ENGINEERING PROPERTIES OF LIGHTWEIGHT CELLULAR CEMENTED CLAY

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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เอนก เนรมิตรครบุรี : คุณสมบัติทางวิศวกรรมของดินซีเมนต์เถ้าลอยมวลเบา (ENGINEERING PROPERTIES OF LIGHTWEIGHT CELLULAR CEMENTED CLAY) อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุขสันติ์ หอพิบูลสุข, 80 หน้า

ดินเหนียวซีเมนต์เซลลูล่ามวลเบามีการประยุกต์ใช้ในงานซ่อมบำรุงและงานก่อสร้างโครงสร้างพื้นฐานอย่างกว้างขวาง วิทยานิพนธ์นี้ศึกษาอิทธิพลของปริมาณน้ำ ปริมาณปูนซีเมนต์ ปริมาณอากาศ และเถ้าลอย ต่อคุณสมบัติทางวิศวกรรม อันได้แก่ หน่วยน้ำหนัก การไหล และกำลังอัด และความคงทนต้านการเปียกสลับแห้งของดินเหนียวซีเมนต์เซลลูล่ามวลเบา ผลการศึกษาแสดงให้เห็นว่าหน่วยน้ำหนัก การไหล และกำลังอัดของดินเหนียวซีเมนต์เซลลูล่ามวลเบาแปรผันตามอัตราส่วนปริมาณความชื้น w/w_L โดยที่ w คือปริมาณความชื้น และ w_L คือปริมาณความชื้นที่ขีดจำกัดเหลว การแทนที่เถ้าลอยในดินเหนียวทำให้ปริมาณความชื้นที่ขีดจำกัดเหลวลดลง และส่งผลเกิดการเปลี่ยนแปลงค่า w/w_L สภาวะทำงานได้ (ปริมาณความชื้นเหมาะสมในการผลิตดินเหนียวซีเมนต์เซลลูล่ามวลเบา) เท่ากับ 1.5 เท่าของขีดจำกัดเหลว ความสามารถในการไหลโดยไม่แปรผันตามปริมาณปูนซีเมนต์ และสามารถประมาณได้จาก w/w_L และปริมาณอากาศ ในฟังก์ชั่นลอการิทึม อัตราส่วนช่องว่างต่อซีเมนต์ (V/C) ซึ่งนิยามว่าเป็นอัตราส่วนระหว่างปริมาณอากาศในดินเหนียวต่อปริมาณซีเมนต์ เป็นพารามิเตอร์หลักที่ควบคุมการพัฒนากำลังในดินซีเมนต์เซลลูล่ามวลเบา แฟบริค (การจัดเรียงของอนุภาคเม็ดดินและช่องว่าง) ซึ่งเป็นผลมาจากปริมาณอากาศและปริมาณน้ำ ถูกควบคุมโดยปริมาณอากาศในดินเหนียว ขณะที่ ความแข็งแรงของพันธะเชื่อมประสานถูกควบคุมโดยปริมาณปูนซีเมนต์ สมการทำนายกำลังอัดในพจน์ของ V/C ที่เวลาการบ่มค่าหนึ่งถูกนำเสนอขึ้นโดยใช้กฎของ Abrams เป็นพื้นฐาน จากการวิเคราะห์ผลการทดสอบ ผู้วิจัยได้นำเสนอแนวทางการออกแบบส่วนผสมเพื่อให้ได้หน่วยน้ำหนัก ความสามารถในการไหล และกำลังอัด ที่ต้องการ

ท้ายสุด ผู้วิจัยได้ศึกษาและวิเคราะห์อิทธิพลของโครงสร้างของดินซีเมนต์ (แฟบริคและพันธะเชื่อมประสาน) ต่อกำลังอัดที่รอบเปียกสลับแห้งของดินเหนียวซีเมนต์เซลลูล่ามวลเบา กำลังที่รอบเปียกสลับแห้งลดลงตามการเพิ่มขึ้นของรอบเปียกสลับแห้ง เนื่องจากความเสื่อมของโครงสร้าง ดัชนีความเสื่อม ซึ่งบ่งบอกอัตราความเสื่อมกับจำนวนรอบเปียกสลับแห้ง ถูกนำเสนอในพจน์ของกำลังอัดเริ่มต้น (ปราศจากรอบเปียกสลับแห้ง) ผู้วิจัยได้พัฒนาสมการทำนายกำลังอัดที่รอบเปียกสลับแห้งต่างๆ ในพจน์ของดัชนีความเสื่อม สมการการทำนายในการใช้สมการนี้มีความแตกต่างกันขึ้นอยู่กับจำนวนรอบเปียก-แห้ง (w-d cycle) สมการที่พัฒนาขึ้นได้รับการตรวจสอบ

ความแม่นยำจากผลทดสอบที่จัดทำขึ้นเฉพาะ ทั้งสมการทำนายกำลังอัดที่รอบเปียกสลับแห้งและวิธีการออกแบบส่วนผสมที่นำเสนอในงานวิจัยนี้มีประโยชน์ทั้งในเชิงวิศวกรรมและเศรษฐศาสตร์

สาขาวิชาวิศวกรรมโยธา ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา 2557 ลายมือชื่ออาจารย์ที่ปรึกษา ______________

ANEK NERAMITKORNBURI : ENGINEERING PROPERTIES OF LIGHTWEIGHT CELLULAR CEMENTED CLAY. THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 80 PP.

AIR FOAM/ CEMENT/ COMPRESSIVE STRENGTH/ FLOWABILITY/ LIGHTWEIGHT MATERIAL/ UNIT WEIGHT/ DURABILITY

Lightweight cellular cemented (LCC) clay has wide applications in the infrastructure rehabilitation and in the construction of new facilities. The roles of water content, cement content, air content, and fly ash replacement on the engineering properties: unit weight, flowability strength and durability against wetting and drying (w-d) cycles of LLC Bangkok clay are investigated and analyzed in this thesis. It is found that the unit weight, flowability strength of LCC clay are strongly controlled by the generalized stress state, w/w_L, where w is the water content and w_L is the liquid limit water content. The FA replacement reduces w_L, resulting in the change in w/w_L. The workable state, the optimum water content to produce LCC clay, is about $1.5w_L$. The flowability is irrespective of cement content and approximated in terms of w/w_L and air content in the logarithmic function. The void/cement ratio, V/C, which is defined as the ratio of the void volume of clay to the cement volume, is proved as the prime parameter governing the strength development in LCC clay. The fabric (arrangement of clay particles, clusters and pore spaces) reflected from both air foam content and water content is taken into consideration by the void volume while the inter-particle forces (levels of cementation bond) are governed by the input of cement

(cement volume). A strength equation in terms of *V/C* at a particular curing time is introduced using Abrams' law as a basis. From the critical analysis of test results, a mix design method to attain the target unit weight, flowability and strength is suggested.

The role of cemented soil structure (fabric and cementation bond) on w-d cycle strength of LCC clay is finally investigated and analyzed. The strength reduction with increasing number of w-d cycles is caused by the degradation of cemented structure. The degradation index, qualifying the rate of degradation with number of w-d cycles, is proposed in terms of initial soaked strength (without w-d cycle). Using the degradation index, the predictive w-d cycle strength equation at different number of w-d cycles is proposed. The applicability of the proposed equation is validated using a separate test data. Both the w-d cycle strength equation and the mix design method proposed are beneficial from both engineering and economic viewpoints.

School of Civil Engineering Student's Signature ________________

Academic Year 2014 Advisor's Signature ________________

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SYMBOLS AND ABBREVIATIONS

FA	=	Fly ash
V/C	=	Void/Cement ratio
PC	=	Portland Cement
CSH	=	Calcium Silicate Hydrate
q_u	=	Unconfined Compressive Strength
q_{uo}	=	Unconfined Compressive Strength
FSR	=	Free Swell Ratio
XRD	=	X-ray diffraction
w/w_L	=	Generalized Stress State
w	=	Clay Water Content
w_L	=	Liquid Limit Water Content
A_c	=	Air Content
C	=	Cement
UC	=	Unconfined Compression
γ	=	Unit Weight
γ_w	=	Unit Weight of Water
G_s	=	Specific Gravity of Soil
G_c	=	Specific Gravity of Cement
C / w	=	Cement/Clay-Water Ratio

CHAPTER I

INTRODUCTION

1.1 Background

Generally, infrastructures such as road embankments and bridge foundations are constructed on soft soil deposits where several geotechnical engineering problems are encountered. These deposits tend to consolidate and undergo large vertical settlement and lateral deformation during and after construction due to incumbent loads. The problems are moreover related to short-term and long-term stability when an unexpected loading (e.g. earthquake) is imposed on the structures and soft ground system.

To solve these problems, the improvement of soft ground by deep mixing technique is commonly applied in Southeast Asia, including Thailand. The mechanical behavior of cement admixed clays were extensively investigated by Terashi et al. (1979 and 1980); Kawasaki et al. (1981); Kamon and Bergado, (1992); Horpibulsuk et al. (2004a and b, 2010) and Suebsuk et al., (2010 and 2011); etc. The improvement cost depends mainly on the thickness of the soft clay. The thicker the soft clay, the higher the improvement cost. Instead of improving the soft ground (foundation), the use of lightweight materials with moderate to high strength as a backfill material to reduce the weight of the structure on the soft clay is an effective alternative means. Lightweight materials have wide applications in the infrastructure rehabilitation and in the construction of new facilities. They can be used as a backfill for quay walls and bridge abutments to reduce the earth pressure behind the wall, as a fill for construction of embankments on soft soil to reduce overburden pressure, as a method of reducing pressure on the tunnel lining.

A mixture of in-situ clay, air foam agent and cementing agent can be used to form a lightweight material, which is designated as "Lightweight Cellular Cemented (LCC) clay" (Horpibulsuk et al., 2012b). LCC clay is a cost-effective construction material in terms of construction time, material consumption and transportation. Over time, strength, stiffness and Poisson's ratio of LCC clay increase; hence enabling further resistance to lateral movement. The LCC clay has been extensively used for highway and port construction in many countries such as Japan and Thailand (Tsuchida et al., 2001; Satoh et al., 2001; Hayashi et al., 2002; Otani et al., 2002; Jamnongpipatkul, et al., 2009; kikuchi and Nagatome, 2010; and Kikuchi et al., 2011).

This research aims to illustrate the impact of water, cement, and air content and fly ash (FA) replacement on the four engineering properties of LCC clay-FA material: unit weight, flowabilty, strength and durability against wetting and drying cycles. The stress state (state of water content) suitable for making the LCC clay-FA material for different FA replacement ratios is determined. Based on the critical analysis, a suggested method to attain the target strength, flow, unit weight and durability is finally introduced.

1.2 Research objectives

The objectives of this research are to

1.2.1) study the role of water content, cement content and fly ash on the unit weight, strength, flowability and durability of LCC clay.

1.2.2) suggest a simple and rational mix design procedure to attain the target unit weight, strength and flowability of LCC clay.

1.2.3) propose a rational empirical relationship between w-d cycle strengths and initial soaked strength (without w-d cycles).

1.3 Scope and limitation of the study

The test clay is Bangkok clay from Yan Nawa District, Bangkok, Thailand at a 4 meter depth. Type I Portland cement (PC), fly ash from Mae Moh power plant in the north of Thailand, air foam from Grace Construction Products Ltd and tap water were used in this study. The clay and fly ash were mixed and then mixed thoroughly with water to attain the clay-water content between 2 and 3 times liquid limit. The cement content was varied from 5 to 30% by weight of dry soil and fly ash replacement was between 0 and 100% of dry soil. The air foam content was from 0 to 50% of total volume. Flowability of the LCC mixture (prior to hardening) was measured to illustrate the role of influential factors (water content, air content and cement content. Unit weight, strength and durability against wetting and drying cycles were also measured to illustrate the role of water content, air content, cement content and curing time. Based on the analysis of the test data, a practical method to determine flowability of LLC mixture and unit weight, strength and durability of LLC material is proposed and verified.

CHAPTER II

LITERATURE REVIEW

2.1 General

Extensive urbanization and industrialization in coastal regions and low land areas of many countries have necessitated to strengthen very soft ground to enhance its shear strength and reduce its compressibility so as to handle its stability and settlement problems. The strengthening processes by cement and lime treatments have been more widely employed in the recent years. After mixing, chemical reactions will take place between chemical admixtures and soil particles.

The materials contained in this chapter deal with comprehensive literature review on the engineering behavior of the cement stabilized soil. It starts with fundamental concepts of cement stabilization and factors controlling the hardening characteristics. Then the attention is paid to engineering and physical properties of cement stabilized clays.

2.2 Fundamental concepts of soil cement stabilization

A Portland cement particle heterogeneous substance contains minute tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and a solid solution described as tetracalcium alumino-ferrite (C_4A) [Lea, 1956]. These four main constituents are major strength producing compounds. When the pore water of the soil encounters with the cement, hydration of the cement occurs rapidly and the major hydration (primary cementitious) products are hydrated calcium silicates (C_2SH_X,

$C_3S_2H_X$), hydrated calcium aluminates (C_3AH_X, C_4AH_X) and hydrated lime $Ca(OH)_2$. The first two of the hydration products listed above are the main cementitious products formed and the hydrated lime is deposited as a separated crystalline solid phase. These cement particles bind the adjacent cement grains together during hardening and form a hardening skeleton matrix, which encloses unaltered soil particles. According to Taylor (1960), the silicate and aluminate phases are internally mixed, so it is most likely that none is completely crystalline. Part of the $Ca(OH)_2$ may also be mixed with other hydrated phases, therefore being only partially crystalline. In addition, the hydration of cement leads to a rise of pH value of the pore water, which is caused by the dissociation of the hydrated lime. The strong bases dissolve the soil silica and alumina (which are inherently acidic) from both the clay minerals on the clay particle surfaces, in a manner similar to the reaction between a weak acid and strong base. The hydrous silica and alumina will then gradually react with the calcium ions liberated from the hydrolysis of cement from insoluble compounds (secondary cementitious products), which hardens when cured to stabilize the soil. This secondary reaction is known as the pozzolanic reaction. The composition of hydrated cement is still not clearly defined by a chemical formula, so considerable variations are feasible. The compounds in the Portland cement are transformed on the addition of water as follows:

$2(3CaO.SiO_2) + 6H_2O = 3CaO.2SiO2.3H2O + 3Ca\,(OH)_2$ (2.1)

(tricalcium silicate) (water) (tobermorite gel) (calcium hydroxide)

$2(2CaO.SiO_2) + 4H_2O = 3CaO.2SiO_2.3H_2O + Ca(OH)_2$ (2.2)

(bicalcium silicate) (water) (tobermorite gel) (calcium hydroxide)

$4CaO.Al_2O_3.Fe_2O_3 + 10H_2O + 2Ca(OH)_2 = 6CaO.Al_2O_3.Fe_2O_3.12H_2O$ (2.3)

(tetracalciumaluminoferite) (calcium aluminoferrite hydrate)

$3CaO.Al_2O_3 + 12H_2O + Ca(OH)_2 = 3CaO.Al_2O_3.Ca(OH)_2.12H_2O$ (2.4) (tricalcium aluminate) (tetracalcium aluminate hydrate)

$$3CaO.Al_2O_3 + 10H_2O + CaSO_4.2H2O = 3CaO.Al_2O_3Ca(OH)_2.12H_2O \quad (2.5)$$

(tricalcium aluminate) (Gypsum) (calcium monosulfoaluminate)

The first two equations whose materials constitute 75% of the Portland cement, show that the hydration of the two calcium silicate types produces new compounds: lime and tobermorite gel, with latter playing the leading role with regard to strength development, since bondage, strength and volume variations are mainly governed by them. The reactions, which take place in soil-cement stabilization, can be represented in the following qualitative equation; the reactions given here are for tricalcium silicate (C_3S) only, because they are the most important constituents of Portland cement.

$$C_3S + H_2O \qquad C_3S_2H_x \text{ (Hydrated gel)} + Ca(OH)_2 \quad (2.6)$$

primary cementitious products

$$Ca(OH)_2 \longrightarrow Ca^{++} + 2(OH)^- \quad (2.7)$$

$$Ca^{++} + 2(OH)^- + SiO_2 \text{ (soil silica)} \longrightarrow CSH \quad (2.8)$$

(secondary cementitious product)

$$Ca^{++} + 2(OH)^- + Al_2O_3 \text{ (soil} \longrightarrow \text{alumina) } CAH \quad (2.9)$$

(secondary cementitious product)

When pH < 12.6, then the following reaction occurs:

$$C_3S_2H_x \longrightarrow C_3S_2H_x \text{ (Hydrated gel)} + Ca(OH)_2 \quad (2.10)$$

In order to have additional bonding forces produced in the cement-clay mixture, the silicates and aluminates in the material must be soluble. The solubility of the clay minerals is equally affected by the impurities present, the crystalline degree of the materials involved, the grain size, etc. In the above equations, the cementation strength of the primary cementitious products is much stronger than that of the secondary ones. At low pH values (pH < 12.6), the relation shown in Equation 2.10 will occur. However, the pH drops during pozzolanic reaction and a drop in the pH tends to promote the hydrolysis of $C_3S_2H_x$, to form CSH. The formation of CSH is beneficial only if it is formed by the pozzolanic reaction of lime and soil particles, but it is detrimental when CSH is formed at the expense of the formation of the $C_3S_2H_x$, whose strength generating characteristics are superior to those of CSH. The cement hydration and the pozzolanic reaction can last for months, or even years, after the mixing, and hence the strength of cement stabilized clay is expected to increase with time.

Thus, it means that in the soil-cement mixture containing fine clay particles, primary and secondary cementing substances are formed. The primary products harden into high-strength additives and differ from the normal cement hydrated in concrete. The secondary processes increase the strength and durability of the soil-cement mixture by producing of an additional cementing substance to further enhance the bond strength between the particles.

2.2.1 Interaction between Soil and Cement

Stabilized soils with cement means the formation of mixture of pulverized soil, cement, and water to produce a modified soil. In concrete, there is barely any fine soil particle, the aggregate has a coarse-grain character and the cement particles usually form sheathes around the granular aggregate and bridge its particles, giving considerable strength. When aggregate and cement mixed with water, cement undergoes an exothermic hydration – hydrolysis reaction. The reaction rate and consequent rate of heat evolution are the functions of total component and the crystal chemical of the cement minerals, the fineness of the powder and the temperature of the setting. Setting and hardening are the results of a complex sequence of processes. Hardened cement paste has a finely intergrown microstructure dominated by the binding component of a very high surface area and submicrometer-sized non-crystalline fibers or particles of calcium silicate hydrate (CSH), which grows between and link together large crystallites and residual anhydrous cement graincores and their perimeter, leaving a microporous material with minimal interconnected capillaries. The solidification of cement paste is regarded as a constant volume process. In the cement stabilized soil, on the other hand, the individual cement particles are surrounded by fine soil grains, giving rise to much weaker bond and consequently lower level of strength development.

Kezdi (1979) describes reaction between soil and cement as follows, with particular respect to the fact that the role played by cement is different in cohesive soils.

In fine-grained silts and clays, the hydration of cement creates rather strong bonds depending on various mineral substances, and forms a matrix, which efficiently encloses the nonbonded soil particles. This matrix develops a cellular structure on which strength of the entire construction depends, since the strength of the individual particles within the matrix is rather low. This matrix pins the particles, thereby increasing the shear strength. Together with strength increase, chemical surface effect of cement reduces the water retention capacity of the clays. The overall volume stability and frost resistance is also increased because of the enclosure of the larger unstabilized grain aggregates.

On the other hand, in granular materials, the cementation effect is similar to that in concrete, without any sand-cement and physico-chemical interactions. The cement paste does not fill the voids, but forms a cohesive membrane around these coarse grains. In the case of coarse-grained soils, strength is mainly derived from the hydration and hydrolysis of cement resulting in hydrated gel particles of large surface area, which reduce the porosity of the system due to solidification.

Kezdi (1979) enunciates the hypothesis on clay-cement interaction as follows. He distinguishes the primary and secondary processes of clay cement mixture.

The primary process is believed to include hydrolysis and the hydration of the cement, in the course of which the usual hydration products appear with the increase in the pH value of the water. The calcium hydroxide produced in that period is believed to react much more strongly than ordinary lime.

The role played by clay is important in the secondary processes. The calcium ions produced during cement hydration transform the clay first into calcium clay, and increase the intensity of flocculation that had been initiated by the increase in electrolyte content due to cement addition. Calcium hydroxide then attacks, thereafter, the clay particles and formation of amorphous compounds. Then the silicates and aluminates dissolved in the pore water are thought of as mixing with the calcium ions, thus precipitating the additional cementing material. The calcium hydroxide consumed during the course of secondary processes is partly replaced by the lime produced by cement hydration. Thus the primary reaction products supply material for the secondary processes.

During the secondary processes, the cementation substances are formed over the surface of the clay particles or in their immediate vicinity, causing the flocculated clay grains to be bonded at the contact points. Still stronger bonds may be created between the hydrating cement paste and the clay particles coating the cement grains.

2.3 Factors that control hardening characteristics of cement stabilized clays

The hardening characteristics of cement stabilized soils are developed by a number of factors. Owing to the large number of alternatives and combinations, it is impossible to tabulate the various mechanical properties as functions of these factors, so the experimental determination is indispensable in most cases. Nevertheless, there are some predominant factors present below. An outline of some superficial factors exerting an influence on the properties of cement stabilized soils.

2.3.1 Type of Cement

The differences in improvement of cement stabilized clays by using different types of Portland cement have been investigated. The stabilization of Type III Portland cement renders better improvement of soil than Type I cement does. Yet, the Type I Portland cement is the most popular cement used in soil stabilization due to its being most readily available at reasonable cost.

2.3.2 Cement Content

Broms (1986) found that the more the cement content, the greater the strength of the cement treated clay. The modulus also increases with the increase in cement content (Huang and Airey, 1993; Yin and Lai, 1998; and Horpibulsuk et al., 2000d, to name a few).

Uddin (1994) has studied on the strength and deformation characteristics of cement stabilized soft Bangkok clay and reported that a sharp increase of strength occurs up to the region of 20% to 25% cement content and then the incremental rate ceases down. He has found that the cement contents between 10% and 20% are the most effective range of stabilization of Bangkok clay.

2.3.3 Curing Time

In a manner similar to that of concrete and lime stabilized soils, the shear strength of cement stabilized clay increases with time. The rate of increase of strength is generally rapid in the early stages of curing period, thereafter, the rate of increase of strength decreases with time. However, the rate of increase in strength for cement stabilized clay is greater than that for lime stabilized clay at early age (Åhnberg et al.,1995).

The formation of the primary and secondary cementitious materials proceeds slowly and continuously for months, even years. It can be expected that the strength of the cement stabilized clays generally increases with time until the completion of the reaction. Broms (1986) has investigated the applications of cement columns in soft clays in the Southeast Asian region, in which the general properties of the clays are relatively similar, and reported the maximum strengths of the investigated case as listed below.

For 16% cement treatment, the 1-month, 2-month and 4-month strengths are 410 kPa, 660 kPa and 700 kPa, respectively and 230 kPa, 320 kPa, and 460 kPa, respectively for 10% cement treatment.

The hardening characteristics of cement stabilized Ariake clays have been investigated under the oedometer and unconfined compression tests (Horpibulsuk et al., 1999). They have revealed that the strength and the yield stress in K_0-consolidation increase with an increase in curing time.

DJM RESEARCH GROUP (1984 and 2000) also reported that an average value of 2/3 of the 28-day strength can be achieved at the 7-day age for all cement contents (q_7/q_{28} = 0.67). Horpibulsuk et al. (2001) have proposed the empirical equation for strength prediction based on the strength data of cement stabilized inland and marine clays. According to the equation, the ratio q_7/q_{28} is equal to 0.60.

2.3.4 Soil Type

The effectiveness of cement and lime decreases with increasing water content and organic content. The effect of organic matter on unconfined compressive strength of clays improved by quick lime and cement was studied by Miura et al. (1988)

and shown in Figure 2.1. Clearly, quicklime performs better than cement when organic matter content is below 6. On the other hand, cement renders better result, especially when the organic matter is higher than 8. To overcome the negative effect of organic matter to the improvement, more quantity of quicklime and cement is necessary, which in turn results in more amounts of non-reacted lime and cement. This non-reacted lime makes the clay friable because it cannot solidify itself in a short time. On the contrary, the un-hydrated cement does not affect strength development.

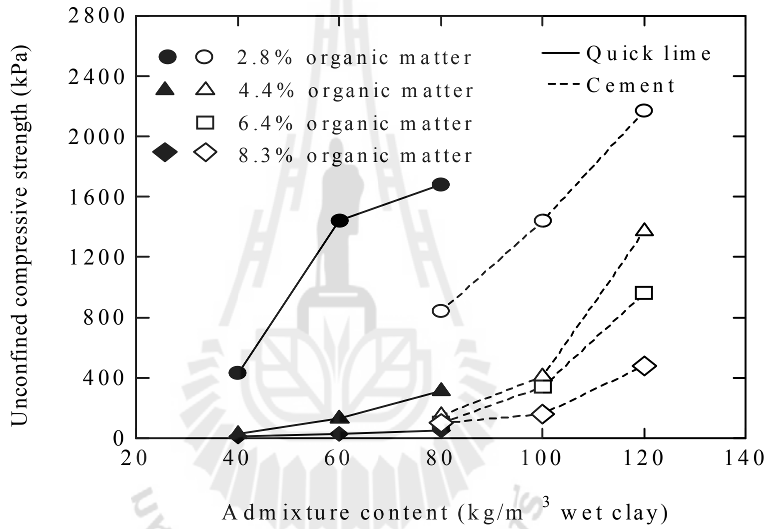


Figure 2.1 Distribution of unconfined compressive strength and organic matter content (after Miura et al., 1988).

The effects of cement gradually decrease with increasing clay content and increasing plasticity index (Woo, 1971). In general, when the activity of a soil is very high, the increase in shear strength of the soil treated with cement is low. The increase in the shear strength due to the flocculation is often relatively small for marine clays deposited in salt water, since these clays already have a flocculated structure (Broms, 1984).

Miura et al. (1988) carried out several tests which small amount of salts was added to the clay specimens together with quick lime and cement. The results are shown in Figure 2.2(a) and 2.2(b). In those tests, salt amounting to 5, 10, and 20 percent together with quicklime and cement powders were added to the clay and then mixed in a soil mixer. Up to certain amount of the salt added, the strength of improved soil increased with the salt content. The addition of salt, NaCl, may act as a catalyzer according to Ariizumi (1977) and the ions Cl^{-}, Na^{+}, Mg^{+2} may accelerate the pozzolanic reaction.

The increase of the strength with cement is often low when the water content exceeds 200% (Babasaki et al., 1996). The increase has also been low for organic soils when the ignition loss exceeds 15% even at cement content above 20%.

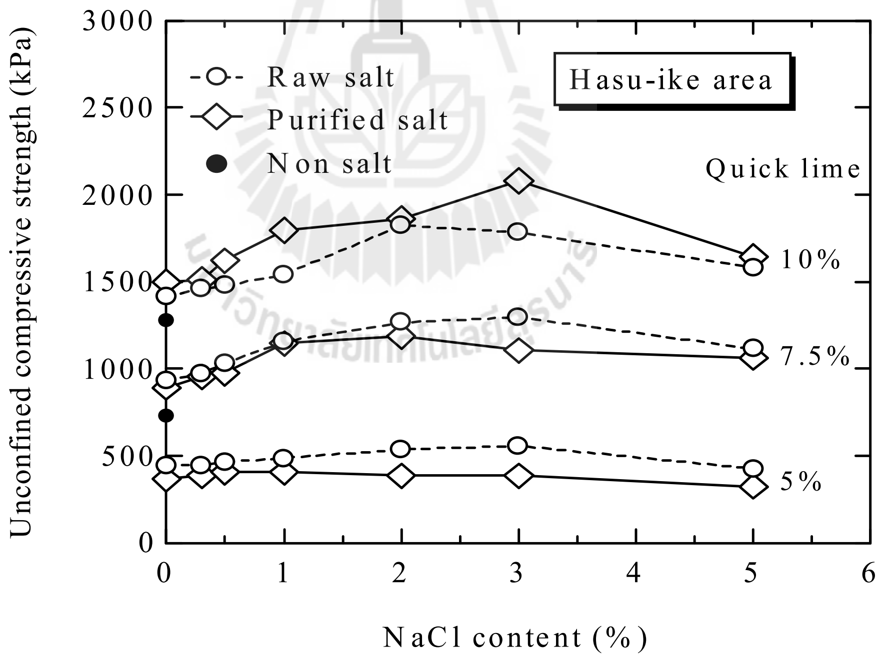


Figure 2.2(a) Influence of NaCl content on the quick lime improvement of Ariake clay (after Miura et al., 1988).

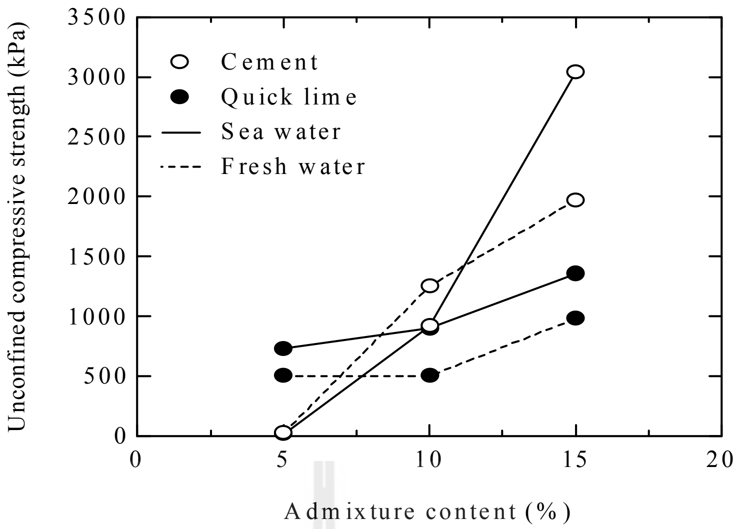


Figure 2.2(b) Relationship between unconfined compressive strength and admixture content (after Miura et al., 1988).

2.3.5 Curing Temperature

The increase of temperature accelerates the chemical reactions and solubility of the silicates and aluminates, thus increasing the rate of strength gain of the stabilized soils (Bergado et al., 1996).

2.3.6 Soil Minerals

In the case of soils with the property of higher pozzolanic reactivity, the strength characteristic of the cement stabilized soils is governed by the strength development of the hardened cement bodies. However, in the case of soils having lower pozzolanic reaction, the strength mobilization of the stabilized soils is governed by the strength characteristics of the hardened soil bodies (Saitoh et al., 1985).

Hilt and Davidson (1960) have observed that montmorillonitic and koalinitic clayey soils are found to be effective pozzolanic agents, as compared to clays, which contain illite, chlorite or vermiculite.

Wissa et al. (1965) have also explained that the amount of secondary cementitious materials, produced during pozzolanic reaction of the clay particles and hydrated lime [$Ca(OH)_2$], is dependent on the amount of material composition of the clay fraction as well as the amorphous silica and the alumina present in the soil. The montmorillonite clay mineral probably react more readily than the illites and kaolins because of their poorly defined crystallinity.

2.3.7 Soil pH

The long-term pozzolanic reactions are favored by high pH values, since the reactions are accelerated due to the increased solubility of the silicates and the aluminates of the clay particles. When the pH value of the stabilized clay is lower than 12.6, the reaction of the Equation 2.10 occurs, where $C_3S_2H_x$ is used up to produce the CSH and the hydrated lime [$Ca(OH)_2$]. This will reduce the strength of the stabilized clay at the expense of stronger cementitious material, $C_3S_2H_x$, to produce the weaker cementitious material, CSH.

2.4 Engineering and physical properties of cement stabilized clays

2.4.1 Strength Characteristics

Strength is one of the most important parameters of soils that is altered by cement treatment. Part of the immediate increase in shear strength is caused by flocculation of clay and part results from the reduction of the water content (Broms, 1986).

Lambe (1960) has explained that the small soil particles are cemented to be larger particles caused by the cement admixture. The large particles are highly interlocked, hence producing greater rates of dilation during shearing. It results in enhancement of shear strength, thus the effective cohesion and friction angle are increased.

Herzogs (1967) has explained an increase in strength of cement stabilized clay that it consists of two processes. The first one occurs with the aggregation of hydrated cement cores and surrounding clay particles, forming a cement-clay matrix structure, which contributes towards the major strength gain by significant interlocking. This enhances the improvement of the friction component (ϕ') of the shear strength. The second process involves the reduction of the thickness of the double-layer water, caused by the ion exchange and the flocculation of the clay particles, reducing the inter-particle space so as to increase the inter-particle bond strength.

Wissa et al. (1965) have indicated that the residual strengths show no effect of cementation and can be described by a single strength envelope independent of amount of cementation. Clough et al. (1981) have studied the artificially and naturally cemented sands under static loading. Their conclusion is drawn that the failure envelope of both the cemented and uncemented sands are essentially straight lines with nearly the same slope. The cohesion intercept increases with increasing amount of cement and the friction angle is not affected by cementation. Kasama et al. (1998) have carried out the consolidated undrained triaxial compression test of cement stabilized Ariake clay at low cement content. They have summarized that the failure state line of clay with cementation is parallel to that of uncemented clay. Consoli et al. (2000) have investigated the influence of curing under stress on the triaxial response of cemented soils. The stress state acting during the cementing process plays a fundamental role in the mechanical behavior of cement stabilized soils. The samples cured under stress exhibit higher strength and less maximum volumetric strain. Balasubramaniam and Buensuceso (1989) investigated the strength and deformation characteristics of lime stabilized Bangkok clay under undrained and drained triaxial compression conditions. Based on the stress~strain characteristics, stress path, pore pressure development and volume change behavior, they have reported that the lime treatment causes a change in strength and deformation characteristics of the soft clay from normally consolidated clay to that of an overconsolidated clay. Horpibulsuk et al. (2000d) have argued that the behavior of the cement stabilized clay is governed by cementation and friction components, which is different from the behavior of overconsolidated clays, mainly controlled by the interlocking.

The in-situ unconfined compressive strength of soil-cement columns on-shore can be as low as one-half to one-fifth of the unconfined compressive strength of the laboratory samples at the same cement content and water content (Kamon, 1997). Ansano et al. (1996) have reported that the shear strength of samples mixed in the laboratory is up to 2 to 5 times higher than the shear strength of samples obtained from columns. The difference of the shear strength is attributed to the difference in the mixing conditions. Horpibulsuk et al. (2000e) have investigated the effect of the mixing conditions on the strength development of the columns. They have found that the ratio of the field strength to laboratory strength at the most effective mixing condition is between 1/3 and 1/2, depending upon the cement content. Nishida et al. (1996); and Miura and Nishida (1998) explained the strength difference between field columns and laboratory samples based on the mixing energy.

The friction angle has a tendency to increase with curing time for soil-cement columns (Åhnberg et al, 1995). Values of 40 to 45 degrees have been reported for soil-cement columns by Wada et al., 1991. Uddin (1994) has revealed that the friction angle increases as the increase in cement content.

Huang and Airey (1993) have carried out a series of triaxial test of cement stabilized sand from cement contents of 0% to 20%. They have found that the yield loci increase with the increase in the cement content and cannot be normalized by the equivalent p'_e. Balasubramaniam et al. (1999) have also reported that the yield loci of the cement stabilized Bangkok clay increase with the increase in the cement content based on the result of triaxial consolidation test at different stress ratio. Moreover, the (η,ε_s) and (q, ε_v) relationship of the cement stabilized Bangkok clay are not unique even at the effective confining pressures being higher than the yield stress (Uddin, 1994). It is due to the effect of cementation (Horpibulsuk et al., 2000d).

The shear strength and the bearing capacity of soil-cement columns increase with time, thereby gain in the modulus of elasticity and the compression modulus. The additional increase after 28 days is in general small. Okamura and Terashi (1975); Bredenberg (1979); Åhnberg and Holm (1986); and Kujala et al. (1993) have reported that the undrained shear strength increases with $\sqrt{D}$. According to Mitchell (1974); Brandl (1981 and 1995); Nagaraj et al. (1996); Nagaraj and Miura (1996); Yamadera et al. (1997); and Horpibulsuk et al. (2000a and 2001), the shear strength increases with log D.

Mitchell (1974) has proposed the following relationships between curing time and q_u.

$$q_D = q_{D0} + K \log \frac{D}{D_0} \tag{2.11}$$

where, q_D = unconfined compressive strength at D days, kPa

q_{D0} = unconfined compressive strength at D_0 days, kPa

K = 480 A_w for granular soils and 70 A_w for fine grain soil

A_w = cement content, % by mass

Nagaraj and Miura (1996) have conducted unconfined compression tests on 4 inland clays, which have different liquid limits and obtained the generalized relation is of the form:

$$\frac{q_D}{q_{14}} = a + b \ln D \tag{2.12}$$

where q_D is the D day strength, q_{14} is the 14-day strength at initial liquid limit water content. It is reported that a = -0.20 and b = 0.458 for inland clays.

Yamadera et al. (1997) have further investigated the strength development with time of three different marine Ariake clays at their liquid limit. They found that a = 0.190 and b = 0.299.

2.4.2 Grain Size Distribution

The soluble products of cement hydration cause the electrolytic concentration of pore pressure and pH value to increase. The dissolved bivalent calcium ions (Ca^{++}) replace the monovalent ions, which are normally attracted to the surface of the negatively charged clay particles (Assarson et al., 1974). The crowding of (Ca^{++}) ions onto the surface of the clay particles brings about the flocculation of the clay (Herrin and Mitchell, 1961). The flocculation can also be brought by the hydration of cement, resulting in a charge of coarser grain size distribution of the soil particles.

2.4.3 Plasticity

The plastic limit of the soil generally increases with the cement content, while the plasticity index reduces. The liquid limit on the other hand is not affected or is only slightly affected. As a result, the shear strength is increased, while the compressibility is reduced (Broms, 1986).

Miura et al. (2001) have explained the change of the plasticity based on the microstructural consideration. The liquid limit state is the state that the microfabric would have been formed thus the addition of cement would not alter the liquid limit as long as the liquid limit is determined within the initial setting of cement. On the contrary, when the dry clay is mixed with water to be closer to plastic limit along with cement, it would exhibit the property of modified soil. Due to the formation of clay clusters, which can hold water caused by the cementation, the plastic limit would increase. As a result, the liquidity index, *LI* of the clay-cement mixture immediately after mixing with cement would increase since the plasticity index is used as the denominator while the clay water content insignificantly changes.

The results reported by Uddin et al. (1997) reinforce the above postulation. The change in the liquid limit due to the treatment is insignificant. On the other hand, the plastic limit significant increases with cement content and curing time. Thus, the decrease in plasticity index of the clay-cement mixture is recognized due to the significant increase in the plastic limit. The change in water content is minimal. As a result, the liquidity index is supposed to increase after adding cement admixture.

2.5 Strength development in lightweight cemented clay

For soft clay admixed with cement, the clay-water/cement ratio, w_c/C was proved as the prime parameter governing engineering properties (Miura et al., 2001; Horpibulsuk and Miura, 2001 and Horpibulsuk et al., 2005). Horpibulsuk et al. (2003; 2011a and b, 2012a) successfully employed this parameter to develop a generalized strength equation based on Abrams' law (Abrams, 1918). The equation is useful for laboratory mix design. This parameter was also successfully used to predict the strength development in cement stabilized coarse-grained soils compacted on the wet side of optimum water content that the degree of saturation is higher than 80% (Horpibulsuk et al. 2006 and Chinkulkijniwat and Horpibulsuk, 2012). Consoli et al. (2007) extended the clay-water/cement ratio hypothesis to analyze the strength development in compacted (unsaturated) cement-stabilized sand at a particular water content. They proposed a key parameter taking the role of air bubble in pore space (void) on the strength development into account. The parameter is designated as void/cement ratio, V/C and is defined as the ratio of absolute volume of void (water and air) to absolute volume of cement of the compacted sand. It was proved that the compression and shear behaviors of cmented sand at a particular water content are governed by *V*/*C* (Rios et al., 2012; Consoli et al., 2012a and b). Horpibulsuk et al. (2012b) successfully employed the parameter *V*/*C* to analyze the strength and compressibility characteristics of lightweight cemented clays with various swelling potentials. Based on the Abrams' law, the strength equation for lightweight cemented clays at a particular water content was proposed (Figure 2.3):

$$q_u = \frac{A}{(V/C)^B} \tag{2.13}$$

where q_u is the unconfined compressive strength, and A and B are constants. This equation if without the air content yields the same equation for cement admixed clays proposed by Horpibulsuk et al. (2011a, b and 2012a). To employ Eq. (1) for assessing the strength of any lightweight cemented clay at different void/cement ratios (air content and cement content), the parameters A and B must be predetermined. This task can be achieved by a back-calculation of at least two trial strength data. Based on the equation, Horpibulsuk et al. (2012b) suggested a mix design method to attain the target strength and unit weight for a given water content.

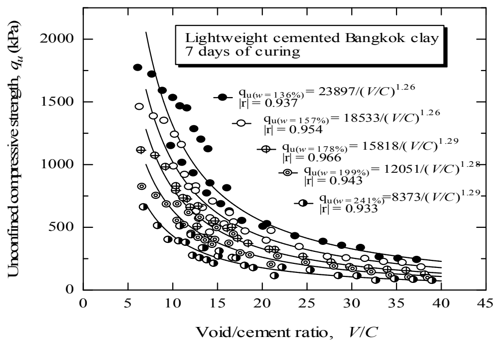


Figure 2.3 Analysis of strength development in lightweight cemented Bangkok clay using *V*/*C* (Horpibulsuk et al., 2012b).

2.6 Reference

Abrams D.A. 1918. Design of Concrete Mixtures. In: **Structural Materials Research Laboratory, Lewis Institute, Chicago, Bulletin** 1, 20p.

Burland J.B., 1990. On the compressibility and shear strength of natural soils. **Géotechnique** 40 (3), 329-378.

Butterfield, R., 1979. A natural compression law for soils (an advance on *e*-log *p′*). **Geotechnique** 29 (4), 469-480.

Consoli, N.C., Foppa, D., Festugato, L. and Heineck, K.S., 2007. Key parameters for strength control of artificially cemented soils. **Journal of Geotechnical and Geoenvironmental Engineering ASCE** 133 (2), 197-205.

Freudelund, T.E. and Aaboe, R., 1993. Expanpolystylene-A light way across soft ground. Proceedings of 14th **International Conference of Soil Mechanics and Geotechnical Engineering. New Delhi, India**, pp. 1256-1261.

Hayashi, Y., Suzuki, A. and Matsuo, A., 2002. Mechanical properties of air-cement-treated soils. **Ground Improvement** 6 (1), 69-78.

Horpibulsuk, S. and Miura, N., 2001. A new approach for studying behavior of cement stabilized clays. Proc. 15th **International Conference on Soil Mechanics and Geotechnical Engineering (ISSMGE). Istanbul, Turkey**, Vol. 3, pp. 1759-1762.

Horpibulsuk, S., Bergado, D.T. and Lorenzo, G.A., 2004a. Compressibility of cement admixed clays at high water content. **Geotechnique** 54 (2), 151-154.

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

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

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

Horpibulsuk, S., Rachan, R. and Suddeepong, A., 2011a, Assessment of strength development in blended cement admixed Bangkok clay. **Construction and Building Materials** 25 (4), 1521-1531.

Horpibulsuk, S., Katkan, W., Sirilerdwattana, W. and Rachan, R., 2006. Strength development in cement stabilized low plasticity and coarse grained soils: Laboratory and field study. **Soils and Foundations** 46 (3), 351-366.

Horpibulsuk, S., Liu, M.D., Liyanapathirana, D.S. and Suebsuk, J., 2010. Behavior of cemented clay simulated via the theoretical framework of the Structured Cam Clay model. **Computers and Geotechnics** 37, 1-9.

Horpibulsuk, S., Phojan, W., Chinkulkijniwat, A., and Liu, M.D., 2011b. Strength development in blended cement admixed saline clay. **Applied Clay Science**.

Horpibulsuk, S., Rachan, R., Suddeepong, A. and Chinkulkijniwat, A., 2011c. Strength development in cement admixed Bangkok clay: laboratory and field investigations. **Soils and Foundations** 51 (2) 239-251.

Horpibulsuk S, Shibuya S, Fuenkajorn K, and Katkan W., 2007. Assessment of engineering properties of Bangkok clay. **Canadian Geotechnical Journal** 44 (2), 173-187.

Horpibulsuk, S., Yangsukaseam, N., Chinkulkijniwat, A., and Du, Y.J., 2011d. Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. **Applied Clay Science** 52, 150-159.

Jamnongpipatkul, P., Dechasakulsom, M, and Sukolrat, J., 2009. Application of air-foam stabilized soil for bridge-embankment transition zone in Thailand. **GeoHuman International Conference, Geotechnical Special Publication** No.190, pp.181-193.

Kamon, M. and Bergado, D.T., 1992. Ground improvement techniques. Proceedings of 9th **Asian Regional Conference on Soil Mechanics and Foundation Engineering**. Vol.2, pp.526-546.

Kawasaki, T., Niina, A., Saitoh, S., Suzuki, Y. and Honjo, Y., 1981. Deep mixing method using cement hardening agent. Proceedings of 10^{th} International **Conference on Soil Mechanics and Foundation Engineering. Stockholm**, pp.721-724.

Kikuchi, Y., Nagatome, T., Mizutani, T., and Yoshio, H., 2011. The effect of air foam inclusion on the permeability and absorption of light weight soil. **Soils and Foundations** 51 (1), 151-165.

Liu M.D. and Carter J.P., 1999. Virgin compression of structured soils. **Géotechnique** 49 (1), 43-57.

Liu M.D. and Carter J.P., 2000. Modelling the destructuring of soils during virgin compression. **Géotechnique** 50 (4), 479-483.

Liu M.D. and Carter J.P., 2002. Structured Cam Clay Model. **Canadian Geotechnical Journal** 39 (6), 1313-1332.

Miki, H., Mori, M. and Chida, S., 2003. Trail embankment on soft ground using lightweight-foam-mixed in-situ surface soil. Proceedings of 22^{nd} **PIARC World Road Congress. Durban**.

Mitchell , J.K., 1993. **Fundamentals of Soil Behavior**. New York: John Wiley&Sons, Inc.

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

Nagaraj, T.S., Pandian, N.S. and Narasimha Raju, P.S.R., 1993. Stress state-permeability relationships for fine-grained soils. **Geotechnique** 43 (2), 333-336.

Otani, J., Mukunoki, T. and Kikuchi, Y., 2002. Visualization for engineering property of in-situ lightweight soils with air foams. **Soils and Foundations** 42 (3), 93-105.

Prakash, K. and Sridharan, A., 2004. Free swell ratio and clay mineralogy of fine-grained soils. **Geotechnical Testing Journal** ASTM 27 (2), 220-225.

Russell, E.R. and Mickle, J.L., 1970. Liquid limit values of soil moisture tension. **Journal of Soil Mechanics and Foundation Engineering Division** ASCE 96, 967-987.

Satoh, T., Tsuchida, T., Mitsukuri, K. and Hong, Z., 2001. Field placing test of lightweight treated soil under seawater in Kumamoto port. **Soils and Foundations** 41 (4), 145-154.

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

Suebsuk, J., Horpibulsuk, S. and Liu, M.D., 2010. Modified Structured Cam Clay: A constitutive model for destructured, naturally structured and artificially structured clays. **Computers and Geotechnics** 37, 956-968.

Suebsuk, J., Horpibulsuk, S. and Liu, M.D., 2011. A critical state model for overconsolidated structured clays. **Computers and Geotechnics** (in press).

Tsuchida, T., Porbaha, A. and Yamane, N., 2001. Development of a geomaterial from dredge bay mud. **Journal of Material in Civil Engineering ASCE** 13 (2), 152-160.

Terashi, M., Tanaka, H. and Okumura, T., 1979. Engineering properties of lime treated marine soils and DMM. Proceedings of 6th **Asian Regional Conference on Soil Mechanics and Foundation Engineering**, Vol. 1, pp. 191-194.

Terashi, M., Tanaka, H., Mitsumoto, T., Niidome, Y., and Honma, S., 1980. Fundamental of lime and cement treated soils. **Report of Port and Harbour Research Institute**, Vol. 19, No. 1, pp. 33-62 (in Japanese).

Whyte, I.L., 1982. Soil plasticity and strength – a new approach using extrusion. **Ground Engineering** 15 (1), 16-24.

Wroth, C.P. and Wood, D.W., 1978. The correlation of index properties with some basic engineering properties of soils. **Canadian Geotechnical Journal** 15 (2), 137-145.

Yasuhara, K., 2002. Recent Japanese experiences with lightweight geomaterials**.** **Proceedings of International Workshop on Lightweight Geomaterial**, pp.32-59.

CHAPTER III

UNIT WEIGHT, FLOWABILITY AND STRENGTH OF LIGHTWEIGHT CELLULAR CEMENTED CLAY

3.1 Introduction

When infrastructures such as road embankments and bridge foundations are constructed on soft soil deposits, several geotechnical engineering problems are encountered. These deposits tend to consolidate and undergo large vertical settlement and lateral deformation during and after construction due to incumbent loads. The problems become more related to short-term and long-term stability when an unexpected loading (e.g. earthquake) is imposed on the structures and soft ground system. The use of lightweight cellular cemented materials with unit weight of 8 to 12 kN/m^3 and moderate to high strength as a backfill material to reduce the weight of the structure on the soft clay is an effective ground improvement technique.

This chapter aims to illustrate the impact of water, cement, and air contents and fly ash (FA) replacement on the three main engineering properties of lightweight cellular cemented clay: unit weight, flowabilty and strength. The stress state (state of water content) suitable for making the lightweight cellular cemented clay for different FA replacement ratios is determined. The V/C is employed to analyze the strengthdevelopment in lightweight cellular cemented clay at different FA replacement ratios. Practical (simple and rational) equations to determine the flow and strength are proposed based on the critical analysis, a suggested design procedure to attain the target strength, flow and unit weight is finally introduced.

3.2 Materials and methods

3.2.1 Soil Samples

Bangkok claywas collected from Bangkok Noi district, Bangkok, Thailand at a 3 meter depth. The clay was composed of 2% sand, 39% silt and 55% clay.The natural water content was 78% and the specific gravity was 2.64. The liquid and plastic limits were 73% and 31%, respectively. Based on the Unified Soil Classification System (USCS), the clay was classified as inorganic clay of high plasticity (CH). Groundwater was had a depth of about 1.0 m from surface. The clay was classified as low swelling type with free swell ratio (FSR) of 1.1. The FSR is defined as the ratio of equilibrium sediment volume of 10 g of oven-dried soil passing a 425 mm sieve in distilled water (V_d) to that in kerosene (V_k) (Prakash and Sridharan, 2004). This method was employed since it is simple and predicts the dominant clay mineralogy of soil satisfactorily (Horpibulsuk et al., 2007).

3.2.2 Cement and air foam agent

Type I Portland cement (PC) and air foam agent,Darex AE4, provided by the Grace Construction Products Ltd, were used in this study. Grain size distribution curve of PC is also shown in Figure 3.1. The curve was obtained from the laser particle size analysis. The specific gravity is 3.15 and the D50 of PC is 0.01 mm (10 micron), which is larger than that of the tested clay. The air foam agent is a blend of anionic surfactants and foam stabilizers. It is a liquid air entraining agent for use in all types of mortar, concrete and cementitious material.

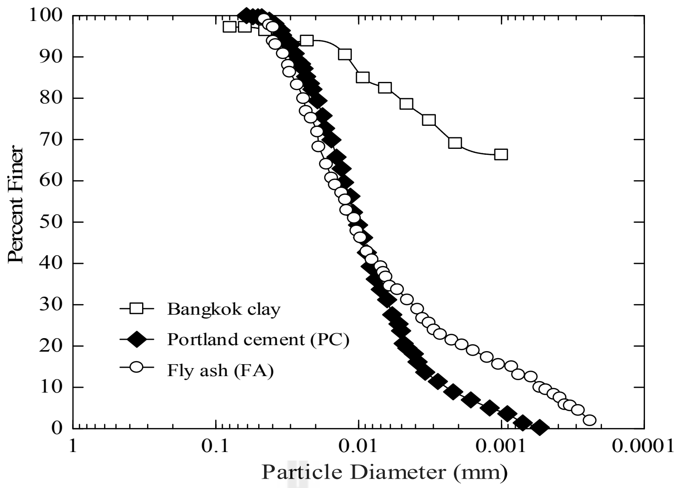


Figure 3.1 Grain size distribution of Bangkok clay, PC and FA.

3.2.3 Fly ash

Fly ash (FA) was obtained from the Mae Moh power plant in the north of Thailand. Table 3.1 summarizes the chemical composition of FA using X-ray fluorescence (XRF). Total amount of the major components SiO_2, Al_2O_3 and Fe_2O_3 in FA are 81.48%. The grain size distribution curve of the FA is also shown in Figure 3.1

3.2.4 Methodology

The clay paste was passed through 2-mm sieve for removal of shell pieces and other bigger size particles, if present and was replaced by FA with the replacement ratios of 0, 40, 60, and 80% dry weight of clay. Index tests on the mixed soil were then performed. The water content of the mixed soil was adjusted to (2-3)w_L for the flow and strength tests. The lower water content possesses high viscosity and resists the air bubble entry into the pore space (Horpibulsuk et al., 2012b). The mixed soil was mixed with air foam. The air contents, *Ac*, were varied between 10 and 100% by volume of the saturated mixed soil, *Vi*. The *Vi*value is the sum of volume of dry soil, *Vs* and volume of water, *Vw*. The *Vs* value was determined from the dry weight of mixed soil, Ws and specific gravity values of mixed soil and water. The clay-water-air-FA mixture was then thoroughly mixed with cement for 10min. The cement content, *C*, was varied from 10 to 30% by weight of dry soil. To verify the role of *V/C* as a prime parameter governing the strength development, the lightweight cellular cemented samples with different cement contents and air contents were also prepared to attain the *V/C* values of 50, 30 and 20. Such a uniform paste was transferred to a flow test container to measure the flowabilityand to cylindrical containers of 50mm diameter and 100 mm height for strength test. After 24 hours, the cylindrical samples were dismantled. The cylindrical samples were wrapped in vinyl bags and stored in a humidity room of constant temperature (20±2°C) until lapse of different curing times as planned. Unconfined compression (UC) tests were run on samples after 7 days of curing. The rate of vertical displacement in UC tests was 1mm/min. The tests were performed according to the American Society of Testing and Materials (ASTM) standards.

3.3 Results

The index properties of clay-FA mixture at different FA replacement ratios are shown in Figure 3.2

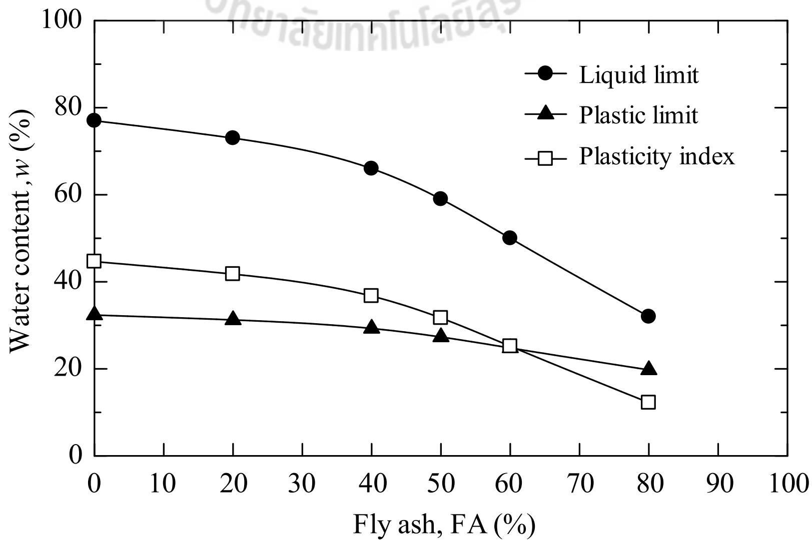


Figure 3.2 Index properties of clay-FA mixture.

Liquid limit decreases with increasing FA replacement. When the FA replacement ratio is greater than 50%, the decrease in liquid limit, w_L, is clearly observed. Plastic limit, w_P, decreases with small magnitude as the FA replacement ratio increases. Consequently, the change in plasticity index, I_p, and liquid limit, w_L with FA replacement is similar where the sudden change is found at about 50% FA replacement. The sharp change in I_p was designated as FA fixation point (Horpibulsuk et al., 2013b). It is of interest to note that even with the change in w_L and wp, the (I_p, w_L) points for all the mixed soils lie above the A-line (vide Figure 3.3), indicating that the mixed soil is classified as clay according to the Unified Soil Classification System (USCS).

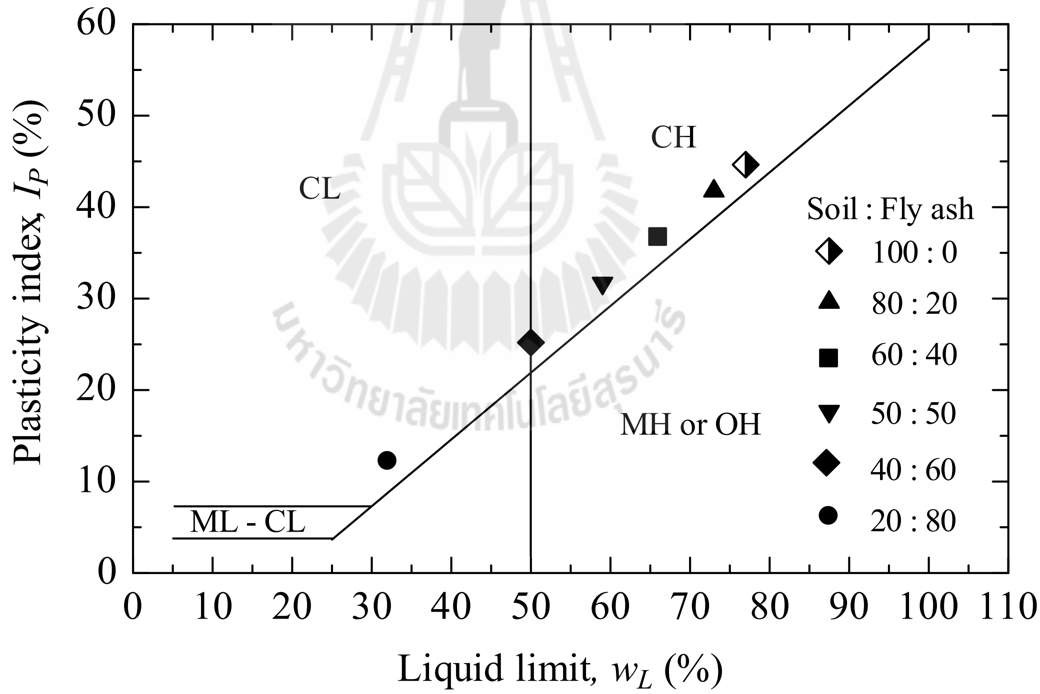


Figure 3.3 State of water content of clay-FA mixture compared with A-line

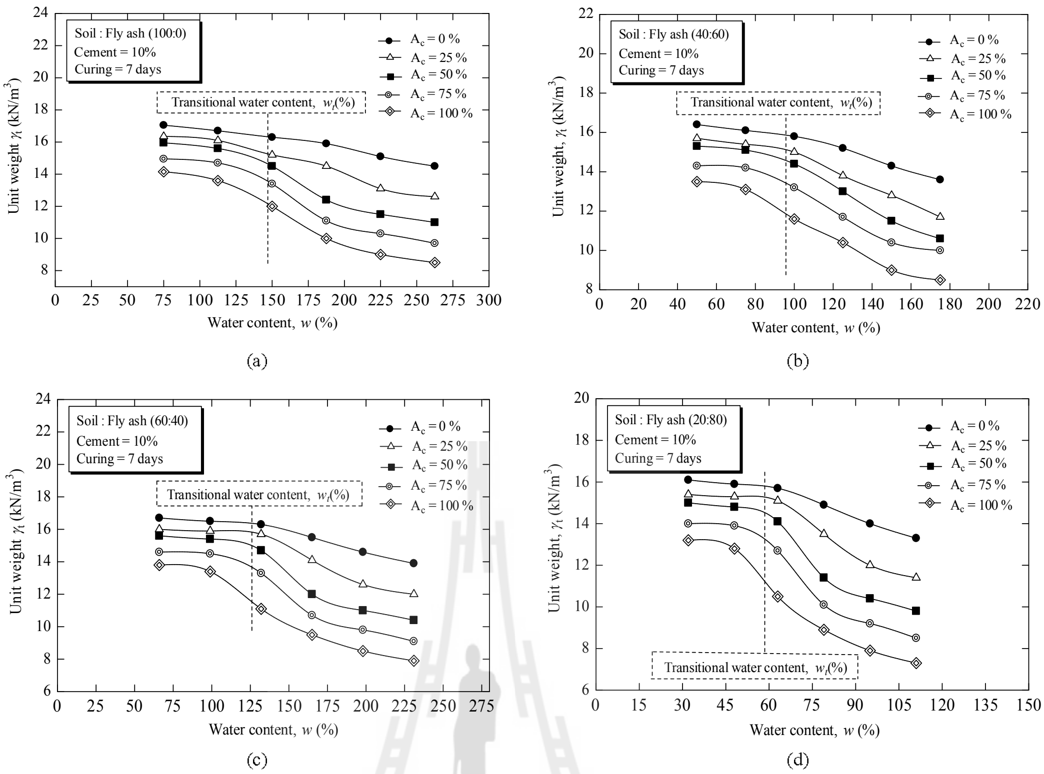


Figure 3.4 Relationship between unit weight and water content at different air contents.

Figure 3.4 shows the effect of water content and air content on the unit weight of the lightweight cellular cemented samples at different FA replacement ratios for a particular cement content of 10%. The air foam significantly decreases unit weight of the lightweight cellular cemented material, especially at high water contents. For a particular air content, the unit weight decreases as the water content increases. However, the decrease in unit weight is insignificant at low water contents. Beyond a certain water content designated as transitional water content, a dramatic reduction in unit weight is observed. The transitional water content, w_t, is essentially identical for different air contents as long as the FA replacement ratio is the same. The reduction in $w_t$with the FA replacement ratio for different cement contents and air contents is depicted by Figure 3.5.

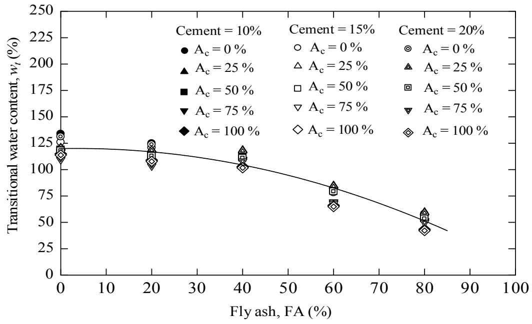


Figure 3.5 Relationship between transitional water content and FA replacement for different air contents and cement contents.

The effect of cement content, air content, water content and FA replacement ratio on the flowabilty of lightweight cellular cemented clay is shown in Figures 3.6 and 3.7.Figure 3.6 shows that for a particular FA replacement, water content and air content, the cement content affects insignificantly the flowability. The role of the air content on the flowbility is essentially the same for different water contents and cement contents i.e., the increase in flowablity with an increment of the air content is essentially the same.

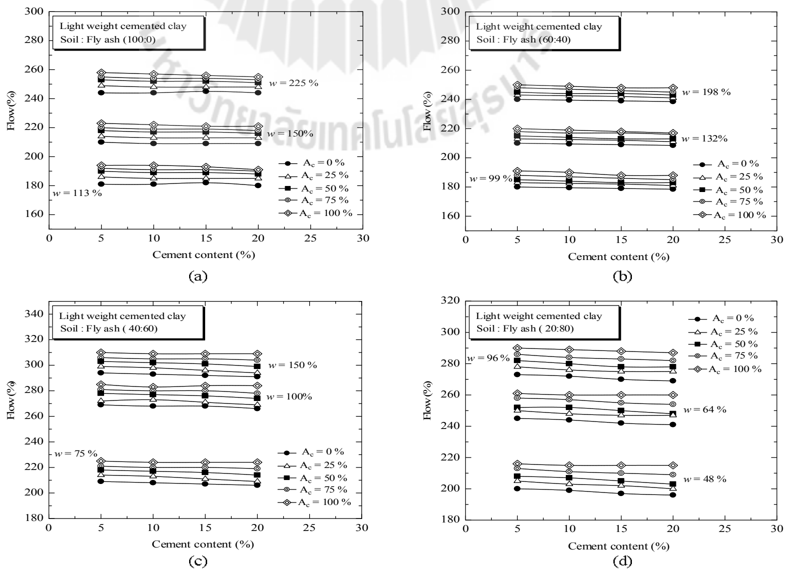


Figure 3.6 Relationship between flowablity and cement content for different replacement ratios.

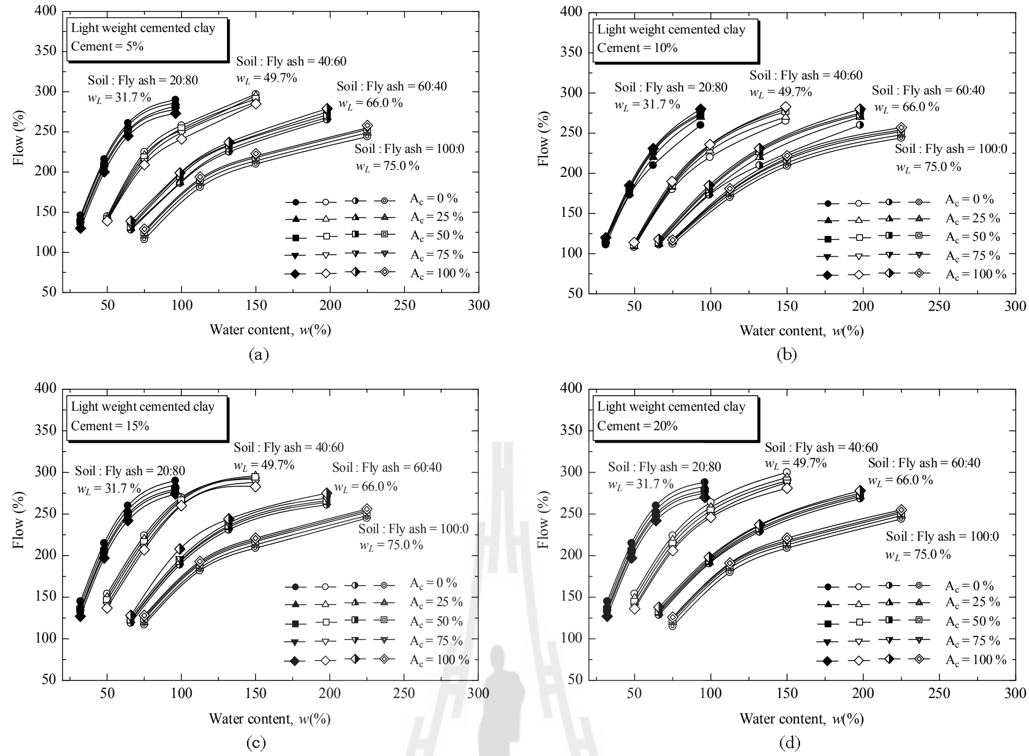


Figure 3.7 Relationship between flowablity and water content for different replacement ratios.

The water content is the main parameter, governing the flowability for a particular FA replacement, i.e. the significant increase in flowablity is clearly observed with increasing water content. The relationship between flowability and water content is in the same manner for different cement contents, FA replacement ratios and air contents as shown in Figure 7. The incremental change in the flowablity is significant at low water content and the change rate approaches zero for very high water content. This is a fact that the ideal highest flowability for the lightweight cellular cemented clay is a constant and equal to that for pure water.

It is now to examine the strength development in lightweight cellular cemented clay. The strength of lightweight cemented clay at a particular water content is dependent upon the air content and cement content (Horpibulsuk et al., 2012b). It was proved that the combined effect of air content and cement content on the stress-strain-strength characteristics is taken into account by the parameter *V/C*. The parameter *V/C* is herein extended to analyze the stress-strain-strength characteristics of lightweight cellular cemented clay for different FA replacement ratios. Figure 8 shows the stress-strain relationships in unconfined compression tests of samples with different air contents and cement contents but with the same *V/C* values of 20, 30 and 50, at 7days of curing. Three different FA replacement ratios are included in the figure, which are 40, 60 and 80%. As the*V/C* value decreases, the cementation bond strength increases and hence strength. Thelightweight cellular cemented samples with the same *V/C*values exhibit the similar stress-strain behavior. To conclude, the *V/C* controls compressive strength for a particular water content and can be applied to lightweight cellular cemented clay samples with a wide range of FA replacement ratios.

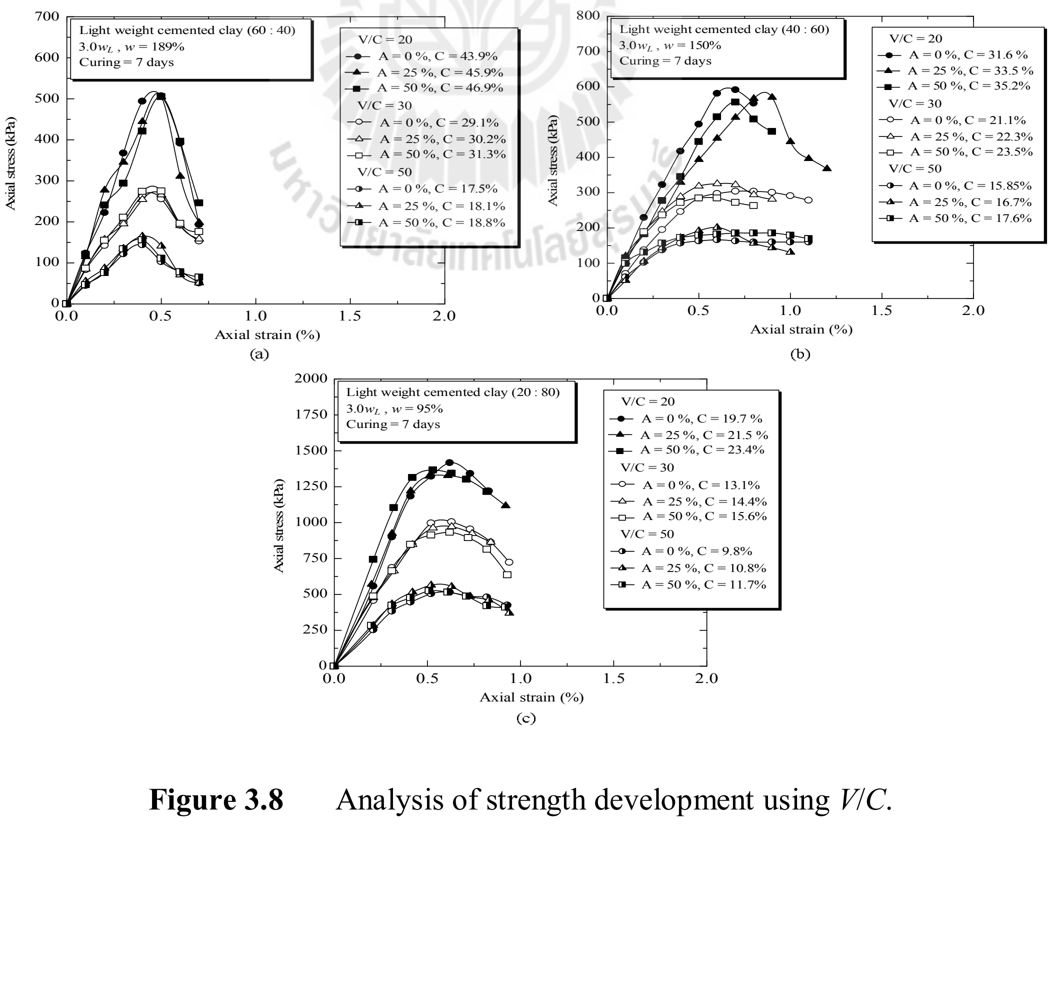


Figure 3.8 Analysis of strength development using *V/C*.

3.4 Analysis and discussion

Even though the index properties of the clay-FA mixture alters with the FA replacement ratios, the clay-FA mixture is still classified as clay according the USCS (vide Figure 3.3). Because FA is a non-plasticity material, the plasticity index of the clay-FA mixture decreases with an increase in the FA replacement ratio. Due to the reduction in wL with the FA replacement ratio, the mixture approaches low plasticity index clay (CL) as the FA replacement ratio increases. The engineering properties of destructured (remolded) clay are governed by the stress state reflected by the liquid limit water content. Liquid limits of clays have the same order of pore water suction (5 – 6 kPa) (Russell and Mickle, 1970; Wroth and Wood, 1978; and Whyte, 1982). Under this state, most clays exhibit hydraulic conductivity of the same order of 10-9 m/sec (Nagaraj et al., 1993 and Horpibulsuk et al., 2007) and the undrained shear strength of about 1.7 – 2.5 kPa (Wroth and Wood, 1978; and Whyte, 1982). Nagaraj and Miura (2001) depicted that different clays at the same generalized stress state, w/w_Lhave practically the same effective stress and shear resistance. As the w/wL decreases, both the effective stress and shear resistance increase (Horpibulsuk et al., 2011c). The w/w_L is thus used to analyze the role of FA replacement on the engineering properties of lightweight cemented clay in this study. This ratio was successfully used to assess the engineering properties of remolded and natural clays (Horpibulsuk et al., 2007 and 2011c).

The stress state suitable for making the lightweight cellular cemented clay is referred to as the transitional water content, w_t (vide Figure 4) where the air content plays a significant role on the reduction in unit weight. The FA-clay mixtures with different FA replacement ratios but with same water content exhibit different values of shear strength and viscosity, i.e. the mixture with lower w_L possess lower shear strength and viscosity.

This causes the reduction in w_t value as FA replacement ratio increases (vide Figure 5). The $w_t$value for different FA replacement ratios can be approximated in terms of w_L as shown in Figure 3.9. The variation in wt/wL values is in a small range between 1.3 and 1.6 with an average value of 1.5, irrespective of cement content and air content. The water content higher than $1.5w_L$ is thus recommended for producing the lightweight cellular cemented clay in practice for different cement contents, air contents and FA replacement ratios. This stress state is designated as the workable state where the clay viscosity is low enough for the air foam to enter into the pore space.

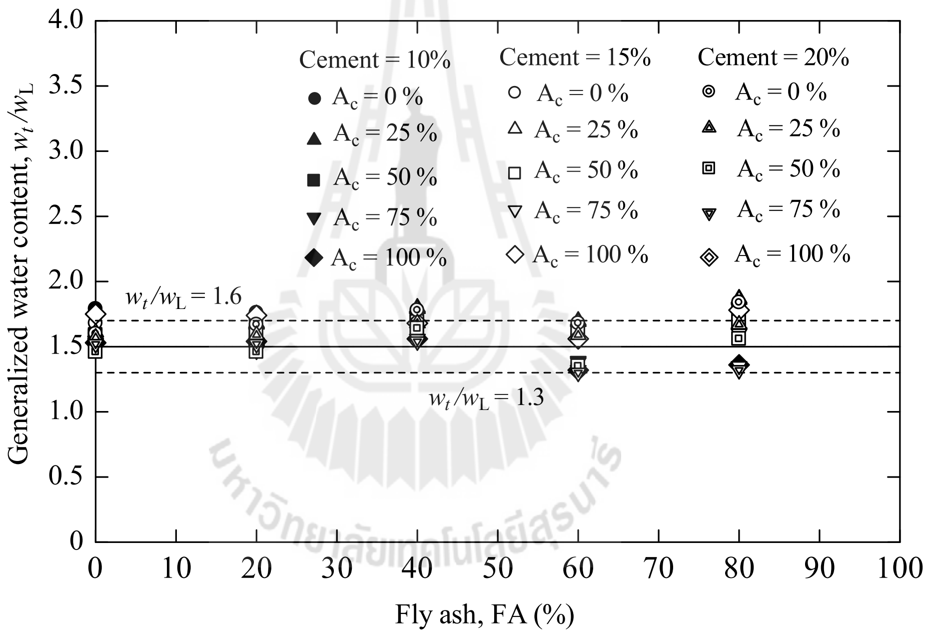


Figure 3.9 Determination of w_t in terms of w_L.

In addition to the workable state, the flowability is controlled by the shear strength and viscosity. In other words, the generalized stress state is possibly employed to analyze the flowablity of the lightweight cellular cemented clay. Figure 3.7 shows the relationship between flowability and water content of the lightweight cellular cemented samples from four replacement ratios. The flowability versus water content relation is approximately logarithmic and the cement content insignificantly affects the flowability.

It is noted that for the same air content, the flowability of the lightweight cellular cemented samples can be the same even though the water contents are different. At liquid limit state, the flowability of the lightweight cellular cemented clay with different FA replacement ratios yield essentially the same value of 100-150% depending upon air content. This implies that for a particular Ac, the viscosity and shear strength responsible for the same order of flowability are of the same, despite the water contents being distinctly different. This possibility is depicted when the flowability and water content relationship is normalized by the respective liquid limit water content (vide Figure 3.10).

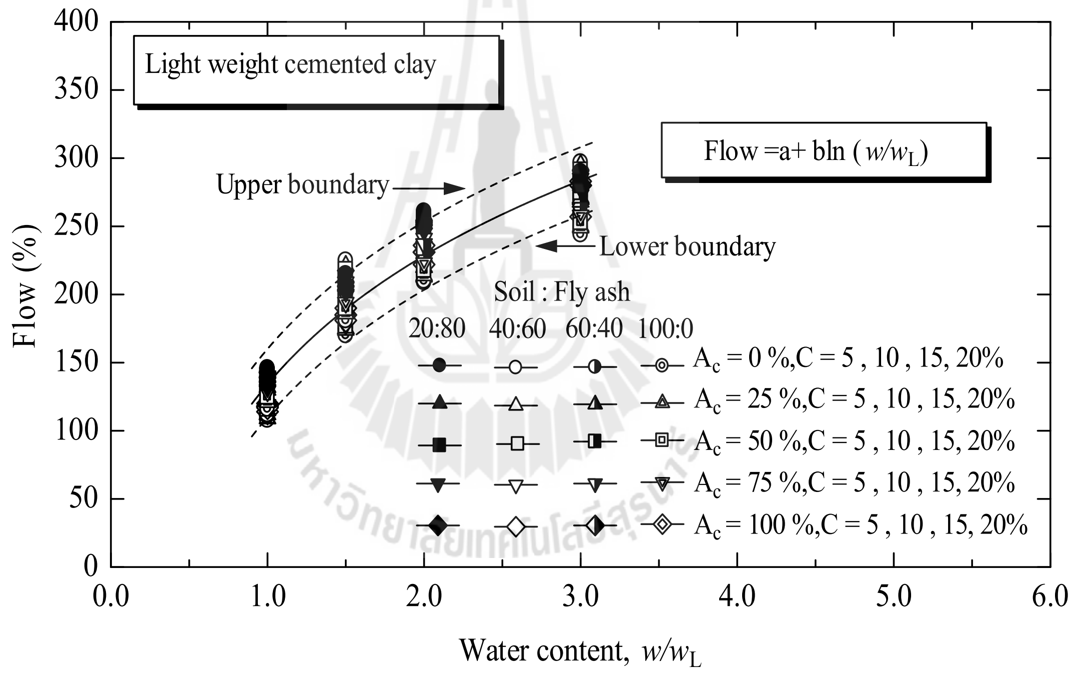


Figure 3.10 Analysis of flowability based on the generalized stress state.

For the practical assessment, a logarithmic relationship for a particular air content obtained from the linear regression analysis is introduced as follows:

$$F = a + b\log\frac{w}{w_L} \tag{3.2}$$

where F is the flowability and a and b are constant. It is observed from Figure 3.10 that the flowability for a given w/w_L increases with air content. Consequently, the a and b values are approximated in terms of air contents.

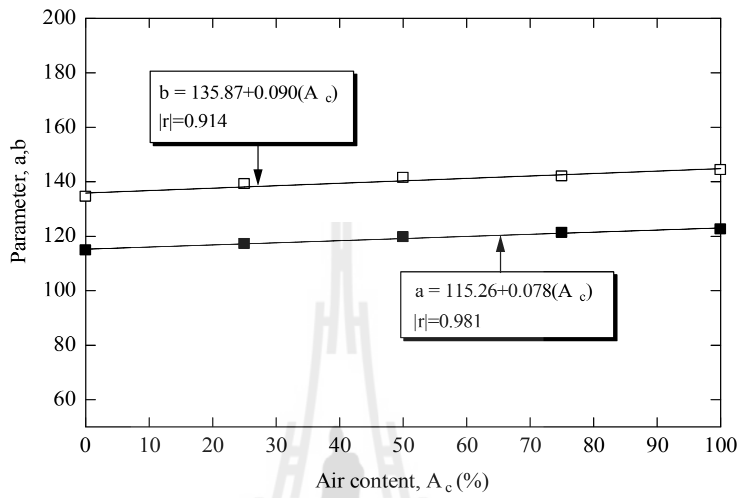


Figure 3.11 Determination of a and b values in terms of *Ac*.

Figure 3.11 presents the relationship between a and b values versus *Ac*:

$$a = 115.26 + 0.078A_c \tag{3.3}$$

$$b = 135.87 + 0.090A_c \tag{3.4}$$

with degrees of correlation of higher than 0.914. Equations (3.2) to (3.4) show that at workable state (w/w_L = 1.5), the flowability is 139% and 149% for Ac = 0% and 100%, respectively. The above analysis shows that workability and flowability of the lightweight cellular cemented clay is improved by the reduction in w_L caused by the FA replacement. The significant reduction rate is found when FA replacement exceeds the FA fixation point (50%). In other words, the FA replacement ratios less than the FA fixation point do not improve the workability and flowability of the lightweight cellular cemented clay but reduce the unit weight due to lower specific gravity as seen by Eq. (3.1). Because the workable state is at w/w_L of greater than 1.5, the investigation of the influence of FA replacement ratio on the strength development in the lightweight cellular cemented clay is illustrated in Figure 12 at w/w_L values of 2 and 3. It has been extensively reported that the strength development of structured clays in both natural and artificial states (Mitchell, 1993; Kasama et al., 2000; Kavvadas and Amorosi, 2000; Rouainai and Muir Wood, 2000; Baudet and Stallebrass, 2004; Lee et al, 2004; Miura et al., 2001; Horpibulsuk et al., 2003, 2005, 2010, 2011a, 2012a; Suebsuk et al., 2010 and 2011) is governed by microstructure (fabric and inter-particle forces). The strength is thus depended upon the FA replacement ratio, which affects wL of the clay-FA mixture (initial state of lightweight cellular cemented clay).

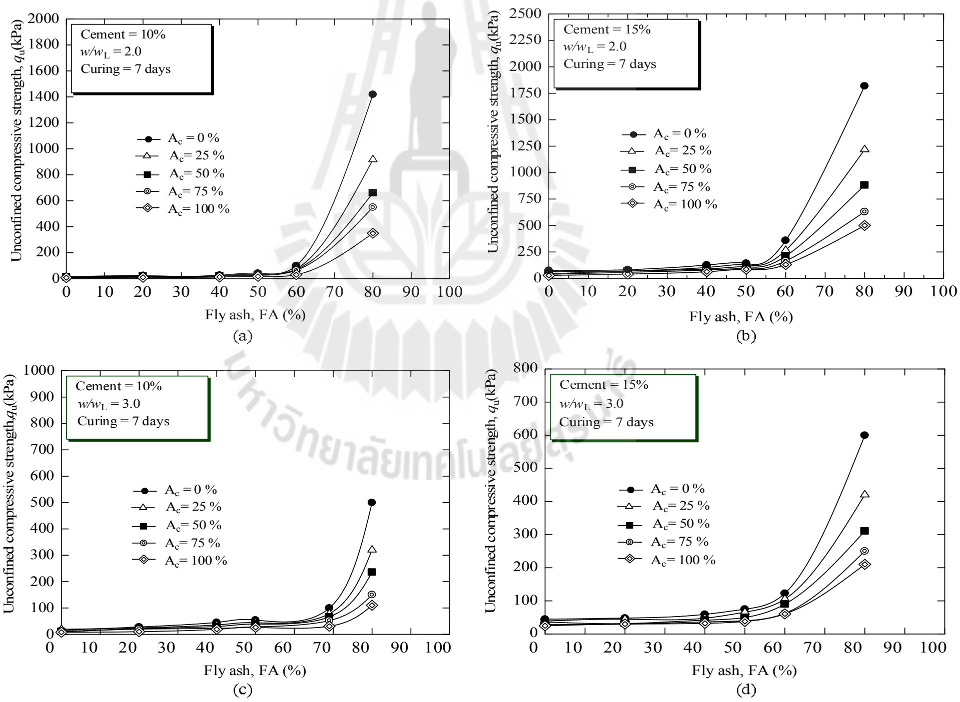


Figure 3.12 Role of FA replacement on the strength development in lightweight cellular cemented clay.

The effect of the FA replacement ratio on the strength of lightweight cellular cemented samples for C = 10% and 15% is shown in the figure. The strength increases with FA replacement ratio. Beyond the FA fixation point, the strength increases remarkably. It is of interest to mention that the advantage of FA replacement on the workability, flowability and strength is realized when the FA replacement ratios are greater than the FA fixation point.

Because the *V/C* is the prime parameter governing the strength development, it is possible to develop arelationship between strength and *V/C* for a particular curing time.

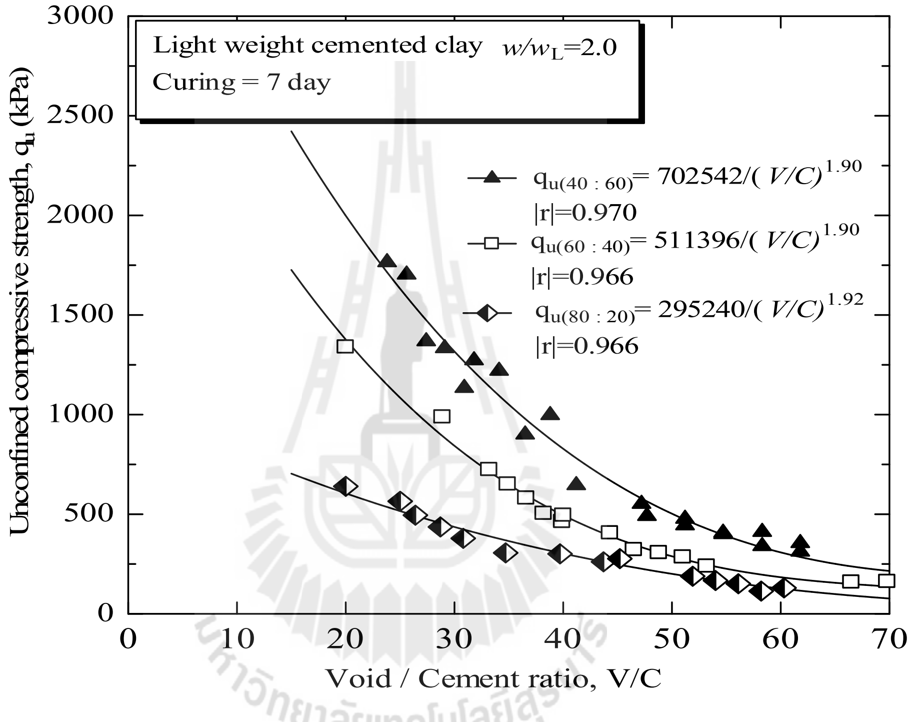


Figure 3.13 Strength development with *V/C*.

Figure 3.13 shows the relationship between 7-day strength and *V/C*of the lightweight cellular cementedBangkok clay for different FA replacement ratios as an example to guarantee the applicability of the *V/C*. For a particular FA replacement ratio, the unique relationship between the strength and the *V/C* can be found for a given w/w_L value of 2 at different cement contents and air contents. Based on the experimental observations (20 <*V/C*< 65 and 7 days of curing), it is possible to advance the following identity:

$$\left\{\frac{V_1}{C_1}\right\} = \left\{\frac{V_2}{C_2}\right\} = \text{Constant} \tag{3.5}$$

Once the void/cement ratio is fixed in the field at the working state (w/w_L> 1.5), if the air content (void volume) is changed to achieve the required unit weight, the cement content can be estimated from Eq.(3.4) to attain the same strength. For a mix design purpose, the relationship between unconfined compressive strength, qu and *V/C* at a certainwater contentis advanced on the basis of Abrams' law (1918).

$$q_u = \frac{A}{(V/C)^B} \tag{3.6}$$

where A and B are constants. This equation when *Ac* = 0 yields the same equation proposed by Horpibulsuk et al. (2011a, b and 2012a) for cement admixed clays. The A-value is dependent upon the FA replacement ratio. The B-value is practically constant and equal to 1.90 to 1.92, irrespective of FA replacement ratios. To employ Eq. (3.6) for assessing the strength of the lightweight cellular cemented clay at different *V/C* values (Ac and C values), the A and B values must be predetermined. This task can be achieved by a back-calculation of at least two trial strength data.

It is logical to relate the elastic properties with unconfined compressive strength because they are governed by the *V/C*.

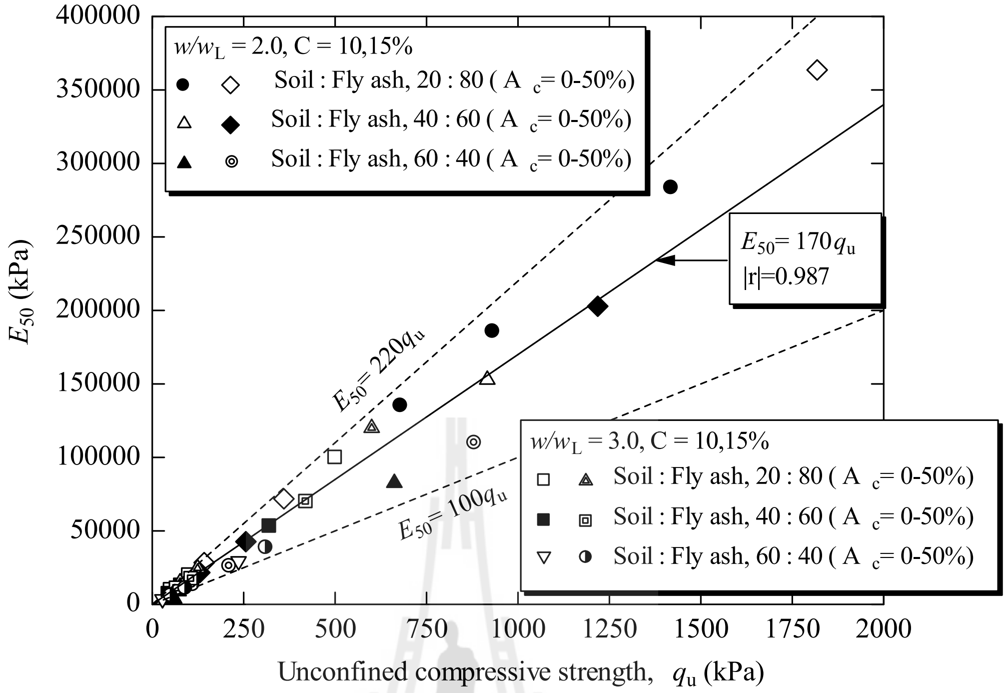


Figure 3.14 Relationship between E_{50} and q_u of lightweight cellular cemented clay.

Figure 3.14 shows the relationship between modulus of deformation at 50% strength, E50 and unconfined compressive strength for cement admixed clay (without air foam) and lightweight cellular cemented clay. The E50 varies between 100 and 220 times qu for different values of *Ac*, C and FA replacement. The relationship is in agreement with that previously reported by Horpibulsuk et al. (2012b) for various lightweight cellular cemented clays (without FA replacement).

3.5 Suggested mix design method

Based on the laboratory investigation, a mix design procedure for lightweight cellular cemented Bangkok clay to arrive at the target unit weight, flowability and strength is suggested and presented by the following steps: in Figure 3.15

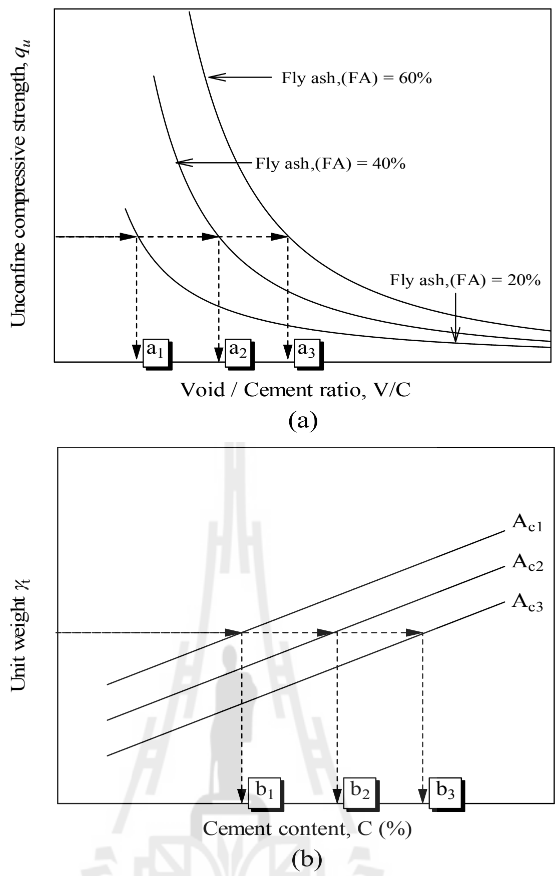


Figure 3.15 Mix design procedure.

3.5.1 Perform index tests on FA-clay mixture at different FA replacement ratios and determine the FA fixation point. FA replacement ratios of greater than the FA fixation point are recommended.

3.5.2 Adjust the water content of the FA-clay mixture to the working state (w/w_L> 1.5) and determine the flowability using Eqs.(3.2) to (3.4).

3.5.3 For a selected water content, conduct at least two trail unconfined compression tests on the lightweight cellular cemented samples with different FA replacement ratios, cement contents and air contents.

3.5.4 Determine the A- and B-values from the back calculation of the strength data.

3.5.5 Develop the q_u-*V/C* relationship for different FA replacement ratios using Eq.(3.6) (vide Figure 3.15a).

3.5.6 From the target strength, determine the required *V/C* at a selected FA replacement ratio (point a1, a2 and a3, respectively in Figure 3.15a).

3.5.7 Develop the unit weight and cement content relationship for different air contents using Eq.(3.1) (vide Figure 3.15b).

3.5.8 From the target unit weight, determine the required Ac at selected C (point b1, b2 and b3, respectively in Figure 3.15b).

3.5.9 Perform cost estimate for different possible mix ingredient to obtain the optimal mix ingredient.

3.6 Conclusions

Results of this study suggest that the generalized stress state, w/w_L is critical for analysis of unit weight, flowability and strength characteristics of lightweight cellular cemented Bangkok clay. The void/cement ratio, *V/C* takes into account the influence of both clay fabric reflected by the air volume and the level of cementation. The conclusion can be drawn as follows.

3.6.1. The clay viscosity prevents the air entry into the clay slurry. FA replacement reduces the clay viscosity for a given water content by reducing w_L. The water content equal to 1.5 w_L is proved as the optimum water content for producing the lightweight cellular cemented Bangkok clay and regarded as the working state.

3.6.2. The flowability of the lightweight cellular cemented clay is strongly dependent upon the clay viscosity. The clay viscosity for a particular water content reduces as the decrease in w_L and the increase in A_c while it is insignificantly affected by the cement content. The flowability is approximated in terms of air content and w/w_L.

3.6.3. For a given soft clay at a particular water content, the cementation bond strength increases *V/C* decreases. Consequently, the compressive strength increases with the decrement of *V/C*. The stress-strain response is practically the same as long as the *V/C* value is identical.

3.6.4. The advantage of FA replacement on the workability, flowability and strength is observed when the FA replacement ratio is greater than FA fixation point. The FA fixation point is simply obtained from the conventional index test.

3.6.5. Because the *V/C* controls the engineering properties in the elastic range (at low effective confining stress), it is logical to relate the E_{50} in terms of q_u. The E_{50} and q_u relationship is found to be essentially independent of cement content, water content, air content and FA replacement ratio.

3.6.6. Based on the void/cement ratio and Abrams' law, a relationship between strength, void/cement ratio for a particular water content and curing time (Eq.6) is proposed. The relationship is useful in estimating the laboratory strength wherein air content and cement content vary over a wide range by a few trial tests. It also facilitates the determination of proper quantity of cement to be admixed for different air contents to attain the target strength. The formulation of the proposed relationship is on sound principle. The *A* and *B* values can be determined by a back-analysis of at least two trial strength data.

3.6.7. Based on the proposed strength, unit weight and flowability equations, the mix design method for the lightweight cellular cemented Bangkok clay is suggested. This method is useful for engineering practitioners in their design of lightweight cellular cemented clay and estimating the mechanical properties.

3.7 Reference

Abrams D.A. 1918. Design of Concrete Mixtures. In: **Structural Materials Research Laboratory, Lewis Institute**, Chicago, Bulletin 1, 20p.

Arulrajah, A., Abdullah, A., Bo, M.W. and Bouazza, A. 2009.**Ground improvement techniques for railway embankments.** Ground Improvement 162 (1), 3-14.

Baudet, B., Stallebrass, S., 2004. **A constitutive model for structured clays.Geotechnique** 54(4), 269-278.

Chai, J.C. and Pongsivasathit, S. 2010. A method for predicting consolidation settlements of floating column improved clayey subsoil. Front. Archit. Civ. Eng. 4 (2), 241-251.

Chinkulkijniwat, A. and Horpibulsuk, S. 2012Field strength development of repaired pavement using the recycling technique. **Quarterly Journal of Engineering Geology and Hydrogeology** 45 (2), 221-229.

Consoli, N.C., Foppa, D., Festugato, L. and Heineck, K.S., 2007. Key parameters for strength control of artificially cemented soils. Journal of Geotechnical and **Geoenvironmental Engineering ASCE** 133 (2), 197-205.

Consoli, N. C., Viana da Fonseca, A., Rios, S., Cruz, R. C. and Fonini, A., 2012a. Parameters controlling stiffness and strength of artificially cemented soils.**Géotechnique.d.o.i.**: 10.1680/geot.8.P.084.

Consoli, N. C., Cruz, R. C., Viana da Fonseca, A. and Coop, M. R., 2012b. Influence of cement-voids ratio on stress-dilatancy behavior of artificially cemented sand.

Journal of Geotechnical and Geoenvironmental Engineering, ASCE, d.o.i.: 10.1061/(ASCE)GT.1943-5606.0000565.

Hayashi, Y., Suzuki, A. and Matsuo, A., 2002. Mechanical properties of air-cement-treated soils. **Ground Improvement** 6 (1), 69-78.

Horpibulsuk, S. and Miura, N., 2001. A new approach for studying behavior of cement stabilized clays. Proc. 15th International Conference on Soil Mechanics and **Geotechnical Engineering (ISSMGE).** Istanbul, Turkey, Vol. 3, pp. 1759-1762.

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

Horpibulsuk, S., Bergado, D.T. and Lorenzo, G.A., 2004a. Compressibility of cement admixed clays at high water content. **Geotechnique** 54 (2), 151-154

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

Horpibulsuk, S., Miura, N., Koga, H. and Nagaraj, T.S. 2004c.Analysis of strength development in deep mixing – a field study.**Ground Improvement** 8 (2), 59-68.

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

Horpibulsuk, S., Katkan, W., Sirilerdwattana, W. and Rachan, R., 2006. Strength development in cement stabilized low plasticity and coarse grained soils: Laboratory and field study. **Soils and Foundations** 46 (3), 351-366.

Horpibulsuk S, Shibuya S, Fuenkajorn K, and Katkan W., 2007.Assessment of engineering properties of Bangkok clay. **Canadian Geotechnical Journal** 44 (2), 173-187.

Horpibulsuk S, Rachan R, and Raksachon Y. 2009. Role of fly ash on strength and microstructure development in blended cement stabilized silty clay. **Soils and Foundations** 49 (1), 85-98.

Horpibulsuk, S., Liu, M.D., Liyanapathirana, D.S. and Suebsuk, J., 2010. Behavior of cemented clay simulated via the theoretical framework of the Structured Cam Clay model. **Computers and Geotechnics** 37, 1-9.

Horpibulsuk, S., Rachan, R. and Suddeepong, A., 2011a, Assessment of strength development in blended cement admixed Bangkok clay. **Construction and Building Materials** 25 (4), 1521-1531.

Horpibulsuk, S., Rachan, R., Suddeepong, A. and Chinkulkijniwat, A., 2011b. Strength development in cement admixed Bangkok clay: laboratory and field investigations. **Soils and Foundations** 51 (2), 239-251.

Horpibulsuk, S., Yangsukaseam, N., Chinkulkijniwat, A., and Du, Y.J., 2011c. Compressibility and permeability of Bangkok clay compared with kaolinite and bentonite. **Applied Clay Science** 52, 150-159.

Horpibulsuk, S., Phojan, W., Chinkulkijniwat, A., and Liu, M.D., 2012a. Strength development in blended cement admixed saline clay. **Applied Clay Science** 55, 44-52.

Horpibulsuk, S., Suddeepong, A., Chinkulkijniwat, A., and Liu, M.D., 2012b.Strength and compressibility of lightweight cemented clays.**Applied Clay Science** 69, 11-21.

Horpibulsuk, S., Chinkulkijniwat, A., Cholphatsorn, A., Suebsuk, J., and Liu, M.D. 2012c. Consolidation behavior of soil cement column improved ground. **Computers and Geotechnics** 43, 37-50.

Horpibulsuk, S., Suddeepong, A. and Chinkulkijniwat, C. 2013a.A key parameter for strength control of lightweight cemented clay.Proceedings of 18th **International Soil Mechanics and Geotechnical Engineering**, Paris.

Horpibulsuk, S., Wijitchot, A., Neramitkornburee, A., Shen, S.L. 2013b.Factors influencing unit weight and strength of lightweight cemented clay.**Quarterly Journal of Engineering Geology and Hydrogeology**.

Horpibulsuk, S., Rachan, R. Suddeepong, A., Liu, M.D. and Du, Y.J. 2013c.Compressibility of lightweight cemented clays.**Engineering Geology**, 159, 59-66.

Jamnongpipatkul, P., Dechasakulsom, M, and Sukolrat, J., 2009. Application of air-foam stabilized soil for bridge-embankment transition zone in Thailand. GeoHuman International Conference, **Geotechnical Special Publication** No.190, pp.181-193.

Kamon, M. and Bergado, D.T., 1992.Ground improvement techniques.Proceedings of 9th **Asian Regional Conference on Soil Mechanics and Foundation Engineering**.Vol.2, pp.526-546.

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

Kavvadas M., Amorosi A., 2000. A constitutive model for structured soils.**Géotechnique** 50 (3), 263-273.

Kawasaki, T., Niina, A., Saitoh, S., Suzuki, Y. and Honjo, Y., 1981.Deep mixing method using cement hardening agent.Proceedings of 10th **International Conference on Soil Mechanics and Foundation Engineering.Stockholm**, pp.721-724.

Kehew, EA. (1995). Geology for Engineers and Environmental Scientists, 2nd Ed. **Prentice Hall Englewood Cliffs, New Jersey**, pp.295-302.

Kikuchi, Y. and Nagatome, T., 2011. Durability of cement treated clay with air foam used in water front structures. **Proceedings of Geo-Shanghai 2010, ASCE Special Publication** No.207, June 2-5, 2010, China, pp.1-30.

Kikuchi, Y., Nagatome, T., Mizutani, T., and Yoshio, H., 2011.The effect of air foam inclusion on the permeability and absorption of light weight soil. **Soils and Foundations** 51 (1), 151-165.

Kitazume M, Yamazaki H., Tsuchida T., 2001. Recent soil admixture stabilization techniques for port and harbor constructions in Japan – deep mixing method, premix method, light-weight method.**Proceedings of International Seminar on Geotechnics in Kochi, Kochi, Japan**, pp.23-40.

Lee, K., Chan D., Lam K., 2004. Constitutive model for cement treated clay in a critical state framework. **Soils and Foundations** 44(3), 69-77.

Liu M.D. and Carter J.P., 1999.Virgin compression of structured soils.**Géotechnique** 49 (1), 43-57.

Liu M.D. and Carter J.P., 2000.Modelling the destructuring of soils during virgin compression.**Géotechnique** 50 (4), 479-483.

Mitchell , J.K., 1993.Fundamentals of Soil Behavior. New York: John Wiley&Sons, Inc.

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

Nagaraj, T.S. and Miura, N. 2001. Soft Clay Behaviour – Analysis and Assessment. A.A.Balkema, Netherlands.

Nagaraj, T.S., Pandian, N.S. and NarasimhaRaju, P.S.R., 1993. Stress state-permeability relationships for fine-grained soils. **Geotechnique** 43 (2), 333-336.

Otani, J., Mukunoki, T. and Kikuchi, Y., 2002. Visualization for engineering property of in-situ lightweight soils with air foams. **Soils and Foundations** 42 (3), 93-105.

Prakash, K. and Sridharan, A., 2004. Free swell ratio and clay mineralogy of fine-grained soils. **Geotechnical Testing Journal ASTM** 27 (2), 220-225.

Rios, S., Viana da Fonseca, A. and Baudet B. A., 2012.The effect of the porosity/cement ratio on the compression of cemented soil. **Journal of Geotechnical and Geoenvironmental Engineering, ASCE**, d.o.i.: 10.1061/(ASCE)GT.1943-5606.0000698.

Rouainia M., Muir Wood, D., 2000. A kinematic hardening model for natural clays with loss of structure.**Géotechnique** 50(2), 153-164.

Russell, E.R. and Mickle, J.L., 1970. Liquid limit values of soil moisture tension. **Journal of Soil Mechanics and Foundation Engineering Division** ASCE 96, 967-987.

Satoh, T., Tsuchida, T., Mitsukuri, K. and Hong, Z., 2001.Field placing test of lightweight treated soil under seawater in Kumamoto port. **Soils and Foundations** 41 (4), 145-154.

Suebsuk, J.,Horpibulsuk, S. and Liu, M.D., 2010. Modified Structured Cam Clay: A constitutive model for destructured, naturally structured and artificially structured clays. **Computers and Geotechnics** 37, 956-968.

Suebsuk, J., Horpibulsuk, S. and Liu, M.D., 2011. A critical state model for overconsolidated structured clays. **Computers and Geotechnics** 38, 648-658.

Tsuchida, T., Porbaha, A. and Yamane, N., 2001.Development of a geomaterial from dredge bay mud. **Journal of Materials in Civil Engineering ASCE** 13 (2), 152-160.

Terashi, M., Tanaka, H. and Okumura, T., 1979. Engineering properties of lime treated marine soils and DMM. Proceedings of 6th **Asian Regional Conference on Soil Mechanics and Foundation Engineering**, Vol. 1, pp. 191-194.

Terashi, M., Tanaka, H., Mitsumoto, T., Niidome, Y., and Honma, S., 1980. Fundamental of lime and cement treated soils. **Report of Port and Harbour Research Institute**, Vol. 19, No. 1, pp. 33-62 (in Japanese).

Whyte, I.L., 1982. Soil plasticity and strength – a new approach using extrusion.**Ground Engineering** 15 (1), 16-24.

Wroth, C.P. and Wood, D.W., 1978.The correlation of index properties with some basic engineering properties of soils. **Canadian Geotechnical Journal** 15 (2), 137-145.

CHAPTER IV

DURABILITY AGAINST WET-DRY CYCLES OF LIGHTWEIGHT CELLULAR CEMENTED CLAY

4.1 Introduction

The investigation of durability against the wetting – drying cycles (w-d cycles), a critical aspect for infrastructure design such as in engineering fills and pavements, is very limited and is the prime focus of this research. The w-d cycles results in tension and surface cracks, which can damage the stabilized pavement structure. The investigation of the service life of the LCC clay via wetting and drying test is significant and is another focus of this research. The compressive strength of the LCC clay at various number of cycles is investigated and analyzed in this chapter to ascertain its performance in construction applications. The strength of LCC clay is dependent upon the cemented soil structure (fabric and cementation bond). As such, tests with a wide range of water contents, air contents, FA contents and cement contents of the LCC clay are undertaken to understand the role of both fabric and cementation bond on the w-d cycle strengths. Based on the analysis of the test results, a rational empirical relationship between w-d cycle strengths and initial soaked strength (without w-d cycles) is proposed. This equation can facilitate the determination of a suitable mix proportion of LCC materials to meet the strength requirement at a target service life.

4.2 Theoretical background

For a LCC clay at water content being between 1.5 and 3.0 times liquid limit, the strength is determined exclusively by the parameter water-void to cement, *w*V/C

(Horpibulsuk et al., 2014b). This parameter is defined as the product of initial clay water content (before mixing with cement and air foam) times *V/C*, where the water content is expressed in decimal. The parameter *V/C* is defined as the ratio of volume of void to the volume of cement in the mix. Strength is independent of water content, air content and cement content in the mix. Based on extensive test results, Horpibulsuk et al. (2014b) have proposed a predictive strength equation in term of curing time, and wV/C for the LCC Bangkok clay as follows:

$$\left\{\frac{q_{(wV/C)_D}}{q_{(wV/C)_{28}}}\right\}=\left[\frac{(wV/C)_{28}}{(wV/C)_D}\right]^{1.27}(0.027+0.300\ln D) \tag{4.1}$$

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

4.3 Materials and methods

4.3.1 Soil Sample

Bangkok clay was collected from Bangkok Noi district, Bangkok, Thailand at a 3 meter depth. The clay was composed of 2% sand, 39% silt and 55% clay as shown in Figure 4.1

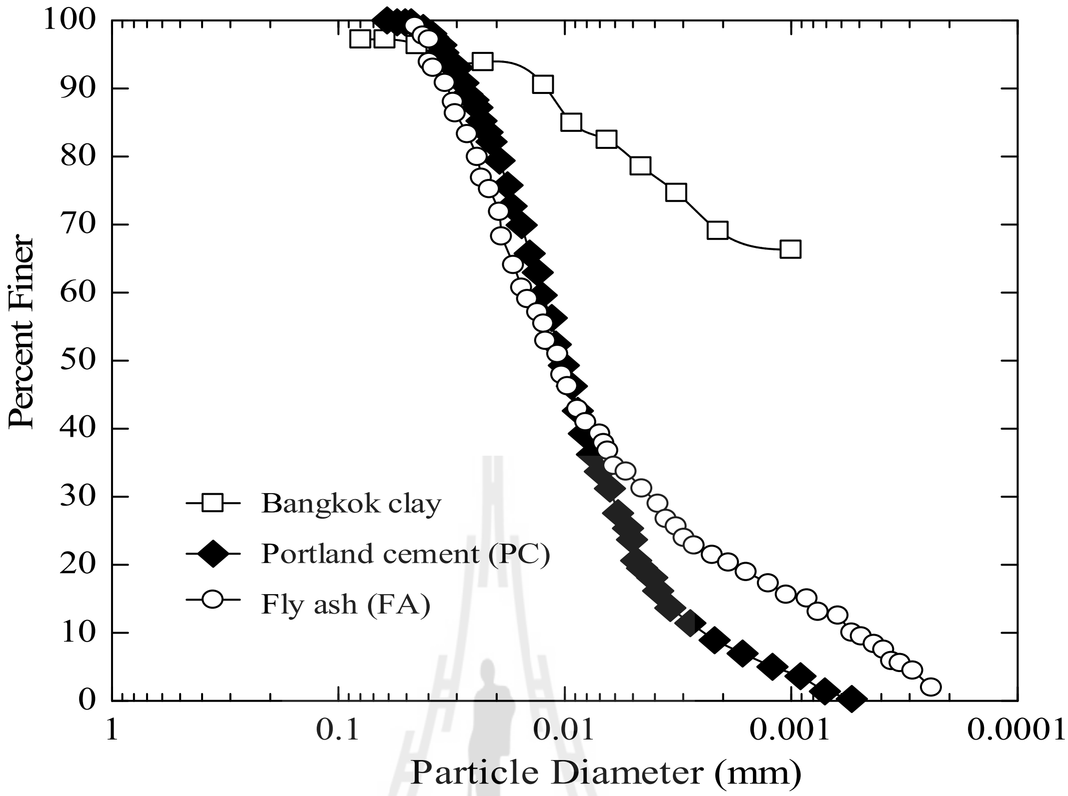


Figure 4.1 Grain size distribution of clay, PC, and FA.

The natural water content was 80% and the specific gravity was 2.64. The liquid and plastic limits were 73% and 31%, respectively. Based on the Unified Soil Classification System (USCS), the clay was classified as inorganic clay of high plasticity (CH). Groundwater was at a depth of about 1.0 m from surface. The clay was classified as low swelling type with free swell ratio (FSR) of 1.1. The FSR is defined as the ratio of equilibrium sediment volume of 10 g of oven-dried soil passing a 425 mm sieve in distilled water (V_d) to that in kerosene (V_k) (Prakash and Sridharan, 2004). This method was employed since it is simple and predicts the dominant clay mineralogy of soil satisfactorily (Horpibulsuk et al., 2007). Table 4.1 summarizes the chemical composition of Bangkok clay using X-ray fluorescence (XRF).

Table 4.1: Chemical composition of Bangkok clay, PC and FA.

Chemical composition (%)	Bangkok clay	PC	FA
SiO_2	62.8	20.9	44.7
Al_2O_3	21.3	4.8	23.7
Fe_2O_3	8.4	3.4	11.0
CaO	0.9	65.4	12.7
MgO	1.5	1.2	2.6
SO_3	1.2	2.7	1.3
Na_2O	0.3	0.2	0.1
K_2O	2.5	0.3	2.9
LOI	0.8	1.1	1.0

4.3.2 Cement and air foam agent

Type I Portland cement (PC) and air foam agent, Darex AE4, provided by the Grace Construction Products Ltd, were used in this study. The grain size distribution curve, obtained from the laser particle size analysis, and chemical composition of PC are also shown in Figure 4.1 and Table 4.1, respectively. The specific gravity is 3.15 and the D_{50} is 0.01 mm (10 micron), which is larger than that of the tested clay. The air foam agent is a blend of anionic surfactants and foam stabilizers. It is a liquid air entraining agent used in various types of mortar, concrete and cementitious material.

4.3.3 Fly ash

Fly ash (FA) was obtained from the Mae Moh power plant in the north of Thailand. Table 4.1summarizes the chemical composition of FA showing that total amount of the major components SiO2, Al2O3 and Fe2O3 in FA are 79.4% and classified as class F. The grain size distribution curve of the FA is also shown in Figure 4.1

4.3.4 Methodology

The clay paste was passed through 2-mm sieve for removal of shell pieces and other larger size particles, if present and was replaced by FA at replacement ratios of 0, 20, 60 and 80% dry weight of clay. Index tests on the mixed soil were performed afterward. The index properties of the tested clay at different FA replacement ratios are given in Table 4.2

Table 4.2: Water contents and liquid limits for mixed clay samples

Soil : FA	Liquid limit	Plastic limit	Plasticity index
100 : 0	77.1	32.4	44.7
80 : 20	72.8	31.2	41.6
60 : 40	66.1	27.3	38.8
40 : 60	50.2	24.8	25.4
20 : 80	32.1	19.8	12.3

The water content of the mixed soil was adjusted to 1.5 to 3 times liquid limit (w_L) for the w-d cycle strength tests. The saturated clay was carefully transferred into a mixer and then tamped to minimize air bubbles before mixing with cement and air foam. The lower water content possesses high viscosity and resists the air bubble entry into the pore space (Horpibulsuk et al., 2012a and 2013). The clay-water-FA mixture was mixed with air foam. The air content (Ac) values varied between 0 and 50% by volume of the saturated mixed soil (Vi). The Vi value is the sum of volume of dry soil (Vs) and volume of water (Vw).

The Vs value was determined from the dry weight of mixed soil (Ws) and specific gravity values of mixed soil and water. The clay-water-air-FA mixture was then thoroughly mixed with cement for 10 minutes. The cement content (C) was varied from 10 to 40% by weight of dry soil. The uniform paste was next transferred to cylindrical containers of 50 mm diameter and 100 mm height for w-d strength test. After 24 hours, the cylindrical samples were dismantled. The cylindrical samples were wrapped in vinyl bags and stored in a humidity room of constant temperature (23±2°C) until 28 days of curing.

Following is a summary of the method of cyclic wetting and drying test (ASTM D 559). The samples were submerged in deionized water at room temperature for 5 hours. They were then dried in the oven at a temperature of 70oC for 48 hours and air-dried at room temperature for at least 3 hours. This process is referred to as 1 w-d cycle. After attaining the target w-d cycles, the samples were immersed in deionized water for 2 hours at the constant temperature of 25±2°C. Unconfined compression (UC) tests were then run with a rate of vertical displacement of 1 mm/min. The 1, 3 and 6 w-d cycles were considered in this study.

Based on a critical analysis of the strength data, a rational predictive w-d cycle strength equation is proposed, which facilitates the mix design to attain the strength requirement at a specified service life for geotechnical and pavement practitioners. In addition to the above mentioned laboratory tests, the results of the strength tests on separate LCC samples at FA replacement ratios of 40% (w = 198 and 132%, and A = 0, 25 and 50%) were taken to verify the proposed predictive equation.

4.4 Results

Figure 4.2 shows the typical role of FA on w-d cycle strengths of LCC clay at different number of w-d cycles. All the samples were prepared at different water contents but at the same w/w_L of 2.0, C = 10% and A = 25% to have the same flowability of the LCC mixture, where w is water content and wL is liquid limit. It has been proved that at the same w/w_L, the LCC mixtures have the same flowability (Horpibulsuk et al., 2014a). Figure 4.2 shows that FA improves w-d cycle strength, qu(w-d), where significant improvement is clearly observed when FA replacement ratio is greater than 40%.

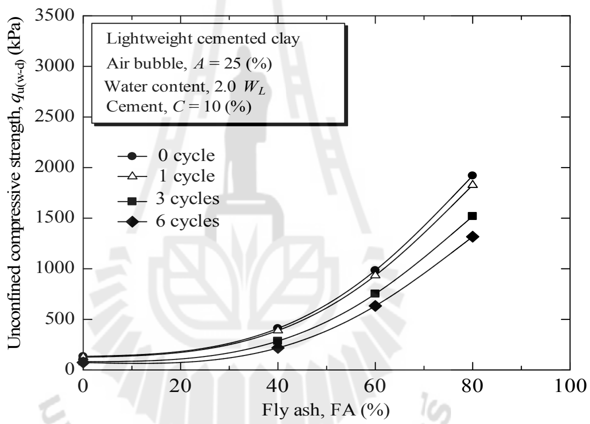
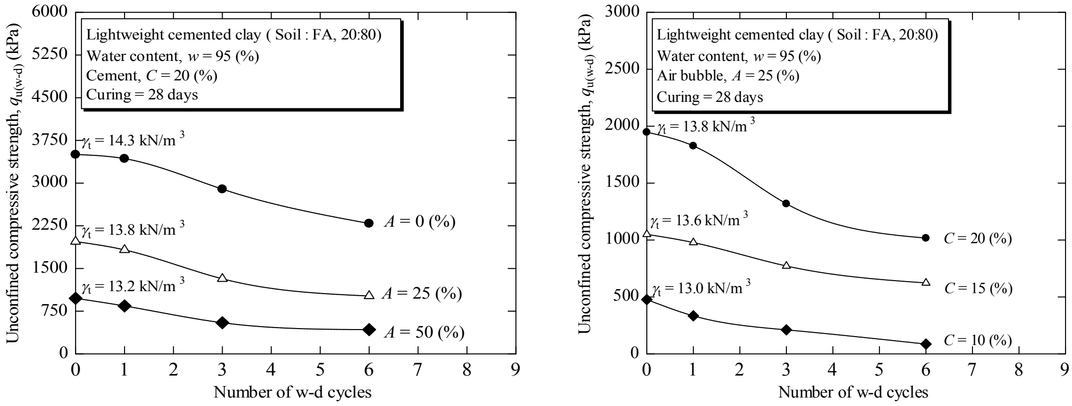
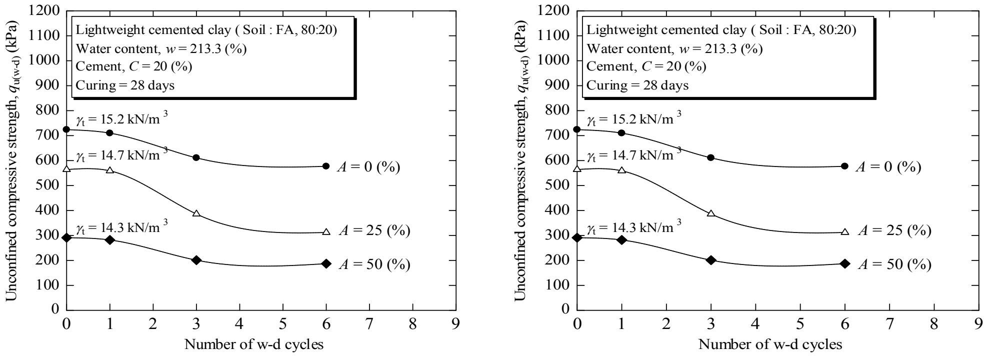


Figure 4.2 Influence of FA on w-d cycle strength.



a) Soil : FA = 20:80



b) Soil : FA = 80:20

Figure 4.3 Influence of cement content and air content on $q_{u(w\text{-}d)}$ for a) Soil : FA = 20:80 and b) Soil : FA = 80:20.

Figure 4.3 shows the role of cement content and air content on w-d cycle strength qu(w-d) for FA replacement of 20% and 80%. The unit weight decreases with increasing air content and decreasing cement content. Although the air foam helps reduce the unit weight of the LCC clay, it causes the strength reduction for a particular cement content. It is evident that the initial soaked (without w-d cycle) strengths (qu0) and w-d cycle strengths (qu(w-d)) decrease with decreasing cement content and increasing air content. For a particular air content, the strength increases significantly with increasing cement content even with slight increase in unit weight. The unit weight of LCC clay can practically be approximated from Eqs.(4.1) and (4.2) as successfully done by Horpibulsuk et al. (2014a). The qu(w-d) and N relationship of LCC clay is divided into three different cycles according to its slope. The strength reduction is minimal for the first 0-1 cycle while the dramatic reduction is noted in the 1-3 cycles. The strength reduction in 3-6 cycles is much larger than the 0-1 cycle but is lower than that of 1-3 cycles. For a particular water content, the qu0 and qu(w-d) values are controlled by cement content and air content.

It has been known from Figure 4.3 that both fabric (water content, air content) and cementation bond (cement content) affect the qu(w-d) of LCC clay. The lower water content and air content and the higher cement content results in the higher qu(w-d). It is now to examine the combination effect of both fabric and cementation bond on qu(w-d) using the structural parameter *wV/C*. Figure 4.4 shows the stress-strain relationship of LCC clay with the same *wV/C* of 29 but different C and A values at FA replacement ratio of 20.

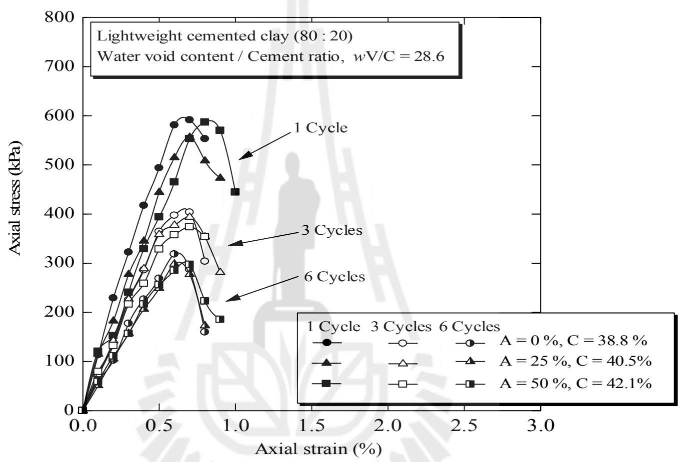


Figure 4.4 Stress-strain relationship for samples with the same *wV/C* of 29.

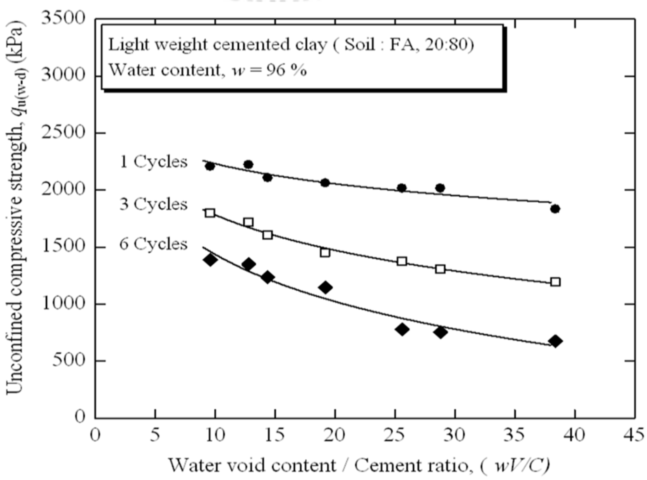


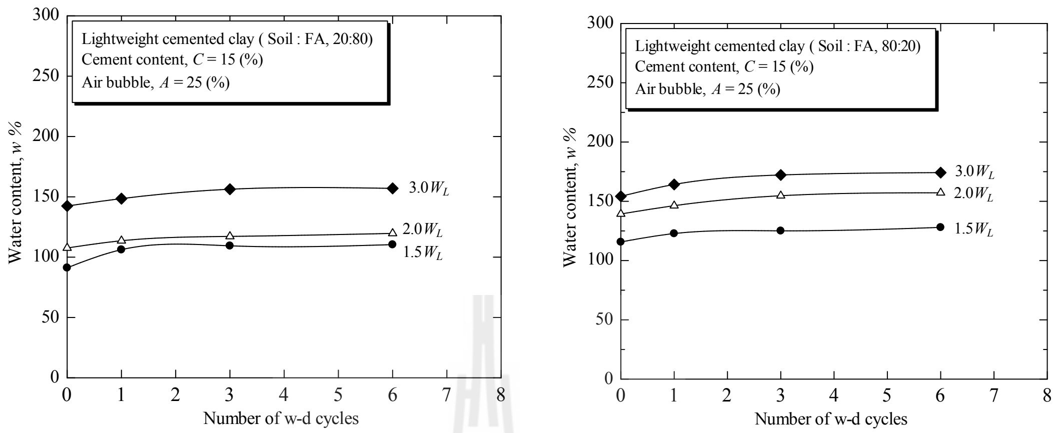
Figure 4.5 Relationship between $q_{u(w-d)}$ and *wV/C*.

Figure 4.5 shows the relationships between qu(w-d) and *wV/C* for the LCC samples with different C and A values. It is evident that the stress-strain relationships and w-d cycle strengths at the three number of cycles tested are essentially the same as long as *wV/C* is the same although the cement content and air content vary over a wide range. In other words, the durability against wetting and drying is dependent upon qu0 because the *wV/C* controls qu0 values of LCC clay. qu0 will be then used as an engineering indicator, indicating the structure strength of LCC clay, to analyze qu(w-d) in the next section.

4.5 Analysis and discussion

Besides unit weight and strength of the LCC material, the flowability of the mixture (before hardening) is also a required parameter for filed construction. The higher flowability results in the lower pump capacity and construction cost. The previous works (Horpibulsuk et al., 2014a and Neramitkornburi, 2014) have shown the flowability of the LCC mixture is controlled by w/w_L. Since the FA reduces wL of the clay-FA mixture (Table 4. 2), the water content, w of the mixture to attain the same w/w_L is reduced after adding FA. At the same w/w_L (Figure 2), the LCC mixture with higher FA replacement ratio exhibits higher qu0 and qu(w-d) due to the pozzolanic reaction between cement and FA and the reduction in water to cement ratio. Consequently, the FA improves not only the flowability of the LCC mixture but also the durability of LCC material.

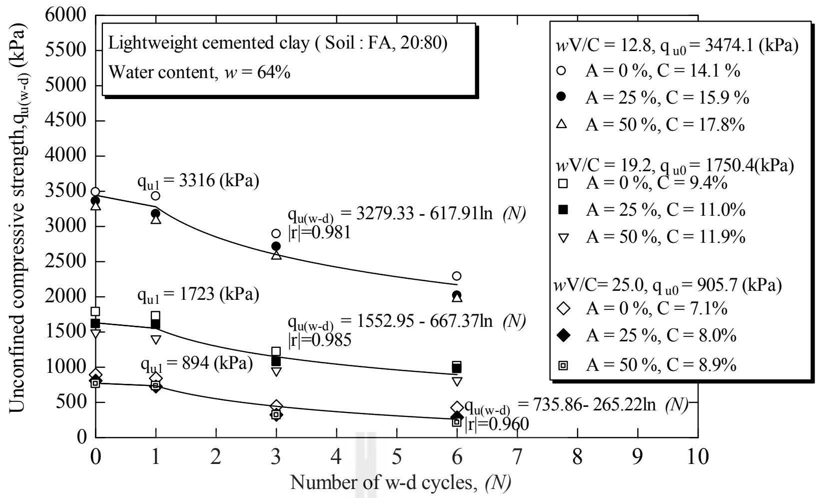
The strength reduction with number of w-d cycles is due to cracking effect. The wetting causes the swelling of the clay particles due to the expansion of diffusion double layer while the drying causes the shrinkage of the clay particles due to the loss of water (Kampala et al., 2014). Thus, the swelling and shrinkage for each w-d cycle leads to the tension cracks on the LCC sample. The cracking effect can be depicted by the increase in water content after the end of each w-d cycle (Figure 4.6). Due to the cracks, the pore space in the samples increases and carries more water content.



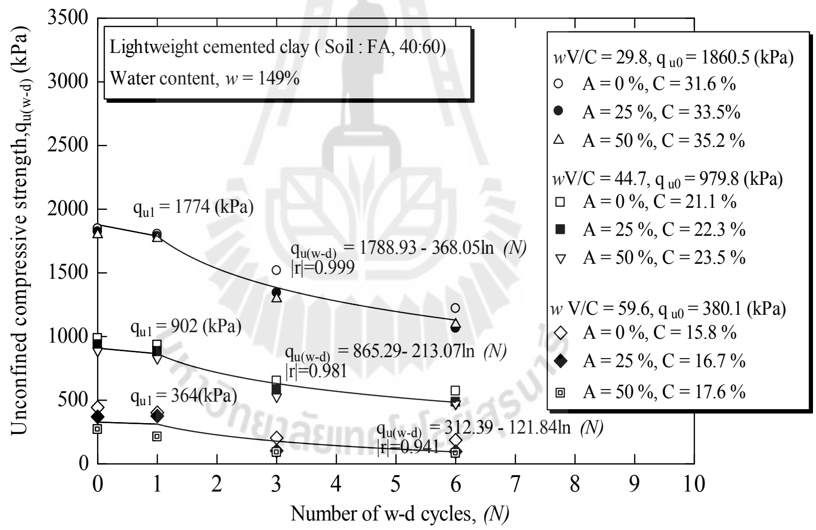
(a) Soil : FA = 20:80 (b) Soil : FA = 80:20

Figure 4.6 Relationship between *w* and *N* for (a) Soil : FA = 20:80 and (b) Soil : FA = 80:20.

It is evident from the test results (Figures 4.4 and 4.5) that the qu(w-d) values at different N is dependent upon qu0 value. As such, qu0 is used as a variable in analyzing the relationships between qu(w-d) versus N as shown in Figure 4.7. The relationships are for samples with various water contents, air contents and cement contents but with the same qu0 (same *wV/C* values) at FA replacement ratios of 80 and 60. For a particular FA replacement ratio, the qu(w-d) versus N relationship of LCC clay are of the same pattern as long as the qu0value is the same, even though the air content and cement content are varied over a wide range. The qu(w-d) versus N relationships can be represented by two functions: linear and logarithm. The linear and logarithm functions fit very well for 0-1 cycle and 1-6 cycles, respectively.



a) Soil:FA = 20:80



b) Soil : FA = 40:60

Figure 4.7 $q_{u(w\text{-}d)}$ versus *N* relationship for a) soil:FA = 20:80 and b) soil:FA = 40:60

To understand the role of qu0 on qu(w-d), the normalized strength qu(w-d)/qu0 is plotted versus N as shown in Figure 4.8 as previously done by Kampala et al. (2014) for Calcium Carbide Residue (CCR) stabilized clay.

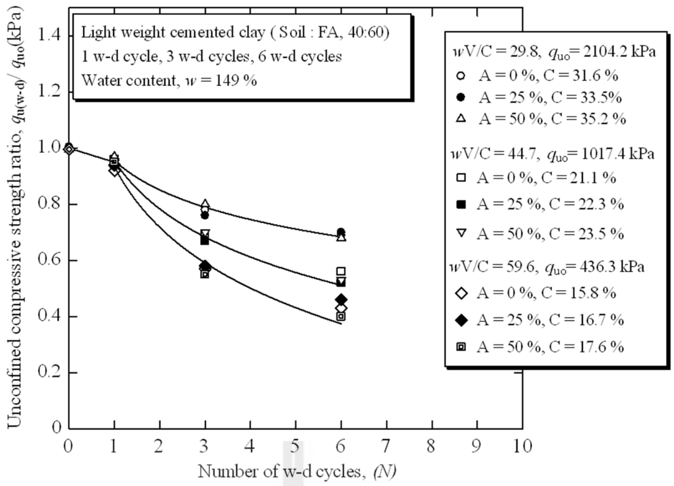


Figure 4.8 Normalized strength, $q_{u(w\text{-}d)}/q_{u0}$ versus N relationship

The qu(w-d)/qu0 for CCR stabilized clay at a particular N is essentially the same for different CCR contents and FA contents. Then, the unique relationship between qu(w-d)/qu0 and N was proposed and useful for mix design purposes. The same is not true for LCC clay, which possesses very high air content. For 1 w-d cycle, the qu(1 w-d)/qu0 is independent of qu0; i.e., qu(1 w-d)/qu0 is constant for all mix properties, where qu(1 w-d) is the 1 w-d cycle strength. Beyond 1 w-d cycle, the qu(w-d)/qu0 is dependent upon the qu0 value. The lower qu0 is associated with the larger qu(w-d)/qu0. This implies that the durability is controlled by qu0; i.e, the samples with the same qu0 exhibit the same qu(w-d) even though they were prepared at different mix proportions of water content, cement content and air content. The samples with higher qu0 exhibit higher qu(w-d). This is the fact that the durability is lower (strength reduction with increasing N is larger) for lower structure strength.

Based on the results shown in Figures 4.7 and 4.8, the relationship between qu(w-d) and N for different FA replacement ratios, water contents, cement contents and air contents can be represented by a logarithm function as follows:

$$q_{u(w-d)} = q_{u(1w-d)} - b\ln N \quad (4.4)$$

where b is the degradation index, quantifying the rate of degradation of structure strength due to w-d cycles. As seen in Figure 4.8, the qu(1 w-d) is slightly lower than qu0 and essentially the same for all mix proportions. The qu(1 w-d) and qu0 relationship can then be developed based on a linear regression analysis of the strength data (Figure 4.9):

$$q_{u(1w-d)} = 0.95 q_{u0} \quad (4.5)$$

with a high degree of correlation of 0.997.

The b value can be approximated in term of qu0 in a power function (Figure 4.10):

$$b = 0.65\left(q_{u0}\right)^{5/6} \quad (4.6)$$

with a high degree of correlation of 0.950.

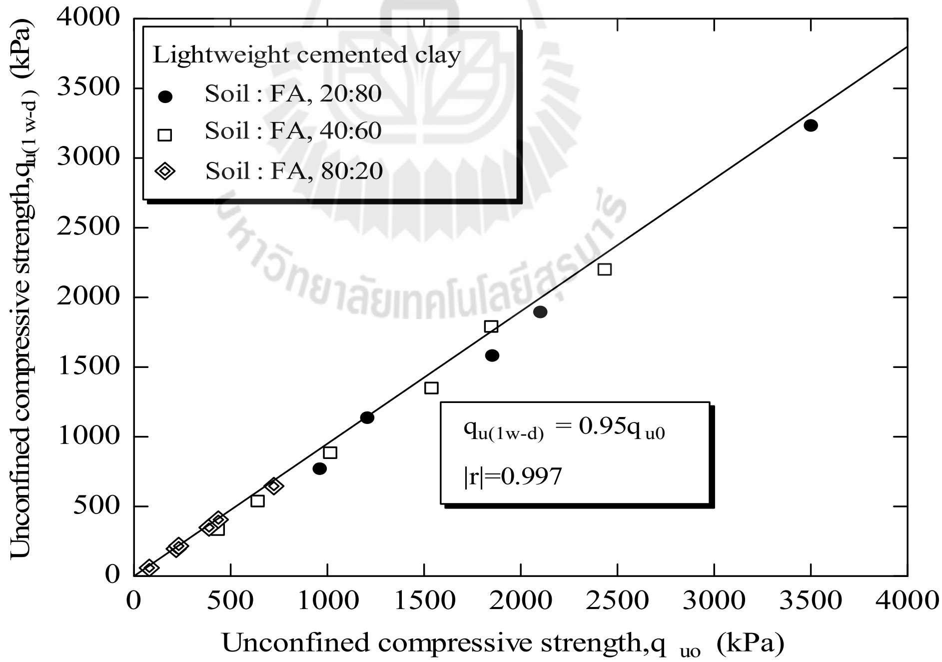


Figure 4.9 Relationship between $q_{u(1\ w\text{-}d)}$ and q_{u0} for soil : FA tested.

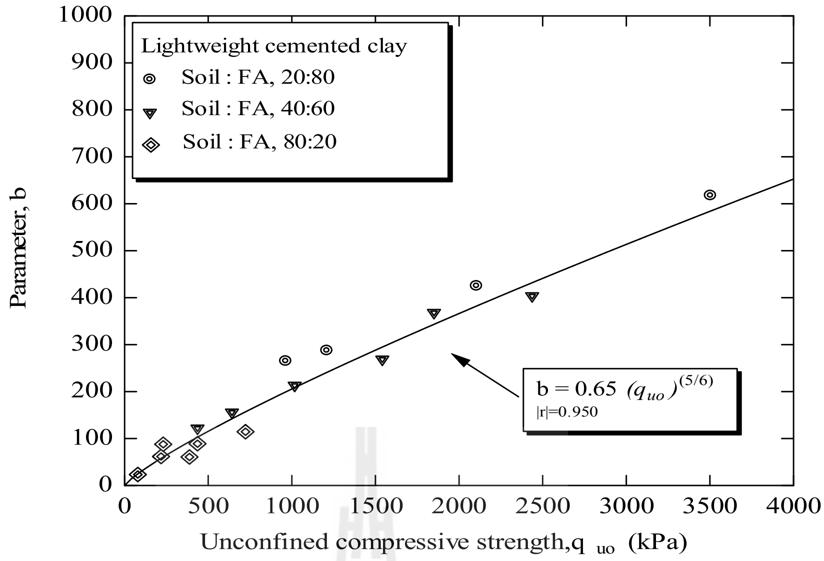


Figure 4.10 Relationship between *b* and q_{u0} for soil : FA tested.

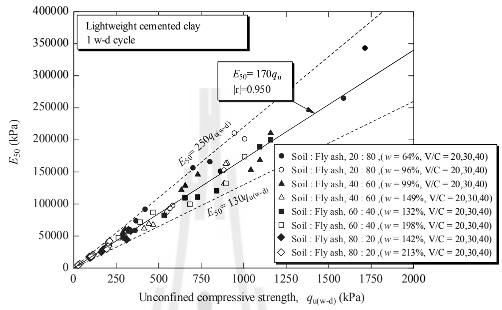
By combining Eqs. (4.4) to (4.6), a predictive w-d cycle strength equation in term of qu0 is shown as follows:

$$q_{u(w-d)} = 0.95 q_{u0} - 0.65 \left(q_{u0}\right)^{5/6} \ln N \tag{4.7}$$

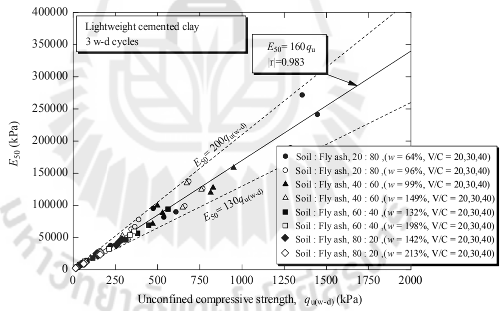
for 150 kPa< qu0< 3500 kPa

Using Eq. (4.7), the w-d cycle strengths of samples with various mix proportions at a target number of w-d cycle can be approximated once the corresponding qu0 is known. The qu0 is simply determined directly from laboratory UC test or approximated by available strength equations such as those proposed by Horpibulsuk et al. (2014b). Eq. (4.7) is thus very useful for pavement and geotechnical practitioners since the durability test is a time-consuming.

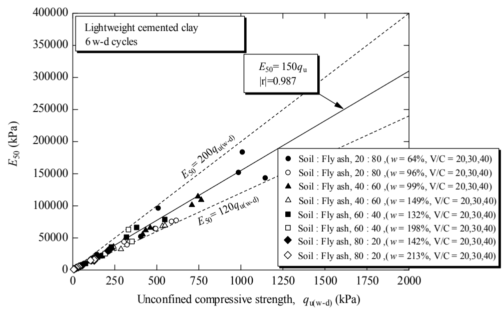
Besides strength, the modulus of the LCC clay subjected to different number of w-d cycles is a required parameter for deformation analysis. It is logical to relate modulus with unconfined compressive strength because both are generally dependent on the cemented structure. Figure 11 presents the relationship between modulus of deformation at 50% strength, E50 and qu(w-d) of LCC samples under various number of w-d cycles. E50 varies between 120 and 200 times qu(w-d) for all number of w-d cycles tested, which is in agreement with the test data by Horpibulsuk et al. (2012a) and Nerimitkrnburi et al. (2014) for LCC clay without w-d cycles. As such, E50 at any number of w-d cycle can be estimated after qu(w-d) is predicted (using Eq.(4.7)).



a) 1 w-d cycle



b) 3 w-d cycles



c) 6 w-d cycles

Figure 4.11 E_{50} and $q_{u(w-d)}$relationship for a) 1, b) 3 and c) 6 w-d cycles

Table 4.3: Predicted qu(w-d) for Soil : FA = 60:40

w (%)	A(%)	C (%)	N	q_{uo}(kPa)	$q_{u(1\ w\text{-}d)}$ (kPa) Eq.(4.5)	b (kPa) (Eq.4.6)	Predicted $q_{u(w\text{-}d)P}$ (kPa) (Eq.4.7)	Measured $q_{u(w\text{-}d)M}$ (kPa)	$\frac{\lvert q_{u(w-d)M} - q_{u(w-d)P} \rvert}{q_{u(w-d)M}} \times 100$ (%)
	0	50.2		1012.0	961.4	207.6	961.4	998.6	3.7
	25	34.5	1	604.0	573.8	135.0	573.8	590.3	2.8
	50	21.3		112.0	106.4	33.2	106.4	104.2	2.1
	0	50.2		1012.0	961.4	207.6	733.3	722.1	1.6
198	25	34.5	3	604.0	573.8	135.0	425.4	385.8	10.3
	50	21.3		112.0	106.4	33.2	70.0	88.4	20.8
	0	50.2		1012.0	961.4	207.6	589.4	665.3	11.4
	25	34.5	6	604.0	573.8	135.0	331.9	281.8	17.8
	50	21.3		112.0	106.4	33.2	47.0	38.0	23.7
	0	39.0		1467.4	1394.0	282.9	1394.0	1442.7	3.4
	25	27.0	1	842.7	800.6	178.2	800.6	831.4	3.7
	50	16.8		327.5	311.1	81.1	311.1	298.7	4.2
	0	39.0		1467.4	1394.0	282.9	1083.2	1126.4	3.8
132	25	27.0	3	842.7	800.6	178.2	604.8	627.1	3.6
	50	16.8		327.5	311.1	81.1	222.0	267.4	17.0
	0	39.0		1467.4	1394.0	282.9	887.1	907.3	2.2
	25	27.0	6	842.7	800.6	178.2	481.2	462.8	4.0
	50	16.8		327.5	311.1	81.1	165.8	197.2	15.9
			Mean Absolute Percent Error, MAPE				$\left(\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n} \frac{\lvert q_{u(w-d)M} - q_{u(w-d)P} \rvert}{q_{u(w-d)M}} \times 100\right)$		6.3

Table 4.3 shows a prediction example of qu(w-d) of the separate LCC samples with FA replacement ratio of 40% (w = 198% and 132% and A = 0 - 50%). The qu0 was obtained from the UC test after 28 days of curing. The qu(w-d) for various water contents, cement contents, and air contents were predicted by Eq.(4.7). It is found that the predicted and measured qu(w-d) values are in a good agreement with a small absolute percent error of 6.3. This reinforces the application of the proposed equation. Even

though Eq. (4.7) was developed from a specific soil, the formulation of the proposed equation is on sound principles and can be used as fundamental for other soils. The empirical equation can be further refined with the analysis of more data.

Eqs (4.1)-(4.3) and (4.7) can be used for mix design purpose to meet both unit weight and strength requirement at a target service life. The strength requirement for stabilized pavement material at the target service life is different for different countries. For instance, the strength requirement is 2068 kPa, 1471 kPa, and 2403 kPa for the U.S. Army Corps of Engineers, the Department of Rural Road of Thailand and the Department of Highways of Thailand, respectively.

4.6 Conclusions

This research investigates the viability of using waste materials (clay and FA) for developing sustainable construction LCC materials. Results of this study suggest that the initial soaked strength is critical for analysis of wet-dry cycle strength of LCC Bangkok clay. The conclusions can be drawn as follows.

4.6.1 FA improves flowability of LCC mixture (before hardening) and durability of LCC material. For the same flowability, the initial soaked strength and w-d cycle strength increase with increasing FA. The significant improvement is found when FA replacement ratio is greater than 40%.

4.6.2 The strength reduction with number of w-d cycles is caused by the swelling and shrinkage of clay particles, which in turn leads to the crack development (degradation of cemented structure). Due to the cracks, the pore space in the samples increases and carries more water content.

4.6.3 The degradation of cemented soil structure is controlled by the initial structure strength. The degradation index (b) is proposed to qualify the strength reduction with number of w-d cycles.

4.6.4 The w-d cycle strength and number of w-d cycle relationship is represented by linear function for 0-1 cycle and logarithm function for 1-6 cycles. Based on the proposed functions and the degradation index, the predictive w-d strength equation is proposed and verified. This equation facilitates mix design to attain the required strength at a target service life, which is very useful for pavement and geotechnical practitioners since the durability test is time-consuming. The formulation of the proposed equation is on sound principles and can be used as fundamental for other soils. The empirical equation can be further refined with the analysis of more data.

4.6.5 Because the cemented soil structure controls the engineering properties at different w-d cycles, it is logical to relate E50 in term of qu(w-d). The E50 and qu(w-d) relationship is found to be essentially independent of cement content, water content, air content, FA replacement ratio and number of w-d cycle. The relationship is similar to that of LCC clay without w-d cycle. Using the proposed equation, E50 at any number of w-d cycle can be estimated once qu(w-d) is predicted.

4.7 Reference

Arulrajah, A., Piratheepan, J., Disfani, M.M and Bo, M.W. 2009.Geotechnical and Geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. **Journal of Materials in Civil Engineering** 25 (8), 1077-1088.

Arulrajah, A., Disfani, M.M., Horpibulsuk, S., Suksiripattanapong, C. and Prongmanee, N. 2014. Physical properties and shear strength response of recycled construction and demolition materials in unbound pavement base/subbase pavement. **Construction and Building Materials** 58, 245-257.

Chai, J.C. and Pongsivasathit, S. 2010. A method for predicting consolidation settlements of floating column improved clayey subsoil. **Front. Archit. Civ. Eng**. 4 (2), 241-251.

Dif, A.E., and Bluemel, W.F. (1991).Expansive soil under cyclic drying and wetting.**Geotechnic Testing Journal**, 14, 96-102.

Hayashi, Y., Suzuki, A. and Matsuo, A., 2002. Mechanical properties of air-cement-treated soils. **Ground Improvement** 6 (1), 69-78.

Horpibulsuk, S., Bergado, D.T. and Lorenzo, G.A., 2004a. Compressibility of cement admixed clays at high water content. **Geotechnique** 54 (2), 151-154

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

Horpibulsuk, S., Miura, N., Koga, H. and Nagaraj, T.S. 2004c.Analysis of strength development in deep mixing – a field study.**Ground Improvement8** (2), 59-68.

Horpibulsuk S, Shibuya S, Fuenkajorn K, and Katkan W., 2007.Assessment of engineering properties of Bangkok clay. **Canadian Geotechnical Journal** 44 (2), 173-187.

Horpibulsuk, S., Liu, M.D., Liyanapathirana, D.S. and Suebsuk, J., 2010. Behavior of cemented clay simulated via the theoretical framework of the Structured Cam Clay model. **Computers and Geotechnics** 37, 1-9.

Horpibulsuk, S., Rachan, R. and Suddeepong, A., 2011a, Assessment of strength development in blended cement admixed Bangkok clay. **Construction and Building Materials** 25 (4), 1521-1531.

Horpibulsuk, S., Rachan, R., Suddeepong, A. and Chinkulkijniwat, A., 2011b. Strength development in cement admixed Bangkok clay: laboratory and field investigations. **Soils and Foundations** 51 (2), 239-251.

Horpibulsuk, S., Suddeepong, A., Chinkulkijniwat, A., and Liu, M.D., 2012a.Strength and compressibility of lightweight cemented clays.**Applied Clay Science** 69, 11-21.

Horpibulsuk, S., Chinkulkijniwat, A., Cholphatsorn, A., Suebsuk, J., and Liu, M.D. 2012b. Consolidation behavior of soil cement column improved ground. **Computers and Geotechnics** 43, 37-50.

Horpibulsuk, S., Rachan, R., Suddeepong, A., Liu, M.D. and Du, Y.J. 2013.Compressibility of lightweight cemented clays.**Engineering Geology**. 159, 59-66.

Horpibulsuk, S., Wijitchot, A., Neramitkornburee, A., Shen, S.L. 2014a.Factors influencing unit weight and strength of lightweight cemented clay. **Quarterly Journal of Engineering Geology and Hydrogeology** 47, 101-108.

Horpibulsuk, S., Suddeepong, A., Suksiripattanapong, C., Chinkulkijniwat, A., Arulrajah, A. and Disfani, M.M. 2014b.Water-void/cement ratio identity of lightweight cellular cemented material. **Journal of Materials in Civil Engineering, ASCE doi**:10.1061/(ASCE)MT.1943-5533.0001110.

Jamnongpipatkul, P., Dechasakulsom, M, and Sukolrat, J., 2009. Application of air-foam stabilized soil for bridge-embankment transition zone in Thailand. **GeoHuman International Conference, Geotechnical Special Publication** No.190, pp.181-193.

Kampala, A., Horpibulsuk, S., Prongmanee, N. and Chinkulkijniwat, A. 2014. Influence of wet-dry cycles on compressive strength of calcium carbide residue-fly ash stabilized clay. **Journal of Materials in Civil Engineering, ASCE** 24 (1), 633-643.

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

Kavvadas M., Amorosi A., 2000. A constitutive model for structured soils.**Géotechnique** 50 (3), 263-273.

Khattab, S. A. A., Al-Mukhtar, M., and Fleureau, J. M. 2007.Long-term stability characterics of a lime-treated plastic soil. **Journal of Materials in Civil Engineering, ASCE**, 19(4), 358-366.

Kikuchi, Y. and Nagatome, T., 2011. Durability of cement treated clay with air foam used in water front structures. Proceedings of Geo-Shanghai 2010, **ASCE Special Publication** No.207, June 2-5, 2010, China, pp.1-30.

Kikuchi, Y., Nagatome, T., Mizutani, T., and Yoshio, H., 2011.The effect of air foam inclusion on the permeability and absorption of light weight soil. **Soils and Foundations** 51 (1), 151-165.

Mitchell , J.K., 1993.Fundamentals of Soil Behavior. **New York: John Wiley&Sons**, Inc.

Neramitkornburi, A., Horpibulsuk, S., Suksiripattanapong, C., Arulrajah, A. and Disfani, MM. 2014.Engineering properties of lightweight cellular cemented clay.**Soils and Foundations** (Under review).

Otani, J., Mukunoki, T. and Kikuchi, Y., 2002. Visualization for engineering property of in-situ lightweight soils with air foams. **Soils and Foundations** 42 (3), 93-105.

Prakash, K. and Sridharan, A., 2004. Free swell ratio and clay mineralogy of fine-grained soils. **Geotechnical Testing Journal ASTM** 27 (2), 220-225.

Rahman, M.A., Arulrajah, A., Piratheepan, J., Bo, M.W. and Imteaz, M.A. 2009. Resilient modulus and permanent deformation responses of geogrid-reinforced construction and demolition materials. **Journal of Materials in Civil Engineering** 26 (3), 512-519.

Rao, S.M., Reddy, B.V.V., and Muttharam, M. 2001. The impact of cyclic wetting and drying on the swelling behavior of stabilized expansive soil.**Engineering Geology** 60, 223-233.

Satoh, T., Tsuchida, T., Mitsukuri, K. and Hong, Z., 2001.Field placing test of lightweight treated soil under seawater in Kumamoto port. **Soils and Foundations** 41 (4), 145-154.

Sazzad, B.S., Rahman, K. Mustafa, Y., and Ireen, A. 2010. The long-term performance of two fly ash stabilized find-grained soil subbase. **Resources, Conservation and Recycling** 54, 666-672.

Shen, S.L., Wang, Z.F., Horpibulsuk, S. and Kim, Y.H., 2013a. Jet grouting with a newly developed technology: The twin-jet method. **Engineering Geology** 152 (1), 87-95.

Shen, S.L., Wang, Z.F., Sun, W.J., Wang, L.B. and Horpibulsuk, S., 2013b.A field trial of horizontal jet grouting using the composite-pipe method in soft deposit of Shanghai.Tunnelling and Underground Space Technology 35, 142-151.

Suebsuk, J.,Horpibulsuk, S. and Liu, M.D., 2010. Modified Structured Cam Clay: A constitutive model for destructured, naturally structured and artificially structured clays**. Computers and Geotechnics** 37, 956-968.

Suebsuk, J., Horpibulsuk, S. and Liu, M.D., 2011. A critical state model for overconsolidated structured clays. **Computers and Geotechnics** 38, 648-658.

Tsuchida, T., Porbaha, A. and Yamane, N., 2001.Development of a geomaterial from dredge bay mud. **Journal of Materials in Civil Engineering ASCE** 13 (2), 152-160.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and conclusions

There is a myriad of problems associated with the engineering construction in soft clay deposits, particularly in coastal regions. In Southeast Asia, soft soil is prevalent in regions such as Chao Phraya Plain in Thailand, Mekong Delta in Vietnam and Cambodia, Central Plains of the Philippines, Coastal Plains of Malaysia, Indonesia, Singapore, Hong Kong, Korea, Japan and Taiwan. This soft soil, located in marine or estuary environments, have low shear strength, low bearing capacity and high natural water content, resulting in high compressibility potential. The usage of Lightweight Cellular Cemented (LCC) construction materials is an attractive and economical ground improvement technique in construction applications such as in embankment, pavement pipe bedding and backfilling. LCC material is a mixture of aggregate, air foam agent and cementing agent. The role of water content, cement content, air content and FA replacement ratio on the strength, unit weight, flowability and durability of the lightweight cellular cemented clay is illustrated in this research. The conclusions can be drawn as follows:

5.1.1 The water content equal to $1.5w_L$ is the optimum water content for producing the LCC Bangkok clay and regarded as the working state. The advantage of FA replacement on the workability, flowability and strength is observed when the FA replacement ratio is greater than FA fixation point. The FA fixation point is simply obtained from the conventional index test.

5.1.2 The flowability of the LCC Bangkok clay can be approximated in terms of air content and w/w_L and the strength can be approximated in terms of V/C.

5.1.3 The w-d cycle strength and number of w-d cycle relationship of the LCC Bangkok clay is represented by linear function for 0-1 cycle and logarithm function for 1-6 cycles. The predictive w-d strength equation is proposed and verified. This equation facilitates mix design to attain the required strength at a target service life, which is very useful for pavement and geotechnical practitioners since the durability test is time-consuming.

5.1.4 The E_{50} and $q_{u(w\text{-}d)}$ relationship is found to be essentially independent of cement content, water content, air content, FA replacement ratio and number of w-d cycle. Using the proposed equation, E50 at any number of w-d cycle can be estimated once $q_{u(w\text{-}d)}$ is predicted.

5.1.5 Based on the analysis of the test data, the mix design method for the lightweight cellular cemented Bangkok clay is suggested. This method is useful for engineering practitioners in their design of lightweight cellular cemented clay and estimating the mechanical properties.

5.2 Recommendations for further research

5.2.1 Permeability, one of the engineering properties of LLC material, should be further investigated.

5.2.2 Possible usage of other ashes in manufacturing the LLC material should be further investigated.

5.2.3 The other sustainable cementing agents such as geopolymer and calcium carbide residual can be used to develop the LLC material.

5.2.4 Microstructural analysis on the LLC material should be investigated to understand the growth of cementitious products with the change of influential factors.

BIOGRAPHY

I, Anek Neramitkornburi, was born on November 16, 1983 in NakhonRatchasima, Thailand. In 2007, I obtained a Bachelor’s degree in Civil Engineering from the Faculty of Engineering and Architecture, Rajamangala University of Technology Isan. In 2009, I obtained a Master’s degree in Civil Engineering from the School of Civil Engineering, Suranaree University of Technology. Then I continued to study for a Philosophical Doctor degree at the same university. I was awarded a Royal Golden Jubilee (RGJ) Ph.D. Program Scholarship from the Thailand Research Fund (TRF) in 2011.