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A unified state parameter for modeling undrained shear behaviors of cementitious material admixed clay

Un paramètre d’état unifié pour la modélisation du comportement non drainé d’argiles cimentées

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ABSTRACT

Portland cement and pozzolanic materials are recently widely used for subsoil improvement, either by cement stabilization or cement columns. However, the requirement of rational engineering approach for the improvement by these materials has revealed several deficiencies in the current design procedures, since there is no single parameter that can represent the overall mechanical behaviors of such mixed materials. This paper presents a physical parameter, termed the ‘state parameter’, which could appropriately represent the dependency of the undrained shear behaviors of cementitious-material admixed clay on different mixing components and shear stress level. Experimental data from unconfined compression and undrained triaxial compression tests on cementitious-material admixed clay at confining pressures ranging from 50 to 200 kPa are presented and the significant engineering parameters of undrained shear behaviors could be captured to be dependent on the proposed state parameter.

RÉSUMÉ

Le ciment de Portland et autres matériaux pozzolaniques sont largement utilisés pour le traitement des sols, à travers la stabilisation par ciment ou par l’intermédiaire de colonnes cimentées. Toutefois, les procédures de dimensionnement actuelles souffrent d’un certain nombre de limitations provenant du fait qu’il n’est pas considéré de paramètre unique pour caractériser le comportement mécanique global de ce type de mélange. C’est pourquoi un paramètre physique est proposé, nommé paramètre d’état, qui permet de représenter de manière pertinente la dépendance du comportement non drainé en fonction de la teneur des différents composants et de l’état de contrainte. Des données expérimentales sont présentées provenant d’essais triaxiaux non drainés avec ou sans confinement (le cas échéant, les pressions appliquées sont comprises entre 50 et 200 kPa). Les résultats révèlent une bonne corrélation entre les principaux paramètres de comportement et le paramètre d’état proposé.

Keywords : state parameter, cementious-material admixed clay, undrained shear behavior

1 INTRODUCTION

1.1 Background

Deep Mixing Method (DMM) is a soil stabilization technique by using chemical additives, generally Portland cement, added to the soft ground to enhance their mechanical properties (Broms 1986). However, a significant amount of Portland cement has to be used in this technique, resulting in higher cost for construction when compared to other techniques. To decrease the cost of construction, mainly governed by the cost of cement, it is necessary to find the lower cost materials for replacing the cement. A number of researches attempting to partially replace Portland cement in soil cement with some Pozzolanic materials, such as fly ash (Jongpradist et al., 2009) and rice husk ash (Jongpradist et al., 2008), have been conducted. They confirmed the potential of utilizing those ashes. At the same time, many researchers have investigated and characterized the behaviors of soil cement to develop its mathematical model (e.g., Lorenzo & Bergado, 2004; Horpibulsuk et al., 2004). To achieve this, a single parameter that is capable of both capturing its behaviors and normalizing parameter, is needed.

1.2 Fundamental parameters of Cementitious Material Treated Clay

A number of researches on cement admixed clay which were mostly performed by means of unconfined compression tests revealed that the engineering behavior of cement-admixed clay is affected by the clay water content (Cw), cement content (Aw), as well as curing time and a few characterizing parameters have been gradually proposed (Uddin et al., 1997; Horpibulsuk et al., 2003). Recently, a new approach of characterizing the strength in terms of unconfined compressive strength and compressibility behavior of cement-admixed clay has been developed by Lorenzo & Bergado (2004). It was proven that this fundamental parameter; the ratio of after-curing void ratio (ea) to cement content (Aw), as Eq. 1, is relevant to characterize the strength and compressibility of cement-admixed clay at high water contents.

\[
e_a = \left( \frac{100 - 0.012A_w + 0.0025A_w \cdot 0.1 \cdot \log t + 1.098}{100} \right) \left( 1 - \frac{A_w}{100} \right) \left( 1 - \frac{0.012A_w + 0.0025A_w \cdot 0.1 \cdot \log t + 1.098}{100} \right)
\]

where \( G_s \) denotes for specific gravity of the base clay

\( t \) represents for curing time (days)

However, this parameter was determined based on cement-admixed clay only in saturated condition. Jongpradist et al. (2007) proposed a new parameter taking into account the existence of water in void space, termed total effective void ratio (Eq. 2) to overcome such difficulty and found that this parameter can capture the strength and compressibility of soil cement, not only for saturated soil-cement but also for the air-foam soil cement (Sittibun et al., 2007) and unsaturated stabilized soils (Chareonrat et al., 2008). The after curing void...
ratio of unsaturated soil cement can be calculated from fundamental equation as shown in Eq. 3.

\[ e_u = C_w \times \ln(e_w / A_w) \]

where \( e_u \) = total effective void ratio \( e_w \) = after curing void ratio by Eq. (1) or void ratio by Eq. (3)

\[ e_u = \left(1 + w_i \right) G_d \frac{\gamma_i}{\gamma} - 1 \]  

(3)

An attempt to characterize the strength characteristic of Pozzolanic material admixed soil cement was conducted by taking into account the equivalent cement content concept (Eq. 4) and replacing the cement content with equivalent cement content as indicated in Eq. 5.

\[ A_w = A_w + k(P) \]

where \( A_w \) = equivalent cementitious content \( P \) = pozzolanic material content

\[ e_u = C_w \times \ln(e_w / A_w) \]

(5)

The performance of the developed parameter, est, is confirmed to be able to characterize the unconfined compressive strengths of cement admixed soils with and without adding pozzolanic materials as shown in Fig. 1.

Figure 1. Relationship between unconfined compressive strength versus effective void ratio, \( e_u \) (Jongpradist et al., 2008).

2 UNDRAINED SHEAR BEHAVIORS OF CEMENTITIOUS ADMIXED CLAY

For over 30 years, the undrained shear behaviors of un cemented clays have been investigated by many researchers. But for cement admixed clay from improvement of soft ground by chemical admixture, the investigations for understanding its behaviors has just been conducted during this decade. Particularly, the characteristics under undrained shear and controlling mechanisms are limited. For this cemented clay, the natural clay is disturbed by construction procedures and mixed with cement or lime, consequently, the cementation is taken over by admixed cementation. For Bangkok soft clay, the lime treatment causes a change in strength and deformation characteristics of the soft clay from a normally consolidated clay to that of an overconsolidated clay (Balasubramaniam & Buensuceso, 1989). Recently, comprehensive investigations have been performed by Horpibulsuk et al. (2004) and Lorenzo & Bergado (2006). They reported that the strength and deformation characteristics are controlled by clay fabric and cementation as well as the level of confining pressure. The undrained shear behaviors of cementitious material admixed clay also exhibit in the same manner as shown in Fig. 2 for fly ash admixed soil cement performed in this study. Although some fundamental parameters and empirical relationships were proposed to characterize the strength behaviors, such fundamental parameters were insufficient to capture the significant parameters of undrained shear behaviors under different stress levels. Since all proposed parameters concern on structural property alone, but the description of stress level is omitted.

![Figure 2: The relationships between normalized peak undrained shear stress and \( e_u \) of fly ash admixed soil cement](image)

3 CONSIDERATIONS FOR STATE PARAMETER

As previously mentioned, the properties of cementitious material admixed clay must be expressed in terms of both structural property and stress level. It is therefore postulated that its behaviors may be characterized in terms of a single parameter that combines the influence of structure and stress.

First, the structure property is considered (the word structure is widely used and this includes fabric, void ratio and composition in the sense of Mitchell (1976)). Unlike sands, it is not the void ratio that governs the behaviors of cement admixed clay in the sense of structure. A number of previous experimental results indicated that it includes its compositions, cement content, water content and curing time. For the sake of simplicity, a single parameter which could combine all those influencing parameters is necessary to represent matrix structure. Since it represents only matrix structure, many commonly used mechanical behaviors of which the state is not reflected, should be able to normalize well to this single parameter as well. Based on the aforementioned idea, the total effective void ratio was selected.

![Figure 3: State diagram for cement admixed clay](image)
Next, consideration on state or stress level is performed. Been & Jeffries (1985) selected the first stress invariant \( I_1 \) as stress measure for incorporating into the state parameter and the state was illustrated in void ratio-stress space. This state parameter has been used for modeling sand behaviors (e.g., Li & Dafalias, 2000). In this study, the \( I_1 \) or \( p' \) was then adopted to represent stress level. Thus, the state was illustrated in total effective void ratio, \( \varepsilon_c \) –stress \( I_1 \) space. The measure from state to reference state is called the state parameter and the symbol \( \psi \) has been used to represent the state parameter. 

\[
\psi = \varepsilon_{st} - \varepsilon_{ssl}
\]  

Whereas the \( \varepsilon_c \) is the total effective void ratio at preshear state. The reference state here is selected to be the steady state, SS which is defined as the locus of point at which a mixed material deforms under condition of constant effective stress. Thus a locus of steady states in void ratio-stress space is steady state line, SSL which represents the reference state to be measure for the state parameter as shown in Fig. 3.

4 CEMENTITIOUS MATERIAL ADMIXED CLAY BEHAVIORS AS A FUNCTION OF STATE PARAMETER

Only summaries of typical and significant features of undrained triaxial test results are presented in order to verify their dependence on the state parameter. For example, the deviatoric stress-strain, development of excess pore water pressure and stress path are shown in Figs. 4-6, respectively. From these figures, the followings can be concluded. For specimens with positive initial state parameters, no clear peak stress can be observed. The excess pore water pressure rapidly develops as increasing deviatoric stress and its reduction after peak stress is not distinct. The stress paths behave in a manner in which \( p' \) starts decreasing at small deviatoric stress due to the rapid development of excess pore pressure. Whereas, for samples with negative initial state parameter, they exhibit the distinct peak stresses. The development of excess pore pressure is not as large as that of samples with positive initial one and as further straining, it decreases to negative value indicating the dilatation of specimens. The stress paths behave in a manner in which the \( p' \) remains unchanged or slightly increases until reaching the peak deviatoric stress. Afterwards, the \( p' \) increases rapidly as the drastic reduction of excess pore pressure.

5 CONCLUSIONS

This study introduces a new state parameter for modeling undrained shear behaviors of cementitious material admixed clay. It is the difference between the total effective void ratio at current state and that of steady state. The total effective void ratio, \( \psi \) combines together the effects of curing time, the equivalent cement content, \( A^* \), and the total clay water content, \( C_w \), representing the structure matrix of material where as the mean normal effective stress represents the state. This proposed state parameter is treated as a state variable which varies from initial value to zero at critical state. From results of isotropic consolidated undrained triaxial compression tests, the
significant behaviors can be captured to be dependent on the state parameter. Moreover, each of all essentially significant engineering parameters of undrained shear behaviors as well as unconfined compressive strength can be characterized as a function of the state parameter.

![Figure 7. Yield stress, $q_u$ and Normalized peak stress as functions of initial state parameter.](image)

![Figure 8. Pore pressure parameter as a function of initial state parameter.](image)

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