A Key Parameter for Strength Control of Lightweight Cemented Clays

Un paramètre clé pour le contrôle des forces de légères argiles cimentées

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ABSTRACT: Lightweight cemented clays have wide applications in the infrastructure rehabilitation and in the construction of new facilities. The void/cement ratio, *V/C*, which is defined as the ratio of the void volume of clay to the cement volume, is proved as the prime parameter governing the strength and compression characteristics of lightweight 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). Three types of clay namely, kaolin, Bangkok clay and bentonite as representatives of non- to high swelling clays were used in this study. A strength equation in terms of *V/C* at a particular curing time is introduced using Abram's law as a basis.

RÉSUMÉ : Les légères argiles cimentées ont de larges applications dans la réhabilitation des infrastructures et de la construction de nouvelles installations. Le rapport de vide/ciment, *V/C*, qui est défini comme le rapport du volume de vide de l'argile au volume de ciment, comme le prouve le paramètre premier régir la force et les caractéristiques de compression des argiles légères cémentées. Le tissu (arrangement de particules d'argile, des grappes et des espaces de pores) à la fois réfléchie par le contenu de mousse à air et la teneur en eau est prise en compte par le volume de vide, tandis que les forces inter-particulaires (niveaux de liaison cémentation) sont régis par l'entrée de ciment (cimenter volume). Trois types d'argile, à savoir le kaolin, l'argile de Bangkok et la bentonite en tant que représentants d'une quantité d'argiles gonflantes ont été utilisés dans cette étude. Une équation de la force en termes de *V/C* à un temps de durcissement particulier est introduite par la loi d'Abram comme base.

KEYWORDS: compressibility, lightweight cemented clay strength, void/cement ratio.

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 use of lightweight 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 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.

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 2012) 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 wherein 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. 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.

Even though the cement stabilized soil have very low water content due to compaction effect, it is composed of water, air, soil solid and cement, which is the same as lightweight cement clay. The modified clay-water/cement ratio (void/cement ratio, *V/C*), is thus considered to describe the engineering properties of lightweight cemented clays which possess very high water contents in this study. Three types of clay namely, kaolin, Bangkok clay and bentonite as representatives of non- to high swelling clays were used for this objective. Finally, the strength equation is proposed based on the parameter *V/C*.

2 MATERIALS AND METHODS

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 inorganic clay of high plasticity (CH). Groundwater was had a depth of about 1.0 m from surface. The undrained shear strength was 12 kPa. 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 inorganic clay of low plasticity (CL) based on the USCS. 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 inorganic clay of high plasticity (CH).

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 (2-5) 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. Even with very high water content up to 5 times liquid limit, all tested clays still have viscosity with low magnitude, indicating that the sorting of the grain size does not occur. The clays were mixed with air foam to attain air contents, A_c, between 10 and 100% by volume of the clay-water-air mixture. This mixture was then thoroughly mixed with cement for 10 min. The cement content, *C*, was varied from 150 to 400 kg/m^3 of the mixture. To verify the *V*/*C* as a prime parameter, the cement content and air content were varied to attain the *V*/*C* values of 30 and 10. 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.

3 VOID/CEMENT RATIO, *V*/*C*

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. The parameter can be simply determined using four phase diagram of soil, water, air and cement (Horpibulsuk et al., 2012b). 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 (A_c = 10-50% of clay volume) in this study.

4 TEST RESULTS

The role of *V/C* on the compressibility is shown in Figures 1 and 2 for lightweight cemented kaolin 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 1 shows the compressibility of lightweight cemented kaolin at water content of 88%. Figure 2 shows the compressibility of lightweight cemented bentonite at water content of 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. The resistance to compression prevails up to a certain stress level beyond which the sample experiences increase in compression. This stress level is identified as yield stress (Horpibulsuk et al., 2005). It does not represent pre-consolidation pressure because the cemented clay was not being subjected to any stress history. 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. 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; Liu and Carter, 1999, 2000 and 2002; and Suebsuk et al., 2010 and 2011).

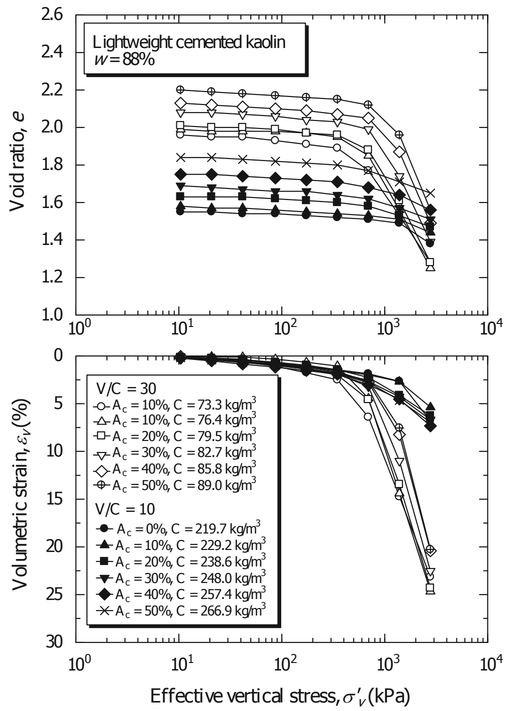

Figure 1. Compressibility of air-cement-admixed kaolin at w = 88%.

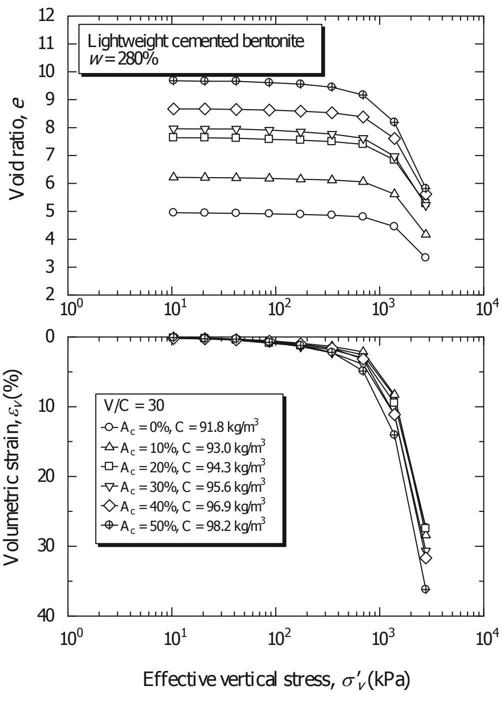

Figure 2. Compressibility of air-cement-admixed bentonite at w = 280%.

Figures 3 to 5 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 3 is for the lightweight cemented kaolin at water content of 88%. Figure 4 is for the lightweight cemented Bangkok clay at water contents of 136%. Figure 5 is for the lightweight cemented bentonite at water contents of 170%. It is noted that as *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. 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).

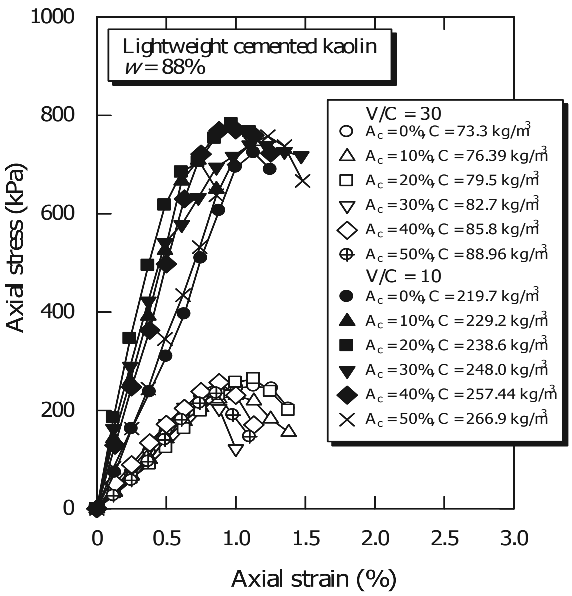

Figure 3. Stress-strain relationship of air-cement-admixed kaolin at w = 88%.

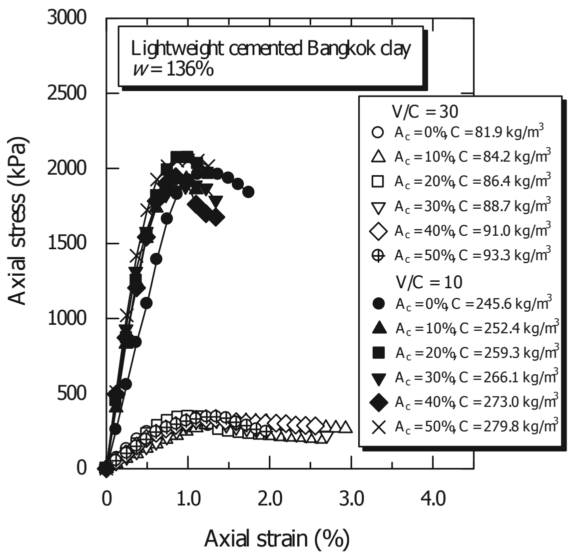

Figure 4. Stress-strain relationship of air-cement-admixed Bangkok clay at w = 136%.

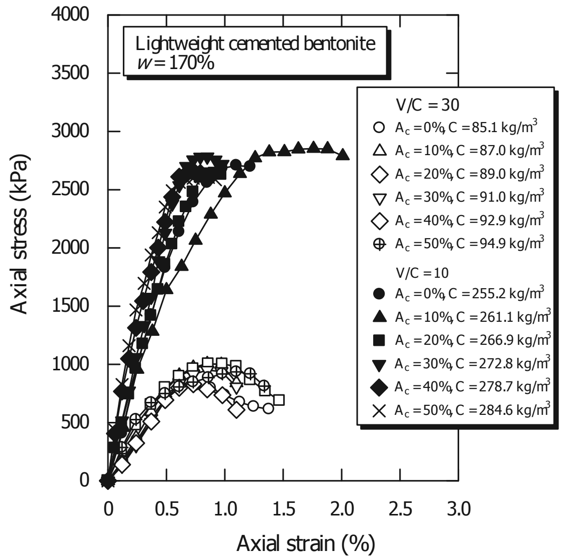

Figure 5. Stress-strain relationship of air-cement-admixed bentonite at w = 170%.

Figures 1 to 5 show the advantage of using air form to produce the lightweight cemented clay. The strength reduction is observed when the void increase by air form due to the increase in contact area per cementation bond. However, the role of air content on the strength development is less significant than that of cement and water. This is because the hydration is strongly depended on the water/cement ratio in the mix. In other words, by using the air form, the unit weight is significantly reduced with less strength reduction.

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 6 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 strength and *V/C* can be found for a given initial water content at different cement contents and air contents. Based on the experimental observations ($5 < V/C < 40$ and 7 days of curing), it is possible to advance the following identity:

$$\left\{\frac{V_1}{C_1}\right\} = \left\{\frac{V_2}{C_2}\right\} = \text{Constant} \tag{1}$$

Once the void/cement ratio is fixed in the field, if the air content (void volume) is changed to achieve the required unit weight, the cement content can be estimated from Eq.(1) 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):

$$q_u = \frac{A}{\left(V/C\right)^B} \tag{2}$$

where q_u is the unconfined compressive strength, *V/C* is the void/cement ratio, and *A* and *B* are constants. This equation when $A_c = 0$ yields the same equation proposed by Horpibulsuk et al. (2011a, b and 2012a). The *A*-value is dependent upon the clay type, curing time and air content. 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 2012a). To employ Eq. (2) 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.

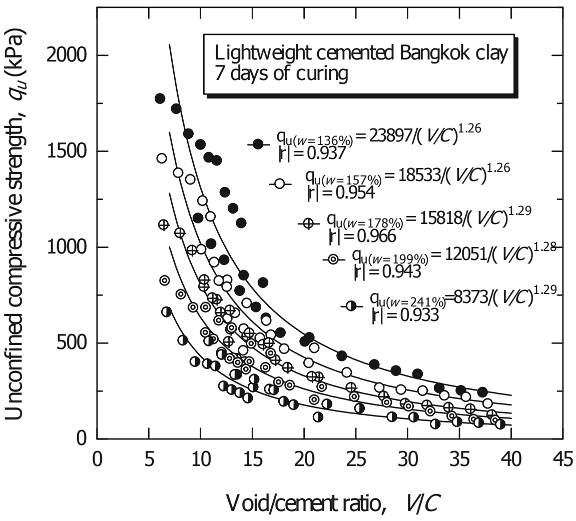

Figure 6. Analysis of strength development in lightweight cemented Bangkok clay using *V/C*.

5 CONCLUSIONS

Based on this study, it is brought out 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 conclusion can be drawn as follows.

1. 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.
2. 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 (Eq.2) 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). The *A* and *B* values can be determined by a back-analysis of at least two trial strength data. It is thus possibly applicable for various clays.

6 ACKNOWLEDGEMENTS

This work was supported by the Higher Education Research Promotion and National Research University Project of Thailand, Office of Higher Education Commission. The financial support and facilities that were provided by the Suranaree University of Technology were appreciated.

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