A new approach for studying behavior of cement stabilized clays

Une nouvelle approche de l'étude du comportement de l'argile améliorée par cimentation

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ABSTRACT: The in-situ deep mixing method is one of the most presently extensively used techniques for formation of columnar inclusion so as to enhance the bearing capacity and reduce settlement of deep soft ground. Although there are researches focusing on the engineering behavior of cement stabilized clays, it is still doubtful. The new parameter, clay-water/cement ratio, *wc/c* is proposed here as a prime factor governing the engineering behavior of cement admixed clay. From the oedometer and the isotropically consolidated drained triaxial compression test results on the cement admixed Ariake clay, which water content of the clay varies over a wide range, the clay-water/cement ratio hypothesis, based on the critical state and state boundary surface concepts are presented. The lower the clay-water/cement ratio, the greater the cementation bond strength, resulting in an increase in the yield stress and the yield surface. The clay-cement mixtures having the same clay-water/cement ratio, *wc/c* develop the identical yield stress in K_0-consolidation but their yield surfaces are different and dependent upon the clay water content and cement content.

RÉSUMÉ: La méthode de mélange en profondeur est aujourd'hui une des techniques les plus largement utilisées pour améliorer la capacité portante du sol tendre profond et réduire son affaissement. Des recherches ont été faites sur le comportement de l'argile améliorée, mais l'analyse de ce comportement reste encore insuffisante. Nous avons montré dans cet article qu'un nouveau paramètre proposé ici,c'est-à-dire le rapport argile-eau/ciment (*wc/c* en anglais) est plus efficace pour prédire le comportement des argiles améliorées par cimentation. L'utilisation de ce paramètre peut bien expliquer les résultats obtenus par des essais de compression triaxiale avec drainage sur de l'argile d'Ariake mélangée à du ciment : plus le rapport *wc/c* est faible, plus augmente la résistance par cimentation ainsi que la contrainte d'écoulement et la surface d'éoulement. Les échantillons ayant un même rapport *wc/c* montrent une contrainte d'écoulement identique sous K_0-consolidation, mais leurs surfaces d'écoulement diffèrent en fonction de la teneur en eau de l'argile et le taux de mélange du ciment.

1 INTRODUCTION

In resent years, design and construction of infrastructure facilities arising due to extensive urbanization and industrialization in coastal area have considerably increased. Need to improve this unfavorable ground to serve the engineering requirement is a challenge to geotechnical engineers. The ground improvement method by chemical admixture is one of the most commonly used techniques for stabilization of soft ground. The engineering behavior of stabilized clays is an important requirement for an appropriate design.

Uddin (1995), Yin & Lai (1998) and others studied the behavior of cement stabilized clays at a particular clay water content using the cement content as an influential parameter.

It is not desirable to study the engineering behavior of cement stabilized clay based on the cement content, which has been done by the previous researches because the cement content is not an independent parameter. The stress–strain and strength characteristics of cement stabilized clays are governed by both water content and cement content. The water content of the clay would significantly change from the in-situ state due to the method of mixing either by deep mixing or by jet grouting. In order to overcome this limitation, the clay-water/cement ratio, *wc/c* was proposed as the prime parameter governing the engineering behavior based on the oedometer, the unconfined compression and the isotropically consolidated undrianed triaxial compression tests (Horpibulsuk et al. 2000). It was proved that this parameter is the structural parameter reflecting effects of fabric and cementaion bond. The investigation of the drained behavior with regard to this parameter is extended and presented in this paper. Based on the oedometer and the isotropically consolidated drained triaxial compression test results, the clay-water/cement ratio hypothesis is proposed.

2 EXPERMENTAL INVESTIGATION

2.1 *Soil sample*

The soil sample used in this paper is the marine Ariake clay collected at Saga, Japan. The sample excavated at about 2-m depth is generally very soft silty clay. The soil is highly plastic clay (CH) with natural water content of about 135-150%. It is composed of 55% clay, 44% silt and 1% sand. The liquid and plastic limits are in the order of 120% and 57%, respectively. The maximum past pressure is about 40-45 kPa. The effective stress parameters are $c' = 0$ and $\phi' = 38°$. The pH of the pore water is about 8.8 and the salinity is about 1.0 g/l.

2.2 *Testing program*

The clay paste was passed in 2-mm sieve for taking off the pieces of shell and the bigger size material. Its water content was decreased and increased until the requirement was realized. The water content of clay for this study covered a wide range starting from liquidity index of 1.0 and extending up to 3.0. The clay was mixed with cement powder (ordinary Portland cement) at two levels, namely *wc/c* = 7.5 and 15 by a soil mixer for 10 minutes and put into oedometer rings (60-mm diamter and 20-mm height) and cylinder containers (50-mm diameter and 100-mm height) for triaxial test, taking care to prevent any air entrapment. After one day, the specimens for triaxial test were dismantled from the containers and wrapped in vinyl bags. The specimens for both oedometer and triaxial tests were placed in a constant temperature (20±2°C) and humidity room until testing.

Oedometer tests were carried out after 7 days of curing. Isotropically consolidated drained triaxial compression (CIDC) tests at effective cell pressures, σ'_c of 100 and 400 kPa were conducted after 28 days of curing. A back pressure of 190 kPa was applied to ensure that degree of saturation of the specimen was higher than 95% by checking B-value. The rate of vertical displacement was 0.0025 mm/min.

3 PARAMETER: CLAY-WATER/CEMENT RATIO, *WC/C*

The clay-water/cement ratio, *wc/c* is defined as the ratio of initial clay water content to cement content (Horpibulsuk et al. 2000). The cement content, A_w is the ratio of cement to clay by weight both reckoned in their dry state. To obtain the same value of *wc/c*, it is possible to vary the water content of the clay or the amount of cement or both as the case might be.

4 EFFECT OF *WC/C* ON ENGINEERING BEHAVIOR

By nature, the cementation, aging and stress history are the main factors controlling the stress~strain behavior of clay. When the clay is mixed and stabilized by cement, its natural cementation bond is destroyed and taken place by the admixture cementation bond. This bond strength is governed by *wc/c*. The effect of *wc/c* on the engineering behavior of cement admixed clay is illustrated by the deformation behavior in K_0-consolidation and the consolidated drained triaxial compression test results.

Figure 1 shows the (ε_v~log σ'_v) relations of the clay-cement mixtures, which have the same *wc/c* values of 15 and 7.5 at 7 days of curing. The mixtures were made up from four conditions of clay water content; namely: 120%, 150%, 180% and 250%. It is noticed the yield stress and deformation behavior at pre-yield stress of all mixtures having the same *wc/c* value is practically the same. It means the cementation bond is identical. But the settlement behavior at the post yield state of the mixtures with high water content is more collapsible than that with low water content due to the break up of cementation bond, which is similar to the behavior of naturally cemented clays.

As a result, it is clear that the lower the *wc/c*, the greater the enhancement of the yield stress. The yield stress is practically the same as long as the *wc/c* is identical for which the fabric (clay water content) would not take into account. The effect of fabric plays a great role on the compressibility after the yield state in which the cementation bond is broken down. This leads to the conclusion that the role of cement admixture is to increase the yield stress in K_0-consolidation resulting in increasing the yield surface and the strength.

The drained behavior of mixtures having the same *wc/c* value is shown in Figures 2 to 5. They present the stress ratio~shear strain (η, ε_s) and stress ratio~volumetric strain (η, ε_v) relations of samples having the same *wc/c* values of 15 and 7.5. The parameters used in this analysis are deviator stress, $q = (\sigma'_1 - \sigma'_3)$, mean effective stress, $p' = (\sigma'_1 + \sigma'_3)/3$, stress ratio, $\eta = q/p'$. The shear strain, ε_s and the volumetric strain, ε_v are defined as $\varepsilon_s = 2(\varepsilon_1 - \varepsilon_3)/3$ and $\varepsilon_v = (\varepsilon_1 + 2\varepsilon_3)$. The σ'_1 and σ'_3 are the major and minor principal effective stresses, respectively. The ε_1 and ε_3 are the major and minor principal strains, respectively. The samples were subjected to the effective cell pressures of 100 and 400 kPa after 28 days of curing. It is clear that the characteristics of both relations before their peak stress ratios of the mixtures with high

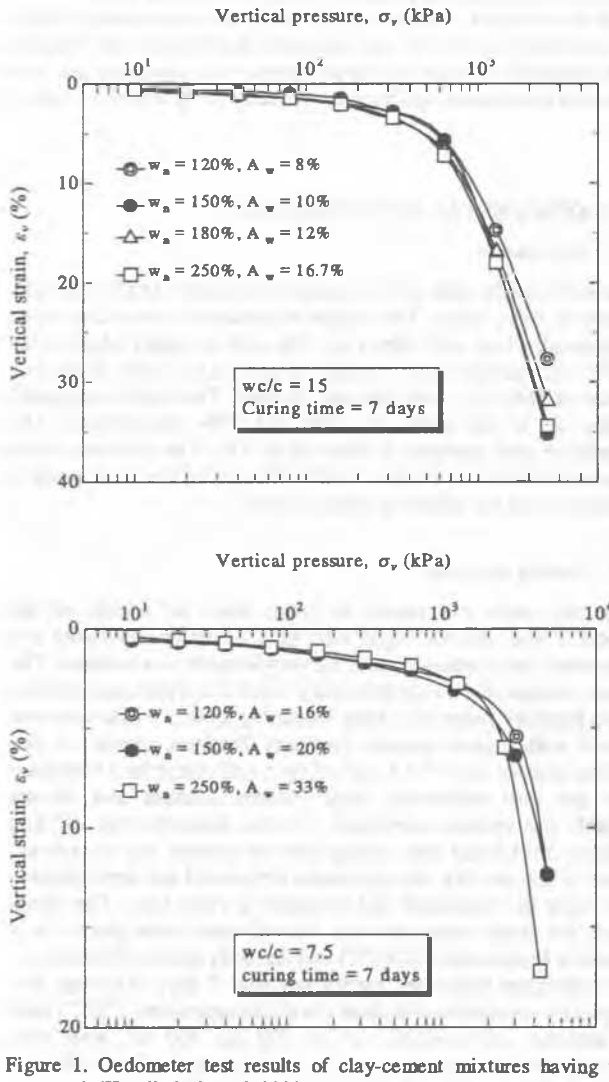

Figure 1. Oedometer test results of clay-cement mixtures having the same *wc/c* (Horpibulsuk et al. 2000).

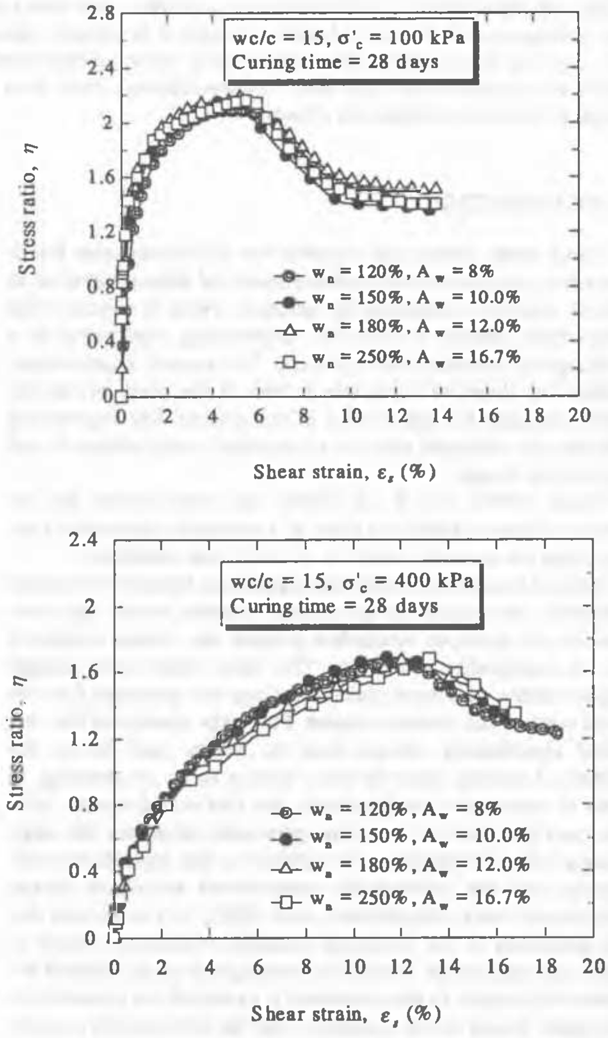

Figure 2. Stress ratio and strain strain plots of stabilized samples having the same *wc/c* value of 15.

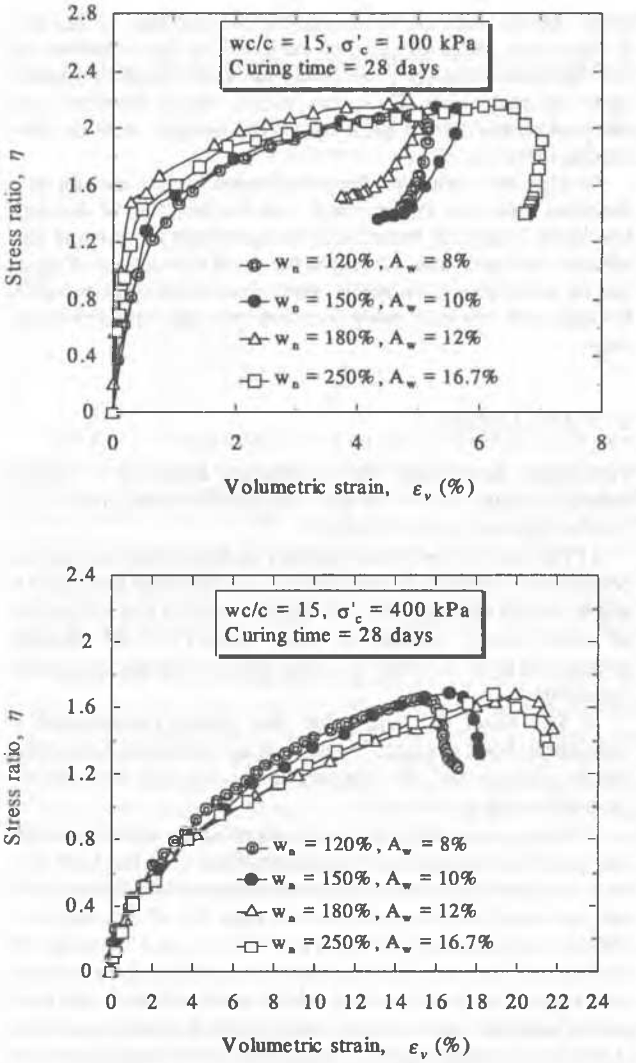

Figure 3. Stress ratio and volumetric strain plots of stabilized samples having the same *wc/c* value of 15.

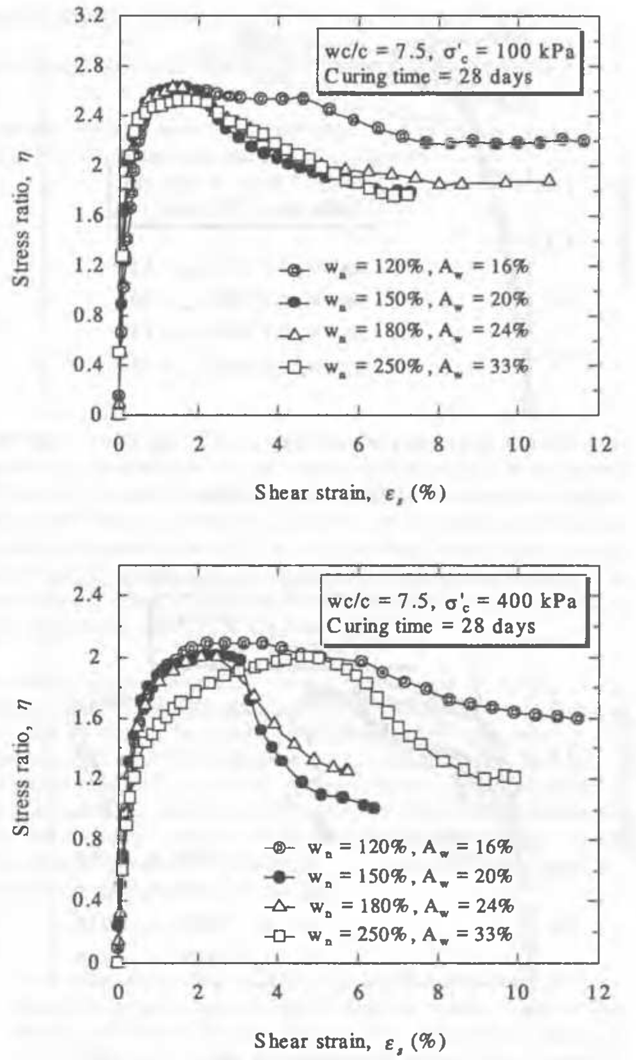

Figure 4. Stress ratio and strain strain plots of stabilized samples having the same *wc/c* value of 15.

wc/c value of 15 are the same for all the effective cell pressures and slightly diverse with approaching to the peak stress ratios.

For the mixtures of low *wc/c* value of 7.5, the relations of all mixtures are alike at low effective cell pressure of 100 kPa. However, at high effective cell pressure of 400 kPa, the mixture made up at higher clay water content of 250% exhibits higher volumetric and shear strains after showing the same manner up to a certain level.

5 CLAY-WATER/CEMENT RAITIO HYPOTHESIS

From the above test results, the clay-water/cement ratio hypothesis based on the critical state and state boundary surface concepts is proposed as follows.

1) The lower the *wc/c* value, the greater the enhancement of the cementation bond strength. It results in increasing the yield stress in K_0-consolidation and the yield surface.

2) The mixtures having the same *wc/c* possess the same level of yield stress even though they are made up from different clay water content and cement content. The cementation effect on the mixtures having the same *wc/c* value can be classified into two groups

2.1) One with the same value of *wc/c*, induces the same yield stress and resistance to plastic deformation, which corresponds to the mixtures made up at high *wc/c* value such as 15. Thus their (η, ε_s) and (η, ε_v) relationships are identical as shown in Figures 2 and 3.

2.2) The other for the same *wc/c* value, induces only the same yield stress. It corresponds to the mixtures with low *wc/c* value such as 7.5. For the samples with high effective stress ratio, ESR (The effective stress ratio is defined as the ratio of mean yield stress to effective cell pressure) such as the samples subjected to low effective cell pressure of 100 kPa, the samples are inside the state boundary surface until failure, then their behavior is the same, which is elastic behavior.

For the samples with low effective stress ratio ESR such as the sample subjected to σ'_c = 400 kPa, their (η, ε_s) and (η, ε_v) relationships are similar at the initial state up to a certain stress ratio, η and then the samples with higher clay water content exhibit higher volumetric and shear strains at the same stress ratio, η. Such behavior can be explained that while the initial states of stress of all samples are inside the state boundary surfaces, the samples have the same mean yield stress in K_0-line. Thus, the elastic behavior is recognized for these samples. The samples with higher clay water content undergo higher volumetric deformation when the states of stress lie on the state boundary surfaces due to the higher compression index beyond the yield stress caused by the break up of the cementation bond. Moreover, the samples with higher clay water content reach the state boundary surface before the samples with lower clay water content as illustrated in Figure 5. The change of small strain zone (elastic behavior) to large strain zone (elasto-plastic behavior) occurs at smaller stress ratio, η for the samples with higher clay water content.

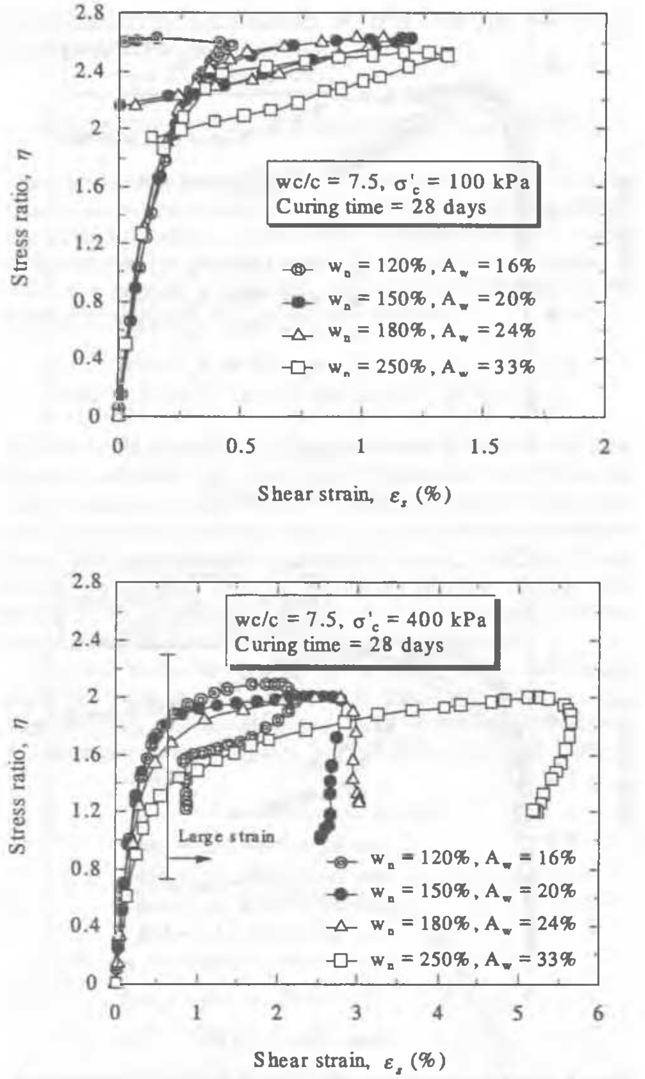

Figure 5. Stress ratio and volumetric strain plots of stabilized samples having the same *wc/c* value of 7.5

The schematic diagram showing behavior of cement stabilized samples having the same *wc/c* is shown in Figure 6. For the mixtures with low *wc/c*, the stress paths of samples, subjected to high effective cell pressure/mean effective stress, p'_H are inside the state boundary surface and then increase with the gradient of d*q*/d*p'* of 3 to the peak states. The behavior changes from elastic to elastoplastic. The sample with higher clay water content reaches the yield surface before the sample with lower clay water content and then the paths keep proceeding up to the peak

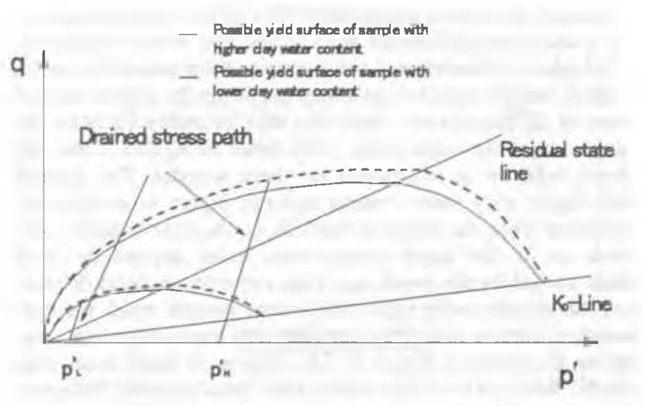

Figure 6. Schematic diagram showing behavior of cement stabilized samples having the same *wc/c*.

states. At this state, the volumetric strain is constant so $d\varepsilon_v/d\varepsilon_s = 0$. The stress paths of samples subjected to low effective cell pressure/mean stress, p'_L are inside the state boundary surfaces up to the peak states. Thus, they exhibit elastic behavior up to the peak states. At the peak states, the samples start to dilate ($d\varepsilon_v/d\varepsilon_s > 0$).

For high *wc/c* mixtures, the compression indices are almost in the same order due to less effect from the break up of cementation bond. Thus their behavior is the same both for low and high effective cell pressures. Owing to the small differences of (η, ε_s) and (η, ε_v) relations, the unique yield surface can be assumed for the high *wc/c* mixtures made from low and high clay water contents.

6 CONCLUSIONS

This paper investigates the engineering behavior of cement stabiized clays based on the clay-water/cement ratio. The conclusions are drawn as follows

1) The *wc/c* is the prime paremter governing the engineering behavior of cement stabilized clay. It is a convinent parameter to adjust cement content when the water content of clay varies (due to either slurry method of deep mixing or jet grouting techniques) so as to obtain the same level of strength at the same curing time.

2) The lower the *wc/c* value, the greater enhancement of cementaion bond strength. It results in increasing the yield stress and the yield surfce. The mixtures having the same *wc/c* possess the yield stress in common.

3) The (η, ε_s) and (η, ε_v) relationships of the mixtures having the same *wc/c* present in two groups. One is of the high *wc/c* mixtures; their yield stress and resistance to plastic deformnation are the same thus the relations are alike for all conditions of effective cell pressure. The other is of the low *wc/c* mixtures; the relations are the same up to a certain stress ratio and the mixtures with higher clay water content exhibit more volumtric and shear strains when they are subjected to the high effective cell pressure. However, the relations are the same for the mixtures subjected to low effective cell pressure because they exhibit the elastic behavior.

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