Undrained Shear Behavior of Induced Cemented Bangkok Clay

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Abstract

Development in equipment and field techniques to implement the in-situ deep mixing techniques have suppressed the basic understanding of soft clay admixed cementing agents. This understanding is of utmost importance for strength and deformation analyses of composite ground. This paper presents and analyses test results of triaxial compression test on cement admixed Bangkok clay. Since the induced cemented clay is stable at meta-stable state, the structure (fabric and cementation) controls the strength and deformation characteristics. The failure envelope is a single straight line for both pre- and post- yield states. Cementation increases the cohesion of Bangkok clay with little increase in the failure friction angle.

1. Introduction

In recent years, design and construction of infrastructural facilities in natural soft ground of Bangkok area arising due to extensive urbanization and industrialization in soft ground, natural or reclaimed, has considerably increased. The desirable practical requirements of the in-situ ground are increased strength, reduced compressibility and appropriate permeability condition to take care of stability, settlement and ground water and other environment related problems. The in-situ deep mixing technique is an effective means to circumvent the effects of high compressibility and low shear strength of soft clay deposits. The increased stiffness and the strength of the stabilized clay, realized with time, result in the improvement of bearing capacity and reduction in settlement of the soft ground.

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. Kasama et al. [1] 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 [2] 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. Horpibulsuk et al. [3] reveals that the

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engineering behavior of cement admixed clays at very high water content is governed by its structure (fabric and cementation). Based on this premise, 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 [4 and 5]. 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 [6].

Even though the analysis of the undrained shear response of the cement admixed clay based on the microstructural consideration [3] is available, it is based from the test results of very high water content Ariake clay (liquidity index, LI is 2.0) with high salinity in pore. To obtain better understanding, the present paper attempts to present the undrained shear characteristics of induced cemented Bangkok clay (at AIT) in which the initial water content is closed to liquid limit (LI is closed to 1.0) and salinity is very low. The microstructural consideration [3] would be employed to analyze the test results.

2. Experimental Investigation

2.1 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. 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 $\phi' = 25.4°$.

2.2 Methodology of Testing

The clay paste was passed through 2-mm sieve for removal of shell pieces and other 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. [4]. 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, wrapped in vinyl bags and stored in a humidity chamber of constant temperature (20±2°C).

Isotropically consolidated undrained triaxial compression (CIUC) tests were run on samples after 28 days of curing. The effective confining pressures, σ'_c, for CIUC tests 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. 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, σ'_3 are the principal effective compressive stresses, q is the deviator stress, and p' is the mean effective stress. All the tests were conducted according to the procedure recommended by Head [7].

3. Test Results

3.1 Compressibility Characteristics

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 (remoulded) clay in Fig. 1. 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. [6] identified this stress level as the yield stress. It does not represent preconsolidation or maximum past pressure since the induced cemented clay was not subjected to any stress history. The mean effective yield stresses, p'_y values are 140, 250, and 400 kPa for cement contents of 5, 10 and 15 percent, respectively.

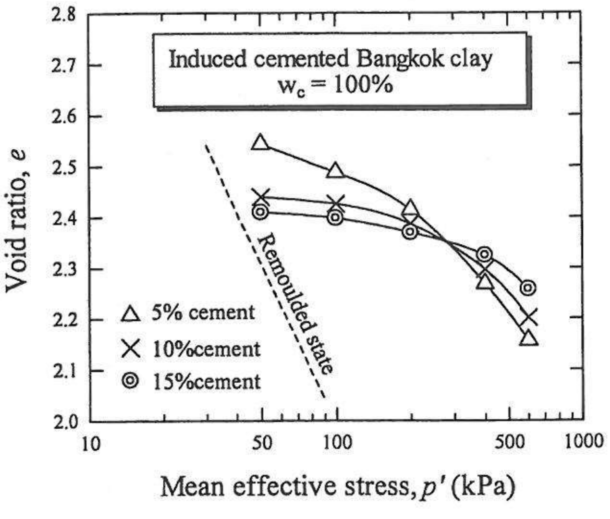

Figure 1 (e, log p') relationship of induced cemented Bangkok clay at cement contents of 5%, 10%, and 15% at the same initial clay water content of 100%.

3.2 Effect of Cementation Bond on Undrained Shear Behavior

The effect of cementation on the deviator stress-shear strain relationship for effective confining pressures less than the mean effective yield stress is presented in Fig. 2. The characteristic shape of the (q, ε_s) curves is that 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 not influenced by the effective confining pressures because the cementation is the main contributory factor when the state of stress is inside the state boundary surface. The effect of cementation is clearly shown from the figure, which indicates that the peak strengths of the induced cemented samples are remarkably higher than those of uncemented samples at the same effective confining pressures. However, the strength of the induced cemented samples is practically the same even as the effective confining pressure increases. This is because the change of the fabric in consolidation process is insignificant.

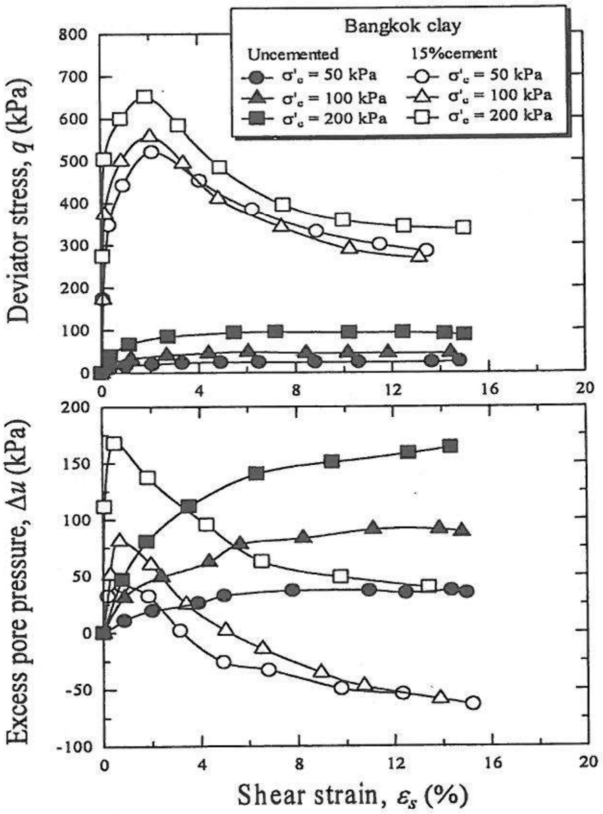

Figure 2 Effect of cementation on the deviator stress and excess pore pressure versus shear strain responses of induced cemented Bangkok clay at cement content of 15%.

Although the (q, ε_s) 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.

It is found that at pre-yield state, samples break into small pieces after peak showing a tendency of dilation. However, under undrained shear, the dilation is prevented, resulting in development of negative excess pore pressure (*see* Fig. 2). 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.

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 shear strain ($\Delta u/\sigma'_c$, ε_s) of the induced cemented clay is presented in Fig. 3. 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 shear strain increases and finally levels off at the residual state. Whereas it has been known that the maximum normalized excess pore pressure, $(\Delta u/\sigma'_c)_{max}$ increases with the decrease in *OCR* for the overconsolidated uncemented clay due to the interlocking effect [3].

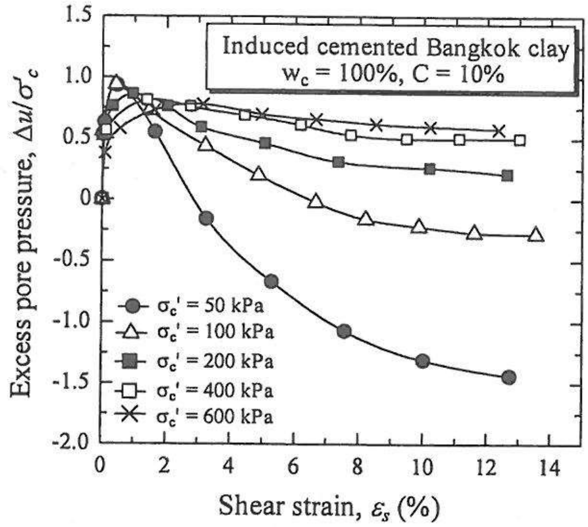

Figure 3 Typical ($\Delta u/\sigma'_c$, ε_s) relationship of induced cemented Bangkok clay.

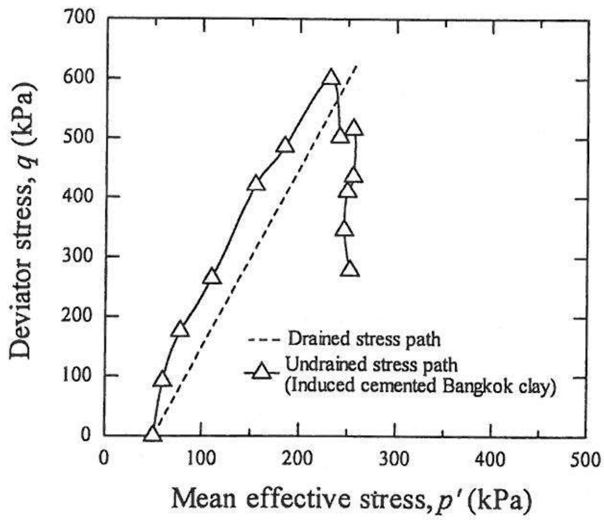

Figure 4 Undrained stress paths of the induced cemented Bangkok clays under very low effective confining pressure.

The typical undrained stress path of the induced cemented clay subjected to the effective confining pressures lower than the mean yield stress is shown in Fig. 4. It shows the results of induced cemented Bangkok clay, subjected to very low effective confining (pre-shear consolidation) pressures of 50 kPa respectively along with drained stress path. The ratio of mean effective yield stress to effective confining pressure (p'_y/σ'_c) is 8. It is proved that the peak strength of the induced cemented clay is insignificantly influenced by interlocking because the undrained stress path locates on the left side of the drained stress path up to the peak values. Afterwards, the path moves to the right side of the drained stress path and level off possibly due to interlocking after peak state. It is of interest to mention that the long-term strength of induced cemented 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.

3.3 Effect of Combination of Cementation and Fabric on Undrained Shear Behavior

All induced cemented Bangkok clay samples are consolidated to the effective confining pressures higher than the mean effective yield stress. At this condition, both cementation and fabric mainly contribute to the mobilization of peak strength, which would not happen in case of normally consolidated uncemented clay. The strain-softening behavior happens even at high effective confining pressures. The change in fabric, caused by increasing the effective confining (pre-shear consolidation) pressures in consolidation process brings the clay particles and clay clusters closer leading to formation of clay cluster; hence, increasing the shear strength and the shear strain at failure.

Figure 5 shows the typical deviator stress-shear strain and excess pore pressure-shear strain relationships of the Bangkok clay in cemented state, along with those in uncemented state. It reveals that (q, ε_s) and (Δu, ε_s) relationships of the induced cemented clays rise up to the peak deviator stresses and peak excess pore pressures at low strain and then level off at the residual state. 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. It is implied that the contribution from the cementation bond to the shear resistance is still available, even when the cementation bond was broken down by such high effective confining pressures ($\sigma'_c > p'_y$).

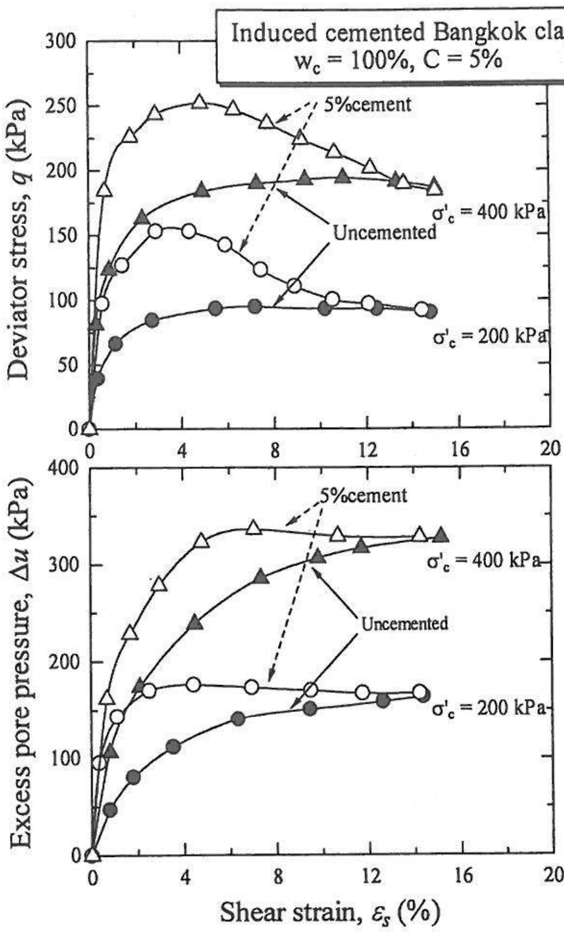

Figure 5 (q, ε_s) and (Δu, ε_s) relationships of induced cemented Bangkok clay at 5% cement compared with those of uncmented Bangkok clay ($\sigma'_c > p'_y$).

The typical characteristic of undrained stress paths of the induced cemented Bangkok clay is depicted in Fig. 6. 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 cemented clay and the critical state line of uncemented clay samples are practically identical. This finding is in agreement with that of cement admixed sand [8].

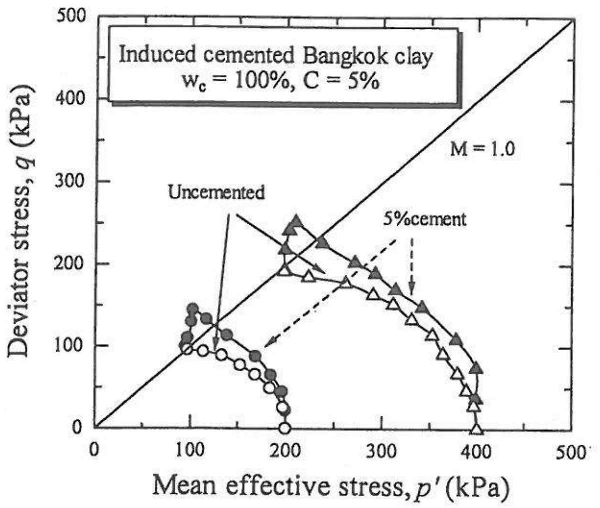

Figure 6 Undrained stress paths of 5 % cement Bangkok clay.

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. Since $\delta p' \neq 0$, the plastic volumetric strain occurs so that the total volumetric stain is null during undraiend shear. Even without the unload-reload test, it can be concluded that the induced cemented clay exhibits the elastoplastic behavior when the stress state lies on the state boundary surface.

3.4 Failure Envelope of Induced Cemented Clay

Figure 7 shows the typical undrained stress paths and failure envelope of the induced cemented samples, subjected to the effective confining pressures lower and higher than the mean effective yield stress. The dotted line is the failure envelope of the uncemented Bangkok clay, 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 the failure envelope of the induced cemented clay 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 envelopes 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. Due to this single failure envelope of the induced cemented clay, it implies that there is insignificant contribution from interlocking to the peak strength. It is because the induced cemented clay can be stable at very high void ratio (meta-stable state) and the yield stress appears due to the cementation, not reloading.

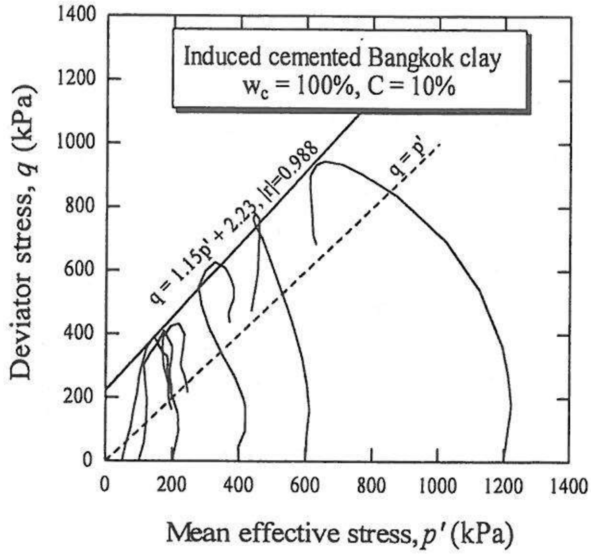

Figure 7 Undrained stress path and failure envelope of 10% cement Bangkok clay

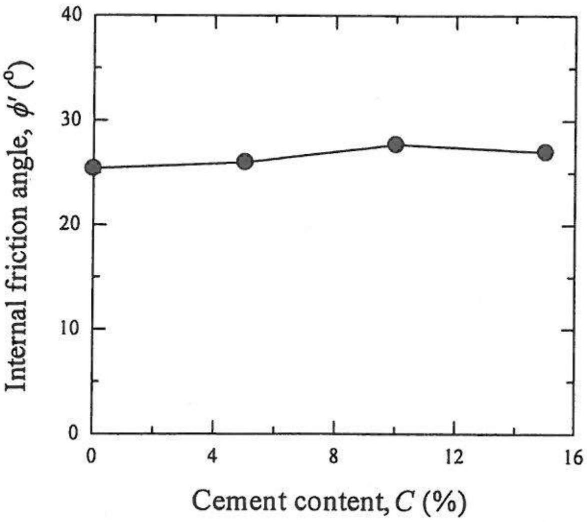

Figure 8 Relationship between failure friction angle and cement content of induced cemented Bangkok clays.

Figures 8 and 9 show the relationship between internal friction angle and cement content and cohesion intercept and cement content, respectively for induced cemented Bangkok clay. 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. This characteristic is in agreement with the result for low content content [1, 8 and 9]. Figure 9 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 small effect on the friction angle.

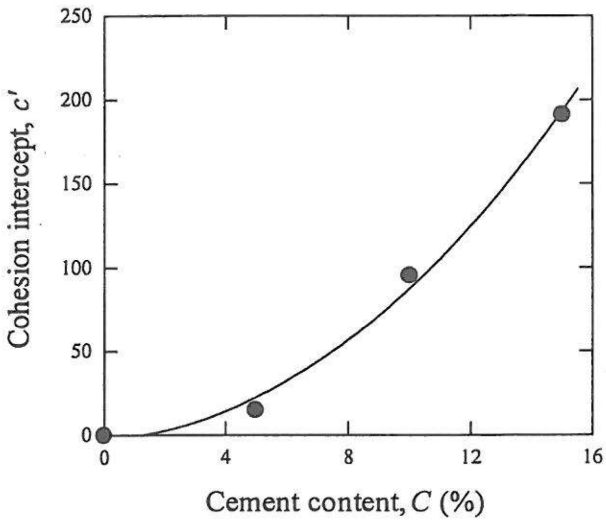

Figure 9 Relationship between cohesion intercept and cement content of induced cemented Bangkok clays.

4. Conclusions

This paper deals with the undrained shear behavior of the uncemented and induced cemented Bangkok clay. The conclusions are drawn 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.

2) The $(\Delta u/\sigma'_c)_{max}$ of both pre- and post-yield state 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 failure envelope in (q, p') plot of the induced cemented Bangkok clay is single for both the 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.

4) Cementation increases the cohesion of the clay with small 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 uncemented clays.

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