Consolidation of an Unsaturated Illitic Clay Soil

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ABSTRACT

Soil stabilizes with time after disturbance as a function of thixotropy and soil water stress. This study was undertaken to delineate the effects of soil water suction history and thixotropy on soil stabilization and effective stress. Unconfined compressive strength, tensile strength, density, and effective stress as a function of water stress history and time were obtained for a Paulding clay soil (very fine, illitic, non acid, mesic Typic Haplaquepts). Compressive strength was five times greater at 64 kPa suction than at 4 kPa suction, and twice as great at 32 d than at 4 d. Density also increased with suction and time. Compressive strength at 2 kPa suction was 1.8 and 3.2 kPa for prestress suctions of 4 and 32 kPa, respectively; and was 4.4 and 8.9 kPa for prestress suction of 64 kPa after 4 and 32 d, respectively. Prestress and time had no effect on tensile strength apparently because no volume change was allowed. The data supported the hypothesis that strength in unsaturated soil was controlled by soil water stress history. Prestress due to drying induced bonding, which persisted after suction was released if volume change was not restricted. Effective stresses due to soil water suction were greater for strength than for volume change and were influenced by soil structure for the case of strength, but not for the case of volume change.

SOIL CONSOLIDATION has important practical implications with regard to changes in soil behavior through the year. A consolidated soil is stronger and denser, and hence requires more energy to till at the same water content than does an unconsolidated soil (Panwar and Siemens, 1972). Consolidation changes soil erodibility as strength and density increase (Dickinson et al., 1982). Quantifying and comparing changes in a soil due to the individual mechanisms of the consolidation process will enhance our abilities to predict changes in soil properties related to tillage and erosion.

To consolidate is "to grow firm and hard; to unite and become solid; as, moist clay *consolidates* by drying" (Webster, 1973). Herein, the term *consolidation* is defined as the increase in soil strength or density due to (i) effective stresses caused by soil water suctions, and (ii) time whereby increases may occur at essentially constant values of suction. These two mechanisms of consolidation correspond respectively to primary and secondary consolidation as defined for the reduction in volume of a soil mass from an externally applied load (American Society for Testing and Materials, 1984).

The stabilizing mechanisms of thixotropy and water stress often, or usually, are superimposed under field conditions. Thixotropic processes that occur after a soil is mechanically disrupted tend to stabilize soil aggregates (Kemper and Rosenau, 1984; Utomo and Dexter, 1981a; Blake and Gilman, 1970), increase soil strength (Utomo and Dexter, 1981b; Mitchell, 1960), and decrease soil erodibility (Sargunam, 1973; Partheniades and Paaswell, 1970; Grissinger, 1966). Soil stabilization also occurs due to negative pore water stress that accompanies drying or suction. Aggregate stabilization as a function of induced pore water suction or drying has been observed by Kemper and Rosenau (1984) and by Utomo and Dexter (1982). Soil shear strength also increases as a function of suction or drying (Formanek et al., 1984; Panwar and Siemens, 1972; Towner, 1961; Williams and Shaykewich, 1970; Gerard, 1965; Gill, 1959; Camp and Gill, 1969).

The increase in strength of a soil due to soil water suctions can be explained in terms of effective stress. The effective stress concept as related to soil water suctions in both saturated and unsaturated soil has been discussed previously (Towner, 1961; Towner and Childs, 1972) and will be presented here only briefly. For a saturated soil the working definition of effective stress, σ', is given by the equation

$$\sigma' = \sigma - u \quad [1]$$

where σ is mechanical stress applied externally to the soil mass and u is pore water pressure. For saturated unconfined soils the applied stress is zero and

$$\sigma' = \Omega \quad [2]$$

where Ω is soil water suction (the negative value of soil water matric potential). For unsaturated soils the effective stress is normally less than the soil water suction due to (i) a portion of the soil pores are empty and thus are not under suction stress and (ii) isolated pockets of pore water may exist at suctions that are less than that of continuous water (Towner and Childs, 1972). Thus for unsaturated unconfined soil,

$$\sigma' = \chi\Omega \quad [3]$$

where χ is an empirical parameter that represents the proportion of soil water suction that contributes to effective stress. The χ cannot be measured. It must be calculated from some form of test in which a relationship between the measured quantity and effective stress is known or assumed. For instance, the parameter χ is often obtained from shear strength tests of unsaturated soil by assuming that the shear strength-effective stress relationship (such as Mohr-Coulomb) is valid for the unsaturated condition (Williams and Shaykewich, 1970; Bishop and Blight, 1963). Volume change relations can also be used (Blight, 1967), since volume change in soils is a function of effective stress. Little available data exist to compare the χ values as determined by strength tests, χ_s, to those from volume change tests, χ_v. Also, since χ is dependent on the water filled soil pores, it is to be expected that χ would vary with soil structure (i.e., pore size distribution). This effect has not been investigated.

Stress history has a major effect on the mechanical behavior (strength and volume change) of saturated soil (Perloff and Osterberg, 1964; Holtz and Kovacs, 1981; Hvorslev, 1960). A sample of soil that is con-

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solidated by a confining pressure and subsequently unloaded to some lesser confining pressure (i.e., an over consolidated sample) has a higher strength than a sample of the same soil consolidated to the same confining pressure but which has not been prestressed. It would be reasonable to expect that prestress due to suction, Ω_p, in unsaturated soil also causes permanent strength increases, but such increases have not been extensively or methodically studied. Nor has the effect of length of time of prestress, t_p, due to suction been studied extensively. Prestress caused by drying may be especially important in the case of erosion since the soil is rewet during erosion events.

This study was undertaken to delineate and compare the effects of soil water stress and time on the compressive strength, tensile strength, and volume change characteristics of an unsaturated illitic clay soil. The effect on strength of both level and duration of prestress due to soil water suction was also investigated. Effective stress relations were compared for strength and volume change of the unsaturated soil with two different soil structures.

MATERIALS AND METHODS

The soil used in this study was a Paulding clay from Defiance, OH. X-ray analysis indicated that the clay mineralogy was primarily illite with lesser but significant amounts of 2:1 expandable minerals and kaolinite. The soil contained 550 g kg^{-1} clay, 350 g kg^{-1} silt, and 100 g kg^{-1} sand. The soil was air-dried and ground to pass a 4.75-mm sieve. For the part of the experiment that tested the effect of structure on effective stress relationships, the soil was further ground to pass a 1.00-mm sieve. Dry aggregate sizes as determined by hand-sieving are shown in Fig. 1. The soil was then wetted by spraying to a water content of 270 g kg^{-1} and stored in a plastic container for 48 h to allow the water to distribute evenly through the soil.

Unconfined Compression Tests

Samples for unconfined compression tests were formed by static compaction (Holtz and Kovacs, 1981) of the moist soil within a brass cylinder to a radius of 19.0 mm, to a length of 75.8 mm, and to a density of 1.10 Mg m^{-3}. The sample was removed from the cylinder, covered on the sides with a Trojan[1] latex membrane, placed on a porous stone, and then placed in a plastic basin. The basin was then filled with deionized water to the top of the sample and left covered for 3 d. The membrane kept the sample from disintegrating while it was being satiated. The effects of time and suction on consolidation were evaluated by placing the samples on tension tables or pressures plates at 4, 16, and 64 kPa for 4, 8, 16, and 32 d before testing. Samples at 64 kPa did not come to equilibrium in 2 d and were discarded. To test the effect of prestress level on strength gain, samples that were at 4, 8, 16, and 32 kPa for 2 d were placed at 2 kPa on tension tables and allowed to reabsorb water and equilibrate for 4 d. The effect of time of prestress was tested by placing samples at 64 kPa for 4, 8, 16, and 32 d before reequilibrating for 4 d at 2 kPa suction. Tension tables were always covered and sealed with stop-cock grease to prevent sample drying. Equilibrium for the samples was tested by comparing the water contents in the bottom, middle, and top of each specimen, and for samples with time treatments by comparing water contents for the different times. Each treatment had three or four replicates.

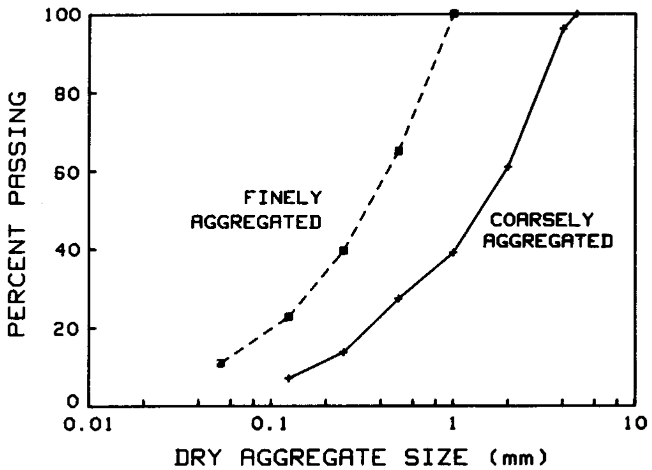

Fig. 1. Dry aggregate size distribution as determined by sieving.

Unconfined compressive strength was measured with an Instron Universal Testing Instrument (Instron Corp., Canton, MA)[1]. Latex membranes were removed before testing. The samples were compressed at a rate of .05 cm min^{-1} until maximum axial stress was reached. Shear strength, τ, was maximum shear stress, or one-half compressive strength, which is the standard interpretation for unconfined tests (Holtz and Kovacs, 1981). Failure occurred at between 3 and 7% strain for all samples. The volume of each sample was determined before strength testing by measuring sample length and diameter with calipers to 0.1 mm.

Effective Stress Relationships

Drained triaxial compression tests were performed in order to compute effective stress parameters for strength and volume change. Samples were prepared similarly to the unconfined compression samples and satiated for 24 h in the triaxial cell. Samples were then compressed three dimensionally to 6, 16, 32, 64, and 128 kPa and volume change was recorded. Samples then underwent uniaxial compression at a strain rate of 0.0005 cm min^{-1} for 40 h. The method of the U.S. Army Corps of Engineers (1970) was used. Samples were not backsaturated. Failure strain was considered to be 15%. The time between consolidation and failure was 3 to 4 d. Triaxial strength was corrected for the effect of the latex membrane (Henkel and Gilbert, 1952). Cohesion and friction angle were calculated assuming a Mohr-Coulumb relationship between strength and effective stress.

Values of χ for strength measurements, χ_s, and volume change measurements, χ_v, were determined for the unconfined samples kept 4 d at 4, 16, and 64 kPa by comparing with results from the triaxial tests. The method for obtaining χ_s was outlined by Bishop and Blight (1963). For volume change, χ_v was calculated from Eq. [3] and the empirical relationship (Eq. [4]) between bulk density (ρ_b) and effective stress (σ')

$$\rho_b = m \log \sigma' + b \quad [4]$$

obtained from the three-dimensional triaxial compression data. In Eq. [4], m represents slope and b represents intercept. The χ values were obtained for both coarsely (< 4.75 mm) and finely (< 1.00 mm) ground materials (see Fig. 1).

Tensile Tests

A tensile strength tester was designed and constructed to measure the tensile strength of a soil sample at low density and high water content. The cylindrical acrylic cells (Fig. 2a) were 11.5 cm long by 5.1 cm o.d. with caps on each end.

[1] Trade names and company names, included for the reader's benefit, do not imply endorsement or preferential treatment of the product listed by the USDA.

Each cell was cut into halves such that the halves could be clamped together with a stainless steel hose clamp. In one end of the cell was a porous ceramic plate and in the other end was a porous corundum stone. Stainless steel tubing, 0.16-cm diam., was placed in the cell walls to the porous stone and plate so that the sample ends could be either connected to a water column or open to the air. Soil samples were formed within the cell by clamping the cell halves together, removing the cap and porous stone from one end, and compacting moist soil into the cell. The porous stone and cap were then replaced on the end of the sample. The resultant sample size was 7.47-cm length by 3.88-cm diam.

To test the sample, the clamp was removed from the tensile cell and the cell was placed horizontally onto a set of rails with ball bearings so that the cell could roll freely (Fig. 2b). Hooks were centered on the caps at each end of the tensile cell. One end of the cell was held fixed in position by a nylon line. The other end of the cell was connected by a nylon line through a guide hole (so that the force exerted was concentric to the cell) and then through a metal eye (to provide a 90° turn of the line from horizontal to vertical) to a load cell on the Instron[1] testing machine. The load cell was mounted on the cross beam of the testing machine so that as the beam moved upwards, at a rate of 0.1 cm min^{-1}, the halves of the tensile cell moved apart from the sample. The force required to fail the sample was measured by the load cell.

Samples of moist soil at a water content of 270 g kg^{-1} were compacted to a density of 1.1 Mg m^{-3} into the tensile cells. The soil was satiated from the porous stone end of the cell for 3 d. Tensions of 0, 1, 3, and 6 kPa were applied through the porous plate end of the cell for 8 d and then the samples were tested. To test for prestress effects, samples were subjected to suctions of 0, 1, 3, and 6 kPa for 4 d and then resatiated for 4 d prior to testing. To test for possible time effects, samples were stored at 3 kPa suction for 4, 8, 16, and 32 d. Finally, since the tensile cells were of constant volume and hence sample density did not change for the treatments, the effect of density on tensile strength was tested. Samples formed at 1.0, 1.1, and 1.2 Mg m^{-3} were held at 3 kPa suction for 8 d before testing. The number of replicates for each treatment ranged from four to seven.

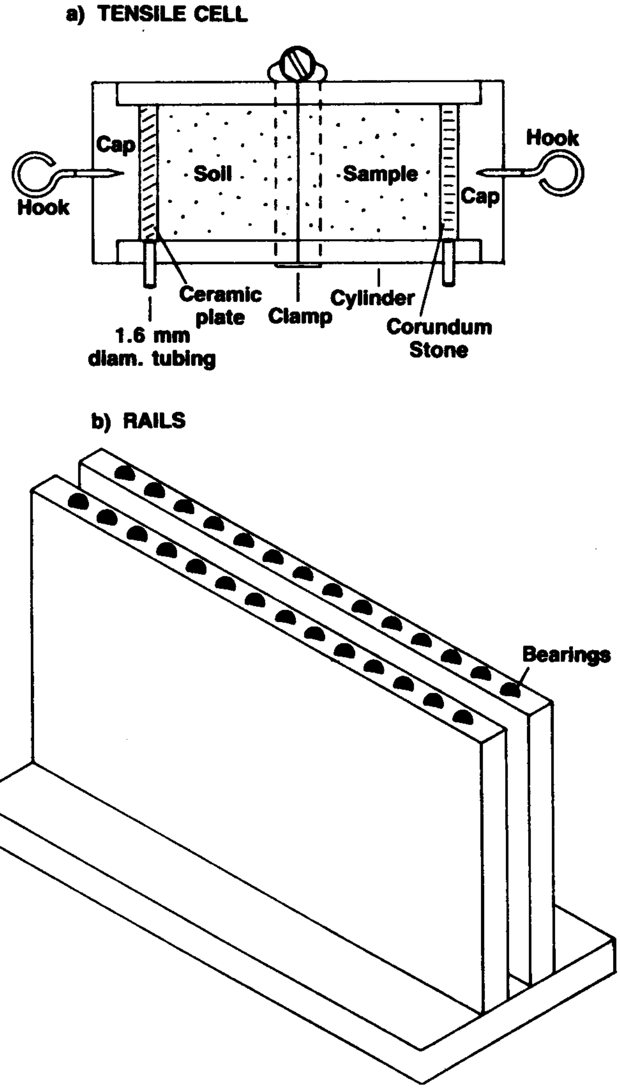

Fig. 2. Schematic of soil tensile strength testing apparatus.

RESULTS AND DISCUSSION

Unconfined Shear Strength

Values of shear strength and density for the unconfined samples for suction and time treatments are given in Table 1. Soil strength increased nonlinearly with suction. For a 16-fold increase in suction (from 4 to 64 kPa) shear strength increased 460, 412, 399, and 362% for the 4-, 8-, 16-, and 32-d treatments, respectively. Strength increased linearly with logarithm of time for each of the three suctions; regression parameters are listed in Table 2. For an eightfold increase in time (from 4–32 d) strength increased 126, 90 and 87% for the 4, 16, and 64 kPa treatments, respectively. Both mechanisms of consolidation, suction and time, stabilized the Paulding samples, with suction having the greater influence over the range of conditions tested in this experiment.

The nonlinearity of the relationship between strength and suction resulted because the fraction of pore water stress that contributed to the effective stress decreased as the soil pores desaturated; i.e., the χ value was not a constant but decreased with suction as soil pores desaturated. This result was, in a general sense, consistent with past results (Towner and Childs, 1972; Bishop and Blight, 1963), and indicates the importance of evaluating χ when predicting consolidation effects due to drying. The χ values are discussed below.

Bulk density also increased as a function of both suction and time (Table 1). It is well known from soil mechanics literature that soil volume changes occur with time when a load is applied even after excess pore water pressures dissipate (Leonards and Ramiah, 1959; Mesri and Godlowski, 1977). From the data presented in this study, the corollary appears to be true also for unsaturated clay. Volume change continued with time when a suction was applied even after the soil water potential came to equilibrium.

Values of shear strength and bulk density for the prestress suction and time treatments are given in Table 3. Strength at 2 kPa suction increased linearly with prestress level over the range tested as

$$\tau = 1.5 + 0.054\,\Omega_p \quad [5]$$

where τ is shear strength in kilopascals. The increase was not as great as was the increase of strength with suction at time of test (Table 1) because of the rewetting, but a portion of the strength gain was maintained. Strength also increased linearly with logarithm

Table 1. Shear strength and density for treatments of suction and time.

Suction	Time	Bulk density $\bar{x}$	Bulk density SD	Shear strength $\bar{x}$	Shear strength SD	No. of samples n
kPa	d	Mg m^{-3}		kPa		
4	2	1.03	0.01	1.80	0.08	4
4	4	1.03	0.01	2.10	0.10	3
4	8	1.04	0.01	2.76	0.06	3
4	16	1.05	0.01	3.74	0.29	3
4	32	1.06	0.01	4.74	1.01	3
16	2	1.04	0.01	2.81	0.23	4
16	4	1.05	0.01	4.66	0.35	3
16	8	1.06	0.01	5.91	0.37	3
16	16	1.09	0.01	7.19	0.40	3
16	32	1.10	0.01	8.87	1.21	3
64	4	1.08	0.01	11.72	0.90	3
64	8	1.09	0.01	14.15	0.63	3
64	16	1.10	0.01	18.65	2.15	3
64	32	1.14	0.01	21.91	0.90	3

of time when prestressed to 64 kPa according to

$$\tau = 4.71 \log t + 1.22\,. \quad [6]$$

Density increased slightly with prestress and also tended to increase with time of prestress.

The strength gain of the clay as a function of soil water suction may be hypothesized to be due to two factors: (i) the soil water stresses due to menisci that tended to hold particles or aggregates together, and (ii) an increase in the number of bonds between particles or aggregates that resulted from these particles being forced together by water stresses. When the suction is released the influence of the first of the two factors listed above is eliminated and strength may be reduced, but some increase in stability is retained due to the bonding mechanism. A reasonable hypothesis is that the longer a water stress is maintained the greater will be the number of bonds retained upon release of the water suction. The data from Table 1 suggest that such bonding does in fact occur and is maintained after the suction is released and that time influences the retention of bonds upon rewetting. This helps to explain why a soil may be more stable to erosion forces after it has dried to some suction for a period of time even though it is rewetted during subsequent erosion events.

Effective Stress Relationships

The drained triaxial friction angle was 30.1° and the cohesion intercept was 0.7 kPa for the Paulding soil.

Table 3. Shear strength and density at 2 kPa suction for treatments of prestress suction, Ω_p, and duration of prestress, t_p.

Prestress suction Ω_p	Duration of prestress t_p	Shear strength $\bar{x}$	Shear strength SD	Bulk density $\bar{x}$	Bulk density SD	No. of samples n
kPa	d	kPa		Mg m^{-3}		
4	2	1.79	0.07	1.02	0.01	4
8	2	2.06	0.12	1.02	0.01	4
16	2	2.29	0.19	1.03	0.01	4
32	2	3.15	0.43	1.05	0.01	4
64	4	4.44	0.94	1.03	0.01	3
64	8	5.30	0.14	1.08	0.03	3
64	16	6.07	0.05	1.08	0.01	3
64	32	8.91	0.74	1.09	0.01	3

Table 2. Linear regression parameters for shear strength, τ, as a function† of logarithm of time at soil water suctions of 4, 16, and 64 kPa.

Soil water suction Ω	Slope m	Intercept b	Coefficient of determination r^2	No. of samples n
kPa		kPa		
4	2.45	0.83	0.86	16
16	4.90	1.45	0.95	16
64	11.66	4.32	0.92	12

† $\tau = m \log t + b$.

The χ_s values as determined by comparison to the triaxial results for the 4-d unconfined tests at 4, 16, and 64 kPa, for fine and coarse materials, were plotted in Fig. 3 as a function of relative soil water content, S. The line $\chi = S$ is shown also, since S is sometimes used as an approximation of χ (Towner and Childs, 1972; Bishop and Blight, 1963). The χ_s and S were greater for the fine material than for the coarse material, but the relationship between χ_s and S was similar for the two materials.

Initial bulk density from the triaxial tests increased linearly with logarithm of effective confining stress as expected according to Eq. [4]. The χ_v values for fine and coarse materials were plotted in Fig. 3 for 4-d unconfined tests at 4, 16, and 64 kPa. Although S was higher for the fine samples, χ_v was not different for the two materials. The difference in pore size distribution and water retention apparently made no difference in volume change behavior of the soil.

Soil structure influenced χ vs. S relationships differently for the case of strength and volume change (Fig. 3). The samples of the fine material held more water than those of the coarse material at the same relative suction and hence distributed the water stress over a greater volume of the soil mass. It is reasonable, therefore, that the strengths at the same relative suctions were higher for the fine than for the coarse materials. Why the same effect was not exhibited for the case of volume change is not known, but it is apparent from the results that effective stress relationships for strength and volume change are different. A possible reason is that the pore sizes that governed the volume

Table 4. Tensile strength for treatments of suction, time, prestress, and density.

Suction at time of test Ω	Time t	Bulk density ρ_b	Prestress suction Ω_p	No. of samples n	Tensile strength $\bar{x}$	Tensile strength SD
kPa	d	Mg m^{-3}	kPa		kPa	
0	8	1.10	NA	6	1.55	0.17
1	8	1.10	NA	5	1.73	0.12
3	8	1.10	NA	4	2.65	0.20
6	8	1.10	NA	4	3.85	0.10
3	4	1.10	NA	4	2.56	0.32
3	8	1.10	NA	4	2.65	0.20
3	16	1.10	NA	5	3.21	0.24
3	32	1.10	NA	7	2.61	0.32
0	8	1.10	0	6	1.55	0.17
0	8	1.10	1	5	1.56	0.22
0	8	1.10	3	6	1.52	0.29
0	8	1.10	6	5	1.51	0.35
3	8	1.00	NA	7	1.60	0.12
3	8	1.10	NA	4	2.65	0.20
3	8	1.20	NA	7	3.24	0.55

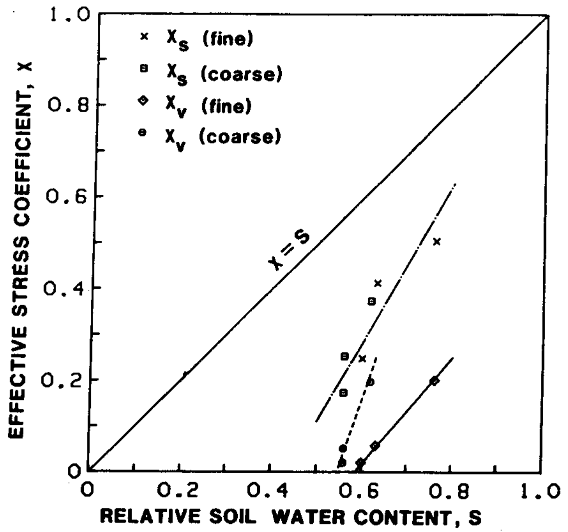

Fig. 3. Effective stress coefficients for strength, χ_s, and volume change, χ_v, as a function of relative soil water content, *S*, for finely and coarsely aggregated soil.

change process were smaller than those that governed strength. There may have been less difference in the number of small pores for the two materials than was the difference in the number of larger pores (macropores).

Past studies of effective stress relationships in terms of χ values have used denser soils and smaller pore sizes than those used in this study. Towner (1961) measured shear strength on a clay paste that was composed essentially of primary clay sized particles. In that case, the χ values were approximately equal to one even at suctions in excess of 400 kPa. Bishop and Blight (1963) compacted clays in their studies using the standard Proctor method that results in densities typically of the order of 1.6 to 2.0 Mg m^{-3} (Holtz and Kovacs, 1981). Densities are much lower and inter-aggregate pore sizes larger for agricultural soils as compared to the soils previously tested for χ values. Effective stress relationships for aggregated soils with low density warrant further investigation.

Tensile Strength

Tensile strength increased linearly with applied suction over the range tested according to the relationship

$$T = 0.394\,\Omega + 1.463 \quad [7]$$

where T is tensile strength (Table 4). Neither prestress nor aging had a measurable effect on the tensile strength as tested here, but tensile strength did increase with increased bulk density.

The results from the tensile tests indicated that the bonding mechanism of strength increase as a result of pore water stress was not active, since strength did not increase as a function of prestress or time. This result may be due to the fact that no volume change of the tensile samples was allowed to occur. These samples, as well as the compression samples, had an initial density of 1.1 Mg m^{-3}. When compression samples were satiated and allowed to swell their densities were reduced to approximately 0.94 Mg m^{-3}. The application of suction again increased their densities, but for the range of times and suctions used in the tensile tests, the volume of sample was never reduced to less than the volume of the tensile cell. The results imply that volume changes must occur in order for prestress or time to increase soil strength. When density differences were created in the tensile cells by packing the cells with different amounts of soil, strength differences were evident.

SUMMARY

The consolidation behavior of an unsaturated illitic clay soil was investigated. The results may be summarized as follows:

1. Soil water suctions and time increased compressive strength and density over the ranges tested. Strength at 64 kPa suction was 4.6 to 5.6 times greater (depending upon time) than strength at 4 kPa suction. Compressive strength increased linearly with logarithm of time. Strength at 32 d was 1.9 to 2.3 times that at 4 d, depending upon suction.
2. Both level and duration of prestress due to suction influenced strength. Compressive strength at 2 kPa water suction increased linearly as a function of previously applied level of water suction and of logarithm of duration of previously applied suction for the ranges of conditions tested.
3. The data supported the hypothesis that strength increase in the unsaturated soil was caused by two mechanisms: (i) level of suction at time of testing, and (ii) increase in bonding due to previous water stress and time. For the compressive tests, strength increased with applied suction at time of test and apparently also as a result of particle bonding induced by aging and prestress caused by drying. For the tensile tests, for which volume was held constant, strength increased with suction at time of test but bonding due to time and prestress was not apparent.
4. At the same relative soil water content, χ values from strength tests were higher than those from volume change measurements. The χ_s was influenced by soil structure, but χ_v was not. The finely aggregated material had higher strength at the same relative suctions than did the coarsely aggregated material but density was the same for both materials. This effect is explained for strength results in terms of moisture retention in the soil macropores.

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