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Characterizing Shear Properties of Fine-Grained Subgrade Soils under Large Capacity Construction Equipment

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ABSTRACT

The routine operations of large capacity off-road construction equipment on fine-grained cohesive soils have become a concern to the construction and equipment manufacturing sectors due to problems with mobility on these soils. In this study, both monotonic and cyclic triaxial tests were conducted to determine shear properties of a fine-grained subgrade soil at the optimum moisture content and 3% above and below the optimum. The complete test results provided an extensive database of material properties including friction angle and cohesion for strength properties and shear modulus of the soil at three moisture states. Mohr-Coulomb failure models were developed together with shear modulus correlations for the soil sample. These models can be used for evaluating the impact of moisture on shear strength and stiffness behavior of fine-grained soils with similar characteristics for their sustainable use in construction applications.

INTRODUCTION

Cohesive fine-grained and cohesionless granular soils all referred to here as geomaterials constitute the foundation of highway and airport pavements as well as railroad track. These materials often exhibit different load bearing capacities at different stress and moisture states under the routine operation of construction haul trucks and shovels. To understand behavior of these materials under large capacity off-road construction equipment it is important to properly address shear strength and modulus characteristics under both static monotonically increasing and dynamic applied or cyclic loading conditions.

The shear strength properties of geomaterials are generally mobilized either due to a cementing action or cohesion and/or grain-to-grain interlock, i.e., angle of friction or repose, under applied loading. Cohesion and friction angle are determined from laboratory and field tests performed on constituted specimens and undisturbed in-situ samples, respectively. The test results are often modeled using the Mohr-Coulomb envelopes [Holtz and Kovacs 1981]. On the other hand, shear modulus governs shear deformation characteristics by the extent of distortion in these materials under applied loads. Shear modulus of soils is traditionally determined from laboratory cyclic triaxial tests in which the radial stress is typically held constant while deviator stress is cycled on the sample. In this test, the shear modulus is always obtained from modulus of elasticity by assuming a representative Poisson's ratio for the soil material tested. The most realistic shear loading, however, occurs when both radial/confining and dynamic stresses are cycled on the sample. Obtaining such loading conditions in the laboratory would require a pure shear loading that can closely simulate the roll and bounce, and the rocking motions of construction haul trucks and shovels in the field.

This paper describes both monotonic compression and cyclic pure shear loading triaxial tests conducted to determine shear strength and shear modulus properties of a fine-grained subgrade soil at three different moisture states. The laboratory test program focused on conducting these triaxial tests at different confining and dynamic stress states representing typical loading conditions of construction equipment in the field. Based on the laboratory test data, the cohesion intercepts and friction angles are used to develop Mohr Coulomb failure models for the soil at the three moisture states. The shear modulus data were also used to establish stiffness correlations with shear strain for the soil tested.

LABORATORY TESTING PROGRAM

Fine-grained soil tested

The fine-grained cohesive soil investigated in this research study was obtained from Caterpillar, Inc. field demonstration test sections in Illinois, and was shipped to the University of Illinois Advanced Transportation Research and Engineering Laboratory (ATREL) for testing. The sample was a clayey soil, a "CL" according to Unified Soil Classification or an "A-6" according to AASHTO classification, with a liquid limit (LL) of 27.2, a plasticity index (PI) of 13.1, and composition of 0.3% gravel, 29.5% sand, 40.9% silt, and 29.3% clay. Accordingly, the soil sample was designated herein as SA-6. From the standard Proctor [AASHTO T 99 2001] test procedure, the maximum dry density obtained was 18.4 kN/m3 at an optimum water content (w_{opt}) of 14.3 %.

Specimen preparation

The quantity of the SA-6 sample required to achieve the maximum density was computed to prepare specimens for the triaxial tests. For the monotonic triaxial compression tests, the soil specimens were mechanically compacted in a split aluminium compaction mold using a standard Proctor compaction hammer in three lifts to achieve the target density. Approximately 50.8-mm diameter cylindrical specimens were prepared for testing. Specimen density was controlled by measuring the mass of material and compacted thickness of each lift, referenced to the top of the mold. The surface of each lift was scarified down to a depth of approximately 10-mm to achieve uniform compaction in 3 lifts.

The pure shear triaxial test specimens were obtained by vibratory compaction. The specimens were prepared at the required water contents and dry density levels using a split aluminium compaction mold, specifically manufactured to produce 150 mm diameter by 150 mm high specimens, to fit in the advanced University of Illinois triaxial cell (UI-FastCell). A pneumatic vibratory compactor was used for compaction. Similarly, specimen density was controlled at each lift during compaction, and the surface of each lift was also scarified up to a depth of approximately 10 mm to achieve uniform compaction in three lifts.

Test procedure and laboratory testing

The monotonic compression shear tests were conducted on the soil sample at optimum (w_{opt} = 14.3%), dry of optimum (w = 11.3%), and wet of optimum (w = 17.3%) water contents to obtain the friction angle ϕ, and cohesion c properties. The tests were performed on the prepared cylindrical specimens, 50.8 mm in diameter by 101.6 mm high, by applying five confining stress levels, i.e., 0, 20.7, 41.4, 69, and 138 kPa. It should be mentioned that due to difficulties encountered during testing at w = 17.3% and confining stress of 138 kPa, the test results were not included in the analyses (see Table 1). This should not have significant effect on the shear strength properties since the remaining 4 tests at w = 17.3% were adequate in number to obtain the strength properties.

The test specimens were monotonically loaded at a strain rate of 1% strain/minute using an Industrial Process Controls, Ltd. (IPC Global) Universal Testing Machine (UTM-5P) pneumatic testing system, and pressurized in a triaxial chamber with air pressure. The applied load was measured through the load cell, whereas, the deformations were measured using the actuator linear variable displacement transducer (LVDT). Figure 1 shows a picture of the triaxial cell with 50.8-mm diameter soil specimen seen inside the confinement chamber.

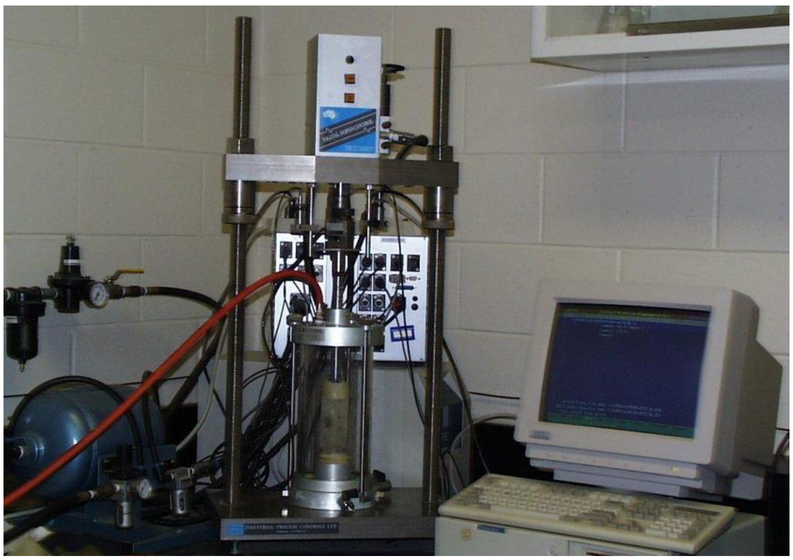
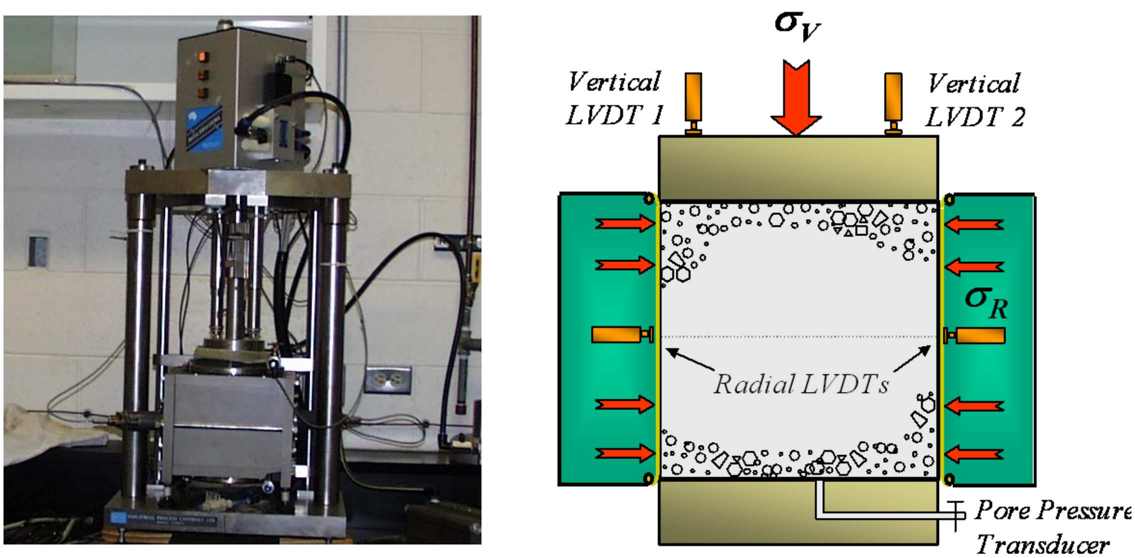


Fig. 1. Triaxial test setup for monotonic loading of the soil specimen

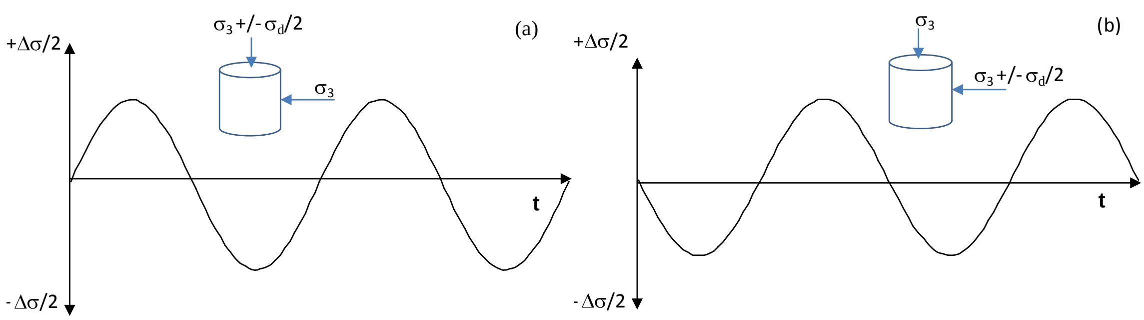
The pure shear loading triaxial tests were also conducted at the three moisture states to obtain shear modulus properties of the soil sample. An existing cyclic/repeated load triaxial testing device at ATREL, UI-FastCell, integrated with IPC Universal Testing Machine (UTM) loading device was used for the pure shear testing. The UI-FastCell has unique capabilities of simulating various dynamic field loading conditions in the laboratory [Tutumluer and Seyhan 1999]. In addition to pulsing stresses in the vertical direction, UI-FastCell offers the ability to apply dynamic stresses in the radial/horizontal direction to better simulate field stress states under large capacity construction trucks and shovels. Figure 2a shows a picture of the UI-FastCell with the confinement cell lowered down on the soil specimen for the testing position. Figure 2b is an illustration of the cylindrical specimen, 150-mm in diameter by 150-mm high under the independently applied vertical and radial stresses and the instrumentation consisting of LVDTs measuring axial and radial specimen deformations.



(a) Photo of UI-FastCell (b) Instrumentation and Cylindrical Specimen

Fig. 2. UI-FastCell Lowered on Compacted SA-6 Soil Specimen for Testing

For the application of the pure shear stresses, two alternating sine load pulses of the same magnitude were applied at the same time in the vertical and radial directions on the soil specimens at the three moisture states. Figure 3 shows the 90 degree out of phase cyclic stresses, $\Delta\sigma/2$, applied on the specimen by decreasing (or increasing) the radial pressure by the same amount $\Delta\sigma/2$, by which the vertical stress is increased (or decreased). The soil specimens were first loaded with a total normal stress for hydrostatic statue of σ_3. The stresses on the specimen were then subjected to an axial stress of σ_3 + ½σd and a radial stress of σ_3 - ½σ_d. Next, the specimen was loaded so that the axial stress is σ_3 - ½σ_d and the radial stress becomes σ_3 + ½σ_d for pure shear loading.



(a) Applied Vertical Cyclic Stress (b) Applied Radial Cyclic Stress

Fig. 3. Pure Shear Loading Applied on the Specimen

Overall, the pure shear tests were conducted on 9 soil specimens at three confining stress levels of 41.4, 69, 138 kPa. For each confining stress state, a minimum dynamic/cyclic shear stress of 20.7 kPa was applied on the test specimens, and increased until the shear stress reached a value equal to the maximum confining stress (see Table 2). A full factorial test matrix comprising 27 tests were conducted on the soil samples at three moisture states with selected loading frequency of 5Hz. Each stress state was pulsed on the specimen with total of 25 load cycles.

At different stress levels, strains in both vertical and radial directions were recorded for the last 5 load cycles. The applied shear stress (τ) and corresponding shear strain (γ) were then computed using Equations 1 and 2, respectively, and the shear modulus (G) was computed from Equation 3.

$$\tau = \sigma_1 - \sigma_3 \tag{1}$$

$$\gamma = \frac{2}{3}(\varepsilon_1 - \varepsilon_3) \tag{2}$$

$$G = \frac{\tau}{\gamma} \tag{3}$$

σ_1, σ_3 = axial and radial (confining) stresses, respectively, and ε_1 and ε_3 are the corresponding axial and radial strains.

ANALYSES OF MONOTONIC COMPRESSION TEST DATA

Table 1 gives the results for the SA-6 sample at three moisture states and five different confining stresses, and Figure 4 shows the effect of water content on shear strength properties, i.e., friction angle $\phi$and cohesion c of the sample. Also, Figures 5 through 7 show the test results represented by Mohr circles at failure for the five tests of the SA-6 soil sample at w = 11.3%, wopt = 14.3% and w = 17.3%. The Mohr-Coulomb failure envelopes obtained are also indicated for the sample tested at the three moisture states.

It can be seen that the differences in cohesion are higher than differences in friction angle of the soil sample. The highest difference in cohesion between dry of optimum and wet of optimum is 215 kPa, whereas the difference in friction angle between the two moisture states is 8.3 degrees. A change in water content of the soil sample by 3% below optimum resulted in about 2.5-degrees increase in friction angle and about 138 kPa increase in cohesion at dry of optimum. On the other hand, a change in water content by 3% above optimum resulted in 5.8-degrees reduction in the friction angle and about 77-kPa decrease in cohesion at wet of optimum. Thus, changing water content by an amount of 3% above or below the optimum water content of this type of cohesive soil in the field could result in considerable changes in cohesion but considerably less change in the friction angle of the soil sample. This trend suggests that the strength behavior of SA-6 sample and soils of similar characteristics could be greatly influenced by increasing or decreasing the water content above or below the optimum. Higher c values are associated with high resistance of the soil material to shearing stresses, and higher ϕ values implies ability of the soil sample to develop strength and resist rutting under off-road construction equipment in the field.

Table 1. Triaxial Shear Strength Test Results for SA-6 Soil

Water content	Peak shear stress @ confining Stress (kPa)					Strength properties	
	0	20.7	41.4	69	138	ϕ (Deg)	c (kPa)
w = 11.3%	971.6	1129.8	1355.9	1401.4	1629.6	42.0	250
w_{opt} = 14.3%	472.5	528.5	641.9	764.3	973.0	39.5	112
w = 17.3%	121.7	152.8	141.2	299.5	-	33.7	35

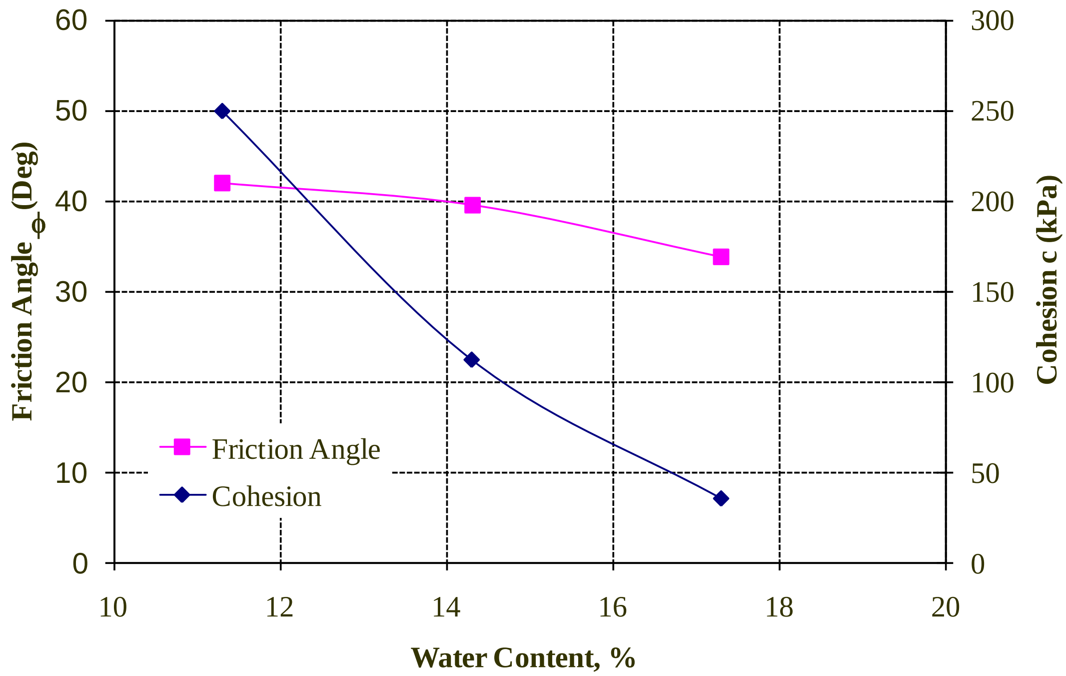


Fig. 4. Pure Effect of Water Content on Shear Strength Properties

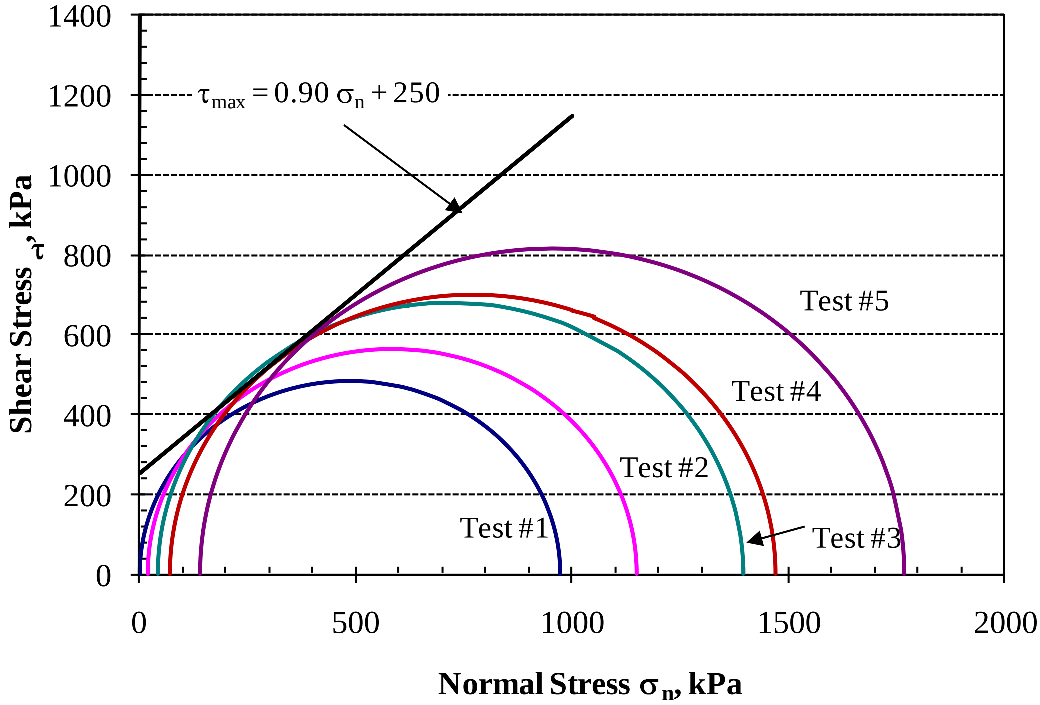


Fig. 5. Mohr Circles and Failure Envelope for SA-6 Soil at w = 11.3%

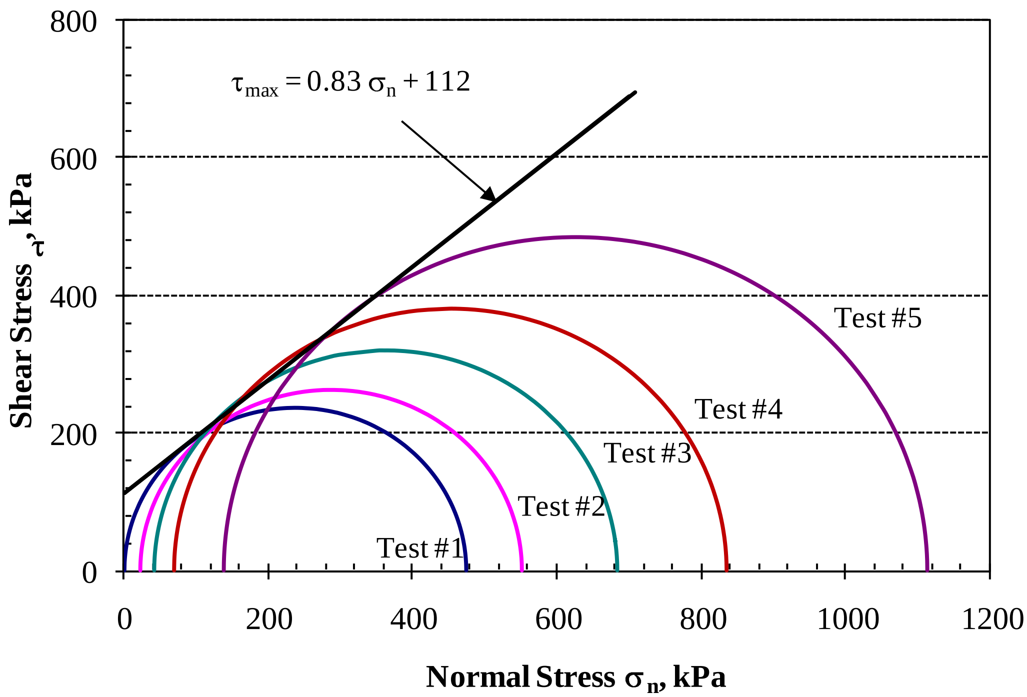


Fig. 6. Mohr Circles and Failure Envelope for SA-6 Soil at wopt = 14.3%

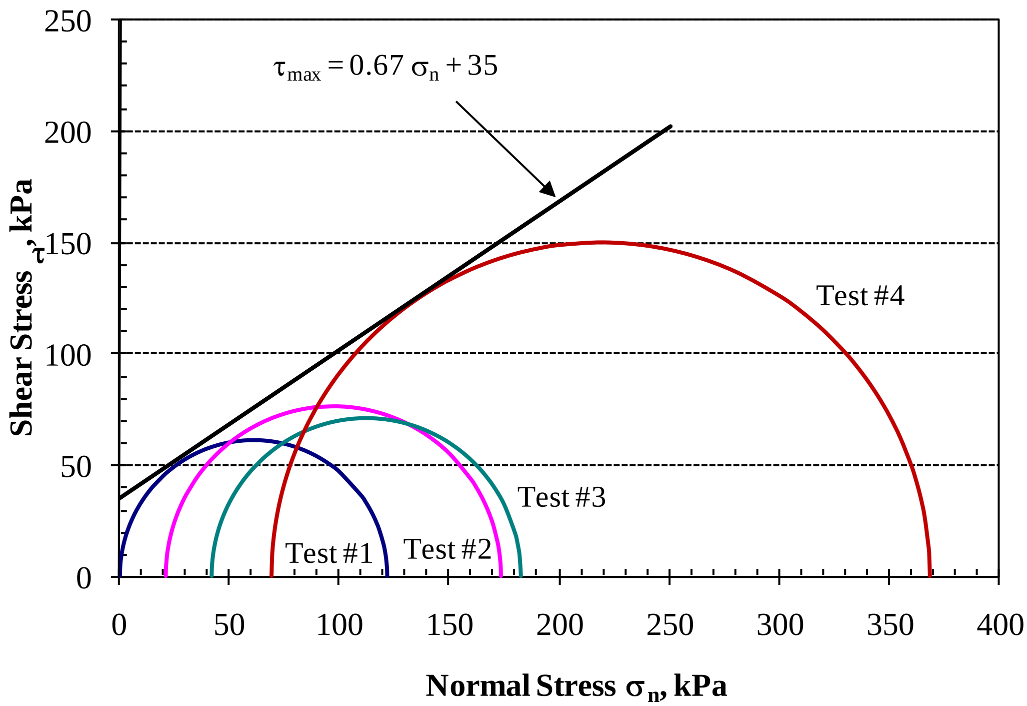


Fig. 7. Mohr Circles and Failure Envelope for SA-6 Soil at w = 17.3%

ANALYSES OF PURE SHEAR LOADING TEST DATA

The SA-6 soil pure shear loading test data were analyzed to obtain shear modulus at the optimum water content (w_{opt} = 14.3%), and dry of optimum (w = 11.3%) and wet of optimum (w = 17.3%) moisture states. A single pure shear loading data set contains 250 stress-strain data points for one specimen. A total of 2,250 set of data points from 9 tests was obtained for the soil sample at each moisture state.

Table 2 gives a summary of the soil test results at the three moisture states, different confining stress and cyclic/shear stress states applied on the SA-6 soil sample. Generally, the shear modulus decreased with increasing applied cyclic stresses at all the moisture states. An average shear modulus measured at the optimum was found to be about 8 times the shear modulus at the wet of optimum moisture state. Also, the average shear modulus at dry of optimum moisture state is about 3.5 times the shear modulus at the optimum. Thus, a change in water content of 3% above or below the optimum resulted in a significant change in the overall stiffness or shear modulus of the soil sample. This trend was expected of the SA-6 soil sample since fine-grained cohesive soils exhibit stress softening behavior under cyclic loading. Also, the shear moduli generally decrease as the confining stresses decrease. A rapid decrease in shear modulus is observed at the high confining stress (σ_3 = 138 kPa) compared with the lower confining stresses. This behavior was observed at all the moisture states. This is an indication that high confining stresses during operations of haul truck and shovels as a result of applied loading and overburden of this equipment would significantly affect the shear stiffness or modulus of the soil sample at different moisture levels.

Table 2. Applied Stress States and Shear Modulus Test Results

Stress states (kPa)		Shear modulus (MPa)		
σ_3	τ_{cyc}	w = 11.3%	w_{opt} = 14.3%	w = 17.3%
41.4	20.7	118.3	50.5	7.5
41.4	41.4	91.9	23.0	4.2
69.0	20.7	145.3	62.3	9.0
69.0	41.4	106.6	30.3	4.9
69.0	69.0	64.4	14.4	5.2
138.0	20.7	273.9	166.6	23.1
138.0	41.4	221.5	112.1	10.1
138.0	69.0	173.1	69.6	7.1
138.0	138.0	89.0	24.0	7.2

Characterization of shear modulus

Several empirical equations based on the maximum shear modulus G_{max} and the shear modulus ratio G/G_{max} or normalized shear modulus have generally been used to characterize the shear deformation characteristics of soils at different strain levels [Hardin and Black 1968, Seed and Idriss 1970, Kramer 1996]. However, these equations are based on strain levels less than 0.001% compared with high strains that these soils would experience under large capacity construction equipment. At low strain levels below 0.001%, it is assumed that the soil shear modulus is equal to G_{max}, i.e., G/ G_{max} is equal to one.

In this study, the shear modulus reduction (or normalized shear modulus) concept is used to characterize the soil material at the three moisture states. Assuming that the minimum shear strain is a good approximation for obtaining the maximum shear modulus from the pure shear loading test data, the maximum shear modulus G' obtained among all the test results was used to normalize the shear moduli of the SA-6 soil sample at the various moisture states (G' = 273.9 MPa). Based on this approach, regression analyses were performed to develop relationships between the normalized shear modulus and shear strain (γ). Figure 8 is a plot of normalized shear modulus against shear strain, and Equations 4 to 6 are regression equations developed for the soil sample at the three moisture states. As seen from the graph, there is a large scatter of the results at w = 17.3%, although the R^2 value is comparable to the R^2 value at w = 11%. As expected, there is a general trend of shear modulus reduction as the shear strain increases at all the moisture states of the soil, implying more shear distortion of the cohesive soil at higher moisture levels. Also, according to Equations 4 to 6, G/G' at all the three moisture states always decreases as γ increases.

$$\frac{G}{G'_{dry}} = 0.1646\,\gamma^{-0.3869} \text{ at w = 11.3\%:} \quad R^2 = 0.65 \tag{4}$$

$$\frac{G}{G'_{opt}} = 0.1015\,\gamma^{-0.5811} \text{ at w = 14.3\%:} \quad R^2 = 0.82 \tag{5}$$

$$\frac{G}{G'_{wet}} = 0.2976\,\gamma^{-0.5015} \text{ at w = 17.3\%:} \quad R^2 = 0.67 \qquad (6)$$

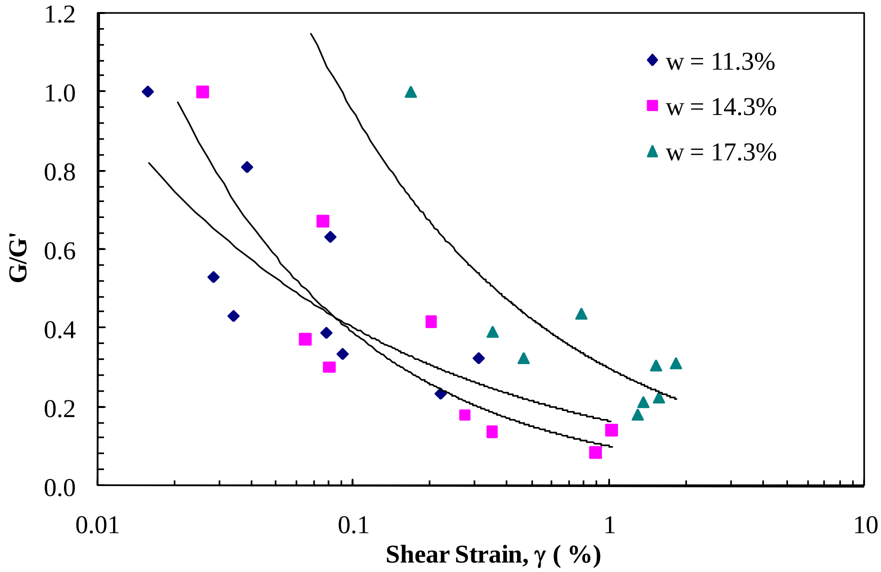


Fig. 7. Normalized Shear Modulus Variation with Shear Strain

SUMMARY AND CONCLUSIONS

Shear properties of a fine grained-cohesive soil were investigated in the laboratory at three different moisture levels using monotonic compression and pure shear loading triaxial test procedures. The soil sample was tested at three moisture states; optimum water content, wopt = 14.3%, dry of optimum, w = 11.3% and wet of optimum, w = 17.3%. The test results provide an extensive database of shear strength and shear modulus properties for the soil at the different moisture states. Moisture content was the main parameter that affected the shear properties of the soil sample. The shear strength properties and shear modulus values of the soil generally increased for the 3% below the optimum moisture condition and decreased for the 3% above the optimum.

Based on the monotonic triaxial compression shear test results, Mohr-Coulomb failure envelopes were established for the soil sample at the three water contents. The results obtained from the pure shear loading tests were used to develop regression relationships with shear moduli as a function of shear strain to characterize the shear modulus behavior of the fine-grained soil at the three moisture states. A combination of varying magnitudes of static and dynamic confining stresses applied in the pure shear loading test is suggested as a better laboratory approach to follow in testing to closely simulate the field loading conditions of large capacity off-road trucks and shovels on the soil material.

Overall, the developed shear strength models and the normalized shear modulus regression characterization relationships would provide essential guidelines with additional soil data for estimating field strength and shear deformation behavior of fine-grained cohesive soil. In addition, the shear strength and shear modulus data provided will be useful for engineers and equipment manufacturers to estimate load bearing capacities and shear stiffness behaviour under construction haul trucks and shovels in the field for the soil tested and other soils with similar characteristics.

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REFERENCES

AASHTO T 99. "Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop." *American Association of State and Highway Transportation Officials, Washington D*C, 13 pages.

Hardin, B.O., and Black, W.L. (1968). "Vibration Modulus of Normally Consolidated Clay." *Journal of Soil Mechanics and Foundation Engineering Division*, ASCE, 94 (SM2), 353-369.

Hardin, B.O., and Drnevich, V.P. (1972). "Shear Modulus and Damping in Soils: Design Equation and Curves." *Journal of Soil Mechanics and Foundation Engineering Division*, ASCE, 98 (SM7): 667-691.

Holtz, R.D., and Kovacs, W.D. (1981). "*An Introduction to Geotechnical Engineering*." Civil Engineering and Engineering Mechanics Series, Prentice Hall, 431-472.

Kramer, S.L. (1996). "*Geotechnical Earthquake Engineering*." Civil Engineering and Engineering Mechanics Series, Prentice Hall, 221-238.

Seed, H.B., and Idriss, I.M. (1970). "Soil Moduli and Damping Factors for Dynamic Response Analyses." Report EERC 70-10. *Earthquake Engineering Research Center*, University of California, Berkeley, CA.

Tutumluer, E. and Seyhan, U. (1999). "Laboratory Determination of Anisotropic Aggregate Resilient Moduli Using a New Innovative Test Device." *Journal of Transportation Research Board*, No. 1687, National Research Council, Washington D.C., 13-21.