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MECHANISM CONTROLLING UNDRAINED SHEAR CHARACTERISTICS OF INDUCED CEMENTED CLAYS

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ABSTRACT: Understanding of undrained shear behavior of induced cemented clay is of utmost importance for strength and deformation analyses of in-situ deep mixed columns under short-term condition. From the critical analysis of two different clays (Bangkok and Ariake clays) admixed with cement, the difference in undrained shear responses of the induced cemented and uncemented clays are brought out. Since the induced cemented clays are in meta-stable state, the strength and deformation characteristics are controlled by the clay fabric and cementation. At pre-yield state, the cementation is the main contributing factor of the strength while the effect of fabric comes into play when the state of stress is at post-yield state. The strain softening behavior is realized even at post-yield state, attribute to the break up of the cementation bond. The failure envelope of the induced cemented clay is a single straight line for both pre- and post-yield states, which is different from that of uncemented clay. The role of the cement is mainly to increase the cohesion intercept with insignificant change in internal friction angle.

Keywords: Cementation, induced cemented clay, fabric, isotropically consolidated undrained triaxial compression (CIUC) test, strength and deformation characteristics

INTRODUCTION

For the improvement of the soft ground by the chemical admixture such as in-situ deep mixing technique, the natural clay is disturbed by mixing wings and mixed with cement or lime. The natural cementation is destroyed and taken over by the admixture cementation. The clay-cement mixture is called “Cement Admixed Clay” or “Induced Cemented Clay” (Horpibulsuk et al. 2004b). The investigations for understanding the behavior of induced cemented clay, which have been examined by earlier researchers, are limited. Most of the investigations are conducted on samples with low cement contents and limited effective confining pressures, while in-situ soil-cement columns are generally designed at medium to high content of cement in which the effective pressure increases with depth. Hence, the typical characteristics of induced cemented clay under undrained shear and controlling mechanisms have not been well brought out so far. Wissa et al. (1965) have indicated that the residual strengths show no effect of cementation and can be described by a single strength envelope independent of amount of cementation. Clough et al. (1981) have studied the induced and naturally cemented sands under static loading. Their conclusion is that the failure envelopes of both the cemented and uncemented sands are essentially straight lines with nearly the same slope. The cohesion intercept increases with increasing amount of cement and the friction angle is not affected by cementation. Kasama et al. (2000) have carried out the consolidated undrained triaxial compression test of induced cemented Ariake clay at low cement content. They have summarized that the failure envelope of clay with cementation is parallel to that of uncemented clay. Balasubramaniam and Buensuceso (1989) investigated the strength and deformation characteristics of lime admixed Bangkok clay under undrained and drained triaxial compression conditions. Based on the stress-strain characteristics, stress path, pore pressure development and volume change behavior, they have reported that the lime treatment causes a change in strength and deformation characteristics of the soft clay from a normally consolidated clay to that of an overconsolidated clay. The novel parameter governing the strength and deformation characteristics of clay-cement mixtures wherein the water content and cement content vary over a wide range has been successfully introduced (Miura et al., 2001 and Horpibulsuk et al., 2005). It is designated as clay-water/cement ratio, w_c/C, which is the ratio of clay water content (%) to cement content (%). It is the structural parameter since the clay water content, w_c, controls the clay fabric and the cement content, C, reflects the degree of cementation. For a given soil admixed with cement, the lower the w_c/C, the greater the strength. The application of this proposed parameter has been incorporated with Abrams’ Law to predict the strength development (Horpibulsuk et al., 2003). From these studies, it is concluded that the structure controls the engineering behaviour of the induced cemented clays.

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Despite the availability of information on the factors controlling the engineering characteristics of induced cemented clay (mentioned above), additional experiments are necessary to understand roles of the cementation and the fabric on the undrained shear behavior and the mechanism controlling shear strength characteristics. Such understanding would facilitate engineering decision on strength and deformation analysis. Also it would be a fundamental for modeling the shear responses of induced cemented clays. This paper reports on an attempt at meeting these objectives. A brief discussion of the basic characteristics of soft clay in uncemented and cemented states precedes details of the experiment.

CHARACTERISTICS OF SOFT CLAYS IN UNCEMENTED AND CEMENTED STATES

The engineering behavior of clays has been recently explained based on the microstructural viewpoint. Mitchell (1993) stated that the engineering behavior of the clay is governed by its structure, which is the inter-particle force and fabric. Nagaraj et al. (1990) have introduced the possible microstructure of fine grained soil based on the diffusion and cluster theory as well as pore size distribution data as shown in Fig. 1. It is illustrated that there are three levels of pores.

a) Intra-aggregate pore between the individual clay platelets in an aggregate with pore diameter less than 20Å.
b) Inter-aggregate pore between two interacting aggregates with diameter between 20Å and 200Å depending on the applied equilibrium pressure.
c) Intra-aggregate large pores held within the group of clusters by surface tension with diameter greater than 200Å.

It is revealed that in a clay-water system, the transfer of the stress takes place through an interacting fluid phase. The soil state realized is due to the equilibrium between the long-range forces and the externally applied stress. Srinivasa Murthy et al. (1988) and (1991) considered the load transfer through physico-chemical interactions and brought out that for clay at normally consolidated state during shear, the clay fabric is distorted to resist the deviator stress as shown in Fig. 2. The dismembering of the clay clusters happens when the clay is at overconsolidated state. The clusters get dismembered during shear; hence, releasing the locked-in energy and causing dilatancy. Their conclusion is strengthened by the microscopic photos and pore size distribution analysis of uncemented and naturally cemented Ariake clay under consolidation as well as under undrained and drained shear (Miura et al., 1999; and Yamadera, 1999).

It is now proposed to examine what is likely to happen when soft clays are admixed with cementing agents. In the case of cement based composites, cement being the only interacting material, the hardened cement paste would provide continuity to its structure with the

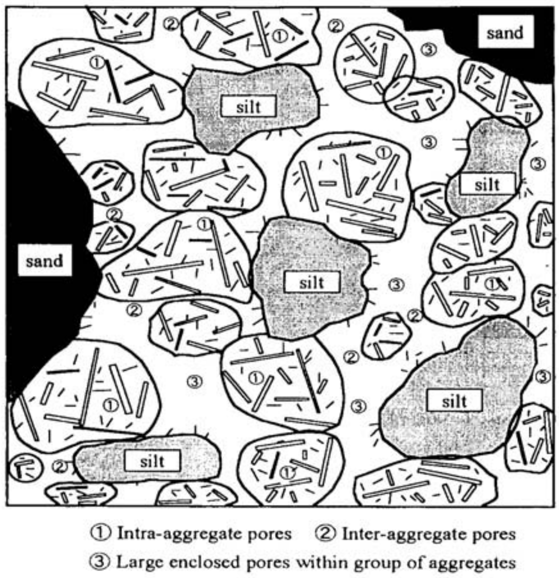

Fig. 1 Structure of clay (Nagaraj et al., 1990)

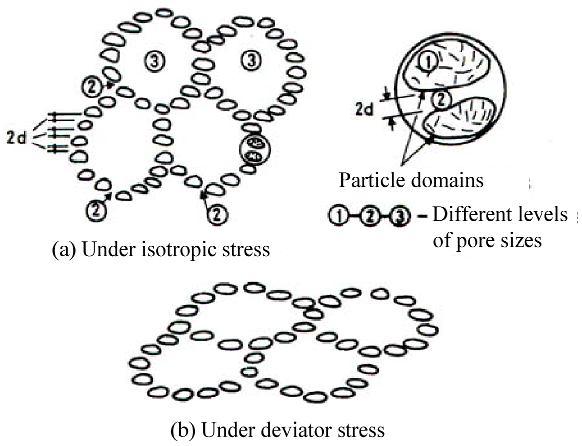

Fig. 2 Structure of clay under (a) isotropic stress and (b) deviator stress (Srinivasa Murthy et al., 1991)

coarse constituents being in the embedded state. In the case of soft clay, the clay is already holding certain level of moisture. Due to physico–chemical interactions with water, the soft clay would have been already transformed into an engineering material with effective stress level corresponding to matrix suction of low but definite value (Nagaraj and Miura, 2001). The soft clay would have a specific micro-fabric formed due to the interacting nature of the clay. Hence, the cementing agents would have freedom to drift to the spacing between clusters and weld the fabric so as to result in a structured state with a defined initial fabric pattern (Miura et al., 2001).

The cementation bonds are treated as a short-range attraction and there is nothing in principle to bar the co-existence of the long-range forces and cementation bonds (Mitchell, 1993; and Nagaraj and Miura, 2001). Hence, the resistance mobilized due to the cementation can operate simultaneously (Fig. 3). As such to understand the undrained shear response, the role of the fabric and the cementation must be brought out.

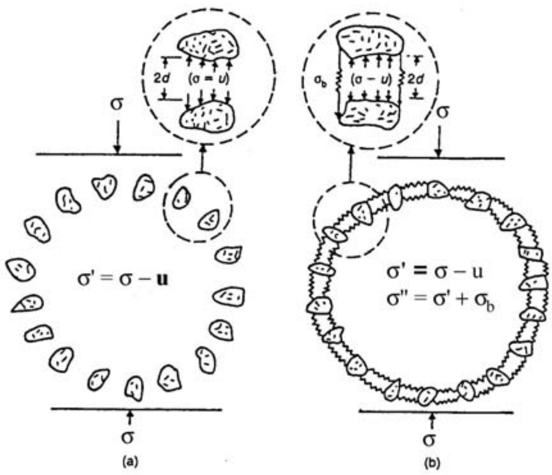

Fig. 3 (a) Microfabric of uncemented clay and (b) Structure of the induced cemented clay (Horpibulsuk et al., 2003)

EXPERIMENTAL INVESTIGATION

Soil Sample

Bangkok clay samples were collected from the campus of Asian Institute of Technology, Bangkok, Thailand for the present investigation. Soil sampling was carried out by an excavator to remove surface weathered soil up to a depth of 3 m. The representative clay sample was collected by an excavator and transferred into plastic containers. This soft soil is dark grey clay generally composed of 72 percent clay, 27 percent silt and only 1 percent sand. The clay is highly plastic with natural water content in the range of 80-90 percent. The bulk density and specific gravity of the soils are 15.0 kN/m^3 and 2.67, respectively. The liquid and plastic limits are in the order of 94 and 38 percent, respectively. The groundwater is located at about 1 meter from the ground surface. The undrained shear strength (S_u) is 15 kPa and the effective strength parameters in compression are c' = 0 and ϕ' = 25.4°.

Methodology of Testing

The clay paste was passed through 2-mm sieve for removal of bigger size particles. The water content of the clay was adjusted to 100%. This intentional increase in water content is to simulate water content increase taking place in wet method of dispensing cement admixture in deep mixing. The clay along with Type I Portland cement at cement content varying from 5% to 15% is thoroughly mixed to obtain a uniform dispersion in the slurry. Cement content, C, is defined as the ratio of cement to clay by weight reckoned in their dry state. The mixing time was arbitrarily fixed at 10 min as done by Miura et al. (2001). The uniform paste was then transferred 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 were wrapped in vinyl bags and stored in a humidity chamber of constant temperature (20±2 °C).

Isotropically consolidated undrained triaxial compression (CIUC) test was run on samples after 28 days of curing. Since Horpibulsuk et al. (2003) revealed that the formation of the cementation is insignificant after 28 days of curing, the effect of the formation of the cementation during consolidation can be ignored, and only the effects of break up of the cementation and the change in fabric are reflected. The effective confining pressures, σ'_c, for CIUC test were 50 to 1200 kPa depending upon the cement content. A backpressure of 190 kPa was maintained to ensure high levels of degree of saturation at all levels of testing. The rate of compression was fixed at 0.0075 mm/min. All the tests were conducted according to the procedure recommended by Head (1998). The stress and strain parameters used in this analysis are calculated as follows:

$$q = \sigma_1 - \sigma_3 \qquad (1)$$

$$p' = \left(\frac{\sigma'_1 + 2\sigma'_3}{3}\right) \qquad (\sigma'_2 = \sigma'_3) \qquad (2)$$

where σ'_1, σ'_2, and σ'_3 are the principal effective compressive stresses, q is the deviator stress, and p' is the mean effective stress.

In addition to the results of induced cemented Bangkok clay, some test results of induced cemented Ariake clay (Horpibulsuk et al., 2004b) are reanalyzed and presented to reinforce the author's discussions and conclusions. This soft soil is gray silty clay generally composed of 55 percent clay, 44 percent silt and only 1 percent sand. It is highly plastic with natural water content in the range of 135-150 percent. The liquid and plastic limits are in the order of 120 and 57 percent, respectively. The effective strength parameters in compression are c' = 0 and ϕ' = 38°.

TEST RESULTS AND DISCUSSIONS

The relationships between void ratio and mean effective stress (e, log p') of the induced cemented Bangkok clay at different cement contents are presented and compared with the relationship of the uncemented (remolded) clay in Fig. 4.

It is noted that the void ratio of the induced cemented clay does not exactly correspond to $e = w_cG$ (G is the specific gravity of clay) for initial clay water contents indicated since upon admixing with cement, it is less due to the fact that hydration products increase the solid weight and the water weight reduces due to utilization of water by cement.

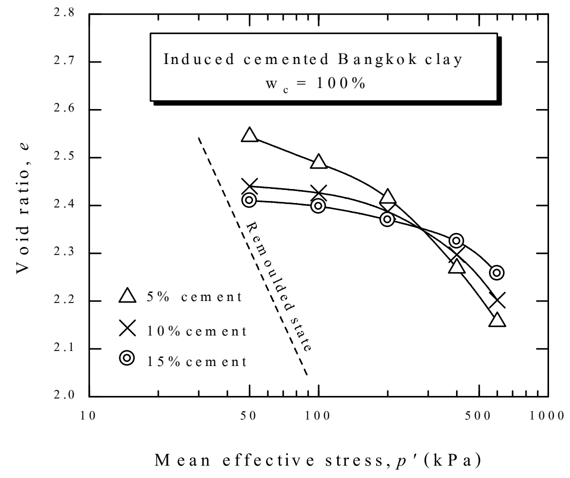

Fig. 4 (e, log p') of induced cemented Bangkok clay at cement content of 5, 10, 15 and 20% at the same initial water content of 100%

Due to the cementation effect, the compression paths of induced cemented samples lie above the path of uncemented sample at the same effective confining pressure. The resistance to compression of induced cemented samples prevails up to a certain stress level beyond which the samples exhibit a large compression. Horpibulsuk et al. (2005) identified this stress level as the yield stress. It does not represent preconsolidation or maximum past pressure since the induced cemented clay was not being subjected to any stress history. 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 p'(Butterfield, 1979 and Sridharan et al., 1991). The mean effective yield stresses, p'_y values are 140, 250, and 400 kPa for cement contents of 5, 10 and 15 percent, respectively.

Deviator Stress vs Axial Strain and Excess Pore Pressure vs Axial Strain Relationships

In order to understand the effect of cementation and fabric on the undrained shear behavior and the strength characteristic of the induced cemented clay, the isotropically consolidated undrained triaxial compression test results at pre- and post- yield states (effective confining pressures, σ'_c, lower and higher than the mean effective yield stress) of induced cemented Bangkok clay are presented and compared with those of induced cemented Ariake clay (Horpibulsuk et al., 2004b).

The typical characteristic shape of the (q, ε_a) and (Δu, ε_a) curves of induced cemented clays at both pre- and post- yield states are presented in Figs. 5 and 6, respectively. It is shown that at pre-yield state the deviator stress increases to a peak value and then reduces to a lower value of q. It is clear that the peak deviator stress is insignificantly influenced by the effective confining pressures. However, the strength of the induced cemented clay is much higher than that of uncemented clay at the same effective confining pressure. Although the (q, ε_a) plots of the induced cemented clay samples are essentially the same, the development of excess pore pressure is different. This depends upon the level of effective confining (pre-shear consolidation) pressure, σ'_c. Due to the peak deviator stress being practically the same for all effective confining (pre-shear consolidation) pressures, the peak excess pore pressure must increase with increasing effective confining pressure so as to reduce the mean effective stress and normal effective stress at failure. After the peak state, the excess pore pressure starts declining and levels off at the residual state.

The (q, ε_a) and (Δu, ε_a) relationships of the induced cemented clay at post-yield state rise up to the peak deviator stresses and peak excess pore pressures at low strain and then level off at the residual state (*see* Fig. 6). The peak strength increases with the increase in the effective confining pressure, σ'_c due to the significant change in fabric. The peak deviator stresses of the induced cemented clay are higher than those of the uncemented clay due primarily to the cementation bond.

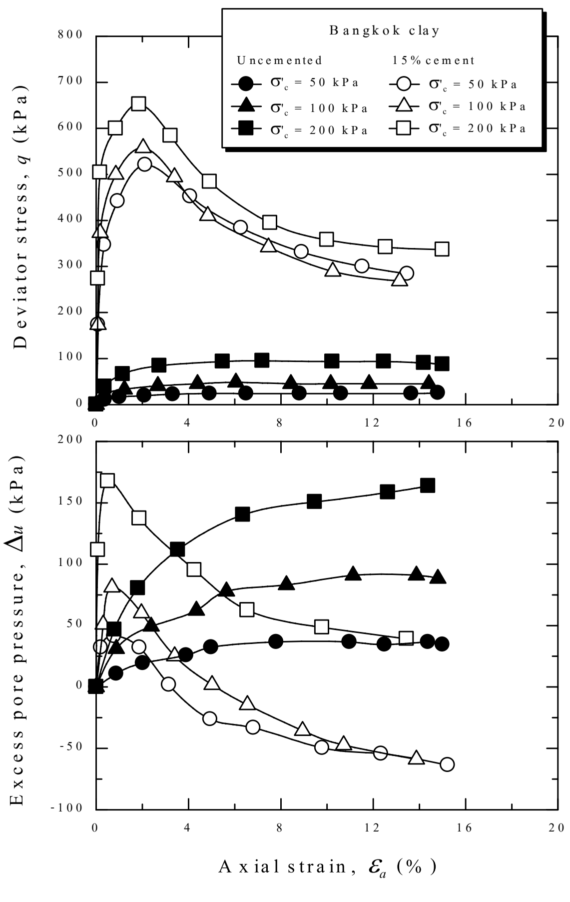

Fig. 5 (q, ε_a) and (Δu, ε_a) of induced cemented Bangkok clay at pre-yield state and at cement content of 15%

In order to compare the typical characteristic of the excess pore pressure development of induced cemented clay and overconsolidated uncemented clay, the relationship between normalized excess pore pressure and axial strain ($\Delta u/\sigma'_c$, ε_a) of the induced cemented clays is presented in Fig. 7.

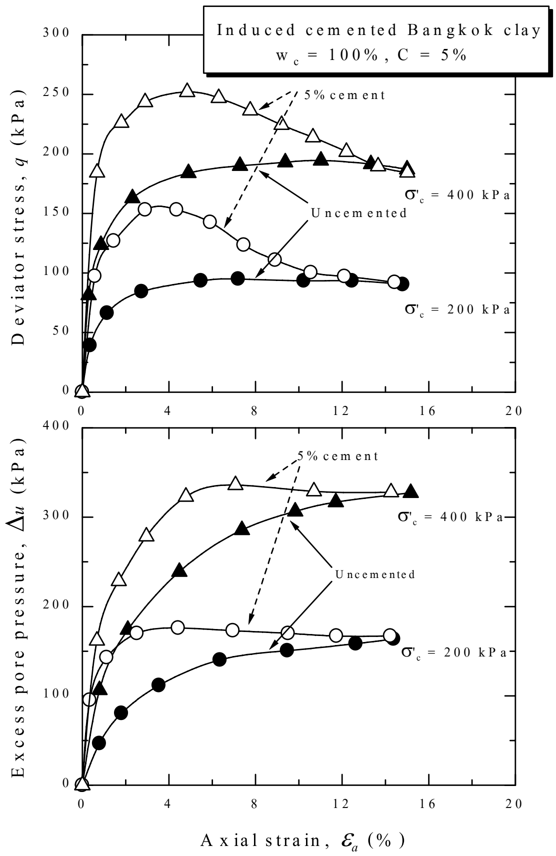

Fig. 6 (q, ε_a) and (Δu, ε_a) of induced cemented Bangkok clay at post-yield state and at cement content of 5%

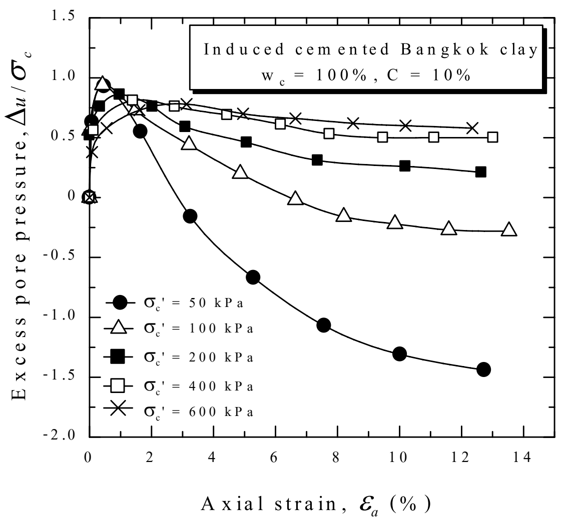

Fig. 7 Typical ($\Delta u/\sigma'_c$) relationship of induced cemented Bangkok clay

It is found that the maximum normalized excess pore pressure $(\Delta u/\sigma'_c)_{max}$ is practically the same for both pre- and post-yield states. This behavior is similar to that of uncemented normally consolidated clay. This is probably because the induced cemented clay is stable in the meta-stable state; hence, the effective confining pressure is the main factor affecting the excess pore pressure development. However, at maximum excess pore pressure, the strain for each confining pressure is different. The higher the effective confining pressure, the greater the strain at the maximum pore pressure. After the peak state, the ($\Delta u/\sigma'_c$) decreases as axial strain increases and finally levels off at the residual state. On the other hand, it has been known that the maximum normalized excess pore pressure, $(\Delta u/\sigma'_c)_{max}$ increases with the decrease in *OCR* (in other words, the increase in the effective confining pressure) for the overconsolidated uncemented clay due to the interlocking effect (dismembering of the clusters).

Undrained Stress Path

The typical undrained stress paths of the induced cemented clays subjected to the effective confining pressures lower than the mean effective yield stress is shown in Fig. 8.

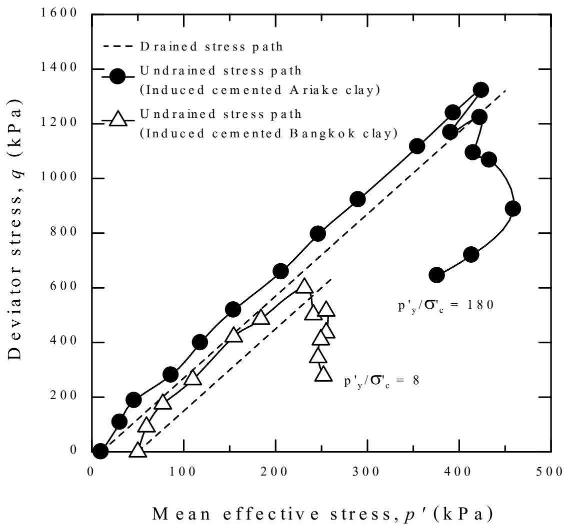

Fig. 8 Undrained stress paths of induced cemented Ariake and Bangkok clays under very low effective confining pressure

It shows the results of induced cemented Bangkok and Ariake clays, subjected to very low effective confining (pre-shear consolidation) pressures of 10 and 50 kPa, respectively along with drained stress paths. The ratios of mean effective yield stress to effective confining pressure (p'_y/σ'_c) are 180 and 8 for induced cemented Ariake and Bangkok clays, respectively. It shows that the undrained stress paths locate on the left side of the drained stress paths up to the peak values.

Afterwards, the paths move to the right side of the drained stress paths and level off possibly due to interlocking after peak state.

To examine the strength characteristics of the induced cemented clay at short and long term strength, the undrained and drained stress paths along with the failure envelope of induced cemented Ariake clay are presented in Fig. 9. It is of interest to mention that the long-term strength of cement admixed clays under the loading condition of compression is always higher than the short-term strength. On the other hand, it is long known that the short-term strength is higher for heavily overconsolidated uncemented clays due to the interlocking effect.

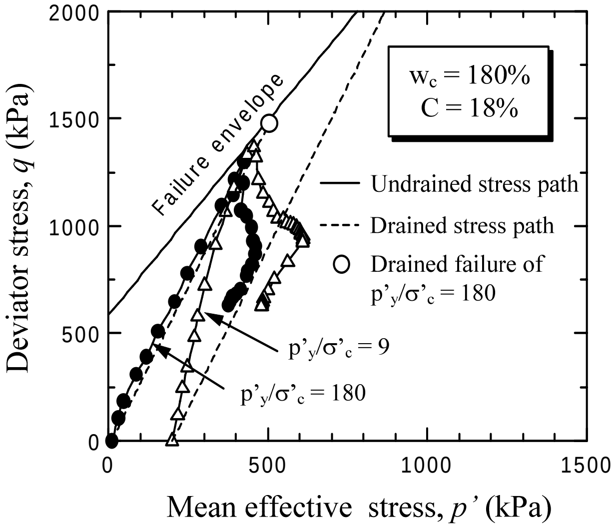

Fig. 9 Undrained stress paths of induced cemented Ariake clay at 18% cement and very low effective confining pressure

Figure 10 shows the typical characteristic of undrained stress paths of the induced cemented Bangkok clay. The solid line in the figure shows the critical state line of the uncemented clay. It is clear that the failure state of the induced cemented clay is located above the critical state of uncemented clay, attributed to the cementation bond. The degree of cementation does not affect the residual state since the residual state line of the induced cemented clay and the critical state line of uncemented clay are practically identical. This finding is in agreement with that of cement admixed sand (Clough et al., 1981). The characteristic of the induced cemented paths is similar to that of the uncemented paths. The path moves to the left side since the excess pore pressure development is positive. It implies that the induced cemented clays exhibit the elastoplastic behavior when the stress state lies on the state boundary surface.

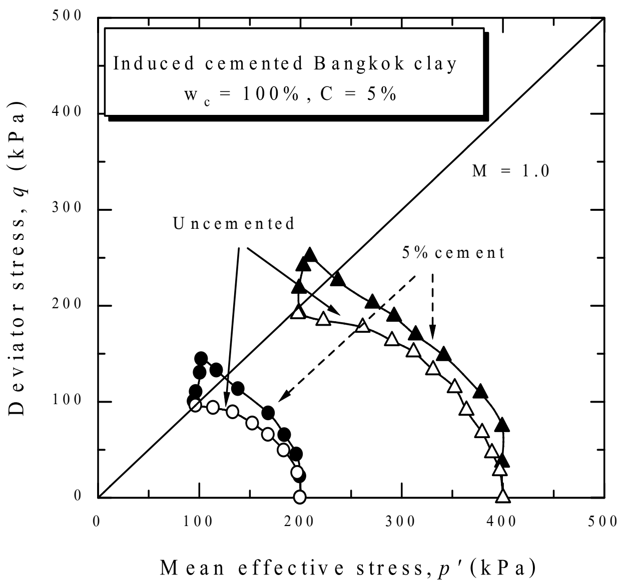

Fig. 10 Undrained stress paths of 6% cement Bangkok clay

Failure Envelope

Figures 11 and 12 show the typical undrained stress paths and failure envelope of the induced cemented Bangkok and Ariake clays, subjected to the effective confining pressures lower and higher than the mean effective yield stress.

The dotted lines in the figures are the failure envelope of the uncemented clays, which is drawn based on the effective confining pressures between 50 and 600 kPa. The prominent aspect, which is different from that of the uncemented clay, is that for a particular clay admixed with cement at a particular cement content, the failure envelope is a single straight line for both states at effective confining pressures lower and higher than the mean effective yield stress. On the other hand, the failure envelope consists of two straight lines for uncemented clays, separately for normally and over consolidated states because the interlocking is the main contribution to the peak strength at the overconsolidated state.

Figures 13 and 14 show the relationships between internal friction angle and cement content and cohesion intercept and cement content, respectively for induced cemented Bangkok and Ariake clays. It is found that the failure friction angle of the induced cemented clay for both low and high cement contents is practically the same as that of the uncemented clay as shown in Figure 13. This characteristic is in agreement with the result for low content content (Wissa et al., 1965; Clough et al., 1981; and Kasama et al., 2000).

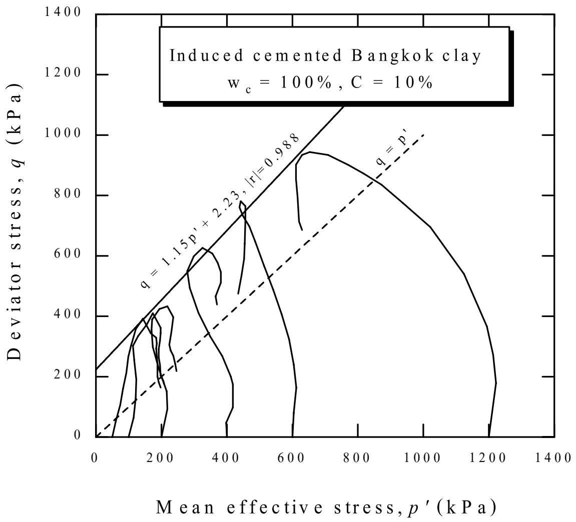

Fig. 11 Undrained stress path and failure envelope of 10% cement Bangkok clay

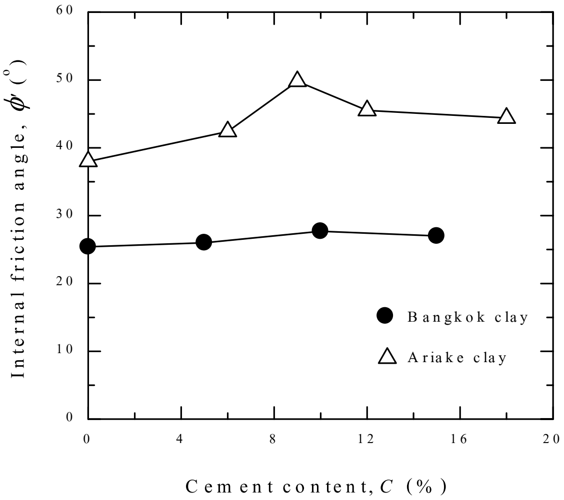

Fig. 13 Relationship between failure friction angle and cement content of induced cemented Bangkok and Ariake clays

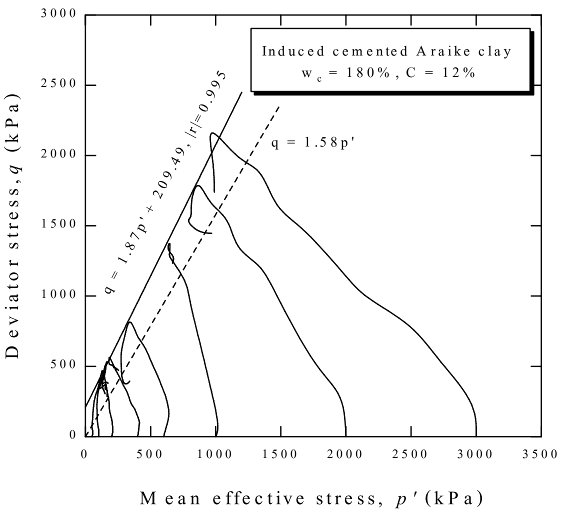

Fig. 12 Undrained stress paths and failure envelope of 12% cement Ariake clay

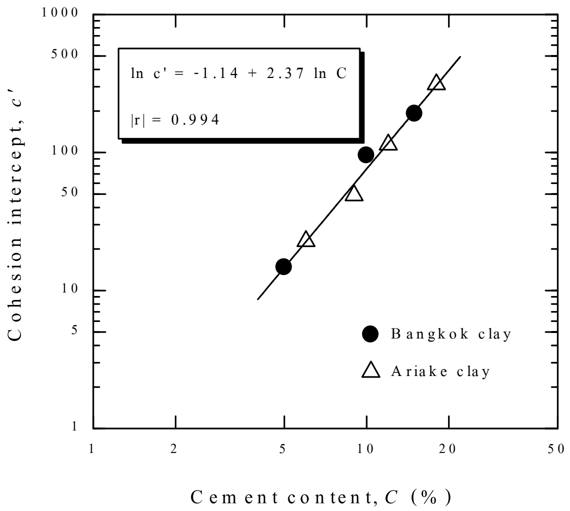

Figure 14: Relationship between cohesion intercept and cement content of induced cemented Bangkok and Ariake clays

Figure 14 shows that only small input of cement remarkably increases cohesion intercept. This implies that the cement content has a large effect on the cohesion intercept and little effect on the friction angle. Moreover, it is of interest to mention from this study that the increase in cohesion intercept is mainly dependent upon the cement content and it can be approximated from the following equation for both the induced cemented clays.

$$\ln c' = -1.14 + 2.37 \ln C \qquad (3)$$

Since the strength characteristics of the induced cemented clays are controlled by the cementation and the fabric, which is governed by the clay water content (Miura et al., 2001; and Horpibulsuk et al., 2005), it must be kept in mind that the cohesion intercept obtained from Eq. (3) might not be valid for any other water content.

DISCUSSION

The cementation and fabric of induced cemented clay during consolidation phase govern the undrained shear behavior. At pre-yield state ($\sigma'_c < p'_y$), the change of the fabric is insignificant as shown by the small reduction of void ratio. The strength of the induced cemented clay is controlled by cementation. As such the maximum deviator stress (q_{max}) is practically the same (*see* Fig. 5). After peak state, the softening behavior is realized. The effect of the interlocking on the failure deviator stress is insignificant. This is proved by the undrained stress path characteristic of the induced cemented clays at effective confining pressure much lower than the yield stress (*see* Figs. 8 and 9). It is found that the undrained stress paths locate on the left side of the drained stress paths up to the peak values. This implies that the excess pore pressure is positive until the failure, hence no interlocking occurs (the interlocking causes the negative pore pressure). Afterwards, the paths move to the right side of the drained stress paths due to the negative pore pressure possibly caused by the interlocking, which is noticed during testing. The samples break into small pieces after peak showing a tendency of dilation. In response, the failure criterion of samples subjected to $\sigma'_c < p'_y$ is the bulging failure and eventually the samples split associated with shear failure. This phenomenon is different form that of over-consolidated clay in which the negative pore pressure occurs before failure, hence the increase in strength.

At post-yield state ($\sigma'_c > p'_y$), the change of the fabric is remarkable as shown by the large reduction of void ratio. The strength of induced cemented clay is influenced by the pre-shear cementation and the pre-shear fabric. The effect of cementation and the fabric are more clearly elaborated by the result of induced cemented Bangkok and Araike clays in Fig. 15. It shows the change of the shear resistance with the increase in the effective confining (pre-shear consolidation) pressure. It is clear that initially, the shear resistance (q_{max}) of the induced cemented clay insignificantly changes as the effective confining pressure increases at pre-yield state. This is because the strength development is mainly governed by the cementation bond strength with insignificant contribution from fabric even the effective confining (pre-shear consolidation) pressure increases. At post-yield state, the cementation bond is broken down, resulting in the considerable change in clay fabric. Despite the cementation bond being broken down, the contribution from the cementation is still available. Due to the induced cemented clay is stable at meta-stable state, there is insignificant contribution from interlocking to the peak strength, hence the failure envelope in (q, p') plot is a single line for both states. Consequently, the shear resistance of induced cemented clay, q_{max}, is the summation of the shear resistance due to the cementation bond, q_b, and the fabric, q_f.

From Fig. 15, the shear resistance due to the cementation bond, q_b can simply be determined from the unconfined compression test (σ'_c = 0). The role of cement content and water content on the unconfined compressive strength has been long known. The higher the cement content and the lower the water content, the greater the strength. Horpibulsuk et al. (2001 and 2003) proposed the new parameter combining these two parameters and designated as clay-water/cement ratio. They stated that "for a given induced cemented clay, the strength at a particular curing time depends upon only one factor, i.e. clay-water/cement ratio, w_c/C". The investigation using this parameter is more advantage than that using cement content and water content as done by previous researchers. The relationship between unconfined compressive strength (q_u) and clay-water/cement ratio can be presented in the form

$$q_u = \frac{A}{B^{(w_c/C)}} \tag{4}$$

where A and B are the constant depending upon the clay type. Based on their work, the effect of clay-water/cement ratio, w_c/C on the strength development of induced cemented Bangkok clay at 3 and 28 days of curing is presented in Fig. 16. Bangkok clay at water content between 110% and 180% was admixed with cement content between 10% and 20%. This figure shows that the strength development of induced cemented Bangkok clay follows the clay-water/cement ratio hyperthesis.

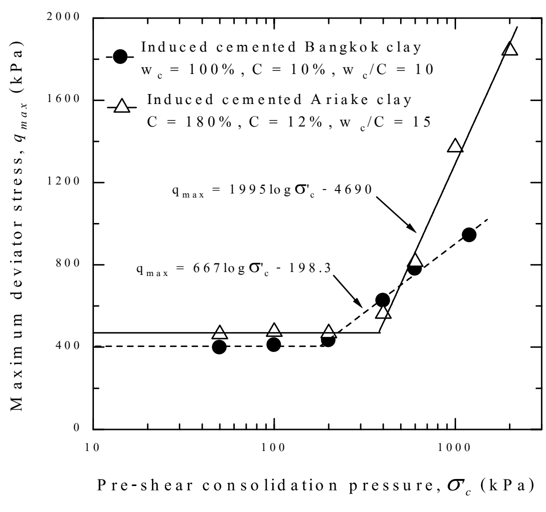

Fig. 15 Effect of cementation and fabric components on strength development of induced cemented clays

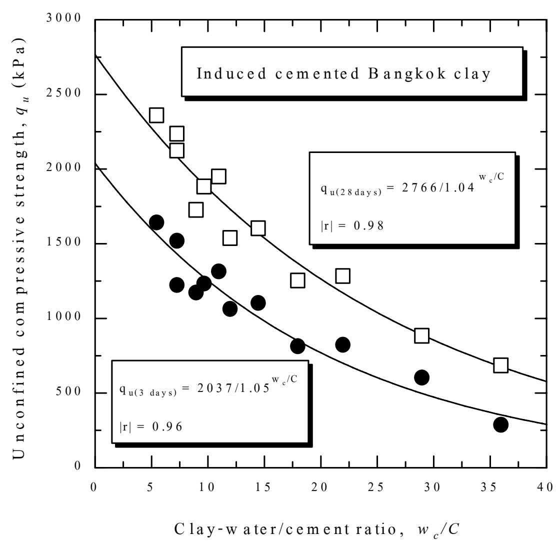

Fig. 16 Variation of strength with clay-water/cement ratio for 3 and 28 days of curing according to clay-water/cement ratio hypothesis

Besides direct determination of unconfined compressive strength, it can be estimated using the following equation (Horpibulsuk et al., 2003).

$$\left(\frac{q_{(w_c/C),D}}{q_{(w_c/C),28}}\right) = 1.24^{\{(w_c/C)_{28} - (w_c/C)_D\}}\left(0.038 + 0.281\ln D\right) \quad (5)$$

where $q_{(w_c/C)_D}$ is the strength of induced cemented clay to be estimated at clay-water/cement ratio of $(w_c/C)_D$ after D days of curing and $q_{(w_c/C)_{28}}$ is the strength of cement admixed clay at clay-water/cement ratio of (w_c/C) after 28 days of curing.

The shear resistance due to fabric increases logarithmically with increasing effective confining pressure (*see* Fig. 15). The transition point where the effect of the fabric comes into the picture can be taken as the effective yield stress, p'_y. The p'_y can be simply estimated by assuming the value of k_0 ($k_0 = \sigma'_h/\sigma'_v$) once the K_0-consolidation yield stress (σ_y) is known.

Based on test results of Ariake, Bangkok and Tokyo clays admixed with cement, Horpibulsuk et al. (2004a) stated that it appears logical to relate the relationship between the unconfined compressive strength and the yield stress since they are dependent on the degree of cementation. The relation is of the form

$$\sigma_y = Cq_u \quad (6)$$

where q_u is the unconfined compressive strength and C is a constant, depending upon clay type and varying from 1.4 to 2.2.

From Fig. 15, even though Ariake clay samples are made up from higher value of w_c/C of 15, the slope of the graph is steeper than that of induced cemented Bangkok clay (w_c/C = 10). It is thus concluded that Ariake clay is more sensitive to cement.

CONCLUSIONS

This paper deals with the undrained shear behavior of the uncemented and induced cemented clays. The conclusions drawn are as follows:

1) Cementation bond plays a dominant role on the strength characteristics of the cement admixed (induced cemented) clay. At pre-yield state, the cementation bond mainly contributes to development of the strength. Both the fabric and cementation components influence the strength when the effective confining pressures are higher than the mean effective yield stress. Even if the cementation bond is broken down, the shear resistance contributed from the cementation bond still persists. The shear resistance does not reduce with the increase in the effective confining (pre-shear consolidation) pressures.

2) The role of the cementation on the maximum excess pore pressure development is insignificant. It is shown that the $(\Delta u/\sigma'_c)_{\max}$ of both pre- and post-yield states is practically the same. This is probably because the induced cemented clay is stable in the meta-stable state; hence, the effective confining pressure is the main factor affecting the excess pore pressure development which is similar to the behavior of normally consolidated uncemented clay.

3) The undrained stress paths of the induced cemented samples at pre-yield state located on the left side of the drained stress path until failure even at very low effective confining pressures ($\sigma'_c << p'_y$), unlike the behavior of heavily overconsolidated clay. This shows that the cementation bond plays a great role on the peak strength with insignificant contribution from the interlocking. Hence, the samples would mainly exhibit the compression during shear up to the peak state. The shear resistance is the summation of the resistance due to the cementation, q_b, and the fabric, q_f.

4) The failure envelope in (q, p') plot of the cement admixed (induced cemented) clay is single for both pre- and post-yield states because the cementation and fabric both contribute to the strength of the induced cemented clay. It is not the same for the case of uncemented clay since the interlocking is the main contributor to the peak strength of the uncemented clay at the overconsolidated state.

5) Cementation increases the cohesion of the clay with little increase in the failure friction angle. Practically, the failure friction angle of induced cemented clays can be assumed to be the same as that of uncemnted clays.

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REFERENCES

Balasubramaniam, A.S., and Buensuceso, J.R. (1989). On the overconsolidated behavior of lime treated soft clay. Proc. 12th Int. Conf. on Soil Mech. and Found. Engrg., 1335-1338.

Butterfield, R. (1979). A natural compression law for soils. Geotechnique, 29(4): 469 -480.

Clough, G.W., Sitar, N., Bachus, R.C., and Rad, N.S. (1981). Cemented sands under static loading. Journal of Geotechnical Engineering Division, ASCE. 107, GT6: 799-817.

Head, K.H. (1998). Manual of Laboratory Soil Testing. John Willey & Sons Ltd., England.

Horpibulsuk, S., Lorenzo, G.A., and Bergado, D.T. (2004a). Compressibility of Cement Admixed Clays at High Water Content. Geotechnique, 54(2): 151-154.

Horpibulsuk, S., Miura N., and Bergado, D.T. (2004b). Undrained shear behavior of cement admixed clay at high water content. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 130(10): 1096-1105.

Horpibulsuk, S., Miura N., and Nagaraj, T.S. (2001). Assessment of strength development in cement admixed clays. Proc. International Conference on Civil Engineering. India: 439-444.

Horpibulsuk, S., Miura N., and Nagaraj, T.S. (2003). Assessment of strength development in cement admixed high water content clays with Abram's law as a basis. Geotechnique, 53(4): 439-444.

Horpibulsuk, S., Miura N., and Nagaraj, T.S. (2005). Clay-water/cement ratio Identity of cement admixed soft clay. Journal of Geotechnical and Geoenviromeal Engineering, ASCE, 131(2): 187-192.

Kasama, K., Ochiai, H., and Yasufuku, N. (2000). On the stress-strain behaviour of lightly cemented clay based on an extended critical state concept. Soils and Foundations, 40(5): 37-47.

Mitchell, J.K. (1993). Fundamental of Soil Behavior. John Willey&Sons, Inc., New York.

Miura, N., Yamadera, A., and Hino, T. (1999). Consideration of compression properties of marine clay based on the pore size distribution measurement. Journal of Geotechnical Engineering, JSCE, No.624/III-47, 203-215 (in Japanese with English abstract).

Miura, N., Horpibulsuk, S., and Nagaraj, T.S. (2001). Engineering behavior of cement stabilized clay at high water content", Soils and Foundations, 41(5): 33-45.

Nagaraj, T.S., Vatsala, A., and Srinivasa Murthy, B.R. (1990). Discussion on "Change in pore size distribution due to consolidation of clays" by F.J. Griffith and R.C. Joshi, Geotechnique, 40(2): 303-305.

Sridharan, A., Abraham, B.M. and Jose, B.T. (1991). Improved technique for estimation of preconsolidation pressure. Geotechnique, 41(2): 263 -268.

Srinivasa Murthy, B.R., Vatsala, A., and Nagaraj, T.S. (1988). Can Cam-clay model be generalized. Journal of Geotechnical Engineering, ASCE, 114(5): 601-613.

Srinivasa Murthy, B.R., Vatsala, A., and Nagaraj, T.S. (1991). Revised Cam-clay model. Journal of Geotechnical Engineering, ASCE, 117(6): 851-871.

Wissa, A.E.Z., Ladd, C.C., and Lambe, T.W. (1965). Effective stress strength parameters of stabilized soils. Proc. 6th International Conference on Soil Mechanics and Foundation Engineering, 412-416.

Yamadera, A. (1999). Microstructural Study of Geotechnical Characteristics of Marine Clays, Ph.D. Dissertation, Saga University, Saga, Japan.