

Elastic and Viscoelastic Behavior of a Chemically Stabilized Sand

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Samples of clean, fine sand saturated with a sodium silicate grout (mix sample No. 7) were prepared and cured in a moist room for 35 days. Four types of tests were performed on identical samples to investigate their elastic and viscoelastic behavior. Results indicate that the isotropic, linear-elastic constitutive law provides a reasonable approximation for characterizing the chemically stabilized fine sand under moving load. Furthermore, for applied vertical stress levels of less than 50 percent, the mixture may be treated as a linear-viscoelastic medium for computing time-dependent deformation under sustained loading.

Although chemical grouting has traditionally been used to form cutoff barriers for seepage control, injected chemical grout in many instances solidifies within the soil matrix to form a treated soil mass considerably different from its original material. Warner (12) concluded that a significant increase in strength can be achieved if desirable chemical grouts are used. These grouts should generally provide rigid gels and longer gel time. Inasmuch as construction activities in the Arctic and subarctic region have increased in recent years, more attention has been directed toward frost heave and spring thaw of soil masses, which can detrimentally affect engineering structures such as highway subgrade, earth embankment, and supporting pedestal of pipelines. The use of chemical grouts to fill the soil voids, thus preventing moisture migration and formation of ice lenses in the soil mass, is considered a possible solution to these problems (1, 11).

The introduction of chemical grouts into a soil matrix by either injection or mixing affects the mechanical behavior of the soil. It is therefore important that the load-deformation characteristics of the chemically stabilized soil be properly determined for the design and construction of any structures founded on chemically stabilized soil masses.

This paper presents the results of a preliminary study of the elastic and viscoelastic behavior of a chemically stabilized sand tested under controlled laboratory

conditions. A limited number of important parameters were considered and the results should be applicable only to the conditions described in the tests. However, accumulated information of this type will provide needed knowledge for proper design of foundations on chemically stabilized soils in many parts of the world.

NOTATION

The following symbols are used in this paper:

D = damping ratio,
E = elastic modulus,
G = shear modulus,
 G^* = complex modulus = τ_0/γ_0 ,
 G_1 = storage modulus = $G^* \cos \delta$,
 G_2 = loss modulus = $G^* \sin \delta$,
 e_0 = initial void ratio,
f = frequency of oscillation,
 $\sigma_{zz}, \sigma_{rr}, \sigma_{\theta\theta}$ = axial, radial, and tangential stresses,
 σ_d = deviator stress,
 $\epsilon_{zz}, \epsilon_{rr}, \epsilon_{\theta\theta}$ = axial, radial, and tangential strains,
 ϕ_d = friction angle from drained test results,
 δ = phase angle,
 $\nu, \nu(t)$ = Poisson's ratio,
 τ_0 = maximum shear stress amplitude,
 γ_0 = maximum shear strain amplitude,
 $\psi_c(t)$ = creep compliance in shear, and
 $\psi_{Ez}(t)$ = modular creep compliance.

LABORATORY TESTING PROGRAM

Material

The soil used was a uniform fine sand with subrounded particles. The sand was washed through a No. 30 sieve to produce a grain size distribution with a median grain size of 0.49 mm and a uniformity coefficient of 1.4. The specific gravity of the sand particles was 2.64. The maximum and minimum void ratios of this sand, in a dry state, were approximately 1.23 and 0.59 respectively (2).

A sodium silicate grout (SIROC) was chosen as the chemical grout. SIROC is a three-component system;

its base chemical is a modified sodium silicate that mixes with the reactant and catalyst solution known as SIROC No. 2 and No. 3 respectively. The manufacturer's formulation directions (8, 9) indicate 18 different suggested mixes of the three solutions for obtaining different grout properties and gel times. SIROC mix sample No. 7 was chosen for this study. The proportions in percentage by volume of the three SIROC components and water were as follows:

Component	Proportion	Component	Proportion
SIROC No. 1	50	SIROC No. 3	9
SIROC No. 2	31	Water	31

Mix sample No. 7 was mixed at a temperature of 20°C and a gel time of 50 min. The SIROC has been shown to provide the best overall solidified mass (12).

Sample Preparation

Two sizes of samples were made. The majority were 5-cm-diameter by 10-cm-high cylindrical samples; however, some cake-shaped specimens of 8-cm-diameter by 3.2-cm-high were prepared for cyclic simple shear testing. The dry density of all the samples was 1.6 g/cm³, corresponding to a relative density of approximately 90 percent. The sample fabrication followed the procedure recommended by Warner (12). It involved pouring a known quantity of dry sand into a waxed cardboard mold about one-third full of the fluid grout. The sand was slowly poured into the mold, and vibration was intermittently applied along the wall of the mold to ensure a uniform, grout-saturated, densely packed sample. Specimens prepared this way have been shown to yield unconfined compressive strengths comparable to those of core samples obtained from the field (12).

All samples were cured in a room with constant humidity (98 percent) and temperature (21°C). The cardboard molds were stripped off after 7 days of curing. The total curing period was 35 days. At the end of this curing period, samples were well solidified and ready for testing.

Types of Tests Performed

The elastic and viscoelastic behavior of the solidified samples was studied by conducting four laboratory tests: repeated uniaxial compression test, resonant column test, uniaxial creep test, and cyclic simple shear test. Table 1 gives information pertinent to the various tests. All tests were performed in a room with a constant temperature of 21°C. A more detailed discussion of the tests and their results follows.

TEST RESULTS

Repeated Compression Test

The conventional repeated triaxial compression test apparatus (6) was used to determine both the axial and tangential elastic (resilient) deformation of a specimen (5 cm diameter and 10 cm height). The rate of repeated loading was 20 cycles/min with a load-on time of 0.3 s/cycle. Because the material was very stiff and rigid (Figure 1), bonded strain gauges were used to ensure accurate response measurements. The strain gauges used for the measurement of both axial and tangential strain were SR-4, type FAE-50-12 SO (2.5-cm active length). Eastman 910 bonding cement was used to bond the strain gauges to the solidified specimen. Two gauges mounted at midheight were used in each of

the axial and tangential directions so that average values of strain could be measured. Each pair of gauges was connected to a set of compensating dummy gauges to form a full bridge. The specimen was properly seated by gluing the ends to the base and cap with hydrostone paste.

Preliminary test results indicated that, to a stress level (applied axial stress/unconfined compressive strength) of approximately 40 percent or 621 kPa, the magnitude of elastic deformation appeared to be independent of the number of load applications (to as many as 12 000 load repetitions). It was therefore decided that multistress level, repeated loading tests could be performed on a given specimen. Tests conducted in this study had applied stress levels ranging from 104 to 621 kPa. At each stress level, 1000 load repetitions were applied. By averaging three sets of test results, the elastic axial and tangential strain values for various repeated stress levels were recorded.

Creep Test

Uniaxial creep tests were performed on cylindrical samples. Both the axial and tangential strains were recorded as shown in Figure 2. Again, bonded strain gauges were used to measure the change in strains with time under a constant load. A total creep time of 1200 s was chosen, and constant stress levels of 276, 552, and 828 kPa were used. Because the creep stress levels were less than 50 percent of the static strength of these specimens, no creep failure was anticipated. The primary creep behavior of the chemically solidified soil mass was adequately described within the 1200-s testing period.

Resonant Column Test

Cylindrical specimens were also used in the resonant column tests to determine the shear modulus and damping ratio. A detailed description of the resonant column apparatus and testing procedures is given by Hardin (3). By applying a forcing torque of given amplitude to the vibration end of the specimen about its axis, the resonant frequency of the soil column can be established. Calculations can then be made to compute, at a given shear strain, the shear modulus and damping ratio of the solidified soil mass. Resonant frequencies were established for various forcing torque amplitudes with axial loads held at 103.5 and 172.5 kPa respectively. For each axial loading condition lateral pressures of 0, 138, and 276 kPa were applied.

Cyclic Simple Shear Test

The cake-shaped specimens were used to determine the viscoelastic behavior of the chemically stabilized soil mass. Tests were performed by using the modified NGI simple shear apparatus (5). A sinusoidal shear displacement was applied to the specimen through a motor-driven, adjustable, eccentric cam. The sinusoidal shear stress was determined by measuring the variation of force transmitted to the base plate by the input motion. From the sinusoidal force and displacement traces of different frequencies (0.5 and 1.5 Hz) and amplitudes (0.01 and 0.05 percent), the variation of phase angle (δ) was computed. All specimens were properly seated and glued to the top and base plates with hydrostone paste. However, vertical pressures of 69 and 138 kPa were applied to ensure that no slippage would take place between the specimen and the plates.

ANALYSIS OF THE TEST RESULTS

Test results obtained from this study were analyzed to

provide preliminary information concerning the elastic and viscoelastic responses of the chemically stabilized sand mass.

Resilient (Elastic) Modulus and Poisson's Ratio

Elastic layered systems of analysis can be used to determine stress and deformation of a pavement system under moving traffic. Therefore, for the last 2 decades,

Figure 1. Unconfined stress-strain relationship for treated sand.

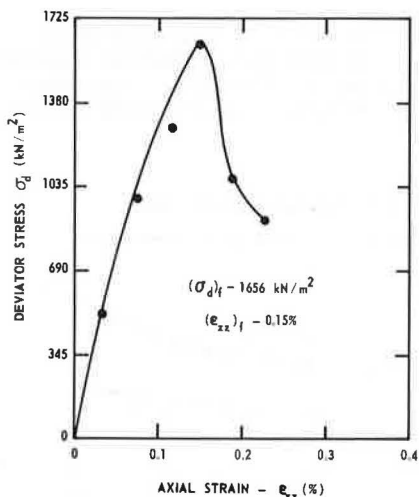


Figure 2. Uniaxial creep test results.

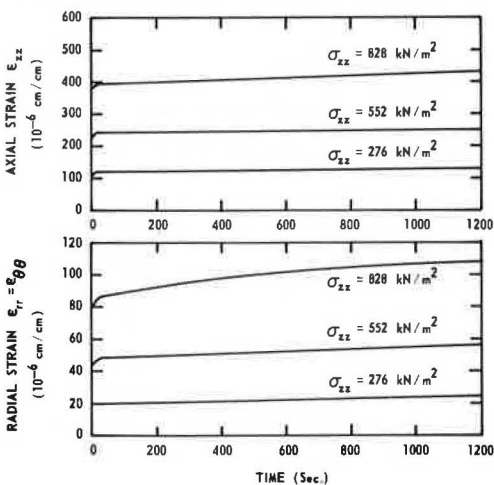


Table 1. Laboratory testing program.

Type of Test	Test Conditions	Measurements	Parameters Determined
Repeated uniaxial compression	$\sigma_{zz} = 103.5, 155.3, 207, 310.5, 414, 621 \text{ kPa}$ $\sigma_{\theta\theta} = \sigma_{rr} = 0$	ϵ_{zz} $\epsilon_{\theta\theta} = \epsilon_{rr}$	E, ν
Resonant column	$\sigma_{rr} = 0, 138, 276 \text{ kPa}$ $\sigma_{zz} = 103.5, 172.5 \text{ kPa}$ Varying the amplitudes of a forcing torque	Resonant frequencies	G, D
Uniaxial creep	$\sigma_{zz} = 276, 552, 828 \text{ kPa}$ $\sigma_{\theta\theta} = \sigma_{rr} = 0$	$\epsilon_{zz}(t)$ $\epsilon_{\theta\theta}(t)$	$\psi_{zz}(t), \psi_{\theta\theta}(t)$ $\nu(t)$
Cyclic simple shear	$\sigma_{zz} = 69, 138 \text{ kPa}$ Frequency = 0.5, 1.5 Hz $\gamma = 1 \sim 5 \times 10^{-4} \text{ cm/cm}$	$\tau(t)$ δ	D, G

the resilient and fatigue properties of pavement component materials such as asphalt concrete, concrete, compacted clay, and stabilized soils have been extensively studied.

For an isotropic, linear-elastic material, only two elastic constants are needed to characterize its elastic behavior (4, 10); and in the elastic layer system of analysis, Young's modulus (E) and the Poisson's ratio (ν) are often used. The uniaxial, repeated load test results were examined and the elastic parameters were computed assuming the material behaves as an isotropic, linear-elastic medium. Figure 3 shows the values of E and ν with respect to the applied repeated stress level. Although it is evident that both E and ν vary with the applied stress level, the variations are rather limited considering the wide range of applied stress levels used. Therefore, it appears that a linear-elastic constitutive law is a valid and adequate representation for describing the behavior of the chemically stabilized soil under traffic loading.

Shear Modulus and Damping Ratio

Both the resonant column test and the cyclic shear test results were used to compute the variations of shear modulus and damping ratio with shear strain. These relationships are shown in Figure 4. The shape of these curves is similar to that of curves reported by Seed and Idriss (7) for untreated soils. The shear modulus and damping ratio are strain dependent: The smaller the strain is, the higher the modulus is and the lower the damping ratio is. Computation of the shear modulus and damping ratio values from cyclic simple shear tests was based on the linear-viscoelasticity theory of a steady-state sinusoidal response. The elastic shear modulus was computed from

$$G_1 = G^* \cos \delta \tag{1}$$

where the symbols are as defined previously. G_1 , the storage modulus, is the shear modulus associated with storage energy of the system (10).

Also shown in Figure 4 is the shear modulus computed from uniaxial repeated loading tests.

Figure 5 shows the effect of frequency and vertical load on the variations of shear modulus and damping ratio with shear strain. Their influence is relatively small compared with the effect of shear strain.

Linear Viscoelastic Parameters

The data obtained from uniaxial creep tests were used to compute $\psi_{\theta\theta}(t)$, $\psi_{zz}(t)$, and $\nu(t)$ under the assumption that the material is linear viscoelastic (4). Figures 6, 7, and 8 show the variations of these parameters with time and applied stress levels. For a wide range of applied stress levels (from 276 to 828 kPa), the variations of linear

viscoelastic parameters remain relatively small such that average values of these parameters may be approximated in linear-viscoelastic formulation. A linear-viscoelastic solution may be used to determine the permanent deformation of a pavement structure containing a chemically stabilized soil layer or to estimate the

time-dependent deformation of a pipeline support foundation resting on a chemically treated soil mass.

SUMMARY AND CONCLUSIONS

Fine sand saturated with SIROC was studied in the laboratory to determine its elastic and viscoelastic behavior under different loading conditions. The mechanical behavior of the chemically stabilized soil is affected by curing temperature, moisture condition, and physical environment. Therefore, both the elastic and viscoelastic behaviors could differ greatly in different environments. Based on this study, the following conclusions may be stated.

1. The mixing of a chemical grout into a fine sand drastically changes the hydraulic and mechanical behavior of the soil. In fact, it forms a solidified soil mass that is much more hydraulically impervious and mechanically stronger and stiffer.

Figure 3. Elastic properties under repeated loading.

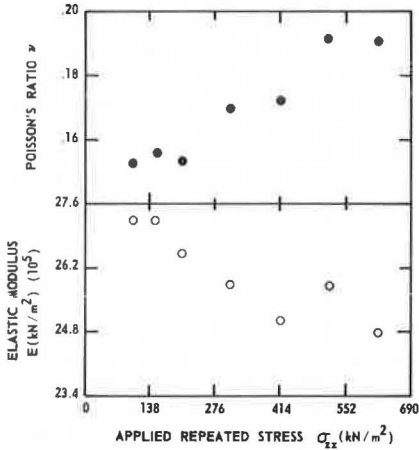


Figure 4. Variations of damping ratio and shear modulus with shear strain.

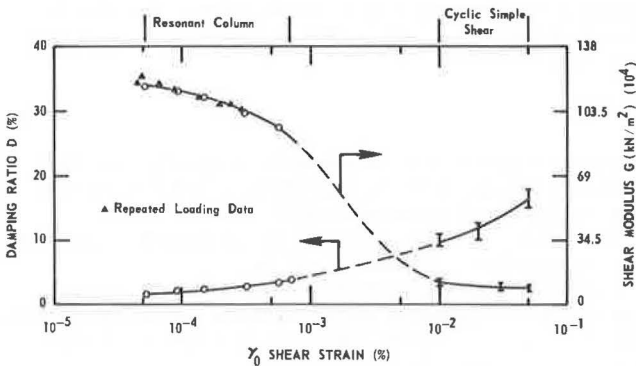


Figure 5. Cyclic simple shear test results.

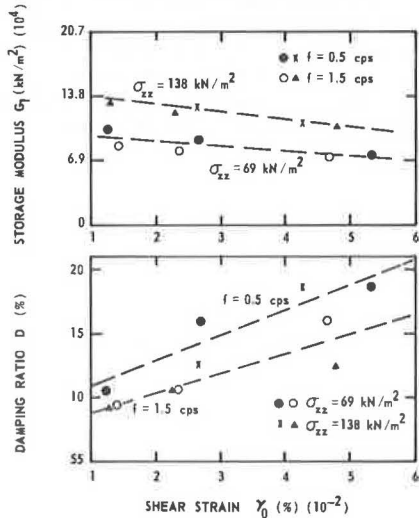


Figure 6. Creep compliance in shear for uniaxial creep test.

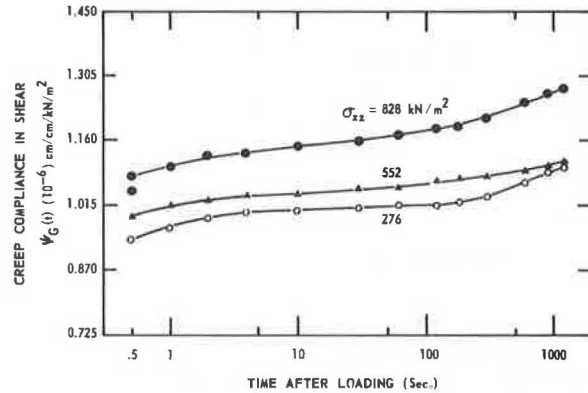


Figure 7. Modular creep compliance for uniaxial creep test.

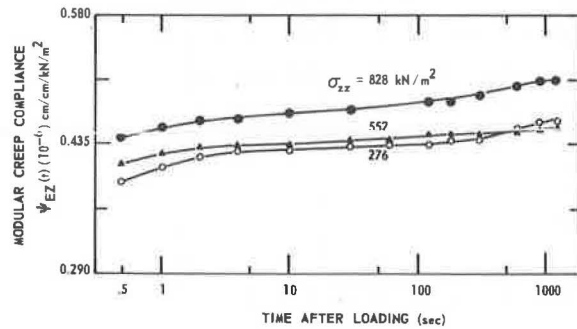
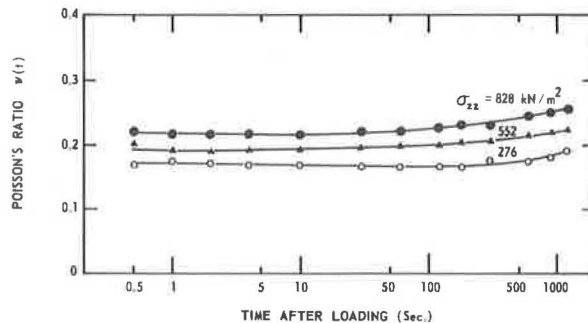


Figure 8. Poisson's ratio for uniaxial creep test.



2. The isotropic, linear-elastic constitutive law appears to provide a reasonable approximation for characterizing the chemically stabilized fine sand under moving load.

3. The magnitude of shear modulus and damping ratio under dynamic testing is dependent on the shear strain applied. The smaller the strain is, the higher the modulus is and the lower the damping ratio is.

4. For applied vertical stress levels of less than 50 percent, the chemically stabilized soil may be treated as a linear-viscoelastic medium for computing time-dependent deformation under sustained loading.

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