Overconsolidated Behavior of Phosphoric Acid and Lime-Stabilized Kaolin Clay

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Consolidation and shear strength properties of a kaolin clay stabilized with hydrated lime or phosphoric acid were investigated. Consolidation test results indicated that lime or phosphoric acid treatments cause a chemically induced preconsolidation effect of the normally consolidated kaolin clay. The overconsolidation behavior caused by chemical addition is influenced by the type and amount of chemicals and the applied original preconsolidation pressure. Lime or phosphoric acid also decreases the rebound compressibility index (C_r) of kaolin clay. Consolidated, undrained, shear box tests indicate that the addition of lime or phosphoric acid to clay increases its cohesion and its angle of internal friction and that the strength gain of chemically treated clay is improved and accelerated by consolidation with aging. These findings encourage consideration of chemical treatment as a possible alternative for the control of settlements of kaolin clayey soils.

The improvement of cohesive soils by chemical additives has been widely practiced to improve soil properties such as high plasticity, poor workability, high volume change potential, and low shear strength.

Efforts are made to select appropriate chemical stabilizers and to use them in the most efficient manner to improve poor soil conditions. Previous soil stabilization studies, for example, Radnor and McGee (1), Demirel et al. (2), Demirel and Davidson (3), Lyons and McEwan (4), Kelley and Kinter (5), Guinne (6), Thompson (7), Kezdi (8), Ghazali (9), Baghdadi (10), Balasubramaniam and Buensuceso (11), Fossberg (12), and Wissa et al. (13), indicated that hydrated lime and phosphoric acid improve many engineering properties of fine-grained soils, making them potentially competitive with other soil stabilizers, such as asphalt or portland cement. A review of the present state of the art of lime or phosphoric acid stabilization reveals that little work has been done on the consolidation behavior of chemically stabilized clays using lime or phosphoric acid and that there is not much detail on the compressibility behavior of stabilized-aged clay soil mixes.

Thompson (7) investigated plastic soils (with plasticity index values of 8 to 29) stabilized with lime and studied their triaxial shear and unconfined compressive strengths. He concluded that the shear strength of lime-treated soils increased primarily because of a greater increase in cohesion with small increase in the angle of shearing resistance. The shear strength of lime-soil mixtures increased with curing periods.

Fossberg (12) investigated some fundamental engineering properties of a lime-stabilized montmorillonitic clay. He concluded that lime-stabilized clays, in the saturated state, could be analyzed in terms of generally accepted concepts in regard to consolidation characteristics, suction, permeability, and shear strength. He reported that the clay behaved like a preconsolidated material on account of cementation of particles. This effect further increased with higher stabilizer content and curing time.

Wissa et al. (13) studied effective stress strength parameters of saturated soil-cement and soil-lime mixes. The study was conducted on Massachusetts clayey silt and Vicksburg Buckshot clay using consolidated undrained triaxial tests with pore pressure measurements. Mohr effective stress strength envelopes were essentially straight lines with slopes independent of curing time; but the cohesion intercept increased with increase in curing time, and the strength envelopes (both for lime and cement mixtures) were sensitive to the type and amount of stabilizer and type of soil.

Balasubramaniam and Buensuceso (11) investigated the strength and deformation characteristics of lime-treated soft Bangkok clays under undrained and drained triaxial conditions. They found that lime treatment causes a change in the strength and deformation characteristics of the soft clay from normally consolidated clay to that of an overconsolidated clay. They reported that this observation was valid for lime contents varying from 5 to 15 percent, and that the strength of treated clay increased with curing time.

Radnor and McGee (1) studied compressive strength of fine-grained soils stabilized with phosphoric acid. They performed series of unconfined and triaxial compression tests and found that the phosphoric acid caused an increase in the strength and that the strengths were higher for the soils with higher clay content. They also found that the confined strength was greater than the unconfined strength.

Demirel et al. (2) and Demirel and Davidson (3) investigated use of phosphoric acid for stabilizing clay soils and found that the strength and durability characteristics of compacted clays improved by phosphoric acid treatment. The improvement depends on the amount of phosphoric acid used and on the types and amounts of clay minerals in the soil. They concluded that there is an optimum amount of phosphoric acid content to produce the highest soaked and unsoaked unconfined compression strengths of stabilized soils. They also found that there appeared to be a curing time beyond which the soaked strengths do not increase further and this time is dependent on type and amount of clay minerals reacting and the amount of phosphoric acid available for the reactions. They reported that because phosphoric acid is a reactive chemical with the kaolin clay minerals (3), its addition to the fine cohesive soils may produce changes in the surface texture and increase angle of friction. But, with excess of acid, the lubrication of particles will tend to reduce angle of friction.

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Such behavior was reported to be dependent on the dry density and water content of the soils investigated.

Lyons and McEwan (*4*) did considerable experimentation with phosphoric acid and different types of clay soils with plasticity index values ranging between 13 and 44. They studied unconfined compression strength of each soil with different acid content and found that the unconfined compressive strengths of all types of clays used increased with the increasing amount of phosphoric acid.

Kelley and Kinter (*5*) studied the plasticity, moisture-density relations, volume change, and unconfined compressive strength of several fine-grained plastic soils stabilized by phosphoric acid. They concluded that phosphoric acid increased unconfined compressive strengths by various degrees. The addition of phosphoric acid brought the moisture absorption and volume changes to satisfactory levels. The moisture-density relationships changed slightly.

These studies indicate that there is a strong interaction between stabilization and consolidation in relation to strength and deformation characteristics. As compared to lime, the literature on phosphoric acid stabilization contains relatively less information on its compressibility characteristics.

An elaborate experimental investigation was carried out to explore the effects of chemical stabilization on compressibility of a clayey soil by choosing lime and phosphoric acid. Large amounts of data were collected over a 3-year period on the consolidation and shear strength properties of hydrated lime and kaolin clay mixes stabilized by phosphoric acid.

MATERIALS AND TESTING METHODOLOGY

The experimental investigation was carried out on pure kaolin clay. The clay was stabilized by adding varying percentages of lime and phosphoric acid. The properties of the tested materials are presented in Table 1. Mineral identification with

X-ray diffraction methods for the pure kaolin clay is shown in Figure 1. The effect of stabilizers on the pH values of kaolin clay is shown in Figure 2.

Saturated specimens were prepared at the respective liquid limits of treated kaolin depending on the type and amount of added stabilizer. In case of lime-treated samples, dry pulverized kaolin was mixed with powdered lime and mixed thoroughly. To this, the required amount of moisture was added to mold test specimens. In case of phosphoric acid, dry pulverized kaolin and water were mixed together first, and to this mixture the required amount of liquid phosphoric acid was added and mixed. In order to compare the results with the pure kaolin condition, sets of data were obtained by running tests on pure kaolin at corresponding similar moisture contents.

In the various consolidation and shear strength tests, the amounts of hydrated lime or phosphoric acid were arbitrarily chosen to be 4, 8, and 12 percent by weight of dry kaolin.
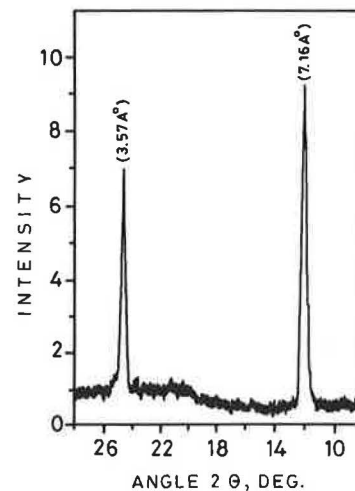
TABLE 1 PROPERTIES OF MATERIALS USED IN TEST SERIES

1.	**Kaolin clay**			
	Source:	Saudi Ceramics Co., Riyadh, Saudi Arabia		
	Mineral:	Kaolin		
	Atterberg limits:	LL	=	56 %
		PL	=	35 %
		SL	=	30 %
2.	**Hydrated Lime**	CaO	=	68.5 % (Powder)
	(Composition)	SiO_2	=	3.0 %
		Al_2O_3	=	1.0 %
		Fe_2O_3	=	0.6 %
		MgO	=	1.0 %
		SO_3	=	0.5 %
		Ignition loss	=	25.4 %
		Total	=	100 %
3.	**Orthophosphoric acid** H_3PO_4 = 98 % (in liquid form)			
	Source : BDH Chemicals Ltd. Poole, England			
	Maximum limits of impurities:			
	Chloride (Cl)	=	0.001 %	
	Nitrate (NO_3)	=	0.002 %	
	Sulphate (SO_4)	=	0.01 %	
	Calcium and Magnesium	=	0.01 %	

FIGURE 1 X-ray diffraction trace of pure kaolin clay.

FIGURE 2 pH of phosphoric acid and lime-stabilized kaolin clay.

The preconsolidation pressures used in the investigation were 61, 122, and 245 kPa in all the test series.

In case of consolidation tests on untreated as well as treated soils, the ASTM D2435 procedure was followed. The specimens were loaded to the desired preconsolidation pressure, and then unloaded, and reloaded to 1 MPa. Taylor's square root fitting method was used to determine the coefficient of consolidation (C_v) values for various loading increments.

In the shear strength test series, the specimens were first preconsolidated to the desired pressure in the odometer rings, from which they were trimmed to give shear box specimens. The applied normal stresses were kept equal to the preconsolidation pressures. The specimens were sheared in undrained condition with a strain rate of 2 percent per minute.

The strength behavior of treated clay specimens with aging was studied under two series over varying periods of time, namely, 0, 7, 14, and 28 days both for lime and phosphoric acid treatments. These tests were carried out for only 8 and 12 percent chemical contents. In the first series (SR I), the unconsolidated, undrained, direct shear tests were conducted on stabilized-cured specimens at various ages. These specimens were molded, wrapped, and cured at room temperature (20°C). In the second test series (SR II), similar specimens were tested in the consolidated undrained conditions.

DISCUSSION OF TEST RESULTS

Atterberg Limits

Atterberg limits decreased because of the addition of phosphoric acid to the kaolin clayey soil. The decreases in plastic limit and shrinkage limit were slight and were more pronounced in the case of the liquid limit (Figure 3).

In case of lime treatment, the liquid limit decreased slightly, whereas the plastic limit increased and the shrinkage limit was almost the same as the value for untreated soil. The plasticity index values in both lime and phosphoric acid treatments decreased by the chemical addition, as shown in Figure 3.
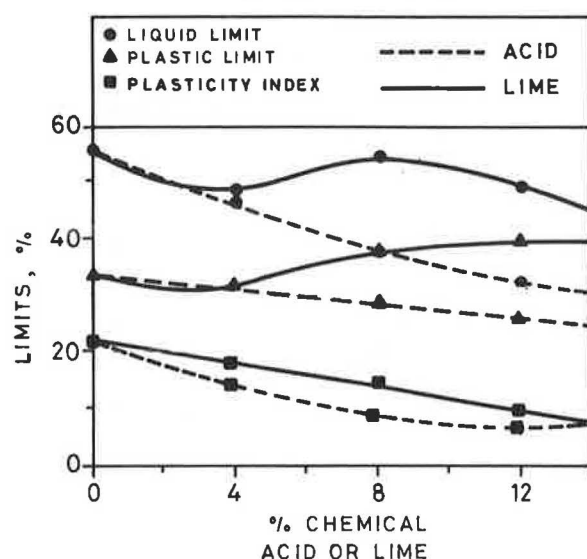
Consolidation Parameters

From 40 consolidation tests, typical plots of settlement versus square root of time, and log P versus void ratio are shown in Figures 4 and 5, respectively, for pure kaolin, acid-treated, and lime-treated soils.

Chemical Preconsolidation Ratio Versus Percent Stabilizer

Figure 6 was obtained from the data presented in Figure 5, both for acid and lime treatments. Both acid and lime impart preconsolidation behavior on the soil. The term chemical preconsolidation ratio (CPR) has been used as a measure of the preconsolidation effects. CPR is defined as the ratio

$$\text{CPR} = \bar{p}_{cn}/\bar{p}_{co} \tag{1}$$

where $\bar{p}_{cn}$ is the new preconsolidation pressure from e-log curve and $\bar{p}_{co}$ is the original applied preconsolidation pressure.

Phosphoric Acid Stabilization The effect of the phosphoric acid stabilizer at different levels of p_{co} is indicated in Figure 6. At low p_{co} (61 kPa), the addition of phosphoric acid increases the CPR for all amounts of acid. At high values of p_{co} (122 and 245 kPa), the addition of phosphoric acid increased the CPR of the 4 percent phosphoric acid. This increase was higher than at low p_{co} (61 kPa), but for 8 and 12 percent phosphoric acid there are decreases in the values of the CPR. This result indicates that the addition of high percentages of phosphoric acid combined with high values of p_{co} will not improve the CPR values.

At a low percentage of stabilizer, the higher the preconsolidation pressure, the higher the CPR. However, at higher percentages of stabilizer, the low preconsolidation pressure caused higher CPR. Thus, a low percentage of stabilizer and
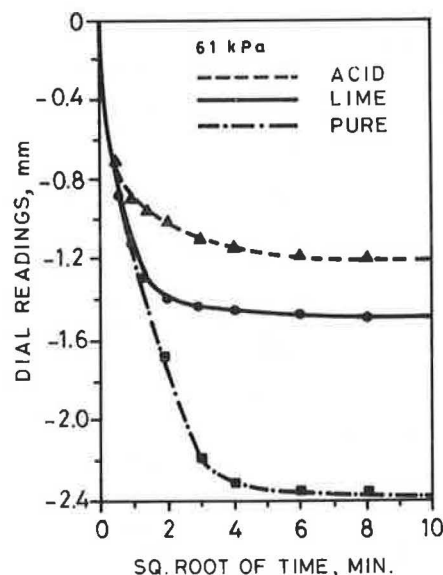
FIGURE 3 Atterberg limits of phosphoric acid and lime-stabilized kaolin clay.

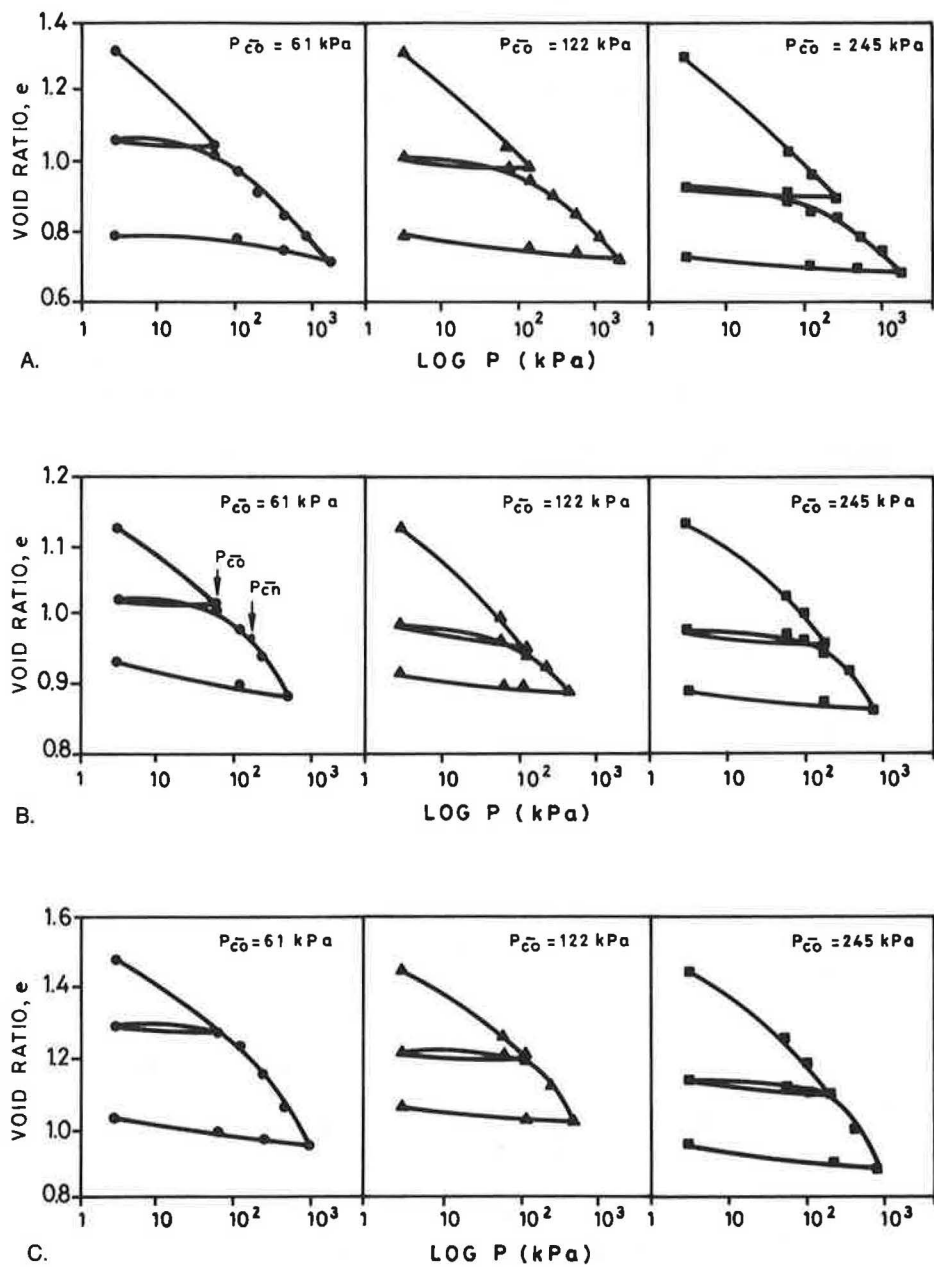FIGURE 4 Typical square root of time versus settlement curves.

FIGURE 5 Typical void ratio versus log pressure curves: *a*, pure kaolin; *b*, acid-stabilized; and *c*, lime-stabilized.
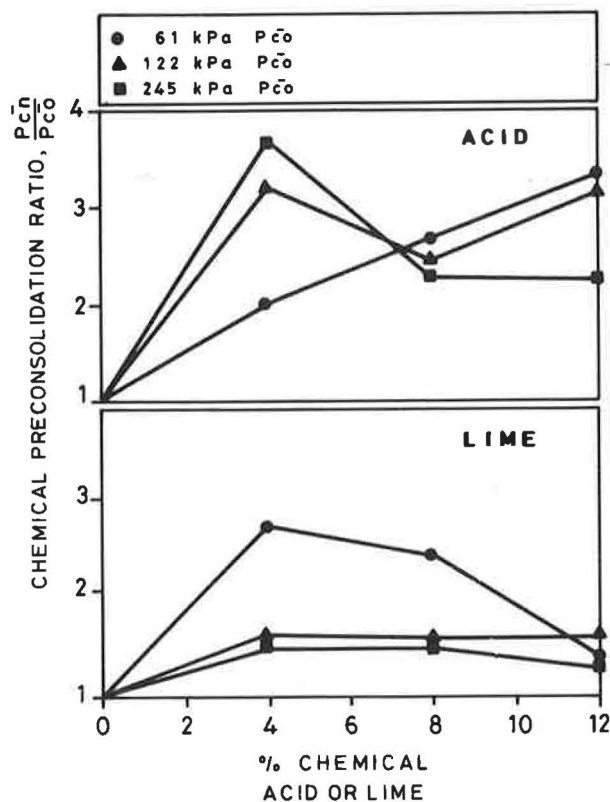
FIGURE 6 Chemical preconsolidation ratios of phosphoric acid and lime-stabilized kaolin clay.

a high preconsolidation pressure are more efficient in producing preconsolidation effects of kaolin clayey soil.

Lime Stabilization As indicated by Figure 6, at low to moderate percentages of lime, the lower the preconsolidation pressure, the higher the CPR value. Thus, a condition of low percentage of lime stabilizer and low preconsolidation pressure is more efficient in producing preconsolidation effects of kaolin clayey soil.

Rebound Compressibility Index (C_r)

The values of C_r were calculated from the consolidation data. The values of C_r (Figure 7) were chosen because of the overconsolidation effects produced as a result of the chemical treatment, and from a practical point of view, it is assumed that the loading will be within the overconsolidation range.

The C_r values were found to be higher in case of untreated soils at different levels of original preconsolidation pressure (p_{co}) for all molding water contents, (corresponding to liquid limits of treated soils), and various percentages of stabilizer. The values of C_r decreased by treating the soil either with phosphoric acid or lime.

The decrease in C_r was most often observed at moderate p_{co} values (122 kPa); at the higher and lower p_{co} values (245 kPa and 61 kPa), the change in C_r was slight. Furthermore, C_r values were generally higher for higher water contents, which indicates more compressibility.
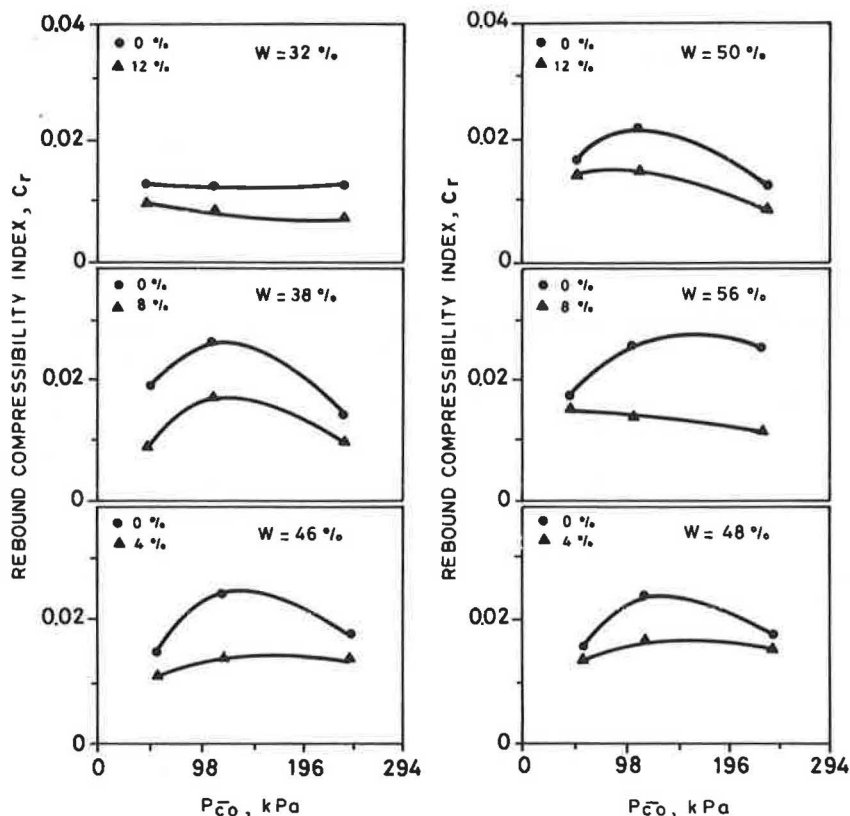

FIGURE 7 Rebound compressibility indices of (*left*) phosphoric acid and (*right*) lime-stabilized kaolin clay.

Coefficient of Consolidation (C_v)

Table 2 presents C_v values for pure and treated kaolin clay, as calculated from data shown typically in Figure 4. Each C_v value is the average of three values of the overconsolidated portion of the $e-\log p$ curve. The overconsolidated C_v values were chosen because of the practical application. Table 2 indicates that for all kaolin clay treated with phosphoric acid and lime, the C_v values are generally equal or less than the C_v values of the untreated clay at equal water contents. This result may be caused by cementation effects and lower permeability (*12*).

Shear Strength

Figure 8 shows that the addition of chemicals to kaolin clay increased the shear strength both for phosphoric acid and lime treatments at different levels of preconsolidation pressures. The increase in shear strength was higher in case of lime than for phosphoric acid. Also, both for cases of lime and phosphoric acid, the shear strength increased with increasing percentages of the chemicals and the applied preconsolidation pressures.

Values of the cohesion c and the angle of internal friction ϕ were obtained from the total failure envelopes of pure and stabilized kaolin clay by different percentages of phosphoric acid or lime (Figure 9). The plots of the untreated soil were at the same water contents as that of the treated soils, corresponding to saturated conditions of all samples. From the data for c and ϕ in Figure 9, lime treatment may be more effective than acid treatment in producing higher shear strength, characterized both by cohesion and angle of internal friction values. The figures also show that increase in shear strength is mainly caused by increase in cohesion, which is probably caused by the developed cementation.

Effect of Aging and Consolidation on Shear Strength

In order to study the effect of aging, the undrained shear strength (S_u) was obtained for a typical normal stress of 122
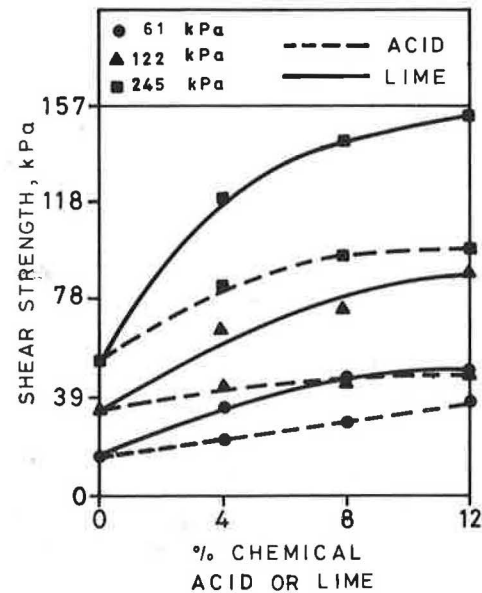

FIGURE 8 Shear strength of phosphoric acid and lime-stabilized kaolin clay.
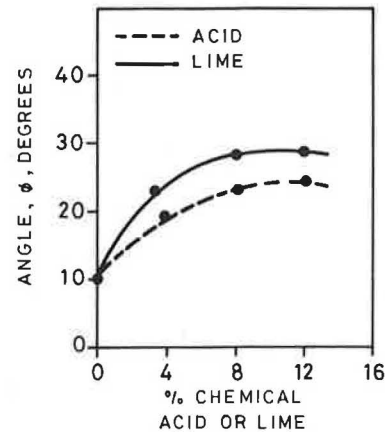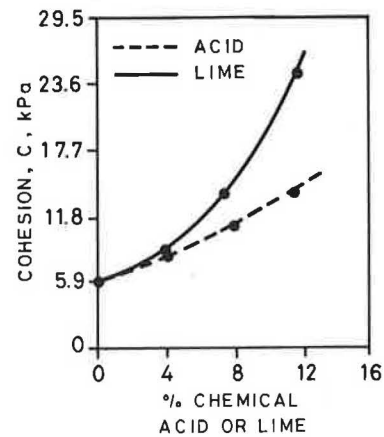

FIGURE 9 Shear strength parameters of acid and lime-stabilized kaolin clay: *top*, cohesion (*c*); *bottom*, angle (ϕ).

TABLE 2 COEFFICIENTS OF CONSOLIDATION (C_v) OF PURE AND TREATED KAOLIN CLAY AT EQUAL WATER CONTENTS

% Chemical	L.L.		Preconsolidation Pressures ($\bar{p}_{co}$) (kPa)					
			61		122		245	
	Acid	Lime	Acid	Lime	Acid	Lime	Acid	Lime
			Coefficient of consolidation (C_v) cm²/min					
0	46	48	0.30	0.30	0.31	0.28	0.33	0.29
4	46	48	0.16	0.30	0.30	0.31	0.18	0.33
0	38	56	0.25	0.33	0.34	0.35	0.42	0.40
8	38	56	0.25	0.32	0.24	0.32	0.35	0.32
0	32	50	0.23	0.36	0.45	0.47	0.41	0.47
12	32	50	0.20	0.36	0.26	0.35	0.15	0.30

kPa of each series (SR I and SR II). Two values, 8 and 12 percent, of both stabilizers were used.

The data shown in Figure 10 indicate increase in S_u with increase in curing period and amount of stabilizer. However, the values of S_u were higher for the consolidated chemically treated clays (SR II) than for the unconsolidated chemically treated clays (SR I). The effect of consolidation is indicated by the hatched areas in Figure 10.

Another way of studying the data is shown in Figure 11, where the ratio of undrained shear strengths $S_u II/S_u I$ are plotted against aging days. Figure 11 indicates that the ratio is high for aging periods up to 14 days, and it is higher for the 12 percent than for the 8 percent samples; after that, the ratio decreases, though still greater than 1; it becomes almost equal to 1 for 12 and 8 percent samples, for aging beyond 14 days. This result may lead to the recommendation of starting consolidation of chemically treated soils soon after placement or addition of chemicals. The results shown in Figures 10 and 11 indicate that consolidation improves and accelerates the strength gain of chemically treated kaolin clayey soils.
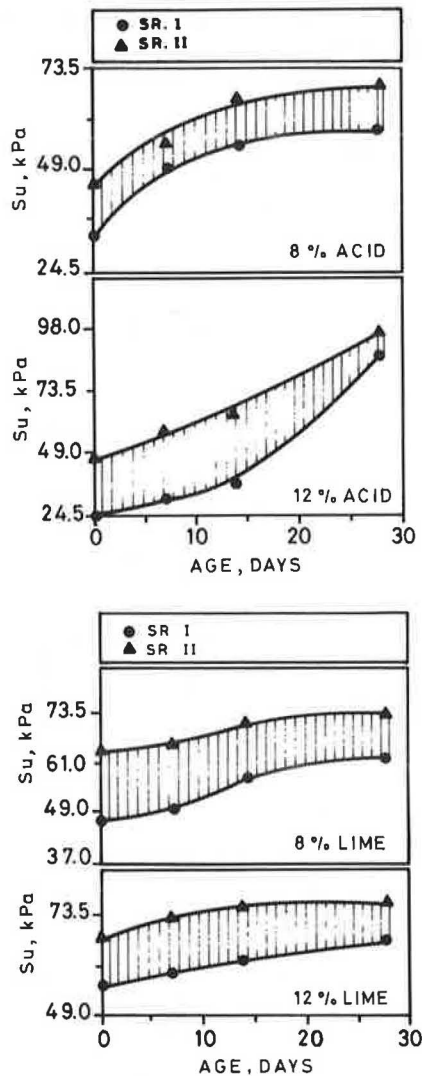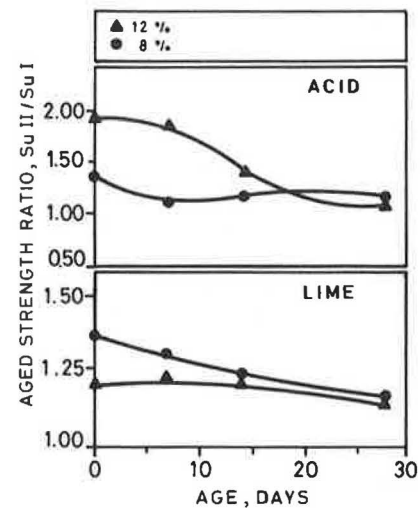

FIGURE 11 Aged strength ratios of phosphoric acid and lime-stabilized kaolin clay.

Hypothetical Example for Settlement Calculations

Problem

It is proposed to construct a 5.0-m-high embankment on top of a 2.0-m-thick pure kaolin clay layer underlain by dense sand. The properties of the pure kaolin and embankment material are shown in Figure 12.

Solutions

An analysis of the settlements of the kaolin clay both in treated (with 8 percent lime or phosphoric acid) and untreated conditions has been carried out using the following formulas (14,15):

$$\Delta H = [H_0/(1 + e_0)]C_r \log (P_0 + \Delta P/P_0) \qquad (2)$$

where

ΔH = settlement,
H_0 = layer thickness,
e_0 = initial voids ratio,
P_0 = original pressure, and
ΔP = incremental pressure.

FIGURE 10 Effect of (*top*) phosphoric acid and (*bottom*) lime treatments on shear strength with aging of kaolin clay.
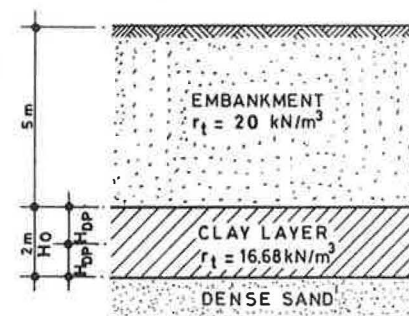

FIGURE 12 Example soil profile showing treated clay layer and embankment fill.

TABLE 3 SUMMARY OF EXAMPLE TEST DATA AND COMPUTED RESULTS

Material	Water content %	γ_t kN/m³	e_0	C_r	C_v cm²/min	ΔH cm	t_{90} min
Pure kaolin clay	38	16.68	1.1539	0.0264	0.34	2.015	24942
Pure kaolin clay	56	16.68	1.4670	0.0254	0.35	1.690	24229
Kaolin clay + 8% phosph. acid	38	16.68	1.1278	0.0178	0.24	1.375	35333
Kaolin clay + 8% lime	56	16.68	1.4640	0.0143	0.32	0.950	26500

$$C_v = T(H_{DP})^2/t \tag{3}$$

where

T = time factor,
H_{DP} = length of drainage path, and
t = time.

The data and calculated results are presented in Table 3.

The settlements (ΔH) of lime- and phosphoric acid-treated soils have been reduced by 44 and 32 percent of the untreated kaolin, respectively. This result means that there are considerable improvements in the settlement behavior of chemically treated kaolin clay, in addition to the improvements of shear strength. However, the settlements in case of treated clay take longer periods of time to achieve 90 percent consolidation, mainly because of reduced permeability.

On the basis of these results, chemical treatment is recommended as a possible alternative to reduce settlement, because of the chemically induced preconsolidation effects.

CONCLUSIONS

The study results warrant the following conclusions:

1. The addition of lime or phosphoric acid to pure kaolin clay decreases the Atterberg limits.
2. Low percentage of phosphoric acid stabilizer and high preconsolidation pressure are more efficient in producing preconsolidation effects of kaolin clay.
3. Low percentages of lime stabilizer and low preconsolidation pressure are more efficient in producing preconsolidation effects of kaolin clay.
4. C_r values decrease when treating the kaolin clay either with phosphoric acid or lime. The decreases in C_r values occur most often at moderate preconsolidation pressure.
5. At equal water contents, values for C_v of stabilized kaolin clay, when treated either with lime or phosphoric acid, are less than the C_v values of pure kaolin.
6. The addition of phosphoric acid or lime to pure kaolin clay increases its c and ϕ values at saturated conditions and equal water contents. These increases are greater for lime treatment than for phosphoric acid treatment.
7. The shear strength increases with the application of preconsolidation pressure both for lime- and phosphoric acid-stabilized kaolin clay mixes.

8. Consolidation with aging up to 14 days improves and accelerates the strength gain of chemically treated kaolin clay for either lime or phosphoric acid.

9. Consolidation of chemically treated kaolin clay is recommended to start soon after the addition of chemicals.

10. For the control of settlements of kaolin clayey soils, chemical treatment is recommended as a possible alternative.

ACKNOWLEDGMENT

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