LOWLAND TECHNOLOGY INTERNATIONAL Vol. 11, No. 1, 20-28, June 2009
International Association of Lowland Technology (IALT), ISSN 1344-9656

BEHAVIOR OF STIFFENED DEEP CEMENT MIXING PILE IN LABORATORY

P. Jamsawang[1], D.T. Bergado[1], A. Bhandari[1] and P. Voottipruex[2]

ABSTRACT: The low strength and stiffness of Deep Cement Mixing (DCM) pile causes unexpected failure that has been mitigated with the introduction of stiffened deep cement mixing (SDCM) pile. The SDCM is a new type of DCM pile reinforced by concrete core pile. In this paper, the interface behavior of SDCM pile and its strength have been studied by various laboratory tests. The cement content was varied from 10 to 20% by dry weight of clay and mixed at the water content corresponding to its liquid limit to obtain optimum strengths. The interface friction between the core concrete pile and the cement-admixed clay was studied by means of the direct shear tests and K_o interface shear tests. The 15% cement content yielded optimum interface shear strength. The CIU triaxial compression test of model SDCM pile revealed that the concrete core pile length should be more than 75% of the DCM pile length in order to have significant improvement.

Keywords: Composite, interface, shear strength, soil-cement, deep mixing

INTRODUCTION

Civil engineers are increasingly facing situations where engineering structures need to be constructed on soft clay. Soft clay areas are fairly widespread in lowlands worldwide including East and Southeast Asia. Deep cement mixing (DCM) pile has been widely used to improve the engineering properties of soft clay layers. DCM piles can effectively reduce settlements of full-scale embankments (Bergado et al., 1999; and Lai et al., 2006), however they have low strength and stiffness Petchgate et al. (2003a,b; 2004) and could lead to low bearing capacity and large settlements (Wu et al., 2005). Consequently, DCM piles are not suitable for medium to high design loads (Dong et al., 2004). Hence, a new composite structure of DCM with a concrete core at the center of the DCM has been introduced and is called stiffened deep cement mixing (SDCM) pile as shown in Fig. 1. The concrete core, which is basically a concrete pile of a higher strength and stiffness, takes most of the load and gradually transmits it to the soil-cement through the interface between the concrete pile and the DCM. Therefore, the interface shear strength between the concrete pile and DCM must be high enough to develop the necessary load transfer mechanism. A series of pile load tests have been performed in China to investigate the behavior of SDCM piles by Dong et al. (2004), Wu et al. (2005), and Zheng and Gu (2005). Most of these tests were concentrated on only bearing capacities of SDCM piles.

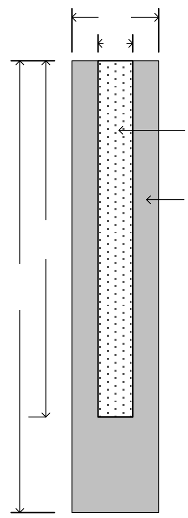


Fig. 1 Schematic diagram of a SDCM pile

The bond strength between the soil-cement and a steel beam used in a DCM pile to increase the bending and the tensile strength were investigated by Kunito and Mashima (1991) and Tungboonterm and Yoottimit (2002) while the bearing capacity of the pile was investigated by (Kitazume et al., 1996). Bergado et al. (2004) studied the shear strength of the interface between the clay surrounding DCM piles. Research on interface shear strength between concrete piles and soil-

[1] GTE Program, School of Engineering and Technology, Asian Institute of Technology, THAILAND
[2] Faculty of Technical Education, King Mongkut's Institute of Technology North Bangkok, Bangkok, THAILAND
Note: Discussion on this paper is open until December 2009

cement, shear strength of SDCM piles and the consolidation behavior of a composite foundation consisting of a SDCM pile and untreated soil are still limited with insufficient experimental data. This paper aims at studying the behavior, such as interface strength, shear strength and consolidation of a SDCM pile in the laboratory.

Direct shear tests and K_o interface shear tests were used to estimate the interface shear strength between the concrete pile and the DCM pile. The K_o interface shear test was employed to simulate field conditions of the SDCM pile and was successfully modeled in the laboratory to study the interface friction. Furthermore, the effect of the boundary was also investigated by varying the diameter of the DCM pile while maintaining the same diameter for the inner concrete pile.

The influence of the concrete pile length and the cement content on the shearing behavior of the SDCM and the overall strength development were also studied by consolidated undrained (CIU) triaxial compression tests by varying the length of core piles and the cement content.

PREPARATION OF CEMENT-ADMIXED CLAY

The base clay utilized in this study was the soft Bangkok clay. The soil samples were taken at the campus of the Asian Institute of Technology (AIT), Thailand. Samples were extracted from 3 to 4 m depth for all tests. The liquid limit was about 103% and the natural water content varied from 76% to 84%.The undrained shear strength obtained from unconfined compression tests ranged between 16 to 17 kPa. Cement admixed clay was prepared by mixing Type I Portland cement in the form of a cement slurry of water-cement ratio (*W/C*) 0.6 with the soft Bangkok clay in a portable mechanical mixer. The soil and the cement slurry were mixed until the mixture was visually homogenous. As per the current practices for DCM in Thailand, the cement content of the cement-admixed clay (A_W) was chosen to be 10%, 15% and 20%. All the specimens were prepared with a mixing time of 3 to 5 minutes. The unconfined compression strength and the one dimensional yield stress of the soft Bangkok clay are greatest when the total clay water content is 105% (Bergado and Lorenzo, 2005 and Lorenzo, 2005). Consequently, a total clay water content of 105% was used in this research. The total clay water content (C_w) is defined as follows:

$$C_w = w^* + W/C\ (A_w) \tag{1}$$

where w^* is the remolding clay water content.

UNCONFINED COMPRESSION TEST

The concrete core-DCM interface strength and the shear strength of the DCM increases with the increase in the cement content of the DCM. To relate the interface strength to the strength of the DCM, a series of unconfined compression tests were performed at A_w of 10, 15 and 20%.

Specimens for the unconfined compression test were prepared by compacting the cement-admixed clay in PVC molds of 50 mm diameter and 100 mm height. Compaction was by applying static pressure (by pushing as opposed to tamping) over the entire surface of the cement-admixed clay as the mold was filled to remove all voids. The specimens along with the mold were waxed and cured in a humid room for 28 days. After curing, the specimens were removed from the mold and only those specimens with a smooth surface and with almost the same densities for a specific cement content were selected for testing.

DIRECT SHEAR BOX TEST

Direct shear tests were performed to determine the interface shear strength between the cement pile and the DCM. Circular specimens, in place of rectangular specimens, were chosen to avoid stress concentrations at sharp corners.

Specimens of size 55 mm diameter and 50 mm height were prepared by first, casting and curing the cement mortar halves and then preparing the cement-admixed clay halves by compacting the cement-admixed clay on top of these mortars. During the pouring and compaction of the cement-admixed clay, the mortar halves and the cement-admixed halves were fixed in place with metallic belts. Static pressure over the entire surface of the cement-admixed clay was applied, by pushing, to compact the cement-admixed clay. The molds together with the specimens were waxed and cured for 28 days in a humid room. After curing the specimens were removed from the molds and checked for surface smoothness and those with smooth peripheral surface were tested. The specimens were set up in the shear box in such a way that shearing would occur at the interface of the lower cement mortar half and the upper cement-admixed clay half as shown in Fig. 2. The rate of shearing applied in all the direct shear tests were 0.6mm/min. Normal

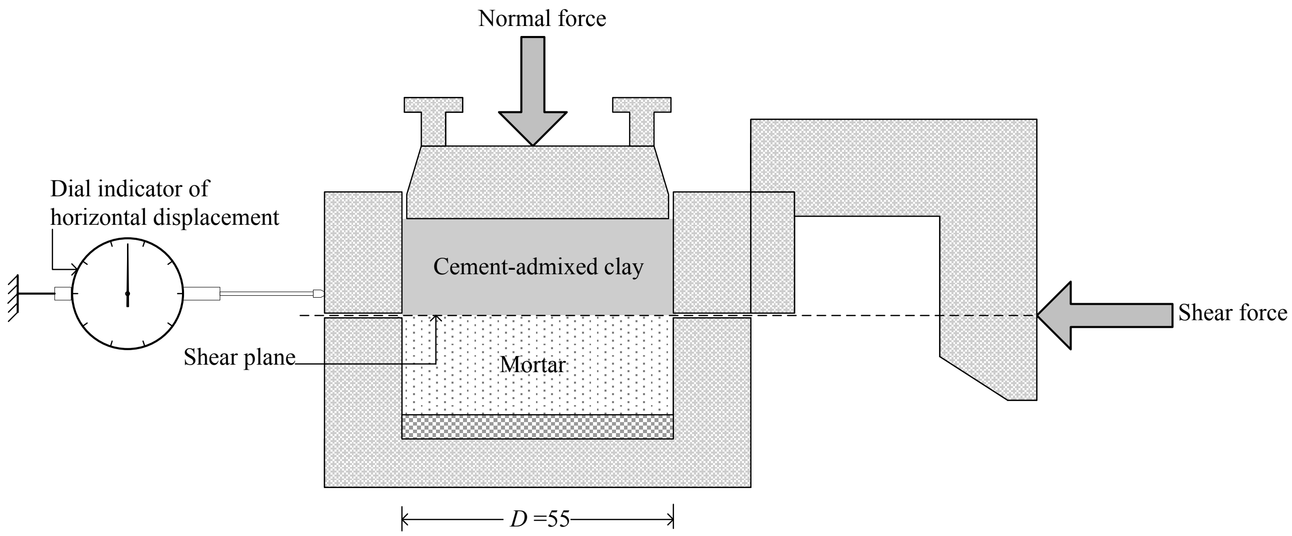


Fig. 2 Direct shear box apparatus (unit:mm)

stresses of 50 kPa, 100 kPa and 200 kPa were applied for each set of tests.

INTERFACE SHEAR TEST

The interface shear test in this study refers to the tests employed to determine the friction between the cement-admixed clay and the concrete core, the cement-admixed clay being subjected to a restrained boundary (K_o condition) because of the PVC mold as shown in Fig. 3. The specimens were tested with the mold intact. The K_o loading condition of this test brings it closer to the real field condition compared to the direct shear test.

The purpose of these tests was to relate the load transfer to concrete core movement and it was found that this could be done best by using a continuous loading method. These tests were performed to determine the movement of the pile needed to mobilize the resisting forces. Similar approach was used, but with different confining pressures in a modified triaxial cell, by Coyle and Reese (1966) for pile soil interaction. They fixed the loading rate at 1.5mm/min. This research maintained nearly the same loading rate as that of the direct shear test for comparison, though the load rate was not exactly the same due to the different rates available on the two machines.

Specimens for the interface shear tests were prepared by inserting a 17 mm diameter and 120 mm long concrete core into PVC molds filled with compacted cement-admixed clay. Compaction was by applying static pressure, by pushing, over the entire area. The concrete cores were inserted immediately after the PVC molds were filled at the rate of 10 mm/min, using a loading apparatus. The specimens were then waxed along with the mold and cured for 28 days in a humid room. After curing, the specimens were checked for the position of the cement mortar piles and only those with their centers within 2 mm from the center of the specimen were tested. The cement-admixed clay was trimmed at both ends so that the length of the cement-admixed clay was 100 mm. The specimens were then placed over a hollow metallic plate in the loading apparatus as shown in Fig. 3. Similar arrangement was made on the top of the specimens in order to apply the vertical load.

Two specimen sizes of 50 mm diameter and 100 mm diameter were prepared and tested; the diameter of the concrete core was 17 mm. The height of the specimens was 100 mm for both the cases. The ratio of the diameters of the concrete core and the DCM was around 3 for the 50 mm diameter specimens and around 6 for the 100 mm diameter specimens. The 100 mm diameter specimens were tested to observe the influence of the boundary on the interface strength.

CIU TRIAXIAL COMPRESSION TESTS

Consolidated undrained triaxial tests were preformed on specimens of SDCM, cement-admixed clay with concrete core, to determine the strength of the SDCM. The length of the concrete core was varied, 60%, 75% and 90% of the DCM length, to observe the effect of concrete core on the strength and failure mechanism of the SDCM.

Specimens of cement admixed clay for the triaxial tests were prepared in the same manner as those for the interface shear tests. After curing for 28 days the specimens were removed from the mold and placed in

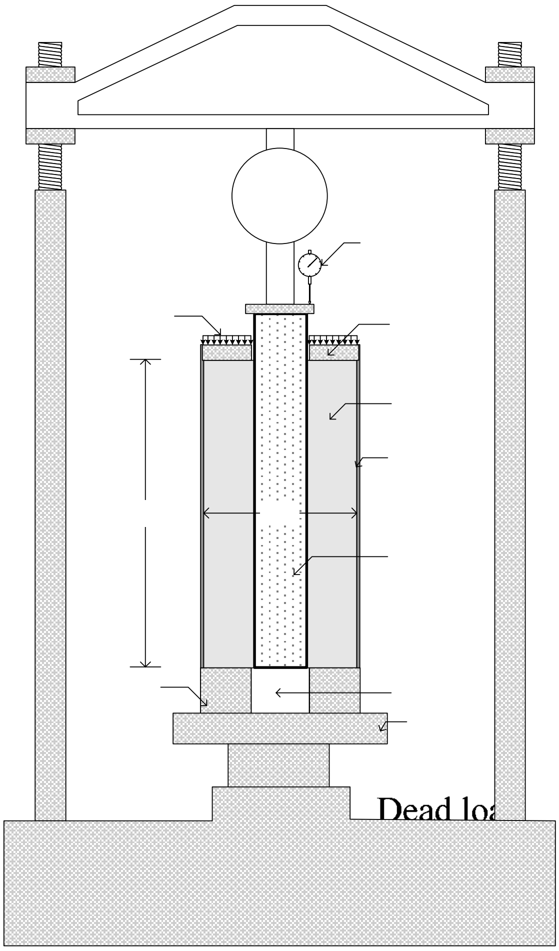


Fig. 3 Interface shear test apparatus (unit:mm)

the triaxial cell for testing as shown in Fig. 4. A back pressure of 250 kPa was applied in stages together with the cell pressure to saturate the specimens. The cell pressure and the back pressure were gradually increased with pressure increment of 25 kPa, the cell pressure being larger by about 10 to 15 kPa. After saturation a pre-shear consolidation pressure of 100 kPa was applied by lowering the back pressure to 150 kPa and maintaining the cell pressure at 250 kPa. After consolidation, the specimens were sheared at the rate of 0.009 mm/min. This rate of strain was the same as that utilized by Lorenzo and Bergado (2004).

TEST RESULTS AND DISCUSSIONS

Unconfined Compression Test

The purpose of this test was to use it as a reference for the other tests like the interface strength tests whenever a comparison was needed. The after-curing void ratio (e_{ot}) and cement content (A_w) are uniquely related to the unconfined compression strength, q_u, of cement admixed clay at high water content (Lorenzo and

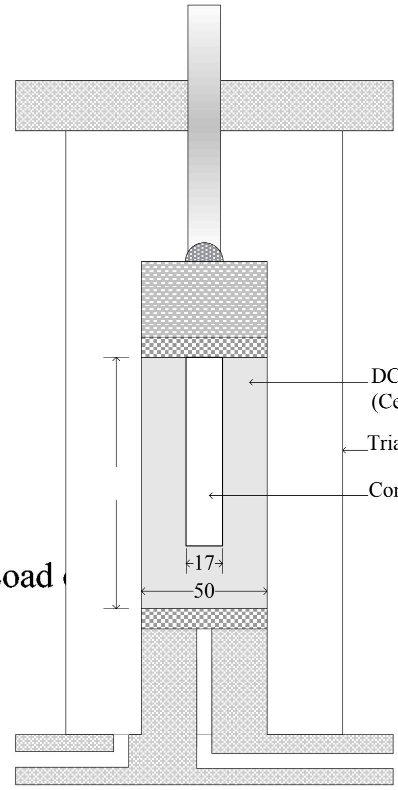


Fig. 4 CIU test apparatus (unit:mm)

Bergado, 2004; 2006). The unconfined compression strength of the cement-admixed clay at 10%, 15% and 20% were 527 kpa, 702 kpa and 937 kpa respectively and are compared with the relationship proposed by Lorenzo and Bergado (2004) in Fig. 5.

Direct Shear Test

Typical stress-strain behavior of the concrete core and the cement-admixed clay interface is shown in Fig. 6. The strain to peak interface shear decreased from 3% when the cement content was 10% to 1% when the cement content was 20%. The peak interface friction angle (δ) increased from 23^o to 26^o and the adhesion (c_a) between the interfaces increased from 42 kPa to 80 kPa when increasing the cement contents from 10% to 20% (Fig. 7).

The results indicate that the adhesion intercept is very sensitive to the cement content compared to the friction angle. The increased cement content increased both the interface friction angle and the adhesion; however, the adhesion intercept increased significantly, from 42 kPa to 77 kPa, by more than 80%, when A_w was increased from 10% to 15% as shown in Fig. 8. However, this increase is only significant over the range of A_w from 10% to 15%. On further increasing the cement content to 20% there was only a marginal increase to 80 kPa. The friction angle increased by three degrees, less than 15%, when A_w was increased from 10% to 20%.

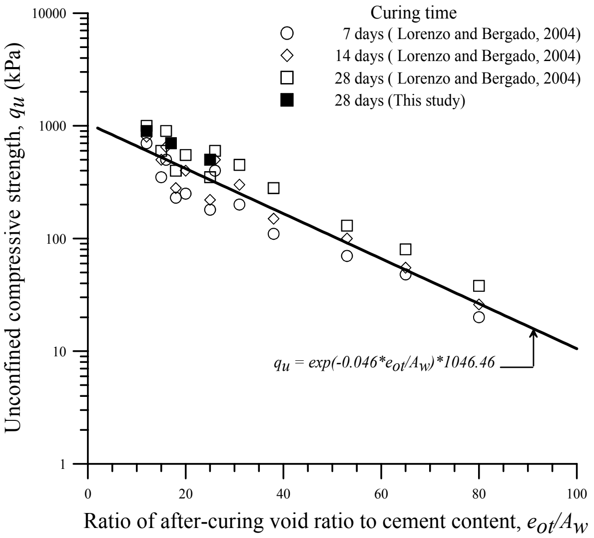


Fig. 5 Unconfined compression strength, q_u, versus e_{ot}/A_w ratio

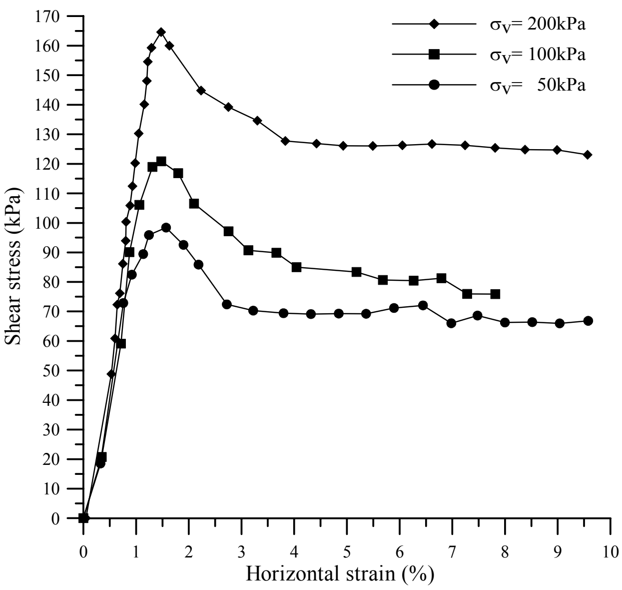


Fig. 6 Typical interface shear stress-strain curves at cement content 15% from direct shear test

Interface Shear Test

The average interface shear strength $\tau_{interface}$ can be calculated from the measured peak load F_{peak} and the cement mortar pile surface area A_{core} as follows:

$$\tau_{interface} = \frac{F_{peak}}{A_{core}} = \frac{F_{peak}}{(\pi D_{core})L_{core}} \quad (2)$$

The peak interface shear strength for the 100 mm diameter specimen in the interface shear test increased from 86.8 kPa to 174.4 kPa when the cement content was increased from 10% to 20% (Fig. 9a). These values

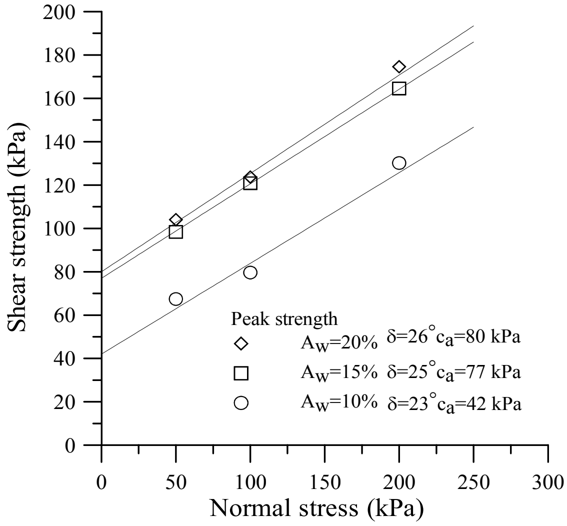


Fig. 7 Results of unconfined compression tests on cement-admixed clay

are similar to those from the direct shear tests. However, the strength of the 50 mm diameter specimen was larger than the 100 mm diameter specimen by about 20 to 25% as shown in Fig. 9b.

Effects of cement content on interface shear strength

The results from interface shear tests indicate that the interface strength between the concrete core and the cement-admixed clay increases with the cement content of the cement-admixed clay as shown in Fig. 10. The compressive strength of the cement-admixed clay also increases with increasing cement content indicating a correlation between the compressive strength of the cement-admixed clay and the interface shear strength between the concrete core and the cement-admixed clay. Wu et al. (2005) defined the ratio of the interface shear strength $\tau_{interface}$ to the unconfined compression strength q_u of the cement-admixed clay cement as adhesive coefficient denoted by α and calculated as follows:

$$\alpha = \frac{\tau_{interface}}{q_u} \quad (3)$$

The interface shear strength equals to $0.19q_u$ and $0.23q_u$ for D_{DCM} = 100 mm (D_{DCM}/D_{core} = 6) and 50 mm (D_{DCM}/D_{core} = 3), respectively, so that the adhesive coefficient α ranges between 0.19 and 0.23 as shown in Fig. 11.

The increased cement content resulted in higher cementation and higher bond strength. Once the displacement exceeded the limit of maximum peak strength mobilization, the bond broke and the strength reduced to similar values irrespective of the cement content. In all the interface shear tests, the maximum

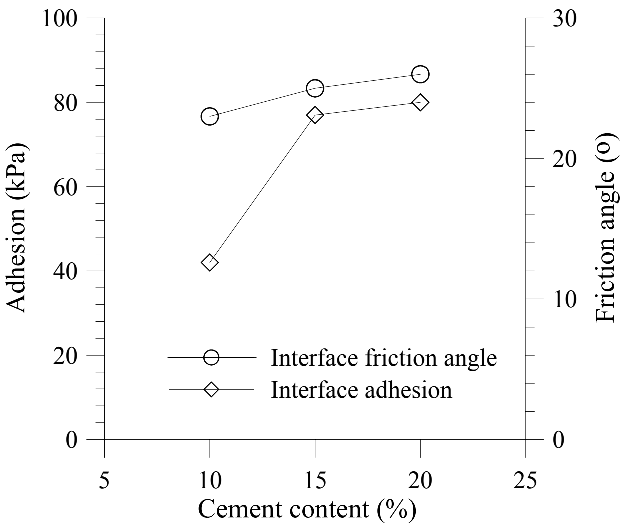
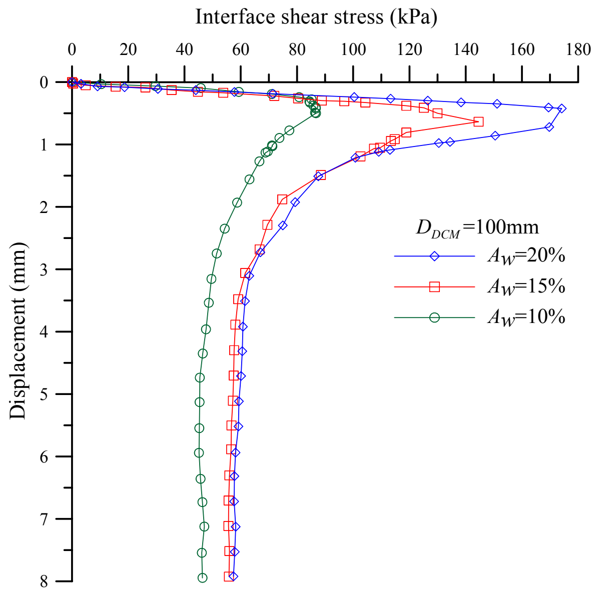


Fig. 8 Variation of interface frictional angle and adhesion with cement content from direct shear test

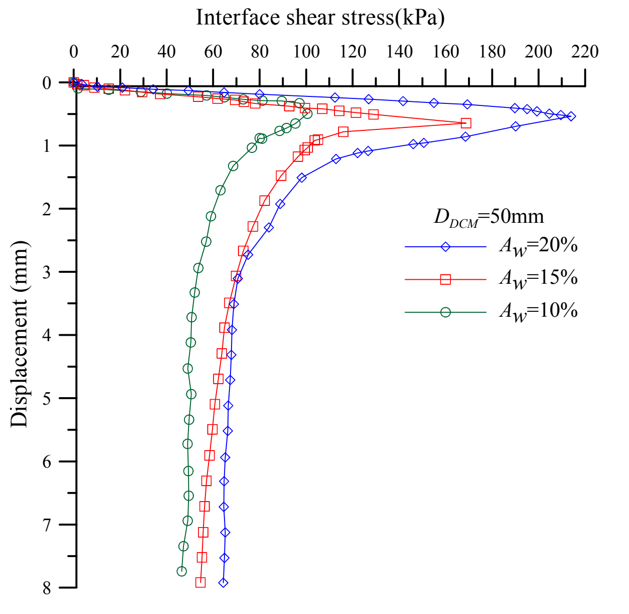
interface strength was observed at smaller displacements than in the direct shear tests. This behavior is similar to the results from pullout test compared with direct shear tests obtained by Chu and Yin (2005).

Influence of DCM diameter on interface shear strength

The peak interface strengths in Figs. 10a, b showed that the interface strength was higher for DCM diameter 50 mm than for DCM diameter 100 mm while using the same concrete core pile diameter of 17 mm. The increase in strength ranged from 20% to 25% which could be due to other reasons besides the scale effect. A brief explanation of the sample preparation is presented to explain this behavior. The core pile was inserted immediately after compacting the cement-admixed clay into the mould. When the core pile was slowly pushed into the cement-admixed clay (DCM), it created a compacted zone around the pile. Obviously, this compaction was greater in the smaller diameter specimen. Some cement-admixed clay flowed out of the top of the mold during the insertion of cement mortar pile.



(a) D_{DCM} = 100 mm



(b) D_{DCM} = 50 mm

Fig. 9 Interface shear stress versus displacement at various cement content with L_{DCM} = 100 mm and D_{core} = 17 mm

CIU Triaxial Compression Test

The typical effects of various L_{core}/L_{DCM} ratios on the deviator stress of the SDCM pile is shown in Fig. 12. The excess pore pressure measurement was used as an indicator for the failure of the cement-admixed clay. The point where the excess pore pressure started to decrease after reaching the peak value, the point of maximum pore pressure, was taken as the failure of the cement-admixed clay. There was no change in the behavior of the cement-admixed clay stiffened by cement mortar pile (SDCM) from that of the cement-admixed clay (DCM) when the length of the cement mortar pile in the SDCM was only 60% (L_{core}/L_{DCM} = 0.60) of the length of the SDCM. Increasing the length of core pile to 75% (L_{core}/L_{DCM} = 0.75) improved the post-failure behavior of the SDCM pile. Though unable to increase the strength, the core pile was useful in maintaining the post failure strength. Further increase of the length of the cement mortar pile to 90% (L_{core}/L_{DCM} = 0.9) resulted in a considerable increase in the strength of the SDCM pile after the primary failure of cement-admixed clay. The

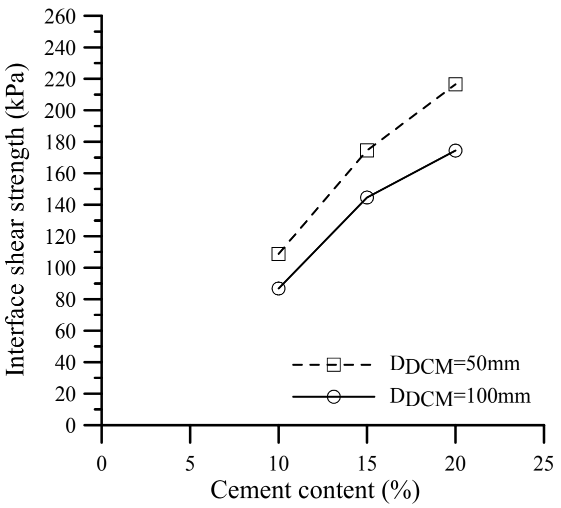


Fig. 10 Variation of interface shear strength with cement content from interface shear test

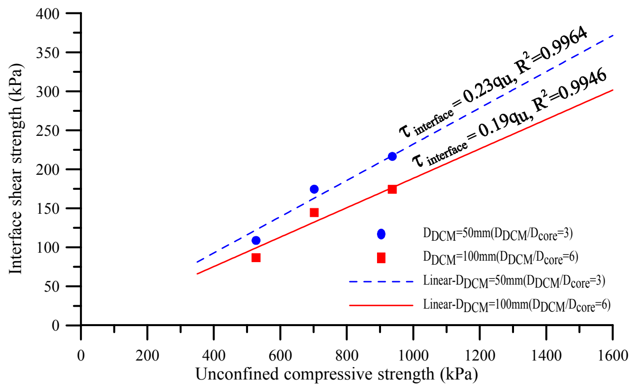


Fig. 11 Interface shear strength versus unconfined compressive strength of clay cement

strength of the SDCM pile was limited by the strength of the concrete core pile in this case.

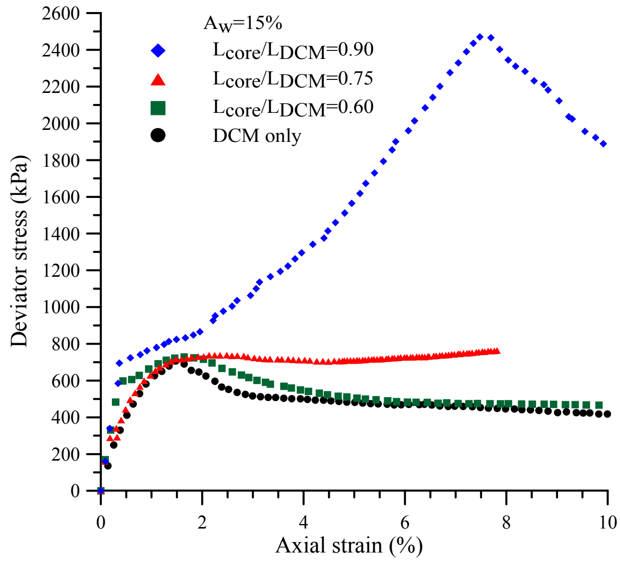
Influence of concrete core pile length on failure mode

When the concrete core pile length in the SDCM was only 60% of the length of the SDCM the failure mode was unchanged compared with the case of only the DCM. However, the failure became more brittle with the increased cement content from 10% to 20% as expected.

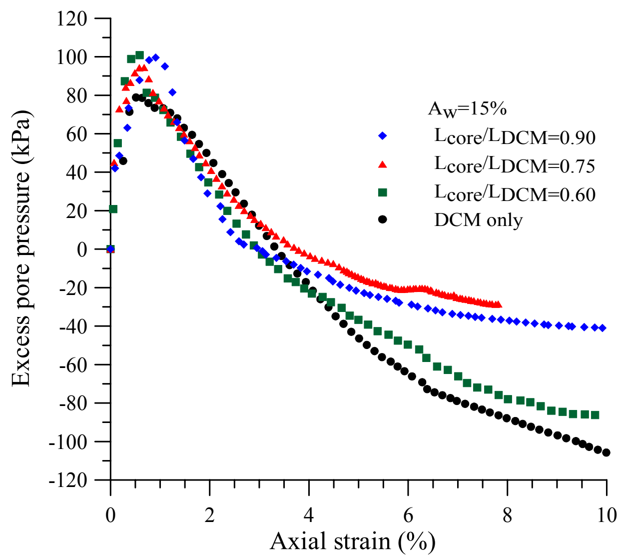
When the core pile was extended to 75% of the length of the SDCM, the strength and the failure mode was not affected but the failure plane was now in the lower 25% of the SDCM, below the tip of the concrete core. The failure plane did not occur along the length reinforced by the concrete core. The longer length of concrete core, however, helped to maintain the strength of SDCM after the failure of cement-admixed clay.

When the concrete core pile was extended to 90% of the SDCM, the failure mode was totally different from the previous cases. The DCM material bulged at the unstiffened end of the SDCM. Though the failure was observed in the DCM material at the same strength as in the previous cases, as reflected by the pore pressure development within the specimen, the load carrying capacity of the SDCM increased until cement mortar pile failed in compression.

Zheng and Gu (2005) categorized the failure mode as crush or crack of DCM material when the concrete core pile is shorter. This failure mode was observed in triaxial test when the concrete core pile length extended only 60% and 75% of the DCM material. Further, they categorized that the failure on the concrete core pile as a governing factor when its length is sufficient but the cross sectional dimension is comparatively small. This failure mode was observed when the concrete core pile



(a) Deviator stress-strain relationship



(b) Excess pore pressure-strain relationship

Fig. 12 Effect of concrete core pile length on strength of SDCM pile from CU tests at A_w=15%

extended 90% of the length of DCM material in the CIU triaxial test.

Influence of cement content on failure mode

The CIU triaxial test was used to compare the strength of the SDCM for a specific core pile length while varying the cement content of the cement-admixed clay. The stress-strain relationship of the SDCM for 60% core pile length (L_{core}/L_{DCM} = 0.60) is shown in Fig. 13a. The failure mode changed towards more brittle behavior when the cement content increased from 10% to 20%. As explained previously, this length of core pile was practically insignificant to bring any improvement on the performance of the SDCM pile. When the length of the concrete core was 75% of the length of the SDCM (L_{core}/L_{DCM} = 0.75) increasing the cement content induced a small decrease in the strength after the peak strength (Fig. 13b). The post failure strength reduced gradually until 5% strain and then again increased.

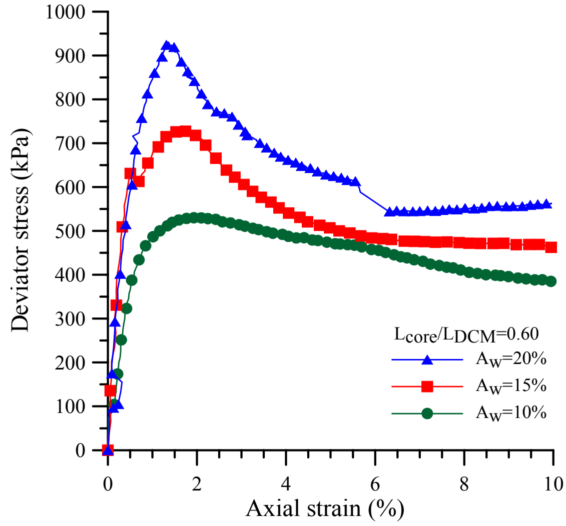
From this study, it is clear that the concrete core pile shared the load only after the failure of DCM material due to the boundary condition for load transfer in triaxial test. The more ductile nature of failure in the case of 10% cement content was thus enhanced by the load sharing of core pile to effectively increase the post failure strength of the SDCM. However, in the 15% and 20% cement content specimens the load taken by the concrete core was compensated by the loss of strength of the DCM material due to brittle failure which resulted into the constant post failure strength of the SDCM.

The stress-strain relationship of the SDCM when the core pile length was 90% of the DCM length (L_{core}/L_{DCM} = 0.90) in Fig. 13c shows two important trends in behavior. The higher cement content tends to mobilize the full strength of the SDCM at smaller strains and the failure of the concrete core governs the failure of the SDCM.

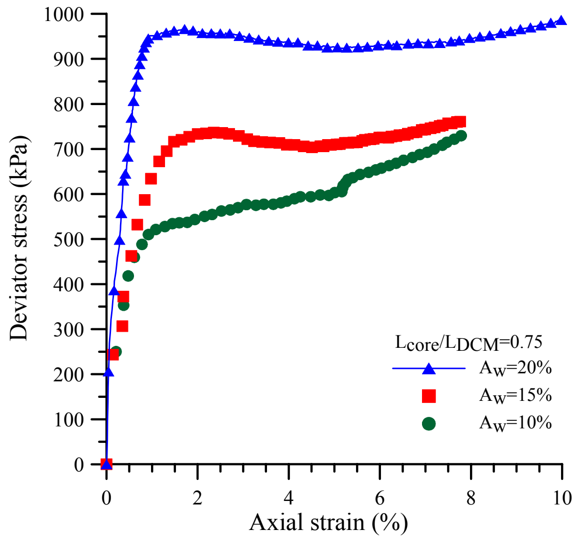
During the test, the specimen bulged laterally in the unimproved portion of the SDCM which was more prominent for lower cement content with consequent large strain before the full strength of SDCM was mobilized. The strength of the SDCM was observed to be higher for higher cement content due to the higher strength of the cement-admixed clay. But the improvement observed in the SDCM beyond the differences in the strength of the cement-admixed clay may have resulted from the possible variation of strength of concrete core pile.

CONCLUSIONS

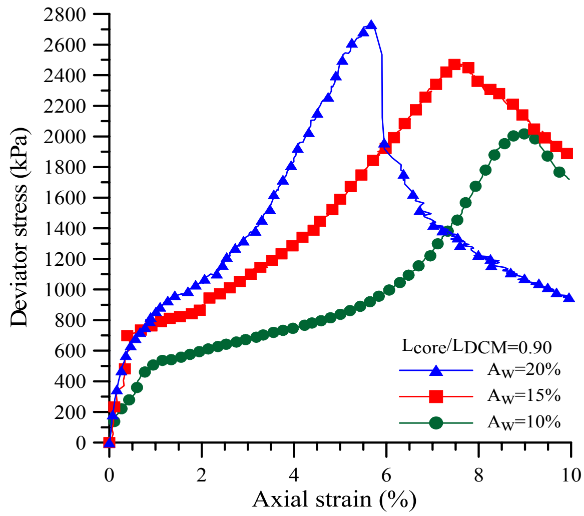
The interface shear strength between the cement-



(a) Deviator stress-strain relationship at L_{core}/L_{DCM}=0.60



(b) Deviator stress-strain relationship at L_{core}/L_{DCM}=0.75



(c) Deviator stress-strain relationship at L_{core}/L_{DCM}=0.90

Fig. 13 Effect of cement content on strength of SDCM pile from CU tests with varying L_{core}/L_{DCM}

admixed clay and the concrete pile showed sharp increase when the cement content was increased from 10% to 15%. Increasing the cement content beyond 15% does not result in any significant gain in strength. The failure mode became more brittle and smaller pile displacement was required for peak strength with increasing cement content of the cement admixed-clay.

At lower cement content, up to 15%, the adhesion intercept is very sensitive to the cement content. The 15% cement content was shown to yield optimum improvement. The adhesive coefficient α was found to be 0.19 and 0.23 for D_{DCM}/D_{core} of 6 and 3, respectively.

The CIU triaxial tests of model SDCM pile revealed that the core pile length should be more than 75% of the DCM length to demonstrate any improvement. The concrete core pile extending 90% of the DCM length yielded significant improvement on the strength of SDCM pile, but it should be clear at this point that the failure on DCM was observed nearly at the same strength irrespective of the length of concrete core pile due to the boundary conditions of the triaxial test. However, the mortar pile length influenced the position of failure plane as well as failure mode. The study revealed that the shorter pile length (L_{core}/L_{dcm} = 0.60 and 0.75) caused the failure on dcm pile while the longer pile length (L_{core}/L_{dcm} = 0.90) but relatively smaller cross sectional area shifted the failure to the concrete core pile.

REFERENCES

Bergado, D.T., Ruenkrairergsa, T., Taesiri, Y. and Balasubramaniam, A.S. (1999). Deep soil mixing to reduce embankment settlement. Ground Improvement J. 3(3): 1-18.

Bergado, D.T., Lorenzo, G.A. and Tran, C.V. (2004). Laboratory shear strength of interface and clay surrounding the DMM pile. Proc. Engineering Practice and Performance of Soft Deposits, Osaka, Japan: 223-228.

Bergado, D.T. and Lorenzo, G.A. (2005). Economical mixing method for cement deep mixing. Proc. ASCE GeoFrontiers 2005 Conference, Austin, Texas, U.S.A.

Chu, L.M. and Yin, J.H. (2005). Comparison of interface shear strength of soil nail measured by both direct shear box tests and pullout tests. J. Geotech. Geoenviron. Engrg. ASCE. 131(9): 1097-1107.

Coyle, H.M. and Reese, L.C. (1966). Load transfer for axially loaded piles in clay. J. Soil Mech. and Found. Div. ASCE. 92(2): 1-26.

Dong, P., Qin, R. and Chen, Z. (2004). Bearing capacity and settlement of concrete-cored DCM pile in soft ground. Geotech. Geol. Engrg. 22(1): 105-119.

Kitazume, M., Tabata, T. and Ishikawa, Y. (1996). Model tests on failure pattern of cement treated retaining wall. Proc. IS-TOKYO’96/The Second International Conference on Ground Improvement Geosystems, Tokyo. 1: 509-514.

Kunito, T. and Mashima, M. (1991). Effects of soils and mixing conditions on bond strength between soil-cement and steel. Soil Improvement: 167-181.

Lai, Y.P., Bergado, D.T., Lorenzo, G.A. and Duangchan, T. (2006). Full-scale reinforced embankment on deep jet mixing improved ground. Ground Improvement J. 10(4): 153-164.

Lorenzo, G.A. and Bergado, D.T. (2006). Fundamental characteristics of cement-admixed clay in deep mixing. J. Materials Civil Engrg. ASCE. 18(2): 161-174.

Lorenzo, G.A. and Bergado, D.T. (2004). Fundamental parameters of cement-admixed clay - new approach. J. Geotech. Geoenviron. Engrg. ASCE. 130(10): 1042-1050.

Petchgate, K., Jongpradist, P. and Jamsawang, P. (2004). Field flexural behavior of soil-cement column. Proc. Fifth Symposium 2004 on Soil/Ground Improvement and Geosynthetics, King Mongkut’s University of Technology, Thonburi, Thailand: 85-90.

Petchgate, K., Jongpradist, P. and Panmanajareonphol, S. (2003a). Field pile load test of soil-cement column in soft clay. Proc. Int. Symposium 2003 on Soil/Ground Improvement and Geosynthetics in Waste Containment and Erosion Control Applications, Asian Institute of Technology, Thailand: 175-184.

Petchgate, K., Jongpradist, P. and Samanrattanasatien, P. (2003b). Lateral movement behavior of cement retaining wall during construction of a reservoir. Proc. Int. Symposium 2003 on Soil/Ground Improvement and Geosynthetics in Waste Containment and Erosion Control Applications, Asian Institute of Technology, Thailand: 195-205.

Tungboonterm, P. and Yoottimit, C. (2002). Factors affecting bond strength of steel reinforcement in cement column. Proc. Int. Symposium on Lowland Technology, Saga Univ. Japan. 193-198.

Wu M., Zhao X. and Dou Y.M. (2005). Application of stiffened deep cement mixed column in ground improvement. Proc. Int. Conference on Deep Mixing Best Practices and Recent Advances, Stockholm: 463-468.

Zheng, G. and Gu, X.L. (2005). Development and practice of composite DMM column in China. Proc. 16th Int. Conference on Soil Mechanics and Geotechnical Engineering, Osaka. 3: 1295-1300.