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STRENGTH AND COMPRESSIBILITY OF LIGHTWEIGHT CEMENTED CLAYS

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ABSTRACT: Lightweight cemented clays have wide applications in the infrastructure rehabilitation and in the construction of new facilities. The strength and compression characteristics of lightweight cemented clays with non- to high swelling potential are investigated and presented in this article. The workable state, the optimum water content to produce the lightweight cemented clay, is about 1.9 times the liquid limit. The void/cement ratio, *V*/*C*, which is defined as the ratio of void volume of the clay to the cement volume, is proved to be the prime parameter governing the strength and compression characteristics of cemented clays. The fabric (arrangement of clay particles, clusters and pore spaces) reflected from both air foam content and water content is taken into consideration by the void volume while the inter-particle forces (levels of cementation bond) are governed by the input of cement (cement volume). A strength equation in terms of *V*/*C* at a particular curing time is introduced using Abram's law as a basis. 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 from both engineering and economic viewpoints.

KEYWORDS: air foam, cement, compressive strength, compressibility, lightweight material

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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 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 for reducing pressure on the tunnel lining.

The lightweight material was first used in Oslo, Norway, where expanded polystyrene (EPS) was utilized in road embankments on soft ground (Freueldelund and Aaboe, 1993). Besides the EPS, two types of lightweight materials were developed and so called "Lightweight geo-material" (Yasuhara, 2002). One is a mixture of natural soil and lightweight materials such as used rubber tire. The other is a mixture of natural soil, air foam agent and cementing agent, designated as “air-cement-admixed clay” or “lightweight cemented clay”. For this research, main attention is paid to a lightweight cemented clays. The advantage of the lightweight cemented clay is cost-effective in terms of construction time, material and transportation. Following is the process of manufacturing lightweight cemented clay (Figure 1). Soft clay is mixed with water to obtain a clay slurry. The clay slurry is pumped into a mixing chamber and mixed with Portland cement. The cement-clay mixture is then transferred to air foam mixing plant and mixed with air foam to have a high workability (high flow value) and low density. After that the air-cement-clay mixture is pumped into the construction site. 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 and lateral earth pressure improves. The lightweight cemented clay has been extensively used for highway and port construction in countries such as Japan and Thailand (Tsuchida et al., 2001; Satoh et al., 2001; Hayashi et al., 2002; Otani et al., 2002; Miki et al., 2003 and Jamnongpipatkul, et al., 2009; and Kikuchi et al., 2011).

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, b and c) 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 on the wet side of optimum water content that the degree of saturation is higher than 80% (Horpibulsuk et al. 2006). Consoli et al. (2007) extended the clay-water/cement ratio hypothesis to analyze the strength development in compacted (unsaturated) cement-stabilized sand. They proposed a key parameter taking the role of air bubble in pore space (void) on the strength development into account. The parameter was designated as void/cement ratio, V/C and was defined as the ratio of absolute volume of void (water and air) to absolute volume of cement of the compacted sand.

To make the lightweight cemented clay, high air foam content does not always reduce the unit weight of cemented clay. The air bubble cannot enter into the pore space of the moist clay unless the water content is sufficiently high to reduce the attractive forces between clay particles and clay clusters. It is thus impossible to make a lightweight cemented clay at low water content. This research aims to illustrate the stress state (state of water content) suitable for making the lightweight cemented clay and to develop practical (simple and rational) equations for determining strength and unit weight. The equations facilitate the determination of cement content and air foam content to attain the target strength and unit weight using a few trial data. The modified clay-water/cement ratio (void/cement ratio, V/C), proposed for the cement stabilized low water content sand, is herein considered to describe the engineering properties of lightweight cemented clays with very high water contents. Three types of clays, which were kaolin, Bangkok clay and bentonite as representatives of non- to high swelling clays (Horpibulsuk et al., 2011d), were used for this study.

2. MATERIALS AND METHODS

2.1 Soil Samples

Bangkok clay was collected from Bangkok Noi district, Bangkok, Thailand at a 3 meter depth. Kaolin and bentonite were obtained from a commercial company. 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 high plasticity (CH). Groundwater was 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 satisfactory (Horpibulsuk et al., 2007).

Kaolin was composed of 0% sand, 22% silt and 78% clay. The specific gravity was 2.65. The liquid and plastic limits were 46% and 36%, respectively. The clay was classified as low plasticity (CL) based on the USCS. The FSR was 0.9 and classified as non-swelling. Bentonite was composed of 0% sand, 50% silt and 50% clay. The specific gravity was 2.63. The liquid and plastic limits were 106% and 60%, respectively. It was classified as high plasticity clay (CH). The FSR was 2.1, which is classified as high-swelling. Grain size distributions of the three clays are presented in Figure 2.

2.2 Cement and air foam agent

Type I Portland cement (PC) and air foam agent, Darex AE4, provided by the Grace Construction Products Ltd, were used in this study. Grain size distribution curve of PC is also shown in Figure 2. The curve was obtained from the laser particle size analysis. The specific gravity is 3.15 and the D_{50} of PC is 0.01 mm (10 micron), which is larger than that of the tested clays. 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.

2.3 Methodology

The aim of this research is to examine the stress state suitable for making lightweight cemented clays, to examine the role of V/C as the prime parameter for describing the engineering properties of lightweight cemented clays, and to develop practical equations for determining the strength and unit weight of different mix proportions. The generalized stress state, w/w_L, was used for the first purpose. The w/w_L was successfully used to assess the engineering properties of remolded and natural clays (Horpibulsuk et al., 2007 and 2011d). 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, clays exhibit the same order of undrained shear strength (1.7 – 2.5 kPa) and exhibit hydraulic conductivity of the same order of 10^{-7} cm/sec (Nagaraj et al., 1993 and Horpibulsuk et al., 2007).

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) 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. The clays were thoroughly mixed with cement and air foam for 10 min. The cement content, C, were varied from 150 to 400 kg/m^3 of clay volume and the air content, A_c, from 10 to 100% of clay volume for the first and last aims. The cement content and air content were varied to attain the V/C values of 30 and 10 for the second aim. Such a uniform paste was transferred to oedometer rings as well as 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 and oedometer samples were wrapped in vinyl bags and they were stored in a humidity room of constant temperature (20±2°C) until lapse of different curing times as planned. Oedometer tests were carried out after 14 days of curing. Unconfined compression (UC) tests were run on samples after 7 and 14 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.

PARAMETERS

In cement admixed clay, the clay-water/cement ratio hypothesis (Horpibulsuk and Miura, 2001; Horpibulsuk et al., 2005; and Miura et al., 2001) is stated as follows:

> "For given cement admixed clay, age and curing conditions, the strength is determined exclusively by the ratio of clay-water content to the cement content in the mix. Strength is independent of clay-water content and cement content in the mix."

As an analogy, the parameter that can be identified for lightweight cemented clays is void/cement ratio, V/C, which is the volume of void to the volume of cement in the mix. To obtain the same value of V/C for a particular clay water content, it is possible to vary the amount of air foam or cement or both as the case might be. In order to examine up to what extent the applicability of V/C is valid, the air foam content is varied over a wide range in this study.

The unit weight of the lightweight cemented clay can be directly obtained from the four phase diagram as shown in Figure 3. The unit weight (in kN/m^3) is determined in terms of water content, cement content and V/C by the following equation:

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

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) and C is cement content (kg/m^3). Eq. (1) was developed based on the assumption that the all air bubbles (air foam) enter into the pore space when mixed with cement and clay. It is noted that for a given water content, the unit weight is dependent upon the V/C and cement content. With the variation in water content and cement content, the air content required to attain the required V/C is

$$A_c = \left(V/C\right)\frac{C}{G_c\gamma_w}\left(1+wG_s\right)-wG_s \tag{2}$$

3. RESULTS

Figure 4 shows the typical relationship between unit weight and generalized stress state, w/w_L, of the lightweight cemented kaolin, Bangkok clay and bentonite at different air contents. 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 varies from 1.5 to 1.9 times liquid limit water content. It is about $1.5w_L$ for bentonite, $1.6w_L$ for Bangkok clay and $1.9w_L$ for kaolin. This transitional water content increases with decreasing the free swell ratio, FSR.

Figure 5 shows the relationship between strength and air content for different initial water contents and cement contents of lightweight cemented Bangkok clay. For a particular air content, the strength decreases with increasing water content and with decreasing cement content due to the increase in clay-water/cement ratio, w_c/C (Miura et al., 2001; Horpibulsuk et al., 2003; 2005; 2011a, b and c). For a certain w_c/C, the addition of air foam reduces not only the unit weight but also the strength. The air foam changes the clay fabric and increases the pore space. The increase in pore space increases the contact area, therefore, reduces the cement per contact area. The results show that the strengths of the lightweight cemented clays are not governed by only w_c/C, which is not the same as cement admixed high water content clays. The combined effect of water content, air content and cement content on the stress-strain-strength characteristics is taken into account by the parameter V/C.

The role of V/C on the compressibility is shown in Figures 6 to 9 for lightweight cemented kaolin, Bangkok clay and bentonite samples with the same V/C values but with different combinations of cement content and air content. The samples were made up from six conditions of air content namely, 0, 10, 20, 30, 40 and 50%. Figure 6 shows the compressibility of lightweight cemented kaolin at water content of 88%. Figure 7 shows the compressibility of lightweight cemented Bangkok clay at water contents of 136 and 241%. Figure 8 shows the compressibility of lightweight cemented bentonite at water contents of 170 and 280%. They show the (e, log σ'_v) and (ε_v, log σ'_v) relations of the samples at V/C values of 30 and 10 after 14 days of curing. Although some similarities are observed to the behavior of naturally structured clays, the behaviour of lightweight cemented clays possesses its special features (Burland, 1990; Horpibulsuk et al, 2003, 2004b; Liu and Carter 2000, 2002). The compression index (C_c and C_s) and yield stress, σ'_y for the three lightweight cemented clays are presented in Tables 1 to 3. The C_c and C_s are the slope of the (e~log σ'_v) plot in pre-yield stress and post-yield stress, respectively. The yield stress was obtained as the point of intersection of two straight lines extended from the linear portions on either end of the compression curve plotted as log (1+e) against log σ'_v (Butterfield, 1980 and Sridharan et al., 1991). The (ε_v, log σ'_v) relationship is plotted so as to take care of the effect of the difference in void ratio for the vertical stresses less than the yield stress. In this stress range, the cementation component is the dominant factor to resist compression. C_s varies in the range of 0.02 to 0.10 with the most values being lower than 0.05. The C_s value insignificantly changes with water content, air content and cement content. For a certain water content, the yield stress and the deformation behavior in pre-yield stress of all samples with identical *V/C* values are practically the same. This implies that *V/C* is a prime parameter governing the compressibility in pre-yield state. The yield stress increases as the *V/C* value decreases. The samples with higher air content are stable at higher void ratios. Beyond the yield stress, drastic compression occurs as vertical pressure increases due the breakup of cementation bond (Horpibulsuk et al., 2004a, Horpibulsuk et al., 2010; and Suebsuk et al., 2010 and 2011). The compression indices in post-yield state of the lightweight cemented clays increase with cement content and water content for a particular V/C value. This is in agreement with the finding reported by Horpibulsuk et al., 2004b that the break-up of the cementation bond is dependent upon the water content and cement content. With the increase in air content, the cement content increases to attain the same V/C. Consequently, the C_c increases as air content increases.

Figures 9 to 11 show the stress~strain relationships in unconfined compression tests of samples with different air contents and cement contents but with the same V/C values of 30 and 10, at 14 days of curing. Figure 9 are for the lightweight cemented kaolin at water content of 88%. Figure 10 are for the lightweight cemented Bangkok clay at water contents of 136 and 241%. Figure 11 are for the lightweight cemented bentonite at water contents of 170 and 280%. It is noted that as the V/C decreases, the cementation bond strength increases and hence strength. The lightweight cemented samples with the same void/cement exhibit the similar stress-strain behavior. To conclude, the V/C controls compressive strength and compression characteristic in pre-yield state for a particular water content, while the unit weight does not, which is different from natural clays.

4. DISCUSSIONS

The water content higher than $1.9w_L$ is recommended for producing lightweight cemented clays, irrespective of cement content and air content. This stress state is designated as the workable state that the clay viscosity is very low and the air foam can enter into the pore space. It is preferable to explain the engineering behavior of lightweight cemented clay based on the structure. The structure is fabric, that is, the arrangement of the particles, clusters and pore spaces in the soil as well as cementation (Mitchell, 1993; Liu and Carter, 1999). The fabric of the lightweight cemented clay reflected by the water content and air foam is taken into account by the void volume while the cement content governs the level of cementation. The *V/C* is thus the prime parameter governing the unconfined compressive strength, yield stress and compressibility in pre-yield state. The effect of air content comes into play when the stress state is in post-yield state. After the break-up of the cementation bond (stress beyond the yield stress), for a particular *V/C* value the samples with higher void ratio (air content) sustain large deformation. This finding is in agreement with that by Horpibulsuk et al. (2005) and Miura et al. (2001) for cement admixed high water content clays. This behavior implies that for a particular water content, the resistance to elastic deformation is controlled by the *V/C* while the resistance to plastic deformation is governed by the air content. To develop a constitutive model for lightweight cemented clays, the plastic properties are significant and can be further investigated from triaxial tests on the cemented samples with different mix proportions as previous done by Horpibuksuk et al. (2004b, 2005, 2010); Miura et al. (2001) and Suebsuk et al. (2010 and 2011) for cement admixed clays.

It is logical to relate the elastic properties with unconfined compressive strength because they are governed by the *V/C*. Figure 12 and 13 show the relationships between yield stress in K_0-consolidation, σ_y, and unconfined compressive strength and modulus of deformation at 50% strength, E_{50} and unconfined compressive strength, respectively for both cemented clays (without air foam) and lightweight cemented clays. Both relationships are unique for both types of cemented clays, regardless of water content, cement content, air content and clay type. The relationship between σ_y and q_u is very close to that previously proposed by Horpibulsuk et al. (2004a) for cement admixed Bangkok clay. The E_{50} varies between 100 and 220 times q_u.

Because the *V/C* is the prime parameter governing the engineering properties in elastic range (at low effective confining stress), it is possible to develop a relationship between strength and *V/C* for a particular curing time. Figure 14 shows the relationship between strength and *V/C* at 7 days of curing of the lightweight cemented Bangkok clay as an example to guarantee the applicability of the *V/C*. The unique relationship between the strength and the *V/C* can be found for a given initial water content at different cement contents and air contents. Based on the experimental observations, it is possible to advance the following identity:

$$\left\{\frac{V_1}{C_1}\right\} = \left\{\frac{V_2}{C_2}\right\} = \text{Constant} \tag{3}$$

Once the void/cement ratio is fixed in the field at the working state ($w/w_L > 1.9$), if the air content (void volume) is changed to achieve the required unit weight, the cement content can be estimated from Eq.(3) to attain the same strength and compressibility characteristics. For a mix design purpose, the relationship between strength and *V/C* at a certain water content is advanced on the basis of Abrams' law (1918).

$$q_u = \frac{A}{\left(V/C\right)^B} \tag{4}$$

where q_u is the unconfined compressive strength, *V/C* is the void/cement ratio, and A and B are constants. This proposed equation yields the same as that by Horpibulsuk et al. (2011a, b and c) when $A_c = 0$. The A-value is dependent upon the clay type, curing time and air content. To employ Eq. (4) for assessing the strength at any void/cement ratio (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. As the water content increases, the A-value decreases. The B-value is practically constant and equal to 1.26 to 1.29, which is the typical values for cemented non- to low-swelling clays (Horpibulsuk et al., 2011b). It was suggested to take the *B*-value as 1.27 for the cemented non- to low-swelling clays (Horpibulsuk et al., 2011a, b and c).

Besides the strength, the unit weight is the other important parameter for the field application, which controls the ground settlement and service life. The unit weight for any water content, cement content and *V*/*C* value can be determined from Eq.(1). Figure 13 shows the comparison between the predicted and measured unit weight of lightweight cemented Bangkok clay at different water contents and air contents for high and low cement contents ($C = 400$ and 150 kg/m^3). 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.

5. SUGGESTED MIX DESIGN METHOD

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. Adjust the clay water content to the working state ($w/w_L > 1.9$).

2. Conduct at least two trail unconfined compression tests on the lightweight cemented samples with different cement contents and air contents.

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

3. Develop the q_u-*V*/*C* relationship using Eq.(4) (*vide* Figure 14a).

4. Develop the unit weight and *V*/*C* relationship for different cement contents using Eq.(1) (*vide* Figure 14b).

5. From the target strength, determine the required *V*/*C* (point a in Figure 14a).

6. From the required *V/C*, determine the required cement content, *C*, to attain the target unit weight (point b in Figure 14b).

7. Determine the required air content, A_c, for the target strength and unit weight using Eq. (2).

6. CONCLUSIONS

Based on this study, it is suggested that the void/cement ratio is the prime parameter for analysis of strength and deformation behavior of lightweight cemented clays with non- to high swelling potential. This parameter takes into account the influence of both clay fabric reflected by the air volume and the level of cementation. The conclusions can be drawn as follows.

1. The clay viscosity prevents the air entry into the clay slurry. The water content of 1.9 times the liquid limit is proved as the optimum water content for producing the lightweight cemented clay and regarded as the working state.
2. For a given soft clay at a particular water content, the cementation bond strength increases as void/cement ratio, *V/C*, decreases. Consequently, the yield stress in K_0-consolidation and compressive strength increases with the decrement of *V/C*. The stress-strain response and compression characteristics in pre-yield state are practically the same as long as the *V/C* value is identical.
3. Because the *V/C* controls the engineering properties in the elastic range (at low effective confining stress), it is logical to relate the E_{50} and σ_y in terms of q_u. The relationships between E_{50} and q_u and σ_y and q_u are found to be essentially independent of clay type, cement content, water content and air content. The samples with higher void ratio sustain large plastic deformation.
4. Based on the void/cement ratio and Abram's law, a relationship between strength, void/cement ratio for a particular water content and curing time is proposed. The

relationship is useful in estimating the laboratory strength wherein air content and cement content vary over a wide range by a few trial tests. It also facilitates the determination of proper quantity of cement to be admixed for different air contents to attain the target strength. The formulation of the proposed relationship is on sound principle and developed from distinct clays (non- to high swelling clays). It is thus possibly applicable for various clays.

5. Based on the proposed strength and unit weight equations in terms of water content, cement content and air content, a mix design method for the lightweight cemented clays is suggested. This method is useful for engineering practitioners in their design of cemented soils and estimating mechanical properties of the treated soils.

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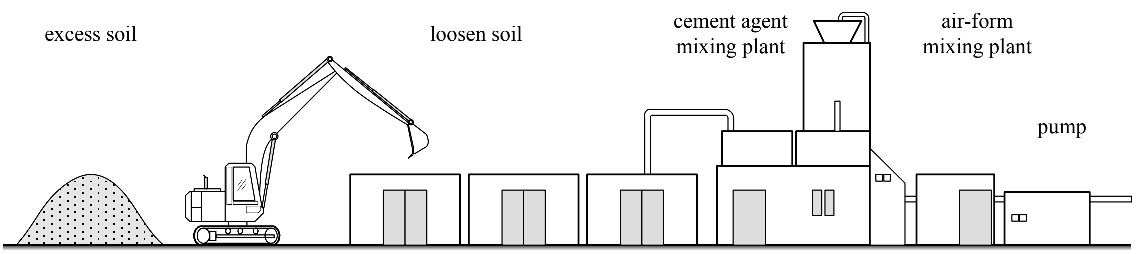


Figure 1: Schematic diagram illustrating the production of lightweight

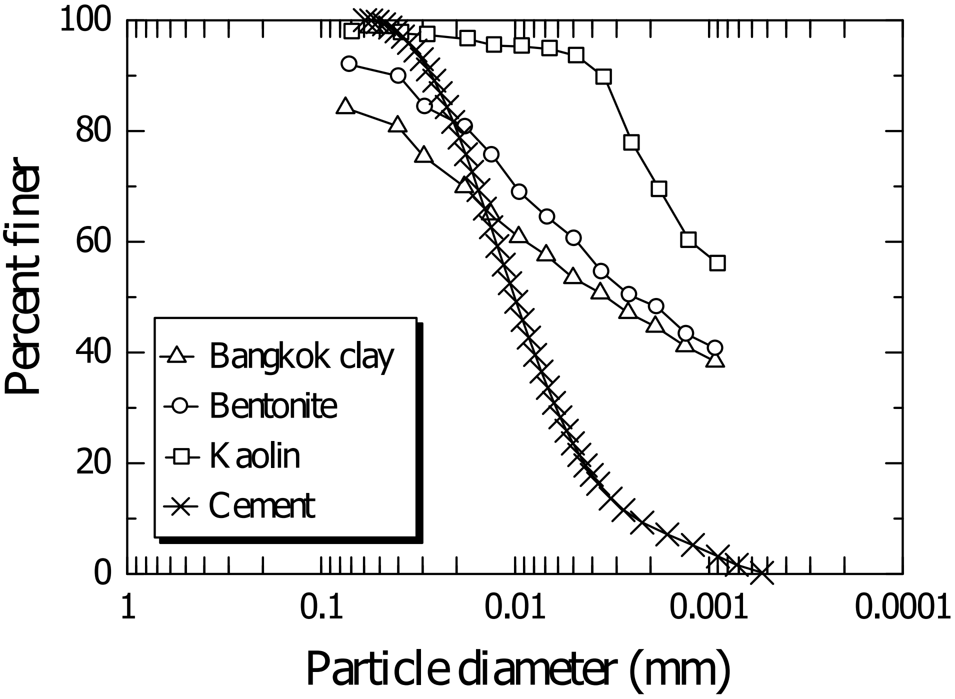


Figure 2: Grain size distribution of Bangkok clay, kaolin, bentonite and cement.

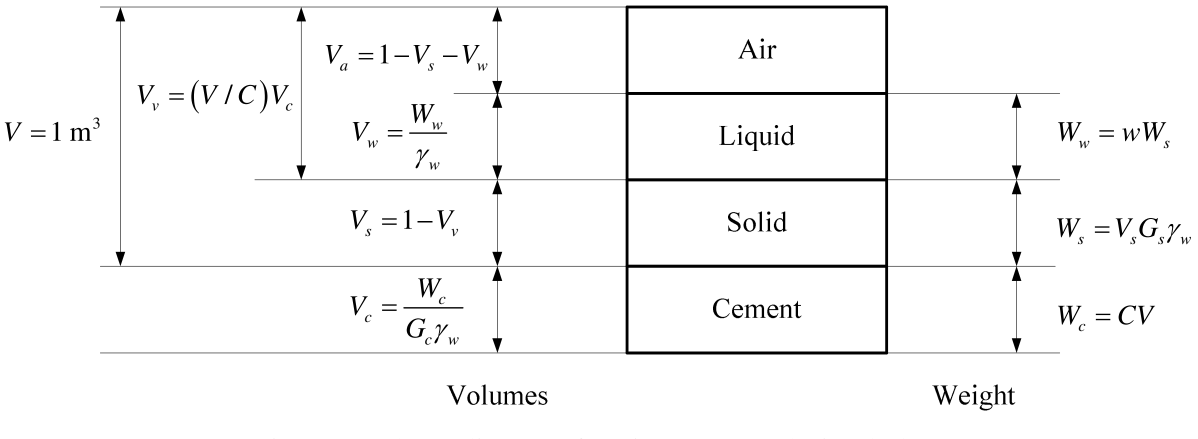


Figure 3: Phase diagram for air-cement-admixed clay.

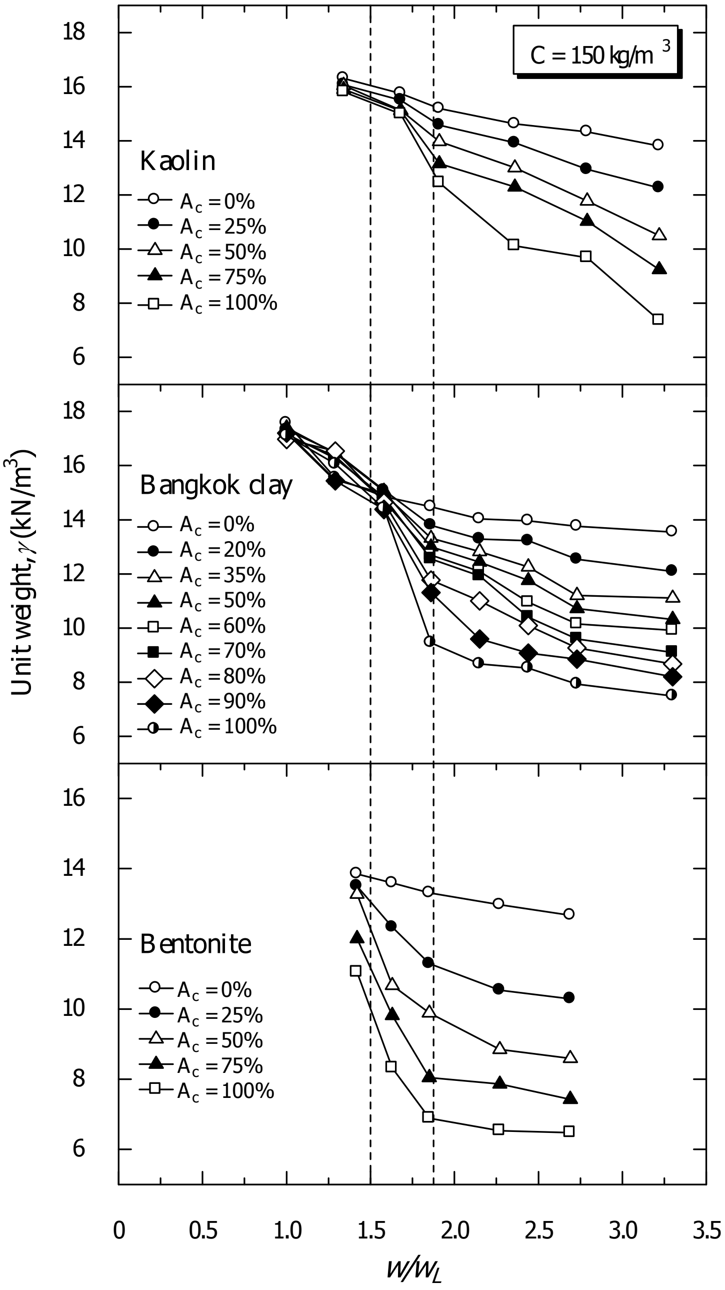


Figure 4: Effect of air foam on unit weight of air-cement-admixed clays at different water contents.

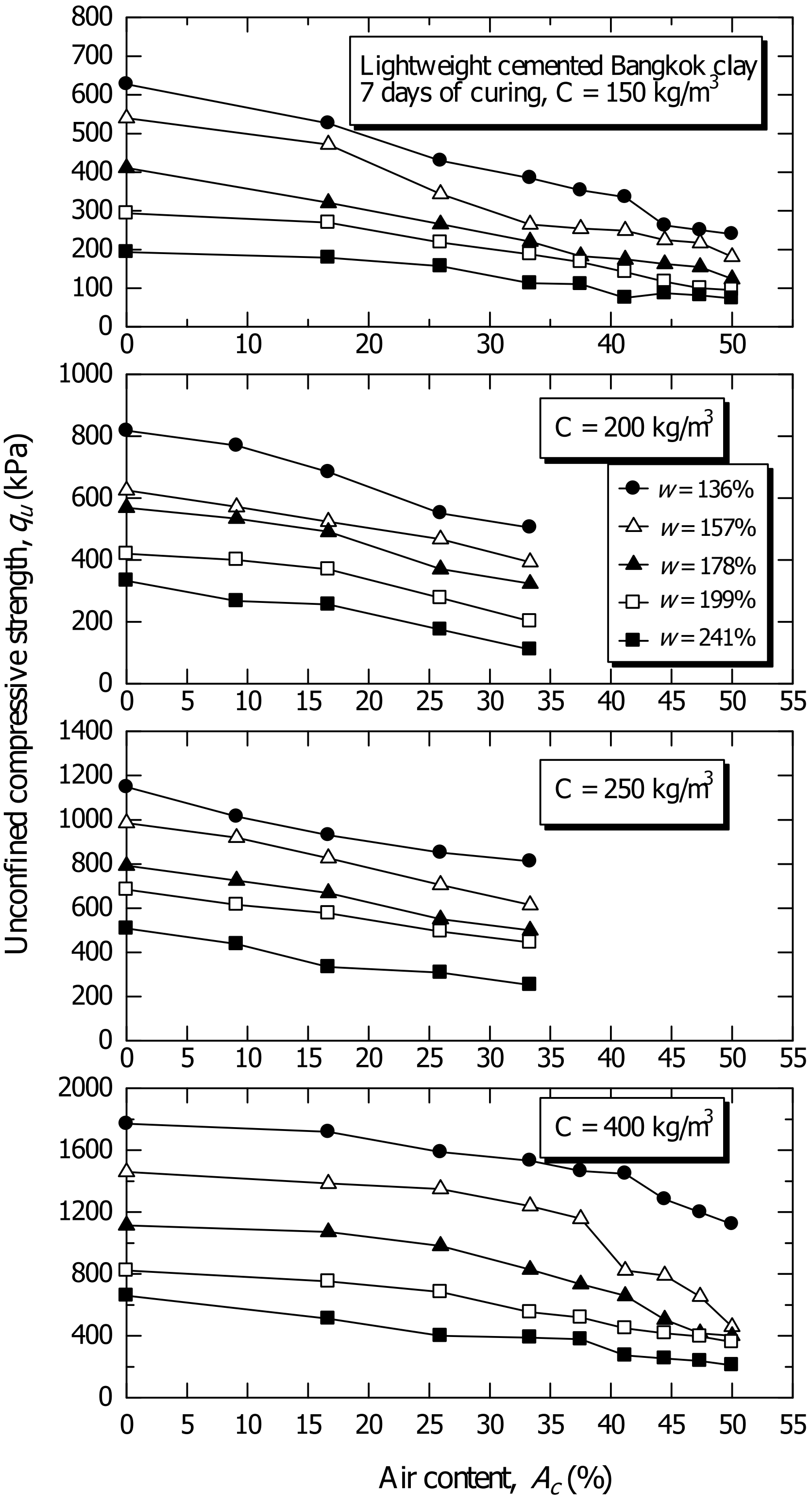


Figure 5: Strength and air content relationship of lightweight cemented Bangkok clay for different initial water contents and cement contents.

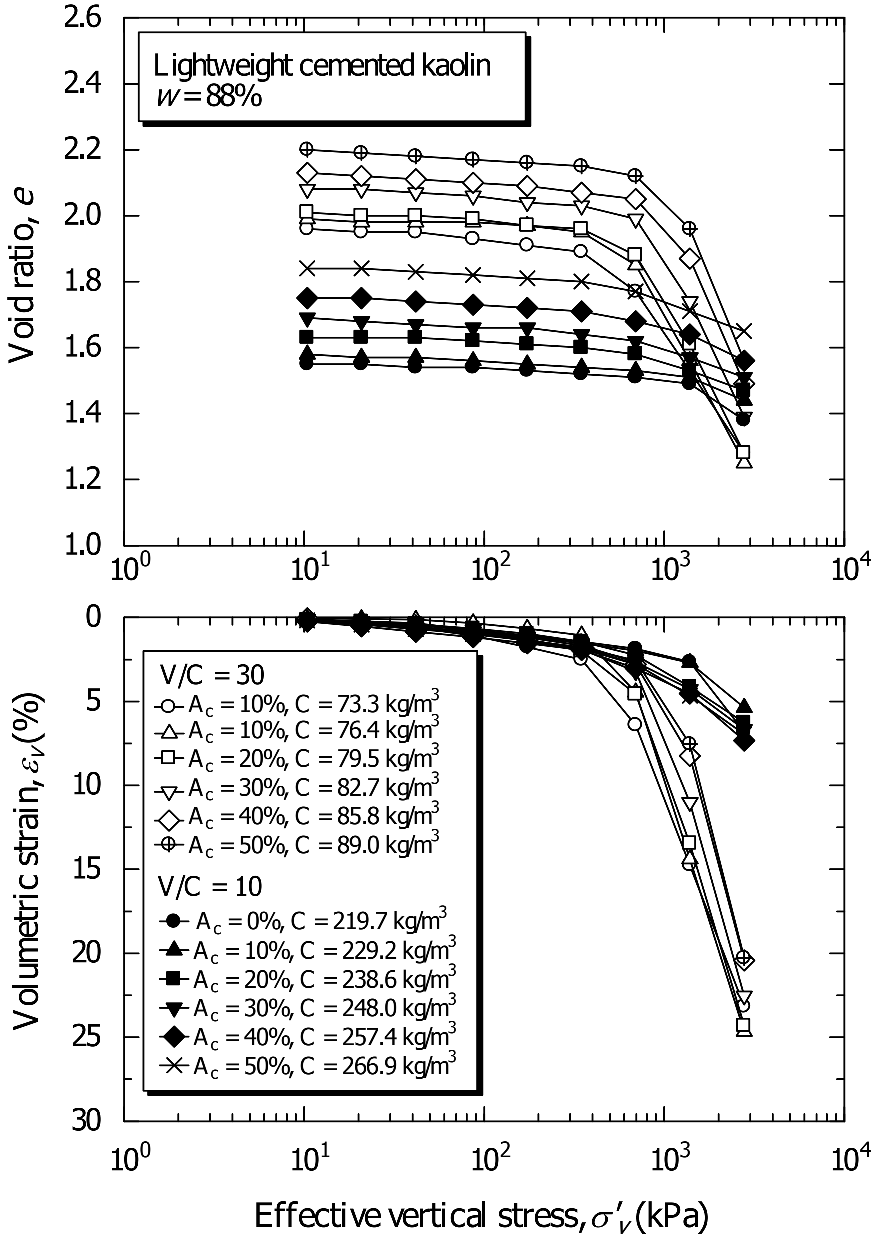


Figure 6: Compressibility of air-cement-admixed kaolin at $w = 88\%$.

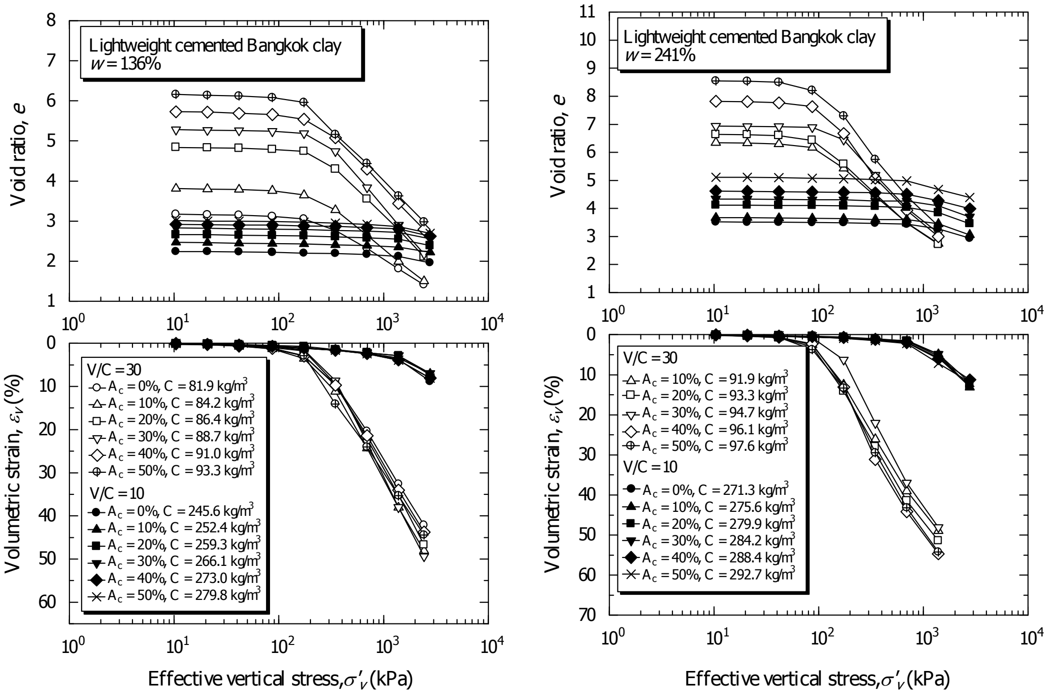


Figure 7: Compressibility of air-cement-admixed Bangkok clay at *w* = 136% and 241%.

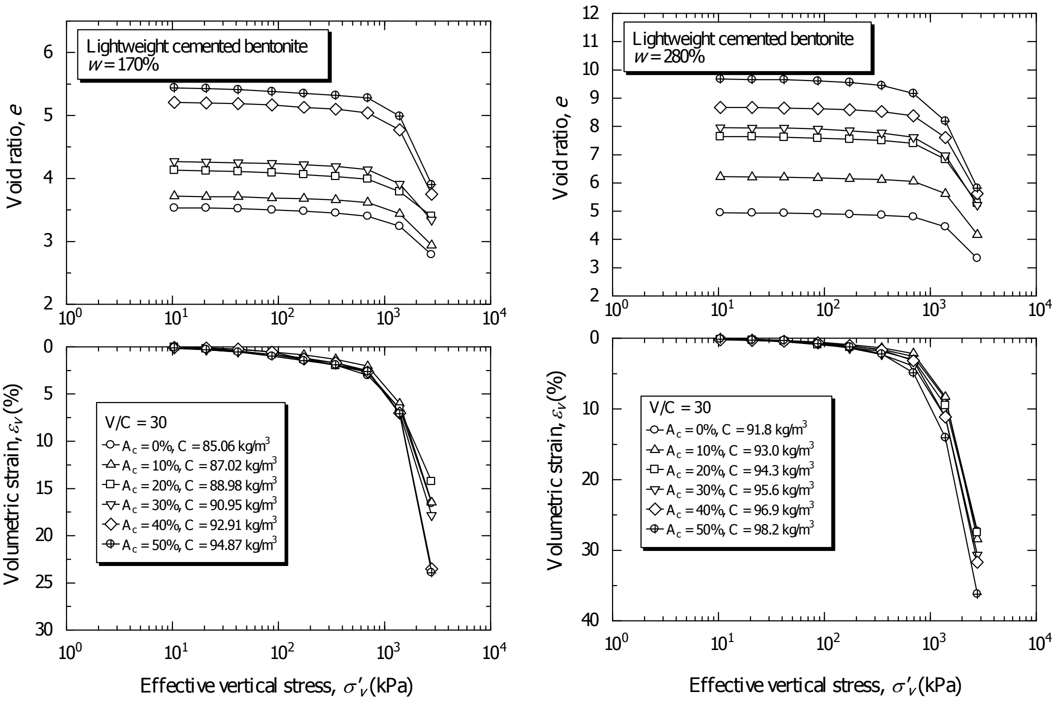


Figure 8: Compressibility of air-cement-admixed bentonite at *w* = 170% and 280%.

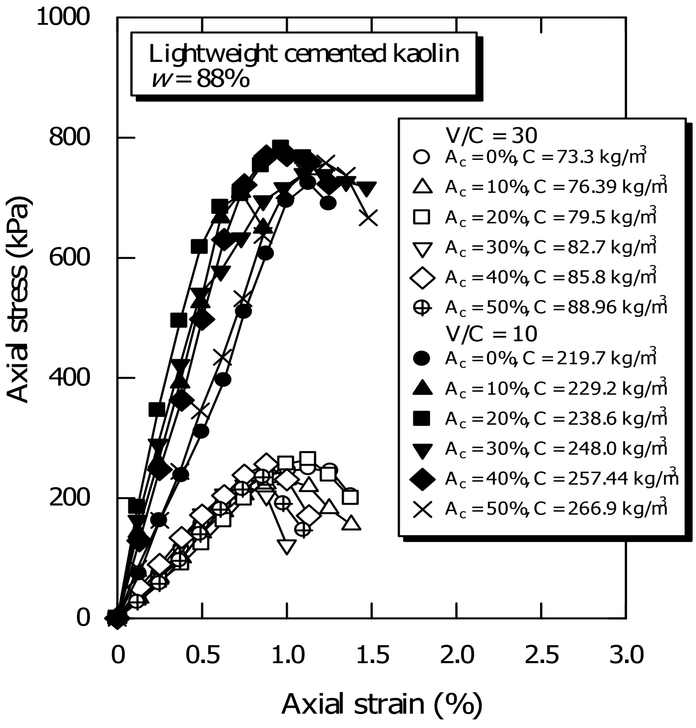


Figure 9: Stress-strain relationship of air-cement-admixed kaolin at w = 88%.

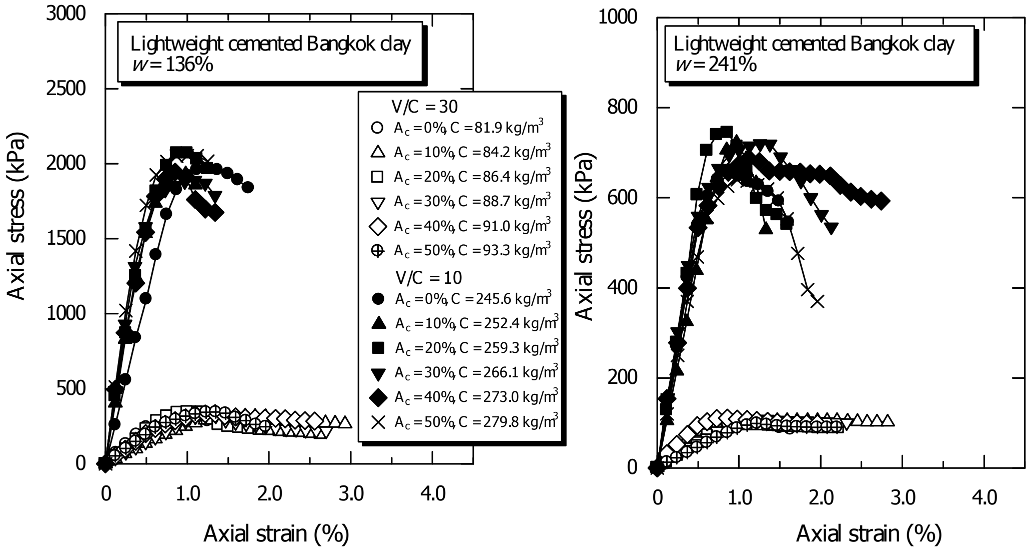


Figure 10: Stress-strain relationship of air-cement-admixed Bangkok clay at w = 136 and 241%.

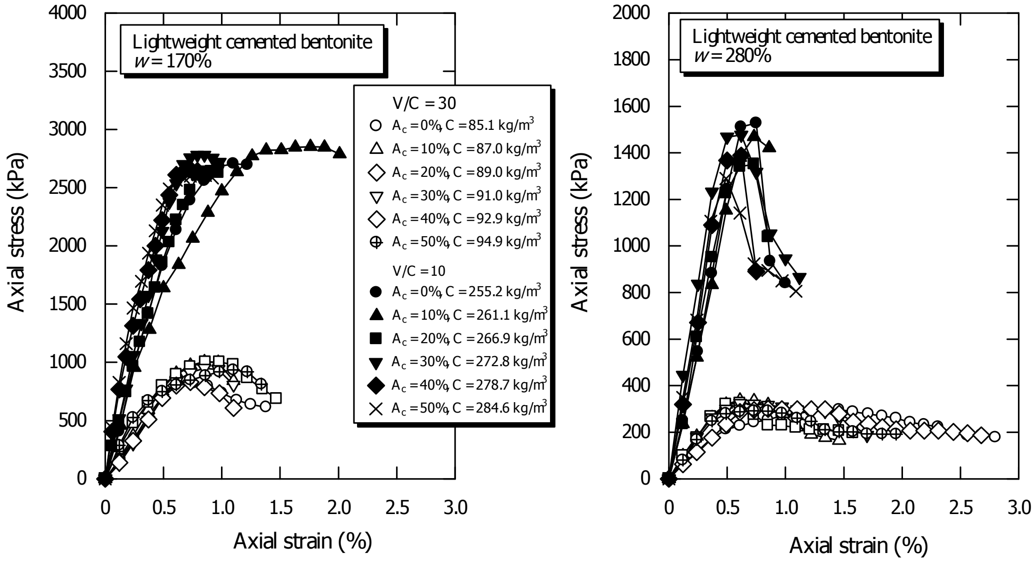


Figure 11: Stress-strain relationship of air-cement-admixed bentonite at *w* = 170% and 280%.

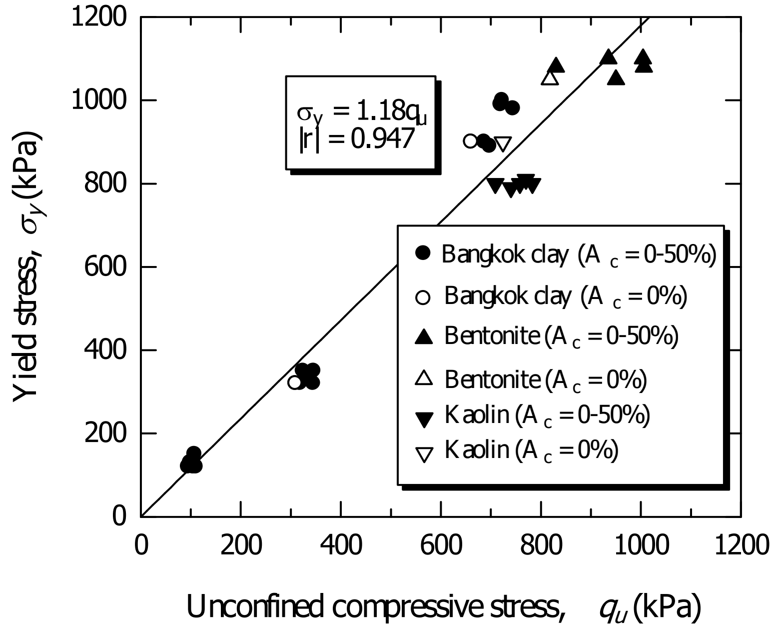


Figure 12: Relationship between yield stress and unconfined compressive strength for lightweight cemented clays.

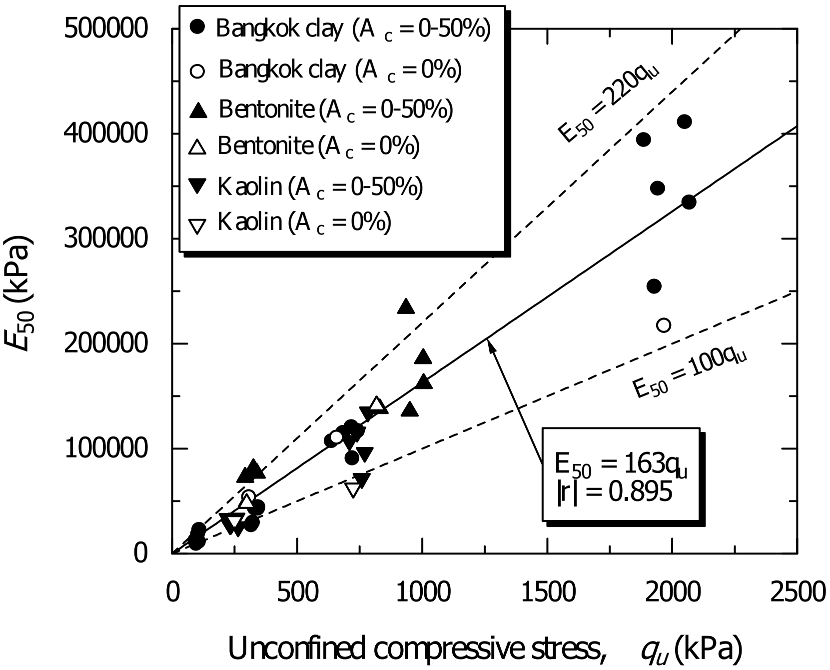


Figure 13: Relationship between modulus of deformation and unconfined compressive strength for lightweight cemented clays.

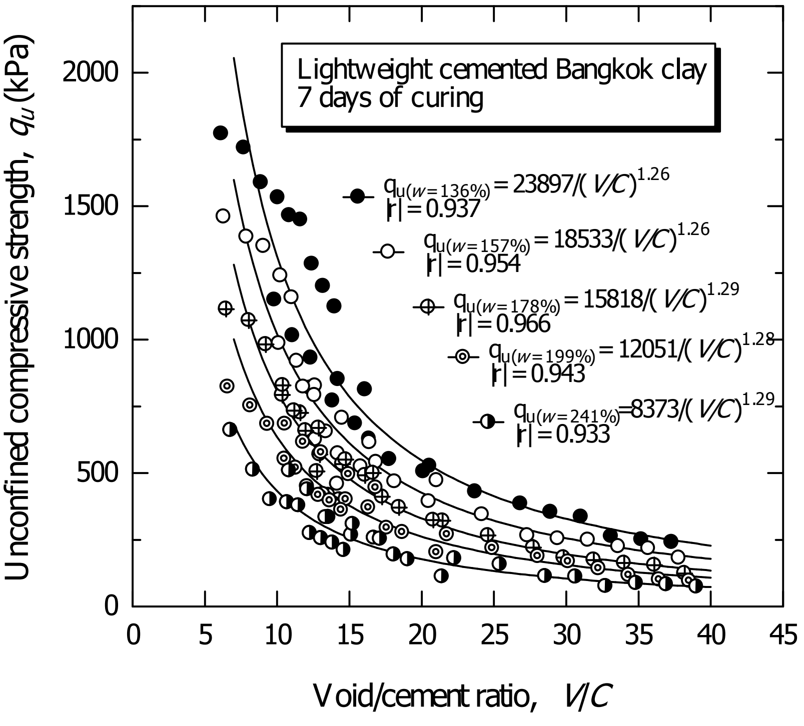


Figure 14: analysis of strength development in lightweight cemented Bangkok clay using *V*/*C*.

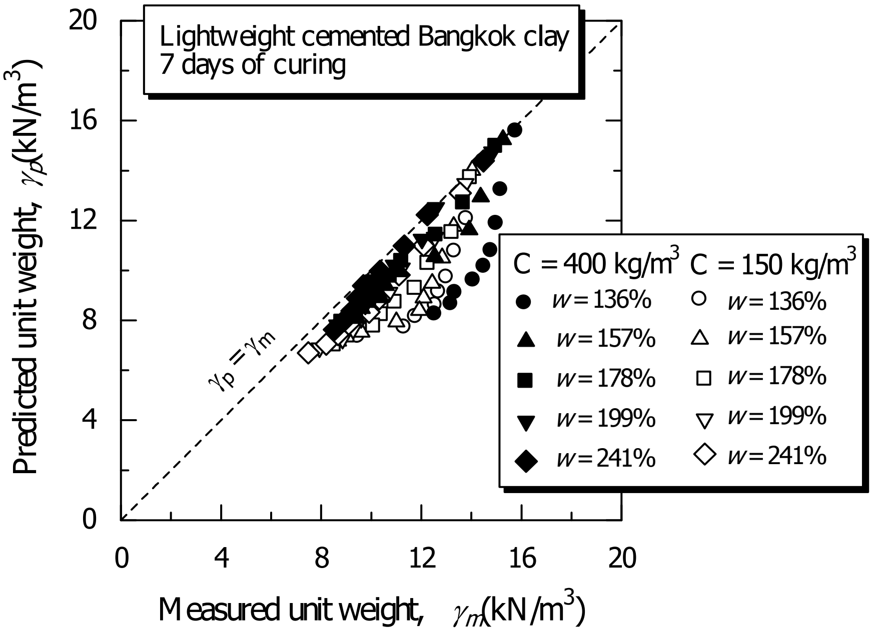
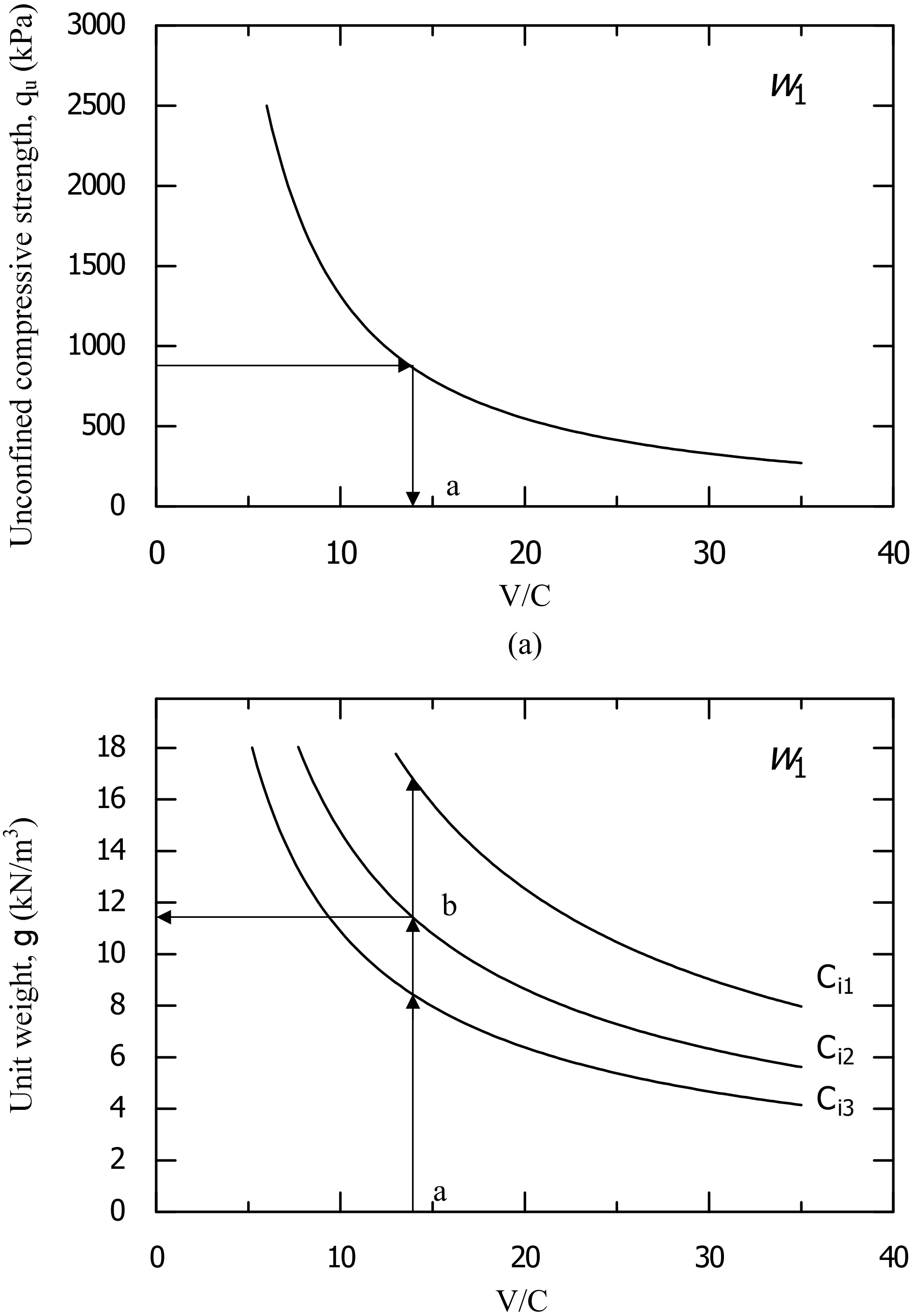


Figure 15: Predicted and measured unit weight of lightweight cemented Bangkok clay.



(a)

(b)

Figure 16: Suggested mix design procedure to attain a target strength and unit weight.