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ENGINEERING PROPERTIES OF AND A CONCEPTUAL MODEL FOR LIME TREATED CLAY

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ABSTRACT : In order to study stress-strain-strength and yielding characteristics of lime treated clay, an extensive testing program was conducted on lime treated clay. It was found that the main effect of lime treatment was to change the soft clay from normally consolidated to overconsolidated behaviour. Heavily overconsolidated characteristics were observed for stress states inside the volumetric yield locus obtained from anisotropic consolidation tests. The volumetric yield loci of lime treated clays were found to be more pronounced than distortional or strain path yield locus. Outside the volumetric yield locus, the behaviour was found to consists of an inital pseudo-elastic phase followed by a stage where the behaviour appears to be similar to that of a work-hardening plastic material as the stress path proceeds towards the curved failure envelopes. The treated clays strain-softend after failure with the residual stress states lying close to the critical state line of the untreated clay. A conceptual model to describe the behaviour of lime treated clay was introduced, in which the presence of distortional yield locus shifts with lime content and curing time.

KEYWORDS :Pozzolanic cementation, volumetric yield locus, distortional yield locus, strain path, pseudo-elastic phase, strain softening, residual stress states, constant-p stress path.

INTRODUCTION

Lime treatment is an emerging advanced ground improvement technique which leads to beneficial effects on the strength, compressibility, plasticity, permeability, workability and compactibility of problematic soft clays. This paper is a part of a comprehensive program conducted at the Asian Institute of Technology (AIT), Bangkok, on lime stabilization wherein attention is focused on the strength, deformation and yielding characteristics of lime treated clay under different tests

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conditions. The study addresses the effect of variability of characteristics with regard to the quantity of hardening agent (lime), the pre-shear consolidation pressure ($\bar{p}_o$), the stress conditions imposed during testing and time dimension. All analyses were done using critical state concepts. The present practice of designing lime stabilized treated ground is still based on the results of unconfined compression tests. The need to describe the mechanical behaviour of lime-treated clay has become of importance. A composite conceptual model to describe the stress-strain-strength and work-hardening behaviour of the treated clay is proposed in the paper. The model conception is illustrative and can be used in practice for design purpose.

SAMPLE PREPARATION AND EXPERIMENTAL PROGRAM

The base clay used in this study was soft Bangkok clay (having organic content of 4.3%) taken from a site within the AIT campus from depths of 4 to 4.5 meters.The properties of the base clay are shown in Table 1. Quicklime or calcium oxide (CaO) powder, commercially produced by May & Baker Ltd, Dagenham, Enland,consisting of not less than 95 percent CaO was used. The sampling was carried out using rotary auger and wash boring techniques.The soft clay in the 250 mm diameter tubes was extruded, then carefully waxed, and were kept in a humid room under constant temperature(25oC) and humidity (97%) until the specified time for the preparation of lime treated samples. Lime column specimen was prepared for every "cake "of soft clay that obtained from the tube samples. The calculated amount of lime was mixed thoroughly with the clay (lime content is the ratio of the weight of lime to the dry weight of the base clay). Mixing was done very carefully with a handy mechanical mixer until the mix was unifrom. The lime-clay mix was then placed into the pre-drilled hole in approximately five equal layers. Each layer was compacted using a 25.4 mm diameter steel rod, applying 30 blows per layer. After the 'mini lime column,' was completed, the mould was removed, and the cake was waxed again and cured for the required curing period inside the humid room until the time of testing. From the waxed soil cakes, the lime treated meterial was cut using cutting wires and further trimmed to the required nominal dimensions of 35.5 mm diameter and 71 mm height (for triaxial and anisotropic consolidation tests). The properties of the treated samples after curing are appended in Table 2.

Table 1. Characteristics Values of the Initial Properties of the Base Clay.

Properties	Values	Proerties	Values
Physical Properties :		**Chemical Properties :**	
Water Content (%)	76-90	Soil pH (1:1, Soil: Water Ratio)	5.8
Liquid Limit (%)	104	Cation Exchange: Capacity (meq/100 g	26.8
Plastic Limit (%)	41	over dry soil	
Plasticity Index (%)	63	Exchange Cations ;	
Liquidity Index	0.62	Na (meg/100 g0	63
Grain Size Distribution		k, (meg/100 g)	3.15
Clay (%)	70	Ca. (meq/100 g)	2.04
Silt (%)	27	Mg. (meq/100 g)	6.60
Sand	3	Total Soluble Salt Content (meq/1)	6.10
Total Unit Weight (kN/m^2)	14.8-15.3	Organic Carbon (%)	8.1
Dry Unit Weight (kN/m^2)	8.1-8.3	Organic Matter (%)	2.47
Activity	0.90	Cation in Porewater	4.26
Special Gravity	2.67-2.68	Na, (meq/1)	0.43
Initial Void Ratio	2.2-2.3	K, (meq/1)	7.44
Sensitivity	7.3	Ca, (meq/1)	9.90
Color	Dark Gray	Mg, (meq/1)	2.10
Mineralogical Composition :		Electrical Conductivity (mmho/cm)	
Clay Fraction :	38		
Montmorillonite (%)	41		
Kaolinite (%)	15		
Illite (%)	6		
Quartz (%)	Mainly		
Silt Fraction	Quartz		

Table 2. Some Properties of Lime Treated Clay

Lime Content (%)	Curing Time (Months)	Total Unit Weight (kN/m^3)	Dry Unit Weight (kN/m^3)	Void Ratio	Water Content (%)	Degree of Saturation (%)
2.5	1	14.61-14.71	8.24-8.33	2.13-2.21	75.62-69.67	94.98-96.32
5	1	14.62-15.0	8.24-8.63	2.02-2.15	74.47-77.49	94.02-97.85
7.5	1	14.71-15.0	8.33-8.73	1.97-2.11	70.99-77.13	93.18-99.04
10	1	14.81-15.42	8.14-8.83	1.92-2.10	72.03-77.55	92.92-97.88
12.5	1	14.81-15.11	8.44-8.83	1.91-2.05	71.13-77.01	96.15-98.0
15	1	14.91-15.11	8.75-8.93	1.85-1.91	68.02-70.75	94.0-96.46
5	2	14.81-15.21	7.95-9.03	1.85-1.19	70.99-77.02	93.8-98.42
7.5	2	14.72-15.49	8.04-9.03	1.85-2.18	70.72-79.34	95.34-100.0
10	2	1.53-15.69	8.63-9.02	1.86-1.99	71.23-75.76	97.98-100.0
Untreated Clay	(-)	14.52-15.00	7.95-8.14	2.20-2.30	76.0-90.0	97.8-99.4
Average for 5 to 10% only	1	14.62-15.40	8.14-8.83	1.29-2.15	70.99-77.55	92.92-99.04
Average for 5 to 10% only	2	14.72-15.70	0.83-0.90	1.85-2.19	70.72-79.34	93.8-100.0

The testing program included a comprehensive series of unconfined compression, oedometer, triaxial undrained & drained tests and anisotripic consolidation tests with several test variables such as lime content, curing time, confining pressure, stress conditions and drainage conditions. For the test for basic engineering properties, chmical analysis and mineral content, the percentage of lime contents used in the study were 2.5, 5, 7.5. 10, 12.5, and 15 percent with curing times up to six months. While for CIU triaxial test, one and two months curing times were used with lime contents of 2.5, 5, 7.5, 10, 12.5 and 15 percent. For CID triaxial test and anisotropic consolidation tests, curing times were one and two months, and lime content used were 5, 7.5 and 10 percent. In the triaxial test, pre-shear consolidation pressures of 50, 100, 150, 200, 400 and 600 kPa were used. In anisotropic consolidation test, the sample was then taken along a conventional drained path with constant cell pressure to the required stress ratios. This step was carried out in 2 increments, with each increment load was maintained for at least 18 hours. Anisotropic consolidation was performed by increasing both cell pressure and hanger loads simultaneously so that the required stress ratio was maintained constant. The consolidation path was divided into increments such that the total increase in cell pressure was 50 kPa in one day. Furthermore, the increase in cell pressure was applied in increaments of 10 kPa. After the cell pressure had been increased by a total of 50 kPa, The load was maintained overnight (at least 8 hours). This scheme of incremental loading was followed until the cell pressure was 800 kPa, after which unloading was performed in small decrement. The anisotropic consolidation tests were carried out at constant stress ratios of 0.0, 0.25, 0.5, 0.75 1.0 and 1.25. For a stress ratio (η), the ratio of the effective principal stresses was calculated as

$$\frac{\sigma_1}{\sigma_3}=\frac{2\eta+3}{3-\eta}$$

PHYSICO-CHEMICAL PROCESS INCURRED DUE TO LIME TREATMENT

The interactions of lime and clay minerals are responsible for its drastic parametric alteration. A series of laboratory tests on basic physical, chemical and mineralogical properties were conducted on treated and untreated clay. From the investigation, it is envisaged that the physicochemical processes that take place upon mixing lime occur due to following reasons:

Reduction in water content: An immediate reduction of the natural water content occurs when quicklime is mixed with a cohesive soil, as water is consumed in the hydration process. To make the ion exchange possible between calcium ions of hydrated lime and the alkali ions of the clay minerals, there must be enough water at the slakening of the quicklime.

Ion Exchange and Flocculation : After mixing, the calcium hydroxide is transformed due to the presence of carbonic acid (H_2CO_3) in the soil. This reaction results in the dissociation of the lime into Ca^{++} (or Mg^{++}) and $(OH)^-$ which modifies the electrical surface forces of the clay mineral. A transformation in the soil structure begins, i.e., flocculation and coagulation of soil particles into larger-sized aggregates or grains and an associated increase in the plastic limt. The change in the soil structure is the consequence of a cation exchange caused by dissociated bivalent calcium ions in the pore water replacing such univalent alkali ions that normally are attracted to the negatively charged clay particles.

Pozzolanic Reaction: Calcium hydroxide in the soil water reacts with the silicates and aluminates (pozzolans) in the clay to form cementing materials or binders, consisting of calcium silicates and/or aluminate hydrates (principally dihydrates). The gel of calcium silicates (and/ or aluminium hydrates) cements the soil particles in a manner similar to the effect produced by the hydration of Portland cement. The shear strength of the stabilized soil gradually increases with time, mainly due to the pozzolanic reactions.

CIU TRIAXIAL COMPRESSION TESTS

Deviator stress strain relationships

The overconsolidated behaviour of treated clays can be seen from the characteristics of the stress-strain plots shown in Figure. 1, the shapes of the curves are typical of overconsolidated behaviour. At $\bar{p}_o$ 50 kPa, the higher the lime content, the larger is the amount of strain softening. The stress-strain curves also indicate that the modulus of the soil is increased by the lime treatment.

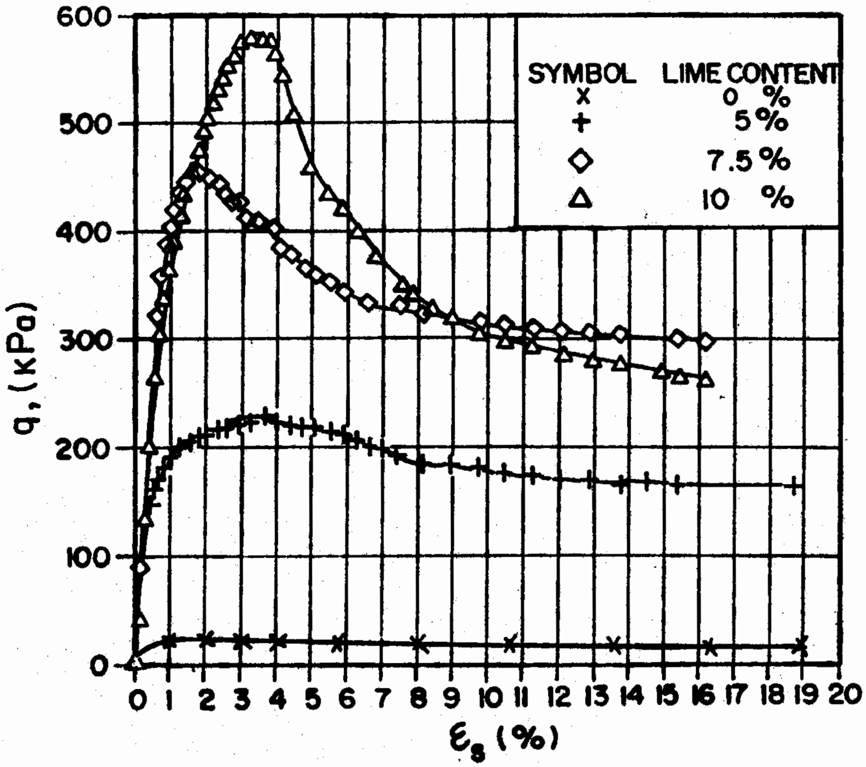

Fig 1. (q-ε_S) Plot with Various Lime Contents from CIU Tests ($\bar{p}_o$ = 50 kPa; 2 Months Curing Time)

Effective Stress Paths

Typical undrained stress paths are shown in Figures 2 to 5. For untreated soft clay, all stress paths are very similar to normally consolidated calys which those for treated clays are similar to overconsolidated clays where less pore pressure developed, which resulted in less rounded stress paths. For example, the stress paths for $\bar{p}_o$= 50 kPa (Fig. 2) resemble to those of lightly overconsolidated samples in which the stress paths rise almost vertically and approximately parallel to the q-axis, In this figure, the stress path for the untreated clay is also shown (curve A), and it can be readily seen that lime treatment has altered the characteristics of the clay significantly. The stress path corresponding to a lime content of 2.5% (curve B) is different from that of the untreated clay. For the samples sheared from $\bar{p}_o$ = 400 kPa (Fig. 3) the stress paths up to the peak deviator stress are similar to normally consolidated samples and approximately rounded. Comparing the stress paths corresponding to $\bar{p}_o$ = 50 kPa and $\bar{p}_o$ = 600 kPa (Fig. 4 and 5), it is remarkable that the degree of overconsolidation brought about by lime stabilization is somewhat erased by the increase in the preconsolidation pressure (consolidation fractures cement bonds transforming the behaviour as normally consolidated). Here $\bar{p}_o$

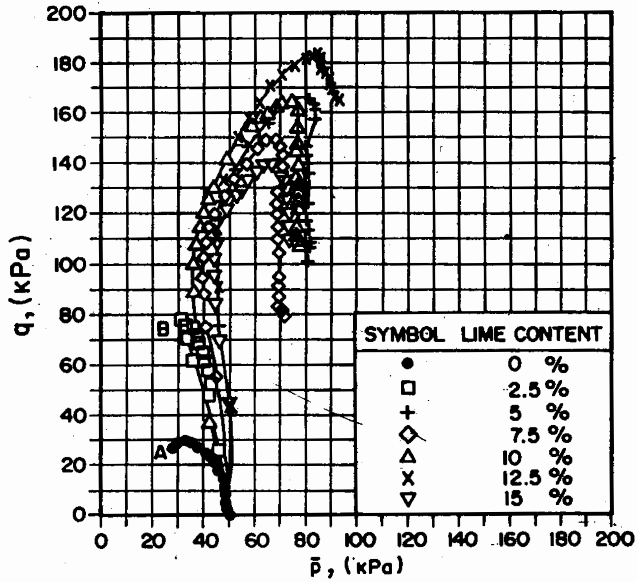

Fig 2. Undrained Stress Paths ($\bar{p}_o$ = 50 kPa; 1 Month Curing Time)

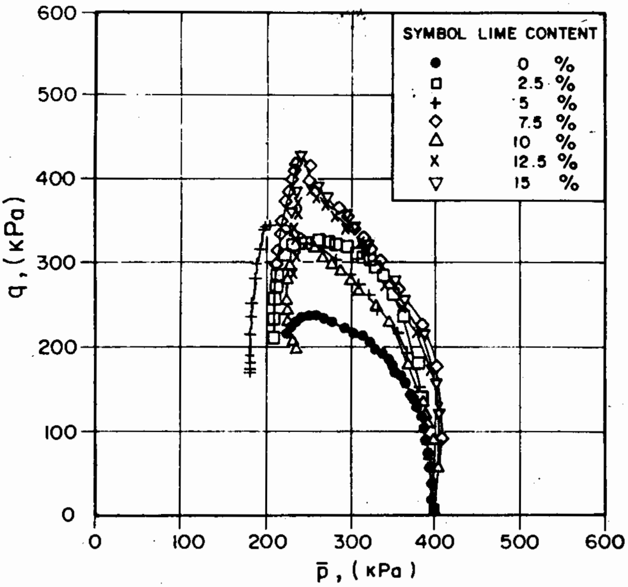

Fig 3. Undrained Stress Paths ($\bar{p}_o$ = 400 kPa; 1 Month Curing Time)

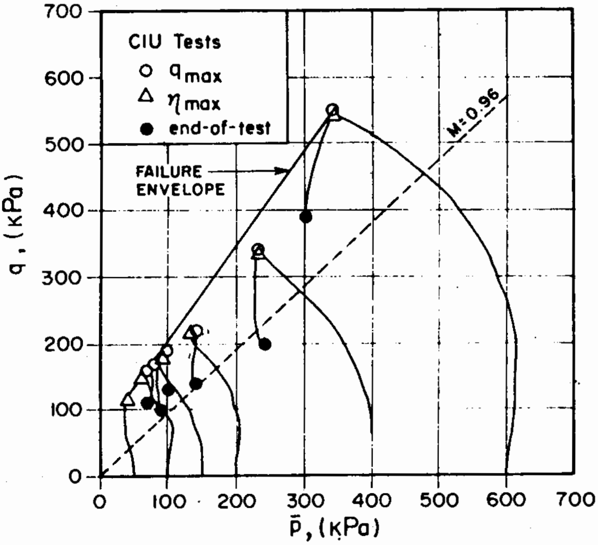

Fig 4. Effective Stress Paths for Lime Treated Clay (10% Lime Content; 1 Month Curing Time)

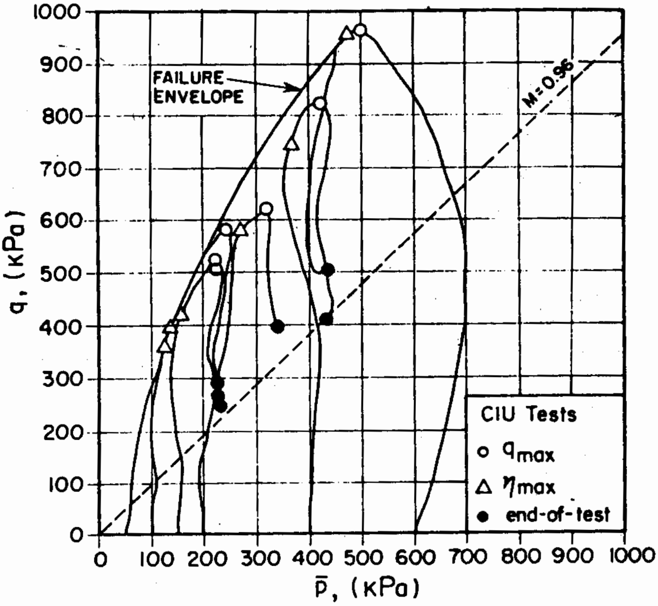

Fig 5. Effective Stress Paths for Lime Treated Clay (10% Lime Content; 2 Months Curing Time)

breakdown pozzolanic bonding. Thus the effect of increasing $\bar{p}_o$, can be noticed in Figures 2 to 5; The stress paths of the samples sheared from $\bar{p}_o$ = 600 kPa, have become similar to normally consolidated samples. Other tests with low $\bar{p}_o$ (Figs, 2, 4& 5) are found to behave like heavily overconsolidated clays; very small pore pressure is developed and in general, the stress paths proceed along path of increasing $\bar{p}_o$at constant q. A comparison os stress paths for 1 and 2 months curing period (Figs. 4 & 5) showed that the shpes of the stress paths change with curing time. For the higher lime contents such as 10%, an increase in curing time produced an effect that caused transformation into a behaviour of higher overconsolidation ratio. The stress paths of 2 months curing period (Fig. 5) seem to correspond to the bahavior of heavily overconsolidated clays (especially at low stresses), whille those for 1 month curing period (Fig. 4) exhibit a behavior similar to theat of lightly overconsolidated clays. Thus it is evident that the pozzolanic reaction continues with curing time, So the shear strength of lime treated clay is enhanced with time.

The above phenomena bring out several interesting aspects on the undrained behavior of lime treated clays. Firstly, lime treatment has changed the intitial normally consolidated characteristics of the clay to that of overconsolidated and a more stiff clay. Moreover, the effects of pozzlanic cementation of lime treatment are affected by the lime content, the curing time and the pre-shear consolidation pressure ($\bar{p}_o$). The curing time has an important role in increasing the overconsolidation, strength and rigidity of the treated smaples since pozzolanic reaction continues with time. The third variable $\bar{p}_o$, was also found to inflence the behavior of the treated clays. It was seen that the $\bar{p}_o$ tends to reduce the positive effect of lime treatment as the values of $\bar{p}_o$ are increased. Thus with higher $\bar{p}_o$ pozzolanic bonding breakdown. It was observed that at low levels of $\bar{p}_o$, lime treatment has resulted in the samples having stress paths which rise parallel to q-axis, indicating that the mean normal stress $\bar{p}_o$, does not vary much during shear. The stress path of the treated sample follows a path which rise to maximum value of deviator stress, and then strain-softens to a lower value of q at the end of the tests.

CID TRIAXIAL COMPRESSION TESTS

Deviator Stress- Volumetric Strain Relationships

The (q. $^{\varepsilon}$v) relationships (Fig. 6) illustrates the existence of an initial phase in which the volumetric strains remain considerably small (with the increase of deviator stress) is clearly seen. The critical stress states corresponding to the transition points from the pseudo-elastic to inelastic states occur at strain of about 0.25%. With higher $\bar{p}_o$, the (q$^{\varepsilon}$v), relationships for the different lime contents of 5% to 10% became closer, especially for the samples with 7.5% and 10% lime contents (Fig. 6). The effect of increasing the $\bar{p}_o$, which is to erase the beneficial effects of lime treatment occurred as a result of breakdown of pozzolanic cementation, is therefore confirmed by CID tests.

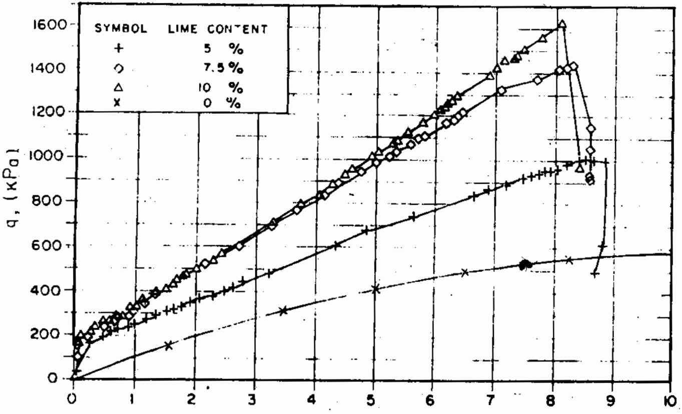

Fig 6. Fig 1, (q-ε_v) Relationships with Various Lime Contents from CID Tests ($\bar{p}_o$ = 600 kPa; 1 Month Curing Time)

ANISOTROPIC CONSOLIDATION TESTS

Volumetric Yield loci and Distortional Yield Loci

The $(^{\varepsilon}v$ log $\bar{p}$ relationships (Fig. 7) shows that the samples with the higher lime content exhibit lower compressibility and overconsolidated behaviour, Moreover, it shows that the increase of curing time reduces compressibility of the treated clay significantly. From each ($^{\varepsilon}v$, log $\bar{p}$) curve, it is possible to obtain volumetric yield points, or the stress states that separate the stress regions for which the volumetric deformations are small from those where the volumetric deformation is large. These volumetric yield points were estimated in a manner similar to the Casagrade method commonly used for the estimation of the maximum past pressure when analyzing the results of the one-dimensional consolidation tests. Similarly, it is possible to define a distortional yield locus for lime treated clays from the relationships of the $(^{\varepsilon}v$, log $\bar{p}$). The procedure used in determining the distoritional yield points was similar to the method used in estimating the volumetric yield points.

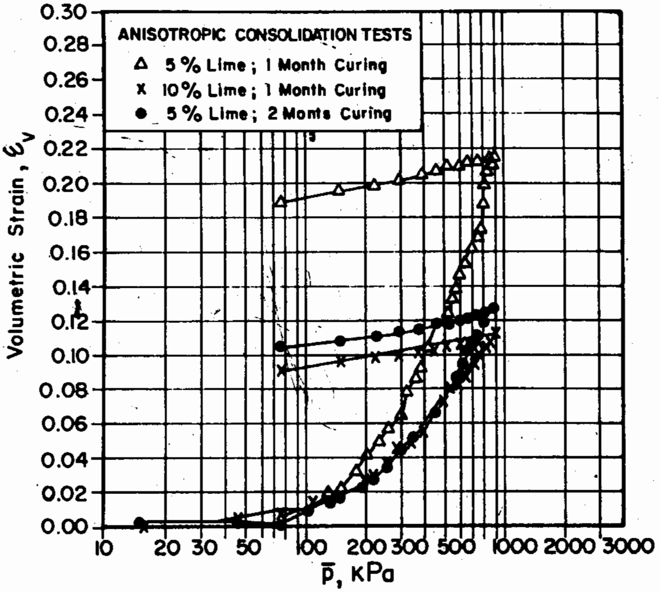

Fig 7. Effect of Lime Content and Curing time on (ε_v-log $\bar{p}$), Relationships (η= 1.0)

Strain Path during Anisotropic Consolidation

From the strain path followed during anisotropic conslidation, it appears that for any particular stress ratio, the strain path consists of nearly two straight linear portions (Fig. 8). Considering the bilinear characteristics of the strain paths, the strain increment ratio $(d^{\varepsilon}v/d\varepsilon_s)$ η during anisotropic consolidation has to be considered in two parts. One part corresponds to the states prior to the transition points in the strain paths, the other to the states outside the state boundary. In Fig. 9, $(d\varepsilon_v/d\varepsilon_s)$ η was plotted with respect to η, Such strain increment ratio-stress ratio relationships are useful for prediciting of strins during drained loading (Roscoe & Poorooshasb, 1993).

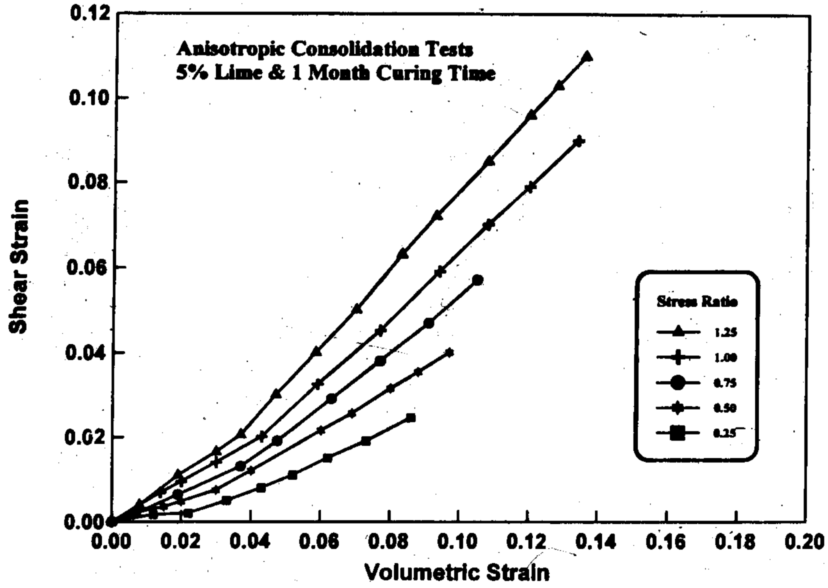

Fig 8. Bilinear Strain Paths during Anisotropic Consolidation (5% Lime Content; 1 month Curing Time)

The point of intersection of the two straight lines (strain path) can be taken to represent a bounday that separates states of large shear strain (after transition) from those with small shear strains (Fig. 8). The stresses corresponding to these transition points were determined, and are plotted in Figure10 to define yield locus based on the characteristics of the strain paths. Volumetric yield locus from ($^{\varepsilon}v$, log $\bar{p}$) and distortional yield locus from ($^{\varepsilon}s$,log$\bar{p}$) have been plotted in this figure as well. The figure shows that the treated soils are capable of undergoing distortional yielding at a lower stress bounday that the stress bounday required for volumetric yielding.

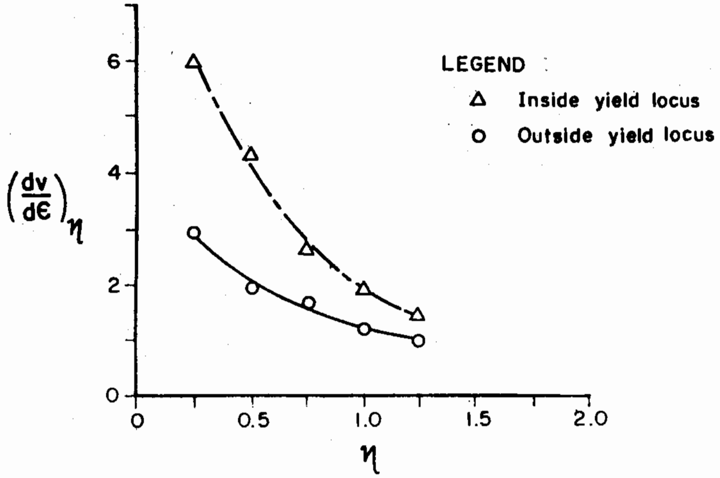

Fig 9. Variation of Strain Increment Ratio with Stress Ratio (5% LIme Content; 2 Months Curing)

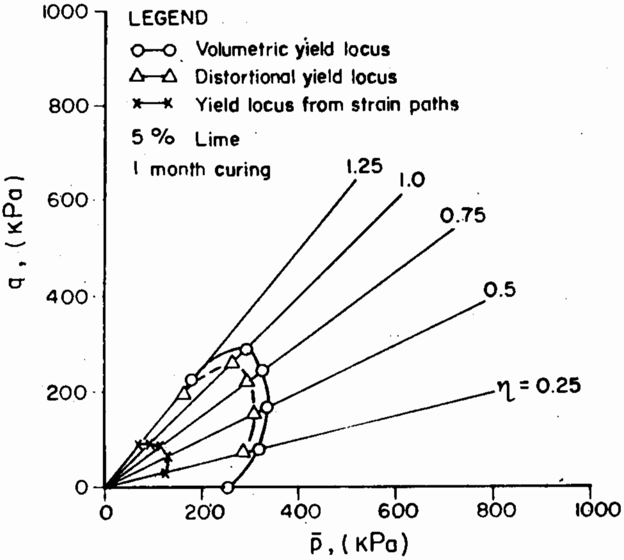

Fig 10. Volumetric and Dististortional Yield Loci from Anisotropic Consolidation Tests (5% Lime Content; 1 Month Curing Time)

Yielding of Lime Trested Clays During Undrained Loading

A schematic diagram showing the difference between the typical undrained behavior of an untreated normally consolidated clay and lightly overconsolidated lime treated clay is shown in Figure 11. The typical undrained stress path for normally consolidated clay exhibits characteristics that show that the soil has yielded for the whole duration of shearing from a pre-shear consolidation pressure $\bar{p}_o$. For lime treated clays, except for heavily overconsolidated smaples for which no evidence of yielding is observed, the undrained stress path first rises vertically in the q . $\bar{p}$) plot (AB in Fig. 11) and only after a critical stress is reached does the pore pressure development start to be significant. Typical illustration of such behavior of treated sample can seen in Figure 3. It can be postulated that the point at which the stress path deviates from the constant $\bar{p}$ path is a yield point (point B in Fig. 11). It is, however, important to emphasize the concept of yielding can be used in a somewhat broader sense. In this case, yielding can refer to the stress point at which the pore pressure development starts to be significant. From the individual undrained stress paths obtained from the CIU tests, it is possible to estimate these critical stresses or yield points. These yield points are shown in the (q, $\bar{p}$) plot in Figure 12. The yield points could be estimated since a distinct deviation from the initial linear portions of the undrained stress paths could be seen.

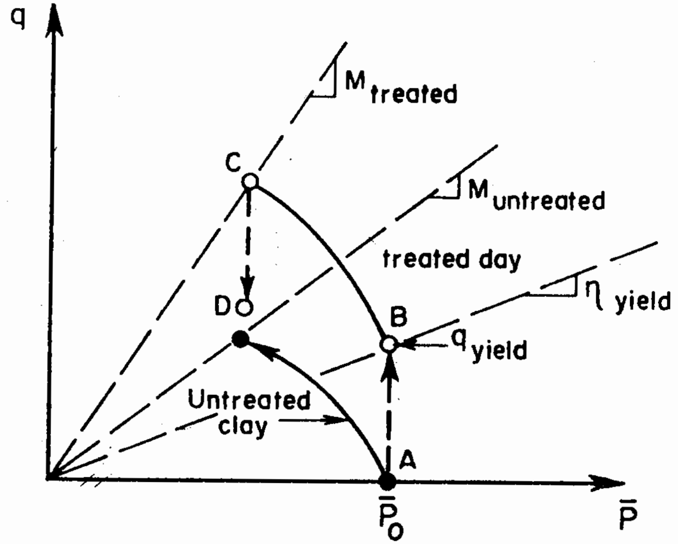

Fig 11. Schematic Diagram of Undrained Stress Path for Lime Treated Clay Showing Yield Point

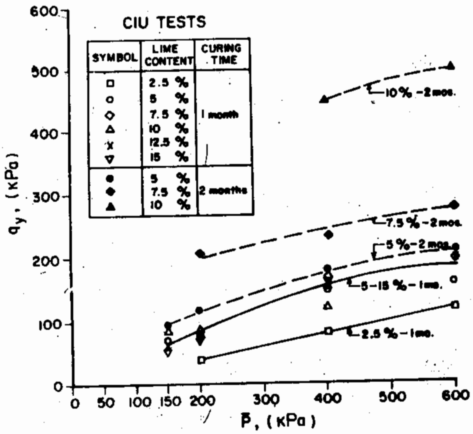

Fig 12. Estimated Yield Points from CIU Tests

Yielding of Lime Treated Clays During Drained Loading

A schematic diagram illustrating the differences between the drained behavior of untreated normally consolidated clay and lime treated clay is presented in Figure 13. For the case of untreated clay, the behavior resembles that type which has already yielded. For lime treated clays, however, the (q.$^{\varepsilon}$v) relationship indicates the presence of an initial stage wherein the volumetric strains are small (the region where the pseudo-elastic type of behavior exists) (AB in Fig. 13) Typical illustration of such behavior of treated smaples can be found in Figure 6. It is then possible to consider the points at which the volumetric deformations start to increase as yield points for the lime treated clays during drained tests.

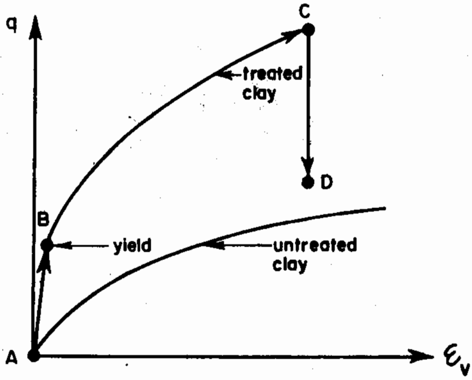

Fig 13. Schematic Diagram of (q-ε_v) Relationship from CID Test for Lime Treated Clay Showing Yield Point

A CONCEPTUAL MODEL OF THE BEHAVIOR OF LIME TREATED CLAY

On the basis of the experimental evidences conerning the strength and deformation characteristics of lime treated clays, it is possible to propose a conceptual model on the development of strains during the shearing of the lime treated clays. An illustration of the typical behavior described by the conceptual model is given in Figure 14.

For applied stress conditions within the yield locus Y_1 (zone1), it is suggested that the behavior is rigid up to failure, similar to the behavior of heavily overconsolidated clay. Typical illustrations of the rigid behavior of the treated samples within zone I are shown in Figure 2 and 4, wherein the undrained stress paths rise vertically for the full range of deviator stresses up to the failure states. It is further suggested that the yield locus Y_1 corresponds to the yield locus obtained from the bilinear characteristics of the strain paths from the anisotropic consolidation tests. This is because outside this yield locus Y_1, but still within the yield loci obtained from the $(^{\varepsilon}v, \log \bar{p})$ and $(^{\varepsilon}s, \log \bar{p})$ relationships from the anisotropic consolidation tests (Fig. 10), the behavior is not fully rigid throughout the shearing process. The shape and position of the yield locus Y_1 are influenced by the lime content and curing time, and in general, the extent of rigid zone I will expand with increasing lime content and curing time, e.g., the region bounded by the yield locus Y_1 in Figure 14. For stress states within zone 11, the development of strains during the shearing of lime treated clays can be separated into three phases. For stress states starting from pre-shear consolidation pressure, up to the distortional yield locus Y_2 (or stress path AB in Fig. 14), the behavior is pseudo-elastic. Within this pseudo-elastic region, the development of pore pressures during CIU tests of volumetric strains during CID tests will be very small. The Yield locus is affected by the lime content, the curing time, the pre-shear consolidation pressure, and is different for the undrained and drained triaxial tests. Specifically, the yield locus for the undrained tests is higher than for the drained tests (Fig. 14). With the increase of curing time, the yield locus Y_2 shifts upwards to Y_2 such that the region of pseudo-elastic behavior increases in size.

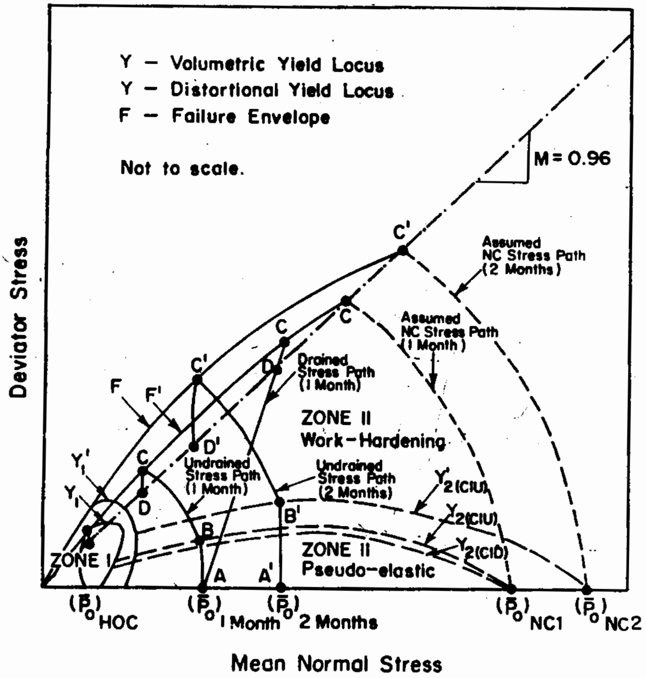

Fig 14. Schematic Diagram of the Behavior of Lime Treated Clay Based on Conceptual Model

As the stress paths cross the yield locus Y_2, the experimental evidence showed that relatively large deformations and pore pressures develops, (e.g., Figs. 3 & 6). It can be suggested that for the stress conditions corresponding to a point in zone II, but from the yield locus Y_2 up to the failure envelope F (or path BC in Fig. 14), the behavior of lime treated clays is similar to that of a work-hardening elasto-plastic material. This proposition brings about the possibility of using an appropriate soil model based on the concepts of plasticity and critical state theory to describe the behavior of lime treated clays within this zone. The work-hardening phase exists only up to the failure of the treated clays; the failure envelopes are curved, and, are affected by the lime content and curing time as illustrated by the shift of the failure envelope F to F' in Figure 14.

Strain-softening occurs beyond the failure states of lime treated clays (path CD in Fig. 14) with very large reduction in strength observed after considerable straining. For this phase, therefore, the behavior can be considered to be unstable and cn not be described in terms of the concepts of continuum mechanics nor with the use of critical state parameters. The residual states of lime treated clays lie very close to the critical state line of the untreated clay; such finding may be useful in limit equilibrium analysis.

Finally, it is suggested that the overconsolidated nature of the lime treated clays may be completely erased during the isotropic consolidation to a sufficiently high pre-shear consolidation pressure, (e.g., $(\bar{p}_o)_{NCI}$ in Fig. 14) such that the behavior of lime treated clays will be normally consolidated throughout the shearing process. The stress states during the loading should, therefore, lie on the corresponding State Boundary Surface of lime treated clays. It seems reasonable to conclude that normally consolidated clay behavior will exist for the samples sheared from $(\bar{p}_o)_{NCI}$ based on the observation that the increase in pre-shear consolidation pressure erases the effects of lime treatment. Also, the pre -shear consolidation pressure $(\bar{p}_o)_{NC2}$ at two months curing period can be assumed to be higher than $(\bar{p}_o)_{NCI}$. The appropriate failure envelope for normally consolidated samples at both one and two monts curing periods is again the critical state line for the untreated clay.

CONCLUSIONS

Lime treatment alters the strength and deformation characteristics of the soft clay from normally consolidated clay behavior to that of an overconsolidated clay. The results of the drained and undrained triaxial compression tests confirmed the overconsolidated nature of lime treated clays, based on the characteristics of effective stress paths, the stress-strain relationships, the pore pressure development and the volume change characteristics. The degree of overconsolidation was observed to be affected by the lime content, the curing time, the pre-shear consolidation pressure and the applied stress path. The effective stress pahts of lime treated clays, from both drained and undrained tests, proceed towards curved failure envelopes. After the peak stress conditions, however, the stress paths were seen to drop such that the stress states at the end of the tests consistently lie very close to the critical state line of the base clay. The yield loci for lime treated clays, obtained from the series of anisotropic consolidation tests, are found to be more pronounced than the limit state curves for natural clays of Tavenas and Leroueil (1977). The shape and orientation of the yield loci are affected by the lime content and curing time. Based on the characteristics of the undrained stress paths and the (q, ε_v) relationships from CID tests, the yield loci defining the region of pseudo-elastic behavior were obtained. The conceptual model suggests that for stress states inside the volumetric yield locus obtained from the bilinear characteristics of the strain paths during anisotropic consolidation, the behavior of the lime treated samples during the triaxial compression corresponds to heavily overconsolidated clay behavior. Outside the volumetric yield locus, however, the conceptual model proposes that the behavior consists of three phases: an initial pseudo-elastic phase (defined by the distortional yield locus), followed by a work-hardening stage up to failure, and finally, a strain-softening phase up to the residual states that lie close to the critical state line of the untreated clay.

REFERENCES

Roscoe, K.H., Poorooshasb, H. B. (1963), "A Theoretical and Experimental study of Strains in Triaxial Compression Tests on Normally Consolidated Clays", Geotechnique, Vol. 13, No. 1, pp 12-38.

Tavenas, F., & Leroueil, S., (1977), "Effects of Stresses and Time on Yielding of Clays", Proceeding 9th Int. Conf. Soil Mech. and Found. Engg., Vol. 1, pp. 319-326.

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$\bar{p}$ = Effective mean normal stress

$\bar{P}_o$ = Pre-shear consolidation pressure
q = Deviator stress $(\bar{\sigma}_1 - \bar{\sigma}_3)$
ε_s = Shear strain
ε_v = Volumetric strain
NC = Normally consolidated
HOC = Heavily overconsolidated