Stress-Strain Behavior of and Hyperbolic Parameters for Structured/Cemented Silts

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Abstract

Isotropically consolidated-drained triaxial compression tests were performed on undisturbed structured/cemented silt to gain a better understanding of the shear behavior of and hyperbolic stress-strain parameters for this material. The results show that the hyperbolic stress-strain parameters for the structured/cemented silt are anisotropic and differ significantly from the hyperbolic parameters developed for silt reconstituted at the field total unit weight and water content. As the confining pressure in a triaxial compression test approaches the preconsolidation pressure, the effects of the structure/cementation are reduced due to bond breakage, and the structured/cemented silt exhibits a stress-strain behavior similar to that of reconstituted silt.

Introduction

The hyperbolic stress-strain model has been shown to be valid for modeling the nonlinear stress-strain behavior of soils prior to failure in soil-structure interaction analyses (Duncan and Clough 1971; Ebeling and Mosher 1996). Ten parameters (modulus number, K, modulus exponent, n, bulk modulus number, K_b, bulk modulus exponent, m, cohesion intercept, c, angle of internal friction at a confining pressure equal to atmospheric pressure, ϕ_0, change in friction angle with increasing pressue, $\Delta\phi$, failure ratio, R_f, unload/reload modulus number, K_{ur}, and unload/reload modulus exponent, n_{ur}) are employed in the hyperbolic stress-strain relationships developed by Duncan et al. (1978) for virgin loading and unloading/reloading conditions. Duncan et al. (1978 and 1980) used the results of isotropically consolidated-drained triaxial compression tests on compacted granular and clayey soils to provide guidance when selecting hyperbolic stress-strain parameters for nonlinear finite-element analyses.

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Stark et al. (1991 and 1994) expanded this guidance to freshly deposited, normally consolidated silts and clayey silts. The present study provides this guidance for naturally occurring structured/cemented silts. This was accomplished by conducting oedometer and isotropically consolidated-drained triaxial compression tests. Structured/cemented and reconstituted specimens were used to evaluate the importance of the structure/cementation on the stress-strain behavior and anisotropy of silts. Also, to investigate the effect of inundation on the drained stress/strain behavior of silts, triaxial compression tests were conducted on structured/cemented and reconstituted specimens at the natural degree of saturation and after laboratory saturation. Finally, to estimate the unload/reload modulus and the effect of unloading/reloading on the degradation of structure/cementation, unload/reload triaxial compression tests were conducted.

Mississippi Loess

The Mississippi loess belt is approximately 110 to 193 km wide, extending eastward from the bluffs along the Mississippi River. Generally, the loess is less than 3 m thick except at the bluffs where it is up to 30 m thick. Mississippi loess contains mainly silt and clay size particles. Scanning electron microscope photographs reveal that the silt particles are subangular to subrounded (Fig. 1). The cementing agents in the loess are predominantly carbonates, iron salts, and clays in various combinations (Krinitzsky and Turnbull 1967). Fig. 1 also presents a close up view of the cementation between two silt particles.

Fig. 1. Scanning electron microscope photograph of cementation joining two silt particles (magnification equals 500 times)

Two undisturbed block samples were hand excavated from a nearly vertical 10-m-high loess bluff at the Waterways Experiment Station in Vicksburg, Mississippi. One of the block samples was used to obtain specimens trimmed in the field orientation and the other block was used to obtain specimens trimmed 90 degrees from the field orientation. The field orientation is referred to as the vertical orientation, and the horizontal orientation corresponds to 90 degrees from the field orientation. Hydrometer analyses revealed that the clay-size fraction, the material finer than 0.002 mm, of the light-brown loess is approximately 10 to 12 percent. Approximately 2 to 3 percent of the loess is fine sand, shells, and organic particles that do not pass the U.S. Standard Sieve No. 200. The loess classifies as a low plasticity silt according to the Unified Soil Classification System and the liquid and plastic limits, natural water content, initial void ratio, degree of saturation, total unit weight, and specific gravity of solids are 30, nonplastic, 19.9%, 0.793, 68.3%, 17.9 kN/m^3, and 2.71, respectively,

Oedometer Testing

Oedometer tests were conducted in accordance with ASTM Standard Test method D2435-94 ("Standard" 1994) to investigate the effect of structure/cementation and inundation on the compressibility of both undisturbed and reconstituted silt specimens and to estimate the preconsolidation pressure. The structured/cemented silt was obtained by trimming a specimen directly from an undisturbed block sample into a rigid oedometer ring in the vertical orientation. Test results show that the partially saturated structured/cemented specimen, trimmed in the field orientation, yielded a preconsolidation pressure, according to Casagrande's construction, of approximately 958 kPa. The corresponding compression and recompression indices, obtained from the void ratio-applied vertical stress relationships, are approximately 0.26 and 0.017, respectively. The oedometer test results were plotted in terms of applied vertical stress and not effective stress because the specimens were partially saturated and capillary pressures were probably present.

An oedometer test was also conducted on a partially saturated reconstituted specimen, obtained by compacting remolded silt in a rigid oedometer ring. The silt was compacted directly into a rigid oedometer ring at the natural water content of 19.9 percent and total unit weight of 17.9 kN/m^3. As expected, the test results show that the reconstituted specimen is more compressible than the structured/cemented specimen (Stark et al. 1996). The reconstituted preconsolidation pressure is approximately 383 kPa, which is less than the structured/cemented value of 958 kPa by a factor of about 2.5. The corresponding compression and recompression indices obtained from the void ratio-applied stress relationships for the reconstituted specimens are estimated to be 0.16 and 0.026, respectively. The compression index is greater for the structured/cemented silt than the reconstituted silt probably because of the collapse of the structure/cementation at stresses that exceed the preconsolidation pressure. The values of the recompression index are less for the structured/cemented silt than the reconstituted silt because of the stiffer behavior at stresses less than the preconsolidation pressure.

Two oedometer tests were conducted to investigate the effect of soaking, or distilled water inundation, on the stiffness and compressibility of the structured/cemented silt trimmed in the vertical orientation. The specimens were inundated by filling the chamber surrounding the specimen container with distilled water, and the test was performed according to ASTM Standard Test Method D2435-94 ("Standard" 1994). However, the specimens were soaked at an applied vertical stress of 115 kPa and 1,101 kPa. An applied vertical stress of 115 kPa corresponds to the recompression range of the silt. An applied vertical stress of 1,101 kPa exceeds the preconsolidation pressure of approximately 958 kPa, and thus corresponds to the virgin compression range.

A negligible difference between the compressibility of the partially saturated and inundated specimens of the structured/cemented silt was observed in the recompression range. Therefore, inundation in the recompression range does not significantly increase compressibility or decrease the stiffness of the structured/cemented silt. However, inundation in the virgin compression range resulted in an increase in axial strain of approximately 1 percent at an applied vertical stress equal to 1,101 kPa. After inundation and an increase in applied vertical stress, the silt exhibited a stress-strain behavior similar to that of the partially saturated specimen.

In summary, inundation of structured/cemented silt in the recompression range did not significantly change the compressibility or stiffness. Therefore it may be concluded that inundation using distilled water does not damage or dissolve the natural structure/cementation of this loess. However, soaking in the virgin compression range may cause an increase in axial strain or a decrease in void ratio. This should be considered when constructing on or inundating structured/cemented silts.

TRIAXIAL COMPRESSION TESTS

Preparation of Structured/Cemented and Remolded Triaxial Specimens

The structured/cemented triaxial specimens were trimmed using a trimming lathe, a fine wire saw, and a 0.3m long razor blade. One set of specimens was trimmed from a block sample oriented in the field orientation and the other set was trimmed from a block sample oriented 90 degrees from the field orientation. The reconstituted triaxial test specimens were fabricated using a stainless steel mold. The remolded silt was compacted directly into the stainless steel mold at the natural water content of 19.9 percent and total unit weight of 17.9 kN/m^3.

Stress-Strain Behavior of and Hyperbolic Parameters for Partially Saturated Silt

A series of isotropically consolidated-drained (ICD) triaxial compression tests were conducted on partially saturated, structured/cemented silt specimens. The specimens were trimmed and tested at the natural water content of approximately 19 percent. Therefore, water was not introduced to the specimens before, during, or after the tests. These tests were conducted at an axial displacement rate of 0.2 mm/minute, which corresponds to an axial strain rate of 1.7 percent/minute. Since the material was partially saturated and the drainage valve to the specimen was open during the consolidation and shear phases of the tests, this axial displacement rate was deemed suitable. However, no water entered or exited the specimens during the tests. Shearing commenced after the specimens came to equilibrium under the applied confining stress (σ_3). The specimens were partially saturated and capillary stresses were probably present at the time of shearing. As a result, the confining pressure is not referred to as an effective stress or a consolidation stress. In addition, the resulting shear strength and hyperbolic parameters are not referred to as effective stress parameters. Since the natural or in situ degree of saturation is approximately 59 percent, no volumetric strain measurements were made during these tests and thus no hyperbolic volume change parameters were derived.

The test results illustrate the effect of structure/cementation and confining pressure on the drained stress-strain behavior of structured/cemented silts. Figs. 2.a through 2.d present the stress difference-axial strain relationships from the four ICD triaxial compression tests on partially saturated, structured/cemented silt (field orientation). The stress difference is defined as the major principal stress (σ_1) minus σ_3. The confining pressures for the four ICD triaxial tests shown in Fig. 2 range from 47.9 to 552 kPa. The resulting Mohr-Coulomb stress cohesion and angle of internal friction are 46 kPa and 28 degrees, respectively (see Table 1).

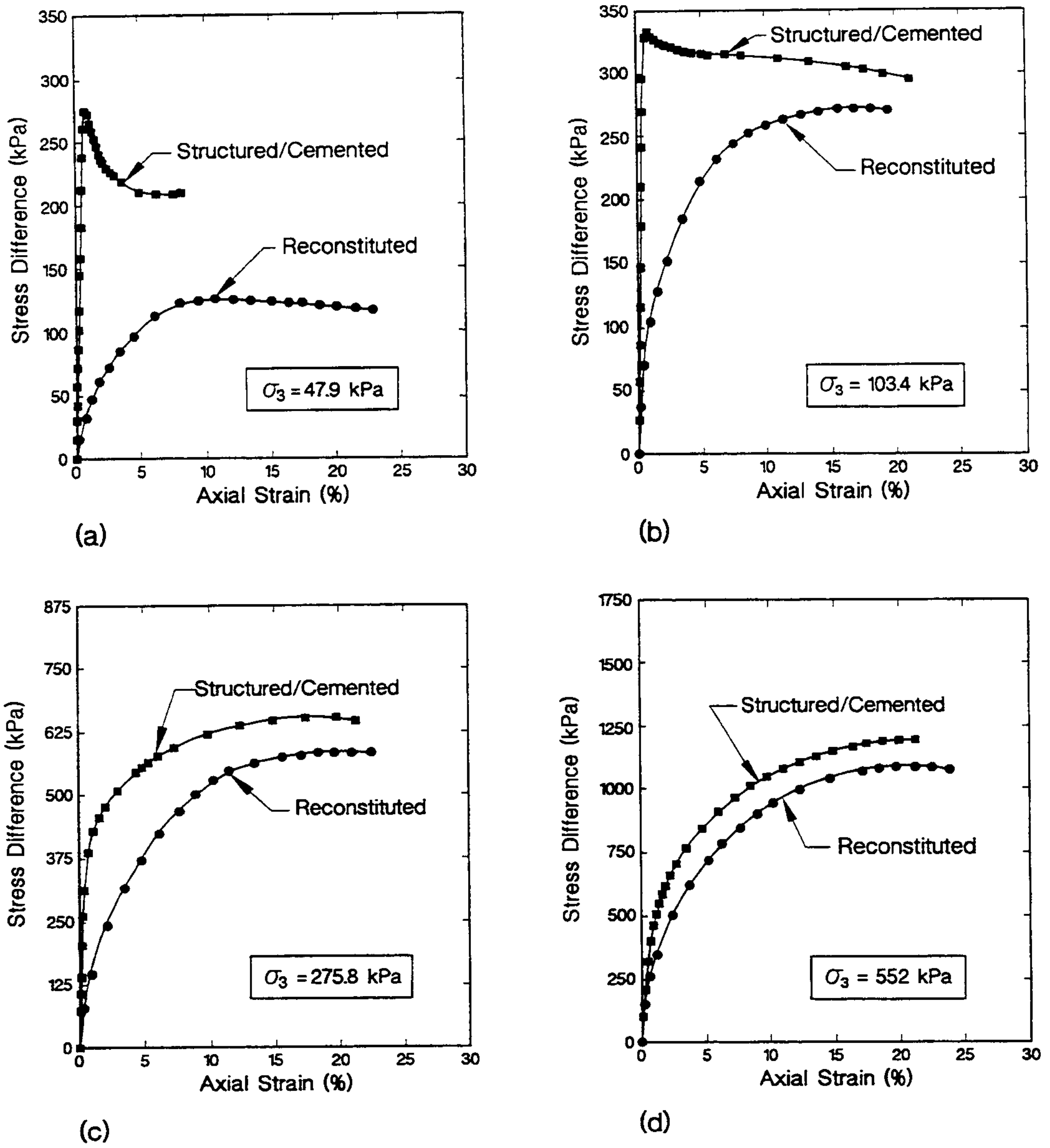

Fig. 2. ICD triaxial compression tests on partially saturated structured/cemented and reconstituted silt tested at field orientation and reconstituted silt at a confining pressure of a) 47.9 kPa, b) 103.4 kPa, c) 275.8 kPa, and d) 552 kPa

Tests on reconstituted specimens were conducted at the same confining pressures as the tests on the structured/cemented silt specimens. These ICD triaxial compression test results are superimposed in Figs. 2.a through 2.d for comparison purposes. At confining pressures of 47.9 kPa and 103.4 kPa, the stress-strain relationship of the structured/cemented silt exhibits a pronounced peak strength and a post-peak strength loss. As the confining pressure increases to 275.8 kPa, the difference in stiffness and maximum stress difference decreases. At a confining pressure of 552 kPa (Fig. 2.d), the structured/cemented and reconstituted silt specimens exhibit similar stiffness and shear strength characteristics. The structured/cemented silt test results in Fig. 2.d no longer exhibit the post-peak behavior attributed to the structure/cementation as shown in Fig. 2.a. Since a confining pressure of 552 kPa is still less than the preconsolidation pressure of approximately 958 kPa, differences in the relationships shown in Figure 2.d are expected. Tests results in Fig. 2 show that the confining pressure can overcome (and possibly "break") the structure/cementation of the undisturbed silt resulting in a stress-strain behavior that approaches the reconstituted silt behavior as the confining pressure approaches the preconsolidation pressure. The cohesion and friction angle are 0 kPa and 30 degrees, respectively, for the reconstituted silt. Therefore, the structure/cementation results in a higher value of cohesion (46 kPa) and a similar value of friction angle (28 degrees) as the reconstituted specimens.

Table 1 - Mohr-Coulomb Shear Strength and Hyperbolic Stress-Strain Parameters for Partially Saturated Structured/Cemented and Reconstituted Silt

Type of Specimen	Average Initial Total Unit Weight (kN/m^3)	Average Initial Water Content (%)	Cohesion (kPa)	Friction Angle (degrees)	Modulus Number (K)	Modulus Exponent (n)	Failure Ratio (R_f)
Structured/ Cemented (Vertical Orientation)	16.7	17.2	46	28	1200	-0.4	0.85
Reconstituted	17.9	19.9	0	30	80	0.8	0.85
Structured/ Cemented (Horizontal Orientation)	17.9	19.9	12	31	305	-0.1	0.95

Table 1 presents the hyperbolic stress-strain parameters obtained from the ICD triaxial compression tests on the partially saturated, structured/cemented and reconstituted silts. The hyperbolic stress-strain parameters for the structured/cemented and reconstituted silt specimens were obtained using the previously reported Mohr-Coulomb shear strength parameters and the best geometric agreement between measured and hyperbolic stress-strain relationships. The geometric agreement was emphasized at axial strains of less than 5 percent to provide a reasonable estimate of the tangent modulus at small strains. The geometric agreement is emphasized at axial strains less than 5 percent because the hyperbolic stress-strain model does not simulate strain softening behavior. The initial estimate of the hyperbolic stress-strain parameters was obtained using the procedure recommended by Duncan et al. (1980) in which the stress difference at 70 and 95 percent of the maximum stress difference are used to estimate the tangent modulus. Figs. 3.a (applied confining stress of 47.9 kPa) and 3.b (applied confining stress of 552 kPa) present typical comparisons of the actual and hyperbolic stress-strain relations for the structured/cemented silts trimmed in the field orientation. It can be seen from Fig. 3a that the best geometric agreement between the actual and hyperbolic relationships occurs at an axial strain less than about 2 percent. Afterwards the structured/cemented silt undergoes a strain softening behavior and the hyperbolic model over predicts the actual stress-strain behavior. However, at an applied confining pressure of 552 kPa, the geometric agreement is better because the structured/cemented silt does not exhibit a strain softening behavior. Table 1 shows that the modulus exponent, n, is negative for the partially saturated, structured/cemented silt. Typically, the modulus exponent is positive, which reflects an increase in stiffness or tangent modulus with increasing effective confining pressure. However, the removal or possible breakage of the structure/cementation with increasing confining pressure causes a decrease in tangent modulus. This behavior is unique to structured/cemented soils and should be incorporated into design considerations.

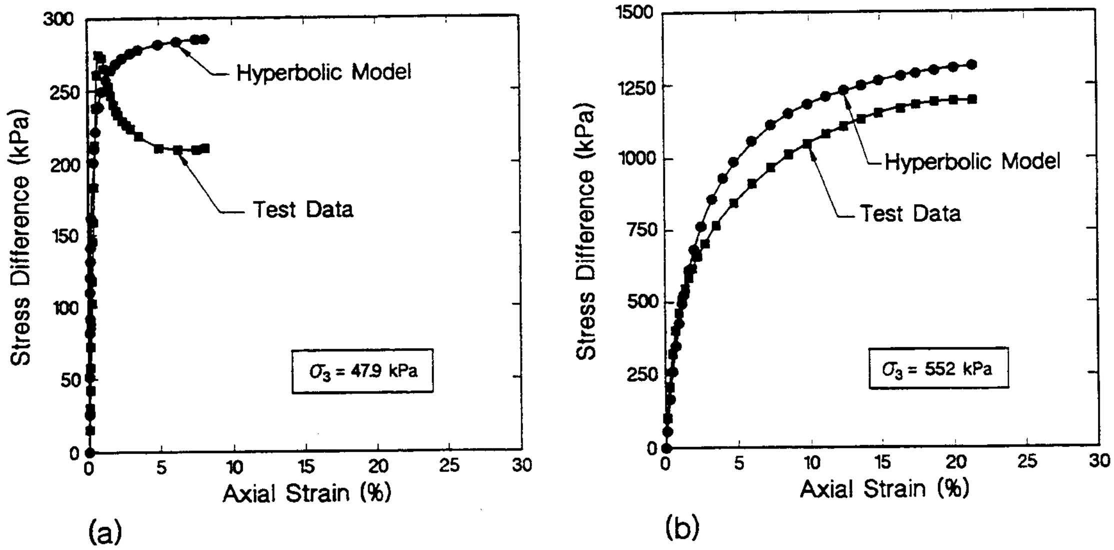

Fig. 3. Comparison of measured and hyperbolic stress-strain relationships of partially saturated structured/cemented silt tested at a confining pressure of a) 47.9 kPa and b) 552 kPa

Figs. 4.a and 4.b present typical comparisons of the actual and hyperbolic stress-strain relations for the reconstituted silts. It can be seen that the actual and hyperbolic stress-strain relationships are in agreement for both applied confining stresses because the reconstituted silt does not exhibit a strain softening behavior. Table 1 also shows the Mohr-Coulomb and hyperbolic parameters for the partially saturated reconstituted silt. In this case, the modulus exponent is positive, which reflects an increase in stiffness or tangent modulus with increasing applied confining pressure. The hyperbolic stress-strain model provides acceptable agreement with the measured stress difference-axial strain data over a significantly larger strain range for the reconstituted silt compared to the results for the structured/cemented silt.

Fig. 5 quantifies the variation in initial tangent modulus (Fig. 5a) and tangent modulus at an axial strain of 0.5 percent (Fig. 5b) for the four structured/cemented silt specimens trimmed in the vertical orientation and the four reconstituted silt specimens. The initial tangent modulus is significantly higher for the structured/cemented silt at low applied confining pressures. However, as the applied confining pressure increases, the difference in initial tangent modulus decreases. This indicates that at higher confining pressures, the effect of structure/cementation is removed and the soil behavior undergoes a transition towards that of a reconstituted material. Because the preconsolidation pressure of the structured/cemented silt is approximately 958 kPa, the structured/cemented and reconstituted silt are expected to approach a similar value of initial tangent modulus at confining pressures in excess of 958 kPa.

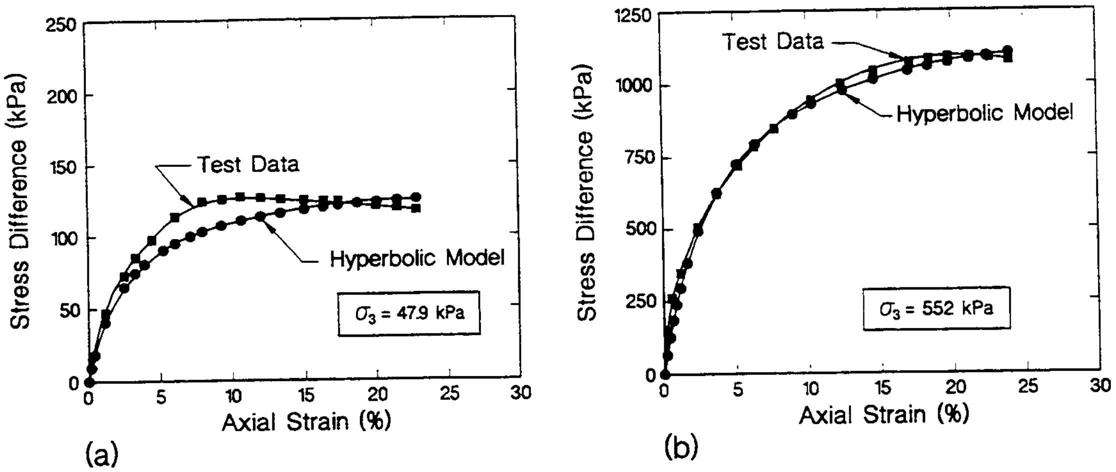

Fig. 4. Comparison of measured and hyperbolic stress-strain relationships of partially saturated reconstituted silt at a confining pressure of a) 47.9 kPa and b) 552 kPa

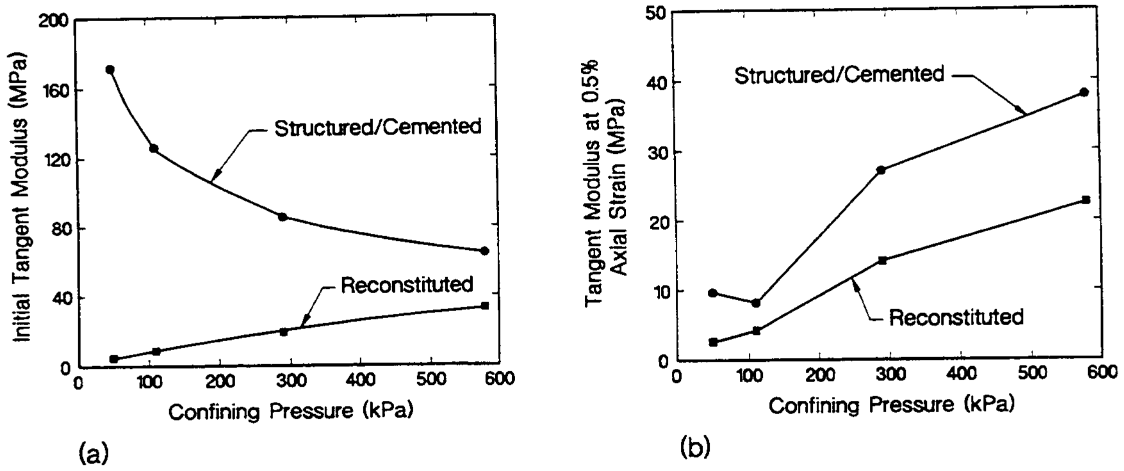

Fig. 5. Variation in tangent moduli for partially saturated structured/cemented and reconstituted silt

The tangent modulus at an axial strain of 0.5 percent increases with increasing applied confining pressure for the structured/cemented and reconstituted silt (Fig. 5 b). The tangent modulus for the structured/cemented silt remains higher than that for the reconstituted silt for confining pressures ranging from 47.9 to 552 kPa.

Anisotropy of Structured/Cemented Silts

Table 1 also presents the Mohr-Coulomb shear strength and hyperbolic stress-strain parameters for partially saturated, structured/cemented silt specimens that were tested in the horizontal orientation. It can be seen that the horizontally oriented silt exhibits similar Mohr-Coulomb shear strength parameters as the vertically oriented silt. However, the horizontal silt exhibits a significantly lower value of modulus number and a greater (less negative) exponent. The modulus number of the vertical silt is approximately four times greater than that of the horizontal silt (Table 1).

The modulus exponent value for the horizontal trimmed silt is -0.10 or nearly zero versus –0.4 for vertical trimmed silt. Therefore, the stiffness or tangent modulus does not decrease as significantly with increasing confining pressure as observed with the vertically oriented specimens. This means a smaller collapse of the structure/cementation occurs in the horizontal orientation. This reinforces the large difference in the modulus numbers, which shows that the structure/cementation is anisotropic. The anisotropy reflects in a stiffer behavior in the vertical orientation.

Stress-Strain Behavior of and Hyperbolic Parameters for Saturated Silt

Silt specimens were saturated to investigate the effect of laboratory saturation on the stress-strain behavior or performance of the structure/cementation in Vicksburg silt. In addition, saturation of the specimens allowed volume change information to be obtained. A series of ICD triaxial compression tests were conducted on structured/cemented silt specimens after the specimens had been saturated in the laboratory. The laboratory saturation technique, referred to as hydrostatic saturation, involved percolating distilled-deaired water through the specimen under a hydraulic head of 0.30 m, or 3 kPa, for a period of 24 hr. A confining pressure of 24 kPa was applied to the specimen prior to the hydrostatic saturation. This saturation process resulted in a B value of 0.95 to 0.99 and therefore it was assumed that little, if any, capillary pressures were present after the saturation process. As a result, the shear strength parameters are referred to as effective stress parameters. After completion of the saturation process, the desired confining pressure was applied. Upon equilibration, the specimen was sheared at an axial displacement rate of 0.02 mm/minute, which corresponds to an axial strain rate of 0.026 percent/minute.

ICD triaxial compression tests were conducted on four saturated/cemented and three reconstituted vertical silt specimens, after hydrostatic saturation. The resulting effective stress cohesion and friction angle were 0 kPa and 33 degrees, respectively, for the structured/cemented specimens, and 0 kPa and 31 degrees, respectively, for the reconstituted specimens (see Table 2). The Mohr-Coulomb shear strength parameters of the saturated structured/cemented silt specimens result in a slightly lower shear strength than that measured for the partially saturated structured/cemented silt ($c = 46$ kPa and $\phi = 28$ degrees). For example, at a normal stress of 192 kPa, a saturated silt specimen exhibited a shear strength that is 15 percent less than that for the partially saturated silt specimen. This finding provides insight to the importance of the various cementation mechanisms in the loess. The two major cementation mechanisms appear to be carbonate and clay/capillary effects (Krinitzsky and Turnbull 1967). Since the partially saturated and saturated triaxial specimens generally yielded similar shear strength and compressibility parameters, it was concluded that the carbonate cementation is resistant to distilled water and is a stronger cementing agent than the clay/capillary effects. The increase in moisture content from approximately 19 to 26 percent during laboratory saturation probably reduced the effect of the clay/capillary bonding. Since the shear strength after laboratory saturation was similar to the shear strength of the loess at the natural water content, the importance of the clay/capillary bonding was assumed to be small. Therefore, the difference between the shear strength of the laboratory saturated structured/cemented and reconstituted specimens is attributed to carbonate cementation.

Table 2 - Mohr-Coulomb Shear Strength and Hyperbolic Stress-Strain Parameters for Saturated Structured/Cemented and Reconstituted Silt

Type of Specimen	Average Initial Total Unit Weight (kN/m^3)	Average Initial/ Final Water Content (%)	Effective Stress Cohesion and Friction Angle (kPa/deg)	Modulus Number and Exponent (K/n)	Failure Ratio (R_f)	Bulk Modulus Number and Exponent (K_b/m)
Structured/ Cemented (Vertical Orientation)	16.7	17.3/ 27.5	0/33	850/ -0.55	0.85	310/ -0.6
Reconstituted	17.2	19.6/ 25.4	0/31	95/ 0.80	0.85	24/ 0.57
Structured/ Cemented (Horizontal Orientation)	17.9	18.2/ 26.0	12/31	305/ -0.10	0.95	50/ -0.4

Table 2 presents the effective stress Mohr-Coulomb and hyperbolic stress-strain parameters for the hydrostatically-saturated, structured/cemented silt (field orientation). The geometric agreement between the data and the hyperbolic stress-strain model was emphasized at axial strains of 5 percent or less because the hyperbolic model does not capture strain softening behavior. Table 2 shows that the modulus exponent is negative, which reflects the degradation of the structure/cementation with increasing confining pressure. The value of modulus number and exponent for the reconstituted structured/cemented silt specimens are 95 and 0.8, respectively (Table 2). These values are within the range of values reported by Stark et al. (1991) for reconstituted clay/silt mixtures and the modulus exponent indicates an increase in stiffness with increasing confining pressure.

Mohr-Coulomb shear strength and hyperbolic stress-strain parameters for saturated, structured/cemented silt, tested in the horizontal orientation, are also presented in Table 2. The horizontally oriented silt exhibits similar effective stress

Mohr-Coulomb shear strength parameters as the vertically oriented silt. However, the horizontal silt exhibits significantly lower values of modulus number and exponent. The modulus number of the vertical silt is approximately three times greater than that of the horizontal silt (Table 2). The modulus exponent value for the nonfield-oriented silt is again -0.10 or near zero. This means there is a smaller collapse of the structure/cementation in the nonfield orientation than in the field orientation even after saturation. Therefore, the anisotropy observed in the partially saturated, structured/cemented silt appears not to be significantly altered by laboratory saturation. This anisotropy should be considered when laterally loading the structure/cemented silt deposit.

Hyperbolic Volume Change Parameters of Saturated Structured/Cemented Silt

Volume change parameters for the laboratory saturated structured/cemented and reconstituted silt specimens, (Table 2) were obtained using the best geometric agreement between measured and hyperbolic stress-strain relationships at low axial strains, i.e., before the specimen exhibited dilation during shearing. Thus, the volume change model is restricted to low strains (e.g., two percent or less). In contrast to the results of the structured/cemented specimens, the volume change model provides a reasonable representation of the volumetric strain relationship for the reconstituted specimens. The reconstituted specimens exhibited no dilation during shearing, which can be attributed to the absence of structure/cementation after the reconstitution process. As expected, the structured/cemented silt specimens exhibited a negative bulk modulus exponent, and the reconstituted specimens exhibited a positive bulk modulus exponent (Table 2). The bulk modulus number of the structured/cemented silt tested in the field/vertical orientation is thirteen times higher than K_b for the reconstituted silt. The bulk modulus number for the horizontal orientation is two times higher than the value of K_b estimated for the reconstituted silt.

Drained Unload/Reload Hyperbolic Stress-Strain Parameters

Four unload/reload isotropically-consolidated triaxial compression tests were conducted to estimate the unload/reload modulus of the structured/cemented silt and the effect of unloading/reloading on the degradation of the structure/cementation. The tests were conducted on partially saturated (i.e., at the natural water content) structured/cemented silt. A partially saturated, structured/cemented specimen was loaded in the vertical orientation to approximately 50 percent of the maximum principal stress difference measured in a previous test (see Figs. 2.a through 2.d) at the same confining pressure. The specimen used in the unload/reload test was sheared to 50 percent of the maximum principal stress difference using an axial displacement rate of 0.2 mm/minute or axial strain rate of 1.7 percent/minute. After reaching 50 percent of the maximum principal stress difference, the specimen was unloaded to a stress difference of zero using an axial displacement rate of 0.2 mm/minute. The specimen was then reloaded to 50 percent of the maximum principal stress difference and unloaded. This was repeated until the specimen had been subjected to four unload/reload cycles. Figs. 6.a and 6.b present the stress difference-axial strain relationships from the ICD unload/reload triaxial compression tests conducted at confining pressures of 47.9 kPa and 552 kPa, respectively. Two other tests (not shown) were conducted in the same fashion at confining pressures equal to 103.4 kPa and 275.8 kPa.

The structured/cemented specimen tested in the ICD unload/reload triaxial test at a confining pressure of 47.9 kPa collapsed unexpectedly after application of a principal stress difference of approximately 36 kPa after the unload/reload cycles (Fig. 6.a). It is important to note that the axial strain scale in Fig. 6.a is exaggerated compared to Fig. 6.b so the specimen collapse could be illustrated. The three remaining structured/cemented specimens were tested at higher confining pressures under unload/reload cycles and were loaded to failure without collapsing (e.g., Fig. 6.b). Therefore, it appears that the structure/cementation is more susceptible to collapse under cyclic loading at low confining pressures.

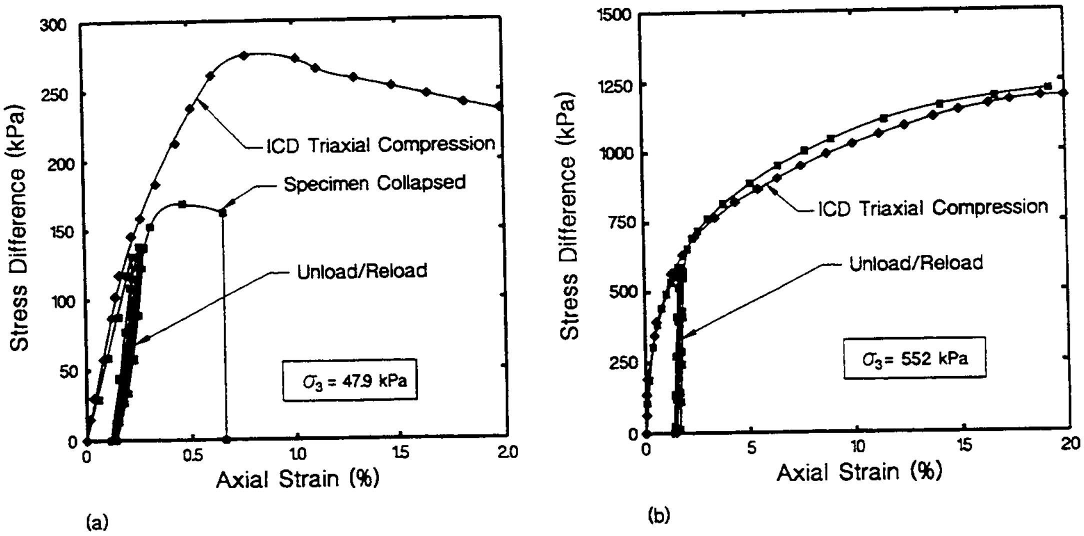

Fig. 6. Comparison of unload/reload and conventional ICD triaxial compression test results on partially saturated structured/cemented silt at a confining pressure of a) 47.9 kPa and b) 552 kPa

The resulting cohesion and friction angle for the cyclically loaded structured/cemented silt are 33.5 kPa and 29 degrees, respectively. The corresponding Mohr-Coulomb shear strength envelope is slightly less than that corresponding to the combined cohesion (46 kPa) and friction angle (28 degrees) measured in conventional ICD triaxial compression tests on partially saturated, structured/cemented silt (Table 1). Therefore, the unloading/reloading of the specimen may have broken or ruptured some of the structure/cementation in the silt. Not all of the structure/cementation was removed during the four unload/reload cycles because the resulting cohesion is greater than the cohesion (c = 0 kPa) measured for the partially saturated reconstituted specimens (Table 1). However, more than four unload/reload cycles or unload/reload cycles with a stress difference greater than 50 percent of the maximum stress difference may result in additional breakage or rupture of the structure/cementation in the silt.

Figs. 6.a and 6.b present a comparison of stress difference-axial strain relationships for unload/reload and conventional ICD triaxial compression tests at confining pressures of 47.9 kPa and 552 kPa, respectively. At a confining stress of 47.9 kPa, the unload/reload cycles resulted in a peak stress difference that is approximately 50 percent lower than that observed in the comparable ICD triaxial compression test (Fig. 6.a). At a confining stress of 552 kPa, the unload/reload cycles did not significantly reduce the peak stress difference (Fig. 6.b). In conclusion, the unload/reload cycles appear to be more detrimental at lower confining pressures. The reduced confinement probably allows some of the structure/cementation to be damaged.

The unload/reload modulus number was estimated using the hysteresis loops obtained from the unload/reload triaxial compression tests and the procedure outlined by Duncan et al. (1980). Values of K_{ur} and n_{ur} equal to 1250 and 0.3, respectively, were estimated from the unload/reload data, some of which is shown in Fig. 6. The value of K_{ur} is approximately equal to the primary loading modulus number (1200) of the partially saturated structured/cemented silt (Table 1). The ratio of K_{ur}/K is approximately unity, which is slightly less than the recommended range of 1.2 to 3 suggested by Duncan et al. (1980).

However, the recommended range of K_{ur}/K is only applicable if n_{ur} equals n (Duncan et al. 1980). Duncan et al. (1980) suggest that, for nonstructured soils, the value of n_{ur} is similar to n, which is the modulus exponent for primary loading. The values of K (1200) and K_{ur} (1250) are similar but the values of modulus exponent differ significantly. Because the difference in exponents is attributed to the structured/cemented nature of the silt, the conclusion that n_{ur} equals n appears unwarranted for structured/cemented soils. As a result, it is recommended that at least one unload/reload triaxial compression test be conducted to estimate the appropriate values of K_{ur} and n_{ur} in structured/cemented materials instead of using K and n to estimate these values. For soil-structure interaction analysis involving the Vicksburg silt/loess, reasonable values of K_{ur} and n_{ur} appear to be 1250 and 0.3, respectively.

Conclusions

Based on the results of this study, the following conclusions appear to be warranted:

(1) The structure/cementation present in Vicksburg, Mississippi loess results in high shear strength and stiffness characteristics. The structure/cementation frequently allows slopes to stand at or near a vertical angle. The two major cementation agents in Mississippi loess appear to be carbonates and clay/capillarity. The carbonate cementation appears to provide the greatest contribution to the overall structure/cementation.

(2) Structure/cementation in the Mississippi loess results in preconsolidation pressures that significantly exceed the effective overburden pressure and preconsolidation pressures measured for reconstituted loess/silt specimens. As a result, this preconsolidation effect is probably not caused by historical prestressing, but by particle cementation.

(3) As the confining pressure in a triaxial compression test approaches the preconsolidation pressure of the Mississippi silt, the effects of the structure/cementation are diminished due to bond breakage and the silt begins to exhibit a stress-strain behavior similar to that of reconstituted silt.

(4) Saturation of the structured/cemented Mississippi loess with distilled water did not significantly alter the compressibility, shear strength, or stress-strain behavior of the material. However, inundation in the virgin compression range in oedometer tests resulted in an increase in axial strain, without a change in applied vertical stress.

(5) The hyperbolic stress-strain parameters for the partially saturated, structured/cemented Mississippi loess differ significantly from the reconstituted values. The modulus number for the structured/cemented silt is three times higher than the value for reconstituted silt. This indicates a higher stiffness, and thus a higher initial tangent modulus. However, the structured/cemented modulus exponent is negative, which indicates that the tangent modulus decreases with increasing effective confining pressure.

(6) Tables 1 and 2 can be used to estimate the Mohr-Coulomb shear strength and hyperbolic stress-strain parameters for partially saturated and saturated (with distilled water) structured/cemented or reconstituted Mississippi loess, respectively.

(7) Horizontally oriented, i.e., 90 degrees from field orientation, Mississippi loess specimens exhibit similar Mohr-Coulomb shear strength parameters as the vertically oriented specimens. However, the horizontally oriented silt exhibits significantly lower values of modulus number and exponent. Therefore, the stiffness of structured/cemented Mississippi loess is anisotropic.

(8) Unload/reload cycles initiated at a principal stress difference corresponding to 50 percent of the maximum principal stress difference in a conventional ICD triaxial compression test resulted in slightly lower values for the Mohr-Coulomb strength parameters compared to the values measured in conventional ICD triaxial compression tests. However, the structured/cemented Mississippi loess appears to be more susceptible to collapse under cyclic loading at low confining pressures. This is reflected in the hyperbolic stress-strain parameters. The average primary and unload/reload modulus numbers of partially saturated, structured/cemented Mississippi loess (vertical orientation) are similar (1200 versus 1250). However, the values of the modulus exponent differ significantly (-0.4 versus 0.3). In summary, unload/reload cycles, especially at low confining pressures, may damage or rupture the structure/cementation.

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Appendix. References

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