ENGINEERING BEHAVIOR OF CEMENT STABILIZED CLAY AT HIGH WATER CONTENT

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ABSTRACT

The in-situ deep mixing technique has been established as a means to effect columnar inclusions into soft ground to enhance the bearing capacity and reduce settlement. Since the inception of this method, developments in the plant and machinery, as well as associated field techniques, have surpassed the basic understanding of strength developments in high water-content clays admixed with cementing agents. In this paper an attempt is made to identify the critical factors governing the engineering behavior of cement-stabilized clay, which helps not only to control the input of cementing agent to attain strength development with curing time and clay water content, but also to understand the subsequent engineering behavior. It is revealed that the clay-water/cement ratio, w_c/c is the prime parameter for the above purposes.

Key words: cementation bond, cement stabilized clay, clay-water/cement ratio, consolidation test, drained triaxial compression test, engineering behavior, fabric, high water content clay, unconfined compression test (IGC: D10)

INTRODUCTION

Soft clay formations, especially when the in-situ water contents are high, unless they are markedly naturally cemented, have large potential for settlement with low inherent shear strength. Preloading on such deposits with vertical drains (such as PVD or sand drain) can enhance the inherent shear strength and reduce the compression. An alternative means is to enhance the level of cementation bond by use of supplementary cementing agents. The resistance to compression and consequent strength development in such a cemented state increase with increasing curing time. It is not practicable to admix a cementing agent with a large volume of in-situ soft clay. Hence in-situ deep mixing methods have been developed during the last two decades primarily to effect columnar inclusions into the soft ground to transform such whole soft grounds to composite grounds.

It was in 1975 during the 5th ARC (Bangalore, India) that the in-situ deep mixing method was introduced as a viable means to achieve columnar inclusion (Broms and Boman (1975) as well as Okumura and Terashi (1975)). In Japan, the research and development of this method was started and put into practice by the Port and Harbour Research Institute. The fundamental mechanical properties of stabilized soils were extensively investigated by Terashi et al. (1979; 1981), Kawasaki et al. (1981) and Kamon and Bergado (1992). The recent developments of

this means of handling soft ground were discussed during the 2nd ICGIGGDM (Yonekura et al., 1996). The behavior of the group column type DMM improved ground has been investigated experimentally by Miyake et al. (1991), Hashizume et al. (1998), and Kitazume et al. (1999). The increase in strength with time of surrounding clay adjacent to soil cement columns was experimentally and numerically studied by Miura et al. (1998) and by Shen and Miura (1999). The factors controlling in-situ strength of soil-cement columns have been investigated by a full scale test at Saga airport (Horpibulsuk et al., 2000).

Investigations by Nagaraj et al. (1995; 1996; 1997; 1998) concentrated on the basic aspects involved in the strength development of high water content clays with cementing agents. Kamaluddin and Balasubramaniam (1995), Uddin (1994), Yin and Lai (1998) and others investigated the laboratory strength and deformation characteristics of stabilized soft clays at a particular clay water content. For improvement of soft clays by the deep mixing technique, the water content of the clay is varied by dispensing cement admixture using the wet method. Thus, the behavior of the stabilized material in various conditions cannot be explained by the study at a particular level of water content. This paper proposes a new factor, clay-water/cement ratio, w_c/c as a standard parameter for investigating the engineering behavior of cement-stabilized clay at high water content.

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EXPERIMENTAL INVESTIGATION

Soil Sample

Ariake clay collected in Saga, Japan from a depth of 2 m was used in the experimental investigation. This soft soil is gray silty clay generally composed of 55 percent clay, 44 percent silt and only 1 percent sand. The clay is highly plastic with natural water content in a range of 135–150 percent. The liquid and plastic limits are in the order of 120 and 57 percent. The pre-consolidation pressure is 40–45 kPa. The effective stress parameters in compression are $c' = 0$ and $\phi' = 38^\circ$. The pH of the pore water is about 8.8 and the salinity is about 1.0 g/l.

Methodology of Testing

The clay paste was passed through a 2-mm sieve for removal of shell pieces and other bigger size particles. The water content was adjusted to the range of liquidity indices (LI) i.e., 1.0, 1.5, 2.0 and 3.0. The liquidity index was used in this investigation as an indicator to refer the initial water content of the clay in relation to plasticity characteristics of the clay before cement is admixed. This intentional increase in water content is to simulate the water content increase taking place in the wet method of dispensing cement admixture in deep mixing and the significant increase taking place in jet grouting. The clay with its water content corresponding to the above levels of LI along with quantity of cement resulting in clay-water/cement ratio of 7.5, 10 and 15 was thoroughly mixed so as to ensure uniform dispersion of the cementing agent (ordinary Portland cement). The mixing time was arbitrarily fixed at 10 min. Such a uniform paste was transferred to oedometer rings as well as to cylindrical containers of 50 mm diameter and 100 mm height, taking care to prevent any air entrapment. After 24 hours the cylindrical samples were dismantled. All the cylindrical samples and the same as along with oedometer rings were wrapped in vinyl bags and these were stored in a humidity room of constant temperature ($20 \pm 2^\circ\text{C}$) until the lapse of different planned curing times.

Oedometer tests were carried out after 7 and 28 days of curing. Unconfined compression (UC) and isotropically consolidated drained triaxial compression (CIDC) tests were run on samples after 28 days of curing. The rate of vertical displacement in UC tests was 1 mm/min. The effective confining pressures, σ'_c for CIDC test were 50, 100, 200 and 400 kPa. A back pressure of 190 kPa was maintained to ensure high levels of degree of saturation at all levels of testing. The rate of displacement was fixed at 0.0025 mm/min.

PARAMETERS

In concrete technology, Abrams' law (Abrams, 1918) is well known, stating as follows:

‘For given concrete ingredients, age and curing conditions, the strength of the hardened concrete is determined exclusively by the ratio of free water content to the cement content in the mix. Strength is in-

dependent of the absolute contents of free water and cement content in the mix.’

As an analogy the parameter that can be identified is clay-water/cement ratio, w_c/c , which is the ratio of the initial water content of the clay (%) to the cement content (%). The cement content, A_w is the ratio of cement to clay by weight both reckoned in their dry state. To obtain the same value of w_c/c , it is possible to vary the water content of the clay, or the amount of cement, or both as the case might be. In order to examine to what extent the applicability of w_c/c is valid, the water content of clay is varied over a wide range in this study. At high clay water content, the spacing between the clusters is large; hence, the required cement content is high to obtain the same level of w_c/c as at low clay water content. Cement contents as low as 8% and as high as 33% were adopted for the clay-cement mixtures of initial clay water content of 120% at w_c/c of 15 and initial clay water content of 250% at w_c/c 7.5, respectively. The specific reasons for identifying these parameters will be discussed in the section of analysis and discussion.

TEST RESULTS

Figures 1 to 3 present the compressibility data of the cement stabilized samples having the same w_c/c values but with different combinations of water content and cement content. They show the $(e, \log \sigma'_v)$ and $(\epsilon_v, \log \sigma'_v)$ relations of clay-cement mixtures at w_c/c ratios of 15, 10 and 7.5 after 7 and 28 days of curing. The compression index (C_c and C_s) and yield stress, σ'_y are presented in Table 1. The C_c and C_s are the slope of the $(e \sim \log \sigma'_v)$ plot at pre-yield stress and post yield stress, respectively. The yield stress is obtained as the point of intersection of two straight lines extended from the linear portions on either end of the compression curve plotted as $\log(1+e)$ against $\log \sigma'_v$ (Butterfield, 1980; Sridharan et al., 1991). The clay-cement mixtures were made up from four conditions of clay water content: 120%, 150%, 180% and 250%. The $(\epsilon_v, \log \sigma'_v)$ relationship is plotted so as to take care of the effect of the difference in void ratio for the vertical stresses less than the yield stress. In this range the cementation component is the dominant factor to resist compression. It is found that the yield stress and the deformation behavior at pre-yield stress of all samples having identical w_c/c are practically the same. But samples with a higher clay water contents are stable at higher void ratios and provide a higher compression indices beyond yield stress, especially for samples made up at a high water content of 250%. This is due to the break up of cementation bond, which is similar to the behavior of naturally cemented clay. The compression indices at post yield state of clay-cement mixtures having an identical initial clay water content are in almost the same order, even if they are made up from different cement content. It is also clear that the lower the value of w_c/c , the greater the enhancement of the yield stress. The clay-water/cement ratio affects not only the deformation characteristic, but also the rate of hardening related to hydra-

Fig. 1. Compressibility of cement-stabilized samples with same w_c/c value of 15 Fig. 2. Compressibility of cement-stabilized samples with same w_c/c value of 10

Fig. 3. Compressibility of cement-stabilized samples with same w_c/c value of 7.5

Table 1. Values of compression index and yield stress corresponding to w_c/c , initial clay water content and curing time

w_c/c	Initial water content (%)	Curing time (days)	C_s^*	C_c^*	Yield stress (kPa)
15	120	7	0.021	0.802	725
		28	0.018	0.807	820
	150	7	0.015	1.050	720
		28	0.011	1.122	810
	180	7	0.027	1.139	730
		28	0.023	1.226	850
10	250	7	0.030	1.442	720
		28	0.031	1.492	900
	120	7	0.007	0.915	1900
		28	0.010	0.850	2100
	150	7	0.018	0.804	1900
		28	0.020	1.011	2300
7.5	180	7	0.019	1.000	1700
		28	0.021	1.431	2150
	250	7	0.020	1.603	1800
		28	0.025	1.559	2000
	120	7	0.014	**	2900
		28	0.014	**	3500
	150	7	0.012	**	3000
		28	0.013	**	3600
	250	7	0.014	1.575	2800
		28	0.014	1.407	3400

* C_s and C_c are the slope of ($e \sim \log \sigma_v'$) plot at pre-yield stress and post yield stress, respectively.

** Data are insufficient to obtain appropriate value.

tion and pozzolanic reactions. Since the deformation patterns of samples having the same w_c/c are alike both for

Fig. 4. Stress-strain relationships of cement-stabilized samples in unconfined compression tests

7 and 28 days of curing, it is concluded that they have the same rate of hardening.

Figure 4 shows the typical stress-strain relationships in unconfined compression tests of samples with different initial water contents and different levels of cementing agent but at the same w_c/c ratio, at a curing time of 28 days. The w_c/c range included in this figure is 7.5 to 15. It reveals that the lower the w_c/c , the greater the enhancement of the cementation bond strength inducing higher strength. The similar stress-strain behavior of all stabilized samples having the same clay-water/cement ratio is

Fig. 5. Effect of w_c/c on drained behavior of cement stabilized samples at initial clay water content of 180% after 28 days of curing

Table 2. Basic properties of cement-stabilized samples for unconfined compression and triaxial tests after 28 days of curing

Initial water content (%)	Cement content (%)	w_c/c	Water content (%)	Density (kN/m^3)	Degree of saturation (%)
120	8	15	111	13.8	98
	12	10	103	14.1	97
	16	7.5	100	14.1	96
150	10	15	131	13.2	98
	15	10	120	13.4	96
	20	7.5	113	13.5	95
180	12	15	143	13.2	99
	18	10	138	13.2	98
	24	7.5	125	13.4	98
250	16.7	15	193	12.5	100
	25	10	168	13.0	100
	33	7.5	156	13.4	100

also shown. Table 2 shows the basic properties of the mixtures at 28 days of curing for unconfined compression and triaxial tests. It is found that the basic properties of

the clay-cement mixtures do not play any significant role in the development of strength.

In Fig. 5, the effect of clay-water/cement ratio, w_c/c on the deviator stress~shear strain and volumetric strain~shear strain relationships is manifested by the results of isotropically consolidated drained triaxial compression (CIDC) test, with variation in effective cell pressures from 50 kPa to 400 kPa, which is in the range of engineering consideration. The stress and strain parameters used in this analysis are

$$q = \sigma'_1 - \sigma'_3$$

$$p' = (\sigma'_1 + 2\sigma'_3)/3 \quad (\sigma'_2 = \sigma'_3)$$

and

$$\eta = q/p'$$

where σ'_1 , σ'_2 , σ'_3 are the principal effective compressive stresses, q is the deviator stress, p' is mean effective stress and η is stress ratio. Similarly, the shear strain, ϵ_s and the volumetric strain, ϵ_v are defined as

Fig. 6. Deviator stress and volumetric strain versus shear strain responses of samples at same w_c/c of 15 with effective cell pressures varying from 100 to 400 kPa

$$\varepsilon_s = 2(\varepsilon_1 - \varepsilon_3)/3$$

and

$$\varepsilon_v = (\varepsilon_1 + 2\varepsilon_3) \quad (\varepsilon_1 = \varepsilon_2)$$

where ε_1 , ε_2 and ε_3 are the principal natural compressive strains.

The axial strain ε_1 is defined as

$$\varepsilon_1 = \int_{L_0}^L \frac{dL}{L} = \ln \left(\frac{L_0}{L} \right) \quad (\text{compression being positive})$$

where L_0 is the initial height and L is the current height.

The volumetric strain ε_v is given by

$$\varepsilon_v = \int_{V_0}^V \frac{dV}{V} = \ln \left(\frac{V_0}{V} \right) \quad (\text{compression being positive})$$

where V_0 is the initial volume and V is the current volume.

It is clear that the strain softening behavior is found for these samples even for the samples with high w_c/c

and subjected to high effective cell pressures, σ'_c . The samples consolidated to a higher σ'_c sustain higher failure strain accompanied by greater deviator stress. The volumetric strain and shear strain relationships also show that the samples having a high w_c/c of 15 propagate similar relationships up to their peak deviator stresses, but their peak and ultimate volumetric strains are different and dependent on σ'_c . A higher σ'_c is generally associated with larger volumetric and shear strains. Samples having low w_c/c values of 10 and 7.5 show dilatant behavior at low deviator stress. The lower the value of effective cell pressure, the greater the degree of dilation. The dilation starts at lower levels of strain for samples, which are consolidated to a lower σ'_c .

The salient aspects of cement-stabilized samples having the same w_c/c are illustrated in Figs. 6 to 8, in which the variation of deviator stress and volumetric strain with shear strain for w_c/c variations of 15, 10 and 7.5 are presented. The characteristics before their peak deviator stresses of clay-cement mixtures with a high w_c/c value

Fig. 7. Deviator stress and volumetric strain versus shear strain responses of samples at same w_c/c of 10 with effective cell pressures varying from 100 to 400 kPa

of 15 are the same for all the effective cell pressures, and slightly diverse approaching the peak deviator stresses. Finally they get close to the same ultimate point (the residual state). In the case of the clay-cement mixtures with low w_c/c values of 7.5 and 10, their (q, ϵ_s) relationships are alike for samples subjected to a low effective cell pressure of 100 kPa. For samples subjected to high effective cell pressures, their (q, ϵ_s) relationships and the shear moduli are the same up to a certain level. Samples with a high clay water content of 250% exhibit higher shear strain at peak deviator stress and lower shear modulus. However, the peak deviator stresses of the samples made up both at low and high clay water contents are almost of the same order. The volumetric strain~shear strain relationships of stabilized samples are also presented in Figs. 6 to 8. The volume change behavior of all samples with a high w_c/c value of 15 shows a similar manner up to their peak volumetric strains, but their ultimate volumetric strains are slightly different. For samples with a low w_c/c of 7.5 and 10 and subjected to low σ'_c of 100

kPa, their relationships are almost the same. However, samples subjected to high effective cell pressures of 200 and 400 kPa exhibit similar characteristics up to a certain level, and then samples with a 250% clay water content attain higher peak volumetric strain.

ANALYSIS AND DISCUSSION

From the above test results, it is revealed that the w_c/c is the prime parameter influencing the engineering behavior of cement-stabilized clay. Often the treatment of clays done conventionally in highway stabilization involves mixing of the clay in a relatively dry state with cement and the water content specified for compaction. What happens to the clay in the presence of moisture and cementing agents is that the clay gets transformed - into modified clay i.e., grouping of particles takes place due to physico-chemical interactions with clay~cement~water interactions. Since these are at the particle level, it is not possible to get a homogeneous mass

Fig. 8. Deviator stress and volumetric strain versus shear strain responses of samples at same w_c/c of 7.5 with effective cell pressures varying from 100 to 400 kPa

which can exhibit the desired levels of strength. External compactive effort is needed to transform this modified soil to a soil state with locked in prestress so as to act as an engineering material. The same is not the case when high water content clays are mixed with cement. It is not the clay to which admixture is made available but to an interacting clay-water system. The interacting clay-water system cannot be identified by clay but by water content. This aspect has been amply elaborated by Nagaraj et al. (1997; 1998). It is useful to explain the engineering behavior of cement-stabilized clay based on its structure. It is preferable to use structure to refer to the fabric that is an arrangement of particles, particle group and pore spaces in the soil as well as cementation. A cluster is a grouping of particles or aggregates into large fabric units and a fabric composed of grouping of clusters (Mitchell, 1993).

The cementing agents can be assumed to drift to the spacing between clusters due to the electro-chemical nature of interaction, and to weld the fabric by gel as subsequent hydration of cement takes place. Hence, there is a possibility of the clay-water/cement ratio reflecting the

contribution of the final structure formed. This structure is a combination of fabric and cementation, so the basic properties of the clay-cement mixtures do not play any significant role in the strength and deformation behavior.

The liquid limit state is the state that the microfabric will form such that the addition of cement will not alter the liquid limit as long as the liquid limit is determined with the initial setting of cement. On the contrary, when the dry clay is mixed with water to be closer to the plastic limit along with cement, it will exhibit the property of a modified soil. Due to the formation of clay clusters, which can hold water caused by the cementation, the plastic limit will increase. As a result, the liquidity index, LI of the clay-cement mixture immediately after mixing with cement increases since the plasticity index is used as the denominator while the clay water content insignificantly changes.

The results reported by Uddin et al. (1997) reinforce the above postulation. The change in the liquid limit due to the treatment is insignificant. On the other hand, the plastic limit significantly increases with cement content

and curing time. Thus, the decrease in the plasticity index of the mixture is recognized due to the significant increase in the plastic limit of the mixture. The change in water content is minimal. As a result, the liquidity index is supposed to increase after adding cement admixture.

Micromechanistic Explanation

Earlier works (Yamadera et al., 1997; Nagaraj et al., 1998) on compressibility and permeability characteristics and pore size distribution data have enabled us to infer that the fabric of soft clay both in uncemented and induced cemented states at the same void ratio is of the same pattern. Hence, the role of induced cementation is to weld fabric. Yamadera et al. (1997) analyzed the strength data with the water content as one of the variables from three different clays at the liquid limit water content, since they considered that the fabric pattern of all soils at such a state is the same. With the liquid limit of clay as a variable parameter, the previous analysis indicated (Yamadera et al., 1997) that as the liquid limit water content of the clay increases the spacing between clusters as well as that between particles increases; hence, strength developed for the same cement content decreases. To enhance the strength to the same level, the cement content has to be increased. Definitely, the identification of the fabric pattern is important to identify the possible cementation sites but it is not complete by itself since the structural state (fabric and cementation) cannot be reflected by the parameter water content alone. The experimental observations in this investigation indicate that it would be advantageous to include the cement content in the same parameter since it would take care of the bonding component of the state represented by water content. Hence, clay-water/cement ratio, w_c/c , is an integrated parameter of the structural state of the soft clay in its induced cemented state. It is a convenient parameter to adjust cement content in order to get the same level of strength with the same curing time.

Analysis of Compression Behavior in K_0 -Consolidation

Figures 1 through 3 reveal that resistance to compression is markedly enhanced before drastic compression occurs, as vertical pressure increases. This is attributed to the induced cementation bond created by cement. It has been observed that as the clay-water/cement ratio increases, which means that cement content is decreased, the yield stress reduces. As the curing time increases for the same input condition, the yield stress further increases. Thus, it implies that the yield stress of the stabilized clay increases with increase in curing time and decrease in w_c/c . It is also revealed that, for Ariake clay with four levels of water content i.e., 120%, 150%, 180% and 250%, the yield stress is practically the same as long as the w_c/c value is identical; the fabric is not taken into account. The effect of fabric plays a dominant role on the compressibility after the yield state in which the cementation bond is broken down. This is reinforced by results showing that clay-cement mixtures with higher clay water contents undergo higher settlement at post-

yield state. This leads to the conclusion that the role of cement admixture is to increase the yield stress in K_0 -consolidation, resulting in an increase in the yield surface and failure envelope. However, the resistance to plastic deformation is governed by the fabric.

Analysis of Stress~Strain and Strength Characteristics

The test results show that the engineering behavior of cement-stabilized clay is dependent upon the clay-water/cement ratio, w_c/c and fabric. The role of w_c/c is that the lower the w_c/c , the greater the yield stress, resulting in enhancement of the yield surface, which means that the failure envelope gets increased; hence, the strength increases. However, the stress~strain behavior is governed by the fabric (clay water content). The higher the water content, the greater the spacing between clusters; this leads to a decrease in shear modulus and an increase in volumetric strain.

With the initial clay water content at $LI=1.0\sim 2.0$, the w_c/c has a greater influence on the engineering behavior than the fabric. The engineering behavior of the mixtures subjected to low and high effective cell pressures is identical as long as the w_c/c is the same, and the clay-cement mixture with lower w_c/c develops higher deviator stress.

If the initial clay water content is high (viz. 250%), the w_c/c and fabric both play a dominant role in the engineering behavior depending upon the effective cell pressure condition and level of cement content. The fabric becomes the significant factor for the clay-cement mixtures made up at low w_c/c (10 and 7.5) and subjected to high effective cell pressures ($\sigma'_c=200$ and 400 kPa). The (q, ϵ_s) and (ϵ_v, ϵ_s) relations of samples having the same w_c/c are identical at the initial state up to a certain level, and samples with a high clay water content of 250% exhibit lower volumetric and shear strains (Figs. 7 and 8). This can be explained by the fact that the engineering behavior is initially governed by the cementation bond, and then the stress paths proceed up to a certain level where the cementation bond is broken down. At this level, the samples at a high initial clay water content of 250% exhibit higher shear modulus and higher volumetric strain because of the large spacing between clusters. On the other hand at a low effective cell pressure (viz. 100 kPa), the effective cell pressure is far lower than the yield stress and thus the change of fabric is minimal during shearing. As a consequence, all samples having the same w_c/c both made up at low and high clay water contents exhibit identical deviator stress and volumetric strain versus shear strain response.

At a high w_c/c of 15, the (q, ϵ_s) and (ϵ_v, ϵ_s) relationships of the clay-cement mixtures of low and high clay water contents, subjected to various confining pressures (from 100 to 400 kPa) are identical. This means that the fabric does not play any significant role in the engineering behavior of cement stabilized clay at a high w_c/c value. This fact is further strengthened by having fabric pattern that varies over a wide range in terms of water content increased from 120 to 250 percent (Fig. 6).

We will now examine why the strength determined by

Fig. 9. Relationship between unconfined compressive strength and cement content of cement-stabilized Hong Kong clay (Yin and Lai, 1998)

Fig. 10. Generalization of unconfined compressive strength of cement-stabilized Hong Kong clay

unconfined compression test of stabilized samples made up at an initial clay water content of $LI=1.0\sim 2.0$ (water contents are between 120% and 180%) exhibits the same level as long as the clay-water/cement ratio is the same (Fig. 4). This is essentially attributed to the cementation bond characteristics. The contribution by the water content of the clay to the stress-strain characteristics is far

lower than that due to the w_c/c (the fabric does not play any significant role in this range); thus the cementation bond is the same for mixtures having the same w_c/c .

When the water content of clay is high and the clay-water/cement ratio is low (e.g. water content=250% and $w_c/c=7.5$), the strength of the clay-cement mixture is slightly lower than that at a lower clay water content be-

cause the spacing between clusters is large, resulting in a reduction in shearing resistance. However, this effect from the fabric is modest when the clay-cement mixtures are made up at a low cement content, such as at a w_c/c of 15. The stress-strain behavior of the stabilized samples at the same w_c/c exhibits identical modulus since the confining pressure equals zero in the unconfined compression test; hence, all samples fail inside the yield surface and the elastic behavior can be recognized according to state boundary surface (Balasubramaniam, 1973, 1975). From the above results, it can be concluded that the lower the w_c/c , the greater the yield stress in K_0 -consolidation and failure envelope; however, the characteristics of plastic deformation and stress-strain behavior are governed by the fabric.

The application of the w_c/c to the other clay types has been investigated based on the relation between unconfined compressive strength and w_c/c , which was proposed by Horpibulsuk et al. (2001). The test results of cement-stabilized Hong Kong clay, which have been reported by Yin and Lin (1998), were reanalyzed and are shown in Figs. 9 and 10. Figure 10 shows that a unique relationship between the unconfined compressive strength and the w_c/c can be realized for the cement-admixed Hong Kong clay at different initial clay water contents. Horpibulsuk et al. (2001) have proposed the relationship between unconfined compressive strength and w_c/c at a certain curing time as follows:

$$q_u = \frac{A}{B^{(w_c/c)}}$$

where q_u is the unconfined compressive strength, w_c/c is the clay-water/cement ratio, and A and B are constants. Figure 10 is an example to reinforce the applicability of the w_c/c as a prime parameter for the cement stabilized clays.

CLAY-WATER/CEMENT RATIO HYPOTHESIS

From the oedometer, unconfined compression and triaxial test results, the clay-water/cement ratio hypothesis is proposed based on the critical state and state boundary surface concepts (Roscoe et al., 1958). The clay-water/cement ratio is described for explaining the drained behavior as follows:

1) The lower the w_c/c , the greater the enhancement of the cementation bond strength, resulting in increase in the yield stress in K_0 -consolidation and yield surface.

2) Clay-cement mixtures having the same w_c/c possess the same level of yield stress even when they are mixed from different clay-water content and cement content. The cementation effect of the mixtures having the same w_c/c can be classified into two groups.

2.1) One with the same value of w_c/c , induces the same yield stress and resistance to plastic deformation, which corresponds to the mixtures admixed at a high w_c/c such as 15. Thus their (q, ε_s) and $(\varepsilon_v, \varepsilon_s)$ relationships are similar, as shown in Fig. 6.

2.2) The other with the same w_c/c value, induces only the same yield stress, which corresponds to mixtures with low w_c/c values such as 10 and 7.5. For the samples subjected to low effective cell pressure such as 100 kPa, the samples are inside the state boundary surface; hence, their elastic behavior is the same until failure, as shown in Figs. 7 and 8.

For samples subjected to high effective cell pressures, their (q, ε_s) and $(\varepsilon_v, \varepsilon_s)$ relationships are the same at the initial state up to a certain stress ratio, η and samples with higher clay water content exhibit higher volumetric and shear strains at the same stress ratio, η . Such behavior can be explained by the fact that, while the initial states of stress of all samples are inside the state boundary surfaces, they have the same mean effective yield

Fig. 11. Stress ratio and volumetric strain relationship of stabilized samples with same w_c/c of 7.5

stress in the K_0 -line. This is attributed to the yield stress being the same. Thus, the elastic behavior is recognized for these samples. Samples with a higher clay water content undergo higher volumetric deformation when the states of stress are on the state boundary surfaces due to the break up of the cementation bond. The transformation of the small strain zone into the large strain zone occurs at a smaller stress ratio, η for samples with a higher clay water content, as illustrated in Fig. 11.

CONCLUSIONS

Based on the test results, it is evident that the clay-water/cement ratio is the prime parameter for analysis of strength and deformation behavior of induced cemented clay at high water content. This parameter is a structural parameter reflecting the influence of both fabric of clay as reflected by its water content and cement content reflecting the level of cementation. At the micro level, it is a combination of fabric and the level of welding of the fabric resulting in the structure of the clay imparting its characteristics of the cemented state. The following conclusions can be drawn:

- 1) For a given soft clay, the cementation bond strength increases as the clay-water/cement ratio, w_c/c decreases. It is demonstrated by the test results of oedometer and unconfined compression tests that the yield stress in K_0 -consolidation of samples increases with the decrease in w_c/c , and samples having the same w_c/c develop practically the same level of yield stress. The stress ~ strain behavior and strength characteristics in the unconfined compression test are practically the same as long as the w_c/c is identical.
- 2) For samples made up at a high w_c/c such as 15, the drained behavior in triaxial test is governed only by w_c/c . The engineering behavior is identical as long as the w_c/c is the same, which is strengthened by test results of samples with water contents varying from 120% to 250%.
- 3) Only the w_c/c is a prime parameter governing the engineering behavior of samples made up at a low w_c/c (such as 10 and 7.5) and subjected to low effective cell pressure, because all clay-cement mixtures exhibit the same elastic behavior. The same stress ~ strain relationships are realized for all samples having the identical w_c/c .
- 4) The fabric has a great influence on the stress ~ strain behavior for samples made up at a low w_c/c and subjected to high effective cell pressures. Their states of stress lie on the state boundary surface where the samples exhibit elastoplastic behavior. It is revealed that samples having the same w_c/c develop practically the same peak deviator stress. However, samples with a high clay water content (the initial water content is 250%) undergo low shear modulus and high volumetric strain. The effect of fabric is also clearly elaborated by the oedometer test results showing that samples having higher clay water contents sustain higher volume change after the yield state.
- 5) For the improvement of soft clay at a high water

content by cement admixture in shallow and deep foundations, in which the water content of the clay varies in the range of liquidity index between 1.0 and 2.0, the w_c/c value is the prime parameter governing the engineering behavior of cement stabilized clays both in compressibility and shear behavior, whereas the effect of fabric can be negligible.

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