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Rate of softening and sensitivity for weakly cemented sensitive clays

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Abstract. The rate of softening is an important factor to determine whether the failure occurs along localized shear band or in a more diffused manner. In this paper, strength loss and softening rate effect depending on sensitivity are investigated for weakly cemented clays, for both artificially cemented high plasticity San Francisco Bay Mud and low plasticity Yolo Loam. Destructuration and softening behavior for weakly cemented sensitive clays are demonstrated and discussed through multiple vane shear tests. Artificial sensitive clays are prepared in the laboratory for physical modeling or constitutive modeling using a small amount of cement (2 to 5%) with controlled initial water content and curing period. Through test results, shear band thickness is theoretically computed and the rate of softening is represented as a newly introduced parameter, $\omega_{80\%}$. Consequently, it is found that the softening rate increases with sensitivity for weakly cemented sensitive clays. Increased softening rate represents faster strength loss to residual state and faster minimizing of shear band thickness. Uncemented clay has very low softening rate to 80% strength drop. Also, it is found that higher brittleness index (I_b) relatively shows faster softening rate. The result would be beneficial to study of physical modeling for sensitive clays in that artificially constructed high sensitivity (up to S_t = 23) clay exhibits faster strain softening, which results in localized shear band failure once it is remolded.

Keywords: sensitive clay; shear band; strain softening; sensitivity; cemented soil; vane shear; strength loss

1. Introduction

Strain softening and strain localization of sensitive clay are important in the stability of sensitive clay slopes or levee embankments. For natural sensitive clay, significant deformation and volumetric collapse due to the loss of structure can be induced by static and/or earthquake loading. It is reported that there have been cases of extensive submarine or in-land landslides for the weakly cemented sensitive clay layer (Andersson-Sköld *et al.* 2005, Azizian and Popescu 2005, Crawford 1968, Geertsema and Torrance 2005, L'Heureux *et al.* 2014, Longva *et al.* 2003, Tappin *et al.* 2003).

The common issue in view of failure is the destructuration and the loss of strength in terms of sensitivity. Sensitive clay generally shows a brittle stress-strain behavior because of a destructuration of initial meta-stable structure generating positive excess pore pressure (Abramson *et al.* 2002). For a strain softening material (i.e., a sensitive material), after reaching the peak

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strength, the shear stress drops to the residual strength. Consequently, a shear band, which is the thin localized zone of plastic deformation, is formed. As the shear band forms, the weakened shearing zone becomes even weaker due to the concentration of strain and continued softening. Typically for strain softening material like sensitive clay, concentrated shear bands create shearing velocity jumps across the shear zone. In contrast, the contractive tendency of strain hardening material produces a more or less diffused shear zone at failure.

Therefore, it is essential to study strain softening behavior with the conjunction of shear band thickness for sensitive clay slopes. For this research purpose, repetitive physical modeling or numerical modeling is preferred because it is highly expensive to use undisturbed block sampling of in-situ sensitive clay. Either design of physical models or development of constitutive models for sensitive clay requires information about strain softening and the rate of softening, which affect the failure mode – either localized (with thin shear band) or diffused deformation.

Recently, there have been significant efforts to investigate the effects of strength loss and/or strain rate and strain softening for soft clays (DeJong *et al.* 2011, Randolph 2012, Yafrate *et al.* 2009, Zhou and Randolph 2009). For physical modeling of sensitive clays, there have been a study to reconstitute high sensitive clays recently (Meijer and Dijkstra 2013). One way to simply make sensitive clay in laboratory for the purpose of physical modeling is to use small amount of cement mix (2 to 5%) combined with initial water content and curing period (Park *et al.* 2010, Park 2012). Information regarding volume change and shear strength of cement treated clay have been published (Verástegui Flores and Van Impe 2009, Bushra and Robinson 2012, Horpibulsuk *et al.* 2010, Sasanian 2011, Suebsuk *et al.* 2009, Kamruzzaman *et al.* 2009, Chew *et al.* 2004, Mitchell 1976, Horpibulsuk *et al.* 2004). However, most references on cement treated clay are concerned about ground improvement and they used cement mixing ratios greater than 5%.

In this paper, stress-strain behavior and the effect of softening rate and sensitivity are investigated for artificially sensitive weakly cemented clays made by recipe shown in Park *et al.* (2010), for both artificially cemented high plasticity San Francisco Bay Mud and low plasticity Yolo Loam. Cement mixing ratios used are 2 to 5% to construct weakly cemented sensitive clays.

A major difficulty in the study of stress-strain relationships for sensitive soil is that we cannot directly measure the strain in most cases because as soon as strain softening occurs, a localized thin shear band forms so that global measurements cannot account for this localized strain. To overcome this issue, vane shear testing is introduced in this study. Destructuration and softening behavior for weakly cemented sensitive clays are demonstrated and discussed through multiple vane shear tests. Vane shear test can exceptionally provide indirect method of estimating stress-strain relationships along the cylindrical shear band by measuring torque-displacement during shearing. Vane shear testing can also provide evidence related to the softening rate as well as sensitivity. From vane shear results, shear band thickness and shear strain within cylindrical shear band are derived in this study.

A new term, $\omega_{80\%}$ is introduced to account for the rate of softening of sensitive clays. Then, the rate of softening is related to the brittleness index (I_b) (Bishop 1967) of artificially cemented sensitive clays. Brittleness index (I_b) is defined as the ratio of the total strength loss from peak to residual strength with respect to peak strength (Bishop 1967).

$$I_b = \frac{S_{peak} - S_{residual}}{S_{peak}} = 1 - \frac{1}{S_t} \tag{1}$$

where S_{peak}: peak shear strength, $S_{residual}$: residual shear strength, S_t: sensitivity (= S_{peak} / $S_{residual}$).

From the definition, brittleness index is directly related to sensitivity (S_t). For quick clays with very high sensitivity, I_b is close to 1, and for insensitive clays, I_b approaches zero. According to Hossain and Randolph (2009)'s study, increased brittleness of soils results in significant strength loss specifically for rate-dependent, strain-softening clays.

Lastly, the relationship of sensitivity and the rate of softening is presented and discussed. Consequently, the main contribution of this research is to understand stress-strain behavior due to strain softening/localization and the rate of softening in artificially sensitive clay. It is therefore beneficial to consider sensitivity relating with the rate of softening for better realization of physical and numerical modeling.

2. Test program

2.1 Material

Two different soils were used. One is San Francisco Bay Mud (denoted as SFBM) and the other is Yolo Loam (denoted as YL).

According to the USCS soil classification, SFBM can be classified as highly plastic CH (fat clay, Liquid Limit, LL = 88, Plasticity Index, PI = 50) while Yolo Loam is CL (lean clay, LL = 29, PI = 10) based on the Atterberg Limit tests. Compared to bay mud, Yolo Loam is less plastic (PI = 10). For context, natural quick clays such as Leda Clay and Norweigan Quick Clay have relatively low plasticity and significant silt content (Andersson-Sköld *et al*. 2005, Mitchell and Soga 2005, Penner 1963). Yolo Loam was used with 2 to 5% cement mix because there was some anticipation that low plasticity clay could make higher sensitivity artificially.

Sensitivity can be altered by introducing chemical agents like cement at reasonable concentration (e.g., 2 to 5% cement). The additive used as a chemical agent in this study is Portland Cement Type 1. De-ionized water was used for mixing. Adding 2 to 5% cement with respect to the mass of solid of soil causes an increase both LL and PI, as described detail in Park (2012). For example, LL and PI of SFBM C3.3W110T5 are measured as 119% and 64%. Increased LL for cement-treated clay means less fluidity at the same water content of LL for raw material.

Based on the multiple laboratory tests (Park *et al*. 2010), weakly cemented clays can easily produce strain softening material with moderate to high sensitivity.

2.2 Test outline

A summary table for the whole test program is given in Table 1. Note that in the table, the abbreviation term, "C" denotes cement mixing ratio with respect to the mass of solid of natural remolded soil, "W" for target initial water content before mixing cement, and "T" for curing period in days before any testing. For instance, SFBM C5W170T5 represents the San Francisco Bay Mud with 5% cement mixing, initial water content of 170%, and 5 day curing.

2.3 Testing methods

Cement treated clay specimens were made with constant mixing time (6 min) and consistent mixing energy using a mechanical mixer. A detailed description of this mixing recipe is shown in Park *et al*. (2010). After mixing, soft cement treated clay was cured for several days.

Table 1 Test outline

	Material	Combination
Vane shear	SFBM	C0.5W135T10, C3W135T9, C3W139T5, C3W159T5, C3W179T5, C4W170T3, C4W195T3, C4W214T2, C5W157T5, C5W191T5, C5W199T5, C5W215T5, SFBM C5W220T2, C5W249T6, C5W249T9 SFBM C5W220T2 at σ'_{vc} = 20 kPa
	YL	YL C0W31T2, YL C2W47T2, YL C2W51T2, YL C2W55T2 YL C2W51T2 at σ'_{vc} = 20 kPa, YL C2W55T2 at σ'_{vc} = 20 kPa

Note that σ'_{vc} is a vertical overburden effective stress

Hand vane shear test was taken to study stress – displacement relationship of weakly cemented clay. The procedure of hand vane shear follows manufacturer's guideline, which is based on the New Zealand Geotechnical Society (2001). It originally comes from the British Standard.

There were two sizes of blades, diameter of 19 mm for measuring higher strength and 33 mm for measuring lower shear strength. Depending on the sizes of vane blades, different cylindrical jars with D70 * H50 mm and D90 * H100 mm were used as containers for clays. For peak strength, the rotation speed was 6°/sec (1 rpm). For remolded strength measurement, the rotation speed was 10 sec/rotation (6 rpm) and took the value after 5 quick, complete rotations. The vane blade was inserted into the soil mass with great care to minimize penetration disturbance effects. The continuous division of torque was recorded together with reading of rotation angle until remolded state. The vane calibration factor between division reading and real torque was determined at the calibration stage before use. The real angle of rotation was calibrated by subtracting rotation angle of spring from the measured rotation angle of head.

Vane shear strengths were measured with angle of rotation for uncemented and cement treated SFBM and YL. For vane shear strength calculation, the uniform distribution of stresses was assumed along the vane blade horizontally and vertically.

2.4 Shear band thickness and the rate of softening for vane shear

Vane shear test is one way of observing strain softening behavior indirectly. From vane shear testing, the rate of softening can be observed through the stress-displacement relation along the cylindrical failure surface. To do this from the original angle of rotation during vane shear, it is necessary to estimate shear strain within cylindrical shear band. Shear strain can come from shear band thickness. Therefore, a reasonable estimation of shear band thickness is necessary.

In this study, the method by Einav and Randolph (2006) was applied to estimate shear strain within a cylindrical shear band. They derived an equation to find the optimal shear band thickness and the maximum shear strain rate for curved shear bands. Based on the assumption of simple uniform strain rate within a shear band, the following Eqs. (2)-(4) are given (Einav and Randolph 2006, Randolph 2004).

The average shear strain rate within a shear band $(\dot{\gamma}_{ave})$ can be

$$\dot{\gamma}_{ave} = \frac{v_p}{t_{sb}} = \frac{\omega \cdot r_o}{t_{sb}} = \frac{\omega \cdot \left(D/2\right)}{t_{sb}} \tag{2}$$

$$\gamma_{ave} = \frac{\left(D/2\right)\cdot\theta}{t_{sb}} \tag{3}$$

where, v_p: peripheral velocity of a vane, t_{sb}: thickness of cylindrical shear band, ω: angular velocity of tip of vane (radian/s), r_o: radius of vane blade, D: diameter (or width) of a vane, θ: angle of rotation.

D of a vane used in this study is 33 mm (r_o =16.5 mm) and ω is 1 rpm (= 0.105 sec^{-1}). Therefore, peripheral velocity (v_p) of the vane is 1.73 mm/s. The required thickness of shear band (t_{sb}) can be found by the equation (Einav and Randolph 2006, Randolph 2004)

$$\frac{t_{sb}}{D} = \frac{1}{\ln(10)\cdot\left(\frac{1}{\lambda}+\log\left(\frac{\dot{\gamma}_{ave}}{\dot{\gamma}_{ref}}\right)\right)-1} \tag{4}$$

where, λ: rate dependent model parameter. Herein λ = 0.1 is assumed based on Biscontin and Pestana (2001), $\dot{\gamma}_{ave}$: average shear strain rate in a shear band, $\dot{\gamma}_{ref}$: reference shear strain rate, typically 1%/hr (= 2.78×10^{-6} sec^{-1}) in laboratory.

In this study, the procedure to obtain stress-strain curves within a shear band can be illustrated as follows. Shear strain at each rotation angle within a shear band was computed by the Eq. (3) as a function of D, θ, and t_{sb}. In Eq. (3), θ was measured values at each angle of rotation (in radians). Eqs. (2) and (4) were used to compute shear band thickness, t_{sb}. Shear band thickness is a function of dimension of vane blade (D), rate parameter (λ), and peripheral velocity. Since rate parameter is assumed as constant (= 10%) for cement treated clays in the study, the author obtained the uniform shear strain rate within a shear band. Actually, the shear strain rate will be faster in the inner edge of shear band and decay toward the outer edge. Shear stress was measured and computed as shown in Fig. 1.

For a given condition in this study, average shear band thickness was computed as 0.93 mm and average shear strain rate within the shear band was predicted as 186 %/s. Note that shear band thickness actually depends on the rate dependent model parameter, λ. Since λ is the rate of increase of shear strength per decade of strain rates, the resulting shear band thickness may be different from each soil. In addition, when shear strength as a function of strain rates is more rigorously expressed using power law or arc sin*h* model, the computed shear band thickness would be different depending on the assumption. For simplicity, the prediction in this study was based on the assumption of λ = 10% and a simple uniform shear strain rate within the shear band.

3. Result and discussion

3.1 Stress-strain behavior

The Fig. 1 shows the derived stress-strain relationships for SFBM and YL specimens. All cement treated sensitive specimens show somewhat brittle, strain softening behavior. Artificially sensitive specimens converge to the certain range of low residual shear strength. It implies the fully remolded residual strength at a very large strain may be comparably very low. In terms of strength loss, approximately, after one revolution of vane, the strength drop was about 80 to 90%

of peak strengths.

To the contrary almost insensitive SFBM C0.5W135T10 and YL C0W31T2 specimens shows relatively much less strength drop and post-peak softening is not apparent. Uncemented YL C0W31T2 after consolidation has a low sensitivity less than 2. Its remolded strength does not drop significantly. But, 2% cement mixed YL at water content of 51 and 55% undergoes significant softening after peak.

The cement mixing ratio is an important factor to determine the peak strength level and the rate of softening. It is observed that peak strength increases with cement mixing ratio. SFBM with 3% cement has relatively lower peak shear strength than 4 to 5% mixed ones. The effect of cement mixing ratio is more apparent for YL. For example, YL C2W51T2 shows the peak S_u of 11.2 kPa at initial water content of about 1.8 LL whereas SFBM C3W159T5 indicates the peak S_u of only 0.5 kPa at almost the same initial water content of 1.8 LL. This is also related to PI. The PI is the amount of water required to change the shear strength of soil about a hundredfold. As the PI of Yolo Loam is 10, obviously there is a significant effect of cement mixing ratio as well as initial water content on the shear strength within a narrow range of water content. For Yolo Loam, 2% of cement is enough to get higher peak strength and higher sensitivity than SFBM with 4% cement.

Although curing period after cement mixing does not affect strength of soil significantly (when 2 days of curing is ensured), it is one of the control parameters. Comparing the curing period under the same conditions, longer duration of curing makes higher peak strength (e.g., SFBM S_u = 5.3 kPa for C5W249T6 and S_u = 7.2 kPa for SFBM C5W249T9). Accordingly, it results in the different rate of softening. However, at large strains, both are basically converged to similar value.

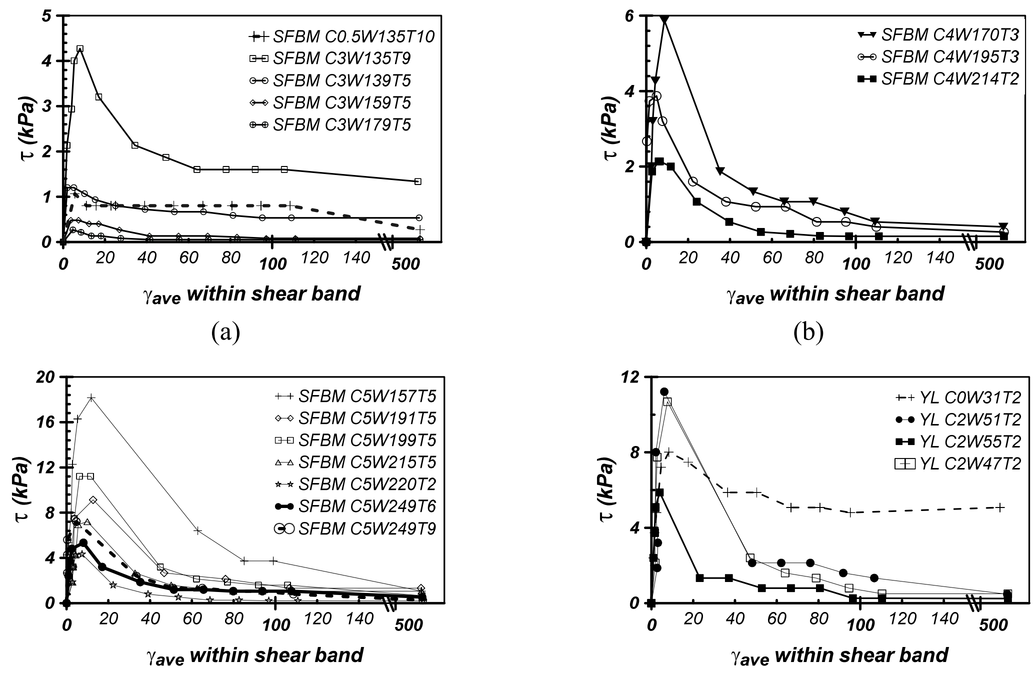

Fig. 1 Back-calculated stress-strain curve within shear band: (a) C0.5 and C3; (b) C4; (c) C5 for cemented San Francisco Bay Mud; and (d) C0 and C2 Yolo Loam specimens. Note that γ_{ave} is the average shear strain

3.2 The rate of softening, brittleness, and sensitivity

The rate of softening is an important factor to determine whether the failure occurs along localized shear band or in a more diffused manner. If the soil is thixotropically sensitive, the rate of softening may be relatively mild. If it is a quick clay, then the rate of softening can be very fast because of sudden destructuration. Typically for strain softening clays, shear band thickness becomes thinner as softening proceeds. How fast strain localization occurs depends on the thickness of shear band. The shear band thickness is governed by sensitivity. Therefore, it is valuable to study the relationship between sensitivity and the rate of softening.

There can be many options to define the rate of softening after peak. In this study, in order to define representative softening rate for vane shear, a new term is empirically introduced, i.e., $S_{u,20\%}$ as the remained strength of 20% from the peak strength to the residual strength, which means 80% strength drop (Fig. 2). A reference level, 20% is an arbitrary number, but it might be a good empirical indicator of significant strength loss within one revolution of vane in this study.

Note that the choice of reference level is from the need of reasonable simplification of the rate of post-peak strain softening. It is believed that the softening rate with window of 80% strength drop might be appropriate for a reasonable linearization of softening rate from the database used in this study. It is equivalent to a few thousands of shear strain (in % unit) and can be typically observed within 180 degrees of vane rotation angle. For sensitive clay showing significant strain softening right after post-peak softening, the window of steeper strength loss is dominant to determine how fast strain is localized as a thin shear band forms.

Hence, the post-peak softening rate index, $\omega_{80\%}$ can be defined as (Fig. 2)

$$\omega_{80\%} = -\frac{S_{u,peak} - S_{u,20\%}}{\Delta\gamma} \tag{5}$$

Fig. 3 exhibits the relationship between brittleness index (I_b) and the softening rate of cement treated clays. Though there are not clear correlations between softening rate and brittleness index, in a broad sense, there is a rough trend that $\omega_{80\%}$ increases as I_b approaches 1. For artificially cemented SFBM and YL, most of specimens show high I_b greater than 0.5, which represents more brittle behavior. Low sensitive clay shows relatively smaller I_b by the definition of I_b, hence, slower $\omega_{80\%}$. Comparing SFBM and YL specimen, cement treated YL showing higher S_t indicates faster softening rate. Thus it may be beneficial to use cement treated YL for higher S_t in physical

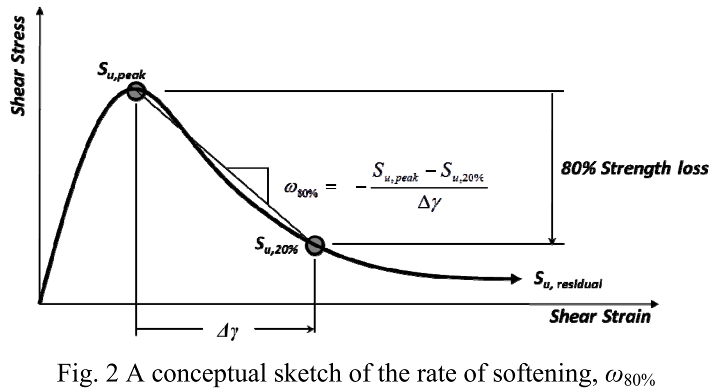

Fig. 2 A conceptual sketch of the rate of softening, $\omega_{80\%}$

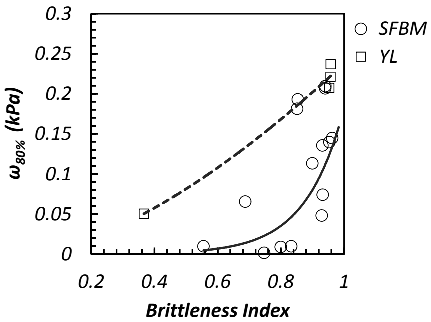

Fig. 3 The relationship of brittleness index and the rate of softening for SFBM and YL specimens

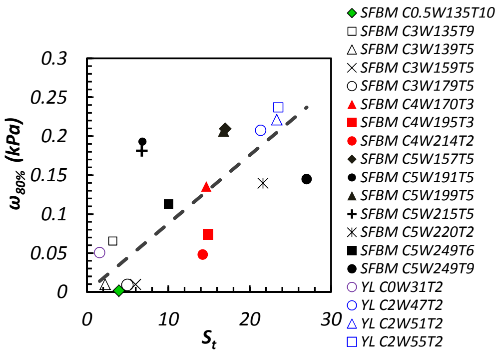

Fig. 4 The relationship of sensitivity and the softening rate

modeling for the purpose of construction of highly brittle, strain softening behavior during failure.

Accordingly, the above correlation leads to the plot of sensitivity and the rate of softening as seen in Fig. 4. There is a rough proportional relationship between $\omega_{80\%}$ and sensitivity. It means more sensitive material shows faster post-peak strain softening, which indicates faster strain localization and faster strength drop.

For this study, cement treated clays with S_t greater than 10 have at least 90% of brittleness index and shows relatively faster softening after peak. Note that the derivation of $\omega_{80\%}$ from vane shear test depends on the approximation of shear strain rate within shear band. In this study, constant shear strain rate was assumed with cylindrical shear band in Eq. (3).

Vane shear tests for the weakly cemented clay demonstrate many useful ideas not only about information of peak and residual strength, but also about the rate of strain softening. It could give the idea regarding how fast the strain softening occurs during destructuration. More data will be necessary for further proof testing.

4. Conclusions

In this paper, strength loss and the rate of softening were investigated for weakly cemented clays, for both artificially cemented (2 to 5%) high plasticity San Francisco Bay Mud and low plasticity Yolo Loam. Softening behavior for the weakly cemented sensitive clay was characterized through multiple vane shear tests. Based on test results, the following conclusions are made.

- Softening rate increases with sensitivity for weakly cemented sensitive clays. Increased softening rate represents faster strength loss to residual state and faster minimizing of shear band thickness. Thus, higher sensitive soil is more susceptible to faster softening rate once it reaches peak strength, which is experimentally validated through this study.
- Vane shear testing is an effective way to study the rate of softening indirectly via stress – displacement relationship. Based on vane shear for 2 to 5% cement-treated clays, it is observed that the higher brittleness index (I_b) apparently produces faster softening rate. As I_b is close to 1, the rate of softening increases rapidly.
- A newly introduced softening rate term, $\omega_{80\%}$ (to account for 80% strength drop) may be an effective parameter to correlate brittleness index and sensitivity of artificially sensitive clays.

The results would be beneficial to study of physical modeling for sensitive clays in that artificially cemented clay can be successfully constructed in a reproductive manner with satisfying desired shear strength and sensitivity. Based on Fig. 4, for example, YL C2W55T2 sample shows high sensitivity (S_t = 23) and relatively fast strain softening which may show a failure pattern of localized shear band if it is fully remolded, and this sample can serve as an efficient material for geo-centrifuge modeling in laboratory. Test data is also contributable to provide references for constitutive modelers in pursuit of structured clay simulation.

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