รายงานฉบับสมบูรณ์

โครงการ : คุณลักษณะทางด้านกำลังและการเปลี่ยนรูปของดินปรับปรุงคุณภาพด้วยปูนซีเมนต์ที่มีปริมาณน้ำในส่วนผสมสูง

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พฤศจิกายน 2552

สัญญาเลขที่ MRG4780037

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สนับสนุนโดย สำนักงานคณะกรรมการการอุดมศึกษา และ สำนักงานกองทุนสนับสนุนการวิจัย

Abstract

Project Code : MRG4780037
(รหัสโครงการ)

Project Title : Strength and Deformation Characteristics of Soil-Cement Mixtures with High Water Content
(ชื่อโครงการ)

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Project Period 2 yesrs (1 July 2003 ถึง 30 June 2006)
(ระยะเวลาของโครงการ)

This research report presents the investigation of strength and deformation characteristics of cement-admixed clay at high water content and the potential of using disposed fly ash to add up in cement-admixed clay. The investigation is done by means of physical property tests, unconfined compression test and one-dimensional compression test. From testing results, the strength and deformation characteristics of cement-admixed clay with and without adding fly ash at high water content are governed by mixing ratio (water-cement-fly ash contents), curing time and curing stress. For cement admixed clay, empirical equations which can reasonably predict the after curing void ratio and the yield stress of cement-admixed clay with and without curing stress were proposed. In addition, a disturb state model was implemented to capture the overall one-dimensional compression characteristics of soil-cement mixtures with different combinations of cement content, water content and curing stress by using a unique set of parameters. For cement-fly ash admixed clay, the ground fly ash can partially replace Portland cement in this mixture if the cement portions are greater or equal 10 percent. Based on the equivalent cementitious material content concept, an empirical equation relating the efficiency factor, α with mixing proportions was proposed. Then, together with this proposed efficiency factor, strength prediction of cement-fly ash admixed clay by Feret's Equation and Abram's law, were carried out and discussed.

Keywords : Strength, Deformation, Cement-admixed Clay, Fly ash, Characteristics

บทคัดย่อ

Project Code : (รหัสโครงการ)	**MRG4780037**
Project Title : (ชื่อโครงการ)	**คุณลักษณะทางด้านกำลังและการเปลี่ยนรูปของดินปรับปรุงคุณภาพด้วยปูนซีเมนต์ที่มีปริมาณน้ำในส่วนผสมสูง**
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Project Period (ระยะเวลาของโครงการ)	**2 ปี (1 กรกฎาคม 2547 ถึง 30 มิถุนายน 2549)**

รายงานวิจัยฉบับนี้แสดงผลการศึกษาคุณลักษณะทางด้านกำลังและการเสียรูปของดินเหนียวผสมปูนซีเมนต์ และศักยภาพการใช้เถ้าลอยผสมเพิ่มเพื่อการทดแทนปูนซีเมนต์ การศึกษาประกอบด้วยการทดสอบทางด้านคุณสมบัติทางกายภาพต่าง ๆ การทดสอบแรงอัดทิศทางเดียว การทดสอบการเสียรูปแบบหนึ่งมิติ และการทดสอบแบบสามแกน ผลการทดสอบระบุว่าคุณลักษณะทั้งด้านกำลังและการเสียรูปของของผสมนี้ขึ้นอยู่กับ อัตราส่วนผสมซึ่งประกอบไปด้วย ดิน-น้ำ-ปูน-และเถ้าลอย ระยะเวลาและความเค้นระหว่างบ่มตัวอย่าง สำหรับดินซีเมนต์สมการอย่างง่ายที่สามารถใช้ทำนายอัตราส่วนช่องว่างหลังจากบ่มและความเค้นครากได้ถูกเสนอและประยุกต์ใช้กับแบบจำลองแนวคิดสภาวะรบกวนเพื่อใช้จำลองพฤติกรรมการเสียรูปของดินซีเมนต์ได้เป็นอย่างดี สำหรับดินซีเมนต์ผสมเถ้าลอยพบว่าเถ้าลอยสามารถใช้แทนที่ปูนซีเมนต์บางส่วนได้หากมีปริมาณปูนซีเมนต์อยู่ในส่วนผสมไม่น้อยกว่า 10 เปอร์เซนต์ นอกจากนี้การศึกษานี้ได้นำเสนอสมการทำนายกำลังอย่างง่ายที่พัฒนาจากพื้นฐานแนวคิดปริมาณซีเมนต์เทียบเท่าและแฟคเตอร์ประสิทธิภาพกับการประยุกต์ใช้สมการของ Feret และ Abram.

คำสำคัญ : กำลัง การเสียรูป ดินเหนีนวผสมปูนซีเมนต์ เถ้าลอย คุณลักษณะ

Executive Summary

This research report presents the investigation of strength and deformation characteristics of cement-admixed clay at high water content and the potential of using disposed fly ash to add up in cement-admixed clay. The investigation is done by means of physical property tests, unconfined compression test and one-dimensional compression test. From testing results, the strength and deformation characteristics of cement-admixed clay with and without adding fly ash at high water content are governed by mixing ratio (water-cement-fly ash contents), curing time and curing stress. For cement admixed clay, the strength and deformation characteristics under one-dimensional compression condition is investigated and a model to predict one-dimensional compression characteristics of cement-admixed clay is developed. To develop the model, a series of oedometer were performed paying special attention to influence of curing stress. From test results, yield vertical stress increased with decreasing water content and increasing of cement content and curing stress. With increasing of water content and decreasing of cement content and curing stress, after curing void ratio increased. The empirical equations which can reasonably predict the after curing void ratio and the yield vertical stress of cement-admixed clay with and without curing stress are proposed as follows.

When P'_{cure} *= 0:*

$$e_{ot} = \left[\frac{1 + C_w + G_{so}}{\dfrac{100}{C_w}} \left(\frac{\dfrac{100}{C_w} - 0.012A_w + 0.012\log_{10}(t) + 0.99\left(1 - \dfrac{A_w}{100}\right)^{0.0807}}{0.0025A_w + 0.01\log_{10}(t) + 1.088} \right) \right] - 1 \qquad \text{(a-1)}$$

When P'_{cure} *> 0:*

$$e_{ot} = \left[\frac{1 + C_w + G_{so}}{\dfrac{100}{C_w}} \left(\frac{\dfrac{100}{C_w} - 0.012A_w + 0.012\log_{10}(t) + 0.99\left(1 - \dfrac{A_w}{100}\right)^{0.0807}}{0.0025A_w + 0.01\log_{10}(t) + 1.088} \right) \right] - \left[1 + \left(0.03045\left(\frac{C_w}{A_w}\right) + 0.001\exp(0.0711P'_{cure}) \right) \right] \qquad \text{(a-2)}$$

and

$$P'_y = \exp\left(\frac{3e_{ot}}{A_w} + 0.0075C_w - 8.297 \right) + P'_{cure}\left(-0.2388\frac{C_w}{A_w} + 0.0191P'_{cure} + 0.6471 \right) \qquad \text{(b)}$$

The disturb state model incorporated with proposed empirical formula can simulate the overall one-dimensional compression characteristics of cement-admixed clay with different combinations of cement content, water content and curing stress.

The potential of using disposed fly ash to partially replace Portland cement is evaluated by conducting a series of unconfined compression tests of cement fly ash admixed clay. From this limited investigation, it is confirmed that, with suitable cement content, this ground disposed fly ash could be successfully added into soil cement to enhance both strength and physical characteristics. The strength of cement-fly ash admixed clay at high water content increased with increasing amount of cementitious material content and duration of the curing time and decreased with increasing water content. The efficiency of fly ash depended on the portion of cement, disposed fly ash and water content in mixtures. To predict strength of clay-cement-fly ash mixtures, equivalent comentitious content concept, Aw*, in conjunction with efficiency factor α, can be successfully employed.

$$A_w^{\,*} = A_w + \alpha F_w \tag{c}$$

where α denotes for efficiency factor of fly ash for replacement or adding up which is the function of chemical composition and grain size distribution of the fly ash and F_w is the fly ash content (%). To calculate the value of α for each proportion by means of strength evaluation, a widely-used Feret's equation modified by Papadakis and Tsimas (2002) as shown below, was adopted.

$$f'c = K\left(\frac{1}{W/(C+\alpha F_w)} - a\right) \tag{d}$$

The efficiency factors, α, of each mixing ratio were then calculated by substituting the obtained unconfined compressive strength and mixing components into Eq. (d) using the pre-determined K and a of each curing time from cement admixed clay without adding fly ash. The equation to calculate the efficiency factor was demonstrated as follow:

$$\alpha = \frac{\left\{\left[\frac{f_c'}{K} + a\right]\cdot W\right\} - A_w}{F_w} \tag{e}$$

Thus, empirical equations to relate the efficiency factor and $A_w/(W+F_w)$ are proposed in this study as Eq. (f) and Eq. (g) for curing time of 7 days and 28 days, respectively.

$$\alpha_{7\text{ day}} = 4.2632\,[A_w/(W+F_w)] - 0.0584 \tag{f}$$

$$\alpha_{28\text{ day}} = 7.3356[A_w/(W+F_w)] - 0.1544 \tag{g}$$

The predictions of strength by proposed empirical equations produced satisfactory agreements with the testing results. However, the proposed empirical equations are based on limited data of specific soil and source of fly ash, broader set of studies are needed for more generalized form of these equations. Moreover, the long-term strength of this mixture should be investigated.

เนื้อหางานวิจัย

Introduction

According to the soil condition of the Central Plain of Thailand, deltaic marine deposit, several ground improvement methods are essentially required to improve the strength and deformation characteristics of soft ground namely: Deep Mixing Method (DMM), Prefabricated Vertical Drains (PVD), Mechanically Stabilized Earth (MSE) and etc. However, the most common method of soft ground improvement is cement stabilization, which widely used in Southeast Asia Region. It has been used as chemical for both shallow and deep soil stabilization. This method of stabilization was initiated in Sweden and Japan in late 1970's including Deep Mixing Method (DMM) until now.

The stabilization of soft clay by cement was considered as improvement techniques utilized for improving the inherent properties of soft soil, such as increasing the strength, reducing the compressibility, improving the swelling or squeezing characteristics and increasing its durability. The use of cement stabilization has been extended to greater depths in which the cement or lime columns act as type of soil reinforcement (Broms, 1984). The present applications include the use of cement column to increase the bearing capacity and reduce the total and differential settlements below lightly-loaded structures. Considering the versatility of cement stabilization, the method has gained wider acceptance especially in the Southeast Asia (Broms, 1984; Bergado et al., 1999; Uddin and Buensuceso, 2002; Petchgate et al. 2003).

The present practice in the design of cement-stabilized ground is still based on the results of unconfined compression test. Moreover, several researchers had already dealt with the study of the engineering characteristics inherent to cement-treated soil (Broms, 1984; Bergado et al., 2003; Uddin et al. 1997; Rotta et al., 2003). Some researchers had developed model equations and derived empirical relationships useful for predicting the strength of cement-treated clay (Horpibulsuk et al., 2003). Few researches also dealt with the bearing capacity analysis (Broms, 1984), and with the settlement analysis (Bergado et al., 1999). The need to describe the mechanical behavior of cement treated clay under various loading conditions become importance. In addition, there is no comprehensive research on the strength and deformation characteristics of cement-admixed clay with high water content.

The most recent researches related to strength and deformation characteristics of cement-treated clay at high water content reveal that the cement content governs the behavior of the post-yield compression line. Variation of water content will influence the values of the initial void ratio after curing, and, hence, the magnitude of the vertical yield stress. The coefficient of consolidation shows a bilinear relationship with void ratio (Horpibulsuk et al., 2004). Moreover, the unconfined compression strength at certain curing period has been effectively characterized by the parameter called " total clay water content-cement content ratio"(Miura et al., 2001). Therefore, at least three parameters, namely; clay water content, cement content and initial void ratio after curing are necessary to characterize the strength and deformation behavior of cement-treated clay.

A number of laboratory tests as well as mathematical models for studying and simulating the deformation characteristics of cement-stabilized clay have been conducted and proposed (e.g., Uddin et al., 1997; Bergado et al., 1999; Miura et al., 2001; Lorenzo and Bergado, 2004; Lorenzo et al., 2006). Most of these researches utilize cement content and curing time as control parameters. From the previous researches, cement-admixed clays have been cured under controlled temperature and moisture without curing stress. However, in the actual field condition, due to different overburden pressures for different depths causing different void ratios and stress histories, this improved soil might have different strengths and deformation characteristics varying with depth (Rotta et al., 2003). For mathematical simulation of deformation characteristics of cement-admixed clay, disturb state model was employed for simulating compression behaviors of Bangkok Clay mixed with cement (Liu et al., 2006). However, in those simulations, the model parameters varied with mixing ratios; therefore, they are not unique for a given cement-mixed clay.

From the views of the above, it is likely that there is very limited research to investigate the effects of curing stress on the deformation characteristics of cement-admixed clay. In addition, there is no mathematical model to simulate the deformation characteristics of cement-admixed clay with and without curing stress by using a unique set of model parameter. Thus, the main objectives of this paper are to investigate the one-dimensional deformation characteristics of cement admixed clay with and without curing stress, and to implement a mathematical model for simulation of one-dimensional deformation characteristics of the afore-mentioned mixed material based on disturb state concept (Liu et al., 2003) with single set of model parameters.

Besides the mechanical behavior issue, as the construction cost is mainly governed by the cement cost, the extent of cement column is limited. Particularly, for wet process with water pre-jet method, a huge amount of cement must be consumed since the strength of soil-cement is controlled by water-cement ratio (Miura et al. 2001). Therefore, a method to replace cement material with other inexpensive materials should be investigated to enhance this application.

Fly ash is a by-product of the combustion of pulverized coal in thermal power plant. It is considered to be useful as a supplementary cementing material (SCM) in combination with Portland cement by pozzolanic reaction. Besides the successes in partially replacing Portland cement in concrete works, a number of researches on study of using fly ash in the field of geotechnical engineering has been reported, such as the stabilization of soil in compaction works of highway embankment or slope without cement or lime (Prabakar et al. 2004), with cement (Kaniraj and Havanagi 1999) and with cement and fiber-reinforcement (Kaniraj and Havanagi 2001), as well as stabilization of expansive soil (Cokca 2001). However, the demand for consumption of fly ash is still less than the production. The unused fly ash was then disposed at the ponds or landfills adjacent to each power plants and this fly ash was called disposed fly ash. Thus, there are still needs in finding new uses and increasing its utilization. Because of the uncertainty of the chemical and physical properties, only little disposed fly ash has been used. Moreover, since disposed fly ash is exposed to weather, it forms big lumps and creates little pozzolanic reaction when used as cementitious material. From all reviewed literature, the authors have not acknowledged any research on the potential of using disposed fly ash in ground improvement for soft clay by soil mixing with high cement content. In addition, there is no research that proposes mathematical equations to predict the strength of cement-fly ash admixed clay with different mixing ratios. Thus, the current paper begins with the investigation of strength characteristic of mixed material at high water content with different mixing ratios. The influencing parameters on the strength characteristic were systematically characterized and an empirical equation which is capable of reproducing the influence of disposed fly ash as well as other parameters was proposed. Finally, strength prediction of cement-fly ash admixed clay via empirical equations in conjunction with the proposed efficiency factor was presented.

Experimental Program

Materials

Three kinds of materials were used in this research, i.e., soft clay, cement and fly ash. The soft clay utilized in this study is typical soft Bangkok clay from King Mongkut's University of Technology Thonburi (KMUTT) located in southern part of Bangkok, Thailand. Sampling was performed from the depth of 4 to 5 m in soft clay layer. The physical properties of the Bangkok clay were summarized in Table 1. The undrained shear strength, S_u, obtained from unconfined compression (UC) tests ranging from 16 to 17 kPa.

Table 1. Index and physical properties of clay

Properties	Bangkok Clay-KMUTT (This study)	Bangkok Clay-AIT (Lorenzo, 2005)	Ariake Clay (Horpibulsuk et al., 2003)
Liquid limit, LL (%)	119	103	120
Plastic limit, PL (%)	41	43	57
Shrinkage limit, SL (%)	14	N/A	N/A
Plasticity index, PI (%)	78	60	63
Water content, w (%)	103	76-84	135-150
Liquidity index, LI	0.79	0.62	1.23
Specific gravity, GS	2.69	2.61	2.67
Total unit weight, g_t (kN/m^3)	14.1	14.3	13.1-13.4
Dry unit weight, g_d (kN/m^3)	6.94	7.73	5.2- 5.7
Initial void ratio, e_i	2.37	2.31	3.6-4.0
Soil Classification (USCS)	CH	CH	CH

Portland cement used in this study is Type I with specific gravity (G_s) of 3.14. The amount of cement in current practice ranges from 100 to 300 kg/m^3 of wet soil. Thus, for future development, corresponding cement content (A_w) in this study covers the range of 5 to 40 percent of dry soil.

It is known that fly ashes generally have negative effects on the concrete strengths at the early ages (Babu and Rao, 1994). However, from recent researches, this can be overcome by grinding the fly ashes to finer fraction for higher performance (e.g. Slanicka 1991; Paya et al. 1997). Ground fly ashes might be partially replacing cement to produce low-cost, environmentally friendly soil cement column. The composition of fly ash varies considerably depending on the nature of the coal burned and the power plant operational characteristics but grinding does not have much effect on chemical composition (Erdogdu and Turker 1998; Songpiriyakij and Jaturapitakkul 1995). This study used disposed fly ash at the disposal time of 6 months from Mae Moh Power Plant, Thailand. These fly ashes were collected from the disposed areas and sun-dried approximately 1-2 days to reduce their high water content to approximately 0.5%. After that, they were sieved through sieve No. 16 and then ground by grinding machine until the amount of ash particles retained on sieve No. 325 was less than 5% by weight. The grain size distribution after grinding is illustrated in Fig. 1 and the properties are shown in Table 2. The specific gravity of the ground disposed fly ash is higher than that of the original disposed fly ash because grinding process, by crushing the hollow or porous particles of coarse fly ash, reduces both the porosity and the particle size of the ash (Cheerarot and Jaturapitakkul 2004; Kiattikomol et al. 2001; Paya et al. 1997). The major chemical compositions of ground disposed fly ash are SiO_2(42.07%), Al_2O_3(21.03%), Fe_2O_3(7.12%) and CaO(14.8%). The sum of SiO_2, Al_2O_3, and Fe_2O_3 is 70.22% which, however, can be classified as Class F according to ASTM C 618 (1997). The loss on ignition (LOI) of fly ash is 7.31% which exceeds 6% as specified by ASTM C 618. However, ASTM C 618 suggests that the use of Class F fly ash containing up to 12% of LOI may be approved by the user if either acceptable performance records or laboratory tested results are made available. It was reported that the coarse fraction of fly ash had less SO_3 than the fine one (Erdogdu and Turker 1998; Jaturapitakkul et al. 1998). Since SO_3 may be harmful to durability, use of ground coarse fly ash as cement replacement may be an advantage.

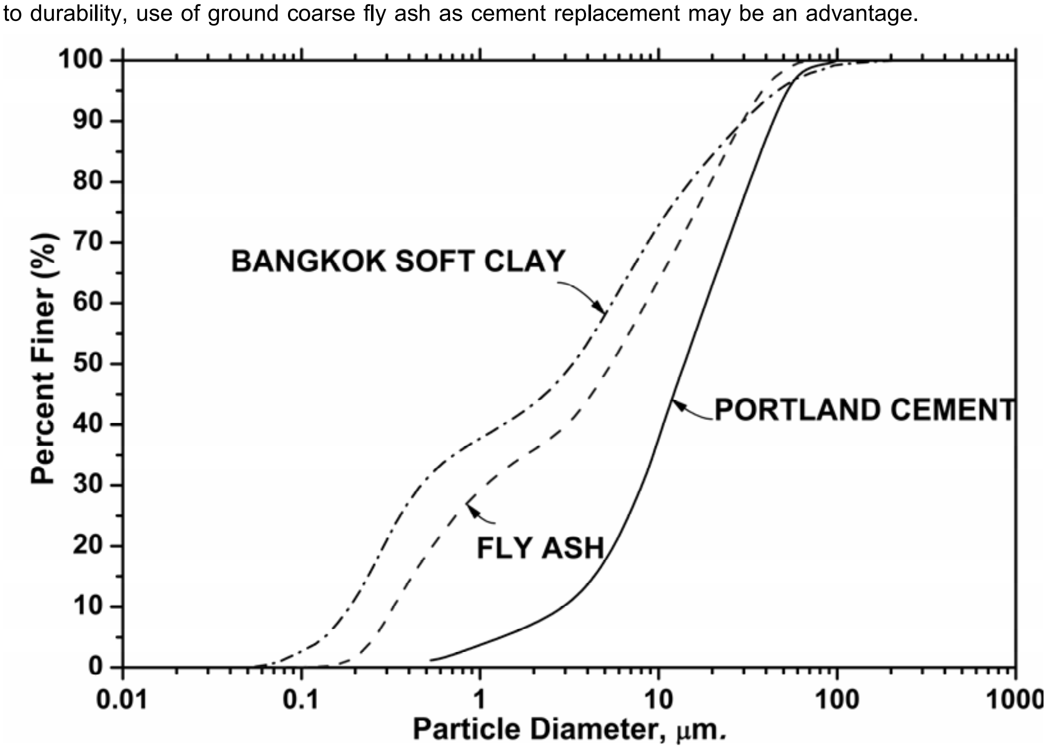


Fig. 1. Grain size distributions of ground fly ash and Portland cement comparing with that of soft clay

Table 2. Physical properties of fly ash and ground fly ash

Properties	original fly ash	ground fly ash
Fineness Amount Retained when		
wet-sieved on 45 micron, (%)	43.8	3-4
Specific Gravity, G_S	2.16	2.51

Unconfined Compression Tests

In this paper, the unconfined compression test was conducted in accordance with ASTM D2166-00(2002). Specimen was 35 mm in diameter and 70 mm in height. After curing, it was extruded from the mold. The unit weight of the specimen was obtained prior to testing. The rate of shearing was maintained to 1.14% per minute (1.14 mm/min) and the test program is summarized in Table 3.

Table 3. Summarizes of the program for unconfined compression (UC) tests

Name of test	Cement content, A_w(%)	Amount of fly ash, F_w(%)	Remolding water content, w^* (%)	Curing time (Days)
1	undisturbed clay			
2	5,10,15,20,25,30,35,40	0	130,160,200	7,28
3	5,10,15,20,25,35	5,10,15,20,25,30	130,160,200	7,28

The clay samples utilize in all tests were remolded to water contents as 130%, 160% and 200%. The purpose of varying the remolding water content is to simulate the actual condition of soil-cement column/pile installation using deep mixing method (DMM) with slurry of cement (e.g. Yang 1997) and jet mixing/grouting method (e.g. Shibazaki 1996). Prior to the introduction of cement slurry, the natural soil was subjected to remolding and mixing with associated addition of water, which increased the water content of the natural soil. The remolding clay water content (w_r) is hereinafter defined as the water content of the remolded clay prior to the addition of cement slurry. The amount of water added to a wet clay to obtain the desired remolding water content was obtained using the following fundamental equation:

$$\Delta W_w = \frac{W_T}{1+w_0}(w_r - w_0) \qquad (1)$$

where ΔW_w is the weight of water to be added,

W_T is the total weight of prepared original untreated clay sample

w_r is the required remolding clay water content and

w_0 is the natural water content of the clay sample

Regarding to the water content in actual mixing condition which is higher than the liquid limit, the high water content clay is in liquid state and, thus, can be uniformly mixed. In this work, the disturbed samples of the clay with the required amount of additional water were placed inside a portable mechanical soil mixer and allowed to mix thoroughly for a few hours to obtain uniform water content, following the previous researches on soil-cement (e.g. Miura et al., 2001, Lorenzo and Bergado, 2004).

The prepared remolded clay sample at particular remolding water content was mixed with cement-fly ash slurry having water-cement ratio (W/C) of 1.0 using a portable mechanical mixer. Due to an amount of water in slurry, the overall water content of the paste just at the time of mixing will be the total remolding water plus the water in the cement-fly ash slurry. The overall water content in the mixture is hereinafter called the total clay water content (w_t). The total clay water content is defined as:

$$w_t = w_r + (W/C)A_w \qquad (2)$$

where w_t is the total clay water content of the paste (%) reckoned from the dry weight of soil only and A_w is the desired cement content (%) defined as the percentage ratio of the weight of cement to the dry weight of soil.

Due to high workability of the clay-water–cement-fly ash paste, each specimen for unconfined compression test is made by dropping the paste into the 35 mm diameter by 100 mm height PVC mold for shrinkage due to hardening and trimming of specimen. Pushing was done to remove air bubbles. The molded paste is allowed to protrude out from the other end of the mold for checking the occurrence of "honeycomb" structure. Pushing was continued until the surface of the protruding specimen is uniform and smooth. The density of each specimen with the same mixing condition was monitored and kept constant. The mold together with the specimen was waxed to prevent moisture loss and, then, was placed for curing in the humidity room. Samples were cured for a period of 7 to 28 days. After curing, each specimen was removed from the mold and made available for the intended tests. Finally, for particular mixing condition, the specimens with smooth surface and with similar densities were selected for testing. After curing, the variation of unit weight of specimen must be in the range of $\pm$1 %.

One dimensional compression test

To investigate the influencing parameters for the compressibility of cement-admixed clay cured under stress, the test program was designed as tabulated in Table 1. The mixing ratio was varied with different portions of remolded water contents, w^*, and the ratio of the cement content to the total clay water content, C_w/A_w (explained in details later) (Horpibulsuk et al., 2004). The mixing ratios and curing stress values were based on the application of wet-process cement column in Thailand (Bergado et al., 1999, Petchgate et al., 2007). To cure sample under stress, stress was applied by static load for the entire curing period of 28 days and then removed just before performing one-dimensional compression test.

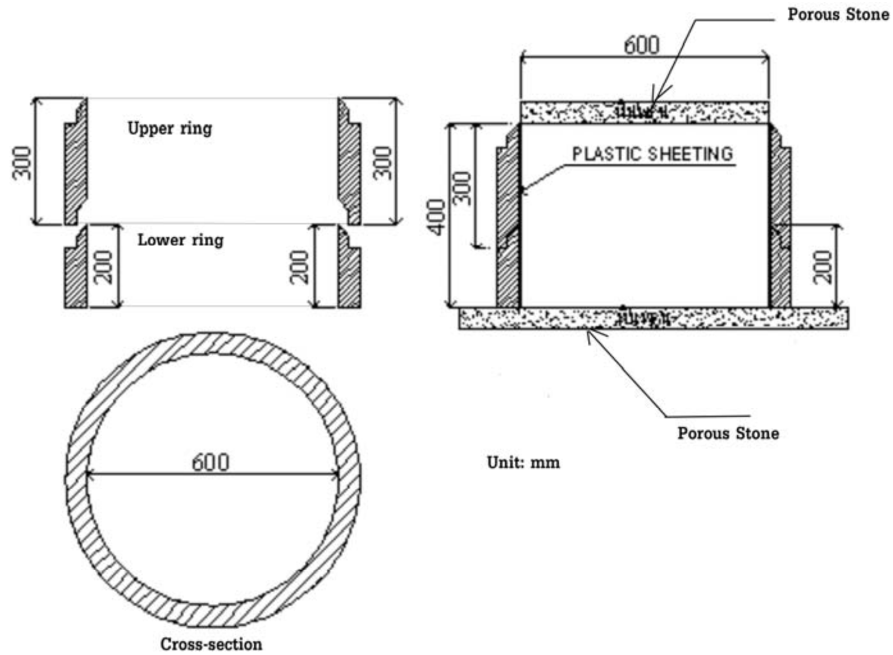


Fig. 2 Oedometer ring for testing

Table 4 Test program in this study

No.	w^* (%)	C_w/A_w	Curing period (day)	Curing stress (kPa)	Nos. of sample
1	-	Undisturbed	-	-	1
2	1.25LL	Intrinsic	-	-	1
3	130	10	28	0 , 43 , 86	3
4	130	15	28	0 , 43 , 86	3
5	130	20	28	0 , 43 , 86	3
6	160	10	28	0 , 43 , 86	3
7	160	15	28	0 , 43 , 86	3
8	160	20	28	0 , 43 , 86	3
9	200	10	28	0 , 43 , 86	3
10	200	15	28	0 , 43 , 86	3
11	200	20	28	0 , 43 , 86	3
Total	-	-	-	-	29

The oedometer ring is schematically shown in Fig. 2. It was modified from the ring used in conventional oedometer tests by adding an upper ring for supporting a large deformation during curing under stress. According to an increase of thickness of the sample, the friction which may be mobilized between oedometer ring and clay specimen was reduced by using plastic sheet and silicone grease method (Fang et al., 2004). The top and bottom of clay specimen were attached by porous stone discs for allowing uniform drainage of water. Due to high workability of the cement-admixed clay paste, each specimen was made by using syringe to inject the paste into oedometer ring. Each cement-admixed clay specimen must be prepared within 45 minutes otherwise the workability would becomes insufficient. (Horpibulsuk et al., 2004). The density of each specimen with the same mixing condition was monitored. Finally, for a particular mixing condition, only specimens with smooth top surface and with similar densities among others were then selected for testing. Subsequently, the specimens were cured under different stress values for 28 days, following Table 4. The variation of unit weights determined after curing of specimens was within a range of ± 1 %.

Physical Characteristics

After-curing unit weight (γ_t) versus fly ash content at various remolding water content, cement content, and curing time are shown in Fig. 3. The unit weight increased with increasing cement content, curing time, and fly ash content. With the higher remolding water content, the unit weight of the treated sample was lower. For a certain remolding water content, the conceivable reason why the unit weight increased with increasing cement content could be attributed to the increasing amount of cementing products being formed. Moreover, some minerals of fly ash (such as compounds of silicon and aluminum) create secondary reaction with the products from hydration process. Thus, partial secondary reaction enhanced solid form which eventually increased the amount of solid phases per unit volume. This can be seen by the reduction of void ratio as illustrated in Fig. 4. Conversely, the reason why the unit weight decreased with increase of remolding water content could be attributed to the subsequent increase of the volume of soil void per unit volume of treated soil.

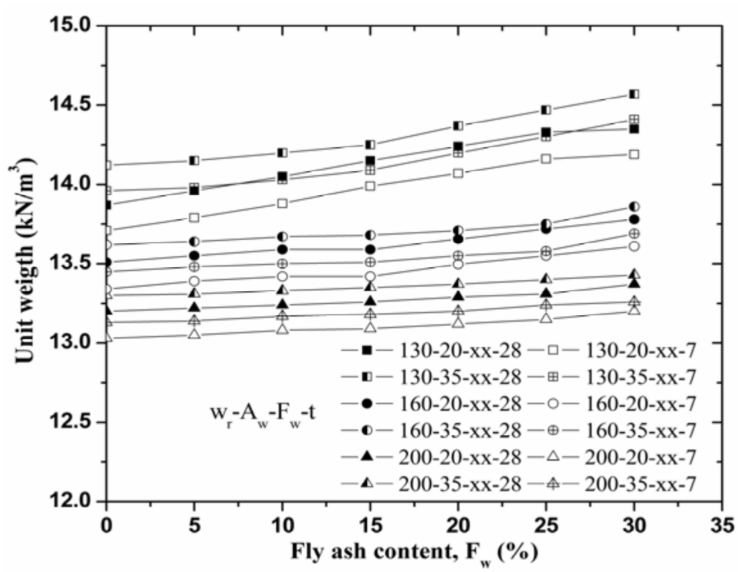


Fig. 3. After-curing unit weight of treated soil at curing time of 7 and 28 days

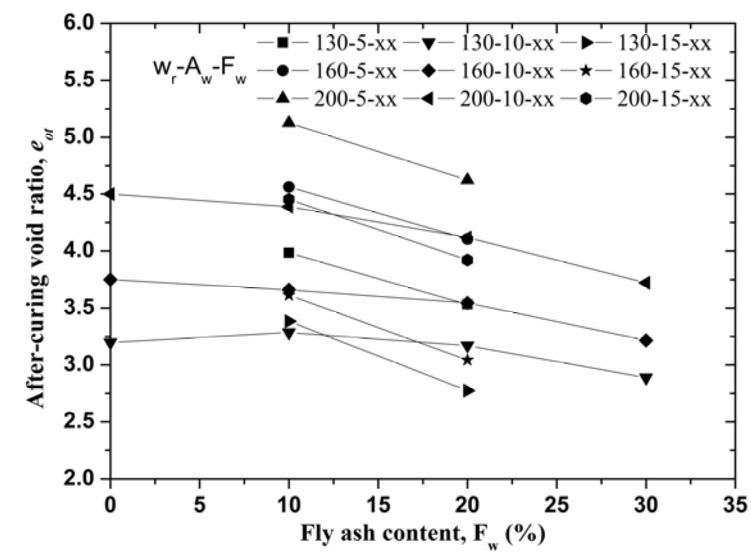


Fig. 4. After-curing void ratio treated soil at curing time of 28 days

Figure 5 shows the relationship of after-curing water content versus fly ash content at varying magnitudes of remolding water content, cement content, and curing times. After-curing water content is the ratio of the weight of water to the weight of dry soil after curing. The after curing water content decreased with increasing cement content and fly ash content. Due to the hydration process of cement and pozzolanic reaction of fly ash, water content decreased with increasing cement content and fly ash content. The after-curing water contents of specimens at curing time of 7 days are higher than those at curing time of 28 days, which is similar to the previous researches of cement-admixed clay (Lorenzo and Bergado 2004). This can be explained as the hydration and pozzolanic reaction at curing time of 28 days are more completely than those at curing time of 7 days.

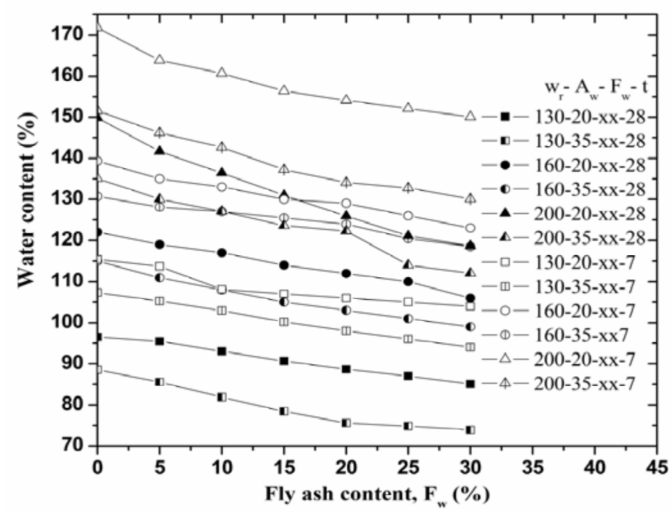


Fig. 5. After-curing water content of treated soil at curing time of 7 and 28 days

Unconfined Compressive Strength Characteristic

The stress-strain relationships of unconfined compression tests of samples with remolding water content of 200%, cement content of 15%, with varying fly ash content are illustrated in Fig. 6. The maximum stress, or strength, of material increased with increasing fly ash content. The increase in strength with fly ash content is due to the attribution of pozzolanic reaction to enhance the strength of the mixtures. The pozzolanic reaction, which is the secondary reaction, is to build up bonding between particles of the mixtures. This demonstrated the preliminary possibility of using fly ash for replacing cement in soil-cement column. However, more studies on long term strength should be investigated since low-strength materials produced with fly ash can lose strength if exposed to saturated conditions for a long period of time.

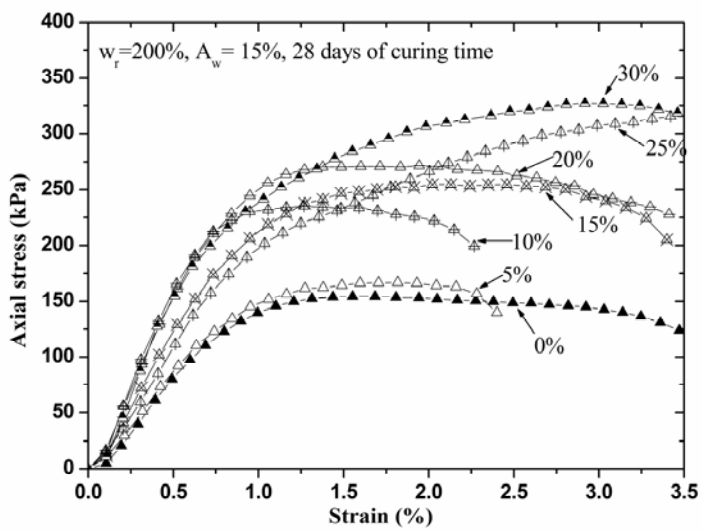


Fig. 6. Stress-strain relationship of unconfined compression test of A_w=15%, w_r =200%, varied fly ash content and curing time of 28 days

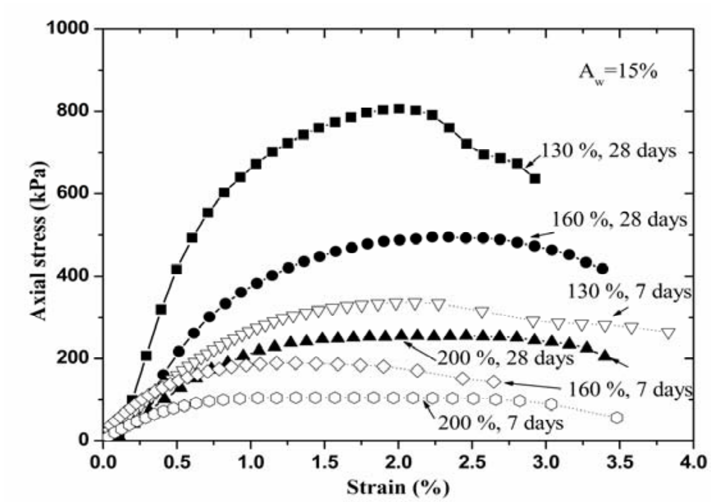


Fig. 7. Stress-strain relationship of unconfined compression test of A_w =15%, F_w=15 % at 7 and 28 days of curing with varied remolded water content

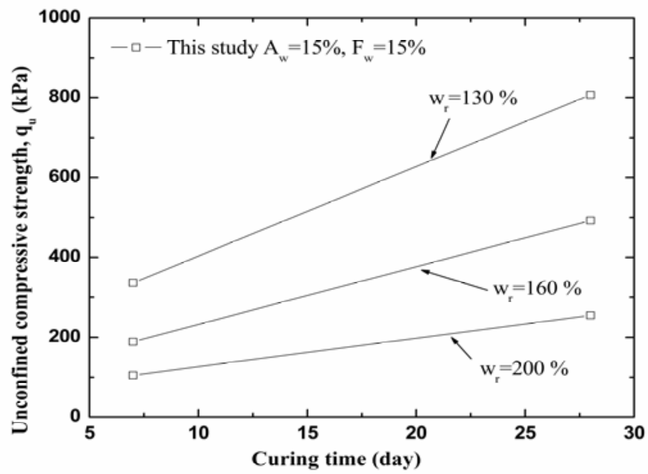


Fig. 8. Relationship between unconfined compressive strength and curing time of cement-fly ash treated soil.

Other prime parameters to control the strength characteristics of mixtures were water content and curing time. The water content is a necessary portion in hydration process to enhance strength characteristics. However, excessive water from hydration process caused the increase in distance between inter-particle or inter-cluster of particle spacing, which affect drop of strength (Miura et al. 2001). Figure 3 shows the increase of void ratio with increasing water content. Thus, the strength of specimen with higher remolding water content was less than that of specimen with lower remolding water content as shown in Fig. 7. The influence of curing time on strength development was illustrated in Fig. 8. The figure depicts for samples with 15% of cement and 15% adding fly ash content for different remolding water content. It can be seen that the strengths at the curing time of 28 days are approximately 2 times of those at the curing time of 7 days.

From overall testing results, it can be concluded that the strength characteristics of cement and cement-fly ash admixed clay depend on mixing ratios: cement content (A_w), fly ash content (F_w), remolding water content (w_r) and curing time (t). The influences of each proportion on unconfined compressive strength of cement-fly ash admixed clay for curing time of 7 and 28 days are summarized in Figs. 9 and 10, respectively.

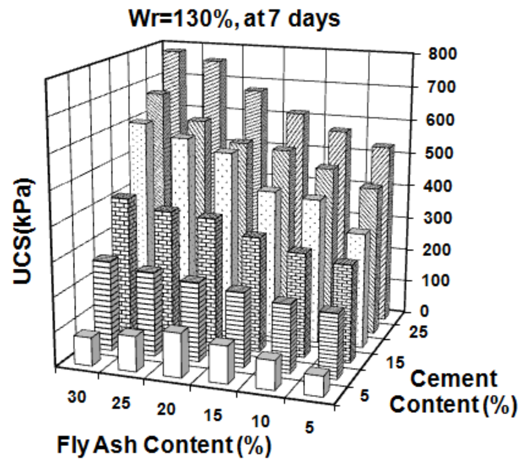
The strength developments from adding fly ash for each mixing proportion are summarized in Fig. 11. To achieve an effective fly ash addition, the required cement content must not be less than 10%. With insufficient cement content, the effectiveness of adding fly ash is unnoticeable. This can be explained as the result of inadequate calcium hydroxide products from hydration process for pozzolanic reaction. Moreover, the effectiveness of fly ash decreased with increasing fly ash content. The efficiency increases with increasing cement and decreasing fly ash content. However, if the cement is greater than 20%, the efficiency can be enhanced to the high content of fly ash.

The relationships of elastic modulus and strength of cement with and without fly ash admixed clay are shown in Fig. 12. Referring to the current application and design method of cement column which serves as bearing resistance and uses 50% of strength, the modulus of elasticity in terms of secant (50% q_u) moduli, E_{50} was selected to be investigated in this study. The E_{50} at curing time of 7 and 28 days can be approximately estimated as 93 q_u and 88 q_u, respectively. While, for cement-fly ash admixed clay, the relationships can be estimated as 129q_u and 96q_u for curing time of 7 and 28 days, respectively. The observed moduli of elasticity of cement-fly ash admixed clay are higher than those admixed with cement at the same strength and curing time. This is probably due to the additional pozzolanic reaction from fly ash. This indicated that by adding with fly ash, not only the strength could be gained, the deformation characteristic was also improved. Furthermore, the ratios of E_{50} and strength of both cement and cement fly ash admixed clays at 7-day curing time were higher than the ones at 28-day curing time. This is consistent with finding in concrete research (Juturapitakkul et al. 2004).

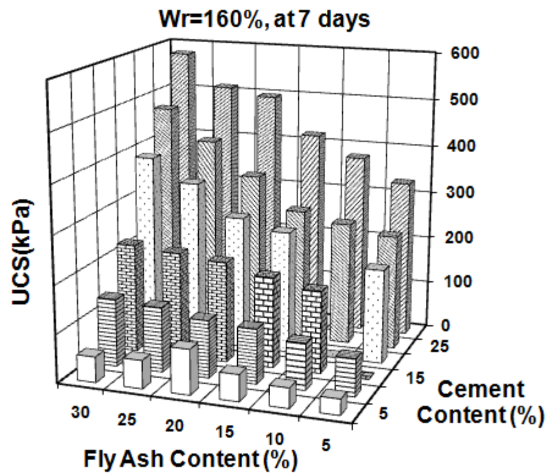
Strength prediction with reasonable accuracy is very important for preliminary design of mixing ratio and cost analysis in the actual implementation of cement treated soft clays. Many previous researches on soil-cement have been conducted to determine the suitable relation for this issue. In all of them, the approach is based on parameters governing strength characteristics including the influencing parameters, such as, water and cement contents and curing time. These include clay water to cement content ratio (w_t /A_w) with Abram's Law (Horpibilsuk et al. 2003 and Lorenzo, 2005), after curing void ratio to cement content (e_{ot}/A_w) with exponential equation (Lorenzo, 2005). In this part, an attempt for strength prediction of cement-fly ash admixed clay is carried out taking into account the effect of fly ash in such mixture. Based on the well known equivalent cementitious material content, the influence of fly ash is considered as an equivalent amount of cement, which can be described as;

$$A_w^* = A_w + \alpha F_w \tag{3}$$

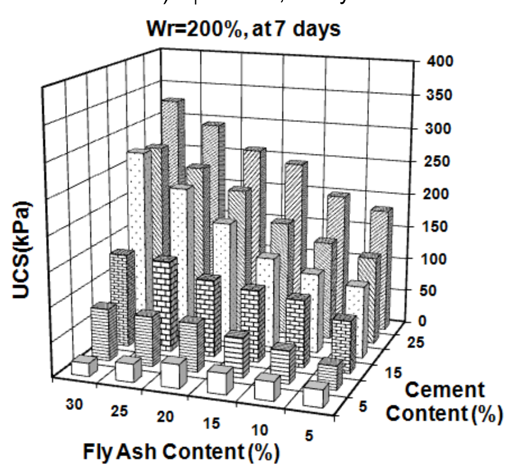
where α denotes for efficiency factor of fly ash for replacement or adding up which is the function of chemical composition and grain size distribution of the fly ash and F_w is the fly ash content (%).



a) w_r =130%, 7 days

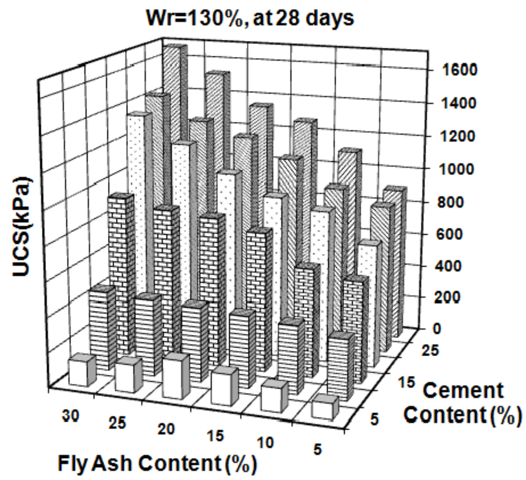


b) w_r =160%, 7 days

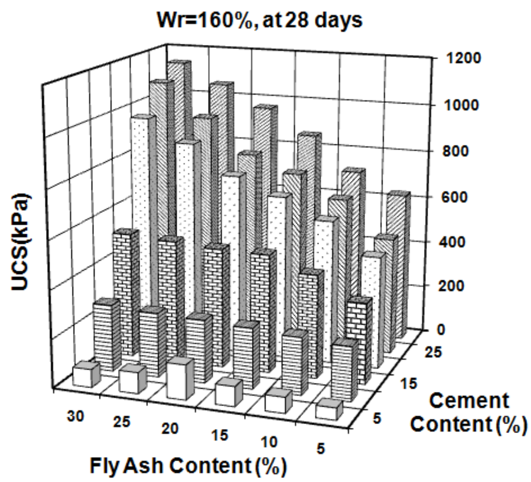


c) w_r =200%, 7 days

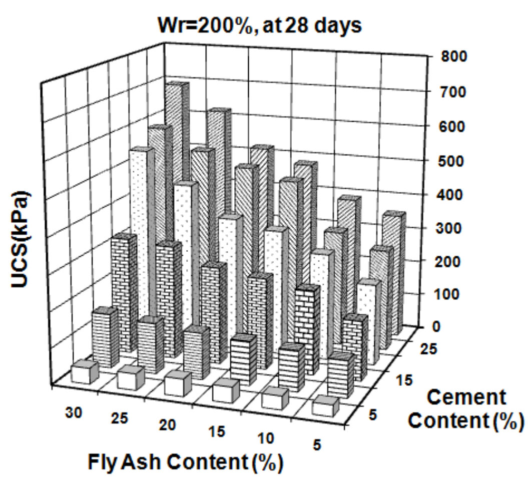
Fig. 9. Relationships between unconfined compressive strength against cement and fly ash contents at 7 days of curing time



a) w_r =130%, 28 days

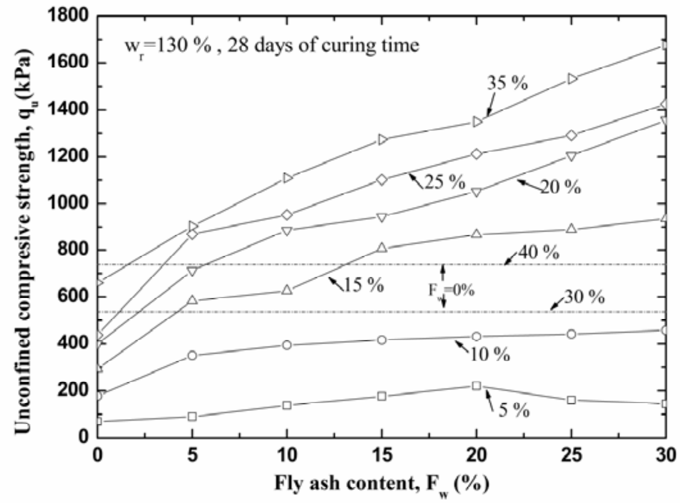


b) w_r =160%, 28 days

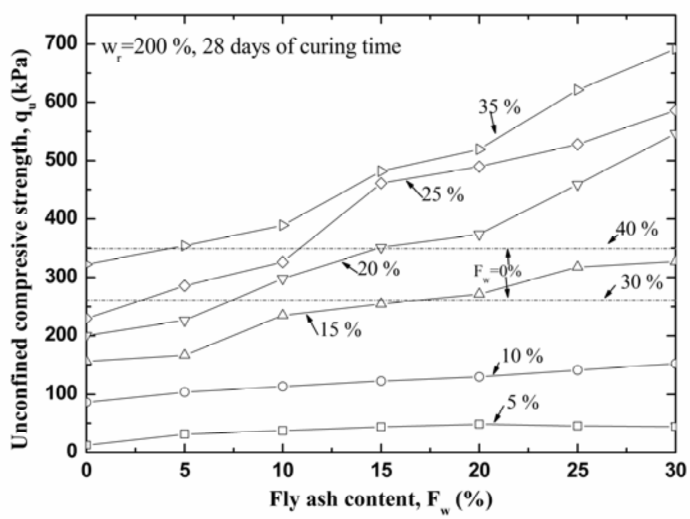


c) w_r =200%, 28 days

Fig. 10. Relationships between unconfined compressive strength against cement and fly ash contents at 28 days of curing time



a) remolding water content 130%

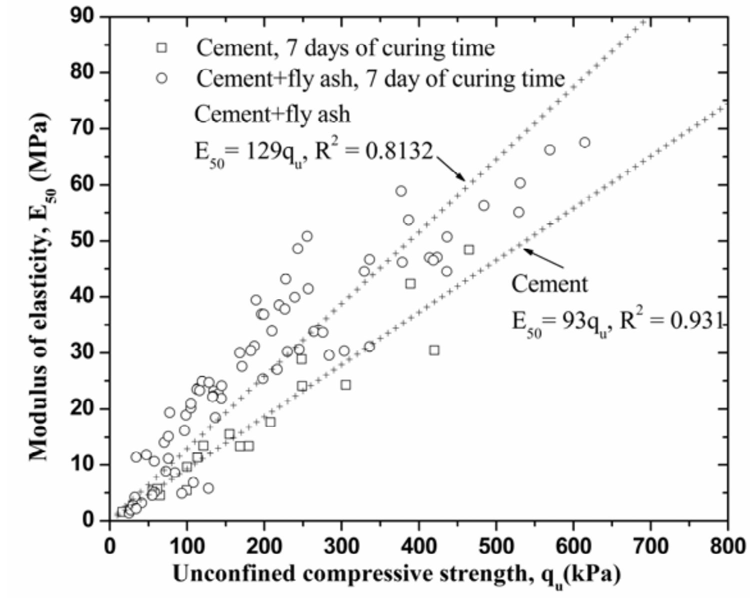


b) remolding water content 200%

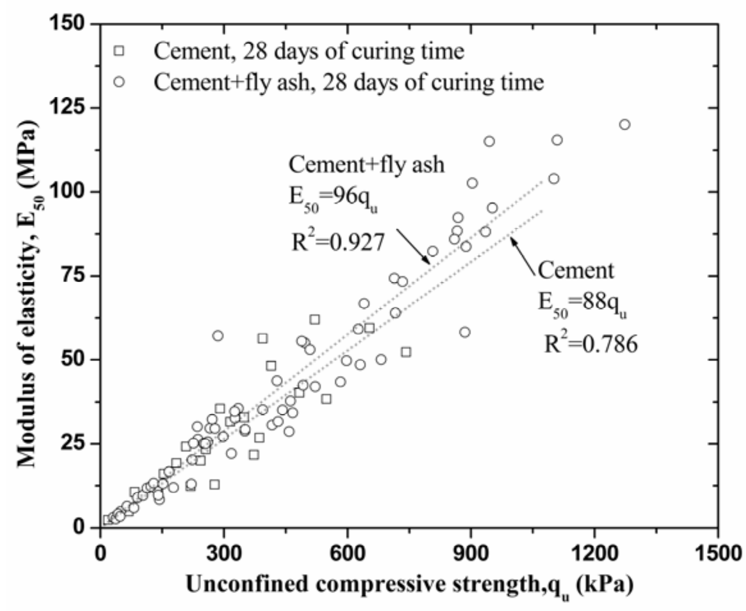
Fig. 11. Relationships between unconfined compressive strength against fly ash contents at 28 days of curing time with varied cement content

Since the influence on strength of each mixing components is similar to that of concrete, it is reasonable to adopt the empirical equation developed in concrete research in strength analysis of this mixture. To calculate the value of α for each proportion by means of strength evaluation, a widely-used Feret's equation modified by Papadakis and Tsimas (2002) as shown in Eq. (4), was adopted.

$$f'c = K\left(\frac{1}{W/(C+\alpha F_w)} - a\right) \quad (4)$$



a) at 7 days of curing time



b) at 28 days of curing time

Fig. 12. Relationship between modulus of elasticity (E_{50}) and unconfined compressive strength of cement and cement-fly ash treated soil

Prior to attaining α, the other parameters in Eq. (4), which are K and a must be calculated. This can be done by considering the mixtures without fly ash. The relationship between unconfined compressive strength and cement-water ratio (C/W) is illustrated in Fig.13. In this study, C is cement content which is A_w whereas W is total water content subtracting by a constant. From the analysis, this constant is found to be 80 which is close to the natural water content of the tested clay. However, further investigations on how this constant changes for clays with other natural water contents should be examined. The K-values for curing time of 7 and 28 days were then calculated from the slopes of the lines. The calculated values are as follows: K_{7days} =1050.2 kPa and K_{28days} = 1702.7 kPa. The parameter a in Papadakis and Tsimas equation was back calculated from testing results and the values of 0.0529 and 0.0374 for curing time of 7 and 28 days were obtained, respectively.

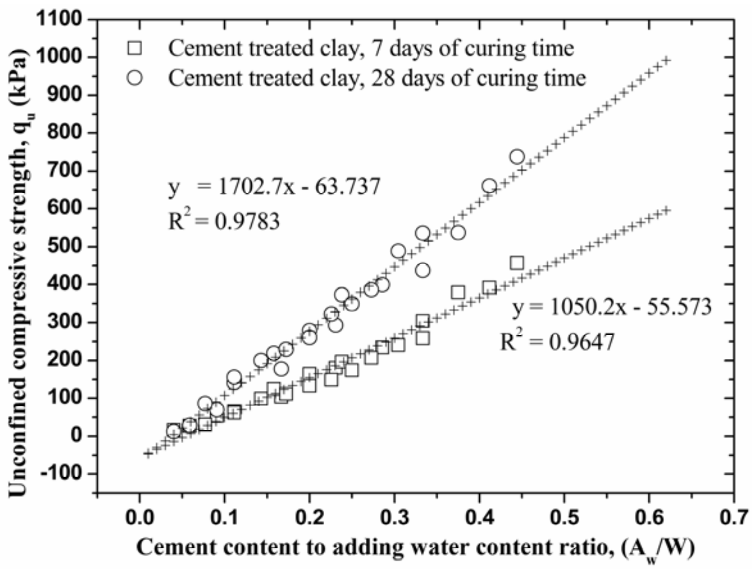


Fig. 13. Unconfined compressive strength q_u versus A_w /W ratio at 7 and 28 days of curing time

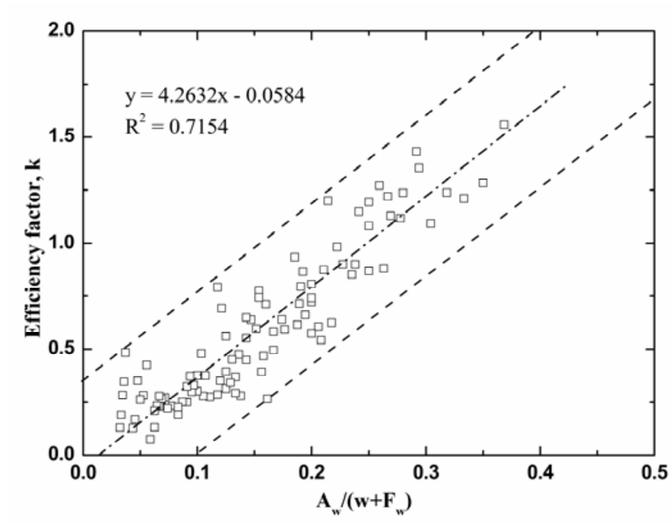
The efficiency factors, α, of each mixing ratio were then calculated by substituting the obtained unconfined compressive strength and mixing components into Eq. (4) using those pre-determined K and a of each curing time. The equation to calculate the efficiency factor was demonstrated as follow:

$$\alpha = \frac{\left\{\left[\frac{f_c'}{K} + a\right] \cdot W\right\} - A_w}{F_w} \tag{5}$$

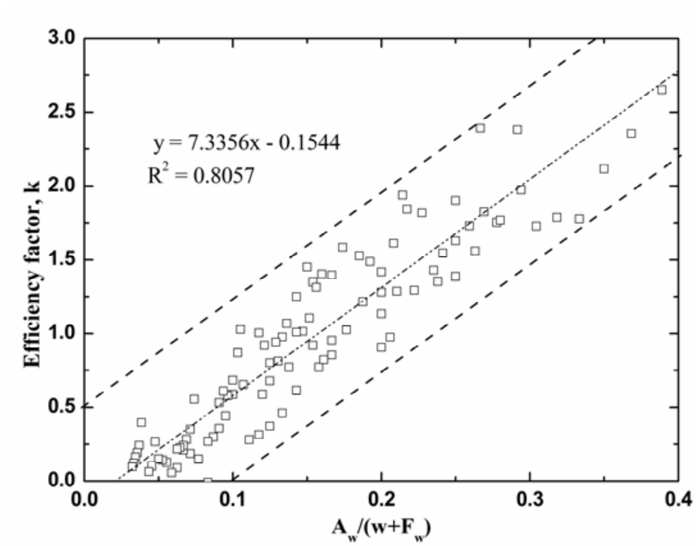
According to the observation of α-values and mixing components, it was found that α tends to increase with increasing cement content. Conversely, α becomes smaller as increasing fly ash and water content. Thus, it is reasonable to characterize α-values with ratio of these mixing components, A_w/(W+F_w), as depicted in Fig. 14. Although scattering of the results is noticed, an acceptable tendency is observed. Thus, empirical equations to relate the efficiency factor and A_w/(W+F_w) are proposed in this study as Eq. (6) and Eq. (7) for curing time of 7 days and 28 days, respectively.

$$\alpha_{7\ day} = 4.2632\ [A_w /(W+F_w)]-0.0584 \tag{6}$$

$$\alpha_{28\ day} = 7.3356[A_w /(W+F_w)]-0.1544 \tag{7}$$



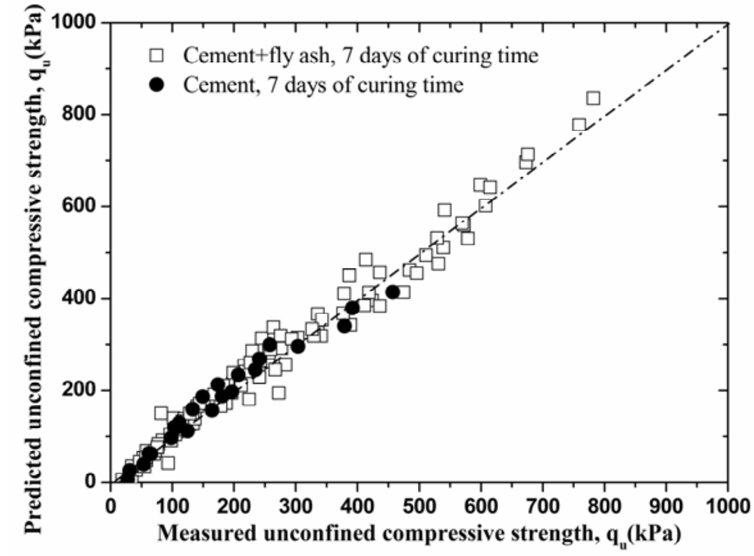
a) at 7 days of curing time



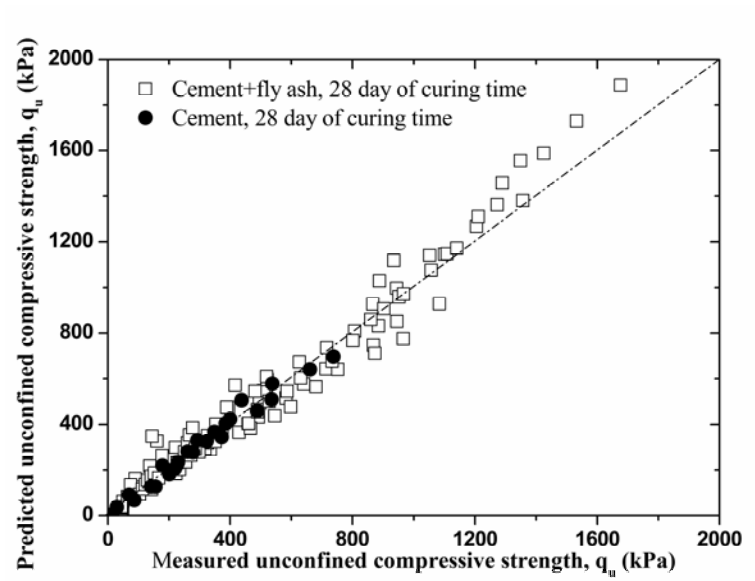
b) at 28 days of curing time

Fig. 14. Relationship between efficiency factor, k with $A_w/(W+F_w)$

From Fig. 14, the highest value of α was about 2.5. From previous concrete researches (e.g., Papadakis and Tsimas 2002), this value does not exceed 1.5. This is probably because excessive fly ash from process of pozzolanic reaction provides additional inter-friction resistance to the mixtures since the grain size of ground fly ash is larger than that of clay particle. Additionally, this excessive fly ash absorbs an amount of water. Figure 15 demonstrates the comparison between predicted and actual values of unconfined compressive strength of both cement treated clays with and without fly ash. The predicted values were calculated from Eq. (4), the α-values were calculated from Eq. (6) and Eq. (7). It can be seen that the predicting strengths satisfactorily agree with experimental results.



a) at 7 days of curing time



b) at 28 days of curing time

Fig. 15. Predicted versus measured unconfined compressive strength

The ability of Abram's law for predicting strength of clay-cement-fly ash mixtures was also studied. The Abram's (1918) concept described that the strength of concrete depends on water-cement ratio with an exponential function, the equation is presented in Eq. (8). Horpibulsuk et al. (2003) and Lorenzo (2005) used this concept for predicting the unconfined compressive strength of cement admixed clay. In this part, Abram's law in conjunction with clay water-cement content ratio and the equivalent cementitious material concept using the proposed efficiency factor equations, was employed to predict the unconfined compressive strength of mixtures. The w_t/A_w was modified to w_t/A_w^*; whereas $A_w^* = A_w + \alpha F_w$ and w_t denotes the total clay water content.

$$q_u = \frac{A}{B^{(w/c)}} \tag{8}$$

where A and B are empirical constants depending on the characteristics of clay, type of cement, and curing time. However, it was found that the predicted values agree well with measurement results solely when w_t/A_w^* is greater than 5. For lower value of w_t/A_w^*, the predicted values were underestimated. The mathematical function for strength prediction should be modified to predict the overall strength characteristics for all mix proportions. Therefore, a modified equation for predicting unconfined compressive strength, was proposed as follows:

$$q_u = \frac{A}{\left(\frac{w_t}{A_w^*}\right)^B} \tag{9}$$

The relationships of unconfined compressive strength and the modified parameter, w_t/A_w^* with modified Abram's law are illustrated in Fig 16.

By employing this modified equation, the results of regression analysis of the fitting give fairly high correlation factor. The results of fitting with previous research results (e.g. Horpibulsuk et al, 2003; Lorenzo, 2005) are also shown in the figure. Thus, the equations for predicting the unconfined compressive strength of cement with and without fly ash content based on modified Abram's law concept were proposed as follows:

At 7 days of curing time

$$q_{u\ 7\ days} = \frac{3123.7}{\left(\frac{w_t}{A_w^*}\right)^{1.4039}} \tag{10}$$

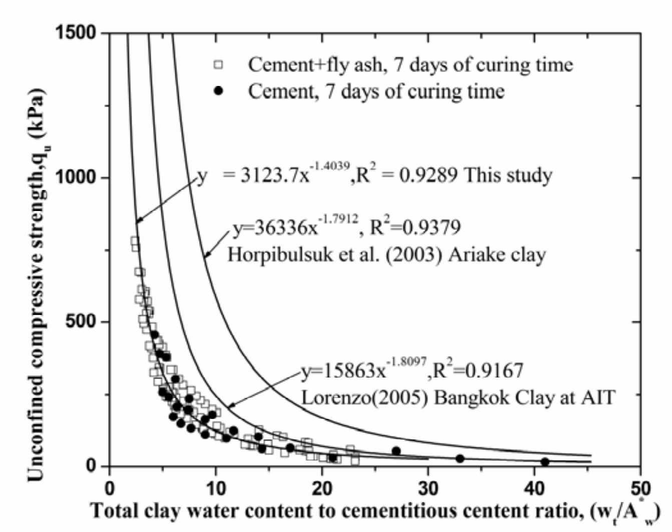
At 28 days of curing time

$$q_{u\ 28\ days} = \frac{4249.9}{\left(\frac{w_t}{A_w^*}\right)^{1.2743}} \tag{11}$$

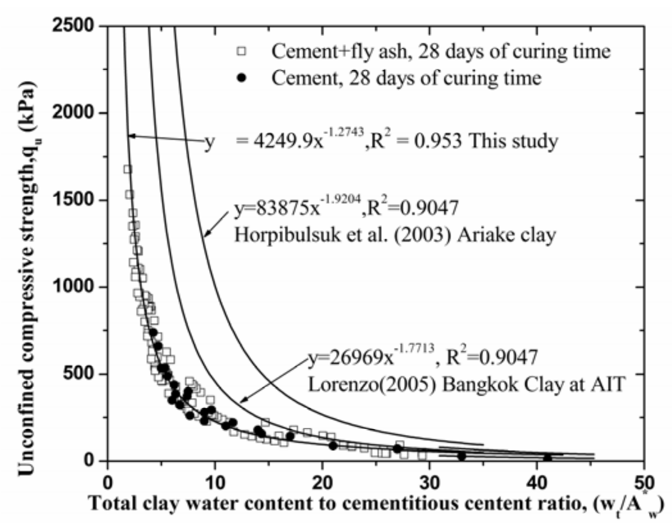
The parameters A and B are relevant to strength development of the mixture. They depend on the curing time, type of cement as well as index and properties of clay (Horpibulsuk et al., 2003), which in turn, depend on the clay mineralogy and composition. The strength increase of such mixture can be explained by the interaction of microstructural mechanisms. These include hydration and pozzolanic reactions, surface deposition and shallow infilling by cementitious products on clay clusters, as well as, the presence of water trapped within clay clusters (Chew et al., 2004). The index and properties of previous researches are included in Table 1 where as Table 5 summarizes the comparison of the mineralogy, chemistry and geotechnical properties between Bangkok clay and Ariake clay from previous research (Ohtsubo et al., 2000).

Table 5. Comparison of mineralogy, chemistry and geotechnical properties between Bangkok clay and Ariake clay

Properties	Bangkok clay	Ariake Clay
Organic Matter (%)	2.9	2.2
Clay mineral composition (%) – at depth		
of 4 m. smectite : kaolinite : mica	60 : 37 : 3	50 : 30 : 20
Activity	1.5	1.4
pH	7.5	8.2



a) at 7 days of curing time



b) at 28 days of curing time

Fig. 16. Relationship between unconfined compressive strength and clay water content/cementitious material content ratio for cement-fly ash treated clay

Compressibility Characteristic

Structure of clay is usually defined as a combination of fabric (the arrangement between the clay particles) and bonding (the force between these particles) (Mitchell, 1993). For untreated clay, due the above-mentioned fabric and bonding, the yield vertical stress in one-dimensional compression exhibited on the right of intrinsic compression line (ICL) as shown in Fig. 17. When the vertical stress state is larger than the yield vertical stress, the clay structure is degraded, changing its structure from a meta-stable to a stable condition. Then, the relationship between void ratio and effective vertical stress tends to converge towards the ICL (Baudet and Stallebrass, 2004). On the other hand, cement-admixed clay can have higher void ratio compared to untreated clay at the same effective vertical stress value due to effects of structure created by bonding of cement. Moreover, the yield vertical stress of cement-admixed clay was significantly higher than that of undisturbed clay. After yield vertical stress exhibited, the structure of cement-admixed clay is significantly degraded but the void ratio at the same effective vertical stress will not reach the ICL of untreated clay due to the effect of existing fabric additionally created by cementation which is similar to the one in the framework proposed by Cotechia and Chandler (2000).

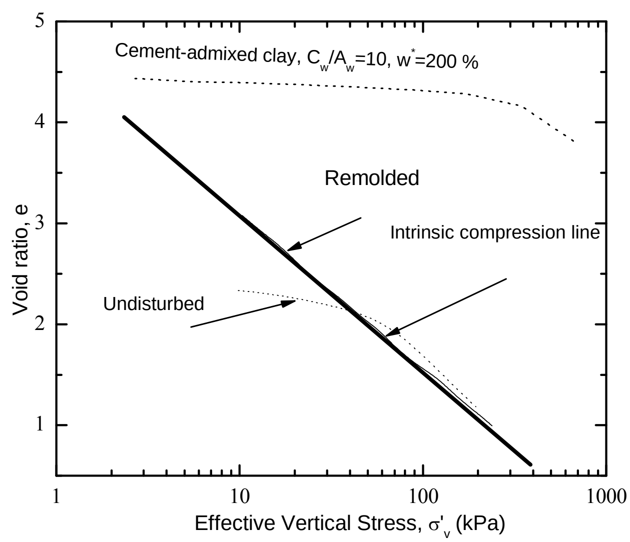


Fig. 17. One-dimensional compression characteristics of remolded and undisturbed untreated clays, compared with cement-admixed clay

One-dimensional compression characteristics of cement-admixed clay with different curing stress values are illustrated in Fig. 18. After yield stresses exhibited, the clay structure is degraded and the relationship between void ratio and the effective vertical stress tends to converge to each other from meta-stable states to a single stable state. It is clearly seen that yield vertical stress increased with increasing of curing stress. Thus, it implies that the existing structure of cement-admixed clay increased with curing stress. Moreover, the after curing void ratio decreased with increasing curing stress. The example of results from one-dimensional compression tests on cement-admixed clay with different mixing ratios were shown in Fig. 19. Simulations presented in these figures are explained later. The recompression index values, C_r, are approximately unique for all mixing ratios. It can be seen that the compression characteristics depend on the mixing ratios, amount of water and cement and amount of clay. In the following sections, effects of the afore-mentioned factors on the behavior of cement-admixed clay is systematically described and simulated by the empirical formulations.

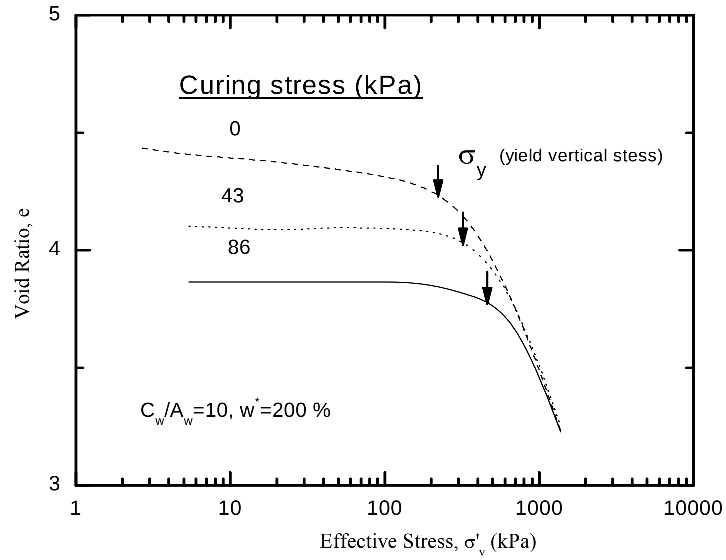
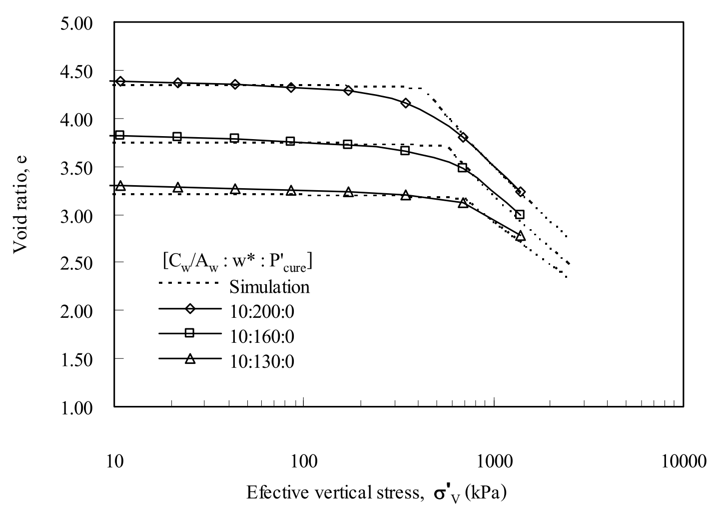
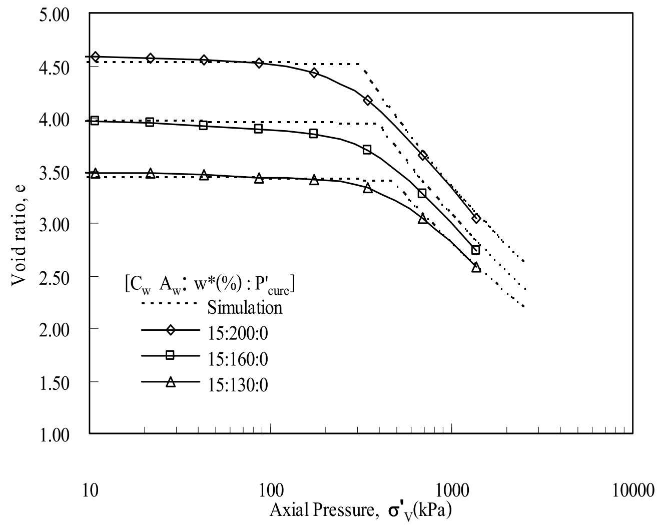


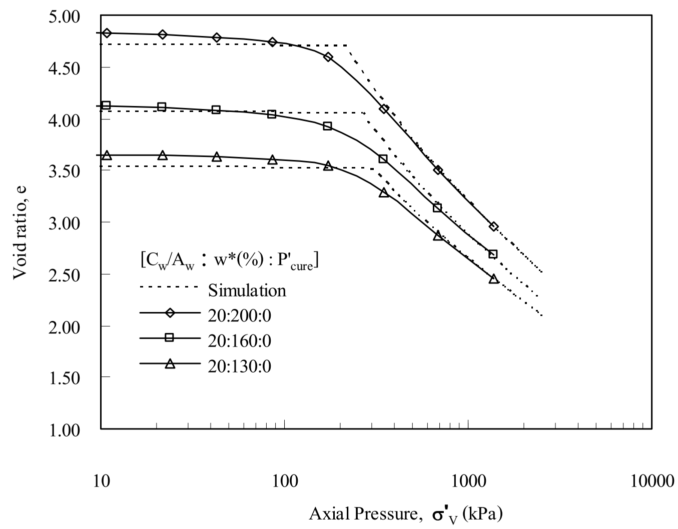
Fig. 18. One-dimensional compression characteristics of cement-admixed clay with different curing stress values



a)



b)



c)

Fig. 19. Comparison between simulated and test results of one-dimensional compression tests on cement-admixed clay at curing stress = 0 kPa for C_w/A_w ratios of: a) 10; b) 15; and c) 20

Empirical Equations for Predicting One-Dimensional Compression

As previously mentioned, to predict one-dimensional compression characteristics of cement-admixed clay, the after curing void ratio and yield vertical stress needed to be properly specified. Thus, in this section, the two important afore-mentioned values will be predicted by means of empirical equations considering the variation of mixing ratios and curing stress.

After Curing Void Ratios

A void ratio is the main influencing parameter that characterizes the behaviors of cement-admixed clay. For example, Lorenzo and Bergado (2004) proposed an empirical formula to predict the after curing void ratio of cement-admixed Bangkok Clay, e_{ot}, as a function of several parameters, that is, total clay water contents, C_w, cement content, A_w, and time (day), t, as shown in the Eq. 12.

$$e_{ot} = \left[\frac{1 + C_w + G_{so}}{\frac{100}{C_w}} \left(\frac{\frac{100}{C_w} - 0.012A_w + 0.012\log_{10}(t) + 0.99\left(1 - \frac{A_w}{100}\right)^{0.0807}}{0.0025A_w + 0.01\log_{10}(t) + 1.088} \right) \right] - 1 \qquad (12)$$

where G_{so} is the specific gravity of clay. This e_{ot} is therefore the initial void ratio prior to application of load. However, this equation was proposed for cement-admixed clay curing without stress. Thus, for simulation of after curing void ratio of cement-admixed clay cured under stresses, the effects of curing stress on the reduction of after curing void ratio at different ratios of total clay water content to cement content, C_w/A_w, as shown in Fig. 20, should be taken into account. The reduction of void ratio (Δe_{ot}) due to curing stress increased with increasing C_w/A_w ratio and they can be approximately related by a linear relation for a given curing stress. It can be seen from Fig. 20 that two linear relations between Δe_{ot} and C_w/A_w ratio for the two different curing stresses have significantly the same slope while their intercepts on y-axis are different. Therefore, an empirical equation can be proposed for predicting the reduction of after curing void ratio, Δe_{ot}, as follows:

$$\Delta e_{ot} = 0.03045\left(\frac{C_w}{A_w}\right) + \beta \qquad (A_w > 0) \qquad (13)$$

where β is the intercept on y-axis. The y-intercept, β, increased with increasing curing stress as shown in Fig. 21. An exponential function inset in Fig. 21 can be fitted to the test data. Therefore, Eq. 13 can be re-written as:

$$\Delta e_{ot} = 0.03045\left(\frac{C_w}{A_w}\right) + 0.001\exp\left(0.0711P'_{cure}\right) \qquad (P'_{cure} > 0) \qquad (14)$$

where P'_{cure} is the curing stress (kPa). From Eq. 12, a new empirical equation for prediction of the after curing void ratio of cement-admixed Bangkok clay cured under stress was proposed as:

When P'_{cure} = 0:

$$e_{ot} = \left[\frac{1 + C_w + G_{so}}{\frac{100}{C_w}} \left(\frac{\frac{100}{C_w} - 0.012A_w + 0.012\log_{10}(t) + 0.99\left(1 - \frac{A_w}{100}\right)^{0.0807}}{0.0025A_w + 0.01\log_{10}(t) + 1.088} \right) \right] - 1 \qquad (15a)$$

When P'_{cure} > 0:

$$e_{ot} = \left[\frac{1 + C_w + G_{so}}{\frac{100}{C_w}} \left(\frac{\frac{100}{C_w} - 0.012A_w + 0.012\log_{10}(t) + 0.99\left(1 - \frac{A_w}{100}\right)^{0.0807}}{0.0025A_w + 0.01\log_{10}(t) + 1.088} \right) \right] - \left[1 + \left(0.03045\left(\frac{C_w}{A_w}\right) + 0.001\exp\left(0.0711P'_{cure}\right) \right) \right] \qquad (15b)$$

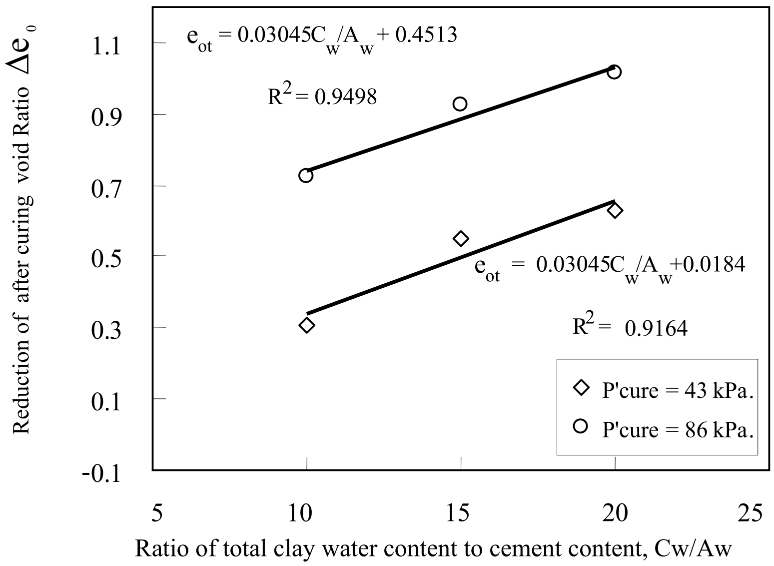


Fig. 20. Relationship between the reduction of after curing void ratio and the ratio of the total clay water content, C_w, to the cement content, A_w

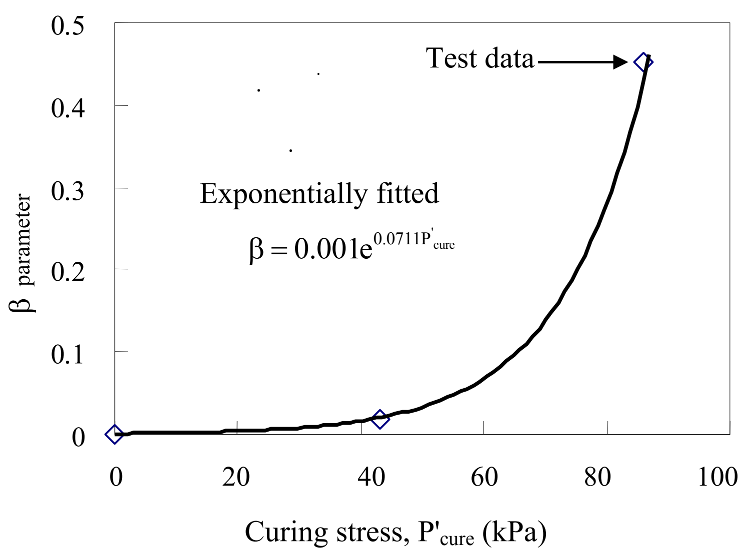


Fig. 21. Relationship between parameter b and curing stress

The additional part on the right-hand side of Eq. 15b was proposed for taking into account the reduction of the after curing void ratio of cement-mixed clay due to curing stress. The comparison between the predicted after curing void ratio and the measured value in the case of curing with and without stress is shown in Fig. 22. It may be seen that the proposed empirical equation for predicting the after curing void ratio can simulate very well the test results.

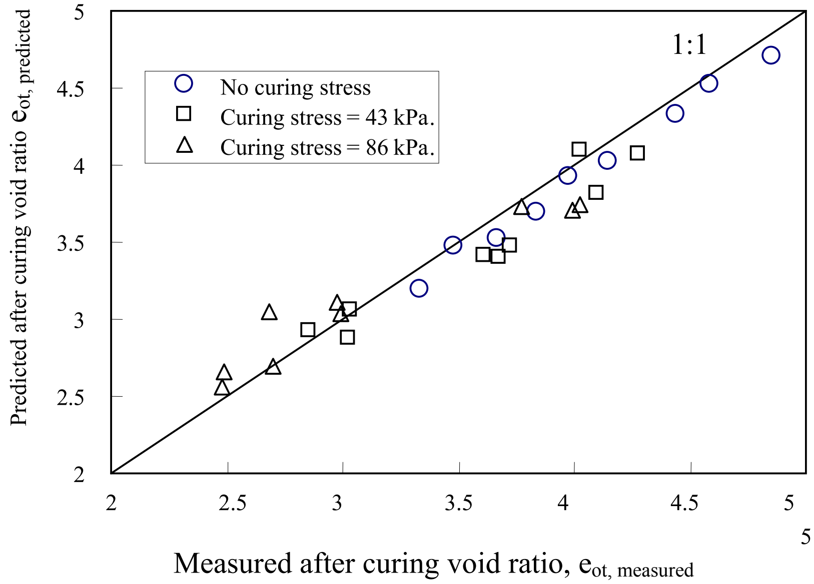


Fig. 22. Comparison of after curing void ratio (e_{ot}) between the proposed model and the laboratory test results

Yield Stress

The relationships between the ratio of the after curing void ratio to the cement contents, e_{ot}/A_w and the yield vertical stress, P'_y, for various remolded water contents, $w*$, without curing stress are shown in Fig. 23. It may be seen that, for the same value of $w*$, yield vertical stress, P'_y, decreases with increasing ratio of the after curing void ratio to cement content (e.g., compare points S' and S). Moreover, P'_y also decreases with increasing remolded water content for the same value of e_{ot}/A_w ratio (e.g., compare points T and S). Consequently, the yield vertical stress can be predicted as follows:

$$P'_y = P'_{yo} + \Delta P'_y \tag{16}$$

The first term on the right-hand side of Eq. 16 (i.e., P'_{yo}) is the yield vertical stress due to the bonding by cementation and interlocking among particles. This can be expressed in terms of the after curing void ratio, e_{ot}, and cement content, A_w, as expressed in the following equation (Eq. 17):

$$\frac{e_{ot}}{A_w} = A\ln\left(P'_{yo}\right) + \alpha \tag{17}$$

From curve fitting, the parameter A is approximately equal to 0.333 while parameter α varies with the total clay water content, C_w, as shown in Fig. 24. A linear relationship between α and C_w can be expressed as follows:

$$\alpha = -0.0025C_w + 2.7655 \tag{18}$$

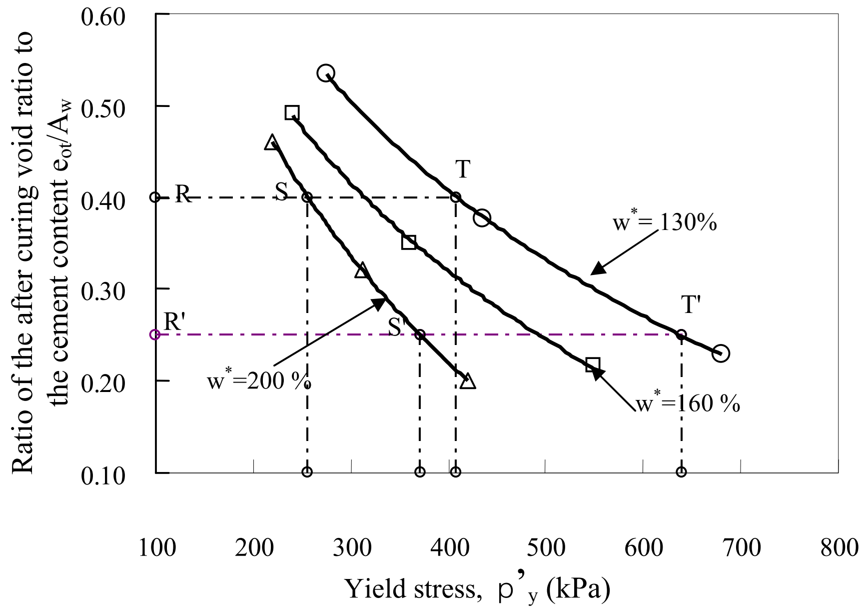


Fig. 23. Relationship between yield vertical stress and the ratio of the after curing void ratio, e_{ot}, to the cement content, A_w

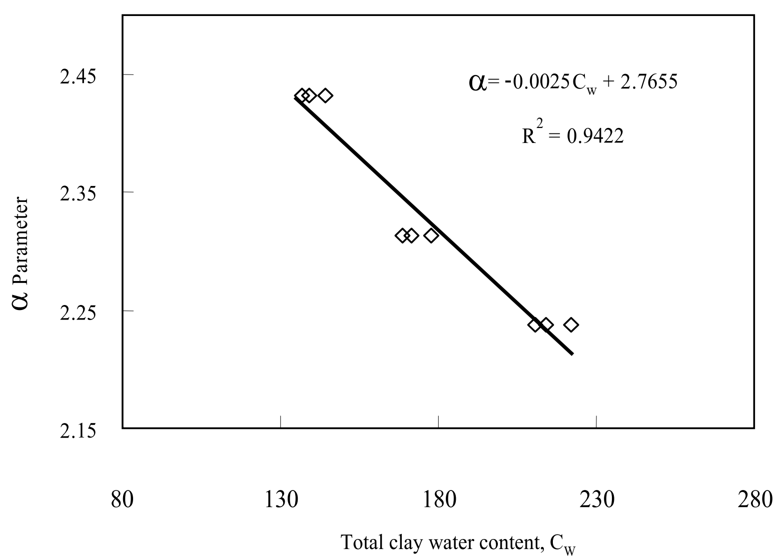


Fig. 24. Relationship between α and total clay water content, C_w

Consequently, the empirical equation for predicting yield vertical stress of cement-admixed clay without curing stress is as follows:

$$P'_{yo} = \exp\left(\frac{3e_{ot}}{A_w} + 0.0075C_w - 8.297\right) \tag{19}$$

As shown in Fig. 18, yield vertical stress increased with increasing of curing stress representing by the second term on the right-hand side of Eq. 16. Thus, for characterization, the ratios of the increment of yield vertical stress to the curing stress, $\Delta P'_y / P'_{cure}$, for different mixing ratios were plotted in Fig. 25. It can be characterized with linear relations as follows:

$$\frac{\Delta P'_y}{P'_{cure}} = -0.2388\frac{C_w}{A_w} + C \tag{20}$$

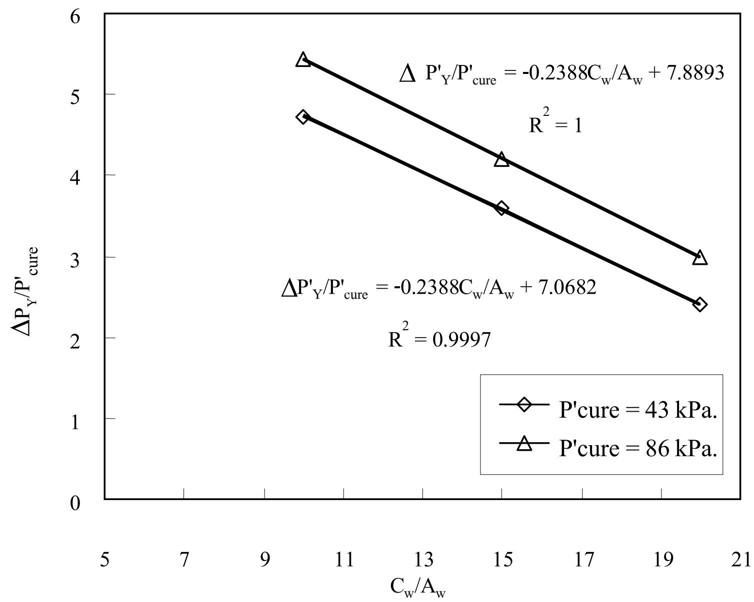


Fig. 25. Relationship between the ratio of yield vertical stress increment by curing under stress to the curing stress, $\Delta P'_y / P'_{cure}$, and the ratio of the total clay water content to the cement content, C_w / A_w

The parameter C increases with curing stress, P'_{cure}, and can be expressed as follows:

$$C = 0.0191P'_{cure} + 0.6471 \quad (P'_{cure}: \ kPa) \tag{21}$$

The changing of yield vertical stress increment according to different mixing ratios and curing stress values can be expressed by:

$$\Delta P'_y = P'_{cure}\left(-0.2388\frac{C_w}{A_w} + 0.0191P'_{cure} + 0.6471\right) \tag{22}$$

Finally, the empirical formula for predicting yield vertical stress was proposed as follows:

$$P'_y = \exp\left(\frac{3e_{ot}}{A_w} + 0.0075C_w - 8.297\right) + P'_{cure}\left(-0.2388\frac{C_w}{A_w} + 0.0191P'_{cure} + 0.6471\right) \tag{23}$$

The predicted yield vertical stress of cement-admixed clay in one-dimensional compression with and without curing stresses from the proposed empirical formula agreed well with the test results as shown in Fig. 26.

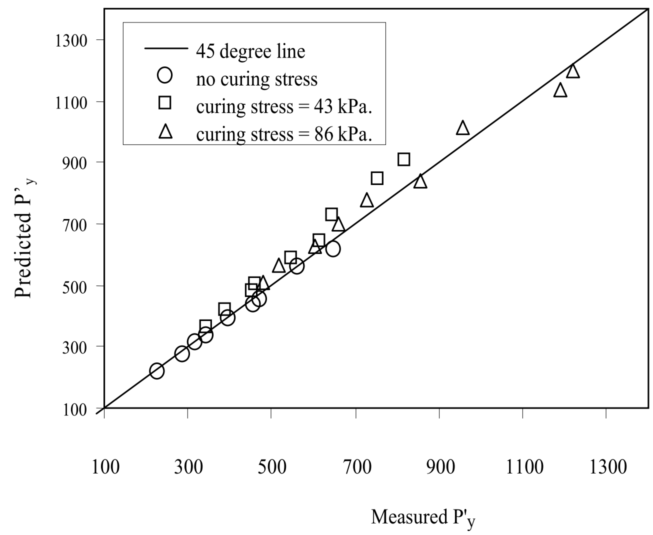


Fig. 26. Comparison of yield vertical stress (P'_y) between the proposed model and the laboratory test results

Disturb State Model for Cement-Admixed Clay

The reference state for the model simulation was postulated from the compression curve of cement-admixed clay prior to reaching yield stress. From the overall test results, the recompression index, C_r, was approximately unique for all mixing ratios. The equation for the reference state is shown as follows:

$$d\varepsilon_v^c = \frac{-0.01}{1+e_o} \cdot \frac{dP'}{P'} \tag{24}$$

where e_o is the initial void ratio. The disturb state model incorporated with the proposed empirical equations was employed to predict the one-dimensional compression characteristics of cement-admixed clay. The parametric study for the influences of parameters b and r on the compression curves was shown in Fig. 27. From parametric study, one-dimensional compression after yield vertical stress exhibited significantly increased with increasing parameter b. The parameters for disturb state model were calibrated by test results. The parameter r was assumed to be constant for all mixing ratio (i.e., r = 0.65), being similar to results by Liu et al. (2003). On the other hand, values of parameter b were not constant for different mixing ratios and curing stresses. From Fig. 28, an empirical equation of parameter b according to cement content, A_w, (Eqs.1 and 2) and the after curing void ratio, e_{ot}, can be proposed as follows:

$$b = \frac{10.36 e_{ot}}{A_w} + B \tag{25}$$

The y-intercept, B, can be characterized as a function of total water contents, C_w, as shown in Fig. 29. Thus, the equation for predicting parameter b of cement-admixed clay curing without stress is as follows:

$$b = \frac{10.36 e_{ot}}{A_w} + 0.0265 C_w - 3.1737 \tag{26}$$

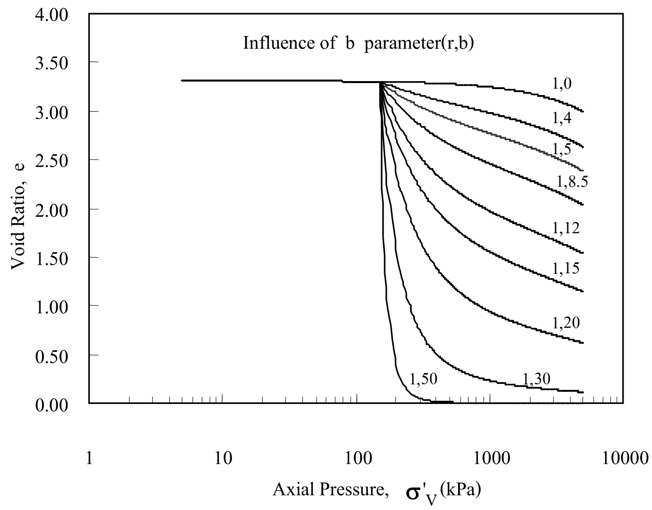


Fig. 27. Response of disturb state model by varying values of parameter b

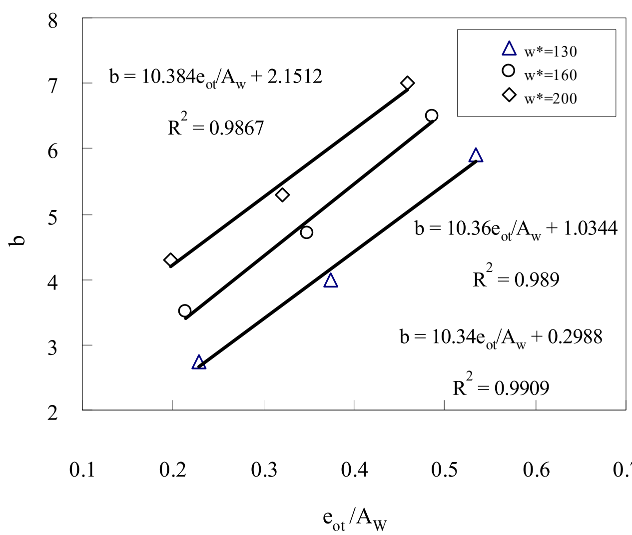


Fig. 28. Relationships between parameter b and e_{ot}/A_w

It can be concluded that one-dimensional compressibility of cement-admixed clay increased with increasing of e_{ot}/A_w ratio and total clay water content.

For the case of curing under stress, the relationships of the increment of parameter b and mixing ratios for different curing stresses were shown in Fig. 30. The magnitude of increment of parameter b increased with curing stress and the ratio of the total water content to the cement content. The empirical equation for predicting the increment of parameter b for different curing stresses is as follows:

$$b = \frac{10.36e_{ot}}{A_w} + 0.0265C_w + 2.171\ln\left(\frac{C_w}{A_w}\right) + 0.0098P'_{cure} - 8.1317 \quad (28)$$

$r = 0.65$

$$\Delta b = 2.171\ln\left(\frac{C_w}{A_w}\right) + 0.0098P'_{cure} - 4.958 \quad (27)$$

where P'_{cure} is the curing stress (kPa). Thus, from Eqs. 26 and 27, the empirical equation for predicting the value of parameter b for disturb state model are as follows

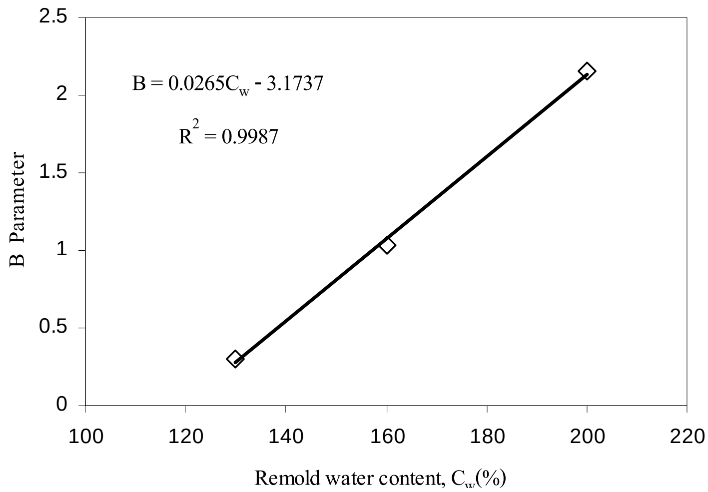


Fig. 29. Relationships between B parameter and remolded water content, C_w

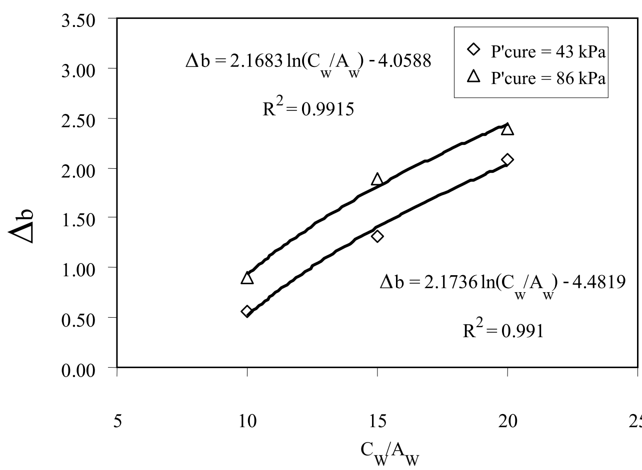


Fig. 30. Relationships between increment of parameter b and C_w/A_w ratio for cement-admixed clay by curing stress

From Eq. 25, it can be concluded that the stiffness of cement-admixed clay in one-dimensional compression after yield vertical stress exhibited decreased with increasing void ratio, remolded water content and curing stress and decreasing cement content.

The result of disturb state model simulation cooperated with a series of empirical equations can broadly simulate the one-dimensional compression test results of cement-admixed clay as shown in Figs. 31 through 33. It demonstrated the capability of the proposed empirical model for simulation of one-dimensional compression characteristics of cement-admixed clay cured with and without stresses with a unique set of parameters.

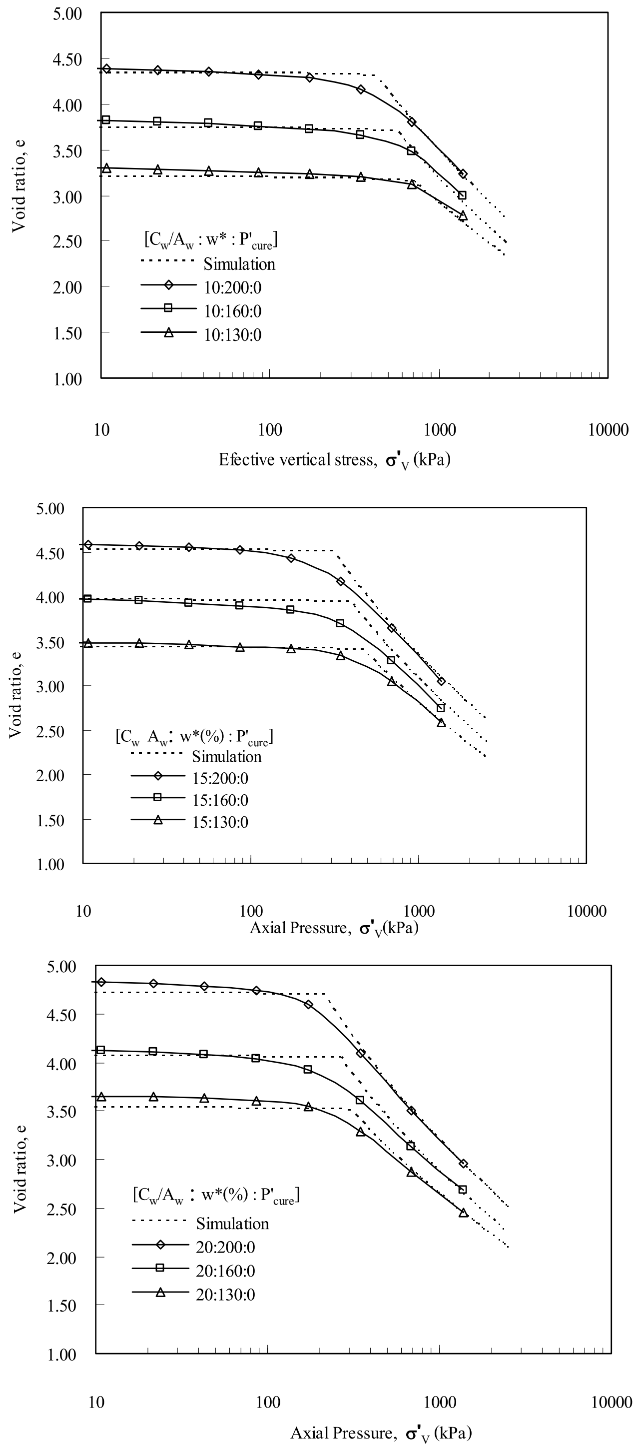
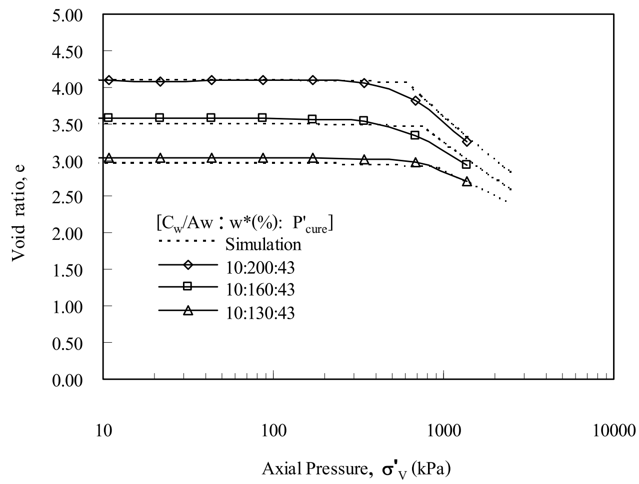
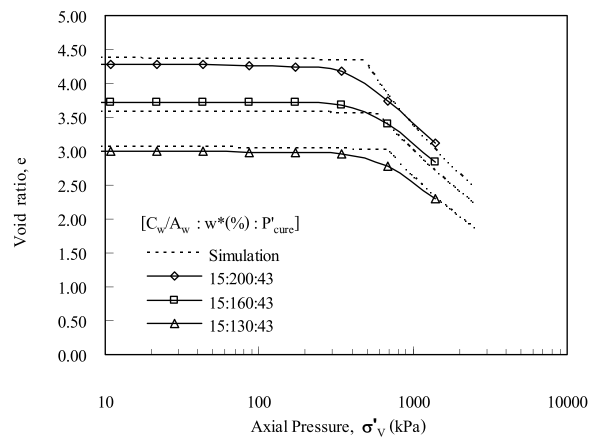


Fig. 31. Comparison between simulated and test results of one-dimensional compression tests on cement-admixed clay at curing stress = 0 kPa for C_w/A_w ratios of: a) 10; b) 15; and c) 20





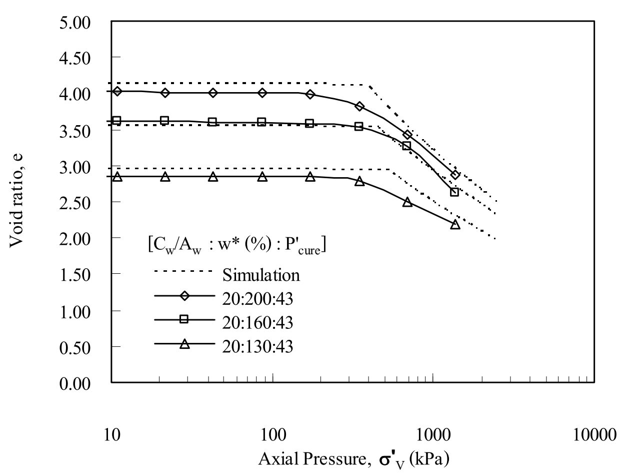


Fig. 32. Comparison between simulated and test results of one-dimensional compression tests on cement-admixed clay at curing stress = 43 kPa for C_w/A_w ratios of: a) 10; b) 15; and c) 20

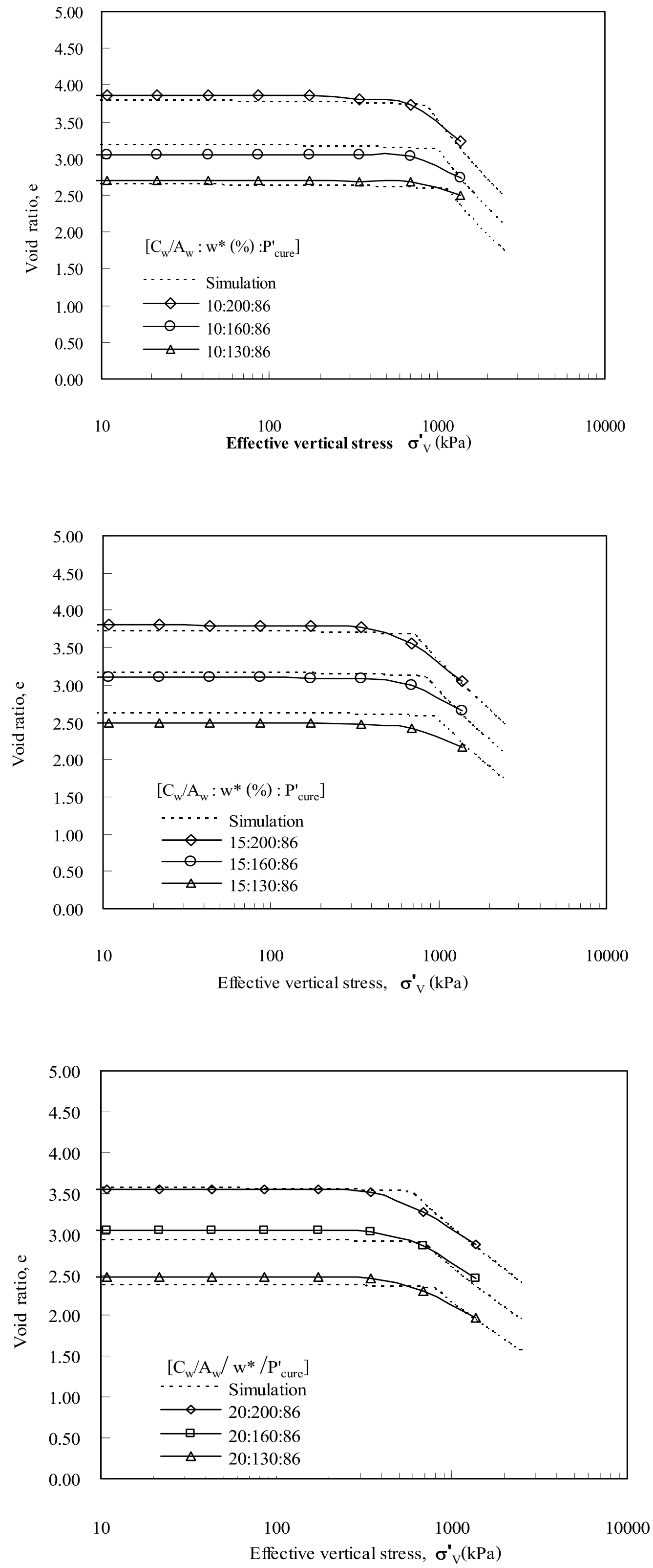


Fig. 33. Comparison between simulated and test results of one-dimensional compression tests on cement-admixed clay at curing stress = 86 kPa for C_w/A_w ratios of: a) 10; b) 15; and c) 20

Conclusions

The potential and efficiency of adding disposed fly ash from Mae Moh electric power plant, Thailand, into cement admixed clay were studied by means of series of unconfined compression and physical tests. From this limited investigation, it is confirmed that, with suitable cement content, this ground disposed fly ash could be successfully added into soil cement to enhance both strength and physical characteristics. The strength of cement-fly ash admixed clay at high water content increased with increasing amount of cementitious material content and duration of the curing time and decreased with increasing water content. The efficiency of fly ash depended on the portion of cement, disposed fly ash and water content in mixtures. To predict strength of clay-cement-fly ash mixtures, equivalent comentitious content concept, Aw*, in conjunction with efficiency factor α, can be successfully employed. The predictions of strength by proposed empirical equations produced satisfactory agreements with the testing results. However, the proposed empirical equations are based on limited data of specific soil and source of fly ash, broader set of studies are needed for more generalized form of these equations. Moreover, the long-term strength of this mixture should be investigated.

To develop a model to predict one-dimensional compression characteristics of cement-admixed clay, a series of oedometer were performed paying special attention to influence of curing stress. From test results, yield vertical stress increased with decreasing water content and increasing of cement content and curing stress. With increasing of water content and decreasing of cement content and curing stress, after curing void ratio increased. The empirical equations which can reasonably predict the after curing void ratio and the yield vertical stress of cement-admixed clay with and without curing stress were proposed. The disturb state model incorporated with proposed empirical formula can simulate the overall one-dimensional compression characteristics of cement-admixed clay with different combinations of cement content, water content and curing stress.

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Output ที่ได้จากโครงการ

จากการศึกษา คุณลักษณะทางด้านกำลังและการเปลี่ยนรูปของดินปรับปรุงคุณภาพด้วยปูนซีเมนต์ที่มีปริมาณน้ำในส่วนผสมสูง ซึ่งสามารถแบ่งได้เป็นหลายส่วน รวมถึง งานที่ได้ปรับเปลี่ยน-เพิ่มเติม ดังที่ได้รายงานในรายงานความก้าวหน้าของโครงการแล้วนั้น output ที่ได้จากโครงการสามารถสรุปได้ ดังต่อไปนี้

1. **บทความที่ได้รับการตอบรับการตีพิมพ์ในวารสารนานาชาติแล้ว 1 บทความ (กล่าวขอบคุณ สำนักงานคณะกรรมการการอุดมศึกษา และ สำนักงานกองทุนสนับสนุนการวิจัยในกิตติกรรมประกาศ) ดังนี้ (สำเนาจดหมายตอบรับและต้นฉบับแสดงในภาคผนวก ก)**
    1) Jongpradist, P., Jumlongrach, N., Youwai, S. and Chucheepsakul S.(2010): Influence of Fly Ash on Unconfined Compressive Strength of Cement Admixed Clay at High Water Content , Journal of Materials in Civil Engineering, ASCE, 22(1) (In press) -(IF-2007 = 0.452)

2. **บทความที่กำลังเสนอเพื่อการตีพิมพ์ในวารสารนานาชาติอีก 1 บทความ (กล่าวขอบคุณ สำนักงานคณะกรรมการการอุดมศึกษา และ สำนักงานกองทุนสนับสนุนการวิจัยในกิตติกรรมประกาศ) ดังนี้ (สำเนาต้นฉบับแสดงในภาคผนวก ข)**
    2) Jongpradist .P, Youwai, S., Manorat, P. Kongkitkul, W. and Chucheepsakul S.: One-Dimensional Deformation Characteristics of Cement-admixed Bangkok Clay Curing Under Stress (To be submitted to Soils and Foundations- IF-2007 = 0.56)

3. **งบประมาณที่ได้จากทุนวิจัยบางส่วน ได้นำไปใช้ร่วมกับโครงการวิจัย ทุนพระจอมเกล้าธนบุรี เพื่อสร้างเครื่องมือ และ อุปกรณ์ รวมถึงค่าใช้จ่ายก่อสร้างในสนามจริง เพื่อการศึกษาหาวิธีที่จะติดตามพฤติกรรมการรับแรง การเสียรูปของเสาเข็มดินซีเมนต์ในสนามด้วย strain gauge ผลเบื้องต้นที่ได้ ประสบความสำเร็จในการติดตั้ง และจะใช้เพื่อนำเสนอโครงการวิจัยต่อเนื่อง**

4. **นอกจากบทความที่เสนอเพื่อการตีพิมพ์ในวารสารนานาชาติแล้ว ผลการศึกษาเหล่านี้ ได้นำมาเขียนบทความในการประชุมวิชาการ ทั้งในระดับ นานาชาติ และ ระดับชาติ และได้รับการตีพิมพ์ (กล่าวขอบคุณ สำนักงานคณะกรรมการการอุดมศึกษา และ สำนักงานกองทุนสนับสนุนการวิจัยในกิตติกรรมประกาศ) ดังต่อไปนี้**

การประชุมวิชาการนานาชาติ (สำเนาต้นฉบับแสดงในภาคผนวก ค)

1. Jongpradist, P., Youwai, S. and Kongkitkul, W.: (2009). A Unified State Parameter for Modeling Undrained Shear Behaviors of Cementitious Material Admixed Clay., Proc. of the 17th Int. Conf. on Soil Mech. And Geotech. Eng., ISSMGE, Alexandria, pp.257-260.
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ภาคผนวก ก

สำเนาจดหมายตอบรับและต้นฉบับ Journal of Materials in Civil Engineering-ASCE

บทความเรื่อง

Influence of Fly Ash on Unconfined Compressive Strength of Cement-Admixed Clay at High Water Content

Influence of Fly Ash on Unconfined Compressive Strength of Cement-Admixed Clay at High Water Content

Pornkasem Jongpradist[1]; Narongrit Jumlongrach[2]; Sompote Youwai[3]; and Somchai Chucheepsakul[4]

Abstract: This research studies the potential of using disposed fly ash to add up or partially replace Portland cement Type I in ground improvement by cement column technique. The strength characteristic of cement-fly ash admixed Bangkok clay was investigated by means of a series of unconfined compression tests, paying special attention to the influence of ground fly ash in this mixture. From testing results, the unconfined compressive strength and elastic modulus improved with an increasing of fly ash content. With the cement portions of greater than or equal to 10%, ground disposed fly ash could be employed as a pozzolanic material for partial replacement of cement in cement column construction. Based on the equivalent cementitious material content concept, an empirical equation relating the efficiency factor, α with mixing proportions was proposed. Then, together with this proposed efficiency factor, strength prediction of cement-fly ash admixed clay by Feret's equation and Abram's law were carried out and discussed.

DOI: XXXX

CE Database subject headings: Compressive strength; Cement; Fly ash; Water content; Clays; Concrete admixtures.

Author keywords: Unconfined compressive strength; Cement admixed clay; Fly ash; Equivalent cementitous material content; Efficiency factor.

Introduction

Soil stabilization technique is well established and implemented in various applications. Among various improvement methods, deep mixing or soil-cement column is one of the most popular techniques. It can be successfully applied to the constructions of many types of civil engineering works. Many projects employ cement columns to increase the bearing capacity or to decrease the settlement of the original soil, such as foundation of structures, road, taxi way for an airport [e.g., Bergado et al. (1999)], as well as to stabilize the safety of excavation work [e.g., Petchgate et al. (2003); Wong and Poh (2000)]. However, as the construction cost is mainly governed by the cement cost, the extent of cement column is limited. Particularly, for wet process with water prejet method, a huge amount of cement must be consumed since the strength of soil-cement is controlled by water-cement ratio (Miura et al. 2001). Therefore, a method to replace cement material with other inexpensive materials should be investigated to enhance this application.

Fly ash is a by-product of the combustion of pulverized coal in thermal power plant. It is considered to be useful as a supplementary cementing material (SCM) in combination with Portland cement by pozzolanic reaction. Besides the successes in partially replacing Portland cement in concrete works, a number of researches on study of using fly ash in the field of geotechnical engineering has been reported, such as the stabilization of soil in compaction works of highway embankment or slope without cement or lime (Prabakar et al. 2004), with cement (Kaniraj and Havanagi 1999) and with cement and fiber reinforcement (Kaniraj and Havanagi 2001), as well as stabilization of expansive soil (Cokca 2001). However, the demand for consumption of fly ash is still less than the production. The unused fly ash was then disposed at the ponds or landfills adjacent to each power plant and this fly ash was called disposed fly ash. Thus, there is still a need in finding new uses and increasing its utilization. Because of the uncertainty of the chemical and physical properties, only little disposed fly ash has been used. Moreover, since disposed fly ash is exposed to weather, it forms big lumps and creates little pozzolanic reaction when used as cementitious material. From all reviewed literature, the writers have not acknowledged any research on the potential of using disposed fly ash in ground improvement for soft clay by soil mixing with high cement content. In addition, there is no research that proposes mathematical equations to predict the strength of cement-fly ash admixed clay with different mixing ratios. Thus, the current paper begins with the investigation of strength characteristic of mixed material at high water content with different mixing ratios. The influencing parameters on the strength characteristic were systematically characterized and an empirical equation which is capable of reproducing the influence of disposed fly ash as well as other parameters was proposed. Finally, strength prediction of cement-fly ash admixed clay via empirical equations in conjunction with the proposed efficiency factor was presented.

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Note. This manuscript was submitted on May 18, 2007; approved on August 10, 2009; published online on XXXX XX, XXXX. Discussion period open until June 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 22, No. 1, January 1, 2010. ©ASCE, ISSN 0899-1561/2010/1-1–XXXX/$25.00.

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Table 1. Index and Physical Properties of Clay

Properties	Bangkok clay—KMUTT (this study)	Bangkok clay—AIT (Lorenzo 2005)	Ariake clay (Horpibulsuk et al. 2003)
Liquid limit, LL (%)	119	103	120
Plastic limit, PL (%)	41	43	57
Shrinkage limit, SL (%)	14	NA	NA
Plasticity index, PI (%)	78	60	63
Water content, w (%)	103	76–84	135–150
Liquidity index, LI	0.79	0.62	1.23
Specific gravity, GS	2.69	2.61	2.67
Total unit weight, g_t (kN/m^3)	14.1	14.3	13.1–13.4
Dry unit weight, g_d (kN/m^3)	6.94	7.73	5.2–5.7
Initial void ratio, e_i	2.37	2.31	3.6–4.0
Soil classification (USCS)	CH	CH	CH

Note: NA=not available.

Laboratory Test

Materials

Three kinds of materials were used in this research, i.e., soft clay, cement, and fly ash. The soft clay used in this study is typical soft Bangkok clay from King Mongkut's University of Technology Thonburi (KMUTT) located in southern part of Bangkok, Thailand. Sampling was performed from the depth of 4 to 5 m in soft clay layer. The physical properties of the Bangkok clay were summarized in Table 1. The undrained shear strength, S_u, obtained from unconfined compression (UC) tests ranged from 16 to 17 kPa.

Portland cement used in this study is Type I with specific gravity (G_s) of 3.14. The amount of cement in current practice ranges from 100 to 300 kg/m^3 of wet soil. Thus, for future development, corresponding cement content (A_w) in this study covers the range of 5–40% percent of dry soil.

It is known that fly ashes generally have negative effects on the concrete strengths at the early ages (Babu and Rao 1994). However, from recent researches, this can be overcome by grinding the fly ashes to finer fraction for higher performance [e.g., Slanicka (1991); Paya et al. (1997)]. Ground fly ashes might be partially replacing cement to produce low-cost environmentally friendly soil-cement column. The composition of fly ash varies considerably depending on the nature of the coal burned and the power plant operational characteristics but grinding does not have much effect on chemical composition (Erdogdu and Turker 1998; Songpiriyakij and Jaturapitakkul 1995). This study used disposed fly ash at the disposal time of 6 months from Mae Moh Power Plant, Thailand. These fly ashes were collected from the disposed areas and sun dried approximately 1–2 days to reduce their high water content to approximately 0.5%. After that, they were sieved through sieve No. 16 and then ground by grinding machine until the amount of ash particles retained on sieve No. 325 was less than 5% by weight. The grain-size distribution after grinding is illustrated in Fig. 1 and the properties are shown in Table 2. The specific gravity of the ground disposed fly ash is higher than that of the original disposed fly ash because grinding process, by crushing the hollow or porous particles of coarse fly ash, reduces both the porosity and the particle size of the ash (Cheerarot and Jaturapitakkul 2004; Kiattikomol et al. 2001; Paya et al. 1997). The major chemical compositions of ground disposed fly ash are SiO_2(42.07%), Al_2O_3(21.03%), Fe_2O_3(7.12%), and CaO(14.8%). The sum of SiO_2, Al_2O_3, and Fe_2O_3 is 70.22% which, however, can be classified as Class F according to ASTM C 618 (1997). The loss on ignition (LOI) of fly ash is 7.31% which exceeds 6%, as specified by ASTM C 618. However, ASTM C 618 suggests that the use of Class F fly ash containing up to 12% of LOI may be approved by the user if either acceptable performance records or laboratory tested results are made available. It was reported that the coarse fraction of fly ash had less SO_3 than the fine one (Erdogdu and Turker 1998; Jaturapitakkul et al. 1998). Since SO_3 may be harmful to durability, the use of ground coarse fly ash as cement replacement may be an advantage.

Unconfined Compression Tests

In this paper, the UC test was conducted in accordance with ASTM D2166-00 (2002). Specimen was 35 mm in diameter and 70 mm in height. After curing, it was extruded from the mold. The unit weight of the specimen was obtained prior to testing.

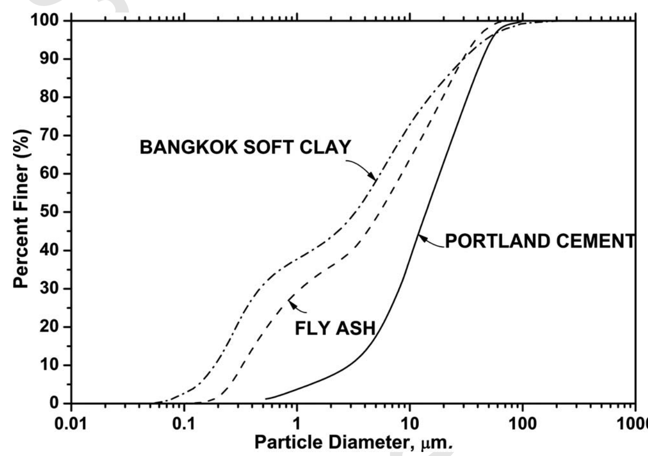

Fig. 1. Grain-size distributions of ground fly ash and Portland cement comparing with that of soft clay

Table 2. Physical Properties of Fly Ash and Ground Fly Ash

Properties	Original fly ash	Ground fly ash
Fineness amount retained when wet sieved on 45 micron (%)	43.8	3–4
Specific gravity, G_S	2.16	2.51

Table 3. Summary of the Program for UC Tests

Name of test	Cement content A_w(%)	Amount of fly ash F_w(%)	Remolding water content w^* (%) (days)	Curing time
1	Undisturbed clay			
2	5,10,15,20,25,30,35,40	0	130,160,200	7,28
3	5,10,15,20,25,35	5,10,15,20,25,30	130,160,200	7,28

The rate of shearing was maintained at 1.14% per minute (1.14 mm/min) and the test program is summarized in Table 3.

The clay samples utilized in all tests were remolded to water contents as 130, 160, and 200%. The purpose of varying the remolding water content is to simulate the actual condition of soil-cement column/pile installation using deep mixing method with slurry of cement [e.g., Yang (1997)] and jet mixing/grouting method [e.g., Shibazaki (1996)]. Prior to the introduction of cement slurry, the natural soil was subjected to remolding and mixing with associated addition of water, which increased the water content of the natural soil. The remolding clay water content (w_r) is hereinafter defined as the water content of the remolded clay prior to the addition of cement slurry. The amount of water added to wet clay to obtain the desired remolding water content was obtained using the following fundamental equation:

$$\Delta W_w = \frac{W_T}{1 + w_0}(w_r - w_0) \qquad (1)$$

where ΔW_w=weight of water to be added; W_T=total weight of prepared original untreated clay sample; w_r=required remolding clay water content; and w_0=natural water content of the clay sample.

Regarding the water content in actual mixing condition which is higher than the liquid limit, the high water content clay is in liquid state and, thus, can be uniformly mixed. In this work, the disturbed samples of the clay with the required amount of additional water were placed inside a portable mechanical soil mixer and allowed to mix thoroughly for a few hours to obtain uniform water content, following the previous researches on soil-cement [e.g., Miura et al. (2001); Lorenzo and Bergado 2004)].

The prepared remolded clay sample at particular remolding water content was mixed with cement-fly ash slurry having water-cement ratio (W/C) of 1.0 using a portable mechanical mixer. Due to an amount of water in slurry, the overall water content of the paste just at the time of mixing will be the total remolding water plus the water in the cement-fly ash slurry. The overall water content in the mixture is hereinafter called the total clay water content (w_t). The total clay water content is defined as

$$w_t = w_r + (W/C)A_w \qquad (2)$$

where w_t=total clay water content of the paste (%) reckoned from the dry weight of soil only and A_w=desired cement content (%) defined as the percentage ratio of the weight of cement to the dry weight of soil.

Due to high workability of the clay-water-cement-fly ash paste, each specimen for UC test is made by dropping the paste into the 35 mm diameter × 100 mm height PVC mold for shrinkage due to hardening and trimming of specimen. Pushing was done to remove air bubbles. The molded paste is allowed to protrude out from the other end of the mold for checking the occurrence of “honeycomb” structure. Pushing was continued until the surface of the protruding specimen is uniform and smooth. The density of each specimen with the same mixing condition was monitored and kept constant. The mold together with the specimen was waxed to prevent moisture loss and, then, was placed for curing in the humidity room. Samples were cured for a period of 7–28 days. After curing, each specimen was removed from the mold and made available for the intended tests. Finally, for a particular mixing condition, the specimens with smooth surface and with similar densities were selected for testing. After curing, the variation of unit weight of specimen must be in the range of ±1%.

Results and Discussions

Physical Properties of Laboratory Specimens

After-curing unit weight (γ_t) versus fly ash content at various remolding water content, cement content, and curing time are shown in Fig. 2. The unit weight increased with increasing cement content, curing time, and fly ash content. With the higher remolding water content, the unit weight of the treated sample was lower. For certain remolding water content, the conceivable reason why the unit weight increased with increasing cement content could be attributed to the increasing amount of cementing products being formed. Moreover, some minerals of fly ash (such as compounds of silicon and aluminum) create secondary reaction with the products from hydration process. Thus, partial secondary reaction enhanced solid form which eventually increased the amount of solid phases per unit volume. This can be seen by the reduction of void ratio, as illustrated in Fig. 3. Conversely, the reason why the unit weight decreased with the increase of remolding water content could be attributed to the subsequent increase of the volume of soil void per unit volume of treated soil.

Fig. 4 shows the relationship of after-curing water content ver-

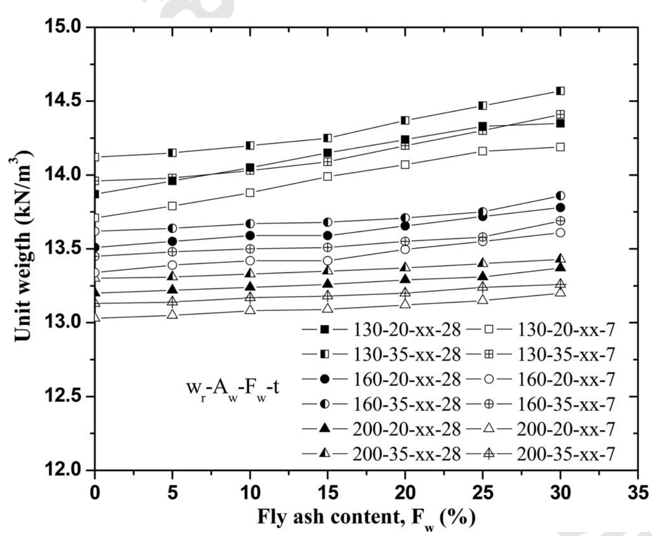

Fig. 2. After-curing unit weight of treated soil at curing time of 7 and 28 days

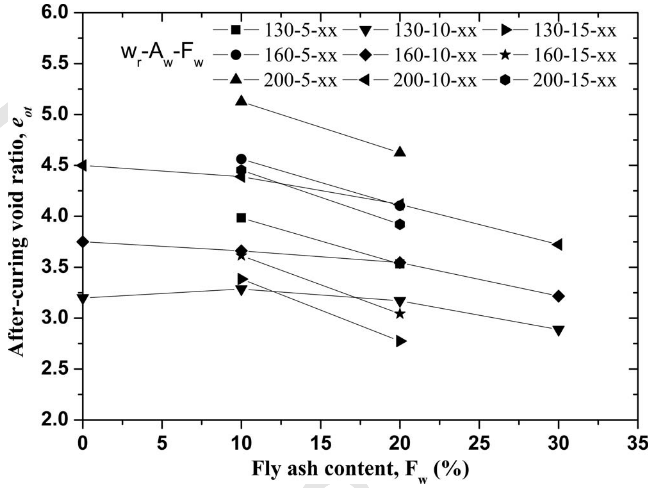

Fig. 3. After-curing void ratio treated soil at curing time of 28 days

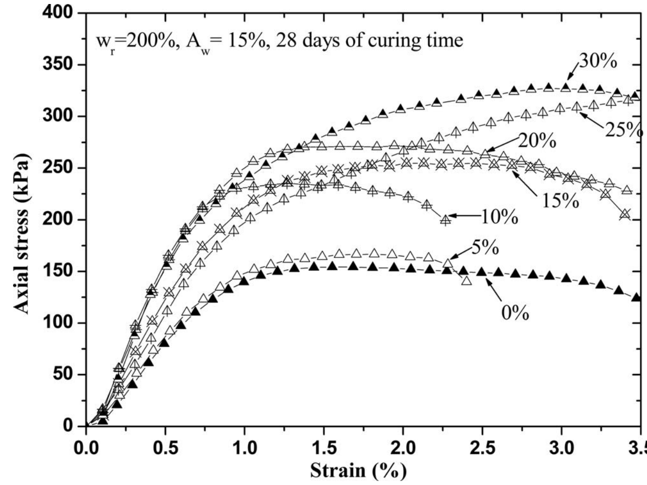

Fig. 5. Stress-strain relationship of UC test of A_w=15%, w_r=200%, varied fly ash content, and curing time of 28 days

sus fly ash content at varying magnitudes of remolding water content, cement content, and curing times. After-curing water content is the ratio of the weight of water to the weight of dry soil after curing. The after-curing water content decreased with increasing cement content and fly ash content. Due to the hydration process of cement and pozzolanic reaction of fly ash, water content decreased with increasing cement content and fly ash content. The after-curing water contents of specimens at the curing time of 7 days are higher than those at the curing time of 28 days, which is similar to the previous researches of cement-admixed clay (Lorenzo and Bergado 2004). This can be explained as the hydration and pozzolanic reaction at the curing time of 28 days are more complete than those at the curing time of 7 days.

Unconfined Compressive Strength

The stress-strain relationships of UC tests of samples with remolding water content of 200%, cement content of 15%, with varying fly ash content are illustrated in Fig. 5. The maximum stress, or strength, of material increased with increasing fly ash content. The increase in strength with fly ash content is due to the attribution of pozzolanic reaction to enhance the strength of the mixtures. The pozzolanic reaction, which is the secondary reaction, is to build up bonding between particles of the mixtures. This demonstrated the preliminary possibility of using fly ash for replacing cement in soil-cement column. However, more studies on long-term strength should be investigated since low-strength materials produced with fly ash can lose strength if exposed to saturated conditions for a long period of time.

Other prime parameters to control the strength characteristics of mixtures were water content and curing time. The water content is a necessary portion in hydration process to enhance strength characteristics. However, excessive water from hydration process caused the increase in distance between interparticle or intercluster of particle spacing, which affect drop of strength (Miura et al. 2001). Fig. 3 shows the increase of void ratio with increasing water content. Thus, the strength of specimen with higher remolding water content was less than that of specimen with lower remolding water content, as shown in Fig. 6. The influence of curing time on strength development was illustrated in Fig. 7. The figure depicts for samples with 15% of cement and 15% adding fly ash content for different remolding water con-

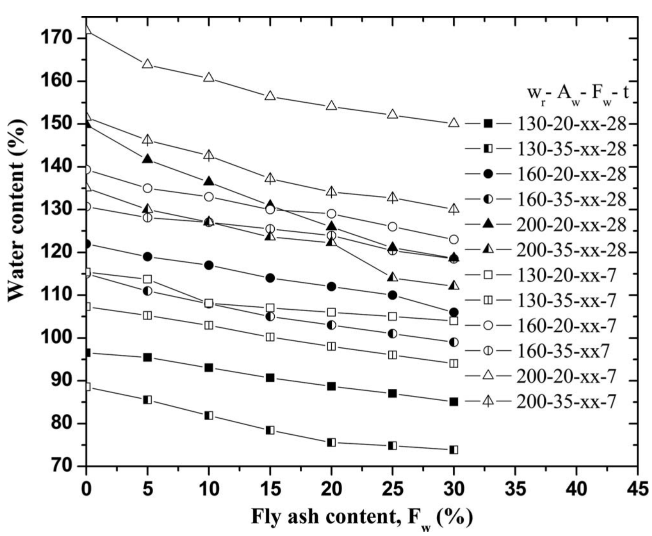

Fig. 4. After-curing water content of treated soil at curing time of 7 and 28 days

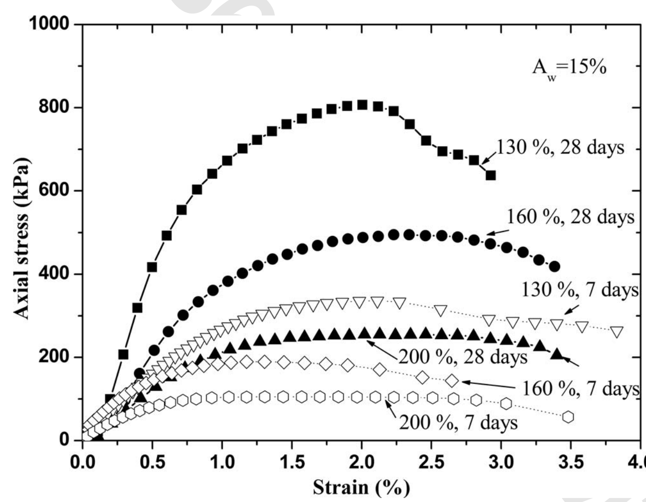

Fig. 6. Stress-strain relationship of UC test of A_w=15%, F_w=15% at 7 and 28 days of curing with varied remolded water content

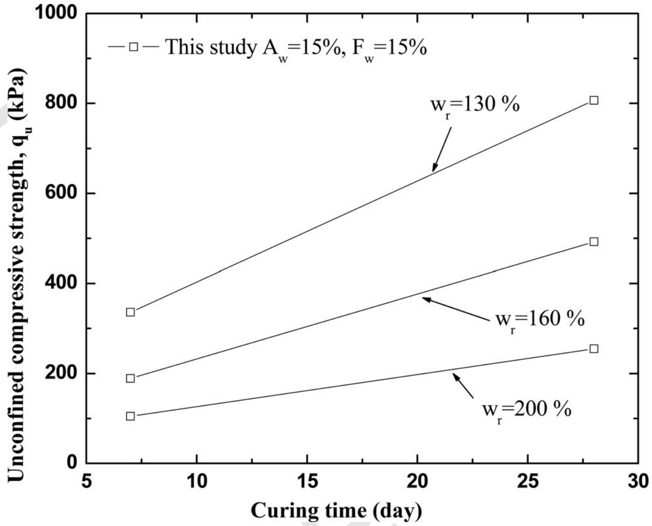

Fig. 7. Relationship between unconfined compressive strength and curing time of cement-fly ash treated soil

tents. It can be seen that the strengths at the curing time of 28 days are approximately two times of those at the curing time of 7 days.

From overall testing results, it can be concluded that the strength characteristics of cement and cement-fly ash admixed clay depend on mixing ratios: cement content (A_w), fly ash content (F_w), remolding water content (w_r), and curing time (t). The influences of each proportion on unconfined compressive strength of cement-fly ash admixed clay for the curing time of 7 and 28 days are summarized in Figs. 8 and 9, respectively.

The strength developments from adding fly ash for each mixing proportion are summarized in Fig. 10. To achieve an effective fly ash addition, the required cement content must not be less than 10%. With insufficient cement content, the effectiveness of adding fly ash is unnoticeable. This can be explained as the result of inadequate calcium hydroxide products from hydration process for pozzolanic reaction. Moreover, the effectiveness of fly ash decreased with increasing fly ash content. The efficiency increases with increasing cement and decreasing fly ash content. However, if the cement is greater than 20%, the efficiency can be enhanced to the high content of fly ash.

Modulus of Elasticity

The relationships of elastic modulus and strength of cement with and without fly ash admixed clay are shown in Fig. 11. Referring to the current application and design method of cement column which serves as bearing resistance and uses 50% of strength, the modulus of elasticity in terms of secant (50% q_u) moduli, E_{50} was selected to be investigated in this study. The E_{50} at the curing time of 7 and 28 days can be approximately estimated as $93q_u$ and $88q_u$, respectively. While for cement-fly ash admixed clay, the relationships can be estimated as $129q_u$ and $96q_u$ for curing time of 7 and 28 days, respectively. The observed moduli of elasticity of cement-fly ash admixed clay are higher than those admixed with cement at the same strength and curing time. This is probably due to the additional pozzolanic reaction from fly ash. This indicated that by adding fly ash, not only the strength could be gained but the deformation characteristic was also improved. Furthermore, the ratios of E_{50} and strength of both cement and cement-fly ash admixed clays at 7-day curing time were higher

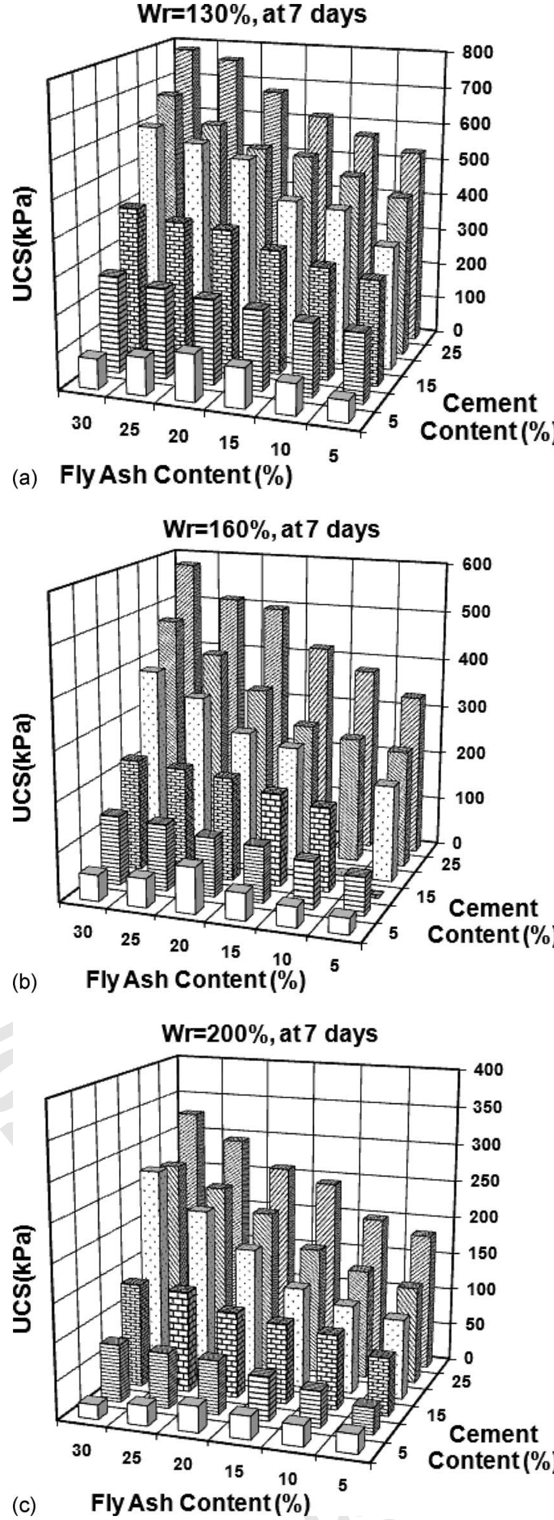

Fig. 8. Relationships between unconfined compressive strength against cement and fly ash contents at 7 days of curing time: (a) w_r =130%, 7 days; (b) w_r=160%, 7 days; and (c) w_r=200%, 7 days

than the ones at 28-day curing time. This is consistent with the findings in concrete research (Jaturapitakkul et al. 2004).

Analysis for Evaluation of Strength

Strength prediction with reasonable accuracy is very important for preliminary design of mixing ratio and cost analysis in the

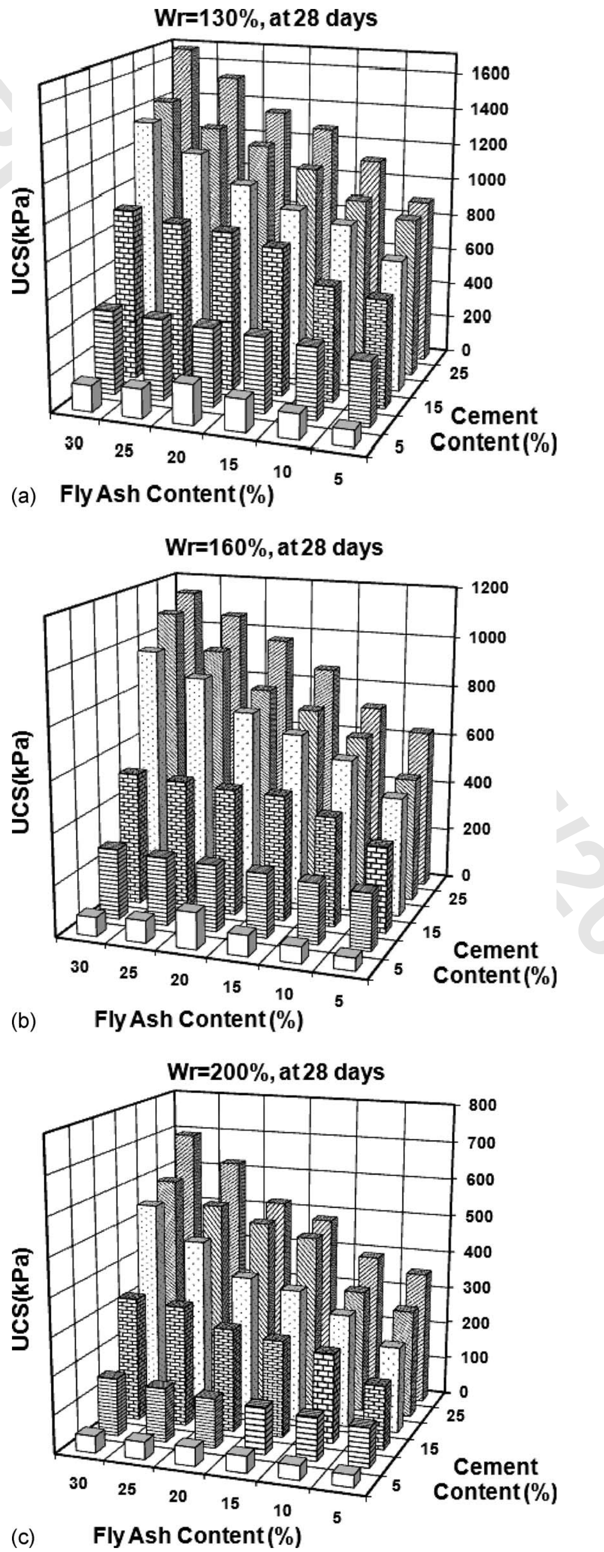

Fig. 9. Relationships between unconfined compressive strength against cement and fly ash contents at 28 days of curing time: (a) w_r=130%, 28 days; (b) w_r=160%, 28 days; and (c) w_r=200%, 28 days

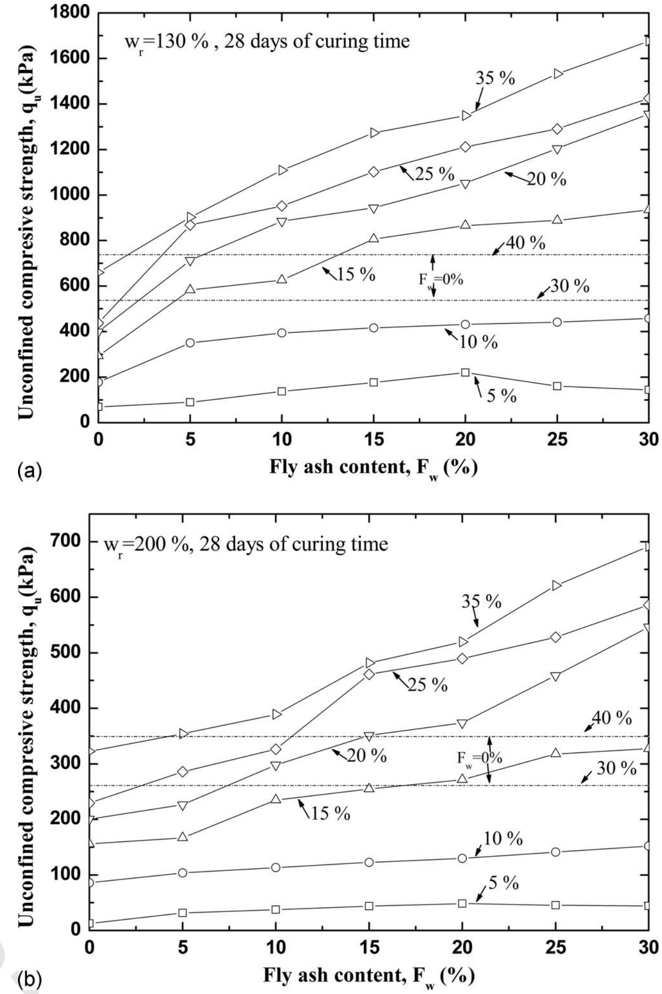

Fig. 10. Relationships between unconfined compressive strength against fly ash contents at 28 days of curing time with varied cement content: (a) remolding water content 130%; (b) remolding water content 200%

actual implementation of cement treated soft clays. Many previous researches on soil-cement have been conducted to determine the suitable relation for this issue. In all of them, the approach is based on parameters governing strength characteristics including the influencing parameters, such as water and cement contents and curing time. These include clay water to cement content ratio (w_t/A_w) with Abram's law (Horpibulsuk et al. 2003; Lorenzo 2005), after-curing void ratio to cement content (e_{ot}/A_w) with exponential equation (Lorenzo 2005). In this part, an attempt for strength prediction of cement-fly ash admixed clay is carried out taking into account the effect of fly ash in such mixture. Based on the well-known equivalent cementitious material content, the influence of fly ash is considered as an equivalent amount of cement, which can be described as

$$A_w^* = A_w + \alpha F_w \tag{3}$$

where α denotes for efficiency factor of fly ash for replacement or adding up which is the function of chemical composition and grain-size distribution of the fly ash and F_w=fly ash content (%).

Since the influence on strength of each mixing component is similar to that of concrete, it is reasonable to adopt the empirical equation developed in concrete research in strength analysis of this mixture. To calculate the value of α for each proportion by means of strength evaluation, a widely used Feret's equation modified by Papadakis and Tsimas (2002), as shown in Eq. (4), was adopted

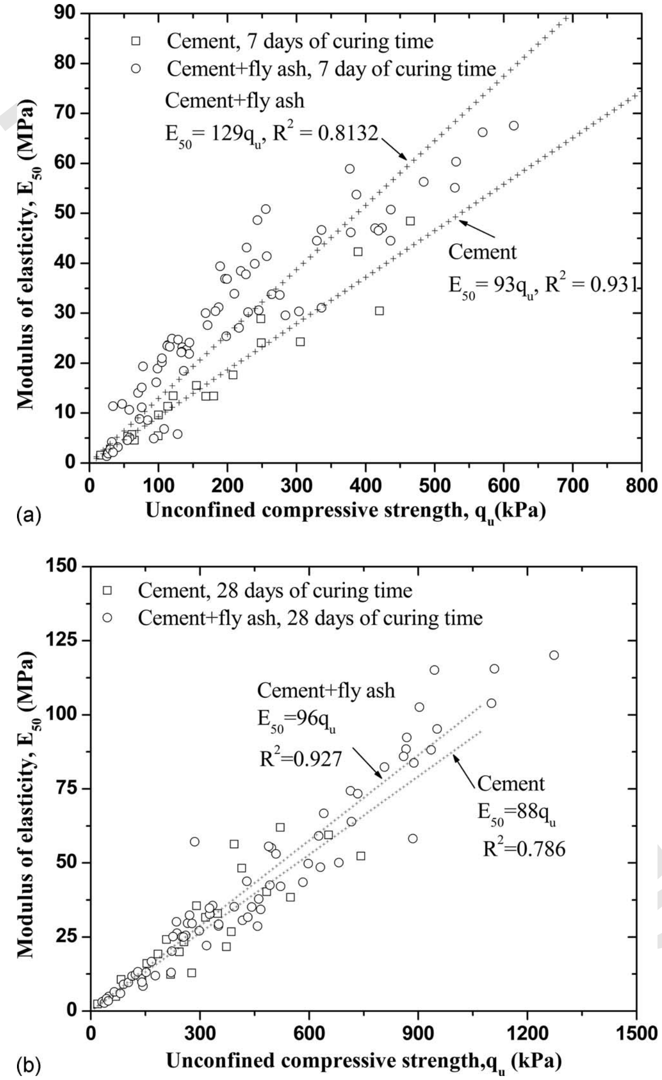

Fig. 11. Relationship between modulus of elasticity (E_{50}) and unconfined compressive strength of cement and cement-fly ash treated clay: (a) at 7 days of curing time; (b) at 28 days of curing time

$$f'c = K\left(\frac{1}{W/(C+\alpha F_w)} - a\right) \tag{4}$$

Prior to attaining α, the other parameters in Eq. (4), which are K and a must be calculated. This can be done by considering the mixtures without fly ash. The relationship between unconfined compressive strength and cement-water ratio (C/W) is illustrated in Fig. 12. In this study, C=cement content which is A_w, whereas W=total water content subtracted by a constant. From the analysis, this constant is found to be 80 which is close to the natural water content of the tested clay. However, further investigations on how this constant changes for clays with other natural water contents should be examined. The K values for curing time of 7 and 28 days were then calculated from the slopes of the lines. The calculated values are as follows: $K_{7\ \text{days}}$=1,050.2 kPa and $K_{28\ \text{days}}$=1,702.7 kPa. The parameter a in Papadakis and Tsimas equation was back-calculated from the testing results and the values of 0.0529 and 0.0374 for the curing time of 7 and 28 days were obtained, respectively.

The efficiency factors, α, of each mixing ratio were then calculated by substituting the obtained unconfined compressive

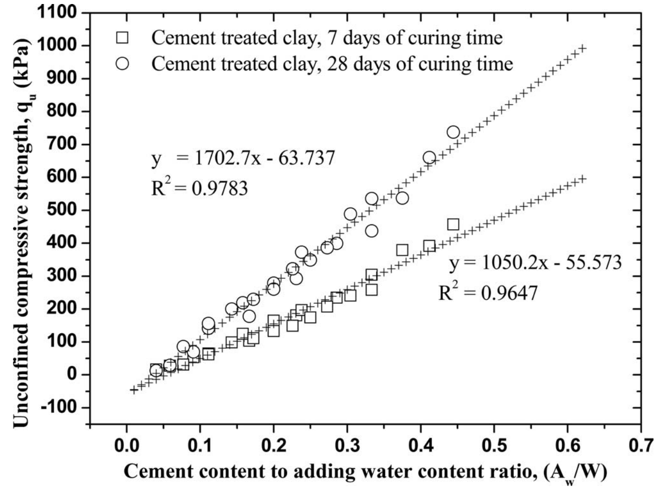

Fig. 12. Unconfined compressive strength q_u versus A_w/W ratio at 7 and 28 days of curing time

strength and mixing components into Eq. (4) using those predetermined K and a of each curing time. The equation to calculate the efficiency factor was demonstrated as follows:

$$\alpha = \frac{\left\{\left[\dfrac{f'_c}{K} + a\right]\cdot W\right\} - A_w}{F_w} \tag{5}$$

According to the observation of α values and mixing components, it was found that α tends to increase with increasing cement content. Conversely, α becomes smaller as fly ash and water content are increasing. Thus, it is reasonable to characterize α values with the ratio of these mixing components, $A_w/(W+F_w)$, as depicted in Fig. 13. Although scattering of the results is noticed, an acceptable tendency is observed. Thus, the empirical equations to relate the efficiency factor and $A_w/(W+F_w)$ are proposed in this study as Eqs. (6) and (7) for the curing time of 7 and 28 days, respectively

$$\alpha_{7\ \text{day}} = 4.263\,2[A_w/(W+F_w)] - 0.058\,4 \tag{6}$$

$$\alpha_{28\ \text{day}} = 7.335\,6[A_w/(W+F_w)] - 0.154\,4 \tag{7}$$

From Fig. 13, the highest value of α was about 2.5. From previous concrete researches (e.g., Papadakis and Tsimas 2002), this value does not exceed 1.5. This is probably because excessive fly ash from process of pozzolanic reaction provides additional inter-friction resistance to the mixtures since the grain size of ground fly ash is larger than that of clay particle. Additionally, this excessive fly ash absorbs an amount of water. Fig. 14 demonstrates the comparison between predicted and actual values of unconfined compressive strength of both cement treated clays with and without fly ash. The predicted values were calculated from Eq. (4), the α values were calculated from Eqs. (6) and (7). It can be seen that the predicting strengths satisfactorily agree with experimental results.

The ability of Abram's law for predicting strength of clay-cement-fly ash mixtures was also studied. The concept of Abram (1918) described that the strength of concrete depends on water-cement ratio with an exponential function, the equation is presented in Eq. (8). Horpibulsuk et al. (2003) and Lorenzo (2005) used this concept for predicting the unconfined compressive strength of cement-admixed clay. In this part, Abram's law, in

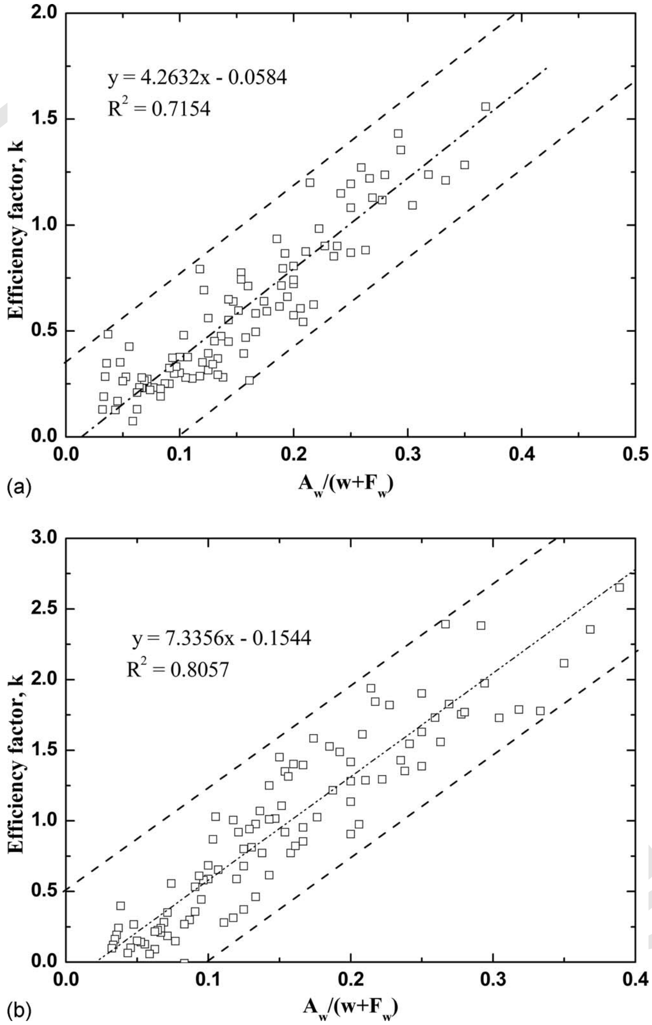

Fig. 13. Relationship between efficiency factor k with $A_w/(W+F_w)$: (a) at 7 days of curing time; (b) at 28 days of curing time

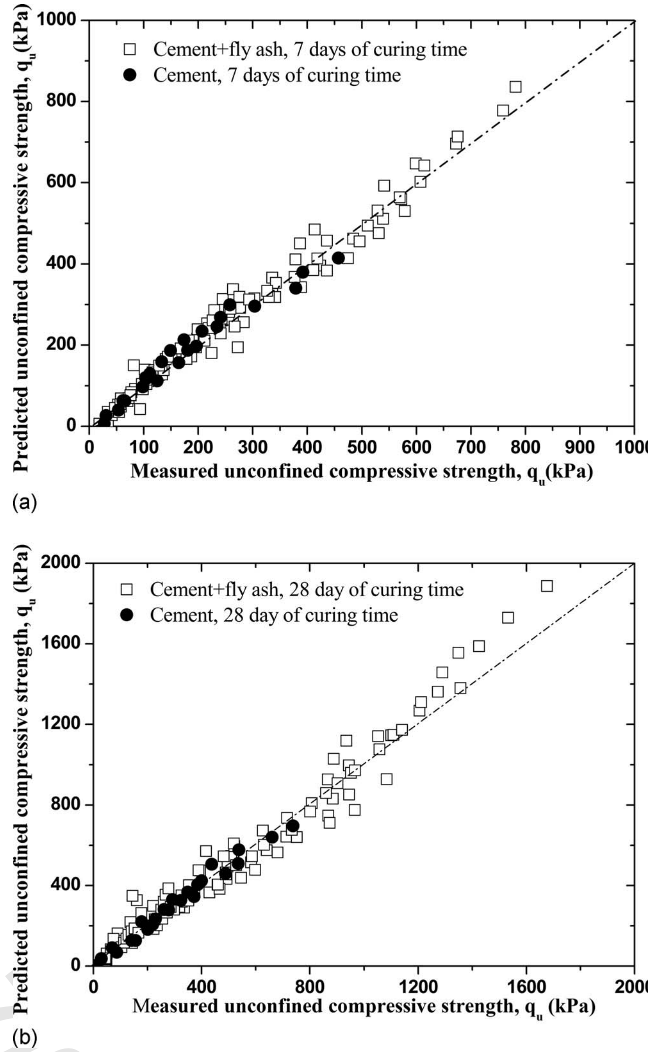

Fig. 14. Predicted versus measured unconfined compressive strength: (a) at 7 days of curing time; (b) at 28 days of curing time

conjunction with clay water-cement content ratio and the equivalent cementitious material concept using the proposed efficiency factor equations, was employed to predict the unconfined compressive strength of mixtures. The w_t/A_w was modified to w_t/A_w^*; whereas $A_w^*=A_w+\alpha F_w$ and w_t denote the total clay water content

$$q_u = \frac{A}{B^{(w/c)}} \tag{8}$$

where A and B=empirical constants depending on the characteristics of clay, type of cement, and curing time. However, it was found that the predicted values agree well with measurement results solely when w_t/A_w^* is greater than 5. For a lower value of w_t/A_w^*, the predicted values were underestimated. The mathematical function for strength prediction should be modified to predict the overall strength characteristics for all mix proportions. Therefore, a modified equation for predicting unconfined compressive strength was proposed as follows:

$$q_u = \frac{A}{\left(\frac{w_t}{A_w^*}\right)^B} \tag{9}$$

The relationships of unconfined compressive strength and the modified parameter, w_t/A_w^* with modified Abram's law are illustrated in Fig. 15.

By employing this modified equation, the results of regression analysis of the fitting give a fairly high correlation factor. The results of fitting with previous research results [e.g., Horpibulsuk et al. (2003); Lorenzo (2005)] are also shown in the figure. Thus, the equations for predicting the unconfined compressive strength of cement with and without fly ash content based on modified Abram's law concept were proposed as follows:

- At 7 days of curing time

$$q_{u\ 7\ \text{days}} = \frac{3{,}123.7}{\left(\frac{w_t}{A_w^*}\right)^{1.403\,9}} \tag{10}$$

- At 28 days of curing time

$$q_{u\ 28\ \text{days}} = \frac{4{,}249.9}{\left(\frac{w_t}{A_w^*}\right)^{1.274\,3}} \tag{11}$$

The parameters A and B are relevant to strength development of the mixture. They depend on the curing time, type of cement, as well as index and properties of clay (Horpibulsuk et al. 2003), which, in turn, depend on the clay mineralogy and composition. The strength increase of such mixture can be

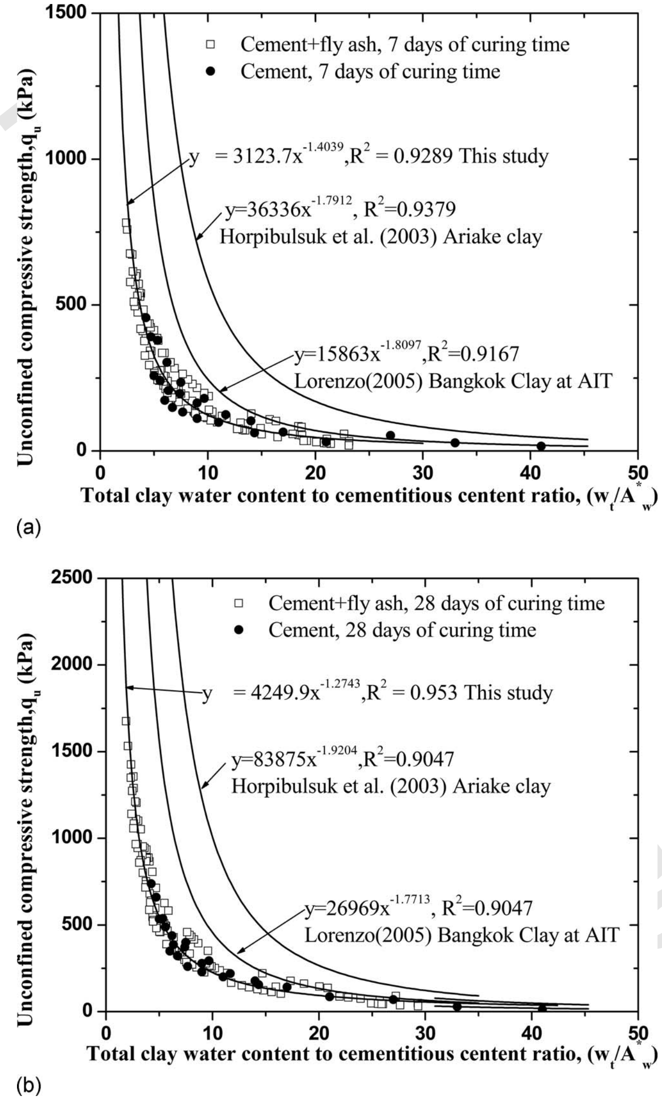

Fig. 15. Relationship between unconfined compressive strength and clay water content/cementitious material content ratio for cement-fly ash treated clay: (a) at 7 days of curing time; (b) at 28 days of curing time

explained by the interaction of microstructural mechanisms. These include hydration and pozzolanic reactions, surface deposition, and shallow infilling by cementitious products on clay clusters, as well as the presence of water trapped within clay clusters (Chew et al. 2004). The index and properties of previous researches are included in Table 1, whereas Table 4 summarizes the comparison of the mineralogy, chemistry, and geotechnical properties between Bangkok clay and Ariake clay from previous research (Ohtsubo et al. 2000).

Table 4. Comparison of Mineralogy, Chemistry and Geotechnical Properties between Bangkok Clay and Ariake Clay

Properties	Bangkok clay	Ariake clay
Organic matter (%)	2.9	2.2
Clay mineral composition (%)—at depth of 4-m smectite:kaolinite:mica	60:37:3	50:30:20
Activity	1.5	1.4
pH	7.5	8.2

Conclusions

The potential and efficiency of adding disposed fly ash from Mae Moh Electric Power Plant, Thailand, into cement-admixed clay were studied by means of a series of UC and physical tests. From this limited investigation, it is confirmed that, with suitable cement content, this ground disposed fly ash could be successfully added into soil cement to enhance both strength and physical characteristics. The strength of cement-fly ash admixed clay at high water content increased with increasing amount of cementitious material content and duration of the curing time and decreased with increasing water content. The efficiency of fly ash depended on the portion of cement, disposed fly ash, and water content in mixtures. To predict strength of clay-cement-fly ash mixtures, equivalent cementitious content concept, A_w^*, in conjunction with efficiency factor α can be successfully employed. The predictions of strength by the proposed empirical equations produced satisfactory agreements with the testing results. However, the proposed empirical equations are based on limited data of specific soil and source of fly ash, broader set of studies are needed for a more generalized form of these equations. Moreover, the long-term strength of this mixture should be investigated.

Acknowledgments

The writers are grateful for financial supports from the Thailand Research Fund (TRF) (Grant No. MRG4780037) and from King Mongkut's University of Technology Thonburi (KMUTT) research fund. The guidance and contribution of Professor Chai Jaturapitakkul are gratefully acknowledged.

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ภาคผนวก ข

สำเนาต้นฉบับส่ง Soils and Foundations

บทความเรื่อง

One-Dimensional Deformation Characteristics of Cement-Admixed Bangkok Clay Curing Under Stress

A unified state parameter for modeling undrained shear behaviors of cementitous material admixed clay

Un paramètre d'état unifié pour la modélisation du comportement non drainé d'argiles cimentées

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ABSTRACT

Portland cement and pozzolanic materials are recently widely used for subsoil improvement, either by cement stabilization or cement columns. However, the requirement of rational engineering approach for the improvement by these materials has revealed several deficiencies in the current design procedures, since there is no single parameter that can represent the overall mechanical behaviors of such mixed materials. This paper presents a physical parameter, termed the 'state parameter', which could appropriately represent the dependency of the undrained shear behaviors of cementitious-material admixed clay on different mixing components and shear stress level. Experimental data from unconfined compression and undrained triaxial compression tests on cementitious-material admixed clay at confining pressures ranging from 50 to 200 kPa are presented and the significant engineering parameters of undrained shear behaviors could be captured to be dependent on the proposed state parameter.

RÉSUMÉ

Le ciment de Portland et autres matériaux pozzolaniques sont largement utilisés pour le traitement des sols, à travers la stabilisation par ciment ou par l'intermédiaire de colonnes cimentées. Toutefois, les procédures de dimensionnement actuelles souffrent d'un certain nombre de limitations provenant du fait qu'il n'est pas considéré de paramètre unique pour caractériser le comportement mécanique global de ce type de mélange. C'est pourquoi un paramètre physique est proposé, nommé paramètre d'état, qui permet de représenter de manière pertinente la dépendence du comportement non drainé en fonction de la teneur des différents composants et de l'état de contrainte. Des données expérimentales sont présentées provenant d'essais triaxiaux non drainés avec ou sans confinement (le cas échéant, les pressions appliquées sont comprises entre 50 et 200 kPa). Les résultats révèlent une bonne corrélation entre les principaux paramètres de comportement et le paramétre d'état proposé.

Keywords : state parameter, cementious-material admixed clay, undrained shear behavior

1 INTRODUCTION

1.1 *Background*

Deep Mixing Method (DMM) is a soil stabilization technique by using chemical additives, generally Portland cement, added to the soft ground to enhance their mechanical properties (Broms 1986). However, a significant amount of Portland cement has to be used in this technique, resulting in higher cost for construction when compared to other techniques. To decrease the cost of construction, mainly governed by the cost of cement, it is necessary to find the lower cost materials for replacing the cement. A number of researches attempting to partially replace Portland cement in soil cement with some Pozzolanic materials, such as fly ash (Jongpradist et al., 2009) and rice husk ash (Jongpradist et al., 2008), have been conducted. They confirmed the potential of utilizing those ashes. At the same time, many researchers have investigated and characterized the behaviors of soil cement to develop its mathematical model (e.g., Lorenzo & Bergado, 2004; Horpibulsuk et al., 2004). To achieve this, a single parameter that is capable of both capturing its behaviors and normalizing parameter, is needed.

1.2 *Fundamental parameters of Cementitous Material Treated Clay*

A number of researches on cement admixed clay which were mostly performed by means of unconfined compression tests revealed that the engineering behavior of cement-admixed clay is affected by the clay water content (Cw), cement content (Aw), as well as curing time and a few characterizing parameters have been gradually proposed (Uddin et al., 1997; Horpibulsuk et al., 2003). Recently, a new approach of characterizing the strength in terms of unconfined compressive strength and compressibility behavior of cement-admixed clay has been developed by Lorenzo & Bergado (2004). It was proven that this fundamental parameter; the ratio of after-curing void ratio (e_{ot}) to cement content (A_w), as Eq. 1, is relavant to characterize the strength and compressibility of cement-admixed clay at high water contents.

$$e_{ot} = \left[\left(\frac{1 + \frac{C_w}{100} G_{so}}{\frac{100}{C_w} + 1} \right) \left(\frac{\left(\frac{100}{C_w} - 0.012 A_W - 0.012 \mathrm{Log}(t) + 0.99 \right) \left(1 - \frac{A_w}{100} \right)^{0.0807}}{0.0025 A_W + 0.01 \mathrm{Log}(t) + 1.008} \right) \right] - 1 \qquad (1)$$

where G_{so} denotes for specific gravity of the base clay
t represents for curing time (days)

However, this parameter was determined based on cement-admixed clay only in saturated condition. Jongpradist et al. (2007) proposed a new parameter taking into account the existence of water in void space, termed total effective void ratio (Eq. 2) to overcome such difficulty and found that this parameter can capture the strength and compressibility of soil cement, not only for saturated soil-cement but also for the air-foam soil cement (Sittibun et al., 2007) and unsaturated stabilized soils (Chareonrat et al., 2008). The after curing void

doi:10.3233/978-1-60750-031-5-257

ratio of unsaturated soil cement can be calculated from fundamental equation as shown in Eq. 3.

$$e_{st} = C_w \times \ln(e_{ot}/A_w) \quad (2)$$

where e_{st} = total effective void ratio
e_{ot} = after curing void ratio by Eq. (1) or void ratio by Eq. (3)

$$e_{ot} = \frac{(1+w_t)G_{st}\gamma_w}{\gamma_t} - 1 \quad (3)$$

An attempt to characterize the strength characteristic of Pozzolanic material admixed soil cement was conducted by taking into account the equivalent cement content concept (Eq. 4) and replacing the cement content with equivalent cement content as indicated in Eq. 5.

$$A^*_w = A_w + k(P) \quad (4)$$

where A^*_w = equivalent cementitious content
P = pozzolanic material content

$$e_{st} = C_w \times \ln(e_{ot}/A^*_w) \quad (5)$$

The performance of the developed parameter, est, is confirmed to be able to characterize the unconfined compressive strengths of cement admixed soils with and without adding pozzolanic materials as shown in Fig. 1.

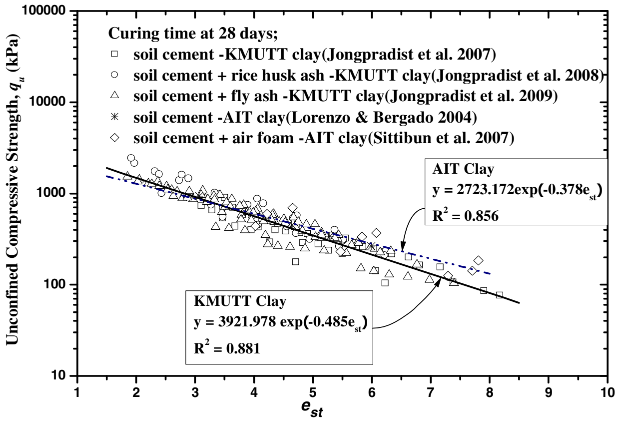

Figure 1. Relationship between unconfined compressive strength versus effective void ratio, e_{st} (Jongpradist et al., 2008).

2 UNDRAINED SHEAR BEHAVIORS OF CEMENTITOUS ADMIXED CLAY

For over 30 years, the undrained shear behaviors of uncemented clays have been investigated by many researchers. But for cement admixed clay from improvement of soft ground by chemical admixture, the investigations for understanding its behaviors has just been conducted during this decade. Particularly, the characteristics under undrained shear and controlling mechanisms are limited. For this cemented clay, the natural clay is disturbed by construction procedures and mixed with cement or lime, consequently, the cementation is taken over by admixed cementation. For Bangkok soft clay, 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 (Balasubramaniam & Buensuceso, 1989). Recently, comprehensive investigations have been performed by Horpibulsuk et al. (2004) and Lorenzo & Bergado (2006). They reported that the strength and deformation characteristics are controled by clay fabric and cementation as well as the level of confining pressure. The undrained shear behaviors of cementitious material admixed clay also exhibit in the same manner as shown in Fig. 2 for fly ash admixed soil cement performed in this study. Although some fundamental parameters and empirical relationships were proposed to characterize the strength behaviors, such fundamental parameters were insufficient to capture the significant parameters of undrained shear behaviors under different stress levels. Since all proposed parameters concern on structural property alone, but the description of stress level is omitted.

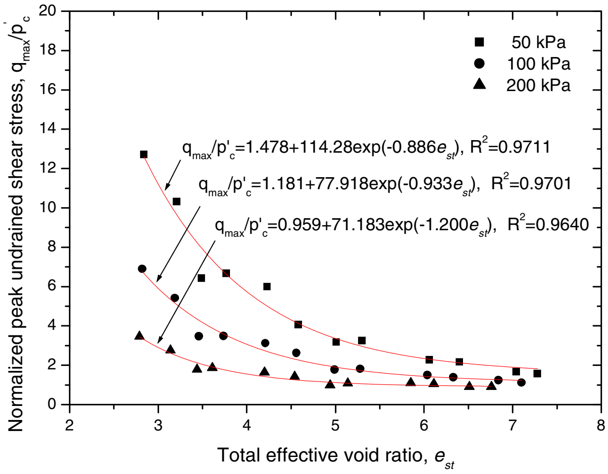

Figure 2. The relationships between normalized peak undrained shear stenss and e_{st} of fly ash admixed soil cement

3 CONSIDERATIONS FOR STATE PARAMETER

As previously mentioned, the properties of cementitous material admixed clay must be expressed in terms of both structural property and stress level. It is therefore postulated that its behaviors may be characterized in terms of a single parameter that combines the influence of structure and stress.

First, the structure property is considered (the word structure is widely used and this includes fabric, void ratio and composition in the sense of Mitchell (1976)). Unlike sands, it is not the void ratio that governs the behaviors of cement admixed clay in the sense of structure. A number of previous experimental results indicated that it includes its compositions, cement content, water content and curing time. For the sake of simplicity, a single parameter which could combine all those influencing parameters is necessary to represent matrix structure. Since it represents only matrix structure, many commonly used mechanical behaviors of which the state is not reflected, should be able to normalize well to this single parameter as well. Based on the aforementioned idea, the total effective void ratio was selected.

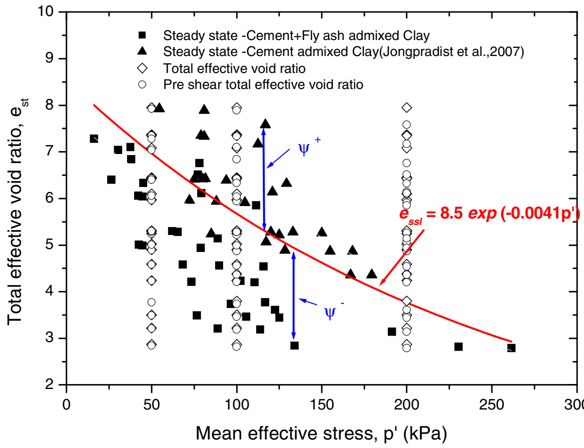

Figure 3. State diagram for cement admixed clay

Next, consideration on state or stress level is performed. Been & Jefferies (1985) selected the first stress invariant I1 as stress measure for incorporating into the state parameter and the state was illustrated in void ratio- stress space. This state parameter has been used for modeling sand behaviors (e.g., Li & Dafalias, 2000). In this study, the I1 or p´ was then adopted to represent stress level. Thus, the state was illustrated in total effective void ratio, e_{st} –stress I1 space. The measure from state to reference state is called the state parameter and the symbol ψ has been used to represent the state parameter.

$$\psi = e_{st} - e_{ssl} \qquad (6)$$

Whereas the e_{st} is the total effective void ratio at preshear state. The reference state here is selected to be the steady state, SS which is defined as the locus of point at which a mixed material deforms under condition of constant effective stress. Thus a locus of steady states in void ratio-stress space is steady state line, SSL which represents the reference state to be measure for the state parameter as shown in Fig. 3.

4 CEMENTITOUS MATERIAL ADMIXED CLAY BEHAVIORS AS A FUNCTION OF STATE PARAMETER

Only summaries of typical and significant features of undrained triaxial test results are presented in order to verify their dependence on the state parameter. For example, the deviatoric stress-strain, development of excess pore water pressure and stress path are shown in Figs. 4-6, respectively. From these figures, the followings can be concluded. For specimens with positive initial state parameters, no clear peak stress can be observed. The excess pore water pressure rapidly develops as increasing deviatoric stress and its reduction after peak stress is not distinct. The stress paths behave in a manner in which p´ starts decreasing at small deviatoric stress due to the rapid development of excess pore pressure.

Whereas, for samples with negative initial state parameter, they exhibit the distinct peak stresses. The development of excess pore pressure is not as large as that of samples with positive initial one and as further straining, it decreases to negative value indicating the dilation of specimens. The stress paths behave in a manner in which the p´ remains unchanged or slightly increases until reaching the peak deviatoric stress. Afterwards, the p´ increases rapidly as the drastic reduction of excess pore pressure.

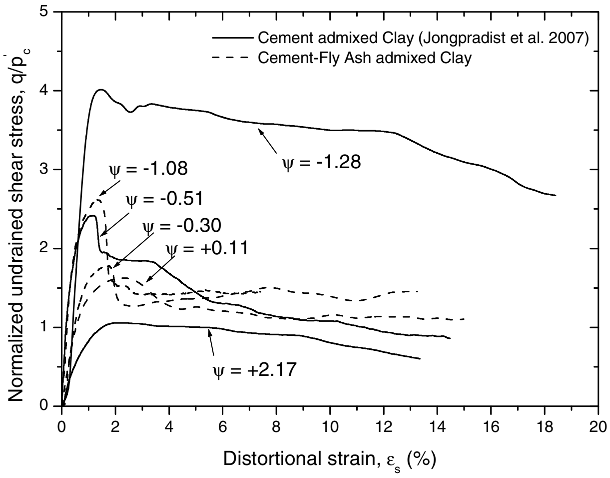

Figure 4. Undrained triaxial tests on cement admixed clays with different initial state parameters.

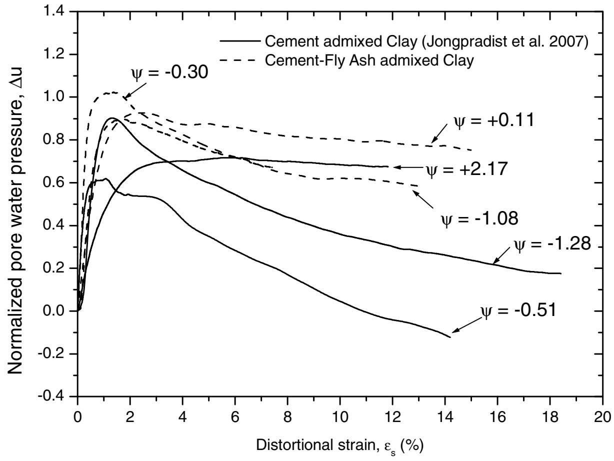

Figure 5. Excess pore water pressure development for samples with different initial state parameters.

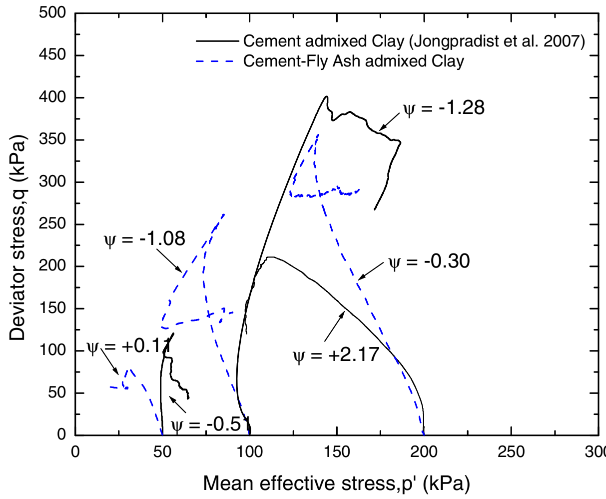

Figure 6. Stress paths for samples with different initial state parameters.

The summarized characterization of undrained shear behaviors in terms of both shear strength and excess pore water pressure by the proposed state parameter was performed to verify the suitability. The behaviors of cementitous material admixed clay, including unconfined compressive strength, normalized peak shear strength and pore pressure parameter, as functions of the initial state parameter are shown in Figs. 7 and 8. Although some scattering is noticed, there is a remarkably good correlation between these behavioral properties and the state parameter. These relationships clearly indicate the usefulness and potential applications of the state parameter concept.

5 CONCLUSIONS

This study introduces a new state parameter for modeling undrained shear behaviors of cementitous material admixed clay. It is the difference between the total effective void ratio at current state and that of steady state. The total effective void ratio, est combines together the effects of curing time, the equivalent cement content, A^*_w and the total clay water content, C_w , representing the structure matrix of material where as the mean normal effective stress represents the state. This proposed state parameter is treated as a state variable which varies from initial value to zero at critical state. From results of isotropic consolidated undrained triaxial compression tests, the significant behaviors can be captured to be dependent on the state parameter. Moreover, each of all essentially significant engineering parameters of undrained shear behaviors as well as unconfined compressive strength can be characterized as a function of the state parameter.

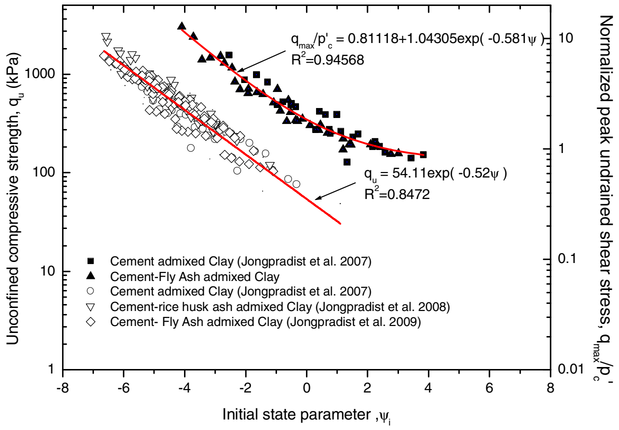

Figure 7. Yield stress, q_u and Normalized peak stress as functions of initial state parameter.

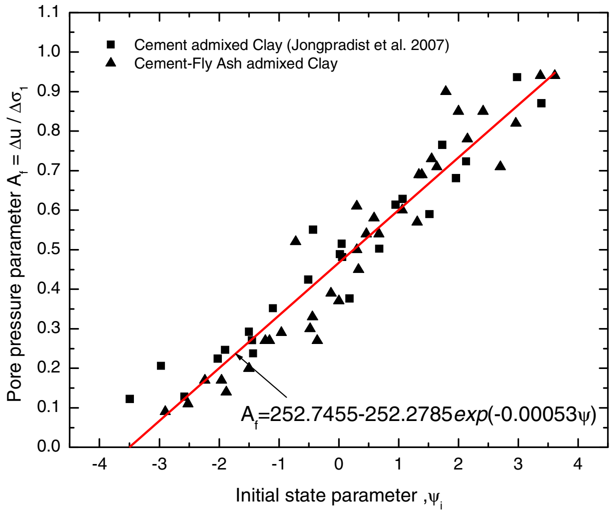

Figure 8. Pore pressure parameter as a function of initial state parameter

ACKNOWLEDGEMENT

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3) **Jongpradist, P., Youwai, S. and Manorat, P. (2007): One-Dimensional Compressibility Characteristics of Soil Cement Curing under Stress, Proc. of 16th Southeast Asian Geotechnical Conference, Kualalampur, 891-894**.

A STATE PARAMETER FOR MODELING UNDRAINED SHEAR BEHAVIORS OF CEMENT ADMIXED CLAY

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ABSTRACT: This paper presents an appropriate physical parameter, termed the state parameter, which could represent the dependence of the undrained shear behaviors of cement admixed clay on different mixing components and stress level. Experimental data from undrained triaxial compression, oedometer and unconfined compression tests on cement admixed clay are presented and the significant engineering parameters of undrained shear behaviors as well as other mechanical characteristics could be reasonably captured to be dependent on this proposed state parameter.

1. INTRODUCTION

1.1 Background

One of the techniques for improving thick deposit of soft clay is the deep mixing method (DMM). The DMM soil stabilization technique uses chemical additives, generally Portland cement or lime, added to the soft ground to enhance their mechanical properties (Broms, 1986). Up to date, a large number of laboratory tests investigating and characterizing the behaviors of soft clay with cement mixtures has been conducted and some mathematical model to predict its behaviors has been proposed (e.g. Uddin et al, 1997; Lorenzo & Bergado 2004; Horphibulsuk et al, 2004a, b). However, there has no been a single parameter being capable of both as an empirical normalizing parameter and for constitutive modeling. In this paper, a single parameter namely state parameter which is capable of both normalizing the significant engineering parameters and capturing the significant behaviors of cement admixed clay under undrained triaxial tests, was introduced.

1.2 Fundamental parameters of Cement Treated Clay

At beginning of researches on cement admixed clay which was mostly done by means of unconfined compression tests, only cement content was utilized as an independent parameter to control the strength of DMM piles for a certain curing period (Uddin et al, 1997). Cement content is defined as the ratio of weight of cement powder to the weight of dry soil. However, later research revealed that the amount of water in the clay-cement paste is also crucial in the development of the strength of cured cement-treated clay (Horpibulsuk et al, 2003). Thus, the engineering behavior of cement-admixed clay is also affected by the clay water content (C_w) presenting in the clay-cement admixture. However, the effect of curing time is not included in this parameter.

Recently, a new approach of characterizing the strength in terms of unconfined compressive strength and compressibility behavior of cement-admixed clay, which essentially considers the effect of total clay water content, cement content, as well as curing time, has been developed by Lorenzo & Bergado (2004). It was proven that this fundamental parameter; the ratio of after-curing void ratio (e_{ot}) and cement content (A_w) is sufficient to characterize the strength and compressibility of cement-admixed clay at high water contents. Although this parameter could also used to comparatively explain the undrained shear behaviors under triaxial compression condition, but it could not characterize such behaviors as a mathematical function. Thus, it can not be employed for developing constitutive model.

2. UNDRAINED SHEAR BEHAVIORS OF CEMENT ADMIXED CLAY

For over 30 years, the undrained shear behaviors of uncemented clays have been investigated by many researchers, making understand their fundamental behaviors. But for cement admixed clay from improvement of soft ground by chemical admixture, the investigations for understanding its behaviors has just been conducted during this decade. Particularly, the characteristics under undrained shear and controlling mechanisms are limited. For this cemented clay, the natural clay is disturbed by construction procedures and mixed with cement or lime, consequently, the cementation is taken over by admixed cementation. For Bangkok soft clay, 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 (Balasubramaniam & Buensuceso 1989). However, these investigations were conducted on samples with low cement contents and limited confining pressures. Recently, comprehensive investigations have been performed by Horpibulsuk et al, (2004a) and Lorenzo & Bergado (2006). They reported that the strength and deformation characteristics are controlled by clay fabric and cementation as well as the level of confining pressure. The samples with same mixing components and curing time exhibits different behaviors at different confining stresses. Some fundamental parameters and empirical relationships were proposed to characterize the strength behaviors. However, in order to model the cement admixed clay with in the framework of critical state soil mechanics, such those fundamental parameters are insufficient to capture the significant parameters of undrained shear behaviors under different stress levels, since all proposed parameters concern about structural property alone, but the description of stress level is omitted.

3. CONSIDERATIONS FOR STATE PARAMETER

As previously mentioned, the properties of cement admixed clay must be expressed in terms of both structural property and stress level. It is, thus, postulated that the behaviors of cement admixed clay may be characterized in terms of a parameter that combines the influence of structure and stress. Moreover, it must be also measured against a reference condition.

First, the structure property is considered. (The word structure is widely used and this includes fabric, void ratio and composition in the sense of Mitchell (1976)) Unlike sands, it is not the void ratio that governs the behaviors of cement admixed clay in the sense of structure. A number of previous experimental results indicated that it includes its compositions, cement content, water content and curing time. For the sake of simplicity, a single parameter which could combine all those influencing parameters is necessary to represent matrix structure. Since it represents only matrix structure, many commonly used mechanical behaviors of which the state is not reflected, should be able to normalize well to this single parameter as well. Based on the aforementioned idea, the after curing void ratio to cement content, e_{ot}/A_w (Lorenzo & Bergado ,2004) was selected since it could reasonably characterize the unconfined compressive strength and compressibility of cement admixed clay. However it could not characterize the undrained triaxial behaviors at the same confining stress with satisfactory manner. The effect of water content still exists. Thus, a modified parameter namely total effective void ratio, e_{st} taking into account the water content into the parameter e_{ot}/A_w is postulated as follows;

$$e_{st} = C_w \times \ln(e_{ot}/A_w) \qquad \text{--------} \quad (1)$$

where C_w = total clay water content

The parameter e_{ot} can be calculated from an empirical equation as Eq. 2.

$$e_{ot} = \left[\left(\frac{1+\frac{C_w}{100}G_{so}}{\frac{100}{C_w}+1} \right) \left(\frac{\left(\frac{100}{C_w} - 0.012A_W - 0.012\mathrm{Log}(t) + 0.99\right)\left(1-\frac{A_w}{100}\right)^{0.0807}}{0.0025A_W + 0.01\mathrm{Log}(t) + 1.008} \right) \right]^{-1} \qquad (2)$$

where G_{so} denotes for specific gravity of the base clay
t represents for curing time (days)

By this new parameter, the maximum principal stress of samples with each confining pressure could be characterized very well as shown in Fig. 1.

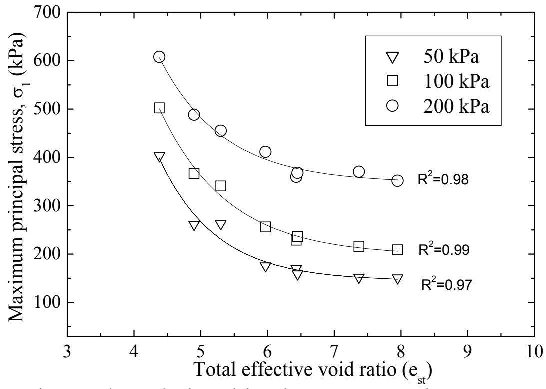

Fig. 1 The relationships between maximum σ_1 and e_{st}

Next, consideration on state or stress level is performed. Been & Jefferies (1985) selected the first stress invariant I_1 as stress measure for incorporation into the state parameter and the state was illustrated in void ratio- stress space. This state parameter has been using for modeling sand behaviors (e.g., Li & Dafalias, 2000). In this study, the I_1 or p' was then adopted to represent stress level. Thus, the state was illustrated in total effective void ratio, e_{st} –stress I_1 space. The measure from state to reference state is called the state parameter and the symbol ψ has been used to represent the state parameter.

$$\psi = e'_{st} - e_{ssl} \qquad \text{----------} \quad (3)$$

Whereas the e'_{st} is the total effective void ratio at preshear state. The reference state here is selected to be the steady state, SS which is defined as the locus of point at which a mixed material deforms under condition of constant effective stress. Thus a locus of steady states in void ratio-stress space is steady state line, SSL which represents the reference state to be measure for the state parameter as shown in Fig. 2.

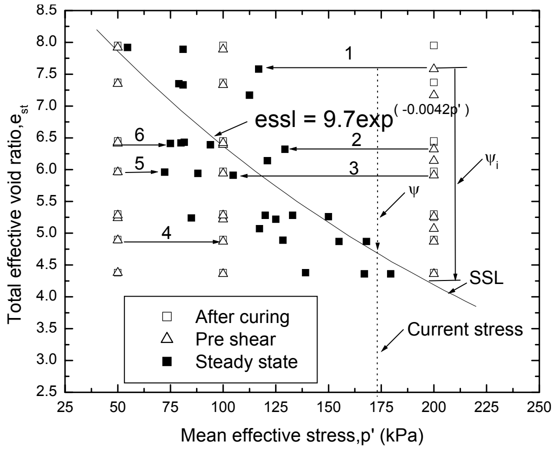

Fig. 2 State diagram for cement admixed clay

4. CEMENT ADMIXED CLAY BEHAVIORS AS A FUNCTION OF STATE PARAMETER

A program of triaxial tests on cement admixed clay at different mixing components and stress levels, was undertaken. Only summaries of typical and significant features are presented in order to verify the dependence on the state parameter. For examples, the deviatoric stress-strain, development of excess pore water pressure and stress path are shown in Figs. 3-5, respectively. From the figures, the followings can be concluded. For samples with positive initial state parameters (samples 1, 2 and 3), no clear peak stress can be observed. The excess pore water pressure rapidly develops as increasing deviatoric stress and its reduction after peak stress is not distinct. The stress paths behave in a manner in which p' starts decreasing at small deviatoric stress due to the rapid development of excess pore pressure.

Whereas, for samples with negative initial state parameter, they exhibit the distinct peak stresses. The development of excess pore pressure is not as large as that of samples with positive initial one and as further straining, it decreases to negative value indicating the dilation of specimens. The stress paths behave in a manner in which the p' remains unchanged or slightly increases until reaching the peak deviatoric stress. Afterwards, the p' increases rapidly as the drastic reduction of excess pore pressure.

The summarized characterization of undrained shear behaviors in terms of both shear strength and excess pore water pressure as well as other engineering behaviors by the proposed state parameter was performed to verify the suitability. The behaviors of cement admixed clay, including unconfined compressive strength, yield stress, normalized peak shear strength and pore pressure parameter, as functions of the initial state parameter are shown in Figs. 6 and 7. Although some of the scatter is noticed, there is a remarkably good correlation between these behavioral properties and the state parameter. These relationships clearly indicate the usefulness and potential applications of the state parameter concept.

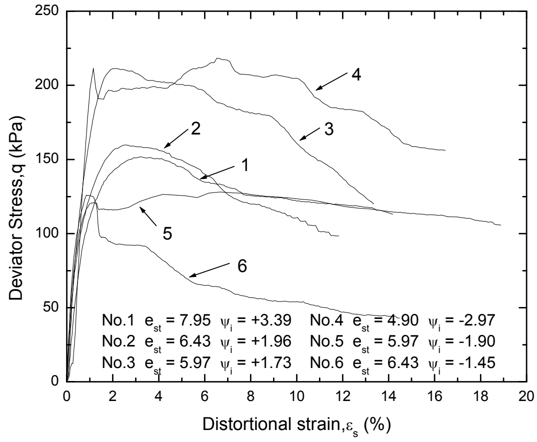

Fig. 3 Undrained triaxial tests on cement admixed clays with different initial state parameters.

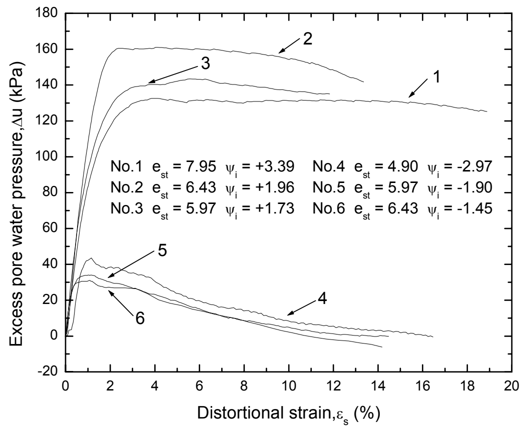

Fig. 4 Excess pore water pressure development for samples with different initial state parameters.

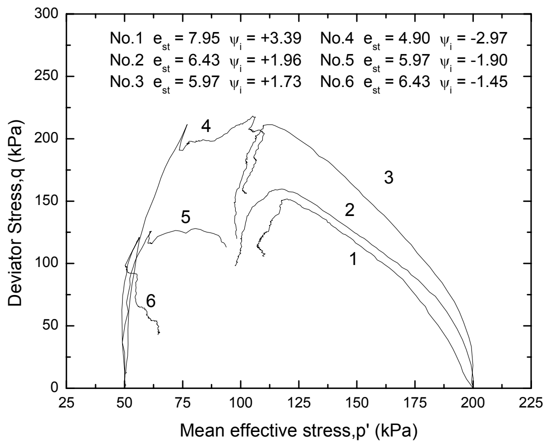

Fig. 5 Stress paths for samples with different initial state parameters.

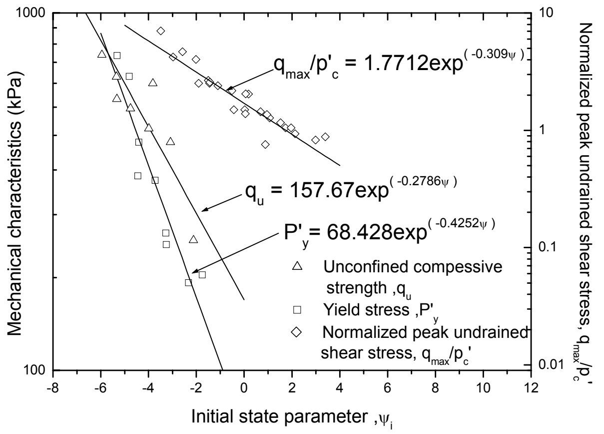

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Fig. 6 Yield stress, q_u and Normalized peak stress as functions of initial state parameter.

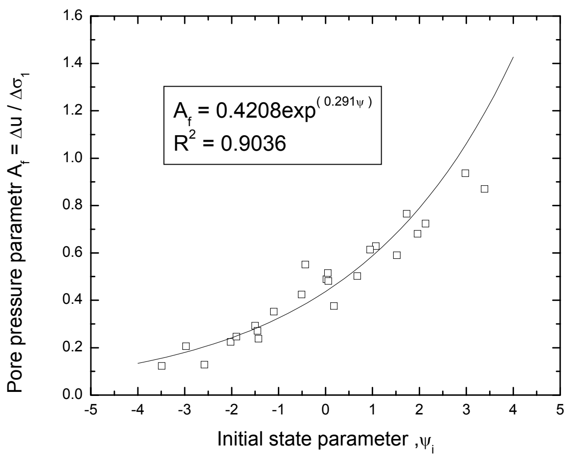

Fig. 7 Pore pressure parameter as a function of initial state parameter

5. CONCLUSIONS

This study introduces a new state parameter for modeling undrained shear behaviors of cement admixed clay. It is the difference between the total effective void ratio at current state and that of steady state. The total effective void ratio, e_{st} combines together the effects of curing time, the cement content, A_w and the total clay water content, C_w , representing the structure matrix of material where as the mean normal effective stress represents the state. This proposed state parameter is treated as a state variable which varies from initial value to zero at critical state. From results of isotropic consolidated undrained triaxial compression tests, the significant behaviors can be captured to be dependent on the state parameter. Moreover, each of all essentially significant engineering parameters of undrained shear behaviors as well as unconfined compressive strength and yield stress can be characterized as a function of the state parameter.

ACKNOWLEDGEMENTS

The authors are grateful for supports from the Thailand Research Fund (TRF) under grant MRG4780037 and from King's Mongkut University of Technology Thonburi Research Fund.

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1) **Jongpradist, P., Jumlongrach, N. and Youwai, S.(2006) Predicting Strength of Cement-Fly Ash Admixed Bangkok Clay at High Water Content, Proceedings of the 6th Symposium on Ground/Soil Improvement and Geosynthetics, Thailand, pp. 61-67.**
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One-Dimensional Compressibility Characteristics of Soil Cement Curing under Stress

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Abstract: A study of one-dimensional compressibility characteristics of high water content admixed soil cement cured under stress is presented. Before conducting consolidation tests, the cement admixed clays at different mixing ratios were cured under stresses ranging from 0 to 86 kPa to represent soil cements at different depths in the cement column when the cementing developed. The influence parameters, which are water content, cement content and curing stress affected to yield stress (P'_Y) and void ratio (e_{ot}) of soil cement, were investigated. From experimental results, yield stress increased with decreasing water content and increasing cement content and curing stress. After-curing-void ratio, which governs the compressibility characteristics of soil cement, increased with increasing water content and decreasing cement content and curing stress. Empirical equations, which can reasonably predict the after curing void ratio and the yield stress for samples with and without curing stress, were proposed.

1 INTRODUCTION

Ground improvement by cement stabilization with deep mixing method (DMM) is widely used to increase strength and stiffness and to reduce compressibility of soft clayey soils. This DMM uses either slurries or powder of cement to form columns of improved soil in the ground. The improved columns act as piles transferring load to the skin and to the bottom-end. The methods of mixing are usually divided into either mechanical mixing or high pressure jet mixing (Porbaha, 1998). The mechanical deep mixing with slurry and jet mixing methods would normally produce high water content cement admixed clay. High water content cement-admixed clay is hereinafter defined as those clay-cement mixtures having the total water content (after mixing) of at least the liquid limit of the base clay. A number of laboratory tests as well as field investigations to study the engineering characteristics and the proper design and implementation of deep mixing have been continuously conducted (Broms 1984; Uddin et al., 1997; Lorenzo & Bergado 2004).

Most of these researchers utilize cement content, water content and curing time as control parameters in the study of the behavior of cement-admixed clay. (e. g. Bergado et. al., 1999; Kamon & Bergado 1991; Uddin 1997; Miura et al., 2001). Currently, Lorenzo & Bergado (2004) proposed a new concept for predicting the strength and deformation characteristics of cement-admixed clay by using a main parameter, which was the ratio between after curing void ratio and cement content. However, those previous researches, cement admixed clay have been cured under controlled temperature without curing stress. This condition may not represent actual ground condition. Due to different overburden pressure, consequently, different lateral pressure at each depth, cement-admixed clay form at different pressure and has different after curing void ratio and stress history (Chin et al., 2004; Rotta et al., 2003). Thus, the deformation characteristics of mixed material are not the same throughout the entire depth which can be as large as 40 m. At such depths, the effective confining stress could be of the order of 300 kPa. To date, there is no research to investigate the effects of curing stress to the deformation characteristics of cement admixed clay. In addition, there is no research to propose the model to simulate the deformation characteristics of cement admixed clay with and without curing stress. The first step to access the model, a parameter which governs its behaviors is necessary. Thus, the main objectives of this paper are to investigate the one-dimensional deformation characteristics of cement admixed clay with and without curing stress and to propose a single parameter which governs the one-dimensional deformation of the aforementioned mixed material and also includes the influence of curing stress.

It has been revealed from previous researches that cement content in mixture has influence on its mechanical properties as structure or bonding. The model for structure soil was then selected as referenced model. Recently, Liu & Carter (1999) have proposed the model for predicting one-dimensional compression characteristics of structural clay based on disturb state concept. The general framework of the one-dimensional compression characteristics are described in Fig. 1. It is divided into two regions by the initial yield stress, $\sigma'_{y,i}$. When stress state being larger than the initial yield stress, the structure of soil is progressively destroyed. The initial yield stress before loading is determined by the initial structure of geomaterial depending on the several factors such as cementation, mechanical, chemical and biological histories the soil experienced.. Thus, to predict the one-dimension compression characteristics of cement admixed clay, the initial yield stress, $\sigma'_{y,I}$ (P'_Y in this study), initial void ratios, e_{ot}, needed to be specified.

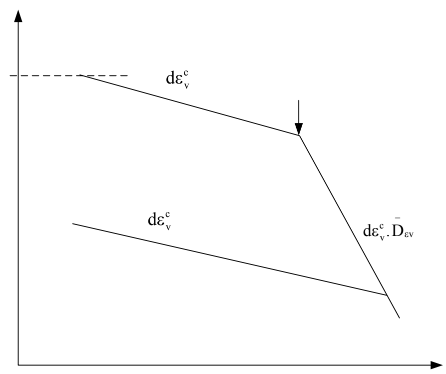


Fig. 1 Schematic diagram of disturb state model

2 EXPERIMENTAL PROGRAM

2.1 *General Description and Investigated Variables*

The experimental program investigates the effects of curing stress as well as previously known factors, which are cement and water contents, on the one dimensional compression behaviors of cement admixed clay. The curing time was kept constant at 28 days throughout the study. The stresses for curing were defined at values of 43 and 86 kPa representing the lateral in situ stresses under K_0 of 0.5 at the mid and end of 20 m long cement column (commonly used for soft Bangkok clay), respectively. The samples were cured under drained condition. The tests of specimens cured without stress were also conducted for comparison.

Models for simulating the strength and deformation characteristics of structure soil have been proposed (Leroueil & Vaughan, 1990; Gen & Nova, 1993; Cotecchia & Chandler, 1997). Recently, Liu & Carter, (1999, 2003) have also proposed a model for prediction of one-dimensional compression characteristics of structural clay. It is divided into two regions by the initial yield stress, σ'_{yi}. When stress state being more than the initial yield stress, the structure of soil is progressively destroyed. The initial yield stress before loading is determined by the initial structure of geo-material. For cement admixed clay, Horpibulsuk et al.(2004) found that post-yield compression behavior was governed by cement content. Thus, the mainly investigated compression characteristics in this study are recompression index, after-curing void ratio and yield stress (P'_Y).

2.2 *Test Material and Specimen Preparation*

The base clay utilized in this study was the typical soft Bangkok clay sampling from the depth of 4 -5 m. The physical properties are summarized in Table 1. The clay samples were first remolded with additional water to obtain the required water contents (w* denotes for remolded water content) and mixed with cement-slurry with a water-cement of 1 to obtain the favorite Cw/Aw (Cw and Aw denote for total clay water content and cement content, respectively). Type I Portland cement was used throughout this study. Mixing was done using a mechanical mixing machine until a homogenous cement-water-clay paste was attained.

The specimens was then obtained by placing the paste directly into the oedometer ring to avoid the disturbance in subsequent sample cutting and fitting into the ring. The friction between oedometer ring and sample was reduced by using plastic sheet and silicone grease method (Fang et al., 2004). Since there must be initial settlement during curing under stress, the thickness of specimen after curing would reduce. The oedometer ring in this study was then modified to increase the height as schematically illustrated in Fig 2.

Table 1 Index properties of Bangkok Clay.

Properties	Characteristics values
Liquid limit , LL, (%)	100
Plastic limit, PL, (%)	40
Plasticity index,PI, (%)	60
Water content, w, (%)	84
Initial void ratio,e	2.37
Specific gravity,Gs	2.72

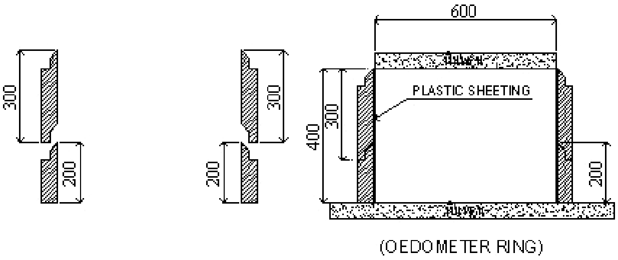


Fig. 2 Modified oedometer ring used in this study

2.3 *Procedure for Curing and Compressibility Tests*

After placing the cement-water-clay paste into the oedometer ring, the load for curing stress must be applied to the specimen within 2 hours since the beginning of mixing, before the cement bond formation would start (Horpibulsuk *et al.,* 2004). The settlements during curing were monitored. As expected, the higher the water content and curing stress, the larger the settlement, which can exceed 10 mm.

To investigate the influence parameters to the compressibility of cement-admixed clay, the test program was designed as tabulated in Table 2. The mixing ratios was varied with different portions of remold water contents, the ratios between total water contents and cement content and curing stress.

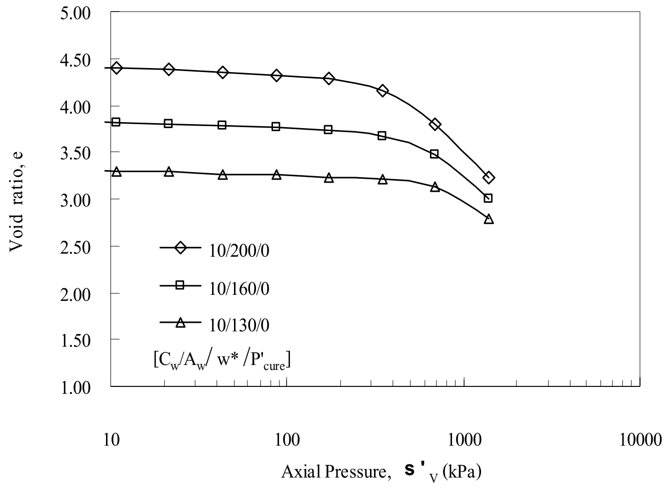
Table 2 Testing program.

No.	w*	C_w/A_w	Curing time (day)	Curing stress (kPa.)
1.	-	Undisturb	-	-
2.	1.25LL	Intrinsic	-	-
3.	130	10	28	0 , 43 , 86
4.	130	15	28	0 , 43 , 86
5.	130	20	28	0 , 43 , 86
6.	160	10	28	0 , 43 , 86
7.	160	15	28	0 , 43 , 86
8.	160	20	28	0 , 43 , 86
9.	200	10	28	0 , 43 , 86
10.	200	15	28	0 , 43 , 86
11.	200	20	28	0 , 43 , 86

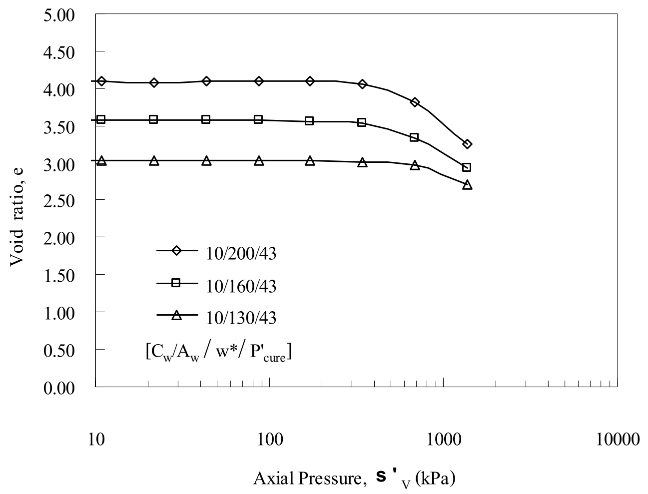
3 ONE DIMENSIONAL COMPRESSIBILITY CHARACTERISTICS

3.1 *Compression Behaviors*

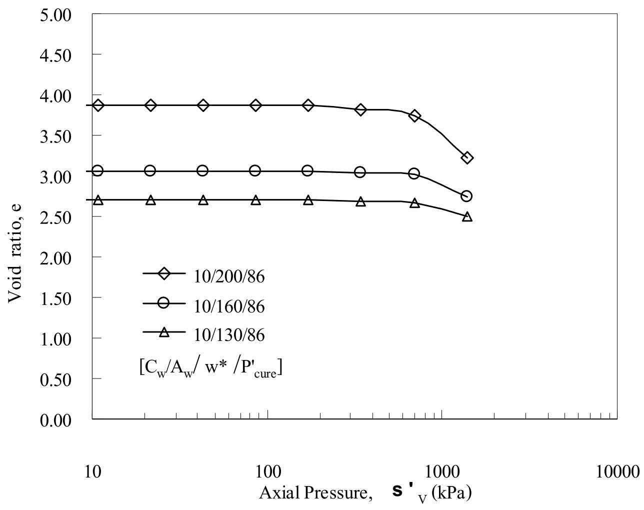
Comparisons of the compression behaviors of cement admixed clay specimens cured with and without stresses for various water contents are shown in Figs. 3 and 4. The figures illustrates only the cases for Cw/Aw = 10 (Fig. 3) and 20 (Fig. 4). The results of specimens cured without stress are depicted in Figs. 3a) and 4a) (curing stress = 0 kPa). From initial examination of the results, it shows the influence of curing stress, as the curing stress increases the after curing void ratio (initial void ratio for oedometer tests) decreased but yield stress increased.



a) Curing stress = 0 kPa

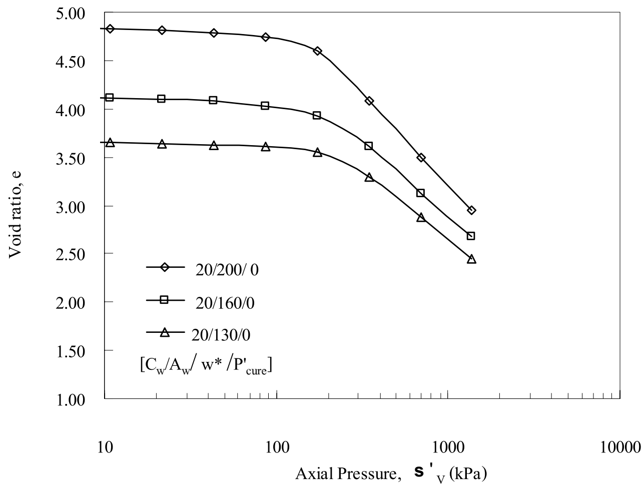


b) Curing stress = 43 kPa

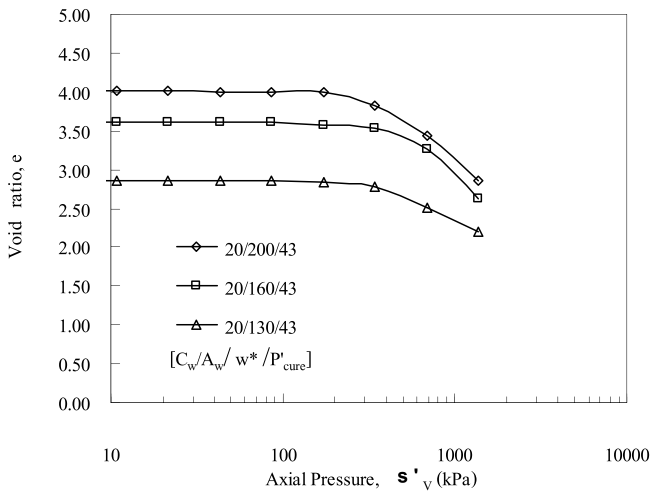


c) Curing Stress = 86 kPa

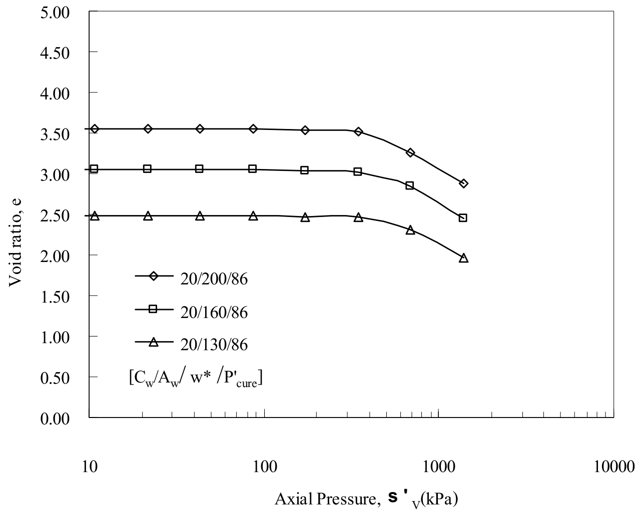
Fig. 3 Compression characteristics of cement-admixed clays with Cw/Aw = 10 cured under different stresses



a) Curing stress = 0 kPa



b) Curing stress = 43 kPa



c) Curing Stress = 86 kPa

Fig. 4 Compression characteristics of cement-admixed clays with Cw/Aw = 20 cured under different stresses

The recompression indexes, C_r, are approximately similar for every mixing ratios. The yield stress increased with increasing cement contents. Beyond yield stress, the structure was initially degraded causing significant increase of deformation.

3.2 *Influencing Factors and Characterization of Compression Behaviors*

The behaviors of natural clay as well as cement admixed clay are described by stress state, stress history and void ratio. Thus, void ratio is the main influence parameter to characterize the behaviors of cemented clay. Lorenzo & Bergado (2004) proposed the empirical formula to predict the after curing void ratio of cement admixed Bangkok Clay, e_{ot} , from those several parameters which are total clay water contents, Cw, cement content, Aw, and time (day), t, as shown in the following equation.

$$e_{ot}=\left[\frac{1+C_w+G_{SO}}{\frac{100}{C_w}}\left(\frac{\frac{100}{C_w}-0.012A_w+0.012\mathrm{Log}(t)+0.99\left(1-\frac{A_w}{100}\right)^{0.0807}}{0.0025A_w+0.01\mathrm{Log}(t)+1.088}\right)\right]-1 \tag{1}$$

where G_{so} is the specific gravity of clay. However, this equation was proposed for cement admixed clay cured without stress.

The experimental results reveal that the changes of after curing void ratio of specimens cured with stress from initial void ratio of specimen cured without stress, increase with increasing curing stress and the Cw/Aw which can be seen in Fig. 5.

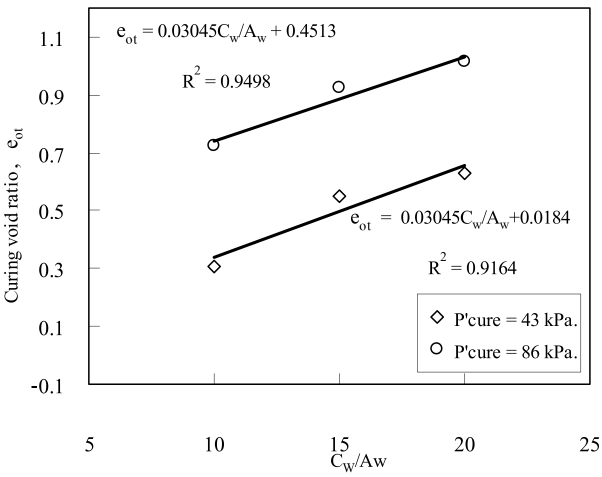


Fig. 5 Relationships between change of void ratio (Δe_{ot}) and Cw/Aw for different curing stresses.

The after curing void ratio of cement-admixed clay cured under stress can then be calculated by subtracting the after curing void ratio without curing stress (Eq. 1) with those changes in void ratio due to curing stress. The new empirical equation for cement admixed Bangkok Clay cured under stress was then proposed as follows:

$$e_{ot}=\left[\frac{1+C_w+G_{SO}}{\frac{100}{C_w}}\left(\frac{\frac{100}{C_w}-0.012A_w+0.012\mathrm{Log}(t)+0.99\left(1-\frac{A_w}{100}\right)^{0.0807}}{0.0025A_w+0.01\mathrm{Log}(t)+1.088}\right)\right]-\left(1+(0.03045\tfrac{C_w}{A_w})+(0.001e^{0.001P'_{cure}})\right) \tag{2}$$

where p'$_{cure}$ is the curing stress. The additional part was proposed from the changing of void ratio of mixed material due to curing stress. The comparison between predicted of after curing void ratio in the case of curing with and without stress is shown in Fig.6. As shown in figure, the proposed empirical equation for prediction after curing void ratio can effectively simulate the laboratory results.

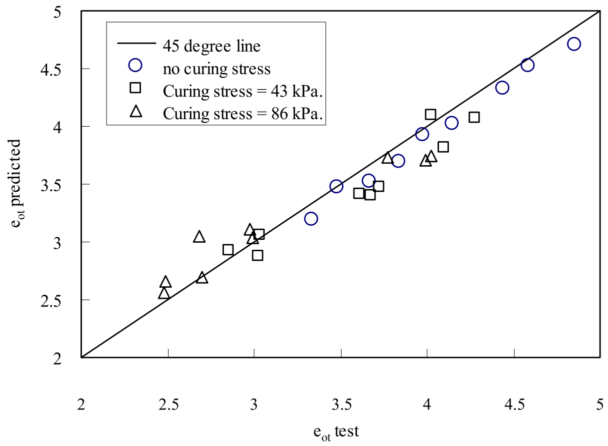


Fig. 6 Comparison of after-curing void ratios from experimental results and predictions.

From the overall testing results, yield stress , P'_Y, decrease with increasing after curing void ratio, total clay water content and increasing cement contents as summarized in Fig. 7. The empirical formula was proposed as follows:

$$P'_Y = e^{3\frac{e_{ot}}{A_w}-0.0075C_w+8.273+P'_{cure}\left(0.02388\frac{C_w}{A_w}+0.0191P'_{cure}+0.6471\right)} \tag{3}$$

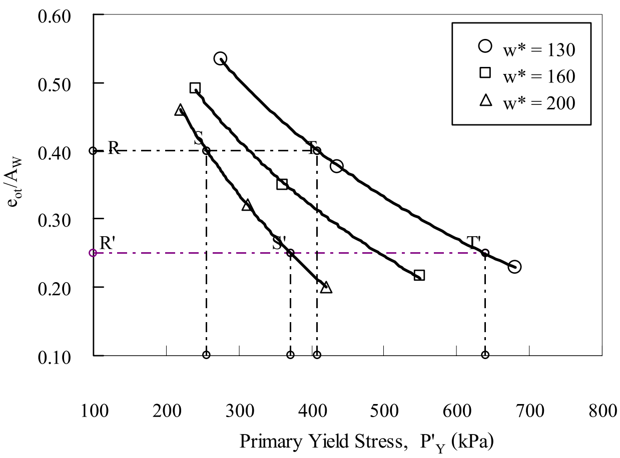


Fig. 7 Relationships between yield stresses and characterized parameter e_{ot}/ Aw for different water contents.

The predict yield stress from the proposed empirical formula agreed well with the testing results as shown in Fig. 8.

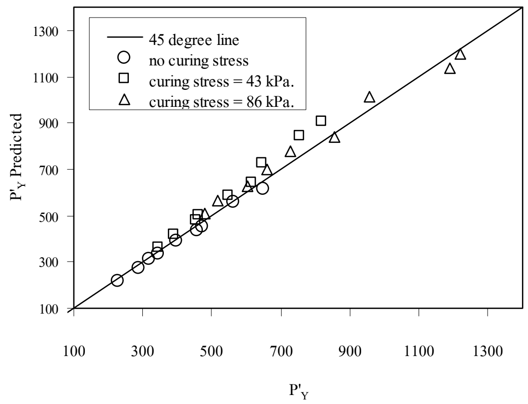


Fig. 8 Comparison of yield stresses from experimental results and predictions.

4 CONCLUSIONS

A study of one-dimension compressibility characteristics of soil cement curing under stress was presented. The influence parameters, which are water content, cement content and curing stress effected to yield stress (P'_Y) and void ratio (e_{ot}) of soil cement were investigated. From laboratory test result, yield stress increased with decreasing water content and increasing cement content and curing stress. After-curing void ratio increased with increasing of water content and decreasing of cement content and curing stress. The proposed empirical equations can reasonably predict the after curing void ratio and the yield stress for samples with and without curing stress:

ACKNOWLEDGMENTS

The authors are grateful for supports from the Thailand Research Fund (TRF) under grant MRG4780037 and from King's Mongkut University of Technology Thonburi Research Fund.

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