Ⅲ - B213

Effects of curing conditions on small strain behavior of cement-treated sand

EDGARD BARBOSA-CRUZ [I], YOSHIKO SATO [II], FUMIO TATSUOKA [III] and KEIICHI SUGO [IV]

Introduction: The design of foundations, like bridge abutments for highways, is usually controlled by small displacements strains rather than failure. Recent experimental data for cement-treated soils suggest that at very small strains (ε<0.001%), the stress-strain response of soil-cement can be idealized as linear elastic, but larger strain behavior is non-linear. In this paper, with the aim of using cement-treated sand on the main body of bridge abutment, the stress-strain behavior of cement-treated sandy soils from CD triaxial compression tests on specimens cured under different conditions at the final stage is examined.

Testing Material and Experimental Procedure: The test material was a cement-mixed sand with 4% of cement per dry weight of soil. Cylindrical specimens (h = 20 cm; d = 10 cm) were prepared at a water content (w_i) equal to 12.5%, corresponding to the optimum water content according to compaction tests, and cured at constant humidity for 137 to 169 days. The average dry unit density was 1.33 g/cm^3. Specimens were made either saturated, or left unsaturated as prepared, immediately before triaxial tests. The specimens were isotropically consolidated at a confining effective pressure of σ_c'=6.0 kgf/cm^2 and sheared in drained triaxial compression at an axial strain rate of 0.015%/minute. During the shearing stage, small unload-reload cycles with a strain amplitude of about 0.005% were applied. Using a pair of Local Deformation Transducers (LDT) attached to the lateral surface of the sample, as illustrated in Fig. 1, small axial strains in the range from 0.001% to 2.5% were measured. An external displacement transducer was used to measure displacements of the loading piston, from which axial strains greater than 2.5% were obtained.

Table 1 summarizes the test conditions. Figs. 1 and 2 show the stress-strain curves at large and small strains. The following parameters were determined: Maximum deviator stress (q_{max}), initial Young's modulus (E_0), secant Young's modulus at 50% of q_{max} (E_{50}), and axial strain at failure (ε_{1f}). For each stress-strain curve the tangent modulus (E_{tan}) and the equivalent Young's modulus (E_{eq}, corresponding to each small unload-reload cycle) were also calculated (see Fig. 2a). The computations were made using the average axial strain obtained from the pair of LDTs.

Effects of loading stop: Stopping and resuming the process of loading at ε_1 = 0.2% or 0.8% during the shear stage caused a sharp increase in the stiffness as shown in the Fig. 2a. A similar, but smaller, increase was observed also by aging at q=0 (Fig. 2b). Subsequently, the tangential stiffness returned to the original values exhibited by test 28. The tangent modulus (E_{tan}) decreases considerably with increasing deviator stress (q), as shown in Figs. 3 (for test 38) and 4 (for the five tests). The values of E_{eq} and E_{tan} in Fig. 4 were normalized by E_0, and the lower bound values of E_{tan} excluding those during and immediately after unload-reload cycles were used. After stopping and resuming the loading, an increase in both E_{eq} and E_{tan} was observed, the increase in the E_{tan} being much more significant. After some additional load (or deformation) occurred, the stiffness (E_{eq} and E_{tan}) returned to the "basic" values attained without the loading stop.

Fig. 5 summarizes the range of deviator stress (Δq) from the restart of loading to the obvious yielding point as a function of ε_1 where loading was temporarily stopped. An increase in the peak strength (Δq_{max}) by temporary stop of loading is also seen from Table 1. The Δq increased with ε_1 or q where loading was stopped, while Δq_{max} is rather independent of the ε_1 value.

Effects of unload-reload cycles: Small unload-reload monotonic cycles (with 0.005% amplitude in axial strain) also temporarily increased E_{tan} immediately after each cycle, as shown in Figure 3 for test 38. This effect gradually disappeared as the axial strain was increased. This behavior corresponds to that observed after a longer stop of loading.

Effects of saturation: Until ε_1 = 0.2 % the behavior of pairs of samples sheared under similar conditions, except for the water content, was quite similar (for example tests 33 and 35; Fig 2a). This result shows that saturation condition itself has no clear effects on the stress-strain behavior. Fig. 5 shows that the effects of temporary stop of loading are larger for the specimens that were made saturated immediately before triaxial tests. The results of these tests suggest that a further benefit can be expected due to additional hydration by saturating the sample even after a relatively long curing period (i.e., about 150 days).

Final remarks: The results stated above suggest the importance of taking into account the effects of humidity conditions and the stress state during curing on small strain behavior of cement-treated soils. An important increase in the stiffness during the process of construction for the cement-treated foundations is suggested by the presented experimental data.

REFERENCE:

1) Sugo K., Sato Y., Tatsuoka F., Yoshimine M., Ohnaka H. (1997): "Effects of curing method on deformation and strength characteristics of cement-mixed sand", Proc. 32th Annual Meeting of JGS, Kumamoto, July 1997.

[I] Graduate student, Department of Civil Engg., Univer. of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113.
[II] Engineer, Kiso Jiban Consultant Co., LTD., 11-5, 1-Chome, Kudan-Kita, Chiyoda-ku, Tokyo 102.
[III] Professor, Department of Civil Engg., Univer. of Tokyo, ditto.
[IV] Technical staff, Department of Civil Engg., Univer. of Tokyo, ditto.

Table 1. Triaxial consolidated drained (CD) tests on sandy soil–cement

Test	ε_1(%) where loading was stopped	Days for loading stop	Moisture condition during T CD	Curing time t_a (days)	q_{max} (kgf/cm²)	***E_0 (kgf/cm²)	E_{50} (kgf/cm²)	$(\varepsilon_1)_f$ (%)
Test 28	*	*	Saturated	137	**18.50	15715	**	**
Test 37	0.0	10	Unsaturated	137	23.65	19625	1937	8.8271
Test 33	0.2	10	Saturated	159	24.72	18331	2868	6.2586
Test 35	0.2	7	Unsaturated	169	24.23	16782	1904	7.5629
Test 38	0.8	10	Unsaturated	159	23.30	18066	1940	8.2929

* Continuous loading

** Estimated; test was stopped before the maximum shear strength was read

*** Determined by extrapolating $E_{eq} - q$ relative to $q = 0$

Cement Content = 4%

w_i = 12.5%

σ_c' = 6.0 kgf/cm²

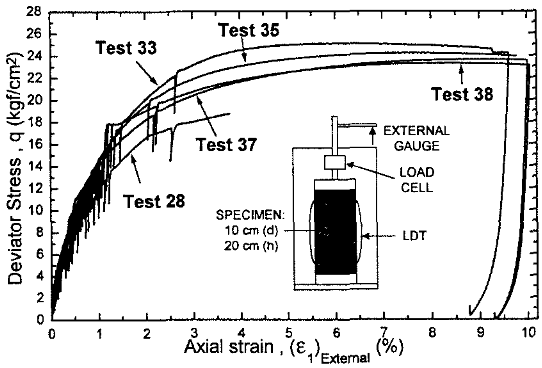

Figure 1

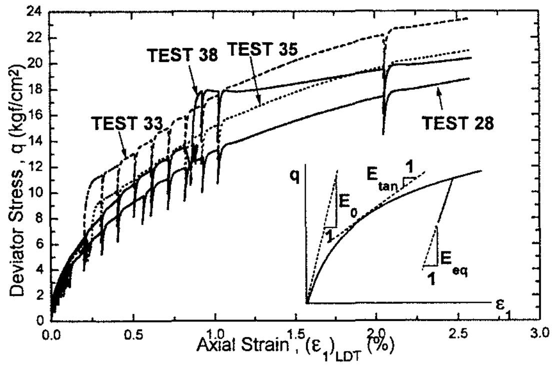

Figure 2a

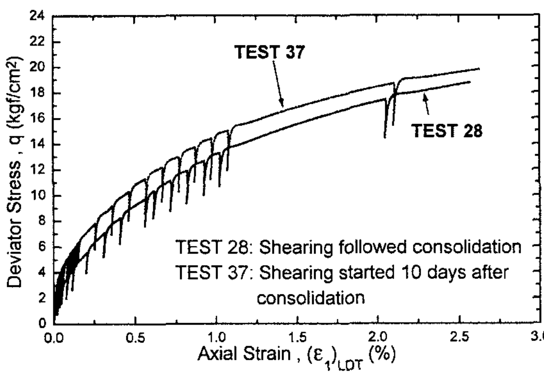

Figure 2b

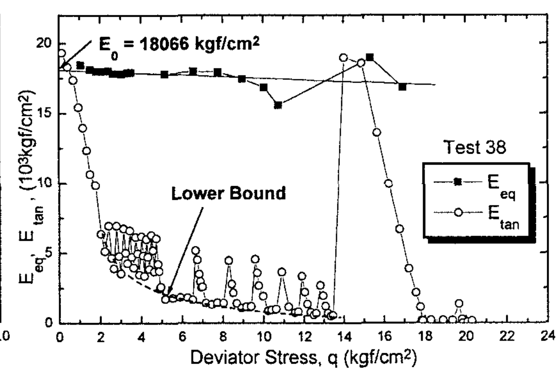

Figure 3

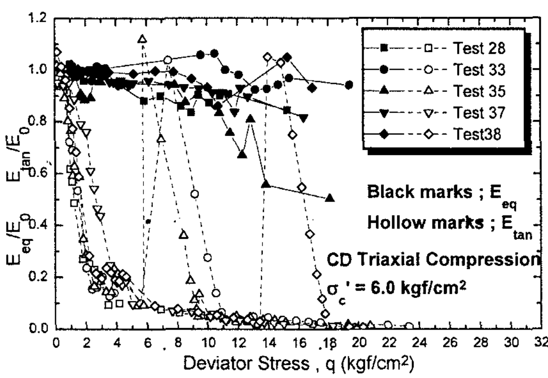

Figure 4

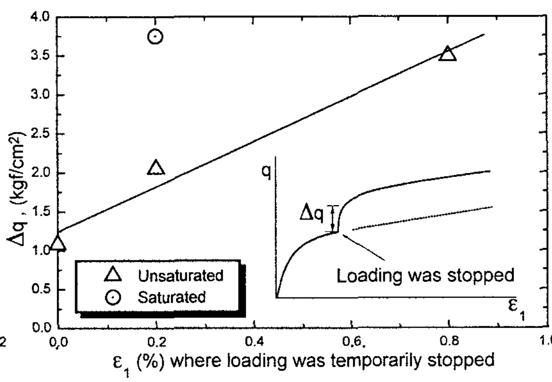

Figure 5