EFFECTS OF SOIL STRUCTURE ON COMPRESSIBILITY OF AN ARTIFICIALLY SEDIMENTED CLAY

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The purpose of this research is to investigate the effects of soil structure on the one-dimensional consolidation behavior of a silty clay. Clays with different soil structures were produced in the laboratory by using different fluids for sedimentation, namely, a calcium chloride ($CaCl_2$) solution, a sodium metaphosphate $(NaPO_3)_x$ solution, and fresh water. In addition, the effects of reduction in the pore fluid salt concentration due to leaching on consolidation behavior of marine clays were also investigated.

MATERIALS AND EXPERIMENTAL PROCEDURES

Soils

The soil used for the preparation of the artificially sedimented clays in this research was a soft silty clay taken from Rangsit, a suburb of Bangkok, at a depth of 4 to 8 m. The soft clay at this depth in the Great Bangkok area is generally a leached marine deposit (MOH et al, 1969). The natural soil used in this study consisted of 68% clay fraction (-2μ) and 32% silt content. The mineralogical composition of the clay fraction is 45% kaolinite, 35-40% montmorillonite and 15-20% illite. The general index properties of the natural soil are presented in Table I.

Salts

To prepare soils with different soil structures, three types of salt solutions were used for sedimentation. Reagent grade calcium chloride and sodium metaphosphate were used to prepare flocculated Ca-soil and dispersed soil respectively. High quality drug-use sodium chloride (NaCl) was used to prepare the sodium soils which were then leached with demineralized water to produce leached samples.

Preparations of Artificially Sedimented Samples

The procedures for sedimentation of soils adopted in this study was basically the same as that used previously at the Norwegian Geotechnical Institute (BJERRUM & ROSENQVIST, 1956). The preparation process for the soil samples could be separated into two stages, i.e. sedimentation and consolidation. For the leached samples, leaching was carried out after the consolidation stage. The following gives a brief description of the procedures adopted. Details are presented in WOO (1975).

Sedimentation. - Preliminary tests were performed to determine the optimum salt concentrations in the sedimentation fluids for producing soils with different structure. The optimum salt concentration for producing the most flocculated structure was found to be 0.6 N of $CaCl_2$ or NaCl, and that for the most dispersed soil was about 50 gm/l of sodium metaphosphate.

Same sedimentation procedures were employed for producing the Ca-clay, Fresh Water Clay and leached Na-clays. Batches of soil slurries at a water content of about 2500% were slowly sedimented in each of the sedimentation tanks until the amount of sediment was sufficient to give a 12.5 cm thick sample after consolidation. For the dispersed soil, it was most important to avoid undesirable stratification. Thicker slurry had to be used and the soil suspension was poured into the sedimentation tank only once which contained sufficient amount of soil solid for producing one sample block.

TABLE I
GENERAL PROPERTIES OF THE ARTIFICIALLY SEDIMENTED CLAYS

Soil Properties	Natural Clay	$CaCl_2$ Flocculated Clay (C)	Fresh Water Clay (W)	Dispersed Clay (D)	Leached Clay (S35)	Leached Clay (S25)	Leached Clay (S10)	Leached Clay (S7)
Particle Size Distribution								
Sand (2–0.074 mm)	0	0	0	0	0	0	0	0
Silt (0.074–0.002 mm)	32	35	30	28	30	30	30	30
Clay (<0.002 mm)	68	65	70	72	70	70	70	70
Specific Gravity	2.67–2.72	2.72	2.70	2.71	2.71–2.72	2.71–2.72	2.71–2.72	2.71–2.72
Water Content, %	80	70–71*	80–87*	86–88*	68–73**	70–78**	70–78**	70–78**
Liquid Limit, %	81	97	88	67	83	82	81	83
Plastic Limit, %	33	35	34	30	31	33	33	34
P.I., %	48	62	54	37	52	49	48	49
Activity	0.71	0.95	0.77	0.51	0.74	0.70	0.69	0.70
Organic Content, %	3.9	N.D.	N.D.	N.D.	1.3	3.2	3.1	2.2
Soluble Salt Content, eq. NaCl gm/1	3.5	36	0.2	-	35	25	10	7
Mineralogical Composition+								
Kaolinite	45	N.D.	N.D.	N.D.	45	45	45	45
Montmorillonite	35–40	N.D.	N.D.	N.D.	35–40	35–40	35–40	35–40
Illite	15–20	N.D.	N.D.	N.D.	15–20	15–20	15–20	15–20
Quartz	trace	N.D.	N.D.	N.D.	trace	trace	trace	trace

* Water content after consolidation in sedimentation tank under $\overline{\sigma}_c = 0.49\ kg/cm^2$.

** Water content after leaching.

\+ Determined from -2μ clay fraction.

Consolidation. - After enough soil solids had been added, the suspension was left to consolidate under its own weight for a period of time and then additional dead loads were applied in increments to consolidate the loose sediments. After the final loadings were applied, the Ca-clay, Fresh Water Clay and Dispersed Clay were left in the tanks for further consolidation before being extruded. The leached soils were subjected to leaching process after completion of the consolidation stage.

Leaching. - The leached soils, denoted as Soil S25, S10 and S7 were soils sedimented in NaCl solution and subsequently leached by fresh water to a final salt (NaCl) concentration of 25 gm/l, 10 gm/l and 7 gm/l, respectively. The control sample S35 was leached with a 0.6 N sodium chloride solution (35 gm/l) which was the same concentration as used for sedimentation. The fresh water used for leaching was applied to the samples with a 4 m hydraulic head at the early stage and was later increased to 7.8 m and finally 10 m. The salt contents in the soils were determined by means of conductivity and ion concentration measurements (using flame photometer) of both the leachate and the soil pore water. Identical results were generally obtained from the two sources which indicated that the leaching process used was effective.

Consolidation Tests

Conventional lever-arm type consolidometers and Anteus consolidometers with pore pressure measurement were employed for the consolidation tests of the Ca-clay, Fresh Water Clay and Dispersed Clay (Test Series I). Conventional standard load-increment ratio of one and load-increment duration of 24 hrs were used. For the leached soils (Test Series II), tests were carried out in lever-arm consolidometers as well as in hydraulic pressurized oedometers with pore pressure measurement. A 'step' load-increment (load-increment ratio ranged from 0.33 to 0.5) was applied. The loading duration for each increment was 2 or 3 days. Tests performed in oedometers with pore pressure measurement was carried out mainly for the purpose of measuring rate of pore pressure dissipation during consolidation. All the soil specimens for consolidation were 6.25 cm in diameter and 1.91 cm in thickness.

TEST RESULTS

General Properties

The general properties of the artificially sedimented clays are listed in Table I. The water contents of the Fresh Water Clay and the Dispersed Clay were somewhat higher than the Calcium Clay, although all the soils were subjected to the same consolidation pressure of 0.49 kg/cm^2 in the sedimentation tanks. For the leached soils, it was found that due to the seepage force of the leaching water, lower water contents were usually obtained at the bottom of the leached samples.

The liquid limit of the Fresh Water Clay and the Dispersed Clay were much lower than those of the Ca-clay. It appears that the Dispersed Clay particles are easier to slide along each other as contained in the liquid limit device. Leaching caused only a slight decrease in the plasticity index. These results were similar to those reported by PUSCH & ARNOLD (1969) on the Swedish clay but in contradiction to the findings of BJERRUM & ROSENQVIST (1956) for the leached Oslo clay.

Compressibility of the Artificially Sedimented Clays

The compression-pressure relationships of the soils sedimented in different types of solutions are shown in Fig. 1(a). The results of the leached soils are presented in Fig. 1(b). The compression-pressure curves for all the soils tested in this study have the same shape regardless of the type of soil structure and of the loading conditions. In the normally consolidated range, the slopes of the compression curves are quite similar. However, in the overconsolidated range, different behaviors of the soils can be observed. The slope of the compression curve in the overconsolidated portion for the Dispersed Clay is steeper than that of the Calcium Clay or the leached Sodium Soils. As shown in Fig. 1(b), slopes in the overconsolidated portion for the leached soils are in the order of Soil S7 > S10 > S25 > S35.

A series of test on remolded leached soils was also performed. The results showed that the compressibility decreased as the salt content decreased in the remolded soil, Fig. 1(b). The slope of a compression curve, as termed compression index C_c, is usually used to express the compressibility of a soil. The C_c values for the various soils of different soil structures are shown in Fig. 2. The C_c values plotted in the figure were measured from the slope of a compression-pressure curve between two loadings. Comparison of the C_c values could be conveniently separated into two portions. On the right hand side of the peaks, the soils were normally consolidated, all the soils in the two test series followed more or less the same relationship. On the left hand side of the peaks, the results in Series I show that C_c for the Dispersed Clay > the Fresh Water Clay > the Calcium Flocculated Clay, and the results in Series II tend to show that a leached soil with lower salt content has higher C_c value.

Maximum Preconsolidation Pressures

The interpretation of the maximum preconsolidation pressure $\bar{\sigma}_{vm}$, which is also termed as the critical pressure, for a soil is an important technique to understand the stress history of that soil. The preconsolidation pressure of the soils determined by using Casagrande's method from e-log $\bar{\sigma}_c$ curves are denoted the 'apparent preconsolidation pressure' in this study. Variations of factors such as load-increment ratio, loading duration (LEONARDS and RAMIAH, 1959; CRAWFORD, 1964), or magnitude of delayed compression (BJERRUM, 1967) could affect the position as well as the shape of the e-log $\bar{\sigma}_c$ curve of a soil, thus also affect the construction and interpretation of the estimated apparent preconsolidation pressure. Because of the effect of delayed compression, values determined from the total compression curves were generally slightly lower than the values measured from the primary compression curves. It was found that the maximum curvature points of the total compression curves could be more clearly defined, which allowed one to estimate the $\bar{\sigma}_{vm}$ value to a better accuracy. Therefore the $\bar{\sigma}_{vm}$ values of the soils presented in Table II were determined from the total compression e-log $\bar{\sigma}_c$ curves.

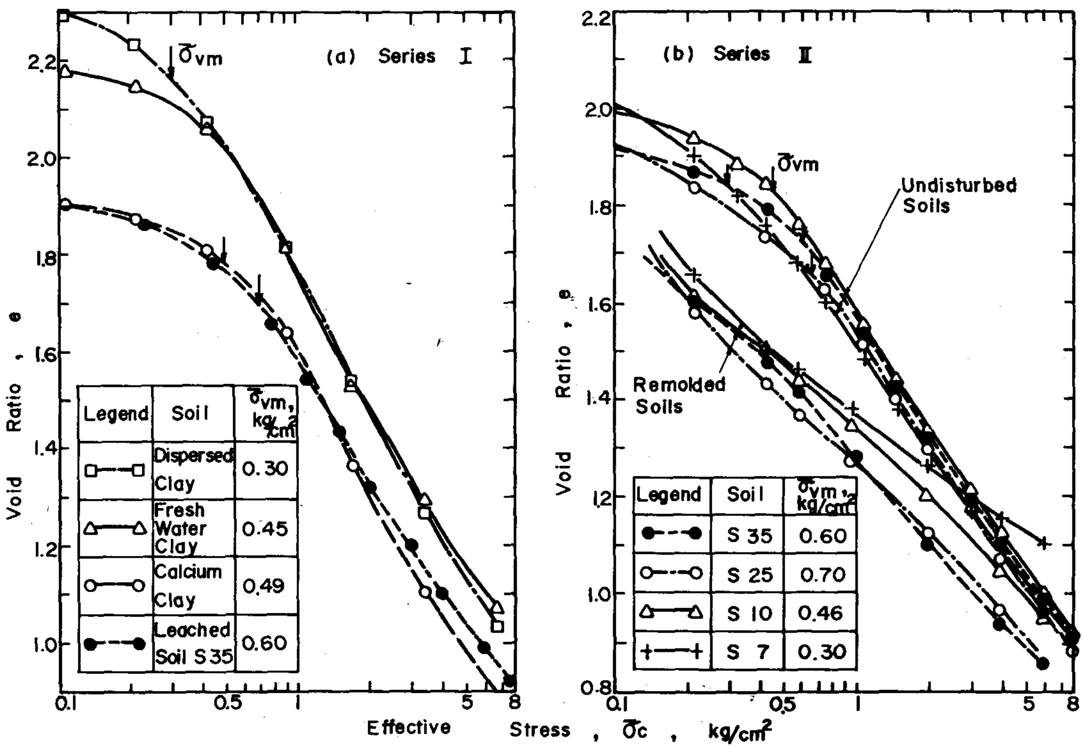

Fig. 1 - Effect of soil structure on compression - pressure relationship.

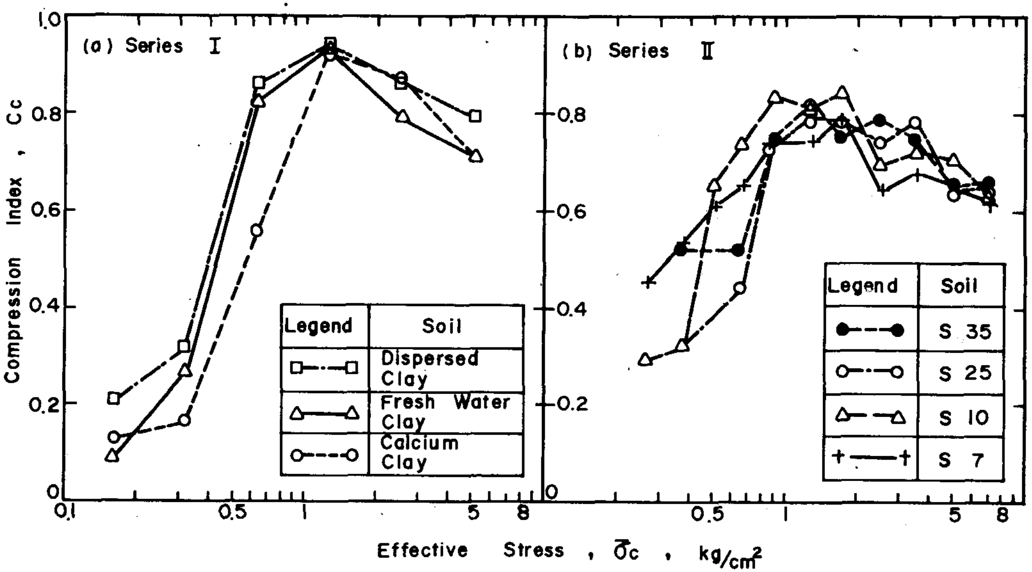

Fig. 2 - Effect of soil structure on variation of compression index with pressure.

TABLE II
COMPARISON OF CALCULATED AND ESTIMATED PRECONSOLIDATION PRESSURES

(1)	(2)	(3)	(4)	(5)	(6)
Test Series	Soils	Calculated $\bar{\sigma}_{vm}$, kg/cm^2	Apparent $\bar{\sigma}_{vm}$, kg/cm^2	Difference of (3) & (4)	Decrease of $\bar{\sigma}_{vm}$ due to Soil Structure, kg/cm^2
I	Ca-flocculated Clay	0.49	0.49	0	control
	Fresh Water Clay	0.49	0.45	0.04	0.04
	Dispersed Clay	0.49	0.30	0.16	0.16
II	Leached Clay S35	0.72	0.60	0.12	control
	Leached Clay S25	0.96	0.70	0.26	0.14
	Leached Clay S10	0.88	0.46	0.42	0.30
	Leached Clay S7	0.80	0.30	0.50	0.38

In Test Series I, all the soils were subjected to a consolidation pressure of 0.49 kg/cm^2 in the sedimentation tank, theoretically, the preconsolidation pressure $\bar{\sigma}_{vm}$ should be equal to 0.49 kg/cm^2 (i.e. the calculated $\bar{\sigma}_{vm}$ in Table II) without considering the slight difference in delayed compression. In Test Series II, the calculated $\bar{\sigma}_{vm}$ for the leached soils were estimated from the consolidation pressure plus the leaching pressure at the particular location of sampling depth of the specimen tested. The apparent $\bar{\sigma}_{vm}$ in Col. (4) of Table II were estimated from the e-log $\bar{\sigma}_c$ curves by Casagrande's method. It is interesting to note that the apparent $\bar{\sigma}_{vm}$ value was always smaller than the calculated one, as shown in Col. (5) of Table II. The difference was very small for the Fresh Water Clay but quite large for the Dispersed Clay and the leached soils. It appears that at least part of this difference between the estimated $\bar{\sigma}_{vm}$ could be attributed to the effect of soil structure.

The apparent $\bar{\sigma}_{vm}$ for the Ca-flocculated Clay was equal to the calculated $\bar{\sigma}_{vm}$. The value in Col. (5) for Soil S35 could be attributed to the effects of load-increment ratio and load duration used for the test series, because in Test Series II, both the load-increment ratio and load duration applied were different from the conventional standard ratio or duration. In order to evaluate the effect of soil structure on the values of $\bar{\sigma}_{vm}$, the Ca-flocculated Clay and Soil S35 were taken as the control test for Test Series I & II respectively. The $\bar{\sigma}_{vm}$ values of the Ca-flocculated Clay and Soil S35 for the corresponding series were subtracted from the other soils. The results are shown in Col. (6) of Table II. It is worthy to note that for the Dispersed Clay the apparent $\bar{\sigma}_{vm}$ was smaller than the calculated $\bar{\sigma}_{vm}$, and the difference between the calculated and apparent $\bar{\sigma}_{vm}$ became larger as the salt concentration decreased in the leached soils.

Coefficient of Consolidation

To determine the rate of consolidation, thus the rate of settlement in field, it is necessary to estimate the coefficient of consolidation, c_v, of a soil. Figure 3 shows the c_v values of the soils studied. The c_v value were determined by using Taylor's square root time fitting method. For each soil, the c_v decreased with the consolidation pressure in the overconsolidated range and became more or less constant for pressures in the normally consolidated range. This relationship between c_v and pressure is to be expected since according to Terzaghi's consolidation theory, c_v is directly related to the soil permeability and inversely proportional to the compressibility.

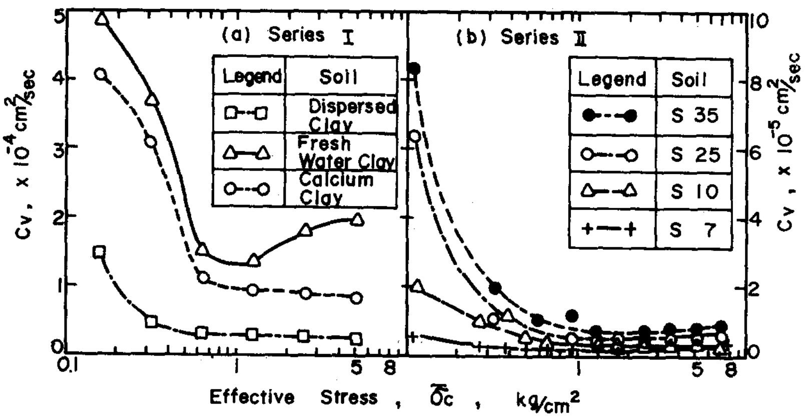

Fig. 3 - Effect of soil structure on coefficient of consolidation

sibility. For pressures below the preconsolidation pressure, the soil permeability decreases and the coefficient of compressibility increases as the loading pressure increases. For pressures in excess of the preconsolidation pressure, both the permeability and the compressibility of the soil decrease with increasing pressure. Comparing the c_v values of the soil in the two test series, it is obvious that through the pressure range applied, c_v values were in the order of Fresh Water Clay > Calcium Clay > Dispersed Clay in Test Series I, and Soils S35 > S25 > S10 > S7 in the leached series. The c_v values for the Sodium Clay S35 were lower than those of the Calcium Clay.

Rate of Pore Pressure Dissipation

The consolidation tests with pore pressure measurement were performed in hydraulic pressurized and Anteus consolidometers. The term degree of pore pressure dissipation refers to the pore pressure dissipation at the measuring surface of the soil specimen. The purpose of this test series was to compare the rate of pore pressure dissipation among the soils with different soil structure. Figure 4 shows typical pore pressure dissipation curves for the various soils. All soils showed similar trends of dissipation

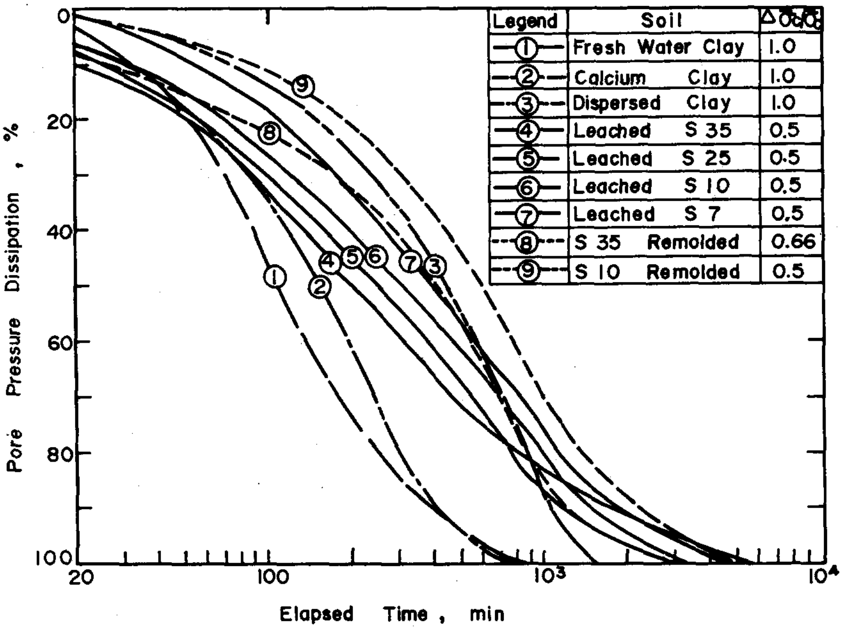

Fig. 4 - Average rate of pore pressure dissipation of various soils in the normally consolidated range.

with time. The rate of pore pressure dissipation was more or less unique for all load increments in the normally consolidated range, in other words, it was independent of the magnitude of the load increment as well as the load-increment ratio used. Each curve in Fig. 4 represents the average rate of pore pressure dissipation of the given soil in the normally consolidated range. The rate of pore pressure dissipation was found to be faster for the Fresh Water Clay and the Ca-flocculated Clay as compared to the Dispersed Clay. The leached soils also appeared to have lower rate of pore pressure dissipation. Among the leached soils, the pore pressure dissipation at any given time was lower for soils with higher degree of leaching. Remolding seems to further delay the rate of pore pressure dissipation.

DISCUSSIONS

Compressibility

In a one-dimensional consolidation test, as that in this study, compression of a soil is measured in terms of the total vertical displacement. Resistance to compression is generally contributed by breakage of interparticle bondings and the interparticle repulsion. In an undisturbed flocculated soil, the particle arrangements are in a random alignment. The double layers around the soil particles in a flocculated soil are generally less developed as compared to a soil with parallel particle arrangement such as in a dispersed soil. Because of the random arrangement of particles, the number of edge to face attractive bonding is high. Consolidation of a flocculated soil, therefore, is likely to have more resistance from particle bondings and less resistance from interparticle repulsion. A dispersed soil is expected to have less particle bondings but higher interparticle repulsion. Leaching tends to increase the interparticle repulsive force and therefore weakens the particle bondings. The similar results of compressibility of soils with different soil structures indicate that the effects of weaker bonding in a soil might be counteracted by the effects of increasing repulsive forces. Remolding of a specimen is to breakdown the soil structure and to align the particles to a more parallel arrangement. The compressibility of a remolded soil is therefore dominantly controlled by the interparticle forces. The test results in Fig. 1(b) tend to imply that the repulsive forces were comparatively highest in the remolded Soil S7, medium in remolded Soil S10 and lowest in remolded Soils S25 and S35. The sequence is in reverse order of the salt concentration after leaching.

Maximum Preconsolidation Pressure

The apparent preconsolidation is a measure of the reserve bonding strength which a soil has developed through past consolidation. The magnitude of bonding force developed in a normally consolidated clay is directly proportional to the effective consolidation pressure and duration of loading. The lower maximum apparent preconsolidation pressure for the Dispersed Clay tends to indicate the effect of lower bonding force of the Dispersed Clay due to higher repulsive force, as compared to the other two soils in the same test series which were consolidated to the same 0.49 kg/cm^2 consolidation pressure in the sedimentation tanks. For the leached soils, all the soils should have developed the same magnitude of bond strength as that of Soil S35 in the tanks before leaching. During leaching, flow of fresh water through the soil mass caused development of osmotic pressure. Moreover, reduction of salt content in the pore fluid increased the repulsive force between particles. The osmotic pressure and repulsive force were resisted by the interparticle bond strength. Hence some of the weaker bondings would be destroyed by leaching and the remaining bond strength became smaller. The lower apparent preconsolidation pressures reflect the weaker bonding strengths of the leached soils. This general finding of reduction of apparent preconsolidation pressure due to leaching is similar to the results reported by TORRANCE (1974) on undisturbed and remolded samples of Norwegian marine clays. Torrance found that the decrease of apparent preconsolidation pressure in a soil was dependent upon the degree of salinity reduction with the major effect occurring when the salinity had been reduced below 2 gm/l.

Coefficient of Consolidation

As described in a previous section, the c_v values obtained for the soils in Series I were in the order of Fresh Water Clay > Ca-flocculated Clay > Dispersed Clay, and the c_v values for the four leached soils in Series II were in the sequence S35 > S25 > S10 > S7. The reduction in c_v could be primarily due to the decrease of permeability caused by the dispersed soil structure or by leaching. As compared with flocculated soils, both the dispersed soil and the leached soils have expanded double layers which resulted in an increase of the midplane potential and reduction of flow channels. The permeability of a soil can be calculated from the following relationship:

$$k = c_v \cdot m_v \cdot \gamma_w \tag{1}$$

where c_v = Coefficient of consolidation
m_v = Coefficient of volume change, and
γ_w = Density of the salt solution.

Based on the c_v data shown in Fig. 3, the calculated permeability of the leached soils are plotted in Fig. 5. The results showed that for every soil the permeability k decreased with increasing consolidation pressure, and at a given consolidation pressure, the soil permeability decreased with leaching. The same effect of leaching on soil permeability was also observed during the leaching process as shown in Fig. 6. The permeability decrease due to leaching appeared to be particularly distinctive when salt concentration in the soil was below 10 gm/l.

Rate of Pore Pressure Dissipation

Factors affecting consolidation time, hence the rate of pore pressure dissipation are given in LAMBE and WHITMAN (1969) as:

$$t = f\left(\frac{mH^2}{k}\right) \tag{2}$$

where t = Consolidation time, or time required for pore pressure dissipation
m = Compressibility of soil
H = Length of drainage path, and
k = Permeability of soil.

In this study, the compressibility of the soils in the normally consolidated range was almost identical. The initial thickness of the specimens was the same and the difference in void ratio of the soils in the normally consolidated range was very small as shown in Fig. 1; therefore, the length of drainage path in each undisturbed soil would be similar too. Hence the different rate of pore pressure dissipation of the various soils could only be attributed to the different permeability of the soils.

When water flows under a hydraulic gradient through a negatively charged channel, the exchangeable cations, thus the double layers, are swept downstream. The viscosity of the double layer water may cause a reduction in the flow velocity. Consequently with the presence of double layer, the permeability of a clay soil will decrease, if other factors (such as shape factor, tortuosity, etc.) remain the same. This is possibly the reason why the Fresh Water Clay had highest permeability. The lower rate of pore pressure dissipation in the leached soils could be attributed to the lower permeability caused by thicker double layers or higher midplane potential. Consider a soil upon remolding, the particle bondings were all destroyed and the soil particles would be in a more parallel alignment. A more parallel particle arrangement results in a more tortuous and longer flow path in a

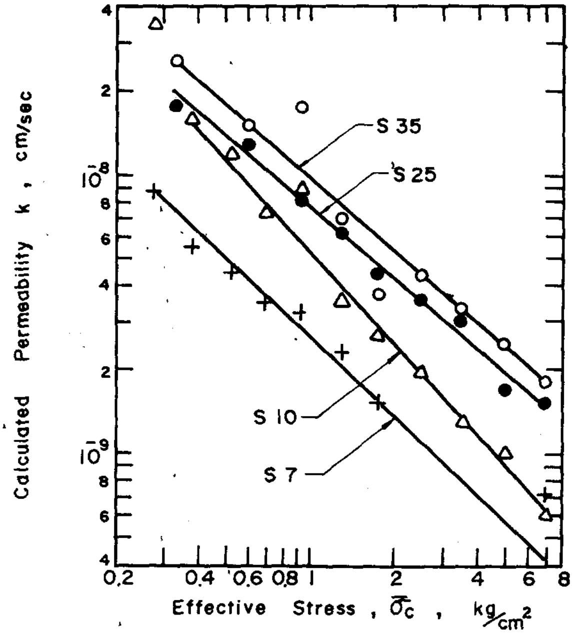

Fig. 5 - Effect of leaching on soil permeability

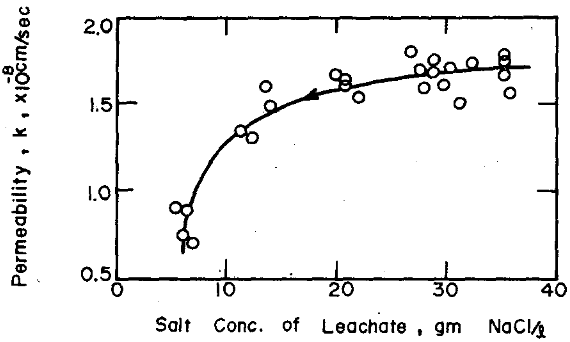

Fig. 6 - Soil permeability decrease due to leaching

one-dimensional consolidation test. Moreover, the more parallel arrangement enables the particles to develop their double layers more fully. Flow of water in this case had to pass through longer interparticle channels with the presence of viscous double layers. Therefore the permeability would decrease and the rate of pore pressure dissipation would be lower. Figure 4 shows that both the remolded Soils S35 had lower rate of pore pressure dissipation than that of the undisturbed soils.

CONCLUSIONS

On the basis of the laboratory experimental investigation results and discussions, the following conclusions were drawn:

(1) Difference in soil structure did not have significant effect on compressibility of clays in the normally consolidated range.
(2) Values of the coefficient of consolidation c_v and rate of pore pressure dissipation were affected by the soil structure.
(3) Leaching caused the maximum preconsolidation pressure $\bar{\sigma}_{vm}$, coefficient of consolidation c_v, permeability k and rate of excess pore pressure dissipation of the soils to decrease.

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