กำลังอัดและความสามารถในการไหลของดินซีเมนต์เถ้าลอยมวลเบา

นายอภิรัตน์ วิจิตรโชติ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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STRENGTH AND FLOWABILITY OF LIGHTWEIGHT CEMENTED FLY ASH-CLAY

Apirat Wijitchot

A Thesis Submitted in Partial Fulfillment of the Requirements for the

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STRENGTH AND FLOWABILITY OF LIGHTWEIGHT CEMENTED FLY ASH-CLAY

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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ดินเหนียวซีเมนต์มวลเบาสามารถนำมาประยุกต์ใช้ในงานซ่อมโครงสร้างพื้นฐานและงานก่อสร้างต่างๆ อิทธิพลของปริมาณน้ำ ปริมาณปูนซีเมนต์ ปริมาณฟองอากาศ และอัตราส่วนการแทนที่เถ้าลอย ต่อกำลังอัด หน่วยน้ำหนัก และความสามารถในการไหล ได้นำเสนอในวิทยานิพนธ์เล่มนี้ ขีดจำกัดเหลวของดินเหนียวมีค่าลดลงตามการเพิ่มขึ้นของอัตราส่วนการแทนที่เถ้าลอย ขีดจำกัดเหลวและดัชนีสภาพพลาสติกมีค่าลดลงเล็กน้อยในช่วงแรกและมีค่าลดลงอย่างรวดเร็วในช่วงหลัง ค่าอัตราส่วนการแทนที่ที่จุดเปลี่ยนนี้เรียกว่าอัตราส่วนแทนที่เถ้าลอยคงที่ การแทนที่เถ้าลอยในดินเหนียวช่วยลดหน่วยน้ำหนัก และเพิ่มความสามารถในการไหล ขณะที่การแทนที่เถ้าลอยปรับปรุงคุณสมบัติด้านกำลังอัดเมื่ออัตราส่วนการแทนที่เถ้าลอยมีค่าเกินกว่าอัตราส่วนแทนที่เถ้าลอยคงที่เนื่องจากอัตราส่วนแทนที่เถ้าลอยคงที่สามารถหาได้ง่ายจากการทดสอบคุณสมบัติดัชนี ตัวแปรนี้จึงมีประโยชน์อย่างมากในการประมาณปริมาณแทนที่เถ้าลอยที่น้อยที่สุดที่ต้องการเพื่อปรับปรุงคุณสมบัติด้านกำลังอัด การเติมฟองอากาศในดินมีประโยชน์มากกว่าการเติมน้ำในการทำดินซีเมนต์มวลเบา สำหรับหน่วยน้ำหนักที่เท่ากัน ดินซีเมนต์มวลเบาที่มีปริมาณฟองอากาศสูง มีค่ากำลังอัดสูงกว่าดินซีเมนต์มวลเบาที่มีปริมาณน้ำสูง สมการที่เสนอโดย Horpibulsuk et al. (2012b) ได้รับการพิสูจน์ว่าสามารถใช้ในการทำนายหน่วยน้ำหนักของดินซีเมนต์มวลเบาที่ปริมาณน้ำ ปริมาณฟองอากาศ ปริมาณปูนซีเมนต์ และปริมาณเถ้าลอยต่างๆ ได้เป็นอย่างดี โดยอาศัยกฎของ Abrams ผู้วิจัยแสดงให้เห็นว่ากำลังอัดของดินเหนียวซีเมนต์มวลเบาที่ปริมาณฟองอากาศค่าหนึ่งๆ แปรผันตามอัตราส่วนปูนซีเมนต์ต่อปริมาณน้ำ ความสัมพันธ์ระหว่างกำลังอัดและอัตราส่วนปูนซีเมนต์ต่อปริมาณน้ำมีประโยชน์อย่างมากในการประมาณกำลังอัด เมื่อมีการเปลี่ยนแปลงของปริมาณปูนซีเมนต์และปริมาณน้ำ เพียงทำการสุ่มทดสอบน้อยครั้ง นอกจากนี้ยังมีประโยชน์ในการประมาณปริมาณปูนซีเมนต์ที่ต้องการสำหรับปริมาณฟองอากาศต่างๆ เพื่อให้ได้กำลังอัดที่ต้องการท้ายสุดผู้วิจัยได้นำเสนอวิธีการออกแบบส่วนผสมเพื่อให้ได้กำลังอัด ความสามารถในการไหล และหน่วยน้ำหนัก ตามข้อกำหนด

สาขาวิชา วิศวกรรมโยธา ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา 2555 ลายมือชื่ออาจารย์ที่ปรึกษา ______________

APIRAT WIJITCHOT : STRENGTH AND FLOWABILITY OF LIGHTWEIGHT CEMENTED FLY ASH-CLAY. THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 87 PP.

FLOWABILITY/FA REPLACEMENT/LIGHTWEIGHT MATERIALS

Lightweight cemented clay has wide applications in the infrastructure rehabilitation and in the construction of new facilities. Effects of water content, cement content, air content and fly ash replacement ratio on the strength, unit weight and flowability of the lightweight cemented Bangkok clay is illustrated in this thesis. The fly ash, FA, replacement slightly decreases liquid limit and plasticity index up to a certain FA replacement. Beyond this value, both liquid limit and plasticity index reduce significantly. This certain FA replacement is designated as FA fixation point. The FA replacement decreases the unit weight and increases the flowablity while it improves the strength when the FA replacement is greater than the fixation point. Because the FA fixation point is simply obtained from the index test, it is a practical indicator to determine the minimum FA replacement for strength improvement. The addition of air foam to the moist clay is more advantage than that of water for manufacturing the lightweight cemented clay. For the same unit weight, the strength of a sample with a high air content is higher than that with a high water content. The equation proposed by Horpibulsuk et al. (2012b) was proved as suitable for predicting the unit weight of the lightweight cemented clay with different water contents, cement contents and air contents. Based on the Abrams' law, a relationship between strength and cement/clay-water ratio for a particular air content is proposed. The relationship is useful in estimating the laboratory strength wherein water content and cement content

vary over a wide range by 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. Finally, a mix design procedure to arrive at the target strength, flowability and unit weight is suggested.

School of Civil Engineering Student's Signature ___________________

Academic Year 2012 Advisor's Signature ___________________

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Apirat Wijitchot

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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
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.

Horpibulsuk et al. (2012b) introduced a prime parameter governing the strength and deformation characteristics of lightweight cemented clay. It was designated as void/cement ratio, V/C. Even though there are available researches on the lightweight cemented clay, they focused on the strength. This research studies the effects of the water content, cement content and fly ash on the strength unit weight and flowability of the lightweight cemented clay.

1.2 Research objective

The Objective of this research is to

1) study the role of water content, cement content and fly ash on the strength and flowability of lightweight cemented clay.
2) propose a generalized strength equation for lightweight cemented clay.

1.3 Scope and limitation of the study

Bangkok clay was mixed with water and fly ash to increase the flowability. It was then mixed with air foam and cement to reduce the unit weight and increase the shear strength. The Bangkok clay was from Yan Nawa Distric, Bangkok, Thailand at a 4 meter depth. Type I Portland cement (PC), fly ash from Mae Moh power plant in the north of Thailand, and tap water were used in this study. The clay-water content was adjusted to 1-3 times liquid limit.

The cement content was varied from 5 to 20% by weight of dry soil. Fly ash replacement was between 0 and 80% of dry soil. The air foam content was from 0 to 100% of total volume. Based on the analysis of the test results, a mix design method is suggested.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

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:

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

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

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

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

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

(tetracalciumaluminoferite) (calcium aluminoferrite hydrate)

$$3CaO.Al_2O_3 + 12H_2O + Ca(OH)_2 = 3CaO.Al_2O_3.Ca(OH)_2.12H_2O \quad (2.4)$$

(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.

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

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.

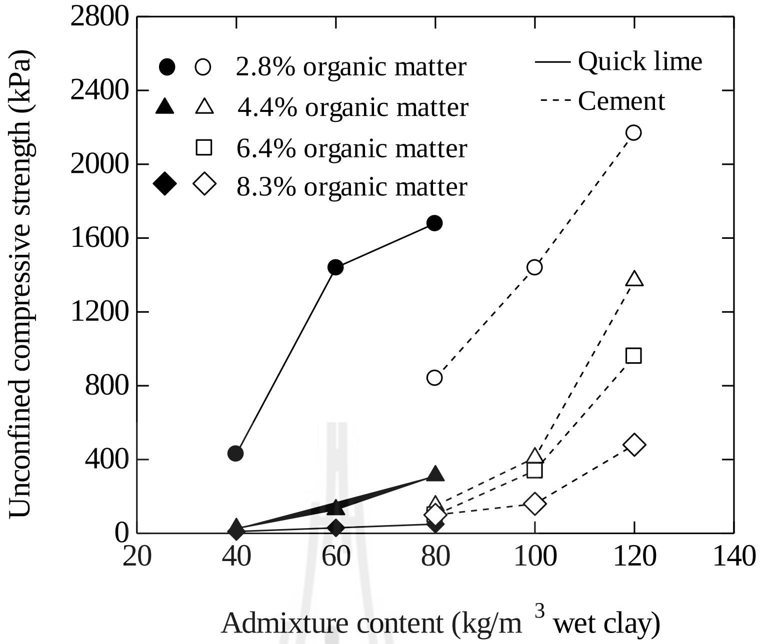


Figure 2.1: Distribution of unconfined compressive strength and organic matter content (after Miura et al., 1988).

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%.

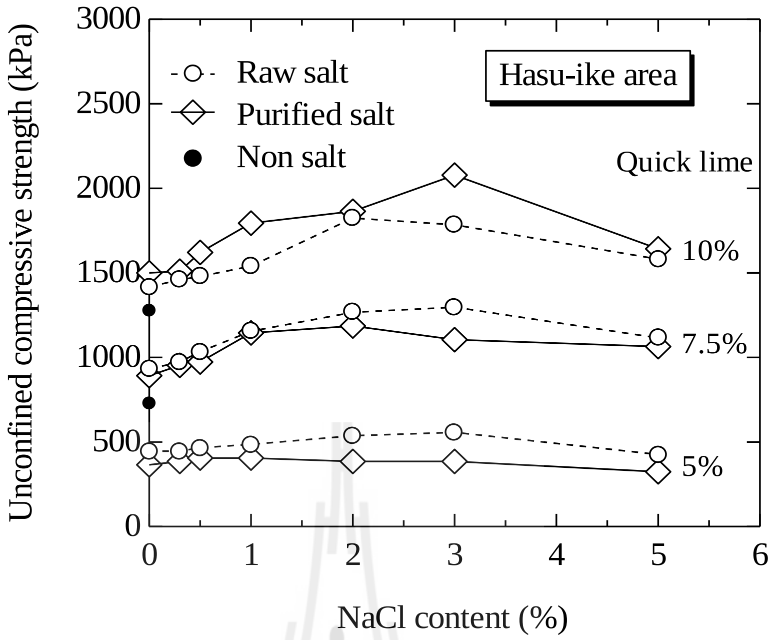


Figure 2.2(a): Influence of NaCl content on the quick lime improvement of Ariake clay (after Miura et al., 1988).

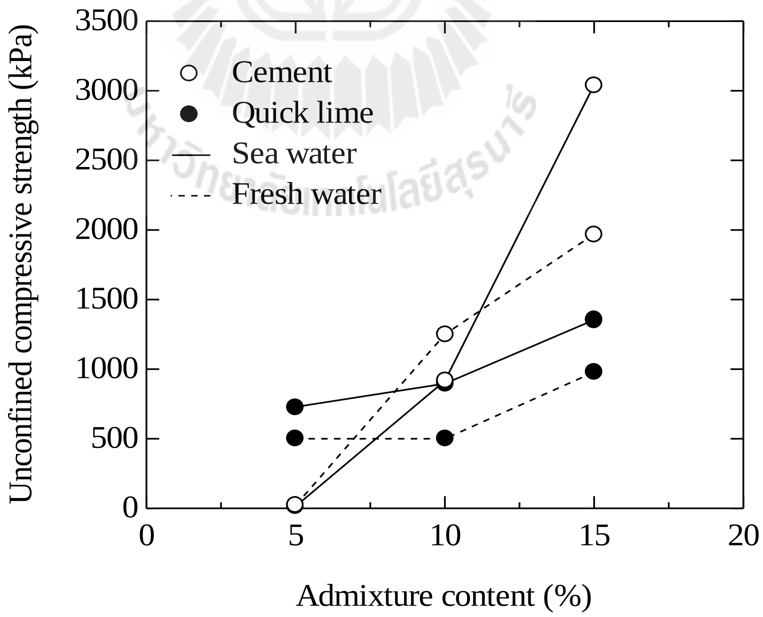


Figure 2.2(b): Relationship between unconfined compressive strength and admixture content (after Miura et al., 1988).

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):

$$q_u = \frac{A}{(V/C)^B} \qquad (1)$$

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.

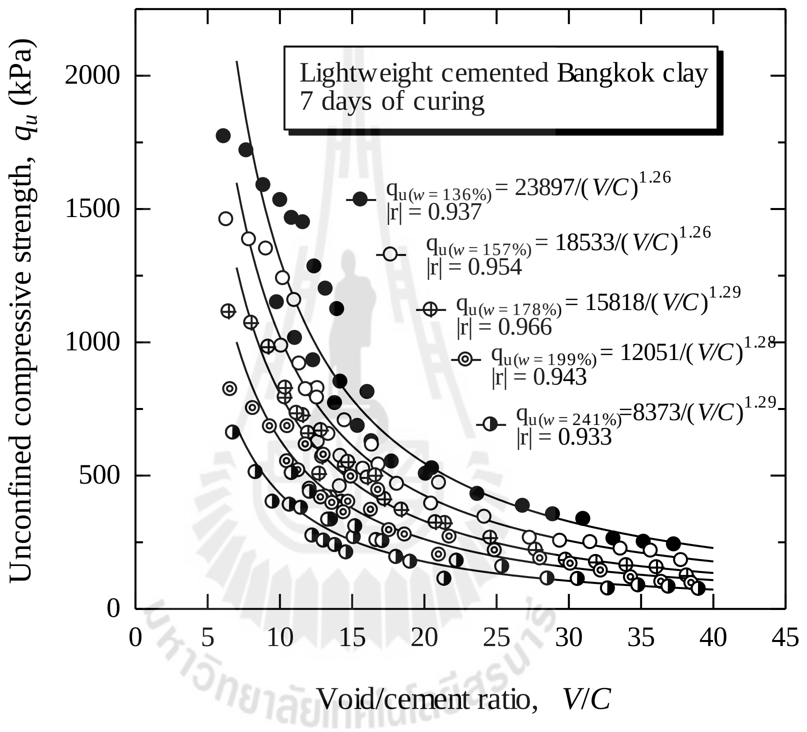


Figure 2.3: Analysis of strength development in lightweight cemented Bangkok clay using *V*/*C* (Horpibulsuk et al., 2012b).

CHAPTER III

RESEARCH METHODOLOGY

3.1 Soil samples

Bangkok clay was collected Yan Nawa District, Bangkok, Thailand at a 4 meter depth. Groundwater was had a depth of about 1.0 m from surface. The grain size distribution, natural water content, specific gravity, index property tests were performed according to the American Society of Testing and Materials (ASTM) standards. Also the free swell test on the sample was performed. The free swell ratio (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 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 was obtained from the laser particle size analysis (vide Figure 3.1). 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 Laser Particle Size Analyzer

3.3 Fly ash

The fly ash from Mae Moh power plant in the north of Thailand was used in this study. It was passed through sieve No. 325. The major components SiO_2, Al_2O_3, and Fe_2O_3 were measured by the X-ray diffraction (XRD) and the fly ash was classified by the ASTM C 618. The grain size distribution curve was obtained from the laser particle size analysis.

3.4 Methodology

The aim of this research is to understand the role of fly ash on the unit weight, strength and flowability and to develop practical equations for determining the strength and unit weight of different mix proportions of lightweight cemented Bangkok clay. The void/cement ratio is the volume of void to the volume of cement in the mix. The generalized stress state, w/w_L, was used for the first purpose where w is the clay water content and w_L is liquid limit water content. The w/w_L was successfully used to assess the engineering properties of remolded and natural clays (Horpibulsuk et al., 2007 and 2011c). 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^{-7} cm/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) although few clays exhibit larger undrained shear strength up to 5.6 kPa (Wasti and Bezirci, 1986).

The clay paste was passed through 2 mm sieve for removal of shell pieces and other bigger size particles, if present. The water content was adjusted to (1-3) times liquid limit. This intentional increase in water content is to simulate the clay slurry with high flow ability for pumping into the construction sites. For the first and last aims, the clay was mixed with fly ash with the replacement ratios between 0 and 80%. The mixtures were mixed with air foam to attain air contents, A_c, from 0 to 100% by volume of the clay-water-air mixture. The mixtures were then thoroughly mixed with cement for 10 min. The cement content, C, was varied from 5 to 20% of dry weight of soil. Such a uniform paste was transferred to cylindrical containers of 50 mm diameter and 100 mm height, taking care to prevent any air entrapment. After 24 hours, the cylindrical samples were dismantled. All the cylindrical samples were wrapped in vinyl bags and were 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 1 mm/min. Both tests were performed according to the American Society of Testing and Materials (ASTM) standards. For all mix proportion, the flow tests were performed according to the ASTM C 109 and C 185. Table 3.1 summarizes the testing program and Figure 3.2 shows the study plan.

Table 3.1 : Summarizes the testing program

Testing	Number of samples
Basic properties	Soil samples From Yan Nawa district, Bangkok
Unconfined compressive strength (four value of water content × four cement quantity × four replacement of fly ash × five value of air content)	320
Flow (four value of water content × four cement quantity × four replacement of fly ash × five value of air content)	320
Unit weight (four value of water content × four cement quantity × four replacement of fly ash × five value of air content)	320

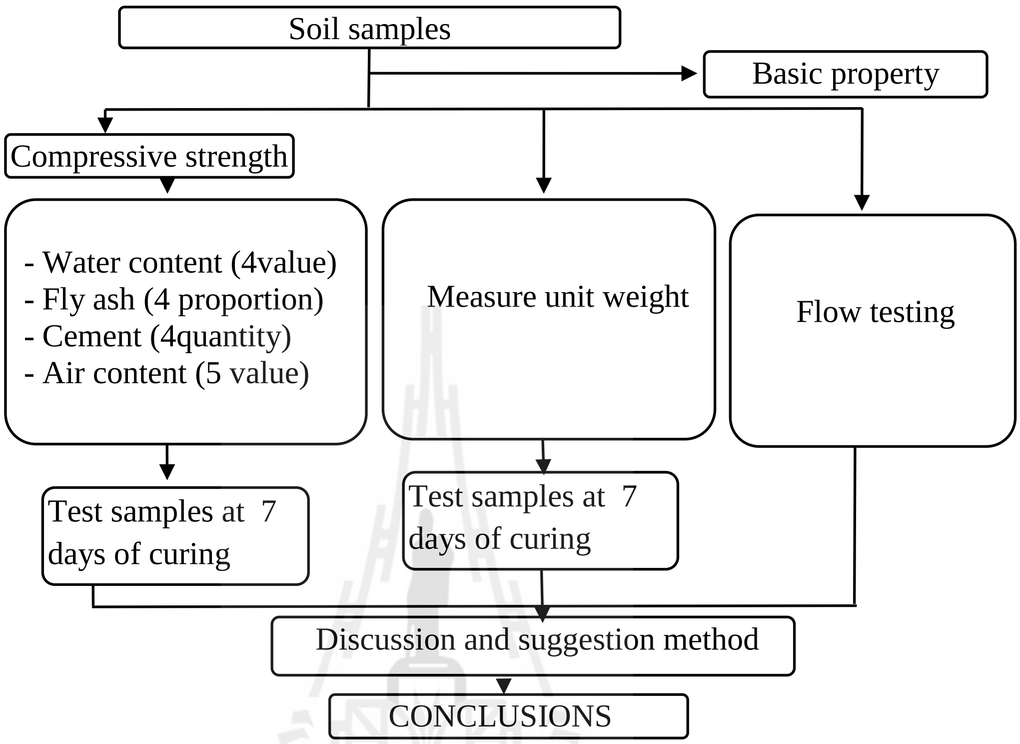


Figure 3.2 : Study plan.

CHAPTER IV

RESULT AND DISCUSSION

4.1 Introduction

The materials contained in this chapter deal with the role of fly ash, cement content, water content and air content on the unconfined compressive strength, flowability and unit weight of the lightweight cemented fly ash-clay.

4.2 Basic soil properties

Bangkok clay was collected Yan Nawa District, Bangkok, Thailand at a 4 meter depth. Groundwater was had a depth of about 1.0 m from surface. Bangkok 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). Grain size distribution curve of Bangkok clay is shown in Figure 4.1 compared with that of cement and fly ash.

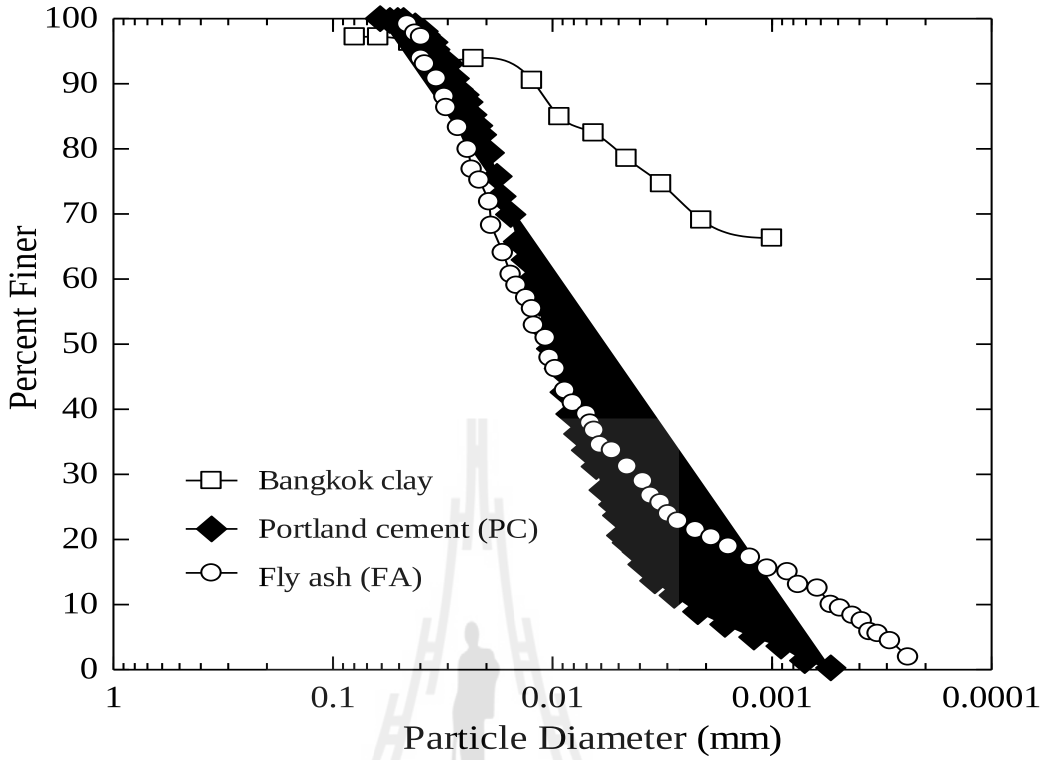


Figure 4.1: Grain size distribution of Bangkok clay, fly ash and cement.

4.3 Consistency limit

The replacement of the fly ash affects consistency limits of the clay. Figure 4.2 shows the change of the consistency limits with the replacement ratio. The liquid limit of the mixed clay reduces gradually with FA replacement when the FA replacement is less than 50% and the reduction in liquid limit becomes remarkable when the FA replacement is greater than 50%. The plastic limit changes insignificantly with the range of FA replacement tested. As such, the reduction in the plasticity index is clearly observed at about 50% FA replacement. This FA replacement is regarded as FA fixation point.

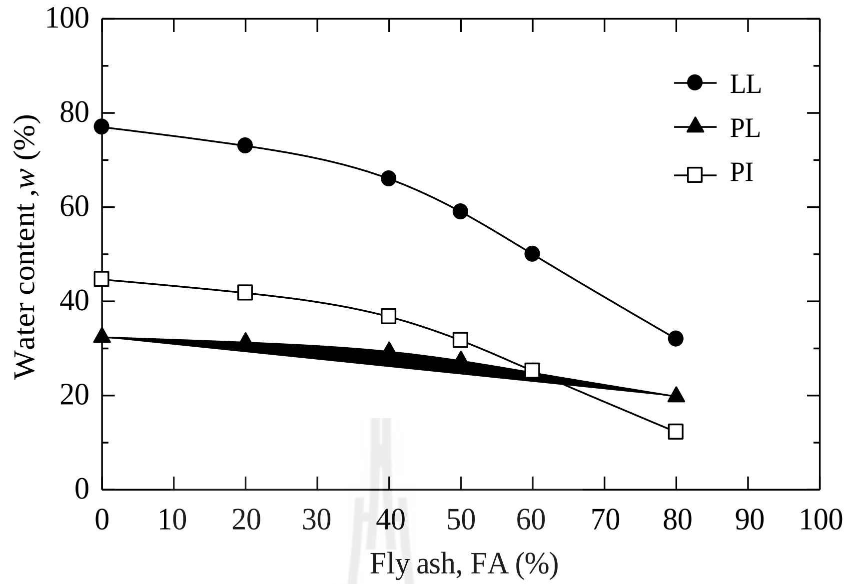
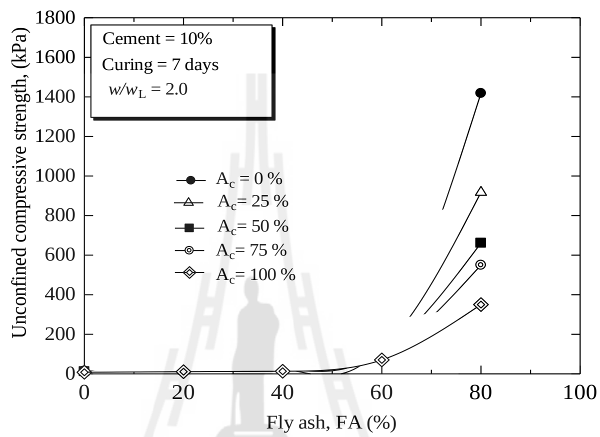


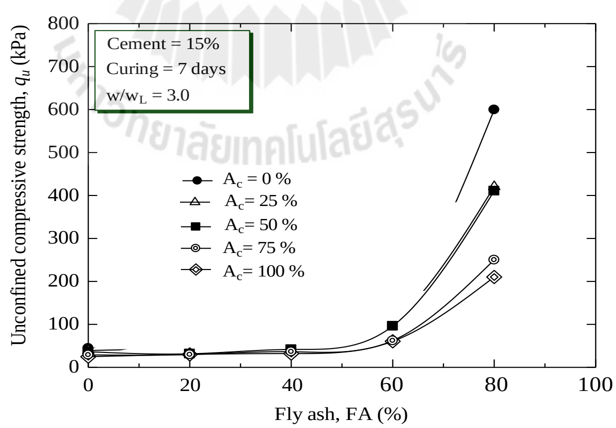
Figure 4.2: Relationship between index properties and FA replacement.

4.4 Influence of fly ash on strength, flowability and unit weight

The FA replacement higher than the FA fixation point modifies the clay fabric by increasing the non-interacting material. The liquid limit and plasticity index decrease with increasing the FA replacement. Figure 4.3 shows the role of FA replacement on the strength of the lightweight cemented clay at the same generalized stress state, w/w_L of 2-3 and cement contents of 10-15%. At this generalized stress state, the mixed clay samples have essentially the same workability (shear resistance), even though their water contents are different. The strength increases gradually with FA replacement for all air contents. In other words, air content does not affect the strength development. Beyond the FA fixation point, the strength increases remarkably. Because the w_L values slightly decrease for the mixed clay samples with the FA replacement less than the FA fixation point (Figure 4.2), the water contents at this stress state decrease slightly with FA replacement and hence insignificant strength development. The same is not true for the mixed clay with higher FA replacement, the w_L values reduce significantly. Thus, the strength development is remarkable with increasing the FA replacement. For the high strength lightweight cemented clay, the air contents controls the strength development.



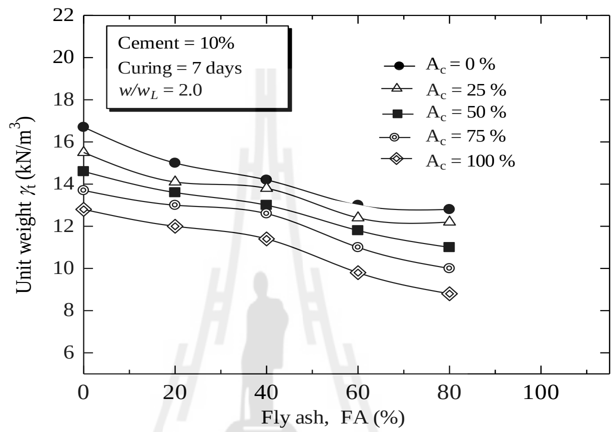
(a)



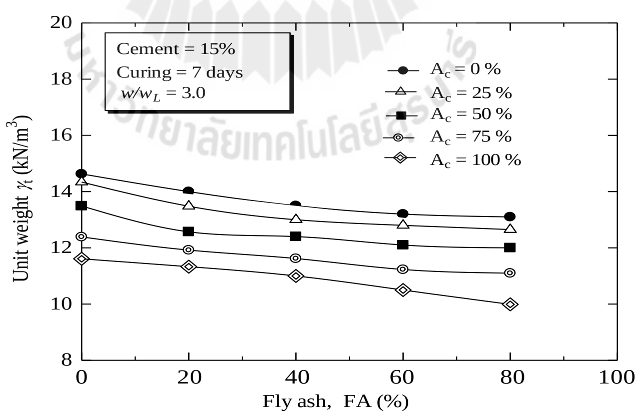
(b)

Figure 4.3: Relationship between strength and FA replacement of lightweight cemented clay samples (a) w/w_L = 2 and C = 10% (b) w/w_L = 3 and C = 15%

Effects of fly ash on the unit weight of the lightweight cemented samples for w/w_L values of 2-3 and cement contents of 10-15% are illustrated in Figure 4.4. The unit weight decreases with increasing FA replacement for all input air contents. The higher the air content, the lower the unit weight. The reduction in γ is because G_s of FA is lower than that of the clay.



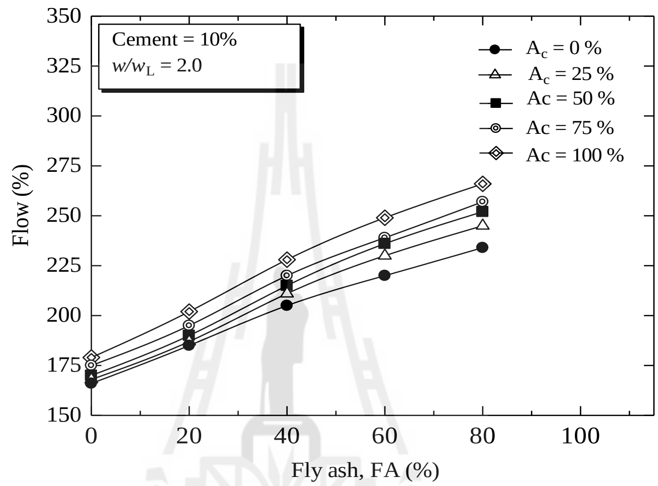
(a)



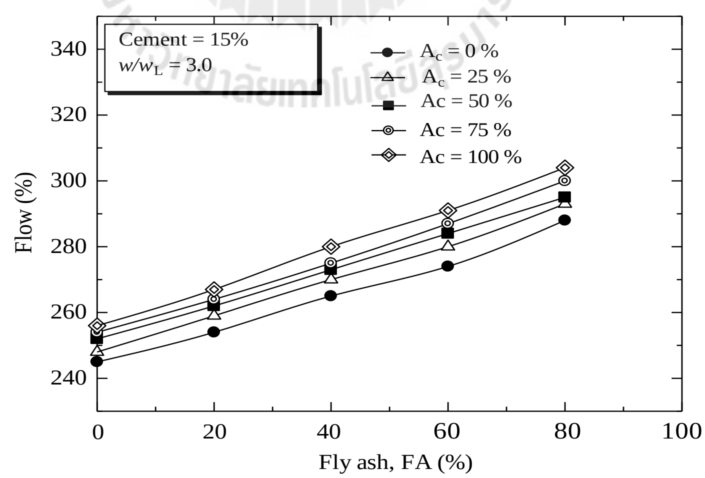
(b)

Figure 4.4: Relationship between unit weight and FA replacement of lightweight cemented clay samples with the same w/w_L of 2-3 and cement content of 10-15%. (a) w/w_L = 2 (b) w/w_L = 3

The role of fly ash on the flowability is shown in Figure 4.5 for lightweight cemented clay. For a particular air content, the flowability increases insignificantly with increasing fly ash because fly ash is sphere and they are material dispersion. The air foam and water content also increases the flowability of the lightweight cemented clay.



(a)



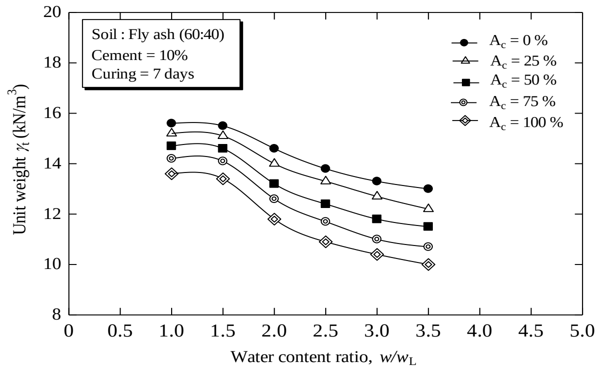
(b)

Figure 4.5: Flowability and fly ash relationship of lightweight cemented fly ash-clay for different air contents. (a) $w/w_L = 2$ (b) $w/w_L = 3$

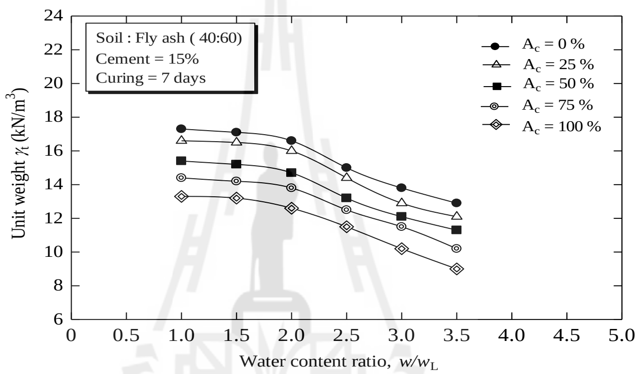
To conclude, the advantage of FA replacement is to decrease unit weight and increase flowability. The advantage in terms of strength is noticed when FA replacement is greater than 50%. Thus, the unit weight, strength and flowability of lightweight samples with low to high FA replacements (40, 60, 80) are illustrated in the following sections.

4.5 Unit weight characteristics

Figure 4.6 shows the relationships between unit weight and generalized stress state, w/w_L, of the lightweight cemented clay at different fly ash replacements. The change in unit weight is of the same pattern for different soil : FA replacement. The unit weights insignificantly change with air content at low water content. The unit weights decrease with air contents when water contents are greater than the transitional water content. This transitional water content is about $1.9w_L$ for lightweight cemented clay. This improves that the suitable water content to produce the lightweight cemented clay is $1.9w_L$. This results is in agreement with that by Horpibulsuk et al., (2012b).



(a)



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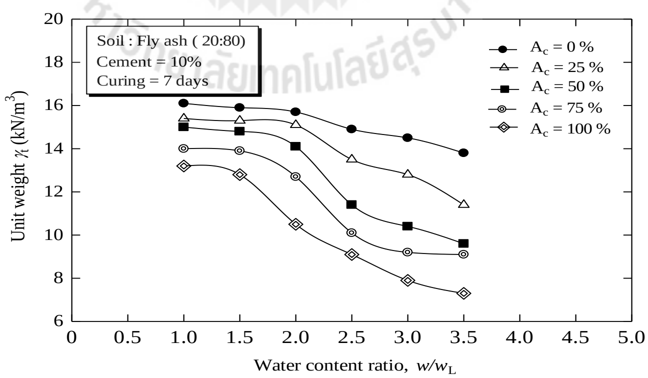


(c)

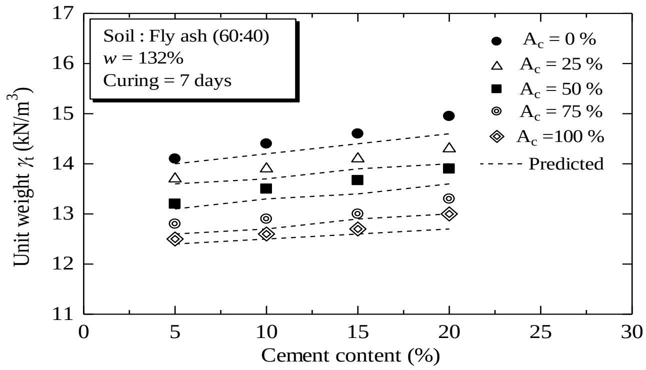
Figure 4.6: Unit weight and water content relationship of lightweight cemented fly ash-clay at different fly ash replacement. (a) Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80

Recently, the unit weight, strength and compressibility characteristics of lightweight cemented clay have been studied extensively by Horpibulsuk et al. (2012b). Based on the phase diagram, the unit weight (in kN/m^3) was determined in terms of water content, cement content and void/cement ratio by the following equation:

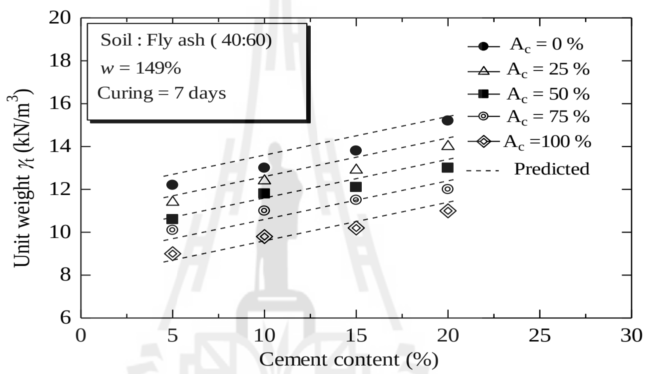
$$\gamma = \frac{\left(\frac{G_c G_s \gamma_w^{\ 2}(1+w)}{C} + G_c \gamma_w\right)}{\left(\frac{G_c \gamma_w}{C} + 1\right)} - (V/C)\left(\frac{G_s \gamma_w (1+w)}{\frac{G_c \gamma_w}{C} + 1}\right) \tag{1}$$

where w is water content (decimal), G_c, G_s are the specific gravity of cement and soil, respectively, γ_w is unit weight of water (kN/m^3), C is cement content (kg/m^3) and V/C is the void/cement ratio, which is the volume of void to the volume of cement in the mix. The theoretical derivation of the equation is referred to Horpibulsuk et al. (2012b). The equation was developed based on the assumption that all air bubbles (air foam) enter into the pore space when mixed with cement and clay.

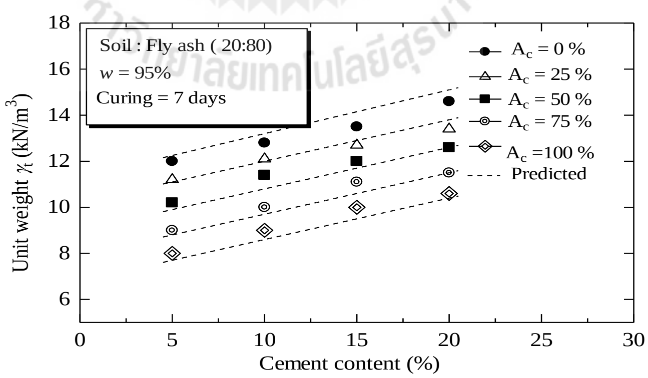
Effects of water content, cement content and air content on the unit weight are illustrated in Figures 4.7, 4.8 and 4.9 for 40, 60 and 80% FA replacement, respectively. The unit weight increases slightly with increasing cement content for all input air contents at a given water content because the cement possesses higher specific gravity than the clay. The air content decreases significantly the unit weight of the lightweight cemented clay. The decrease rate is almost the same for different water contents. The water content also plays a significant role on the reduction in unit weight of the lightweight cemented clay. For all air contents, the unit weight decreases significantly with increasing the water content. The change in unit weight with cement content, air content and water content can be predicted by Eq. (1) as shown by the dashed lines. In the prediction, G_s was taken as the specific gravity of the mixed clay (clay and fly ash).



(a)

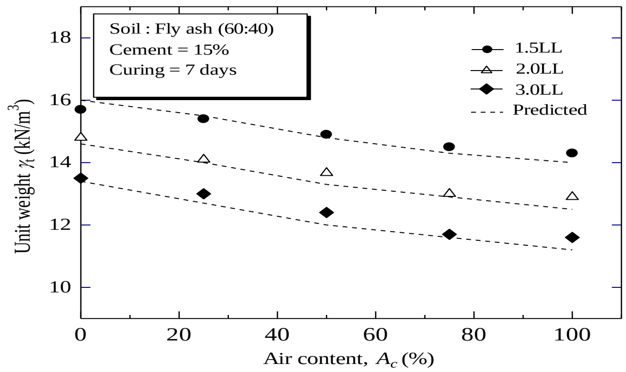


(b)



(c)

Figure 4.7: Effects of cement content on unit weight of lightweight cementedclay. (a)Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80



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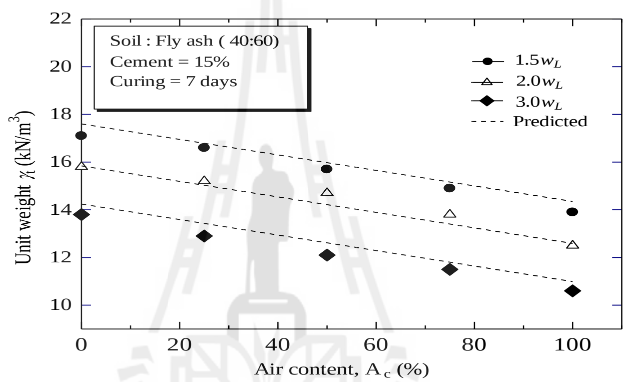

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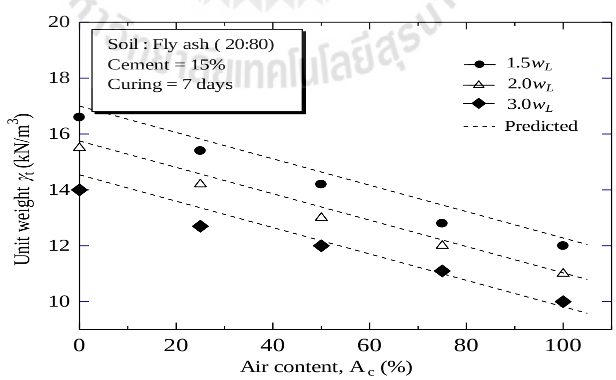


(c)

Figure 4.8: Effects of air content on unit weight of lightweight cemented clay.

(a) Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly-ash = 20:80

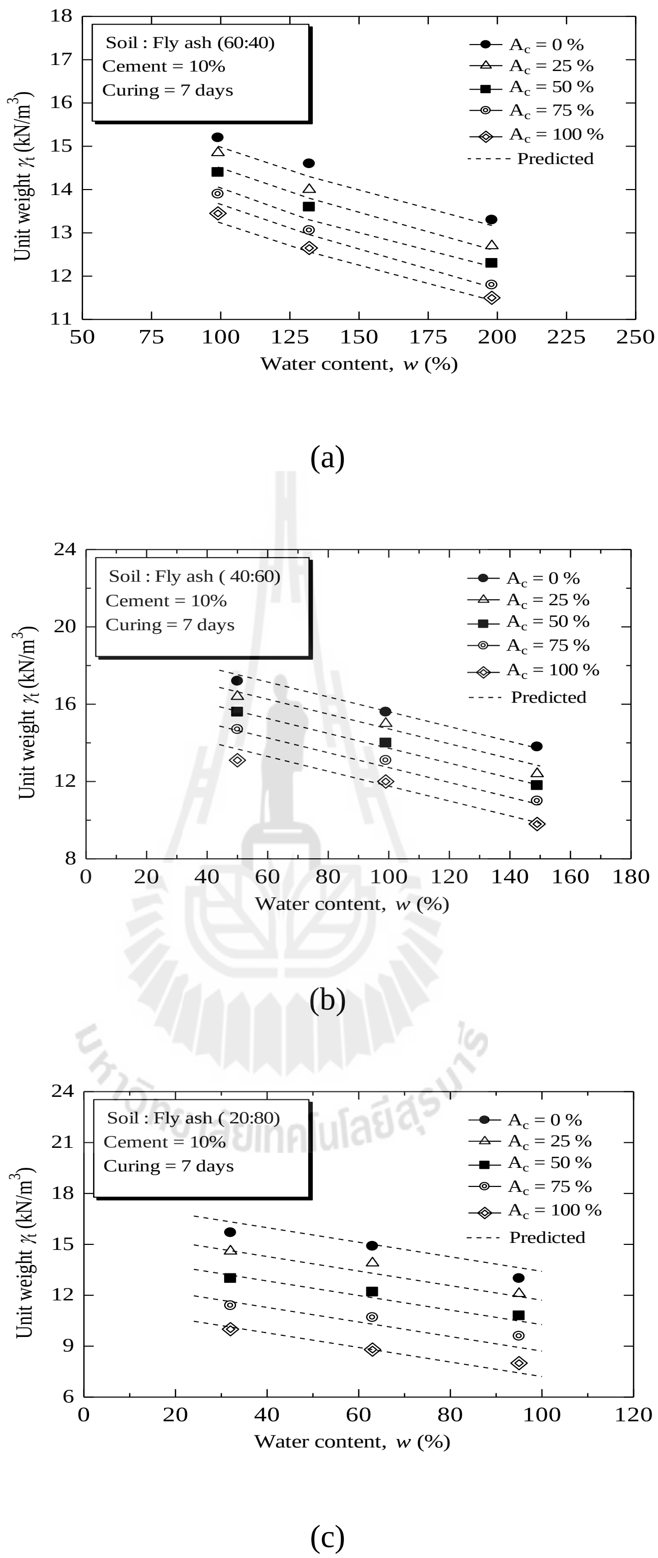


Figure 4.9: Effects of water content on unit weight of lightweight cemented clay. (a) Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : fly ash = 20:80

Figure 4.10 shows the comparison between the predicted and measured unit weights of lightweight cemented clay at different water contents and fly ash replacements. The predicted unit weights are generally higher than the measured ones because all the air foams cannot enter into the pore space due to the viscosity of the clay. Because the viscosity decreases as the clay-water content increases, the prediction error decreases with increasing water content.

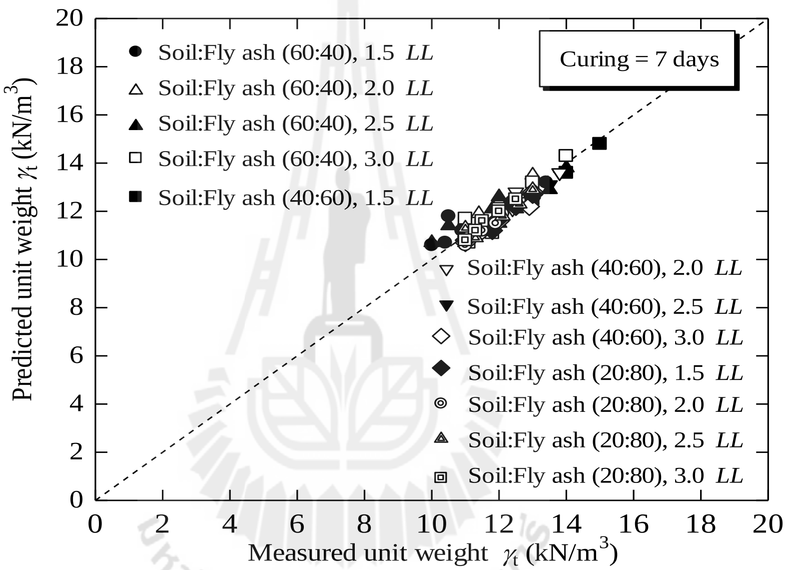
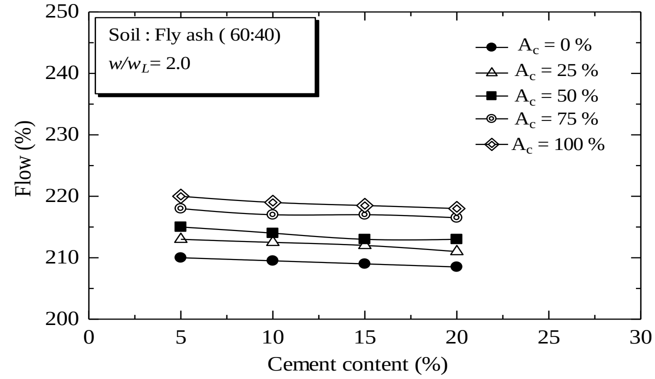


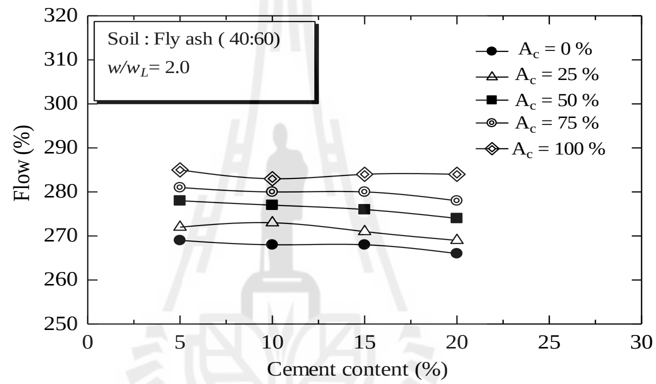
Figure 4.10: Predicted and measured unit weights of lightweight cemented fly ash-clay.

4.6 Flowability characteristics

The role of cement on the flowability is shown in Figure 4.11 for lightweight cemented clay at different fly ash ratios of 60:40, 40:60 and 20:80 and w/w_L of 2. The cement content insignificantly affects the flowability for a particular water content and air content.



(a)



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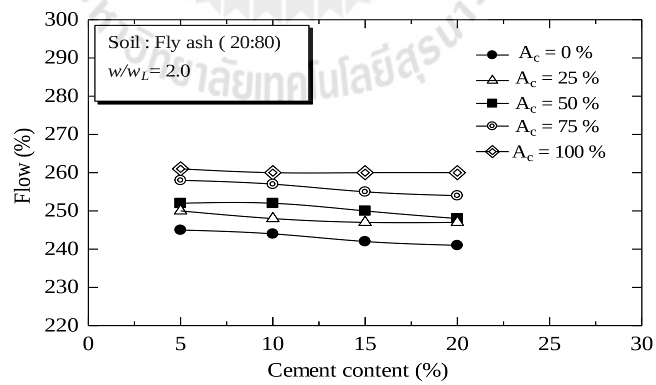
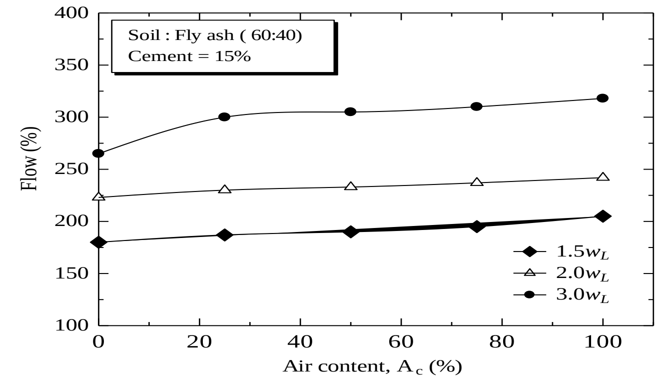


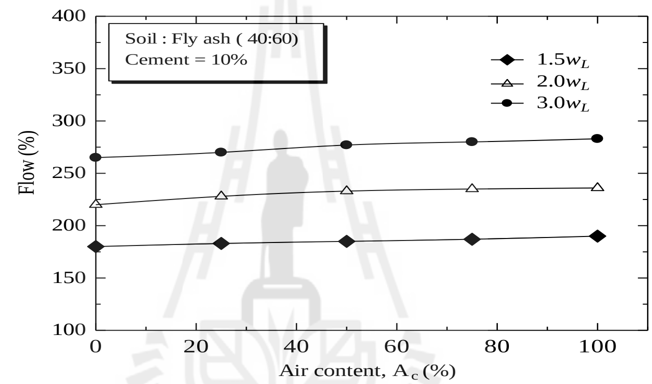
(c)

Figure 4.11: Flowability and cement content relationship of lightweight cemented fly-ash-clay for different air contents and fly ash replacements. (a) Soil : Fly-ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80

The change in flowability with air content for different water contents is shown in Figure 4.12. From Figures 4.11 and 4.12, it is shown that the flowability is significantly dependent upon water content irrespective of cement content. The change in flowability with air content from 0 to 100% for different water contents tested is within 10%.



(a)



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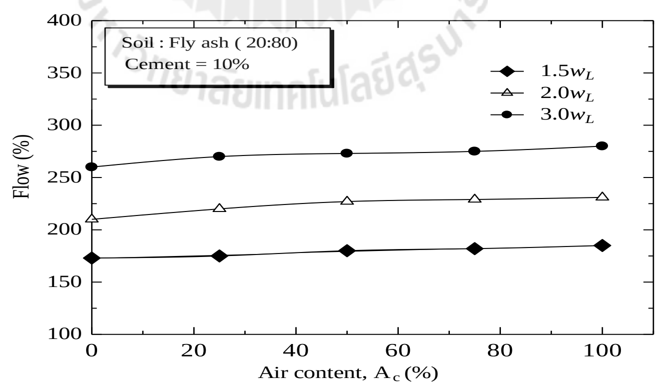


(c)

Figure 4.12: Flowability and air content relationship of lightweight cemented fly ash-clay for different water contents and fly ash replacements. (a) Soil : Fly-ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80

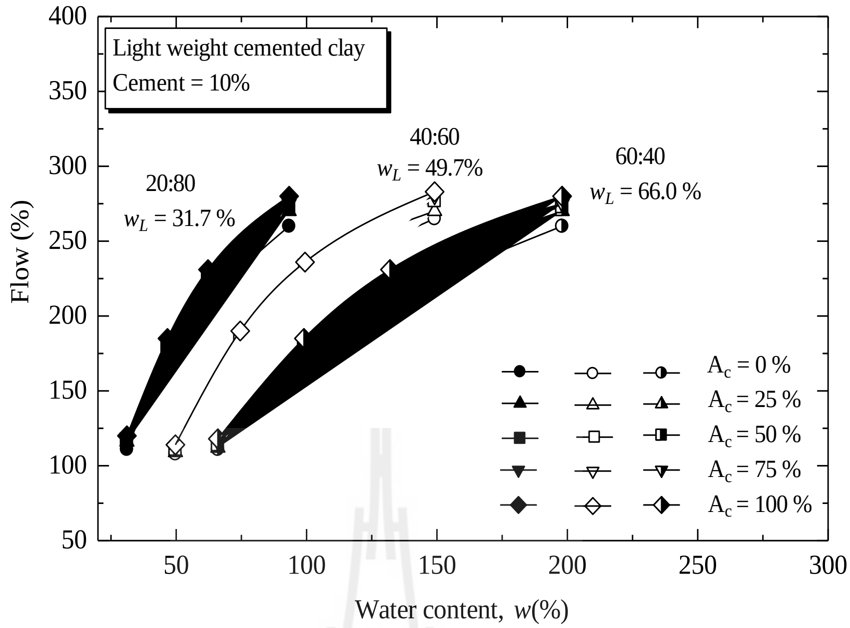


Figure 4.13: Flowability and water content relationship of lightweight cemented fly ash-clay for different air contents and fly ash replacements.

Figure 4.13 summarizes both effects of water content and air content on the flowability for different soil : FA ratios. It is shown that for a particular air content the water content required to obtain the same flowability is less for the samples with higher FA replacement. Since the flowability is directly related to shear strength, both are controlled by the generalized stress state. Figure 4.14 shows the flowability and w/w_L relationship for different air contents. This figure shows that for the same air content, the flowability is significantly dependent upon w/w_L and the flowability increases with air content for the same w/w_L .

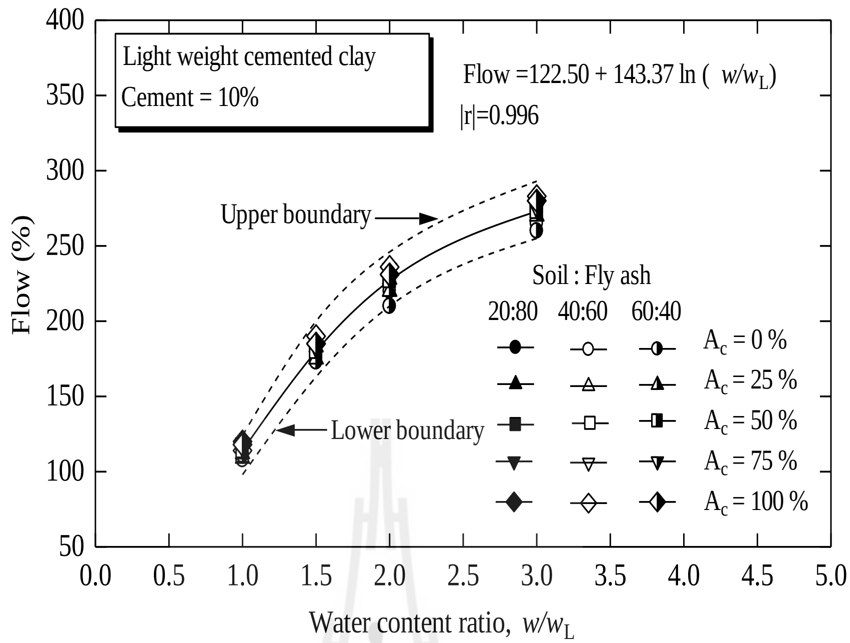
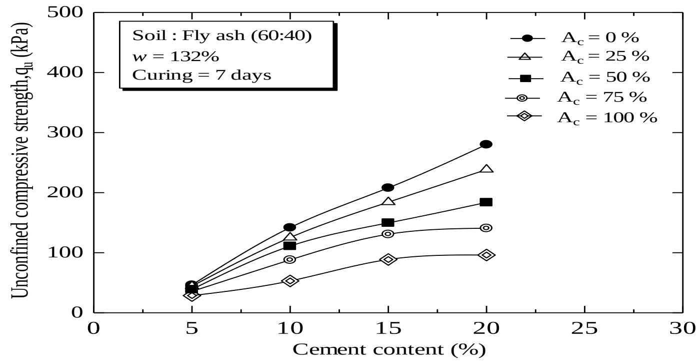


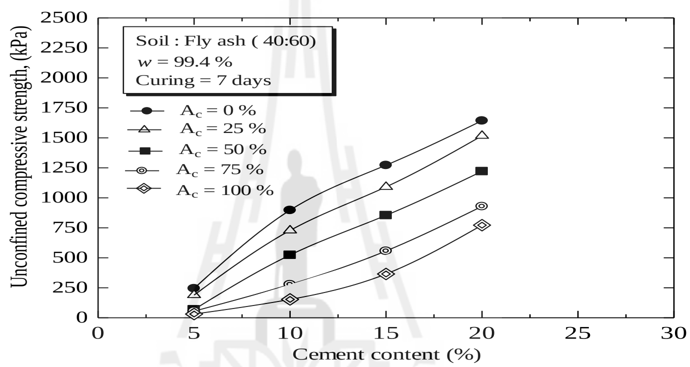
Figure 4.14: Flowability and w/w_L relationship of lightweight cemented clay

4.7 Unconfined compressive strength characteristics

Figures 4.15, 4.16 and 4.17 show the influence of the water content, cement content and air content on the strength of lightweight samples with 40, 60 and 80% FA replacement. As expected, for a given water content and air content, the strength increases significantly with cement content. On the other hand, the strength decreases remarkably with the increase in water content and air content, which increases the pore space among the clay clusters (decreases cement per contact area) (Miura et al., 2001; Horpibulsuk et al., 2003, 2005, 2011a and 2012a). It is of interest to note that the reduction in the strength due to the increase in air content (from 0 to 100%) is remarkably less than that due to the increase in water content (compare Figures 4.16 and 4.17).



(a)



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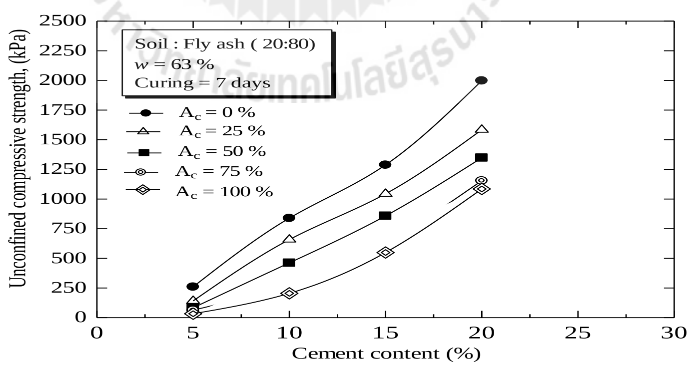
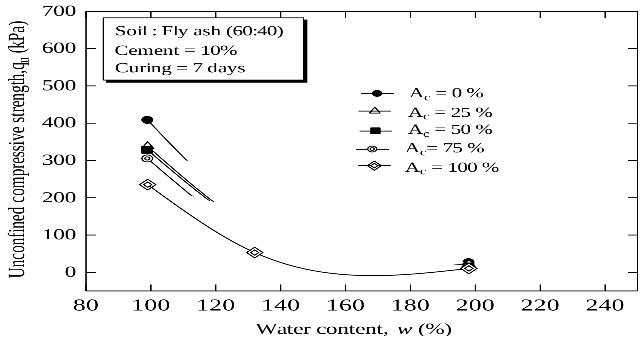
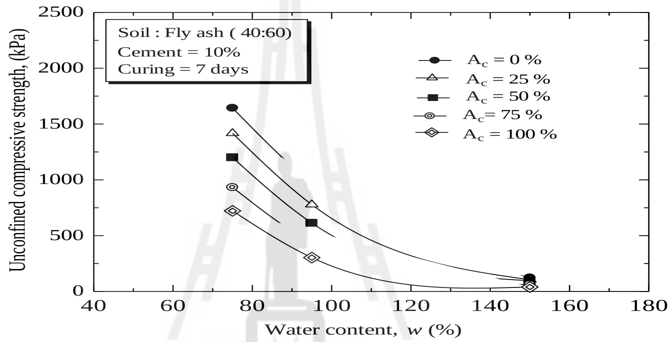


(c)

Figure 4.15: Effects of cement content on strength of lightweight cemented clay. (a) Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80



(a)



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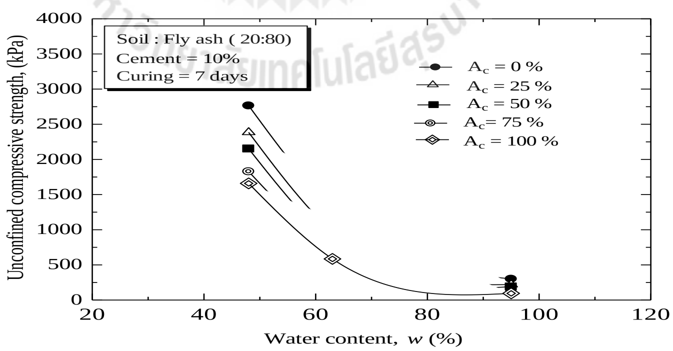
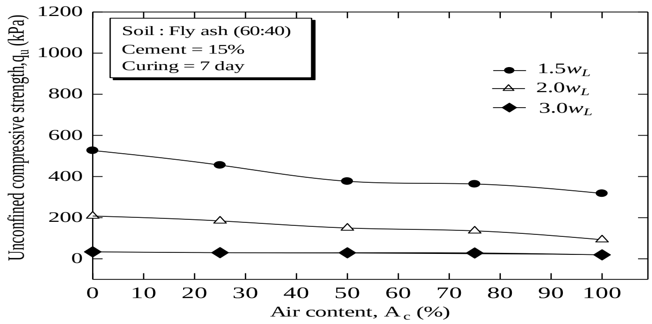


(c)

Figure 4.16: Effects of water content on strength of lightweight cemented clay.

(a) Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80



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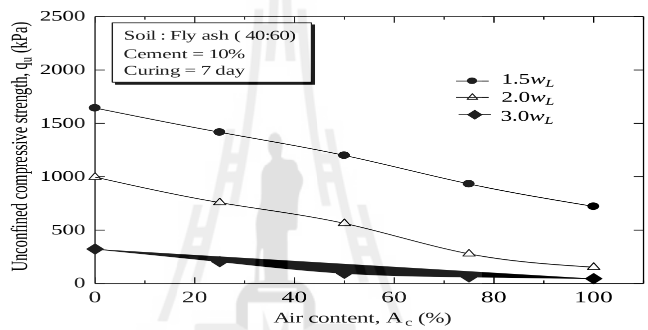

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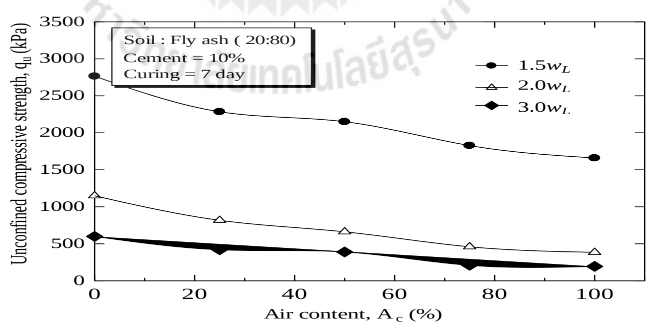


(c)

Figure 4.17: Effects of air content on strength of lightweight cemented clay. (a) Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80

4.8 Mix design

The reduction in unit weight by both increasing water content and air content is generally associated with the reduction in strength. The advantage of adding air foam over adding water to make the lightweight cemented clay in terms of strength development is illustrated in Figure 4.18. It shows the relationships between strength and unit weight of lightweight cemented samples for different water contents and air contents but the same input of cement. For a same range of unit weight, the lightweight cemented samples with lower water content but higher air content have higher strength than those with higher water content but lower air content. For example, at unit weight of 15 kN/m^3, the strengths are 25 kPa, 50 kPa and 210 kPa for 198%, 132 and 99%, respectively.

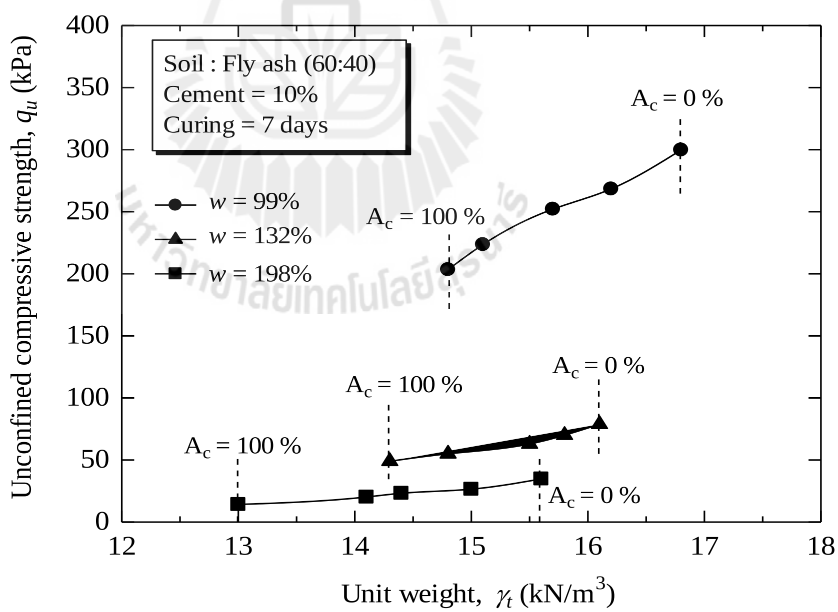
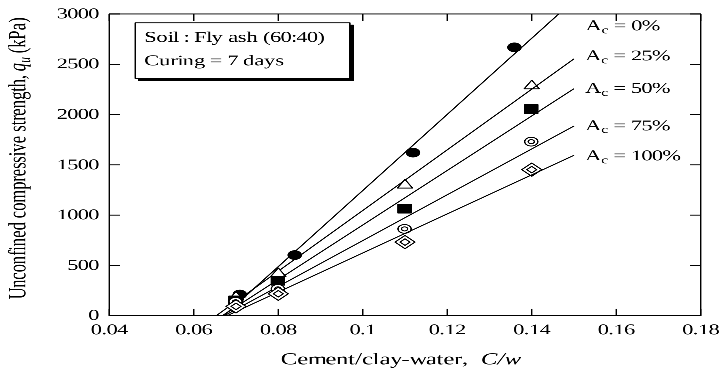
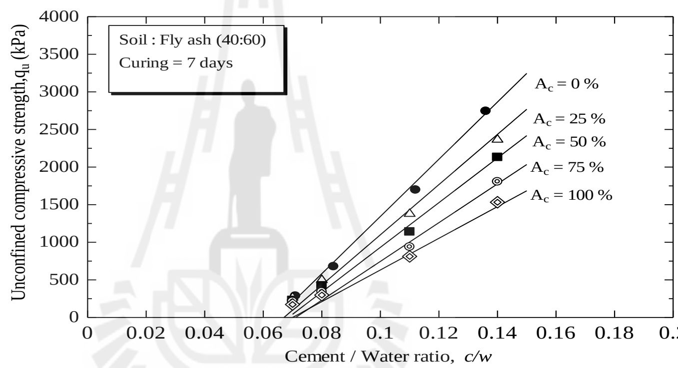


Figure 4.18: Relationship between strength and unit weight of lightweight cemented clay samples with different water content for the same cement content and replacement ratio.

Based on the concrete technology (Abrams' 1918), the strength of cemented material is governed by the ratio of cement to water. As an analogy, the parameter that can be identified for cemented clays is cement/clay-water ratio, C/w (Miura et al., 2001; Horpibulsuk et a., 2003, 2005, 2011a, b and 2012a), which is the ratio of cement content (%) to initial clay water content (%). The cement content, C is the ratio of cement to clay by weight both reckoned in their dry state. The relationships between strength and C/w for w/w_L = 1.5-3.0 can be represented by linear function (Figure 4.19) for different air contents. For the same C/w, the strength decreases as the air content increases due to the increase in cementitious products per contact areas. Using these linear relationships, the strength of the lightweight cemented clay at different water contents and cement contents for a design air content can be approximated based on few trial tests.



(a)



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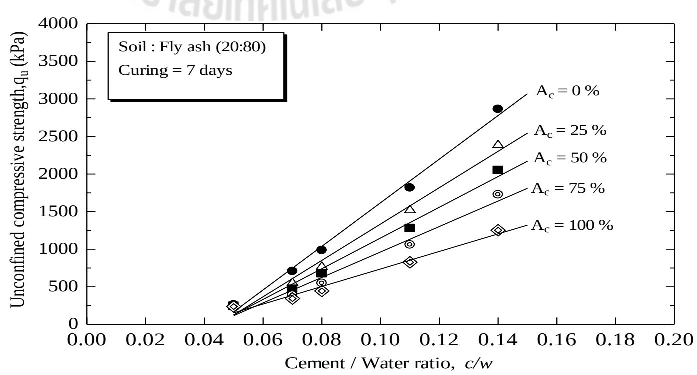

(c)

Figure 4.19: Strength development with cement/clay-water ratio. (a) Soil : Fly ash = 60:40 (b) Soil : Fly ash = 40:60 (c) Soil : Fly ash = 20:80

The unit weight of the lightweight cement clay can then estimated from Eq. (1) and flowability boundary from Figure 4.14. Based on the laboratory investigation, a mix design procedure to arrive at the target strength unit weight and flowability is suggested and presented by the following steps:

1. Determine the FA content to be mixed with a moist clay. FA content should be greater than FA fixation point. The FA fixation point can be simply obtained from the index test.
2. Adjust the clay water content to a range of w/w_L = 1.5 to 3.0.
3. Conduct trail unconfined compression tests on the lightweight cemented samples with different water contents, cement contents and air contents.
4. Develop the relationship between strength and C/w for different air contents.
5. From the target strength, determine the required C/w and air content.
6. For a selected air content, adjust water content and cement content to attain the target unit weight using Eq.(1).
7. Using Figure 4.14, determine the flowability.

CHAPTER V

CONCLUSIONS

The role of water content, cement content, air content and replacement ratio on the strength unit weight and flowability of the lightweight cemented clay is illustrated in this research. The FA replacement slightly decreases liquid limit when FA replacement is less than FA fixation point. Beyond this value, the liquid limit reduces significantly. Because the FA fixation point is simply obtained from the index test, it is a practical indicator to determine the minimum FA replacement. The addition of air foam to the moist clay is more advantage than that of water in terms of strength. For the same unit weight, the strength of a sample with a high air content is higher than that with a high water content. Eq. (1) was proved as suitable for predicting the unit weight of the lightweight cemented clay with different water contents, cement contents and air contents. Based on the Abrams' law, a relationship between strength and cement/clay-water ratio for a particular air content is proposed. The relationship is useful in estimating the laboratory strength wherein water content and cement content vary over a wide range by 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. Finally, a mix design procedure to arrive at the target strength flowability and unit weight is suggested.

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APPENDIX A

PUBLICATION

Publication

Horpibulsuk, S., Wijitchot, A., Nerimitknornburee, A., and Shen, S.L. **Factors influencing unit weight and strength of lightweight cemented clay**. (submit)

Technical note to Quarterly Journal of Engineering Geology & Hydrogeology

FACTORS INFLUENCING UNIT WEIGHT AND STRENGTH OF LIGHTWEIGHT CEMENTED CLAY

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FACTORS INFLUENCING UNIT WEIGHT AND STRENGTH OF LIGHTWEIGHT CEMENTED CLAY

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ABSTRACT: Lightweight cemented clay has wide applications in the infrastructure rehabilitation and in the construction of new facilities. Effects of water content, cement content, air content and fly ash on the unit weight and strength of lightweight cemented clay are analyzed and presented in this article. Fly ash, FA decreases liquid limit and plasticity index of the clay. Consequently, it improves the unit weight, strength and workability to the lightweight cemented clay. For the same generalized stress state, w/w_L, the lightweight cemented clay with higher replacement ratio has higher strength for the same input of cement due to higher cement/clay-water ratio, *C/w*. The FA fixation point is a practical indicator to obtain a minimum FA replacement because it is simply obtained from index test. The prediction of unit weight of the lightweight cemented clay for different water contents, air contents, fly ash replacement ratios and cement contents is performed and verified. From the critical analysis of test results, a mix design method to attain the target strength and unit weight is suggested. This method is useful for both engineering and economic viewpoints.

KEYWORDS: air foam, cement, compressive strength, fly ash, lightweight material, unit weight

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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 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 around the world, including Thailand (Arulrajah et al., 2009; Chai and Pongsivasathit, 2010; and Horpibulsuk et al., 2004c; 2011b; 2012c). 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. Instead of improving the soft ground (foundation), the use of lightweight 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 alternative means. Lightweight materials have wide applications in the infrastructure rehabilitation and in the construction of new facilities.

The advantage of the lightweight cemented clay is cost-effective in terms of construction time, material and transportation. This material does not require compaction and saves the transportation cost of the suitable granular backfill material from distant sources. With time, strength, stiffness and Poisson's ratio of lightweight cemented clay increase; hence, the resistance to lateral movement. The lightweight cemented 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; and Kikuchi et al., 2011). Recently, the unit weight, strength and compressibility characteristics of lightweight cemented clay have been studied extensively by Horpibulsuk et al. (2012b). Based on the phase diagram, the unit weight (in kN/m^3) was proposed in terms of water content, cement content and void/cement ratio by the following equation:

$$\gamma = \frac{\left(\frac{G_c G_s \gamma_w^{2}(1+w)}{C} + G_c\gamma_w\right)}{\left(\frac{G_c\gamma_w}{C}+1\right)} - (V/C)\left(\frac{G_s\gamma_w(1+w)}{\frac{G_c\gamma_w}{C}+1}\right) \quad (1)$$

where w is water content (decimal), G_c, G_s are the specific gravity of cement and soil, respectively, γ_w is unit weight of water (kN/m^3), C is cement content (kg/m^3) and V/C is the void/cement ratio, which is the volume of void to the volume of cement in the mix. The theoretical derivation of the equation is referred to Horpibulsuk et al. (2012b). The equation was developed based on the assumption that all air bubbles (air foam) enter into the pore space when mixed with cement and clay.

To reduce the construction cost of the lightweight cemented clay, the replacement of cement by waste materials such as fly ash and biomass ash is one of the best alternative ways. Application of fly ash for geotechnical works has been reported by many researchers (Kawasaki et al., 1981; and Kehew, 1995). The role of fly ash on the strength development in the blended cement admixed clay has been investigated both from micro- and micro observations (Horpibulsuk et al., 2009). Fly ash disperses large clay-cement clusters formed due to physicochemical interaction into smaller clusters. The dispersion leads to the increase in the reactive surface, and hence strength enhancement.

Even though there are available studies on the engineering properties of lightweight cemented clay, the study on the effect of blended cement (cement and fly ash) on the unit weight and strength is so far very limited. This article aims to illustrate the role of fly ash, on the improvement of the soil index properties and hence unit weight and strength improvement. The applicability of Eq.(1) to predict the unit weight of lightweight cement clay for different mix proportions is depicted. Discussion on effects of water content and air content on the unit weight of the lightweight cemented clay for different cement contents is made. Finally, a suggested method for mix design of the lightweight cemented clay is introduced based on a critical analysis of the test results.

2. MATERIALS AND METHODS

2.1 Soil Sample

Bangkok clay was collected from Bangkok Noi district, Bangkok, Thailand at a 3 meter depth. Bangkok 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).

2.2 Cement, fly ash and air foam agent

Type I Portland cement (PC), fly ash (FA) from Mae Moh power plant in the north of Thailand and air foam agent, Darex AE4, provided by the Grace Construction Products Ltd, were used in this study. The specific gravity of PC is 3.15 and the median particle size (D_{50}) is 0.01 mm (10 micron). 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. Total amount of the major components SiO_2, Al_2O_3, and Fe_2O_3 in FA are 79.44%. FA is classified as class F fly ash in accordance with ASTM C 618. The D_{50} of FA is 0.009 mm (9 micron) and the specific gravity is 2.54.

2.3 Methodology

The clay paste was passed through 2-mm sieve for removal of shell pieces and other bigger size particles, if present. The water content was adjusted to (1.5-3) times liquid limit as recommended by Horpibulsuk et al. (2012b). The lower water content possesses high viscosity and resists the air bubble entry into the pore space. The clay was replaced by the fly ash with the replacement ratios of 0, 40, 50, 60, and 80% and mixed with air foam. The air contents, A_c, were varied between 10 and 100% by volume of the clay-water-air mixture. The clay-water-air-fly ash mixture was then thoroughly mixed with cement for 10 min. The cement content, C, was varied from 10 to 40% by weight of dry mixed soil (clay and FA). Such a uniform paste was transferred to cylindrical containers of 50 mm diameter and 100 mm height, taking care to prevent any air entrapment. After 24 hours, the cylindrical samples were dismantled. All the cylindrical samples were wrapped in vinyl bags and were stored in a humidity room of constant temperature (20±2°C) until lapse of different curing times as planned. Unit weights and unconfined compressive strengths of the samples were measured after 7 days of curing. The rate of vertical displacement in UC tests was 1 mm/min. The tests were performed according to the American Society of Testing and Materials (ASTM) standards.

3. RESULTS

Fly ash and soil are particulate materials, which are composed of individual units. The particulate materials can be regarded as either non-interacting or interacting materials, dependent upon the absence or presence of physicochemical interactions with the pore fluid. Fly ash, silt, and sand are non-interacting materials, primarily due to their low specific surface and non-electrical nature of surfaces. The replacement of the fly ash thus affects consistency limits of the clay. Figure 1 shows the change of the consistency limits with the replacement ratio. The liquid limit of the mixed clay reduces gradually with FA replacement when the FA replacement is less than 50% and the reduction in liquid limit becomes remarkable when the FA replacement is greater than 50%. The plastic limit changes insignificantly with the range of FA replacement tested. As such, the reduction in the plasticity index is clearly observed at about 50% FA replacement. This FA replacement is regarded as FA fixation point.

Effects of water content, cement content and air content on the unit weight are illustrated in Figure 2 for 40% FA replacement. The unit weight increases slightly with increasing cement content for all input air contents at a given water content because the cement possesses higher specific gravity than the clay. The air content decreases significantly the unit weight of the lightweight cemented clay. The decrease rate is almost the same for different water contents. For instance, the unit weights decrease from 15.8 kN/m^3 to 14.2 kN/m^3 for water content of 100% and from 13.5 kN/m^3 to 11.8 kN/m^3 for water content of 200% when the air content increases from 0 to 100%. The water content also plays a significant role on the reduction in unit weight of the lightweight cemented clay. For all air contents, the unit weight decreases significantly with increasing the water content. The change in unit weight with cement content, air content and water content can be predicted by Eq. (1) as shown by the dashed lines. In the prediction, G_s was taken as the specific gravity of the mixed clay (clay and fly ash). The predicted unit weights are slightly lower than the measured ones because all the air foams cannot enter into the pore space due to the viscosity of the clay.

Figure 3 shows the influence of the water content, cement content and air content on the strength for 40% FA replacement. As expected, for a given water content and air content, the strength increases significantly with cement content. On the other hands, the strength decreases remarkably with the increase in water content and air content, which increases the pore space among the clay clusters (decreases cement per contact area) (Miura et al., 2001; Horpibulsuk et al., 2003, 2005, 2011a and 2012a). It is of interest to note that the reduction in the strength due to the increase in air content (from 0 to 100%) is remarkably less than that due to the increase in water content (compare Figure 3a to 3c).

4. DISCUSSIONS

The FA replacement higher than the FA fixation point modifies the clay fabric by increasing the non-interacting material. The liquid limit and plasticity index decrease with increasing the FA replacement. The generalized stress state, w/w_L, can be used to illustrate the role of fly ash on the strength development where w is the clay water content and w_L is liquid limit water content. The w/w_L was successfully used to assess the engineering properties of remolded and natural clays (Horpibulsuk et al., 2007 and 2011c). 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^{-7} cm/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). Different clays at the same w/w_L have practically the same effective stress and shear resistance. As the w/w_L decreases, both the effective stress and shear resistance increase (Horpibulsuk et al., 2011c).

Figure 4 shows the role of FA replacement on the strength of the lightweight cemented clay at the same generalized stress state, w/w_L of 3 and cement content of 15%. At this generalized stress state, the mixed clay samples have essentially the same workability (shear resistance), even though their water contents are different. The strength increases gradually with FA replacement. Beyond the FA fixation point, the strength increases remarkably. Because the w_L values slightly decrease for the mixed clay samples with the FA replacement less than the FA fixation point (Figure 1), the water contents at this stress state decrease slightly with FA replacement and hence insignificant strength development. The same is not true for the mixed clay with higher FA replacement, the w_L values reduce significantly. Thus, the strength development is remarkable with increasing the FA replacement. The unit weight of the lightweight cemented clay is governed by both the water content and specific gravity for a particular cement content. Figure 5 shows the relationships between unit weight and FA replacement of the lightweight cemented clay at the same w/w_L of 3 and cement content of 15%. The unit weight decreases with increasing the FA replacement even though the water content decreases. This means that the low specific gravity of FA plays greater role on the reduction in unit weight. From Figure 4 and 5, it is of interest to mention that the advantage of FA replacement is the increase in workability and strength; and the decrease in unit weight. However, the FA replacement of less than FA fixation point is useless.

The reduction in unit weight by both increasing water content and air content is generally associated with the reduction in strength. The advantage of adding air foam over adding water to make the lightweight cemented clay in terms of strength development is illustrated in Figure 6. It shows the relationships between strength and unit weight of lightweight cemented samples for different water contents and air contents but the same input of cement. For a same range of unit weight, the lightweight cemented samples with lower water content but higher air content have higher strength than those with higher water content but lower air content. For example, at unit weight of 15 kN/m^3, the strengths are 25 kPa, 50 kPa and 210 kPa for 198%, 132 and 99%, respectively.

Based on the concrete technology (Abrams' 1918), the strength of cemented material is governed by the ratio of cement to water. As an analogy, the parameter that can be identified for cemented clays is cement/clay-water ratio, C/w (Miura et al., 2001; Horpibulsuk et al., 2003, 2005, 2011a, b and 2012a), which is the ratio of cement content (%) to initial clay water content (%). The cement content, C, is the ratio of cement to clay by weight both reckoned in their dry state. The relationships between strength and C/w for w/w_L = 1.5-3.0 can be represented by linear function (Figure 7) for different air contents. For the same C/w, the strength decreases as the air content increases due to the increase in cementitious products per contact areas. Using these linear relationships, the strength of the lightweight cemented clay at different water contents and cement contents for a design air content can be approximated based on few trial tests. The unit weight of the lightweight cement clay can then estimated from Eq. (1). Based on the laboratory investigation, a mix design procedure to arrive at the target strength and unit weight is suggested and presented by the following steps:

1. Determine the FA content to be mixed with a moist clay. FA content should be greater than FA fixation point. The FA fixation point can be simply obtained from the index test.
2. Adjust the clay water content to a range of w/w_L = 1.5 to 3.0.
3. Conduct trail unconfined compression tests on the lightweight cemented samples with different water contents, cement contents and air contents.
4. Develop the relationship between strength and C/w for different air contents.
5. From the target strength, determine the required C/w and air content.
6. For a selected air content, adjust water content and cement content to attain the target unit weight using Eq.(1).

6. CONCLUSIONS

The role of water content, cement content, air content and replacement ratio on the unit weight and strength of the lightweight cemented clay is illustrated in this article. The FA replacement slightly decreases liquid limit when FA replacement is less than FA fixation point. Beyond this value, the liquid limit reduces significantly. Because the FA fixation point is simply obtained from the index test, it is a practical indicator to determine the minimum FA replacement. The addition of air foam to the moist clay is more advantage than that of water in terms of strength. For the same unit weight, the strength of a sample with a high air content is higher than that with a high water content. Eq. (1) was proved as suitable for predicting the unit weight of the lightweight cemented clay with different water contents, cement contents and air contents. Based on the Abrams' law, a relationship between strength and cement/clay-water ratio for a particular air content is proposed. The relationship is useful in estimating the laboratory strength wherein water content and cement content vary over a wide range by 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. Finally, a mix design procedure to arrive at the target strength and unit weight is suggested

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Figure Captions

Figure 1: Relationship between index properties and FA replacement.

Figure 2: Effects of cement content, air content and water content on unit weight of lightweight cemented clay.

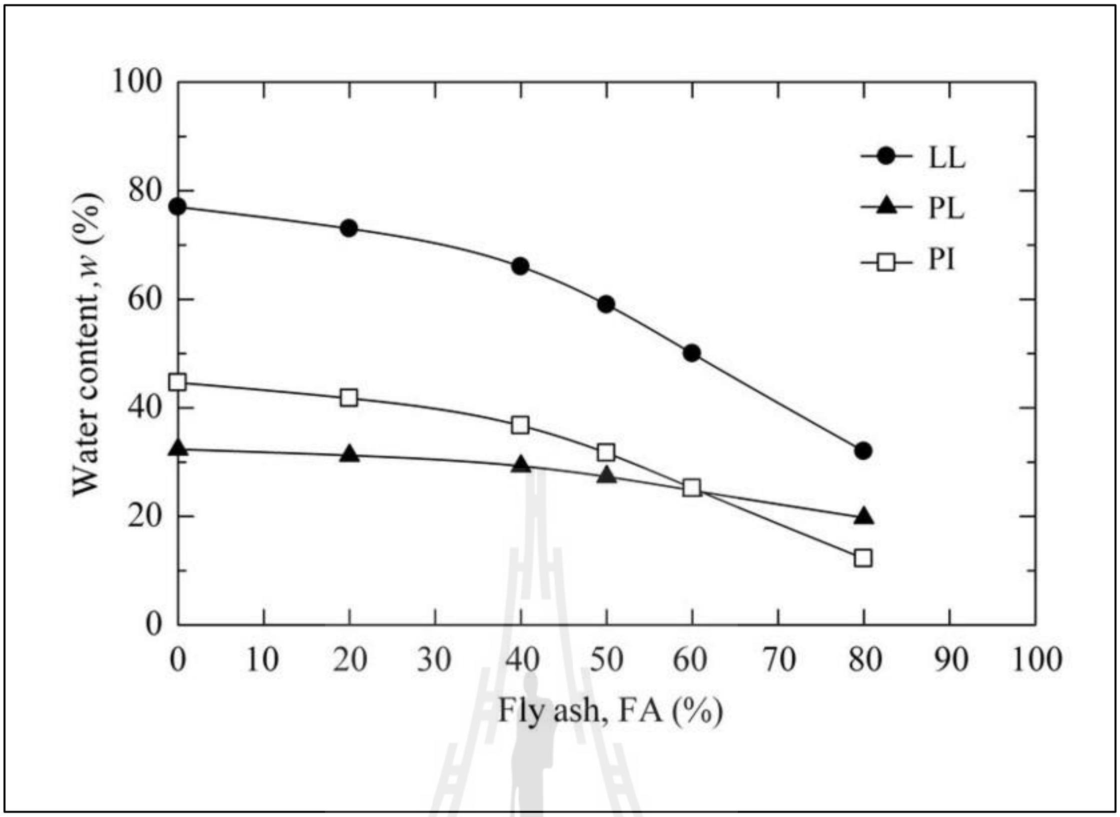
Figure 3: Effects of cement content, air content and water content on strength of lightweight cemented clay.

Figure 4: Relationship between strength and FA replacement of lightweight cemented clay samples with the same w/w_L of 3 and cement content of 15%.

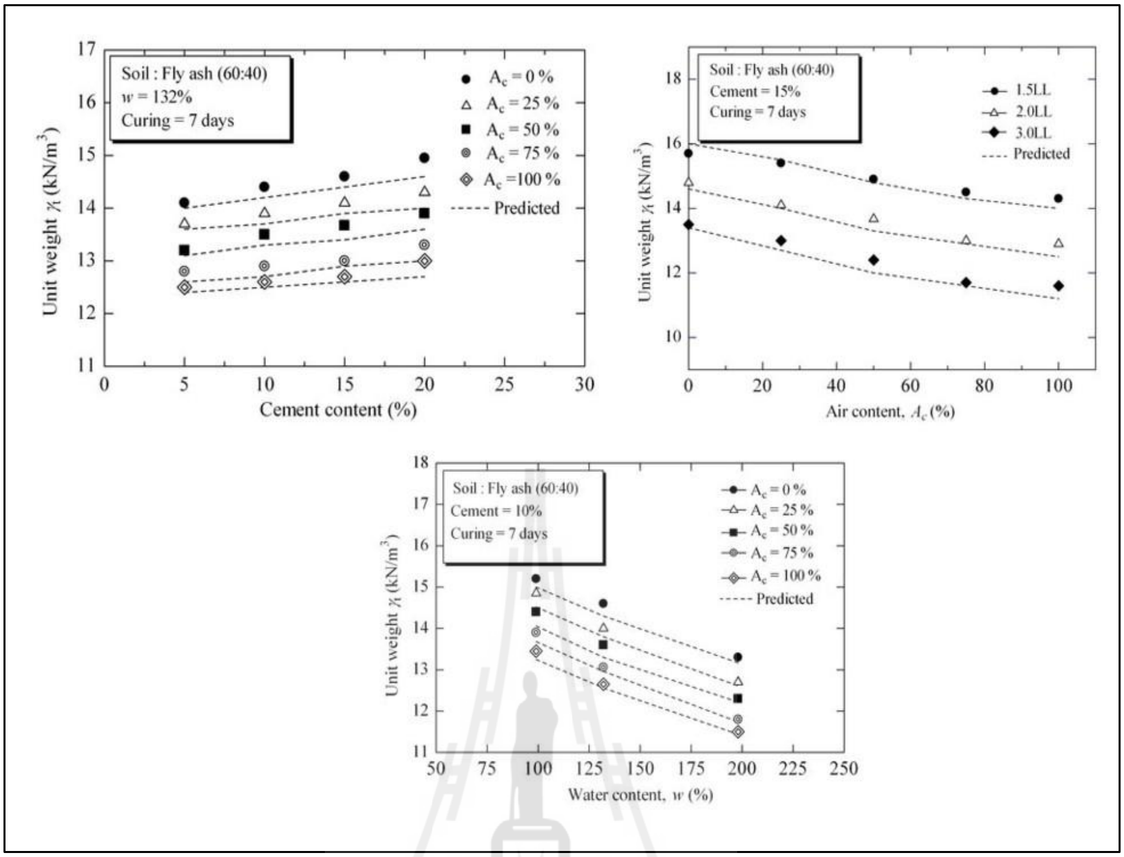
Figure 5: Relationship between unit weight and FA replacement of lightweight cemented clay samples with the same w/w_L of 3 and cement content of 15%.

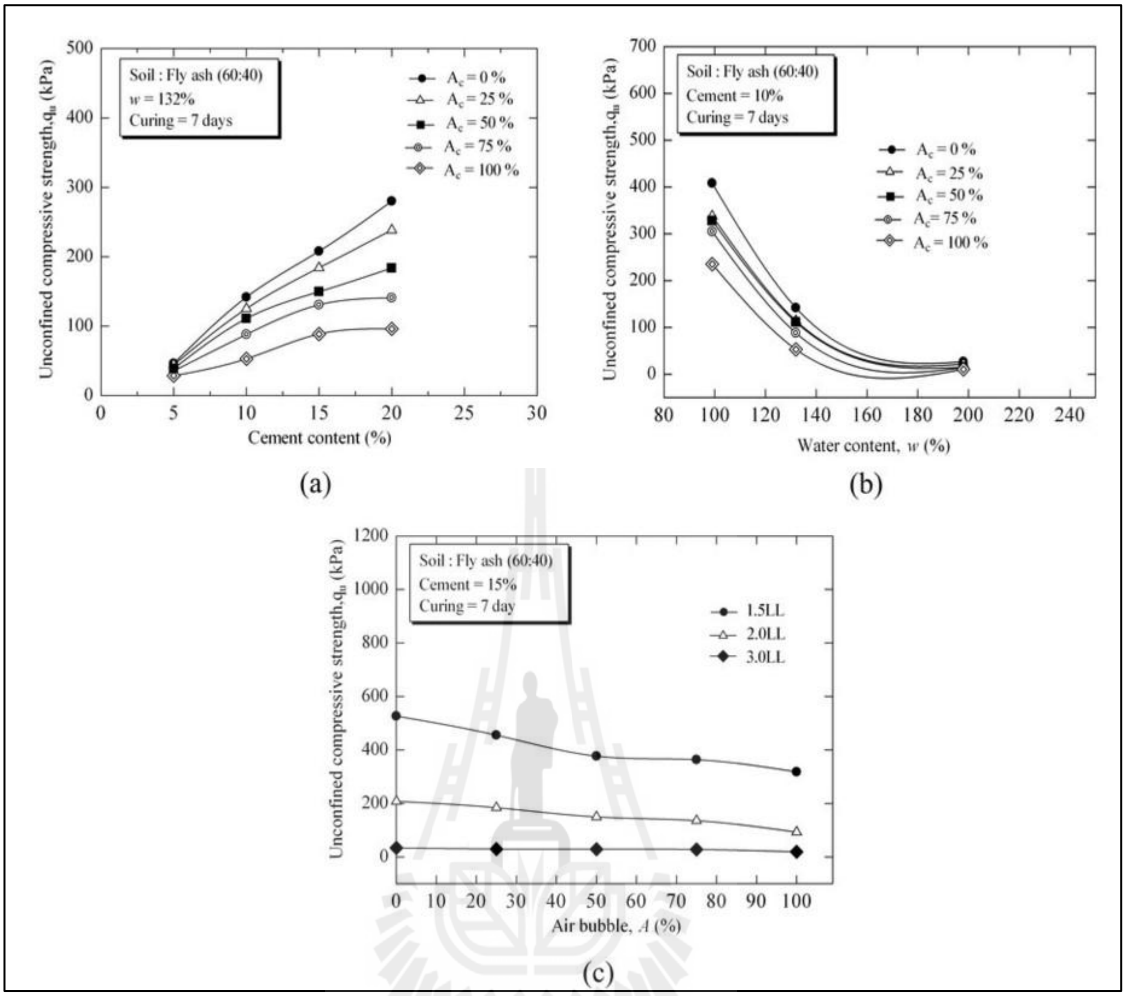
Figure 6: Relationship between strength and unit weight of lightweight cemented clay samples with different water contents for the same cement content and replacement ratio.

Figure 7: Strength development with cement/clay-water ratio.

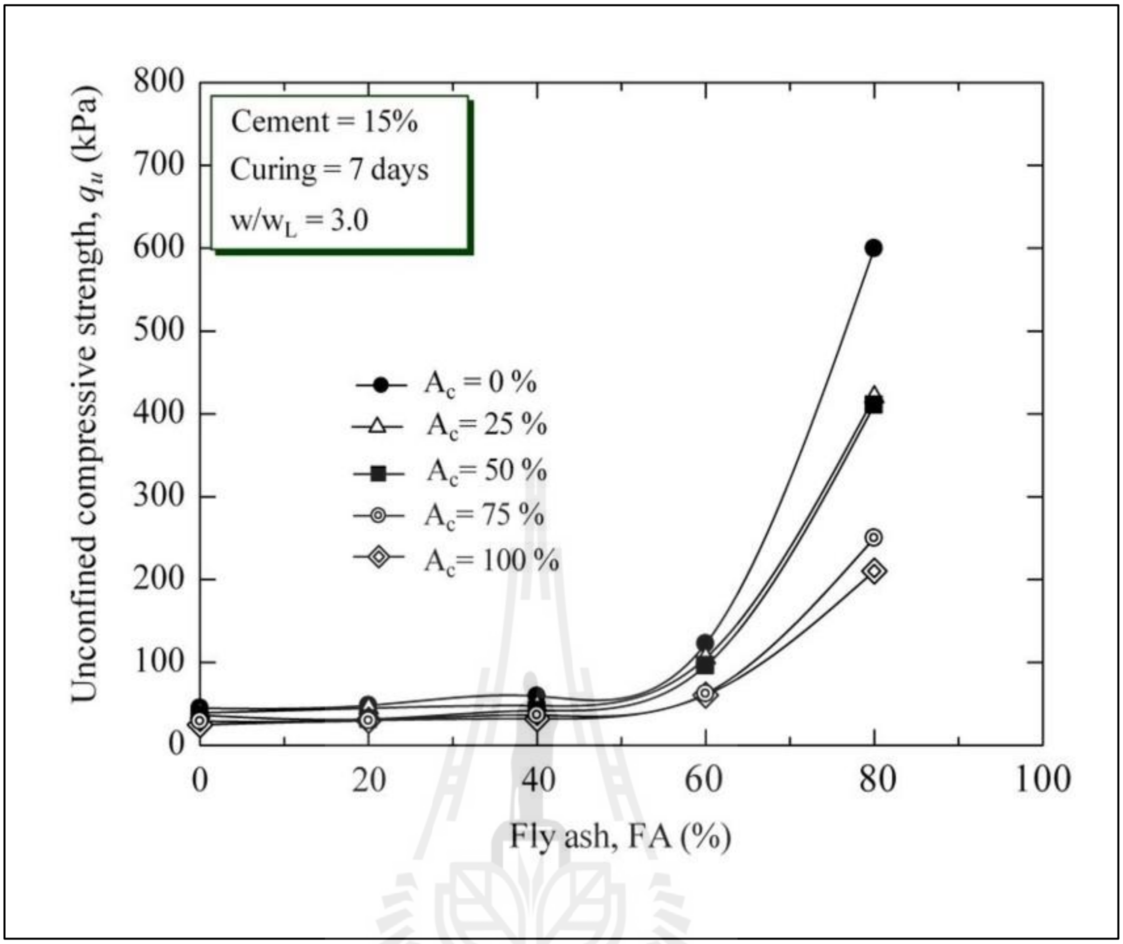


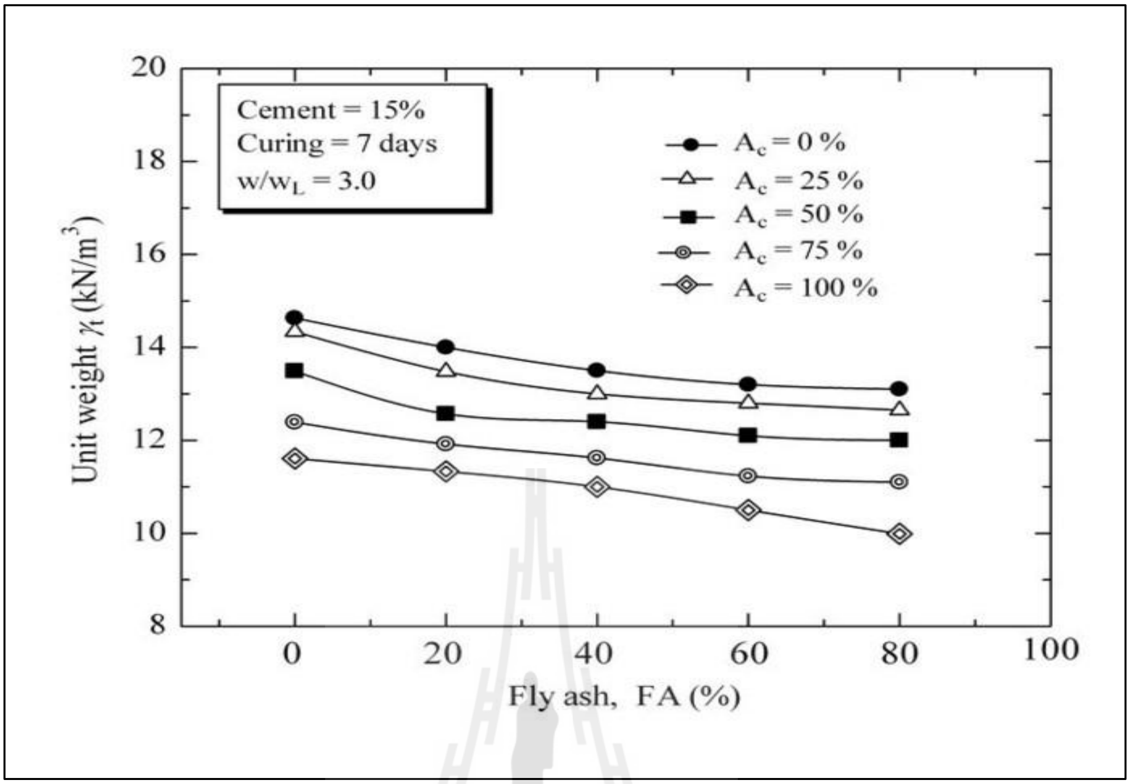
Water content, w (%)
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80
90
100
Fly ash, FA (%)
LL
PL
PI

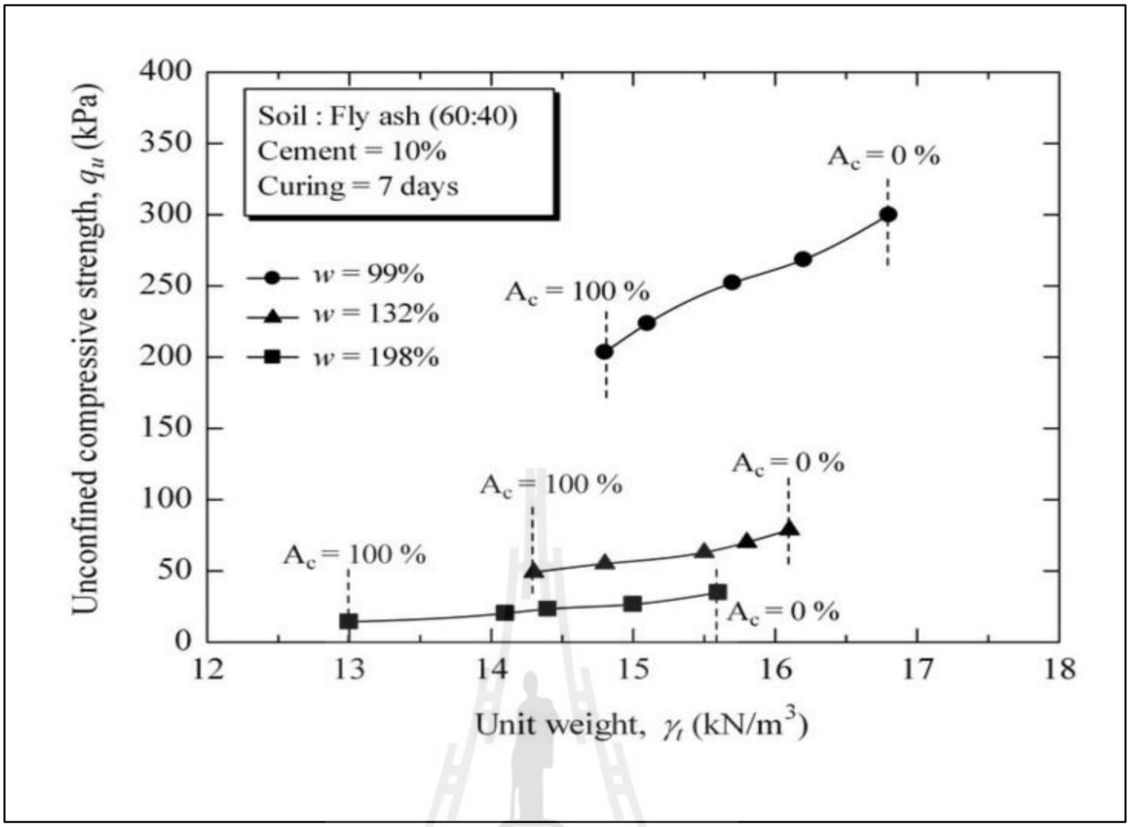

Soil : Fly ash (60:40)
w = 132%
Curing = 7 days
A_c = 0 %
A_c = 25 %
A_c = 50 %
A_c = 75 %
A_c =100 %
Predicted
Unit weight γt (kN/m3)
Cement content (%)
Soil : Fly ash (60:40)
Cement = 15%
Curing = 7 days
1.5LL
2.0LL
3.0LL
Predicted
Air content, A_c (%)
Soil : Fly ash (60:40)
Cement = 10%
Curing = 7 days
Water content, w (%)



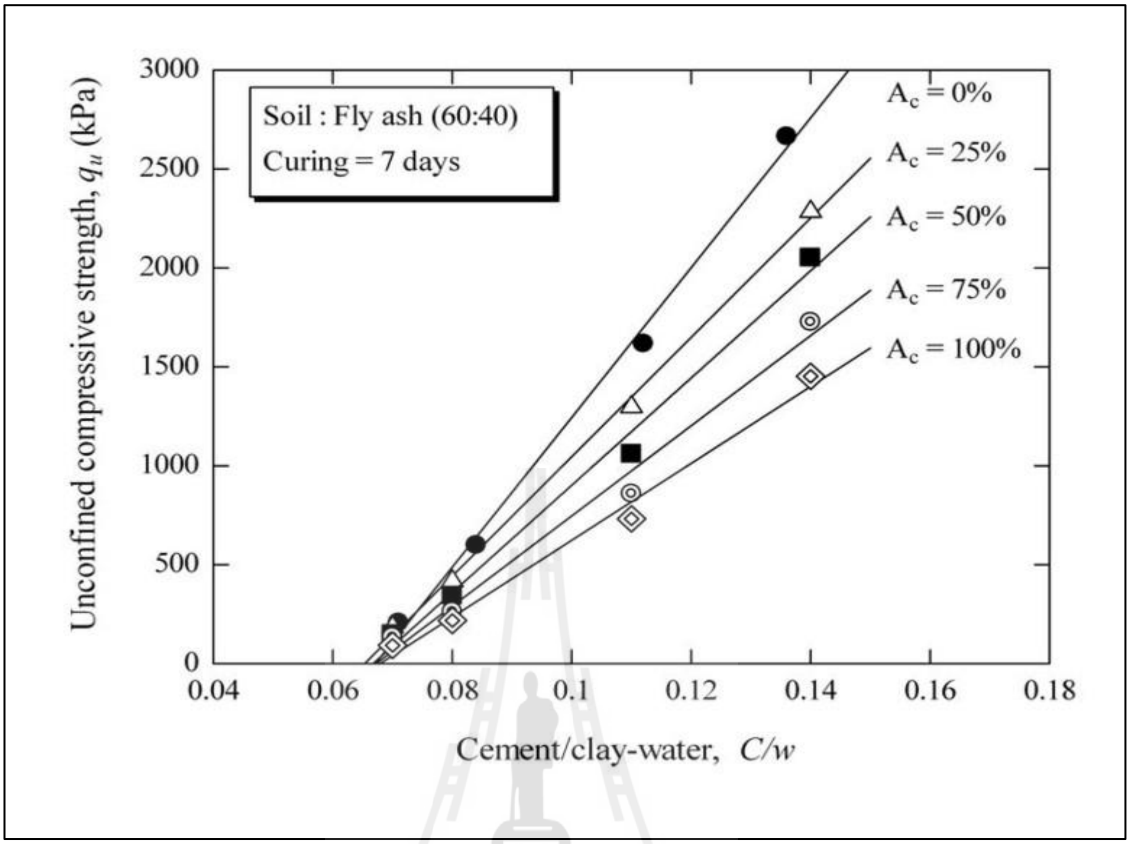
Soil : Fly ash (60:40)
w = 132%
Curing = 7 days
A_c = 0 %
A_c = 25 %
A_c = 50 %
A_c = 75 %
A_c = 100 %
Unconfined compressive strength, q_u (kPa)
Cement content (%)
(a)
Soil : Fly ash (60:40)
Cement = 10%
Curing = 7 days
Water content, w (%)
(b)
Soil : Fly ash (60:40)
Cement = 15%
Curing = 7 day
1.5LL
2.0LL
3.0LL
Air bubble, A (%)
(c)


Cement = 15%
Curing = 7 days
w/wL = 3.0
Ac = 0 %
Ac= 25 %
Ac= 50 %
Ac= 75 %
Ac= 100 %
Unconfined compressive strength, qu (kPa)
Fly ash, FA (%)
0
100
200
300
400
500
600
700
800
0
20
40
60
80
100


Cement = 15%
Curing = 7 days
w/wL = 3.0
Ac = 0 %
Ac = 25 %
Ac = 50 %
Ac = 75 %
Ac = 100 %
Unit weight γt (kN/m3)
Fly ash, FA (%)
20
18
16
14
12
10
8
0
20
40
60
80
100



Soil : Fly ash (60:40)
Cement = 10%
Curing = 7 days
w = 99%
w = 132%
w = 198%
Ac = 0 %
Ac = 100 %
Ac = 0 %
Ac = 100 %
Ac = 100 %
Ac = 0 %
Unconfined compressive strength, qu (kPa)
Unit weight, γt (kN/m3)
0
50
100
150
200
250
300
350
400
12
13
14
15
16
17
18


Soil : Fly ash (60:40)
Curing = 7 days
A_c = 0%
A_c = 25%
A_c = 50%
A_c = 75%
A_c = 100%
Unconfined compressive strength, q_u (kPa)
Cement/clay-water, C/w
3000
2500
2000
1500
1000
500
0
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

BIOGRAPHY

Mr. Apirat Wijitchot was born on September 11, 1985 in Ratchaburi Province, Thailand. He received his Bachelor’s Degree in Engineering (Civil Engineering) from Suranaree University of Technology in 2007. After graduation, he continued with his graduate studies in Geotechnical Engineering Program, Institute of Engineering, Suranaree University of Technology.