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EFFECT OF LEACHING ON UNDRAINED SHEAR STRENGTH BEHAVIOR OF A SEDIMENTED CLAY

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ABSTRACT

Leaching is one of the major environmental changes which could occur to a marine clay post deposition due to seepage of rain water and/or flood water through the soil. Reduction of salt concentration in the pore fluid of a clay upsets the balance of the interparticle electrical forces and the particle alignment, which results in instability of the soil structure. A laboratory experimental investigation was carried out to study the effect of leaching on the shear strength behavior of a sedimented clay from the Bangkok area. Artificially sedimented samples were prepared by sedimenting the clay in sodium chloride solution and then leached with fresh water to various final salt concentration. Laboratory vane shear tests and isotropically consolidated undrained triaxial tests with pore pressure measurement were performed on the leached samples.

Test results showed that leaching of the salt concentration increased the soil sensitivity. Both the undrained shear strength and the effective angle of shearing resistance decreased with leaching.

INTRODUCTION

Soil deposits sedimented under marine environment, commonly known as deltas or coastal plains, are expected to have initial pore water salt concentration the same as the concentration of sea water, i.e. 35 gm/l. After being exposed above the sea-level, the salt concentration in the pore water was gradually reduced due to leaching by rain water and/or flood water. Leaching out the salt from a marine deposit is one of the major environmental changes which is of great concern to the geotechnical engineers. It had been reported that leaching reduced the shear strength of a marine clay and changed the soil into a 'quick' condition (BJERRUM, 1954). Despite of the increasing importance of utilization of land areas on deltas and coastal plains, detailed studies on the effects of leaching on the engineering characteristics of marine deposit are still limited. It was the principal objective of this research to study the fundamental characteristics of undrained shear strength of soils with different degree of leaching. The findings of this work could be of practical importance to geotechnical engineers working in areas with marine deposits.

EXPERIMENTAL INVESTIGATION

Soils

The soil used in this study was taken from the Rangsit area in Bangkok, Thailand. The general properties of this soil have been reported in MOH et al (1969). The subsoils in the Greater Bangkok region, the so-called 'Bangkok Clay', are young marine deposits originated from sedimentation of the delta of the Chao Phraya River. The soil has very low undrained shear strength and high compressibility (MOH et al, 1969).

Disturbed soil samples taken from a depth of 4 m to 8 m were used to prepare artificially sedimented samples. The soils denoted as Soil S35, S25, S10 and S7 in this study were leached samples having salt (NaCl) concentration of 35 gm/l, 25 gm/l, 10 gm/l and 7 gm/l respectively. The general properties of the leached soils are given in Table 1.

Preparation of Artificially Sedimented Clay

The procedure for sedimentation adopted in this study was basically the same as that used by BJERRUM and ROSENQVIST (1956) except that larger sedimentation tanks were used. The sedimentation tanks, 26.7 cm diameter and 50.8 cm high, made of 0.5 cm thick steel cylinders, were designed for the purposes of sedimentation, loading, consolidation and leaching.

Table 1 General Properties of Soil Samples Tested

Soil Soil Properties	Natural	S35	S25	S10	S7
Grain Size: Silt 2-74μ	32	30	30	30	30
Clay<2μ	68	70	70	70	70
Physical Properties:					
Specific Gravity	2.69	2.72	2.72	2.72	2.72
Water Content, %	80	68-73	70-78	70-78	70-80
Liquid Limit, %	81±2	83±1	82±1	81±1	83±2
Plastic Limit, %	33±2	31±2	33±2	33±2	34±2
Plasticity Index, %	48	52	49	48	49
Activity	0.71	0.74	0.70	0.69	0.70
Liquidity Index	0.98	0.76	0.84	0.86	0.84
Chemical Properties:					
Total Soluble Salt					
(eq. NaCl)	3.5g/l	35g/l	25g/l	10g/l	7g/l
(meq./100gm)**	4.8	42.2	31.6	16.5	9.0
Total Cations					
Na meq./100gm	9.6	91.0	52.5	37.0	31.0
K	3.3	0.8	1.0	1.2	1.1
Mg	13.6	2.6	3.5	4.1	3.8
Ca	5.4	3.0	2.7	2.0	3.2
C.E.C.	37.0	35.6	31.8	28.0	33.6
pH (Soil:Water=1:2.5)	7.0	7.8	8.1	8.2	7.5
Organic Matter, %	3.9	1.3	3.2	3.1	2.2
Mineralogical Composition*:					
Kaolinite	45	45	45	45	45
Montmorillonite	35-40	35-40	35-40	35-40	35-40
Illite	15-20	15-20	15-20	15-20	15-20
Quartz	trace	trace	trace	trace	trace

*Determined from -2μ clay fraction

**Milliequivalent of NaCl per 100 gm of dry soil

In the sedimentation process, the disturbed samples were first diluted to a soil slurry of water content about 2500% having salt concentration of 35 gm/l. The soil slurry was poured into the sedimentation tank for sedimentation. Additional portions of soil slurry were added until the soil solids in a tank were sufficient to produce a 12.5 cm thick sample after consolidation.

The soil samples in the tank were first allowed to consolidate under their own weight for six weeks. Dead loads were then added to a lever arm loading system where pressure could be transferred onto the top of the samples. All samples were consolidated with double drainage up to a pressure of 0.6 kg/cm^2, with increments of 0.1 kg/cm^2.

The samples were leached with fresh demineralized water to different salt concentrations after completion of the consolidation stage. The leaching process adopted involved the flow of fresh water from the top to the bottom of the samples under a constant head. This slow seepage of water led to a slow exchange of fresh water for the salt water in the soil pores. Flame photometer and conductivity tests were carried out on the leachate to determine the salt contents of the soils. The soil sample in one of the tank was leached with a salt water with salt concentration same as that present in the soil pores. This soil sample was used as a control sample and designated as Soil S35. Detailed procedures for the preparations of artificially sedimented samples were reported in WOO (1975).

Tests on Strength Characteristics

Laboratory vane shear tests The laboratory vane shear strength of all soil samples in both undisturbed state and remolded state were determined. Undisturbed soil blocks of 10 cm diameter were placed into steel molds with slightly larger diameter. The gaps between the specimen and the mold were filled with paraffin wax to keep the specimen in position and to prevent lateral expansion during shearing. The size of the vane used was 2 cm square and the rate of rotation was 20° per minute.

Isotropically consolidated undrained ($\overline{\text{CIU}}$) tests $\overline{\text{CIU}}$ tests were carried out to determine the shear strength characteristics of the undisturbed and remolded leached soils. The testing procedures adopted for the triaxial tests were essentially similar to those described by BISHOP and HENKEL (1962) except that the pore fluid in the back pressure system and the pore pressure measuring system was a salt solution of the same concentration as the pore fluid in the test specimen. Porous stones and side drain filter paper strips were also saturated with the same fluid. Pore pressures were measured by electrical transducer attached at the base of a cell. A back pressure of 2 kg/cm^2 was applied for saturation. The undisturbed specimens were consolidated isotropically under different pressures ranging from 1 kg/cm^2 to 8 kg/cm^2. Slightly lower consolidated pressures were applied to the remolded samples. The loading rate used to shear the specimens was 0.0040-0.0046 cm/min.

RESULTS AND DISCUSSIONS

Effect of Leaching on Soil Sensitivity

The sensitivity of the leached soils in this study was determined from laboratory vane shear tests. The term soil sensitivity is therefore defined here as the ratio of undisturbed vane shear strength to the remolded vane shear strength. Figure 1 shows the increasing of soil sensitivity upon leaching. The data were in good agreement with the results obtained by GHAFOOR (1970). Leaching from a salt concentration of 35 gm/l down to 7 gm/l, the sensitivity of the Rangsit Clay increased from 2 to 5. The soil sensitivity appeared to increase more rapidly when the salt concentration of the soil was reduced to less than 10 gm/l. This finding generally supports the results obtained by BJERRUM (1954) for the Norwegian Clays. However, the increase in sensitivity of the Rangsit Clay was found to be much lower, as seen in

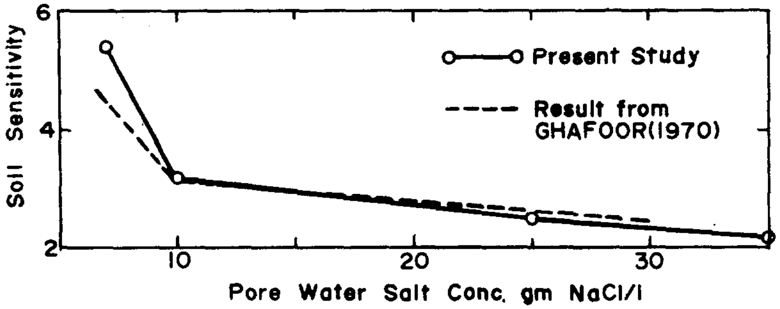

Fig. 1 Effect of Leaching on Soil Sensitivity as Measured from Vane Shear Test

Fig. 2. For the Norwegian Clays (BJERRUM and ROSENQVIST, 1956), soil sensitivity increased from 5 to 110 after the salt concentration in the pore water of the soils was reduced from 35 gm/l to 5 gm/l.

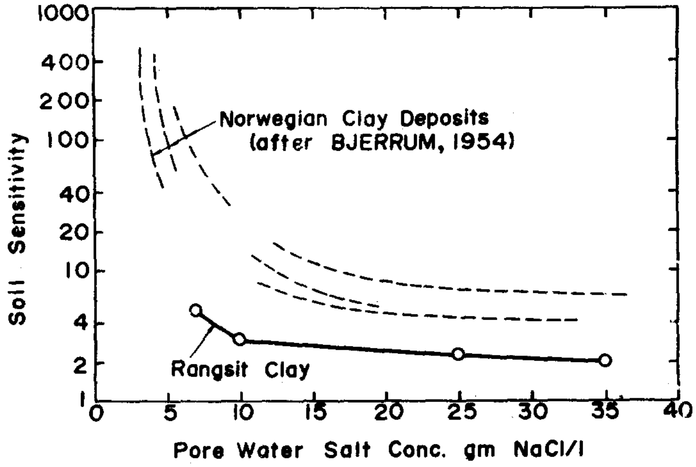

Fig. 2 Soil Sensitivity vs Salt Concentration for the Norwegian Clays and Rangsit Clay

Effect of Leaching on Shear Strength Behavior

Strength envelope, stress path and strength parameters The total and effective strength envelopes for the leached soils studied were found to be straight lines passing through the origin. Figure 3 plots the effective stress paths and p-q envelopes for the leached soils S35 and S7. The angles of inclination, α, for each of the total and effective envelopes of the various soils are listed in Table 2. The values of the Mohr-Coulomb angles of shearing resistance ϕ, computed from $\sin\alpha=\tan\phi$, are also listed in the same table. It is evidently shown that both the ϕ and $\bar{\phi}$ values decreased with leaching. The decrease of ϕ and $\bar{\phi}$ was particularly pronounced when the soils were leached to salt concentration below 10 gm/l. The reduction of ϕ and $\bar{\phi}$ indicates that the soil became less stable when the salt content in the pore fluid decreased.

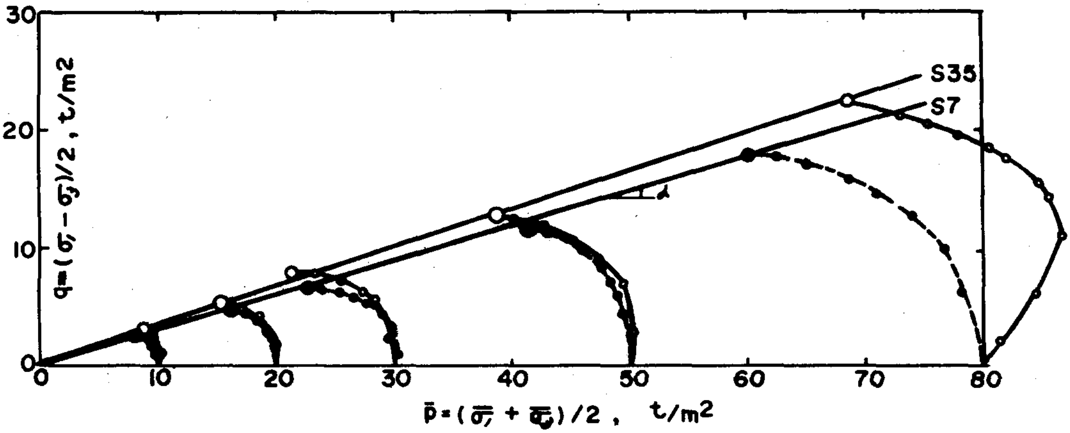

Fig. 3 Effective Stress Paths and Envelopes of Soils S35 and S7

Table 2 Undrained Shear Strength Parameters

Type of Clay		Total Stress at $(\sigma_1-\sigma_3)_{max}$		Effective Stress at $(\sigma_1-\sigma_3)_{max}$		Effective Stress at $(\bar{\sigma}_1/\bar{\sigma}_3)_{max}$	
		α	ϕ	$\bar{\alpha}$	$\bar{\phi}$	$\bar{\alpha}$	$\bar{\phi}$
Leached Clays	S35	12.0	12.3	18.0	19.0	19.0	20.2
	S25	11.5	11.8	19.0	20.2	20.0	21.4
	S10	11.0	11.2	17.5	18.4	18.5	19.6
	S7	10.5	10.7	16.0	16.7	16.0	16.7
Remolded Leached Clays	S35	13.5	13.9	21.0	22.6	21.0	22.6
	S25	13.0	13.4	21.0	22.6	21.0	22.6
	S10	12.0	12.3	17.5	18.4	17.5	18.4
Results from PAMCHAREON (1972)	Calcium Clay	11.0	11.2	19.0	20.1	19.5	20.7
	Sodium Clay	11.0	11.2	19.0	20.1	19.5	20.7
	Fresh Water Clay	11.0	11.2	17.0	17.8	17.5	18.4

α, ϕ, $\bar{\alpha}$, $\bar{\phi}$ in degree

For the remolded soils, the ϕ values also showed a slight decrease due to leaching. The $\bar{\phi}$ values were similar for Soils S35 and S25, but for Soil S10, the $\bar{\phi}$ was considerably lower. Comparing the undisturbed and remolded leached soils, the soil in the remolded state had higher ϕ values. This is probably because when a remolded soil was consolidated to the same pressure, the final water content was lower than the water content in the undisturbed soil. As shown in Table 2, the ϕ and $\overline{\phi}$ values for the Rangsit clay sedimented in solutions with different type of ions did not vary significantly. It is worthy to note that leaching away the salt from this soil appears to have more influence on the values of the shear strength parameter than the effect of changing the types of ion in the soil.

Normalized deviator stress By examining the stress-strain relationships, it appears that there exists a unique relationship between the normalized deviator stress and axial strain for the undisturbed leached soils. The curves representing the unique relationships for each of the four leached soils are plotted in Fig. 4. It can be seen from the figure that the average normalized deviator stress was higher in soils with higher salt content. The compressibility of the four soils under isotropic consolidation condition was found to be quite similar, and the water contents at failure of the various soil were also very close to each other. The decrease of the normalized deviator stress with pore water salt concentration could thus only be attributed to the removal of salt from the pore water.

The curves in Fig. 4 were all similar in shape, indicating that the soil fabrics or particle alignments of the various samples were substantially alike. The decrease of the maximum normalized deviator stress associated with the removal of salt from the soil pores might be further related to the decrease of interparticle repulsive forces (WOO et al, 1977).

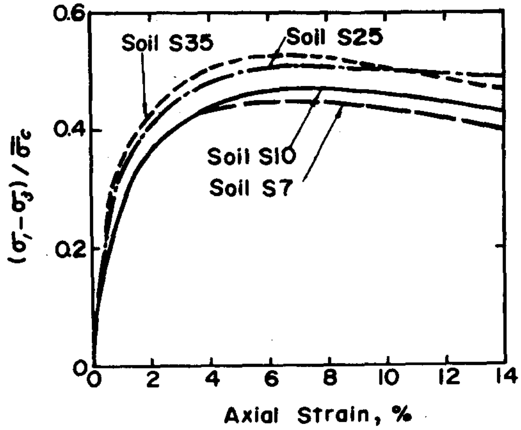

Fig. 4 Comparison of Normalized Deviator Stresses for the Leached Soils

Obliquity ratio Obliquity ratio is the ratio of the major and minor effective principal stresses which can be used as a failure criterion for a soil (TAYLOR, 1948). In Fig. 5, the maximum obliquity ratio of the leached soils are compared with the maximum obliquity ratio of Soil S35. For the undisturbed soils, it is seen that the ratio did not change until the soil was leached to a salt concentration below 25 gm/l, and when the soil was leached down to 7 gm/l, a 15% reduction in the obliquity ratio resulted. For the remolded soils, the reduction of the obliquity ratio with decrease of the salt content was gradual. The change of the obliquity ratio with leaching was compatible with the undrained shear strength. The maximum obliquity ratio is considered to be related to the rigidity of soil skeleton. It is evident that in both undisturbed and remolded leached soils, removal of salt reduced the rigidity of the soil.

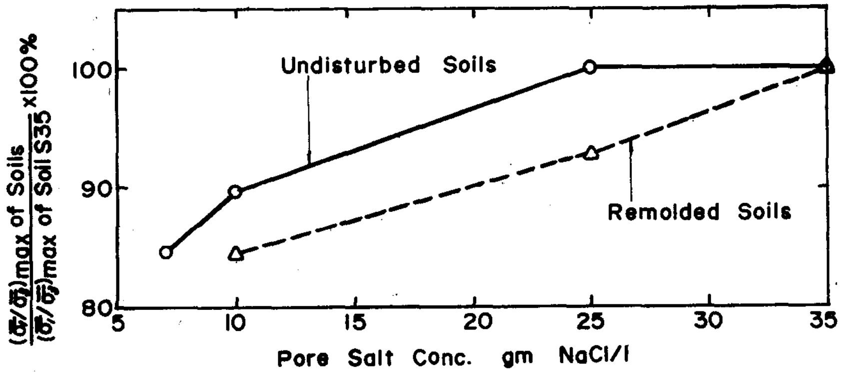

Fig. 5 Effect of Leaching on Maximum Obliquity Ratio of the Leached Soils

The normalized undrained strength of a soil can be expressed as:

$$\frac{s_u}{\bar{\sigma}_c} = \frac{(\sigma_1-\sigma_3)_f}{2\bar{\sigma}_c} = \left(\frac{\bar{\sigma}_{3f}}{2\bar{\sigma}_c}\right)\left(\frac{\bar{\sigma}_{1f}}{\bar{\sigma}_{3f}} - 1\right) \qquad \text{---------(1)}$$

Thus it can be seen that the controlling factors are $\bar{\sigma}_{3f}$ and the obliquity ratio $(\frac{\bar{\sigma}_{1f}}{\bar{\sigma}_{3f}})$. The value of $\bar{\sigma}_{3f}$ is related to the pore pressure at failure. Table 3 compares some typical data on values of $s_u/\bar{\sigma}_c$, $\bar{\sigma}_{3f}$ and $\bar{\sigma}_{1f}/\bar{\sigma}_{3f}$ for the undisturbed and remolded leached soils.

It is interesting to note that for both types of soils, $\bar{\sigma}_{3f}$ increased with leaching. This indicates that less positive pore pressure developed during shear. On the contrary, the obliquity ratio $\bar{\sigma}_{1f}/\bar{\sigma}_{3f}$ decreased with leaching, which means that the soil skeleton became less rigid with leaching. It can thus be concluded that decrease of the undrained shear strength of the leached soils found in this study was primarily due to the result of decreasing in the inter-particle bondings, rather than development of higher positive pore pressure as it was suggested for highly sensitive leached soils (BJERRUM and ROSENQVIST, 1956).

Table 3 Values of $s_u/\bar{\sigma}_c$, $\bar{\sigma}_{3f}$ and $\bar{\sigma}_{1f}/\bar{\sigma}_{3f}$

Type of Clay		$\bar{\sigma}_c$, ton/m^2	$s_u/\bar{\sigma}_c$	$\bar{\sigma}_{3f}$	$\bar{\sigma}_{1f}/\bar{\sigma}_{3f}$
Leached Clays	S35	10	0.317	4.70	2.35
	S25		0.262	4.89	2.15
	S10		0.256	5.43	1.94
	S7		0.258	5.63	1.92
	S35	30	0.269	13.10	2.23
	S25		0.257	14.17	2.09
	S10		0.250	16.37	1.92
	S7		0.222	15.94	1.84
Remolded Leached Clays	S35	5	0.373	2.06	2.82
	S25		0.337	2.52	2.34
	S10		0.325	2.99	2.09
	S35	30	0.287	14.00	2.23
	S25		0.279	15.84	2.06
	S10		0.264	19.84	1.80

Effect of Leaching on Pore Pressure Development

Undisturbed leached soils The trend of pore pressure development of the leached soils in this study was found to be similar to an ideally normally consolidated clay, i.e. having a unique relationship between the normalized excess pore pressure and axial strain. Fig. 6 compares the normalized pore pressure of the four leached soils tested under the same consolidation pressure. All the four soils showed similar trend of pore pressure development with axial strain. The

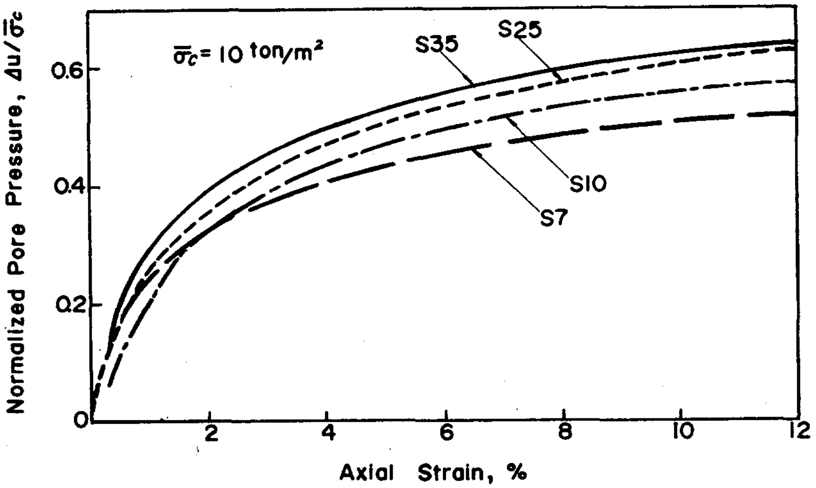

Fig. 6 Comparison of Pore Pressure Development for the Leached Soils

results in Fig. 6 clearly showed that soils subjected to higher degree of leaching would induce lower excess pore pressure during shear. This may be due to the weaker bonding strength and, hence, lower deviator stress in a highly leached soil. The almost unique value of the pore pressure parameter A for the leached soils as shown in Fig. 7 indicates that the pore pressures developed in these soils were mainly related to the magnitudes of the deviator stress carried by the soil sample. In other words, the stronger the bond strength, the higher was the pore pressure developed after breakage of the bonds.

Remolded leached soils Presented in Fig. 8 are the normalized pore pressure curves of the remolded leached soils. The pore pressures in Soil S10 is seen to be much lower than that developed in the other two Soils S35 and S25. The lower pore pressure developed in Soil S10 was partly due to the lower deviator stress in this soil and partly due to the higher repulsive force resulted from leaching. Comparing the pore pressure parameter A of the three remolded soils, Fig. 9, Soil S10 was found to have lower A values too. This behavior was unlike the undisturbed soils, whilst all the soils had similar A values. The

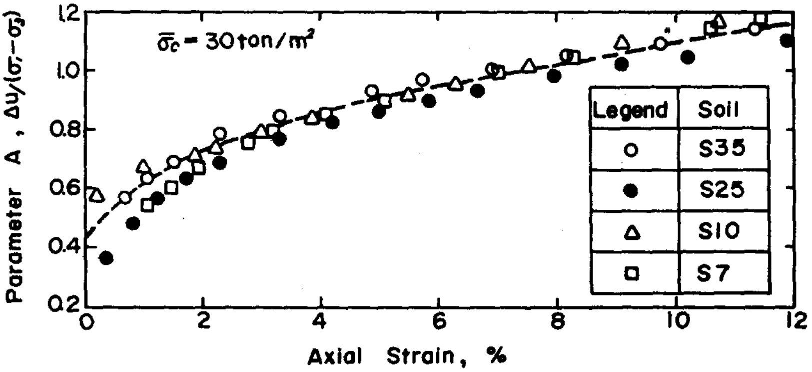

Fig. 7 Comparison of Pore Pressure Parameter A for the Leached Soils

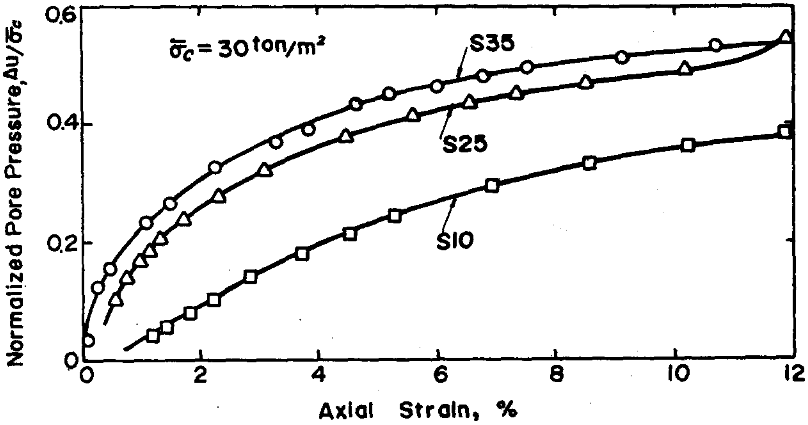

Fig. 8 Comparison of Pore Pressure Development for the Remolded Leached Soils

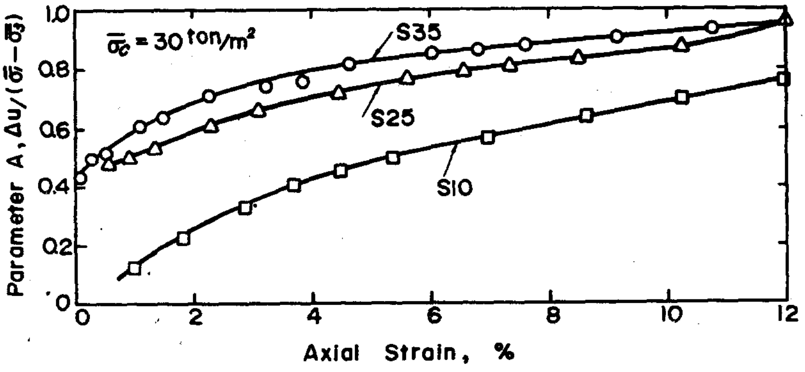

Fig. 9 Comparison of Pore Pressure Parameter A for the Remolded Leached Soils

lower A values in the remolded Soil S10 reflected the existence of higher interparticle repulsive forces, due to which the sample had a tendency to swell during shear.

CONSLUSIONS

On the basis of the results obtained in this study on artificially sedimented samples, the following conclusions can be drawn on the effects of leaching on the shear strength characteristics of sedimented Rangsit clay:

(1) Leaching of salt concentration (NaCl) from 35 gm/l to 7 gm/l increased the soil sensitivity from 2 to 5.

(2) Both undisturbed and remolded undrained shear strength decreased due to leaching. The angle of shearing resistance in terms of both total and effective stress decreased by 2-3 degrees.

(3) The decrease of shear strength in a leached soil could be attributed mainly to the lower rigidity of the leached soil skeleton rather than caused by higher excess pore pressure at failure.

(4) The excess pore pressure developed in the leached soils during undrained shear decreased with increasing in the degree of leaching.

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