Effect of Lime on Volume Change and Compressibility of Expansive Clays

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Heave and settlement of clayey soils pose a difficult problem to civil engineers. Several methods are usually suggested to control this problem. The most common method is the addition of stabilizing agents, such as lime. An evaluation of the soil-lime system for two soils typical of the highly expansive soils existing in Irbid city in northern Jordan is presented. The lime was added to the soils at 0 to 9 or 12 percent. The soil-lime specimens were cured for 1 hr, 7 days, and 28 days, after which they were subjected to laboratory tests. The properties obtained were the grain size distribution, consistency limits, chemical composition, swell potential, swell pressure, compression and rebound indices, rate of swell and consolidation, immediate settlement, and primary consolidation as percent of total settlement. Generally, lime is found to be most effective in stabilizing heave and settlement of expansive clays.

Geotechnical engineers know that excessive heaving and settlement of clayey soils almost always cause serious damage to overlaying structures. In the past few decades, several investigators have conducted studies to evaluate the important factors that influence both heave and settlement of soils. In addition, various researchers have suggested different methods of stabilization to modify and improve soil properties (1– 3). Stabilization techniques are usually mechanical or chemical, or both. Generally, the addition of chemical stabilizing agents, such as lime, cement, fly ash, salt, etc., are favored (1,2,4–7). Lime has been the most widely used chemical for clays. However, most researchers have concentrated on the effect of lime on the swelling of expansive clays with little attention given to the compressibility problems in such soils.

The effectiveness of lime in reducing the volume change of expansive clays and the possibility of lime stabilization to improve the compressibility characteristics of clays were investigated.

LIME-SOIL REACTION

When lime is added to clay soils in the presence of water, several reactions occur that alter some of the soil properties. These changes cause amelioration (5,8). Commonly, lime stabilization proceeds through a combination of (a) cation exchange, (b) flocculation and agglomeration, (c) carbonation reaction, and (d) pozzolanic reactions (7–10). Furthermore, lime addition to soils increases the pH of the soil-water system, reaching a maximum of about 12.3 when the soil is fully

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saturated with lime (11). In general, most researchers agree that fine-grained soils react favorably with lime, resulting in beneficial changes in soil plasticity, workability, and swell. Yet, in some cases lime is not the ideal solution to the volume change problem. There are several cases in the literature on lime-induced heave (11,12); however, this phenomenon is rare.

Hunter (11) stated that, under certain conditions, both the sulfate and clay minerals react with lime to form thaumasite and ettringite minerals, which cause the heave. Mitchell (12) reported a failure through ettringite growth in a parking lot in Wichita, Kansas. Additional cases of lime-induced heave were uncovered in Texas and Utah by Hunter (11).

SOILS OF IRBID CITY

Irbid city, located in the northern part of Jordan, has a semi-arid climate. This climate is known to aggravate swelling problems, especially with the existing native soils. Generally, the soils in Irbid are mainly dark to reddish brown, weathered, firm, intensely fissured clay with an average clay content of about 65 percent. Most of these soils contain highly plastic and expansive clays (Figures 1 and 2) and hence have problems caused by swelling. This fact inevitably calls for stabilization. With the abundance of lime in Jordan, it seemed to be the most logical choice. For this study, two typical soils (termed Soils A and B) in Irbid were selected. The physical properties of the soils (Table 1 and Figures 1 and 2) and chemical analysis of the pore water (Table 2) are presented.

SAMPLE PREPARATION AND EXPERIMENTAL PROGRAM

The testing was conducted in two phases. Phase I entailed the determination of grain size distribution, consistency limits, and chemical analysis of the pore water in the soil that directly or indirectly affected both the volume change and compressibility. Phase II consisted of ascertaining the swelling and compressibility characteristics of the soils.

The soil, oven-dried for 4 days at 50°C, was then mixed with a calculated amount of hydrated lime to obtain a predetermined lime percentage, which varied from 0 to 9 or 12 percent. Water was added until it was equivalent to optimum water content plus 3 percent. The soil-lime-water was thoroughly mixed and kneaded by hand until the mixture became homogeneous. A specific weight of this mixture producing a wet unit weight as that in Table 1 for Soils A and B was then
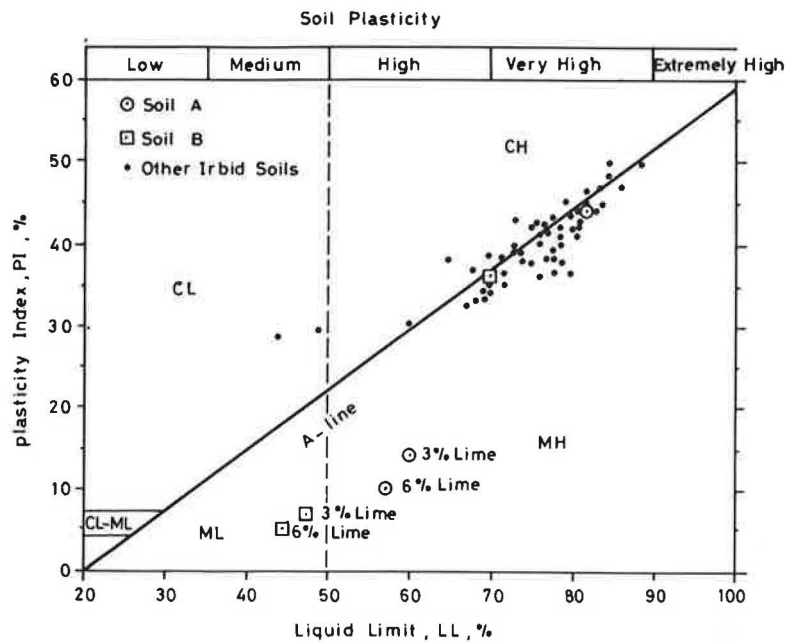
FIGURE 1 Plasticity chart of Irbid clay.

compacted at maximum dry unit weight in a standard Proctor compaction mold and a consolidation ring (of 76-mm diameter and 20-mm height) for tests in Phases I and II, respectively. The specimens were wrapped in plastic and tightly encased in a plastic bag to prevent moisture loss and were set to cure at 22°C and 70 percent relative humidity for 1 hr, (0 days), 7 days, and 28 days. After the prescribed curing period, about 1 kg of the soil in the compaction mold was thoroughly sieve-washed. The soil passing sieve #200 (<75 μm) was oven-dried (4 days at 50°C) for hydrometer analysis to determine the clay size distribution. The remaining soil in the mold was used for the consistency limits test.

Similarly, the consolidation ring containing the soil was placed in the loading apparatus after the curing period. An

initial seating pressure of 25 kN/m² was applied, which was assumed to be the surcharge load. Dial readings were recorded until deformation stopped, which occurred within the first 2 min of loading. The specimen was then submerged in water and dial readings were recorded at ¼, ½, 1, 2, 4, 8, 15, 30, 60, 120 min, and 24, 48, and 72 hr. In most cases, full expansion occurred after 24 hr, when the specimen was consolidated under incremental pressure levels. The swell pressure in this case is defined as the pressure required to consolidate a preswollen sample to its initial void ratio (or height).

PRESENTATION AND ANALYSIS OF RESULTS

Phase I

Effect of Lime on Grain Size Distribution

Variations in coarse grain fractions (>75 μm) and clay size fractions (<2 μm) of the soil for the various lime percentages and curing times are shown in Figures 3 and 4, respectively. Increasing lime percentage and curing time causes the clay particles to amass by cementation and to form silt and sand-like grains. This assertion is further substantiated by scanning electron micrographs (×200 magnification) of Soil A with 0, 3, 6, and 9 percent lime cured for 28 days (see Figure 5). Clearly, as the lime percentage increases, the soil becomes more granular.

Effect of Lime on Chemical Composition

Treated and untreated samples of Soils A and B were chemically analyzed for Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+}, Al^{3+}, NO_3^-, HCO_3^-, Cl^-, SO_4^{2-}, and PO_4^{3-} by extracting the soluble ions in the soils at a water-soil ratio of 50:1. Figures 6 and 7 show the changes in the anions and cations with varying per-
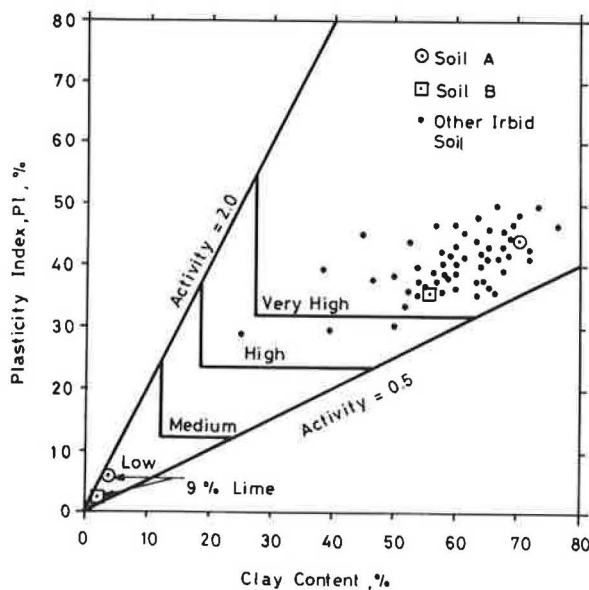

FIGURE 2 Potential expansiveness of Irbid clay.

TABLE 1   PROPERTIES OF TESTED SOILS

Physical Property	Soil A	Soil B
Depth of sampling (meters)	1.3	1.6
Natural water content, w_n (%)	33.8	29.2
Dry unit weight, γ_d (kN/m^3)	15.0	18.0
Optimum water content, w_{opt} (%)	30.5	26.8
Maximum dry unit weight, $\gamma_{d_{max}}$ (kN/m^3)	14.5	17.6
Specific Gravity, G_s	2.67	2.75
Initial void ratio, e_o	0.75	0.50
Liquid limit, LL (%)	81.5	70.0
Plasticity index, PI (%)	44.1	35.5
Shrinkage limit, SL (%)	2.9	14.1
Sand percent		
Course (2000 μm – 600 μm)	0.0	1.0
Medium (600 μm – 200 μm)	1.0	3.0
Fine (200 μm – 75 μm)	4.0	6.0
Silt percent (75 μm – 2 μm)	25.0	35.0
Clay percent (< 2 μm)	70.0	55.0
Liquid limit of particles < 2 μm (%)	112.0	98.0
Plastic limit of particles < 2 μm (%)	66.0	55.0
Activity, A	0.63	0.65
Free Swell (%)	120.0	90.0

TABLE 2   CHEMICAL ANALYSIS OF THE PORE WATER OF THE
UNTREATED SOILS

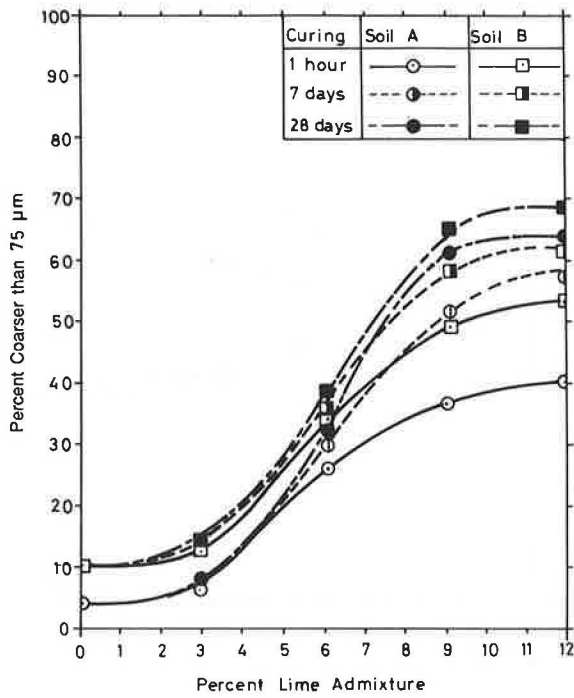| Ions	Soil A		Soil B	
	mg/g of soil	% of total milliequivalent/liter	mg/g of soil	% of total milliequivalent/liter
Cations				
Na^+	1.41	51.26	1.36	66.92
K^+	0.15	5.45	0.10	4.35
Ca^{2+}	0.83	30.17	0.37	18.21
Mg^{2+}	0.19	6.91	0.13	6.40
Mn^{2+}	0.00	0.00	0.00	0.00
Al^{3+}	0.17	6.18	0.08	3.95
Anions				
NO_3^-	0.02	0.40	0.03	0.93
HCO_3^-	1.51	39.81	1.45	45.13
Cl^-	1.50	39.55	1.22	37.97
SO_4^{2-}	0.75	19.77	0.50	15.56
PO_4^{3-}	0.02	0.47	0.01	0.40

FIGURE 3   Effect of lime admixture and curing time on the coarser-grain fraction of Soils A and B.
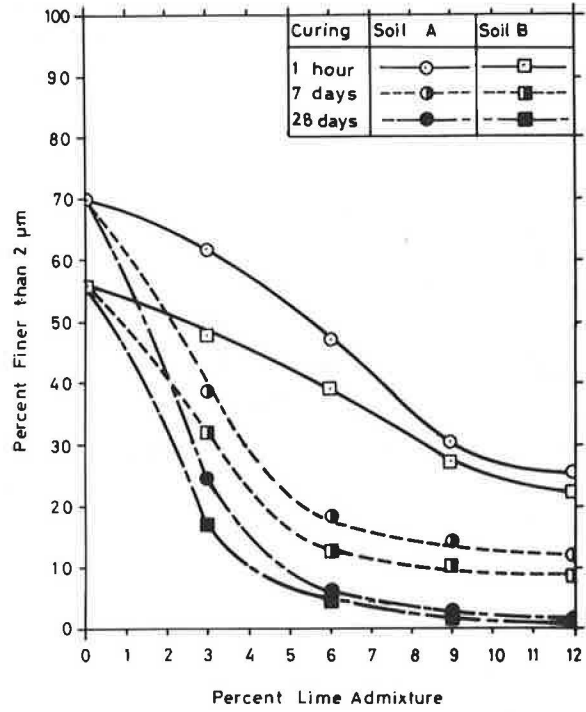
FIGURE 4   Effect of lime admixture and curing time on the clay size fraction of Soils A and B.
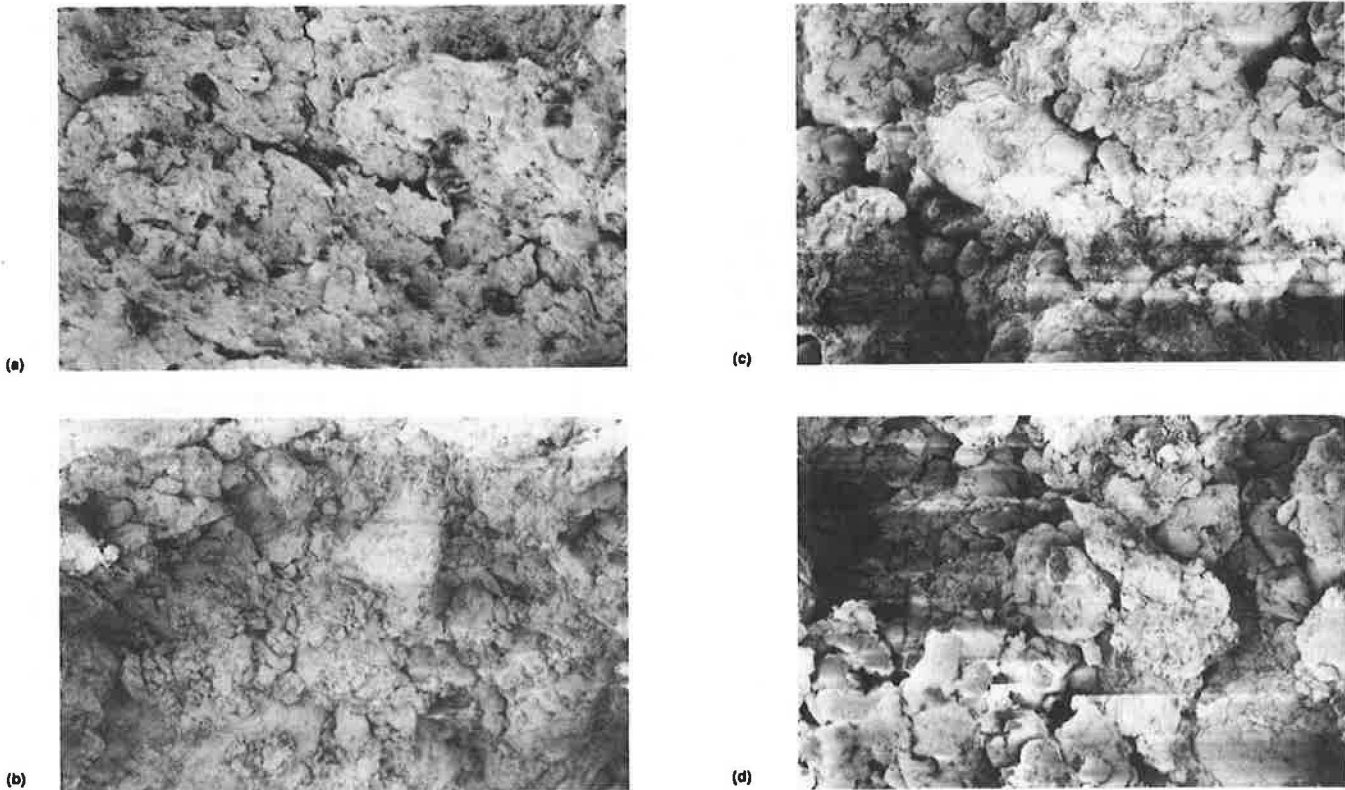

FIGURE 5   Scanning electron micrograph of Soil A with (a) 0 percent, (b) 3 percent, (c) 6 percent, and (d) 9 percent lime, cured for 28 days. (Magnification: ×96)
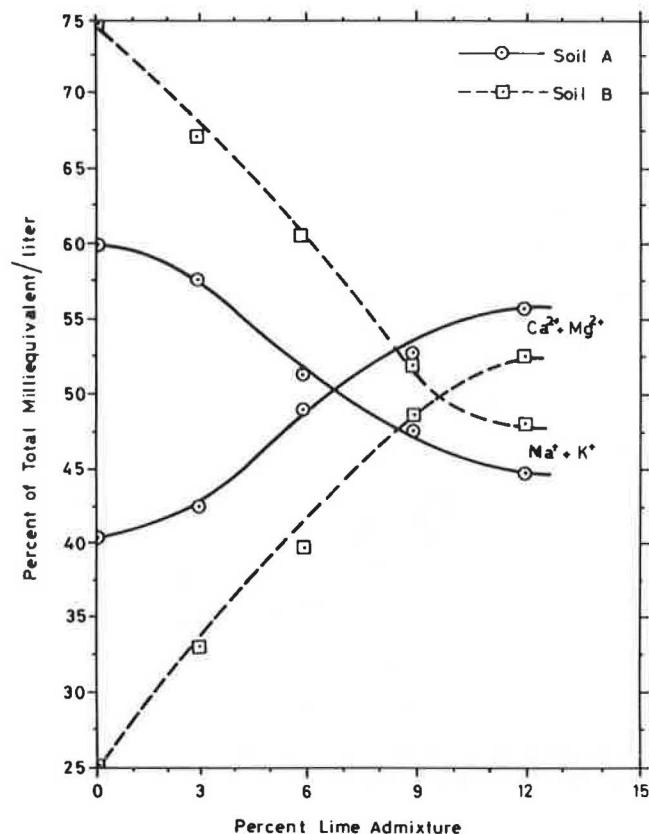
FIGURE 6 Variation of cations with lime for Soils A and B.

FIGURE 7 Variation of anions with lime for Soils A and B.

cents of lime. Flocculating agents Ca^{2+} and Mg^{2+} increase with increasing lime, whereas deflocculating agents Na^+ and K^+ decrease with increasing lime.

Effect of Lime on Consistency Limits

The results of the consistency limits test are shown in Figures 8 and 9 for Soils A and B, respectively. The plasticity index (PI) values of the soils are substantially decreased and the shrinkage limit is increased with increasing lime. However, no significant effect of curing time is noted. The reduction in plasticity can be ascribed to the increasingly granular nature of the soils with lime.

Phase II

Effect of Lime on Volume Change

Figures 10 and 11 show the effect of lime percentage and curing time on swell potential and swell pressure for Soils A and B. The swell pressure is obtained by consolidating the swollen sample to its initial height, i.e., the pressure in Figure 12 at zero expansion. Figure 12 shows a typical result. As can be seen from Figures 10 and 11, lime percentage and curing time profoundly reduce swell potential and swell pressure. The optimum water content plus 3 percent and the maximum unit weight were used as initial values. The decrease in swell
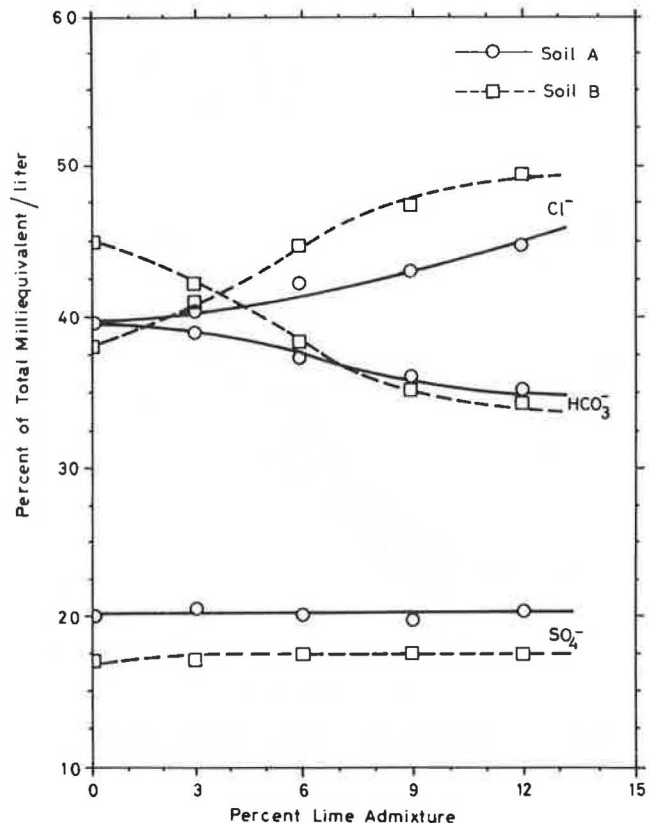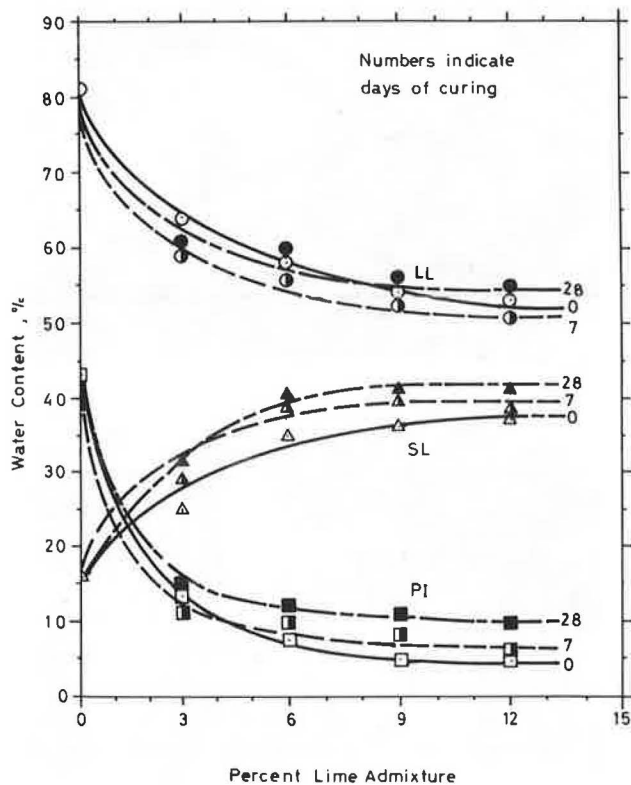

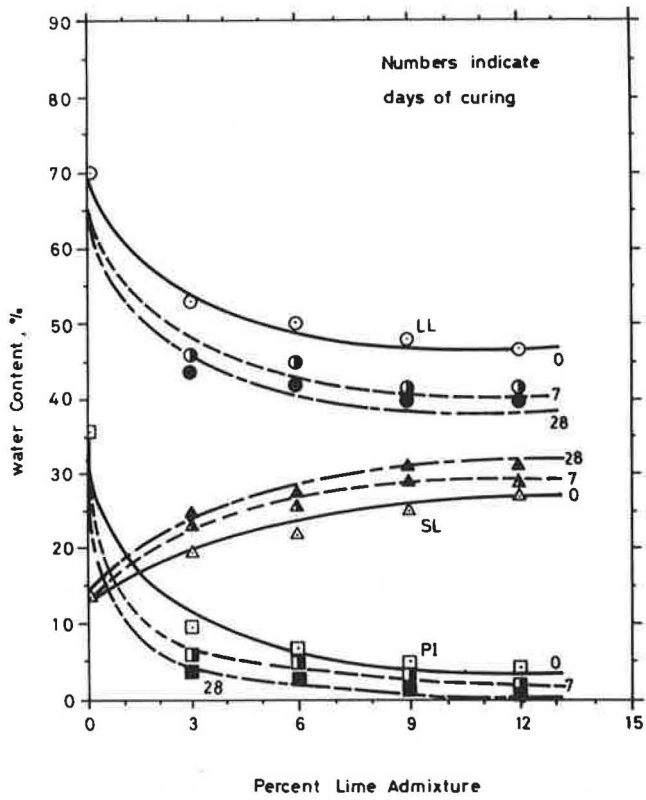FIGURE 8 Effect of lime admixture and curing time on the consistency limits for Soil A.

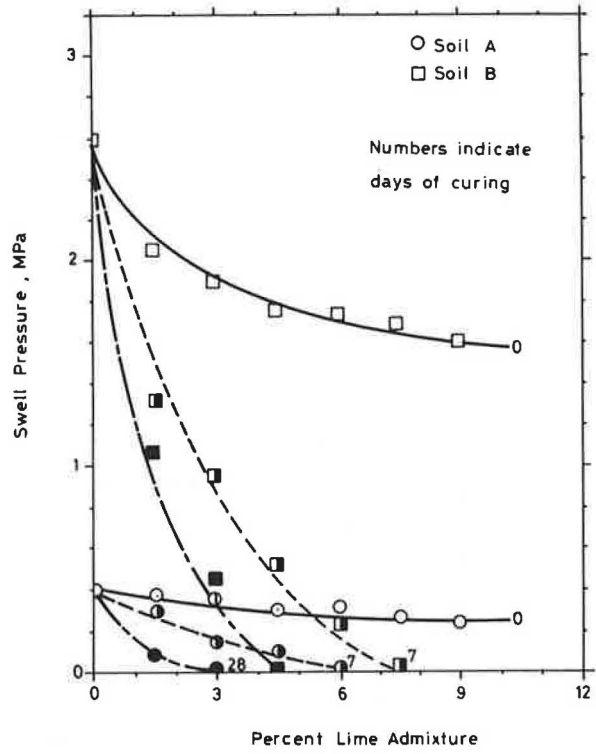FIGURE 9 Effect of lime admixture and curing time on the consistency limits for Soil B.

FIGURE 11 Effect of lime admixture and curing time on the swell pressure of Soils A and B.
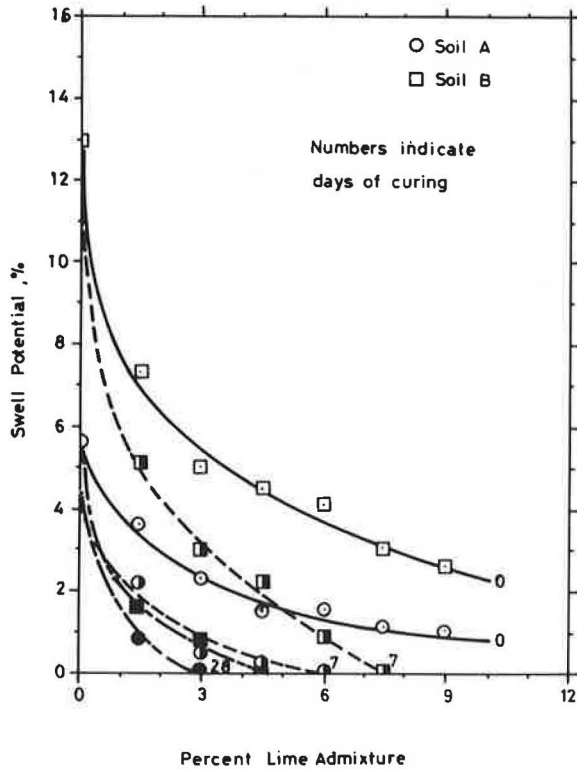

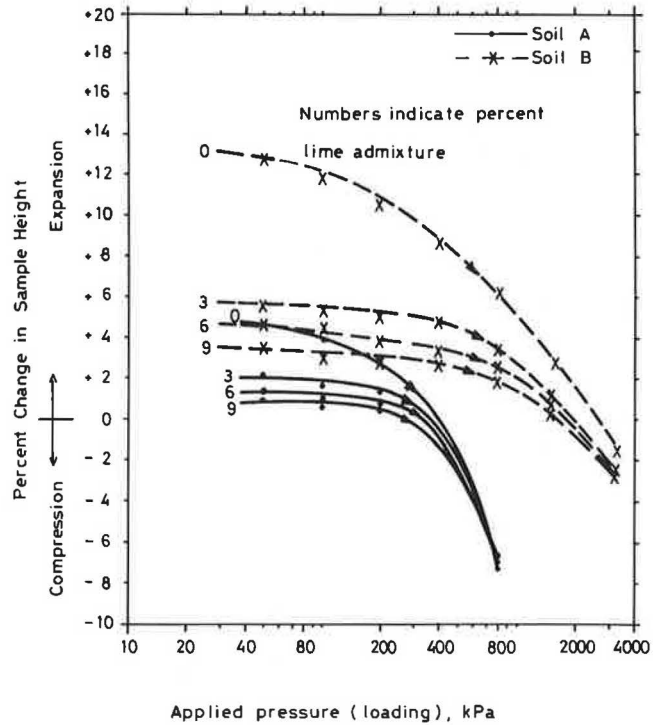FIGURE 10 Effect of lime admixture and curing time on the swell potential of Soils A and B.

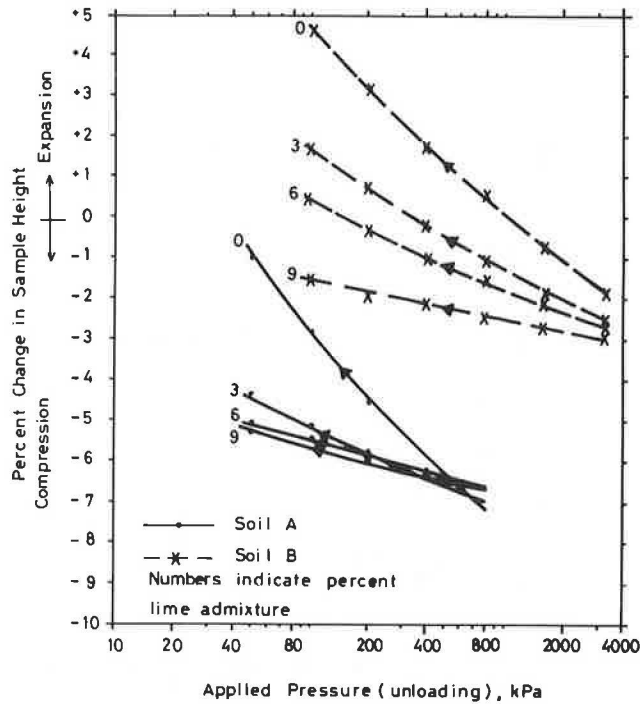FIGURE 12 Percent change in sample height versus loading applied pressure for 1-hr curing time.

FIGURE 13 Percent change in sample height versus unloading applied pressure for 1-hr curing time.
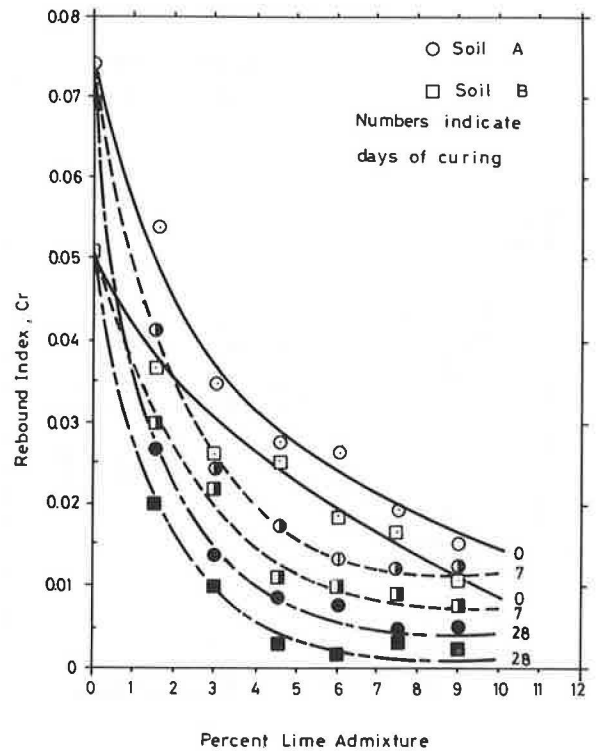

FIGURE 15 Effect of lime admixture and curing time on the rebound index for Soils A and B.
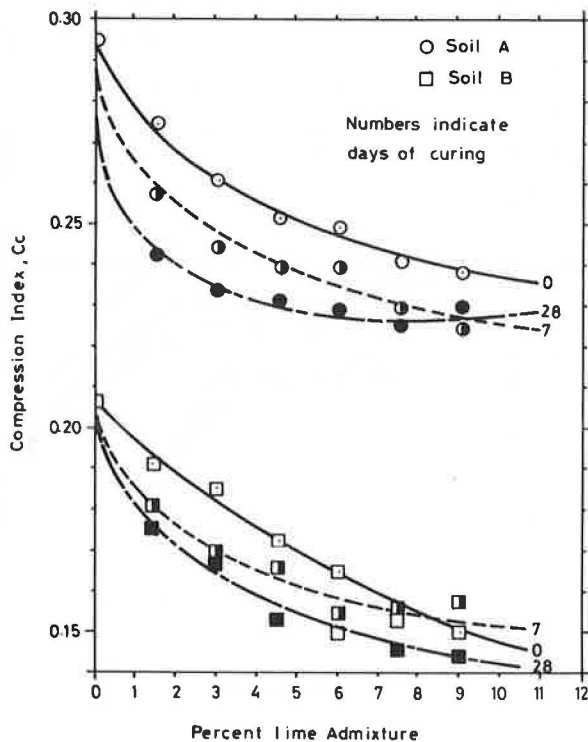

FIGURE 14 Effect of lime admixture and curing time on the compression index for Soils A and B.

characteristics can be attributed to the reduced water absorption tendency of the calcium-saturated clay and the development of a cementitious matrix that can resist expansion.

Effect of Lime on Compressibility and Rebound

Treated and untreated preswollen specimens with different curing periods were consolidated under incremental pressure levels. After the specimens were brought to their initial heights or beyond this point, the loads were gradually removed to study the rebound characteristics. Figures 12 and 13 show typical observed results. Using data from these figures, the compression and rebound indices are plotted in Figures 14 and 15, respectively. These figures suggest that both percent of lime and curing time have influence both on compression and rebound indices, but the effect is more pronounced on the rebound index. This increased tendency to resist compression and rebound can be accounted for by the cementing ability of lime.

Effect of Lime on the Type of Compression

Using the deformation versus time plots, the immediate settlement and primary consolidation were evaluated. Figures 16 and 17 show the variation of percent immediate settlement and primary consolidation of the total compression with per-
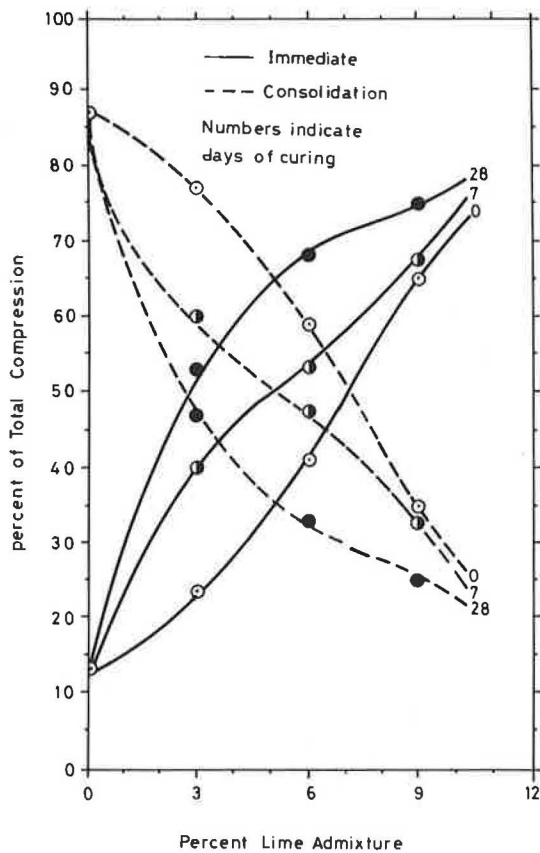
FIGURE 16 Effect of lime admixture and curing
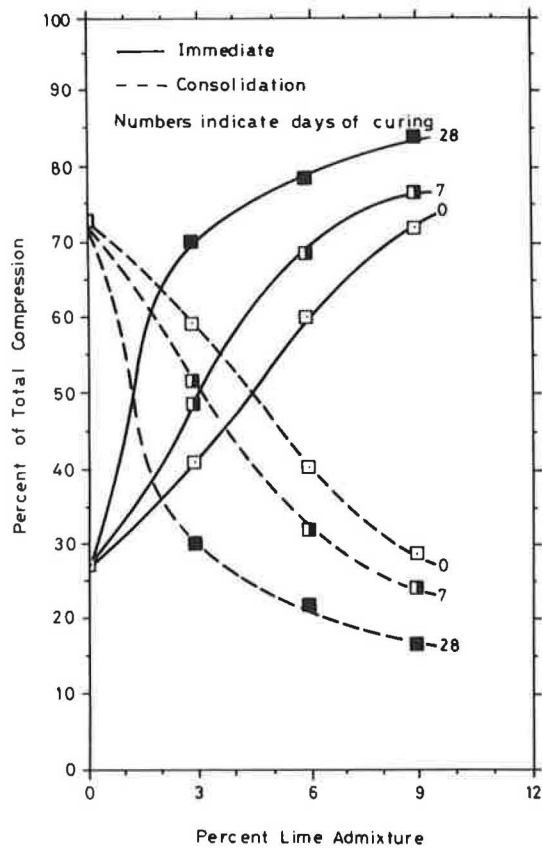time on the type of settlement for Soil A.

FIGURE 17 Effect of lime admixture and curing
time on the type of settlement for Soil B.

cent lime and curing time at 800 kPa pressure level. These
figures demonstrate an increase in immediate settlement and
decrease in primary consolidation with increasing lime and
curing time, indicating that the soils are approaching granular
soil behavior.

Effect of Lime on Rate of Compression and Swell

The rate of compression, or consolidation in the case of satu-
rated soils, is usually governed by the rate at which the pore
water can escape from the soil. One parameter commonly
used to define the rate of consolidation is c_v, which is de-
fined as

$$c_v = \frac{k}{m_v \gamma_w} \qquad (1)$$

where

k = coefficient of permeability,
m_v = coefficient of volume change, and
γ_w = unit weight of water.

Alternatively,

$$c_v = \frac{T_v d^2}{t_{\alpha c}} \qquad (2)$$

where

T_v = time factor,
d = one-half the thickness of the specimen for two-way
     drainage, and
$t_{\alpha c}$ = time to α percent consolidation.

If α is taken as 50 percent, for instance, then $T_v = 0.196$;
and with d being almost constant for a given pressure incre-
ment, then c_v will simply be a function of $t_{\alpha c}$. Thus, the rate
of consolidation will be defined in terms of t_{50c}. For swelling,
on the other hand, there is no readily available method for
measuring the rate. Therefore, the rate of swell will be defined
as the time to 50 percent swell, t_{50s}, i.e., the time to half the
full swell. Figures 18 and 19 show t_{50c} and t_{50s}, respectively,
as functions of percent lime and curing time for Soils A and
B. Figure 18 was prepared for a pressure increment of 800
kPa. From these figures, both the rate of compression and
swell increase, i.e., t_{50c} and t_{50s} decrease, with increasing lime.
In explanation, as the percent lime and curing time increase,
the soil becomes more granular, which implies that the perme-
ability increases.

LIME TREATMENT COMPRESSION RATIO

One of the most important parameters usually used to define
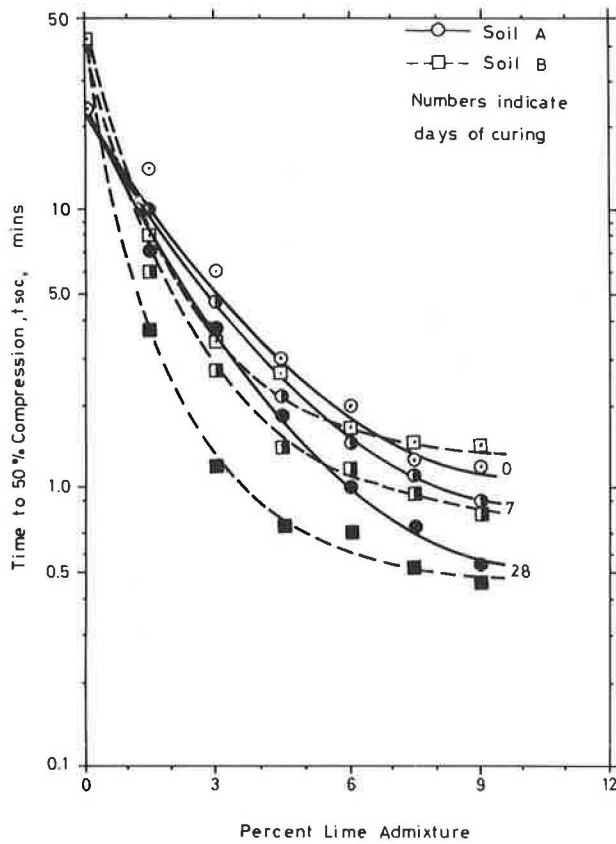the compression of clays is the preconsolidation pressure, p_c.

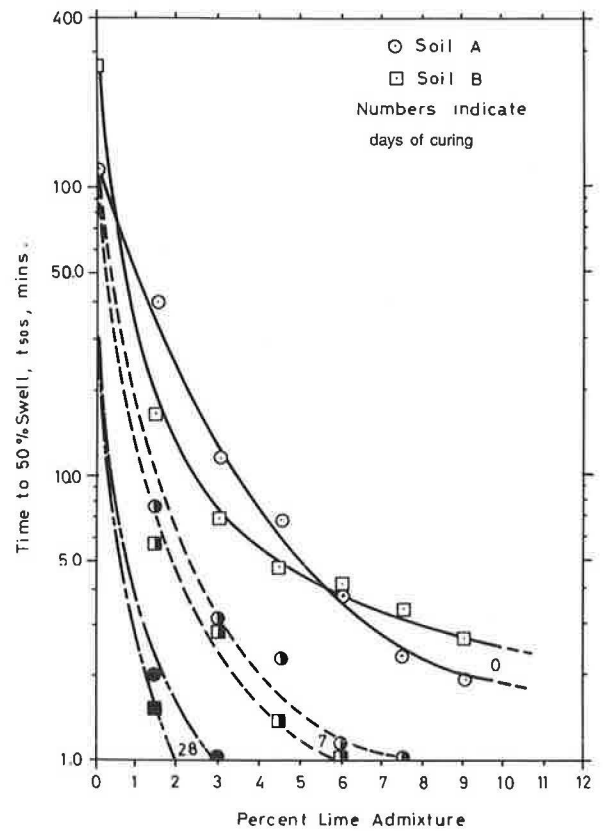FIGURE 18 Effect of lime admixture and curing time on the rate of compression for pressure $p = 800$ kPa.

FIGURE 19 Effect of lime admixture and curing time on the rate of swell.

Higher p_c values indicate smaller compressibility of the clay as long as the applied pressure is less than p_c. Using this concept, the preconsolidation pressures of lime-treated specimens were estimated by Casagrande's method from the compression versus applied pressure plots. In order to determine how compressible a lime-treated specimen is in relation to an untreated specimen, the lime treatment compression ratio (LTCR) is defined as follows:

$$\text{LTCR} = p_c(T)/p_c(U) \tag{3}$$

where $p_c(T)$ and $p_c(U)$ are the preconsolidation pressures of treated and untreated specimens, respectively. Thus, higher LTCR implies lesser compressibility. Figure 20 shows LTCR in relation to the percent lime admixture for Soils A and B. Observe that LTCR increases with percent lime and curing time; therefore, compressibility decreases. Also, LTCR is independent of the type of soils tested. This observation, however, may not be true for different soils. Furthermore, the preconsolidation pressure of lime-treated specimen bears no physical meaning, yet, it could still be considered as a good artificial measure of compressibility.

CONCLUSIONS

The effect of lime treatment on volume change and compressibility of two soils from Irbid City was presented. Lime
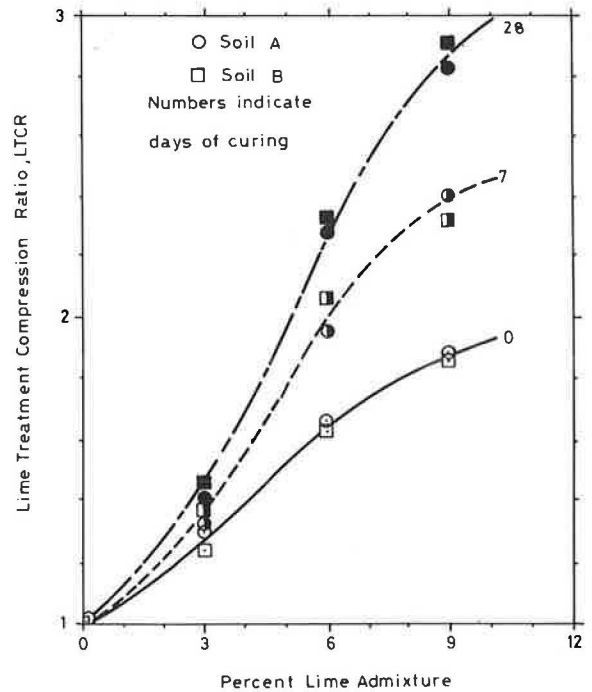

FIGURE 20 Variation of LTCR with lime and curing time.

was introduced as an admixture up to a maximum of 12 percent by dry weight of the soil. From the results obtained and for the percentages of lime used, the following conclusions are warranted:

1. The grain size distributions of the soils tested are greatly altered by the addition of lime. The coarse-grain fractions increased whereas the clay fractions decreased with increasing lime and curing time.

2. Concentrations of calcium and magnesium ions in pore water increased, whereas those of sodium and potassium ions decreased with increasing lime.

3. Liquid limit and plasticity index decreased whereas shrinkage limit increased with percent lime. No significant effect of curing time was observed.

4. Addition of lime changed classification of treated soil from MH–CH for untreated to MH and ML at 3 and 6 percent lime for Soils A and B, respectively (see Figure 1). The classification at 9 percent lime was SM.

5. The changes in the physical properties caused by the addition of lime decreased the potential expansiveness of the soils from very high to low (see Figure 2). This is further reflected both in swell percent and swell pressure measurements, which decreased with increasing percent lime and curing time.

6. A reduction in compression and rebound indices is achieved with increasing percent lime. Curing time had no marked influence.

7. Increasing percent lime and curing time increased immediate settlement and decreased primary consolidation.

8. The rate of swell and consolidation increased with percent time.

9. The concept of LTCR was introduced and LTCR was found to increase both with percent lime and curing period. Higher LTCR signifies lower compressibility.

ACKNOWLEDGMENTS

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