2	1618.42	414.78	0.5161	0.1449	75.28
N2–N3	1611.85	414.78	0.5099	0.1449	76.19
N3–O	1608.37	404.30	0.5067	0.1413	74.74
O–P	1604.69	375.98	0.5032	0.1314	69.98
P–Q1	1604.05	375.98	0.5026	0.1314	70.07
Q1–Q2	1602.15	375.98	0.5008	0.1314	70.31
Q2–Q3	1600.62	375.98	0.4994	0.1314	70.52
Q3–R	1598.77	372.67	0.4977	0.1302	70.14
R–S	1596.09	354.74	0.4952	0.1239	67.10
S–T1	1595.42	354.74	0.4945	0.1239	67.19
T1–T2	1594.45	354.74	0.4936	0.1239	67.31
T2–T3	1593.32	354.74	0.4926	0.1239	67.45
T3–T4	1592.16	354.74	0.4915	0.1239	67.60
T4–T5	1590.09	354.74	0.4895	0.1239	67.87
T5–T6	1589.14	354.74	0.4887	0.1239	68.00
T6–T7	1587.48	354.74	0.4871	0.1239	68.21
T7–T8	1586.16	354.74	0.4895	0.1239	68.39

Note: V_f = final total volume; V_{wf} = final water volume; e_f = final void ratio; w_f = final water content; S_f = final degree of saturation.

TABLE 3—*Volumetric properties of soil specimen during the S_4 series of experiments.*

Process	V_f (cm³)	V_{wf} (cm³)	e_f	w_f (%)	S_f (%)
A–F	1682.15	598.93	0.5267	20.28	≈100.00
F–G	1679.62	591.96	0.5244	20.01	≈100.00
G–H	1678.23	591.06	0.5231	20.01	≈100.00
H–I	1676.32	588.18	0.5214	19.91	≈100.00
I–J	1662.47	560.29	0.5088	18.97	≈100.00
J–K1	1662.02	560.29	0.5084	18.97	≈100.00
K1–K2	1661.03	560.29	0.5075	18.97	≈100.00
K2–L	1657.06	554.88	0.5039	18.79	99.39
L–M	1651.97	487.05	0.4993	16.49	88.52
M–N1	1651.61	487.05	0.4990	16.49	88.58
N1–N2	1651.27	487.05	0.4987	16.49	88.64
N2–N3	1650.47	487.05	0.4978	16.49	88.76
N3–O	1648.14	481.64	0.4958	16.31	88.15
O–P	1645.10	423.21	0.4931	14.33	77.89
P–Q2	1644.54	423.21	0.4926	14.33	77.97
Q2–Q4	1643.63	423.21	0.4917	14.33	78.10
Q4–R	1641.67	417.43	0.4899	14.13	77.31
R–S	1639.81	393.02	0.4883	13.31	73.04
S–T2	1639.14	393.02	0.4877	13.31	73.04

Note: V_f = final total volume; V_{wf} = final water volume; e_f = final void ratio; w_f = final water content; S_f = final degree of saturation.

of the water content, w versus $(u_a - u_w)$ relationship, for the *In-*
reasing Matric Suction tests are much steeper than those for the *nsolidation* tests, indicating that the water content decreases .e significantly during the *Increasing Matric Suction* test as opposed to during the *Consolidation* test.

The change in water volume (V_w/V_o) versus $(u_a - u_w)$ relationships from all the test series (i.e., S_1, S_2, S_3, and S_4) are combined in Fig. 16 together with the relationship obtained from Tempe cell tests (see the (V_w/V_o) curve in Fig. 4). All tests have similar initial volumetric water content values, (V_w/V_o) around 0.45. The void ratios associated with these tests were essentially the same (Fig. 17), even though the test corresponded to various net normal stresses. In other words, the results show that the effect of net normal stress (Fig. 16) is negligible.

The distinct and significant difference between the slope of the water volume change (V_w/V_o) versus $(u_a - u_w)$ curve and the m_2^w coefficient associated with the *Consolidation* and *Increasing Matric Suction* tests appears to be consistent in all the test series as indicated in Fig. 16. The m_2^w coefficient of water volume change for the *Consolidation* test is smaller than the m_2^w coefficient for the *Increasing Matric Suction* test. This distinct difference in the m_2^w coefficient can also be observed in the combined plot of gravimetric water content, w versus $(u_a - u_w)$ (Fig. 18) and the volumetric water content, θ_w versus $(u_a - u_w)$ (Fig. 19). The differing water volume change behaviors during the *Consolidation* and *Increasing Matric Suction* tests can be visualized from the idealized plot shown in Fig. 20.

The different water volume change characteristics during the *Consolidation* and *Increasing Matric Suction* tests can be attributed to hysteresis in the unsaturated soil. This is analogous to comparing the virgin compression and recompression curves associated with the conventional consolidation test on a saturated clay. During the *Increasing Matric Suction* test, the matric suction increases to a maximum magnitude to which the soil has never been subjected. In the following *Constant Water Content* loading, which precedes the *Consolidation* test, the matric suction is reduced from its maximum value. Subsequently in the *Consolidation* test, the soil is reloaded towards its maximum matric suction to which it was previously subjected. The volume changes associated with the reloading branch are significantly smaller than those along the virgin loading curve. As a result, the m_2^w coefficient for the *Consolidation* test is smaller than the m_2^w coefficient for the *Increasing Matric Suction* test, although both tests underwent an increase in matric suction. The *Consolidation* curves in Fig. 20 are similar to the scanning curves commonly associated with going between wetting and drying, limiting curves for a soil (Fig. 21). The m_2^w coefficient for the *Consolidation* test is smaller than the m_2^w coefficient for the *Increasing Matric Suction* test, indicating a faster rate of excess pore-water pressure dissipation during the *Consolidation* test as compared to the pore-water pressure decrease in the *Increasing Matric Suction* test (Rahardjo and Fredlund 1995).

The Increasing Matric Suction curves obtained from the test series are essentially the soil-water characteristic curves for the silty sand. However, these water content versus matric suction curves from the test series appear to be higher than the soil-water characteristic curves obtained from the Tempe cell tests, as shown in Figs. 16, 18, and 19. In other words, the soil specimen had a higher water content during the *Increasing Matric Suction* test in the K_o-cylinder than during the same test using the Tempe cell. This discrepancy of the soil-water characteristic curves might be attributable to the application of the net normal stress during the test series in the K_o-cylinder. The Tempe cell test is performed without the application of a net normal stress. Another *Increasing Matric Suction* test (S_6 series) was performed on a slurried specimen without the application of any net normal stress in the K_o-cylinder. The soil-water characteristic curves from the S_6 test series appear to coincide with the *Increasing Matric Suction* curves from the other test series, as shown in Figs. 16 and 18. This means that the soil-water characteristic curves obtained from the K_o-cylinder are the same with and without the application of net normal stress. The influence of net normal stress on the void ratio has been shown Fig. 17 to be negligible at matric suctions greater than approximately 10 kPa.

The change in volume of water, (V_w/V_o) from the Tempe cell test is still lower than the (V_w/V_o) from the S_6 series. Both curves start from the same initial water content at zero matric suction. However, the Tempe cell curve appears to decrease more rapidly at matric suctions below 5 kPa than the S_6 series curve, and both curves are essentially parallel to each other beyond 5 kPa matric suction. Both curves appear to merge at high matric suctions.

The reason for the differences in the water content, (V_w/V_o) curve from the Tempe cell test and the K_o-cylinder was attributed to the different consolidation pressures caused by the self-weight of the soil. The height of the specimen in the K_o-cylinder (i.e., 250 mm) is about five times greater than the height of the specimen in the Tempe cell (i.e., 50 mm). As a result, the tall specimen in the K_o-cylinder has a lower void ratio due to consolidation by its self-

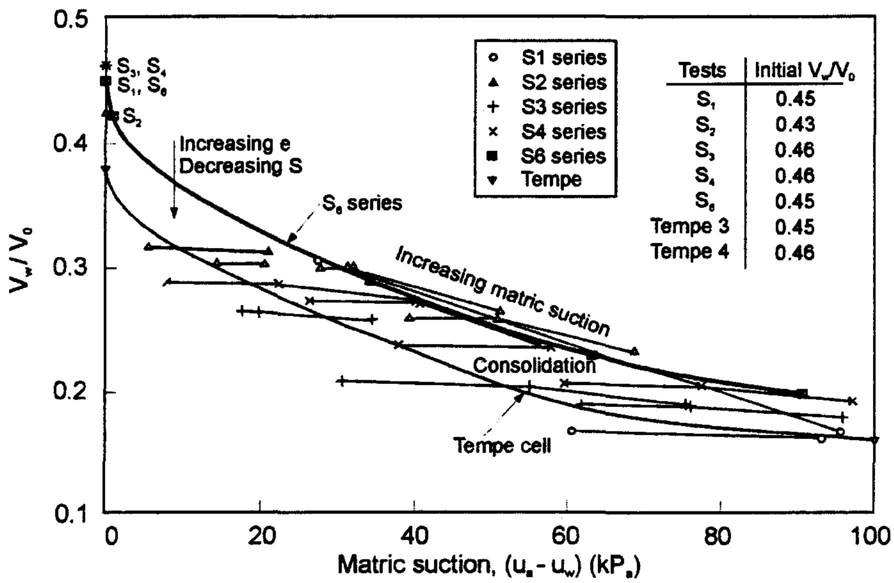

FIG. 16—*(V_w/V_o) versus matric suction relationship obtained from the experimental series.*

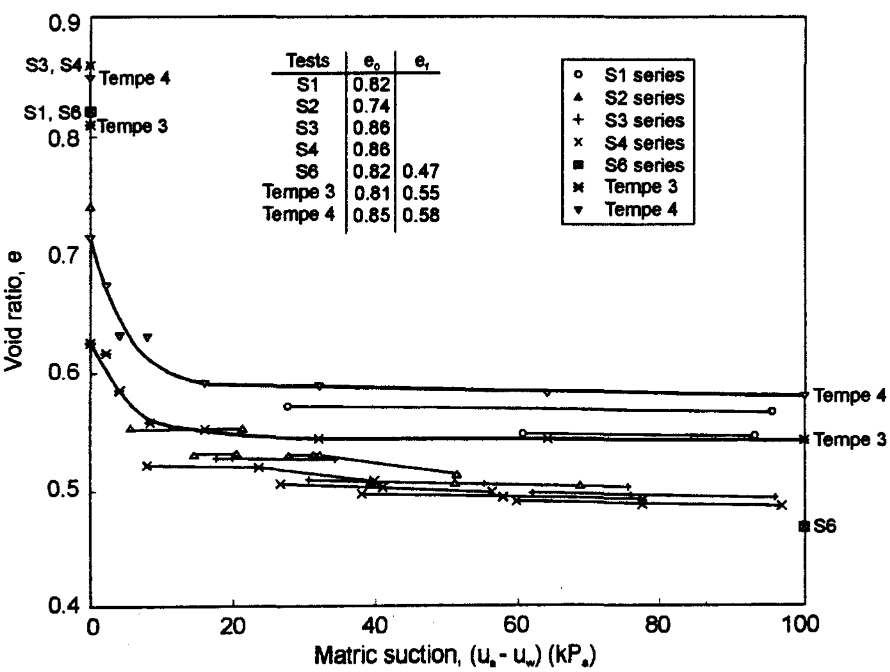

FIG. 17—*Void ratio versus matric suction relationship obtained from the experimental series.*

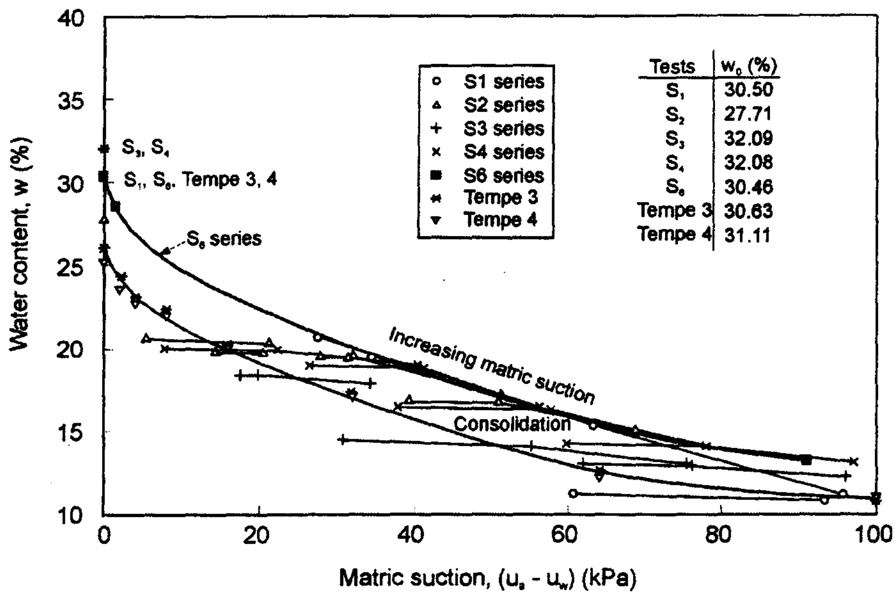

FIG. 18—*Water content versus matric suction relationship obtained from the experimental series.*

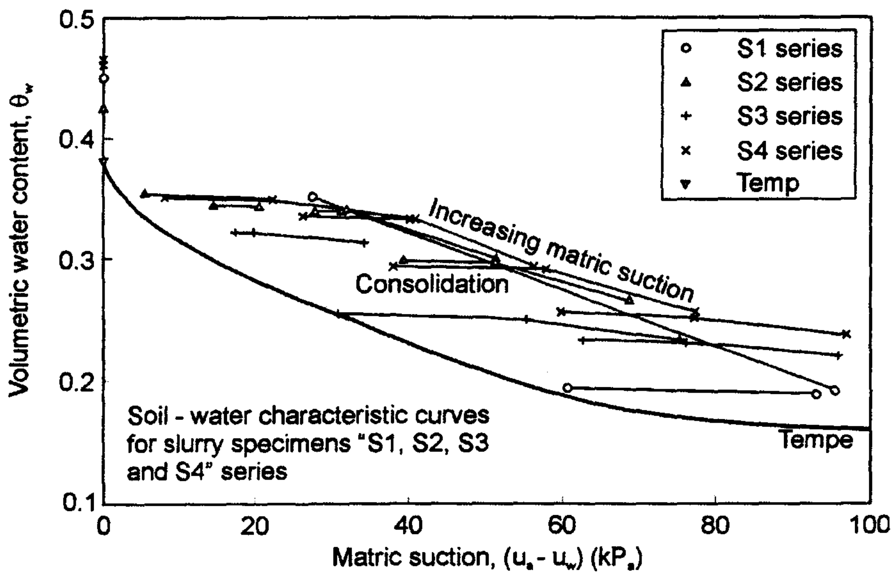

FIG. 19—*Volumetric water content versus matric suction relationship obtained from the experimental series.*

weight, as compared to the short specimen in the Tempe cell (Fig. 17). The void ratios in the Tempe cell specimens remain higher than the void ratios in the S_6 specimen until the end of the test at a matric suction of 100 kPa.

The specimen in the Tempe cell at low applied matric suctions would be expected to contain large and small pores, and the larger pores would drain first upon increasing the matric suction causing soil to desaturate at low matric suctions (Fig. 22). The specimen the K_o-cylinder had been consolidated under a pressure applied at the beginning of the test, and as a result, the soil contained smaller pore sizes. The reduction in size of the large pores was observed by Griffiths and Joshi (1989) who stated: "The volume decrease due to consolidation of clays has been found to be due to changes in the volume of the largest existing pores. The change is represented as a reduction in total porosity and a shift towards smaller pores." This means that the soil specimen in the K_o-cylinder would desaturate at a higher matric suction due to the smaller pore sizes in the soil as compared to the specimen in the Tempe cell (Fig. 22). The early desaturation process in the Tempe cell test results in a lower volume of water in the soil specimen as compared to the specimen in the K_o-cylinder. Therefore, the soil-water characteristic curves from the Tempe cell tests are lower than the curves from the experimental test series in the K_o-cylinder (Figs. 16 and 18).

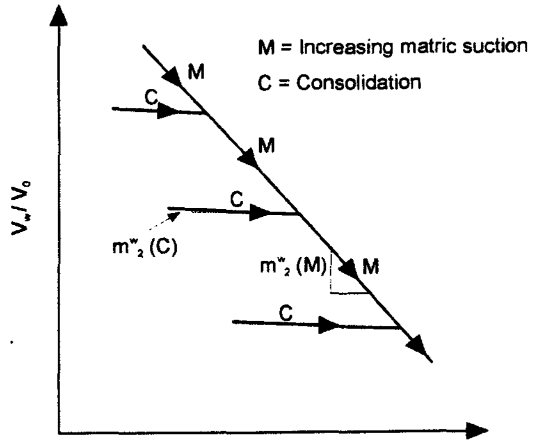

FIG. 20—*Idealized relationship between the volume of water and matric suction during consolidation and increasing matric suction tests.*

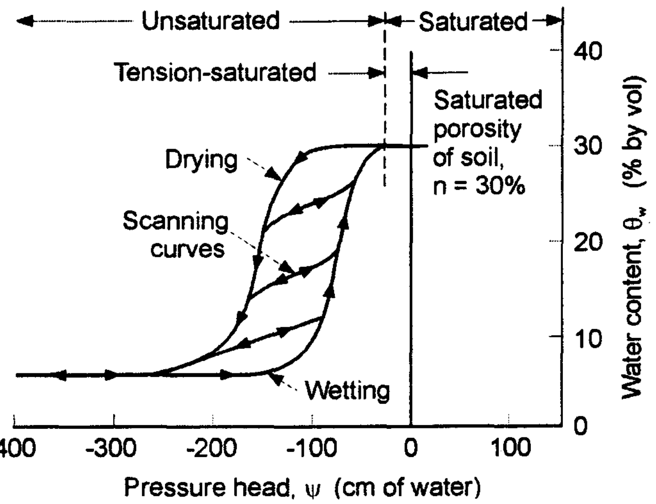

FIG. 21—*Hysteretic function relationship between volumetric water content, θ_w, and matric suction for a naturally deposited sand (from Liakopoulos 1965, and Freeze and Cherry 1979).*

Conclusions

The following conclusions can be drawn from the experiments carried out in this study:

1. The total volume changes associated with the different types of loading, *Increasing Matric Suction*, *Constant Water Content*, and *Consolidation* of unsaturated soil specimens were smaller than the water volume changes associated with these tests, indicating an increasing stiffness of the soil structure as the soil became unsaturated.
2. The *Increasing Matric Suction* and *Consolidation* tests are analogous to the virgin compression and reloading curves from a conventional consolidation test on a saturated clay. It appears that the water coefficient of volume change, m_2^w, for the *Increasing Matric Suction* test is much larger than the m_2^w coefficient for the *Consolidation* test. In other words, an unsaturated soil will experience a large water volume change if it is subjected to a higher matric suction than the soil has previously experienced. However, the water volume change is small when the matric suction in an unsaturated soil is reduced and then increased to the maximum matric suction the soil previously experienced. The water volume change will become large when the soil is subjected to a matric suction higher than the maximum past matric suction.
3. The experimental results obtained from this study illustrate that an unsaturated soil has a memory with respect to matric suction, in the same manner as a saturated soil has a memory with respect to effective stress. Therefore, it is appropriate to consider that an unsaturated soil has independent memories with respect to net normal stress and matric suction, particularly in the development of an elastic-plastic model for unsaturated soil. The experimental data presented herein can be used to support such a theoretical model. However, these independent memories would not have been detected if a single-valued stress equation were used in describing the mechanical behavior of unsaturated soil.
4. The application of a preconsolidation pressure on an unsaturated soil, either due to the application of total stress or due to the self-weight of the soil will have an effect on the pore-size

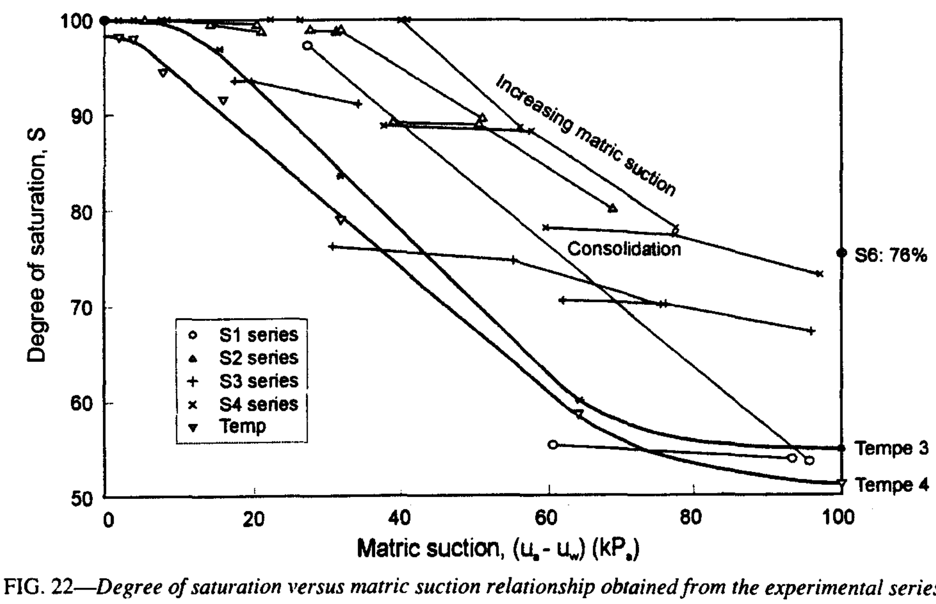

FIG. 22—*Degree of saturation versus matric suction relationship obtained from the experimental series.*

distribution causing the soil-water characteristic curves to be changed. The preconsolidated soil contains smaller pore sizes that desaturate at a higher matric suction. The soil not subjected to a preconsolidation pressure contains larger pores that will drain first upon increasing the matric suction, causing the soil to desaturate at a low matric suction. As a result, the preconsolidated soil will have a higher water content in the soil-water characteristic curve. It is important to consider whether a soil specimen should be preconsolidated before conducting a pressure plate test in order to obtain a soil-water characteristic curve.

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