Strength and Stress-Strain Characteristics of a Lime-Treated Cohesive Soil

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Strength and stress-strain characteristics of a cohesive soil in natural and lime-treated states were investigated and compared. For this purpose, a cohesive soil from a semiarid region in Jordan was selected and subjected to various laboratory tests. The experimental program involved three levels of treatment (3, 6, and 9 percent) with hydrated lime and a range of curing times (0, 7, 14, 21, and 28 days). The experimental results indicated that increasing the percent lime increases grain size, calcium ions, and the pH value, whereas it decreases the plasticity index, sodium ions, and dispersion. The compaction characteristics of the soil studied were not significantly affected by lime. Furthermore, the unconfined compressive strength and the undrained angle of internal friction increased because of the addition of lime and curing time. The undrained cohesion decreased with lime treatment up to 3 percent and increased for lime content >3 percent. The lime treatment strength ratio (LSR), defined as the ratio of the unconfined compressive strength of a treated specimen to an untreated one, was introduced. Greater values of LSR indicate that lime is more effective in stabilizing the soil as far as strength is concerned. For the soil studied, LSR increased both with lime percentage and curing time. In addition, the undrained modulus, E_u, increased significantly for values of LSR between 1.0 and 2.0. For LSR > 2.0, the increment in E_u was much smaller.

The stabilization of cohesive soils by lime has been of great interest for many years. In practice, lime has been used as an effective additive to improve various engineering properties of cohesive soils. Lime treatment in cohesive soils generally causes a decrease in plasticity, dispersion, compressibility, and volume change potential, and an increase in particle size, permeability, and strength (*1–3*). Such changes in engineering properties can be attributed basically to two types of chemical reactions that occur when lime is added to a wet soil. First, there are the reactions that take place immediately after mixing lime with soil—within a few minutes to an hour. These reactions are colloidal in nature and involve cation exchange and agglomeration-flocculation reactions that take place because of varying double-layer characteristics of individual clay particles. In this first stage, immediate changes occur in soil plasticity, workability, volume change potential, strength, and deformation properties. Second, the pozzolanic reaction is time dependent and takes place for a long period of time, several years in some instances. This reaction causes the formation of various types of cementation products that increase the strength and durability of the mixture much more than do the products from the reactions in the first stage (*4–6*).

The basic objective was to thoroughly study the stress-strain behavior in terms of the undrained modulus of elasticity and axial strain at failure as obtained from the unconfined compression test. This approach provides better insight to the general strength behavior and durability of cohesive soils treated with lime. Furthermore, the strength of lime-treated cohesive soils has been investigated by many researchers using the unconfined compressive strength more so than any other strength parameter. Therefore, as a second objective, the triaxial compression test was used to examine the variation in undrained cohesion and undrained internal friction angle caused by lime treatment. For this purpose, a cohesive soil located in a semiarid region in northern Jordan was selected. Also, a parameter for judging the effectiveness of lime treatment as far as strength is concerned was defined.

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LABORATORY INVESTIGATION

The selected cohesive soil was from the Irbid city area located in a semiarid region in northern Jordan. Samples were collected from a depth of 1 m below the ground surface. Previous studies performed on Irbid clay indicated that it is highly plastic, fissured, overconsolidated at shallow depths because of desiccation, and highly expansive in character (*7*).

The experimental program entailed three different levels of lime treatment: 3, 6, and 9 percent by dry weight of the soil. The specimens were cured at 22°C and 70 percent relative humidity for 1 hr (0 days), and 4, 7, 21, and 28 days. Hydrated lime, which is produced and commercially available in Jordan, was used throughout the study.

The soil characteristics studied here can be divided into two groups. The first group involved physical, compositional, and compaction characteristics that were measured with the intention of studying the effect of lime on them and to search for any systematic influence of these properties on the general strength behavior of the soil. (However, in determining these properties, curing was not taken into account except for consistency limits.) The second group comprised strength and stress-strain characteristics for which the effects of lime content and curing time were investigated in detail.

Physical, Compositional, and Compaction Characteristics

The soil both in natural and lime-treated states was subjected to various laboratory tests in accordance with ASTM standard procedures. These tests included grain size distribution, consistency limits, and standard Proctor compaction. A fourth level of treatment with 12 percent lime was considered only

for consistency limits. The results are presented in Table 1, which also includes the plasticity index (I_p) values and the classification according to the Unified Soil Classification System. The effect of curing time on consistency limits was also studied in soils treated with lime and no significant variation was recorded.

In order to examine the effect of lime on the concentration of soluble ions existing in the soil, two extreme cases, natural and 9 percent lime-treated specimens of the soil, were analyzed for Ca, Mg, Na, K, Mn, Al, SO_4, NO_3, PO_4, and Cl ions. Pore water specimens extracted at a water-soil ratio of 50:1 were used for this purpose. Cations were analyzed using an atomic absorption spectrophotometric method. Anions of PO_4, SO_4, and NO_3 were analyzed using the same method, whereas Cl was studied using a titration procedure. The results are presented in Table 1.

The pH values of the natural soil and all the soil-lime mixtures were also measured. For this purpose, all specimens were extracted at a water-soil ratio of 1:1. An electronic pH meter with glass electrodes was used. The results are presented in Table 1. Marks and Haliburton (*5*) stated that pH values >10 increase the solubility of quartz and silica, and thus act as a catalyst to accelerate pozzolanic reaction in the soils. As presented in Table 1, the pH values obtained for 3, 6, and 9 percent lime treatment levels were all >10, ensuring the solubility of quartz and silica.

In order to study the effect of lime treatment on soil dispersion, the double hydrometer test was performed both on the natural soil and on all the soil-lime mixtures. In this experiment, the specimen was first subjected to the standard hydrometer test in which a dispersing agent was used; then the specimen was tested without using a dispersing agent. Oven-dried soil passing the No. 200 sieve was used in both cases. The percent dispersion is defined as the percent of particles smaller than 0.005 mm without using a dispersing agent divided by the percent of particles smaller than 0.005 mm using a dispersing agent. The percent dispersion values obtained for the natural soil and soil-lime mixtures are also presented in Table 1.

Strength and Stress-Strain Characteristics

Specimens, one in each set, were subjected to a standard unconfined compression test to obtain the unconfined compressive strength (q_u) and the stress-strain behavior of the natural soil and all the soil-lime mixtures. In addition, the effect of a range of curing times on these parameters was

TABLE 1 PROPERTIES OF NATURAL AND LIME-TREATED SOILS

Property	Percent Lime				
	0	3	6	9	12
Grain-size Distribution					
Sand, % (2 mm - 75 μm)	2.3	6.1	30.5	59.1	-
Silt, % (75 μm - 2 μm)	43.7	77.9	65.5	38.8	-
Clay, % (< 2 μm)	54.0	16.0	4.0	2.1	-
Consistency Limits					
Liquid limit, w_L, %	74.7	57.2	54.5	50.7	50.5
Plastic limit, w_P, %	35.7	46.7	47.2	45.3	46.8
Plasticity Index, I_P, %	39.0	10.5	7.3	5.4	3.7
Unified Soil Classification	CH-MH	MH	MH	SM	-
Compaction					
w_{opt}, %	31.0	29.0	30.0	29.5	-
$\gamma_{d_{max}}$, kN/m³	13.9	14.2	14.1	14.2	-
Ion concentration, mg/liter					
Na	8.16	-	-	6.06	-
K	0.44	-	-	0.46	-
Ca	7.47	-	-	15.49	-
Mg	1.11	-	-	0.03	-
Al	0.20	-	-	0.21	-
Mn	0.06	-	-	0.00	-
Cl	28.20	-	-	28.20	-
NO_3	1.90	-	-	3.20	-
SO_4	17.00	-	-	17.00	-
PO_4	0.68	-	-	0.68	-
pH value	7.9	10.5	11.2	11.5	-
Percent dispersion	66.7	60.4	32.7	32.7	-

"-" indicates that the specimen was not tested for that property

studied. All specimens were compacted before testing by using a standard Proctor compaction effort at 30 percent water content, which was within a ±1 percent range of the optimum water content values (see Table 1). Furthermore, specimens were tested in an unconsolidated-undrained (UU) triaxial test to determine the undrained cohesion c_u and angle of internal friction ϕ_u. In this test, three all-around pressures were used: 150, 300, and 450 kPa. The results of the strength tests are presented in Table 2, which contains the compressive strength (q_u), the undrained modulus of elasticity (E_u) (as obtained from the initial tangent of the stress-strain diagram), the axial strain at failure (ε_f), and the undrained shear strength parameters c_u and ϕ_u for various levels of lime treatment and curing times.

DISCUSSION OF EXPERIMENTAL RESULTS

Physical, Compositional, and Compaction Characteristics

The combined results of sieve and hydrometer analyses for the natural and lime-treated soils indicate that the percent of sand particles increases and the percent of clay size particles decreases as the lime content increases. Figure 1 shows the influence of lime treatment on particle size characteristics of the soils studied. The increase in particle size by the addition of lime can be attributed to the cation exchange phenomenon taking place at the surface of the clay particles by which the particles become electrically attracted to one another, causing flocculation and aggregation.

The results obtained from the double hydrometer test indicate that the percent dispersion decreases with increasing lime content up to 6 percent and remains constant beyond this point. Previous studies have also shown that the addition of lime converts a dispersive soil into nondispersive, erosion-resistant soil (*2,8*). Although the sodium ion is known to be the most effective factor causing dispersion in soils, the calcium ion is commonly accepted to be a flocculating agent (*9*). As indicated in Table 1, addition of lime causes the calcium ion concentration to increase and the sodium ion concentration to decrease. These effects in turn affect the double layer characteristics of clay particles and lead to an increase in attraction, thus causing flocculation and aggregation and consequently a decrease in dispersion.

TABLE 2 STRENGTH TEST RESULTS

Percent Lime	Curing Time, days	Unconfined Compression			Triaxial Compression	
		q_u kPa	E_u MPa	ϵ_f %	c_u kPa	ϕ_u degrees
0	0	290	16.7	3.25	212	2.8
	4	316	17.5	3.00	-	-
	7	359	19.3	3.25	-	-
	14	326	23.7	2.00	-	-
	21	342	27.9	1.50	-	-
	28	483	25.6	2.50	-	-
3	0	306	20.2	2.00	139	18.7
	4	370	29.6	1.50	-	-
	7	321	22.9	1.50	141	25.8
	14	415	27.6	1.75	-	-
	21	387	30.3	1.50	-	-
	28	445	37.9	1.25	146	27.4
6	0	385	28.7	1.25	219	20.5
	4	729	44.1	2.00	-	-
	7	949	47.3	2.25	313	28.8
	14	1267	53.7	2.50	-	-
	21	1383	54.5	2.50	-	-
	28	1540	50.6	3.00	368	37.2
9	0	390	29.1	1.50	243	22.3
	4	959	45.1	2.25	-	-
	7	993	52.7	2.00	356	32.6
	14	1640	57.8	3.00	-	-
	21	1737	56.6	3.00	-	-
	28	2049	56.6	3.50	418	38.3

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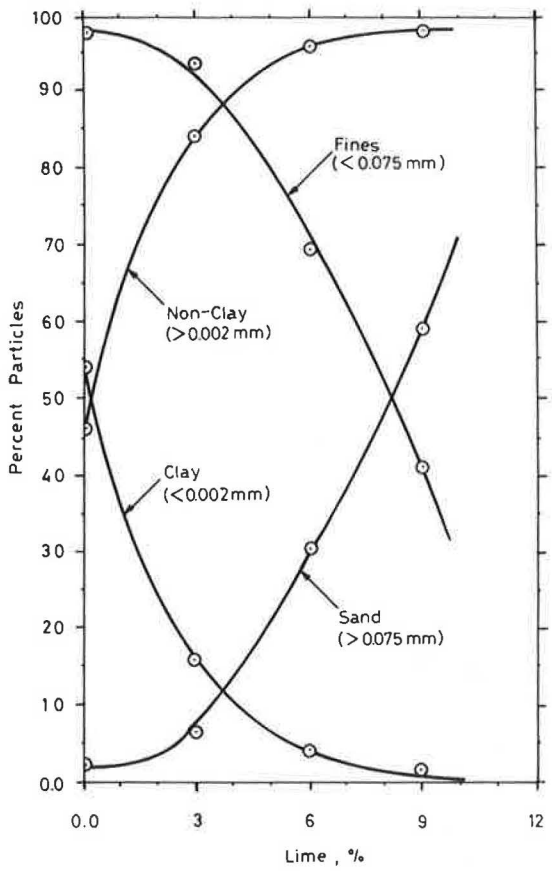

FIGURE 1 Effect of lime treatment on particle size characteristics.

The effect of lime treatment on consistency limits is indicated in Table 1. As lime content increases, causing a reduction in the plasticity index, the liquid limit decreases and the plastic limit increases. On the other hand, the curing time did not have any significant effect on the values of consistency limits. These results can be attributed to the flocculation of the clay particles by lime treatment, producing a soil with coarser particles and causing less plastic character.

The variations in particle size distribution and consistency limits also influence the classification of the soil. As shown in the plasticity chart of Figure 2, the natural soil is almost on the *A*-line in the high plastic range, but by the addition of lime at 3 and 6 percent levels, the soil becomes highly plastic silt, MH type of soil well below the *A*-line. At 9 percent lime treatment level, the soil is a coarse-grained soil with about 60 percent sand-size particles, and can be classified as silty-sand, SM type of soil.

The effect of lime treatment on the compaction characteristics is also presented in Table 1. From these results, it is clear that the maximum dry unit weight, $\gamma_{d_{max}}$, and optimum water content, w_{opt}, are not significantly affected by lime. This observation seems to contradict the general conception that lime reduces $\gamma_{d_{max}}$ and increases w_{opt}. However, El-Rawi and Awad (*1*) indicated that an increase in w_{opt} is attributed to pozzolanic reaction and a decrease is possibly caused by cation exchange. Thus, a balance between these two mechanisms will result in little or no change in w_{opt}, and consequently $\gamma_{d_{max}}$ is unchanged. This balance seems to be the case here.

Strength and Stress-Strain Characteristics

The variation of unconfined compressive strength with the level of lime treatment and curing time is shown in Figure 3. The natural soil exhibited a marginal gain in strength with time, indicating that it is slightly thixotropic in character. This observation is in agreement with the general thixotropic behavior of overconsolidated clays. As Figure 3 shows, the addition of 3 percent lime resulted in a relatively small increase in strength even after 28-day curing, indicating that this level of treatment is not sufficient to produce the required degree of pozzolanic reaction for the formation of adequate cementitious products. On the other hand, 6 and 9 percent lime treatment increased the unconfined compressive strength rather significantly. Thus, the unconfined compressive strength has

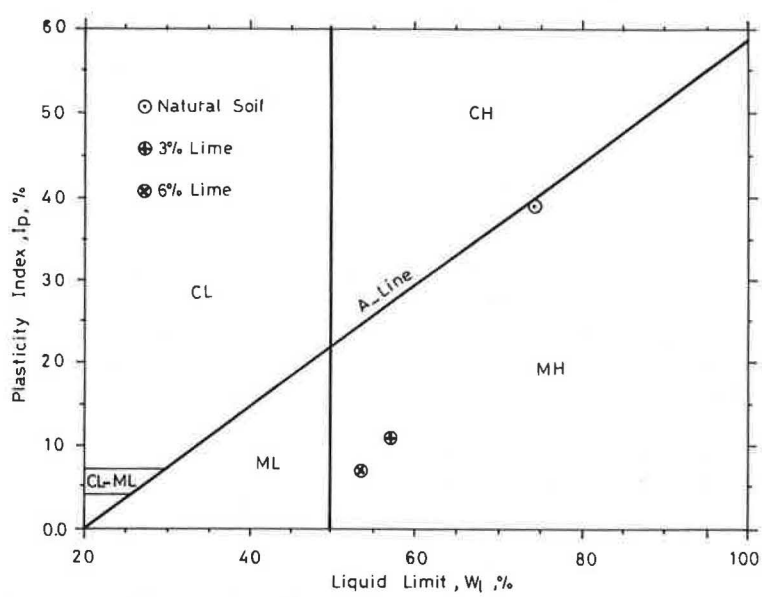

FIGURE 2 Plasticity chart.

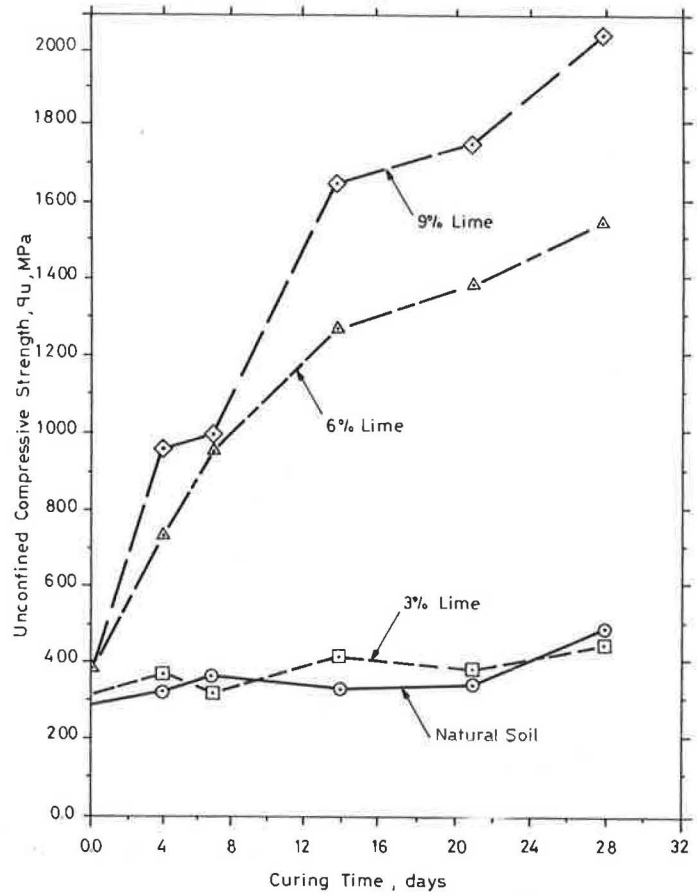

FIGURE 3 Effects of lime content and curing time on unconfined compressive strength.

a tendency to increase as the lime content and curing time increase. Because the increment in strength is small immediately after the addition of lime and larger increments require time, it is clear that the pozzolanic reaction is responsible for strength gain.

The specimens for the triaxial UU-test were prepared by compaction at optimum water content. They were not fully saturated for testing. This latter fact explains the nonzero measured values of ϕ_u for all tested specimens, as indicated in Table 2. The effects of lime content and curing time on c_u and ϕ_u are shown in Figures 4 and 5, respectively. These figures indicate that c_u decreases as ϕ_u increases at 3 percent lime treatment. This observation may be justified by the earlier assertion, in particular, that 3 percent lime merely causes cation exchange to take place with little pozzolanic reaction. Consequently, 3 percent lime content would be adequate enough to result in flocculation and aggregation but insufficient to form cementitious products. The basic changes, therefore, taking place with this amount of lime are in particle size and plasticity of the soil. Clay size content, for instance, drops drastically from 54 percent to 16 percent and plasticity index decreases from 39.0 to 10.5 percent, immediately after the soil is treated with 3 percent lime. These variations in physical properties suggest that the soil is approaching a granular nature, thus, causing a decrease in c_u and an increase in ϕ_u. With 6 and 9 percent lime, on the other hand, the pozzolanic reaction becomes more effective resulting in cementation and consequently in higher cohesion and internal friction angle. Furthermore, Figures 4 and 5 indicate that the curing time influences c_u and ϕ_u; however, its impact is more pronounced at higher levels of lime treatment. As expected, varying physical characteristics affect the internal friction angle more directly. Figures 6 and 7, respectively, show the effects of varying plasticity index and percent nonclay fraction on ϕ_u together with the influence of curing time.

Flocculation and cementation processes resulting from chemical reactions in lime-treated soils are expected to produce a brittle material. Such materials generally have steeper stress-strain diagrams associated with higher modulus of elasticity and are known to fail abruptly at the ultimate compressive load. Comparing various soils of similar strengths, the more brittle the soil is the smaller the axial strain at failure. The stress-strain diagrams presented in Figure 8 indicate that lime treatment leads to a more brittle behavior. This assertion can be justified by the fact that, although the increasing level of lime treatment does not cause any significant increase in strength at 0 days' curing, the axial strain at failure has a tendency to decrease whereas the undrained modulus of elasticity increases as the diagrams become steeper. At 28-day curing, both the natural and 3 percent lime-treated soils do not gain much strength, but they have an even smaller ε_f and greater E_u. The soils treated with 6 and 9 percent lime gain high strengths and they exhibit an abrupt type of failure at the ultimate compressive stress. Because of this high strength,

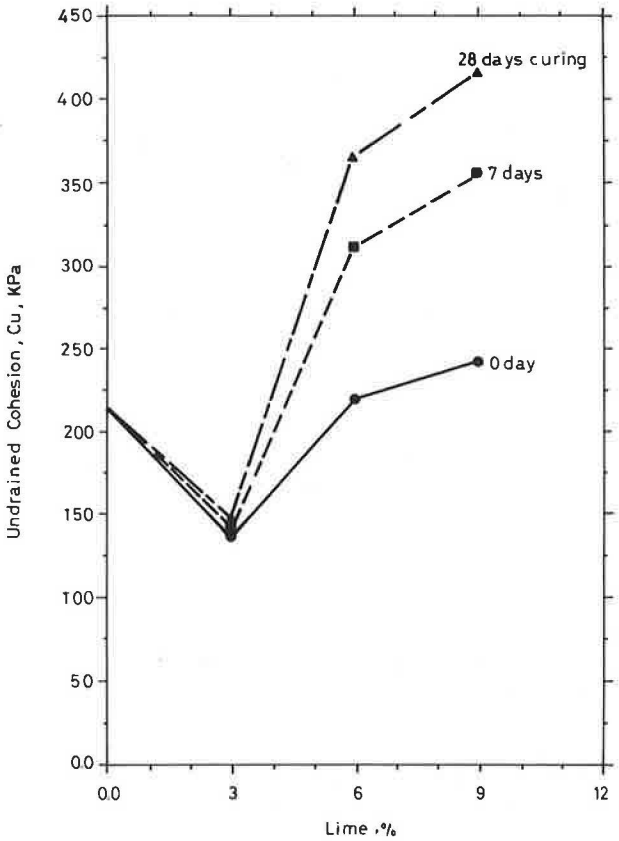

FIGURE 4 Effects of lime content and curing time on undrained cohesion.

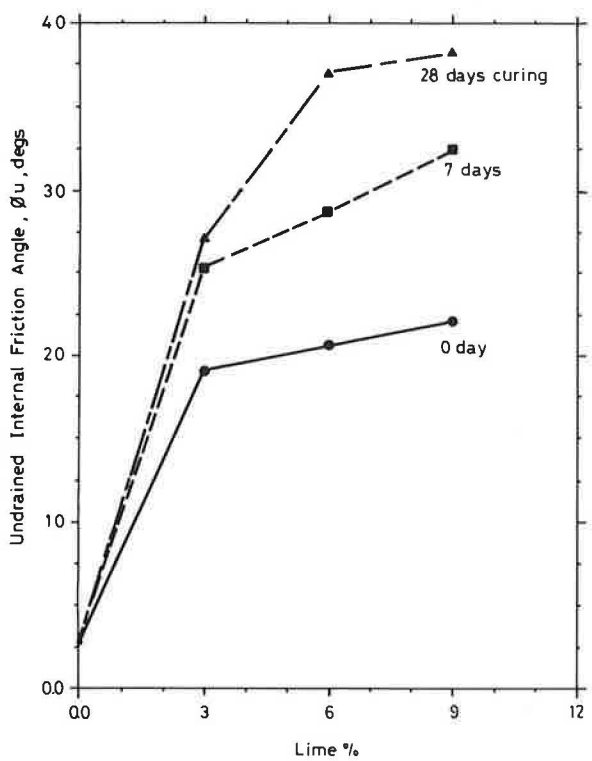

FIGURE 5 Effects of lime content and curing time on undrained angle of internal friction.

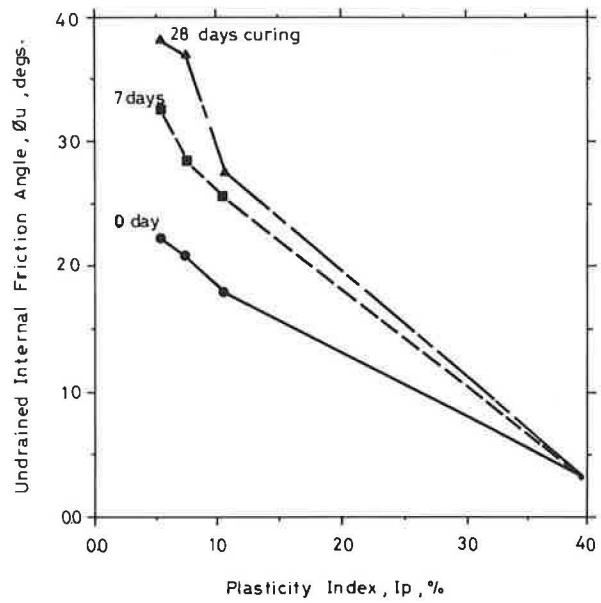

FIGURE 6 Effects of plasticity index and curing time on undrained angle of internal friction.

they resist failure until they undergo larger axial strains. The modulus values, on the other hand, become greater with steeper stress-strain relationships. Figures 9 and 10 show the variations in ε_f and E_u with varying lime content and curing time, respectively, in a more descriptive manner. Figure 11 shows the combined effects of lime content and curing time on the stress-strain characteristics, in particular, ε_f and E_u.

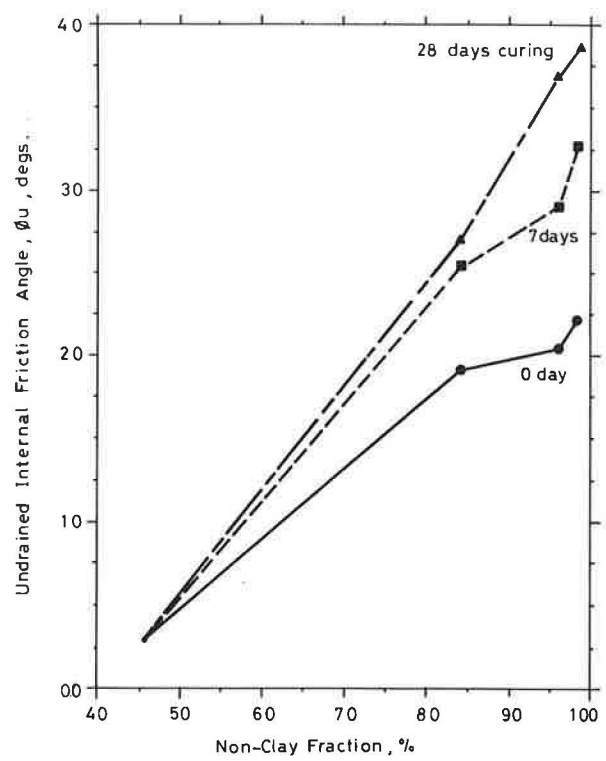

FIGURE 7 Effects of nonclay fraction and curing time on undrained angle of internal friction.

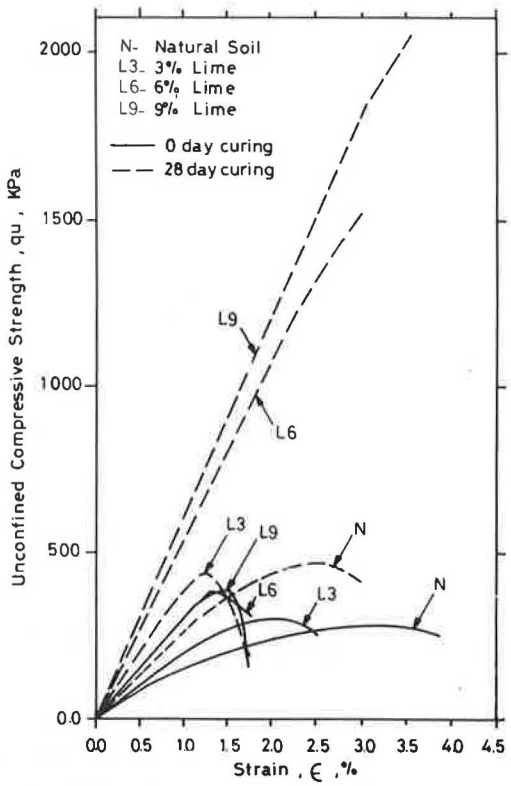

FIGURE 8 Stress-strain diagrams of the natural and lime-treated soils.

A parameter relating the effect of lime on strength characteristics of soils may be useful. With such a parameter, it should be possible to classify different types of soils in their response to lime treatment in terms of strength. Thus, the lime treatment strength ratio (LSR) is defined as the unconfined compressive strength of lime-treated soil compacted at optimum water content divided by the unconfined compressive strength of natural soil compacted at optimum water content. Figure 12 shows the variation of LSR with varying lime content and curing time. For up to 3 percent lime treatment, LSR remains at about the same value for any curing period. However, higher amounts of lime and curing time result in a significant increase in LSR. This suggests that up to the 3 percent level of lime treatment a gain in strength is not produced. Higher percentages of lime and longer periods of curing, however, will ensure a higher value of LSR, leading to a stronger soil caused by cementation, which is a direct result of pozzolanic reaction.

Figure 13 relates E_u with LSR. As this relation indicates, E_u increases in large amounts as LSR increases within the range of 1.0 to 2.0. For values of LSR >2.0, the increment in E_u becomes much less. This observation indicates that the stress-strain diagram steepens more at the initial stages of strength gain. After this stage, large increments in strength would not cause much change in E_u. This argument can be justified by studying Figure 10. In this figure, E_u reaches its maximum value almost within 7-day curing, especially with 6 and 9 percent lime-treated soils, whereas the strength keeps on increasing (Figure 3).

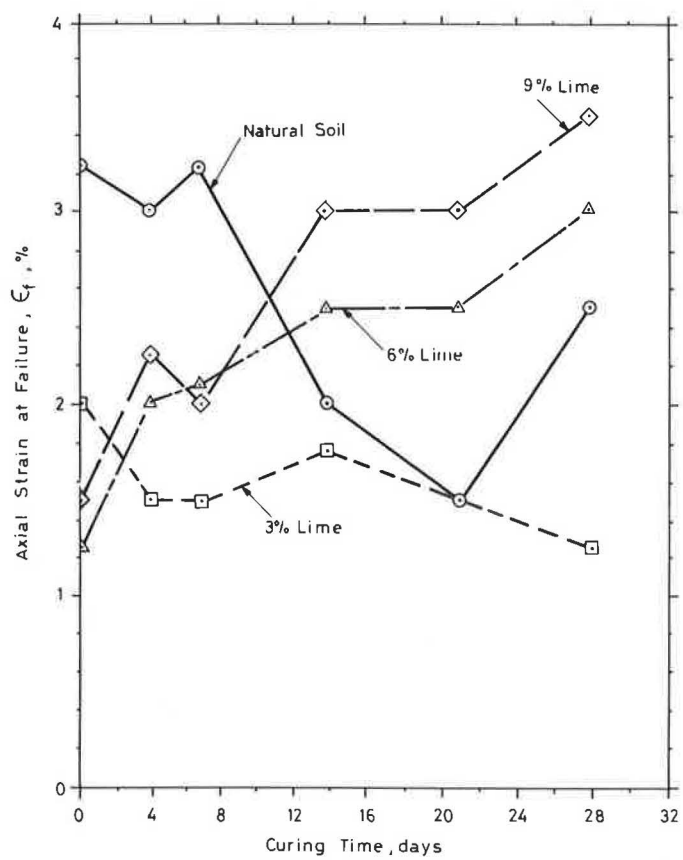

FIGURE 9 Effects of lime content and curing time on axial strain at failure.

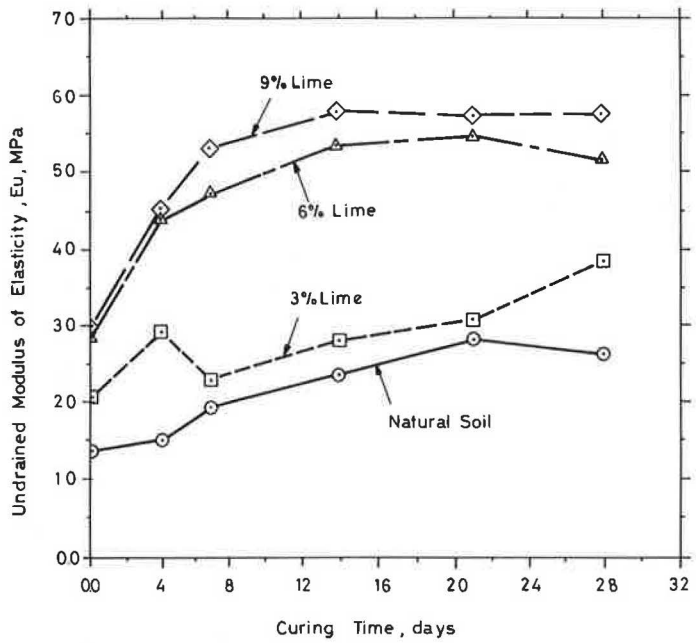

FIGURE 10 Effects of lime content and curing time on the undrained modulus of elasticity.

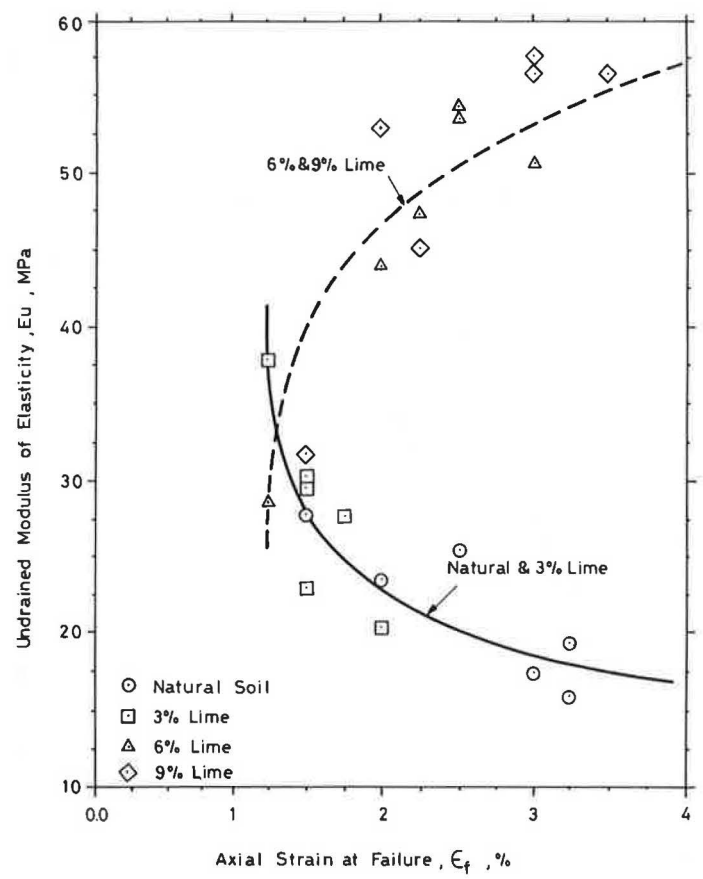

FIGURE 11 Undrained modulus of elasticity versus axial strain at failure for various lime contents.

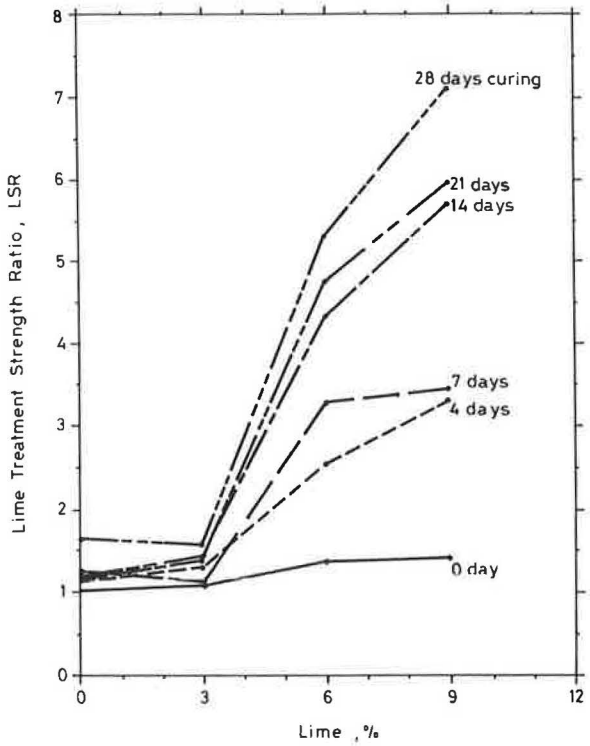

FIGURE 12 Effects of lime content and curing time on LSR.

CONCLUSIONS

On the basis of the findings of this study and the conditions evaluated, the following conclusions can be reached:

- Lime treatment influenced the physical, compositional, and compaction characteristics as follows:
  - —Particle size increased;
  - —Liquid limit decreased and plastic limit increased, consequently, plasticity index decreased;
  - —Percent dispersion decreased;
  - —Na ion concentration, which is responsible for dispersion, decreased, whereas flocculating Ca ion concentration increased;
  - —The pH increased; and
  - —Maximum dry density and optimum water content remained practically at the same level.
- The strength characteristics studied included unconfined compressive strength, q_u, undrained cohesion, c_u, and undrained internal friction angle, ϕ_u. The effects of lime treatment on these parameters are as follows:
  - —q_u had a tendency to increase with increasing lime content and curing time, as long as the amount of lime was sufficient to cause the pozzolanic reaction required to form adequate cementitious products.
  - —c_u decreased slightly during the initial stages of lime treatment (up to 3 percent lime) and then appreciably increased with increasing lime and curing time. This behavior indicates that to have an increase in c_u, a sufficient amount of lime must be added to the soil to cause the occurrence of pozzolanic reactions.
  - —ϕ_u exhibited a significant increase even at low levels of lime treatment and curing time, indicating that the cation exchange phenomenon is effective in addition to pozzolanic reactions. Cation exchange causes variation in the physical properties that bring the soil to a more granular nature.
- Lime treatment made the soil more brittle and the stress-strain behavior of a lime-treated soil was similar to that of a brittle material. This point can be readily justified by examining the variations in strength, undrained modulus of elasticity, and axial strain at failure that resulted from lime treatment.
- A parameter termed "lime treatment strength ratio," LSR, is introduced. LSR is defined as the ratio of the unconfined compressive strength of the lime-treated soil to an untreated soil compacted at optimum condition. LSR was found to in-

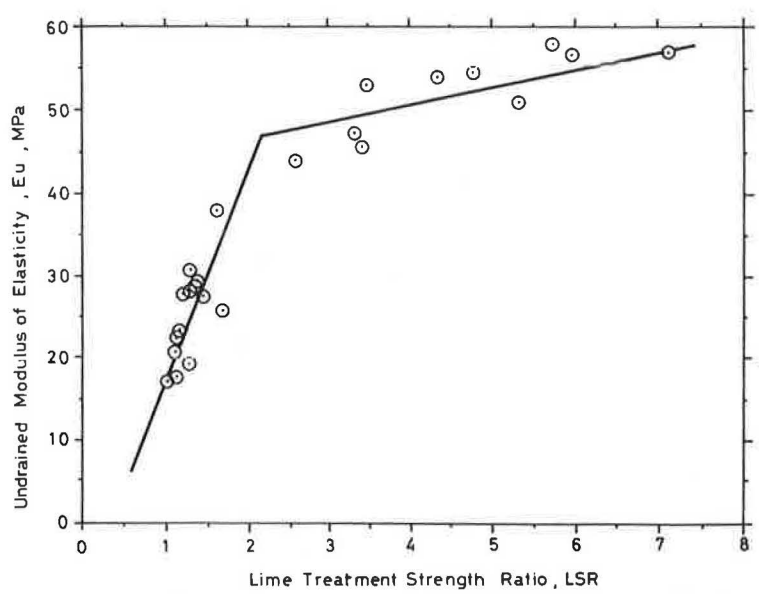

FIGURE 13 Relation between E_u and LSR.

crease both with lime and curing time. In addition, for the soil studied herein, the undrained modulus, E_u, increased significantly as LSR increased within the range of 1.0 to 2.0. However, for values of LSR > 2, the increase in E_u is less.

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REFERENCES

1. N. M. El-Rawi and A. A. Awad. Permeability of Lime Stabilized Soils. *Transportation Engineering Journal*, ASCE, Vol. 107, No. TE1, 1981, pp. 25–35.
2. M. I. Hayden and T. A. Haliburton. Improvement of Dispersive Clay Erosion Resistance by Chemical Treatment. In *Transportation Research Record 593*, TRB, National Research Council, Washington, D.C., 1976, pp. 27–33.
3. T. W. Kennedy, R. Smith, R. J. Holmgreen, Jr., and M. Tahmoressi. An Evaluation of Lime and Cement Stabilization. In *Transportation Research Record 1119*, TRB, National Research Council, Washington, D.C., 1987, pp. 11–25.
4. J. C. Cabrera and C. A. Nwakanma. Pozzolanic Activity and Mechanism of Reaction of Red Tropical Soil-Lime System. In *Transportation Research Record 702*, TRB, National Research Council, Washington, D.C., 1979, pp. 199–207.
5. B. D. Marks and T. A. Haliburton. Acceleration of Lime-Clay Reaction with Salt. *Journal of Soil Mechanics and Foundations Division*, ASCE, Vol. 98, No. SM4, 1972, pp. 327–339.
6. J. M. Ozier and R. K. Moore. Factors Affecting Unconfined Compressive Strength of Salt-Lime-Treated Clay. In *Transportation Research Record 641*, TRB, National Research Council, Washington, D.C., 1977, pp. 17–23.
7. E. R. Tuncer, A. A. Basma, and S. Taqieddine. *Geotechnical Properties of Some Selected Irbid Soils*. Report 14/87. Jordan University of Science and Technology, Irbid, 1990.
8. G. Machen, L. R. Squier, L. Grove, O. S. Diamond, E. Leo, and S. Rafael. Laboratory Study of the Effectiveness of Cement and of Lime Stabilization for Erosion Control. In *Transportation Research Record 641*, TRB, National Research Council, Washington, D.C., 1977, pp. 24–28.
9. E. R. Tuncer, M. I. Ordemir, and M. Oud. Soil Susceptibility to Dispersion. In *Proc., 12th International Conference on Soil Mechanics and Foundation Engineering*, Vol. II, Rio de Janeiro, 1989, pp. 2115–2118.

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