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UNDRAINED SHEAR STRENGTH OF CEMENT-TREATED SOILS

KIYONOBU KASAMA[i], KOUKI ZEN[i] and KIYOHARU IWATAKI[ii]

ABSTRACT

In order to evaluate the effects of cementation on the mechanical properties of cement-treated soil, a series of isotropic consolidation and undrained triaxial compression shear tests were performed for cement-treated specimens of Ariake clay, Akita sand, Rokko Masado and Toyoura sand. This paper evaluates factors affecting the shear strength of these cement-treated soils. The following conclusions are obtained: 1) Cement-treated soil has a normally consolidated line in e-ln p' space which depends on the mixing cement content. The consolidation yield stress, p'_y, of cement-treated soil increases with increasing cement content and initial specimen density. 2) Changes in cohesive strength due to cement-treatment can be represented by a tensile effective stress, p'_t. Strength properties can then be normalized by the augmented consolidation stress, $(p'_c+p'_t)$. 3) The shear strength properties of quasi-overconsolidated clay can be represented by the yield stress ratio, $R=(p'_y+p'_t)/(p'_c+p'_t)$. 4) The undrained shear strength of cement-treated soils can be represented as a power law relation of the yield stress ratio, R, and the augmented consolidation stress.

Key words: cement stabilization, consolidation, overconsolidation ratio, shear strength, undrained shear, yield stress (**IGC**: D6/D10)

INTRODUCTION

Conventional cement stabilization such as deep mixing method (Terashi and Tanaka, 1981) has been used mainly for improving the bearing capacity of soft ground. In recent years, new cement stabilization methods have been developed in order to make effective use of recycled geomaterials with appropriate considerations of environmental impacts. For example, dredged soils mixed with cement have been widely used as fills in many reclamation projects in Japan (e.g. Tang et al., 2001). Sandy soils mixed with cement by the pre-mixing method (Zen et al., 1992) have been used in reclamation works in Japan to mitigate against liquefaction in reclamated land. From these backgrounds, a number of types of cement-treated soil (namely cement mixed soil) have been created for the purpose of increasing the bearing capacity of soft ground, reducing the unit weight of fills, liquefaction countermeasures and recycling of construction surplus soil.

In general, the primary factors affecting the shear strength of cement-treated soil, are the amount of mixed cement (e.g. Terashi et al., 1980; Matsuo and Nishida, 1969), types of cement (e.g. Kurihara et al., 1994; Kamon and Katsumi, 1999), physico-chemical properties of the nature soil (e.g. Kuboi and Nishida, 1999; Okabayashi et al., 1999), curing conditions (e.g. Minowa et al., 1998; Mishima et al., 1995), and, specimen size (e.g. Hayashi et al., 1997), etc. These factors have been examined through unconfined compression tests which are favored due to their simplicity and ability to represent properties at low confining pressures. In recent years, the strength-dependency on confining pressure (Yajima et al., 1997; Ue et al., 1997), dynamic shear properties (Ito et al., 1994; Yamamoto et al., 1996) and low strain characteristics (Shibuya et al., 1992) have been reported using triaxial compression tests. These prior studies have clarified the mechanical properties of cement-treated soils.

Various indexes have been used to represent the strength of cement-treated soil as shown in Table 1. These include: a) the weight ratio of cement to dried soil (called "cement content") and b) cement weight per wet soil volume of 1 m^3 (called "cement amount"). Cement content and cement amount are widely used in practical mix design for cement-treated ground. In addition, Yajima et al. (1996) have characterized the failure criterion for light-weight cement-treated soil using void ratio and unconfined compression strength, while Minamigawa et al. (1987), Miura et al. (2001) and Suzuki (1990) evaluated strength using the conventional water-cement ratio (i.e. weight ratio of water to cement) similar to the concrete. Omine et al. (1998) proposed a two-phase mixture model for predicting the stress-strain relationship of cement-treated soil based on the consideration of stress distribution and strain energy. Tang et al. (2001) evaluated the variation of unconfined compression strength of in-site cement-treated soil due to the change of water content and cement amount.

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Table 1. Indexes for describing the strength of cement-treated soils

Target strength	Function	Index	Comments	Reference
q_u	$q_u=f(A_w)$	A_w(%): weight ratio of cement to dried soil (cement content)	For cement-treated sandy soil by the pre-mixing method	Zen et al. (1990) and (1992)
q_u	$q_u=f(C)$	C(t/m^3): cement weight per wet soil volume of 1 m^3 (cement amount)	For cement-treated soft cohesive clay by the deep mixing method	Terashi et al. (1980); Terashi and Tanaka (1981)
s_u, s_d	$2s_u=2s_d=Mp'+A$	M: inclination of failure line in p'-q space A: intercept of failure line in p'-q space p': mean effective stress e_i: initial void ratio of specimen	For light-weight-cement-treated soil M: $2.65-0.59e_i$ A: $0.92q_u$	Yajima et al. (1996)
q_u, s_u	q_u, $s_u=f(w_0/A_w)$ or $f(A_w/w_0)$	w_0/A_w: weight ratio of cement to water (water-cement ratio) w_0: initial water content	For cement-treated cohesive soil with high water content	Miura et al. (2001); Suzuki (1990); Minamigawa et al. (1987)
$q_{u(F)}$: q_u of in-situ treated soil	$q_{u(F)}=\dfrac{(b-1)f_s+1}{bf_s^2/q_{u(L)}+\alpha(1-f_s)/q_{u(*)}}$ $q_{u(L)}$: q_u of treated soil prepared in laboratory $q_{u(*)}$: q_u of in-situ soil	b: stress distribution parameter f_s: improve ratio α: a coefficient representing the strain ratio of in-situ treated soil and original soil at a half of maximum stress	For in-situ cement-treated soil considering the mixing level	Omine et al. (1998)
q_u	$q_u=\dfrac{K(C-C_0)}{(G_s w/100+1)^2}$	K: strength coefficient C: cement amount C_0: minimum cement amount to increase q_u	For cement-treated dredged cohesive soil	Tang et al. (2001)

q_u: unconfined compression strength, s_u: undrained shear strength, s_d: drained shear strength

In some applications such as cement-treatment of clay of very high water (i.e. above the liquid limit) and low cement-content treatment of sand for prevention of liquefaction, large reduction of void ratio (dry density) can occur due to self-weight. In these cases, the effects of overburden pressure need to be considered in estimating the strength of cement-treated soil.

In order to control the strength properties of cement-treated soil and make good use of cement-treated soil for future practical application in various fields of geotechnical engineering, this paper considers the role of consolidation on the strength of cement-treated soil based on a series of isotropic compaction and undrained triaxial compression shear tests carried out on cement-treated specimens of Ariake clay, Akita sand, Rokko Masado and Toyoura sand.

Table 2. Physical properties of test soils

	Ariake clay	Akita sand	Rokko Masado	Toyoura sand
ρ_s (Mg/m^3)	2.609	2.682	2.620	2.640
e_{max}	—	1.300	1.012	0.977
e_{min}	—	0.793	0.479	0.605
D_{50} (mm)	0.0034	0.17	1.40	0.175
U_c	—	1.41	19.2	1.52
F_c (%)	96	1.3	9.00	0
w_L (%)	86.5	—	—	—
I_p	51.3	—	—	—

U_c: uniformity coefficient, F_c: fine content

SAMPLE PREPARATION AND TEST PROCEDURE

The four test materials in this study are 1) Ariake clay 2) sand from Akita Port in Akita Prefecture (called "Akita sand") 3) decomposed granite from south Suzurandai area in Hyogo Prefecture (called "Rokko Masado"), and 4) Toyoura sand. The physical properties of these materials are in Table 2.

Ariake clay was prepared with cement contents of 5%, 7% and 10% and initial water contents of $1.5w_L$, $1.7w_L$, $2.0w_L$ and $2.5w_L$. It is noted that the water content of cement-treated soil was calculated by treating the weight of cement as the solid part of soil. The sample for Ariake clay was prepared according to JGS-0821 (Japanese Geotechnical Society, 2000). The specimen size for cement-treated Ariake clay was 35 mm in diameter and 70 mm in height. In preparing cement-treated Ariake clay, Ariake clay was mixed with cement together with adding water to keep the slurry a target initial water content. The slurry was gently poured into the mold (35 mm in diameter and 70 mm in height) with a spoon in three layers. In order to remove air bubbles in the slurry, the mold with the slurry was thoroughly tapped in the lower part of the mold with a hammer for every layer. After

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Table 3. Experimental conditions for Ariake clay

Cement content	Standard of sample preparation	Initial water content w_0	Average water content after 27 days curing	Consolidation pressure p'_c (kPa)
Untreated	JGS 0812-2000	173% ($2.0w_L$)	77.8%	98, 196, 294
1%			83.3%	
3%			99.1%	
5%			119.0%	
5%	JGS 0821-2000	130% ($1.5w_L$)	112.0%	98, 196, 294
		173% ($2.0w_L$)	166.7%	
7%		130% ($1.5w_L$)	117.3%	98, 196, 294
		173% ($2.0w_L$)	162.0%	
		216% ($2.5w_L$)	206.4%	
10%		147% ($1.7w_L$)	128.4%	47, 98, 196, 294
		173% ($2.0w_L$)	157.3%	98, 196, 294
		216% ($2.5w_L$)	201.8%	

Table 4. Experimental conditions for sandy soils

Base material (cement content)	Isotropic consolidation test	Undrained triaxial compression shear test	
	Initial relative density	Initial relative density*	Consolidation pressure p'_c (kPa)
Akita sand (5.5%)	9, 35, 79%	−46%	49, 98, 196
		44%	
		73%	
Rokko Masado (5.5%)	26, 41, 85%	20%	49, 98, 196
		68%	98, 196
		92%	
Toyoura sand (5.5%)	−20, 31, 63, 95%	27%	98, 196, 294

*Note: These values are defined from e_{min}, e_{max} of 'untreated' soils and do not account for presence of cement and cement reaction.

filling the mold with the slurry, the top of the mold was sealed with high polymer film to prevent any change in water content. Samples of untreated 'reconstituted' Ariake clay were prepared by mixing with de-aired water to give the slurry an initial water content, $w=2w_L$, followed by one-dimensional consolidation to a preconsolidation pressure of 49 kPa. Table 3 summarizes the water contents of the cement-treated Ariake clay specimens after 27 days of curing, immediately prior to testing. Water contents have slight differences between the initial and 27th day due to chemical reactions between the cement and water. It should be noted that test results for the untreated clay and samples with the cement contents 1% and 3% were originally reported by Kasama et al. (2000).

Cement content of 5.5% was used for the tests on Akita sand, Rokko Masado and Toyoura sand. These tests used specimens 50 mm in diameter and 100 mm in height. These cement-treated sandy specimens with the initial water content of 5.5% was thoroughly mixed and gently poured into the mold (50 mm in diameter and 125 mm in height) filled with de-aired water with a spoon in three layers. In order to adjust the density of the specimen, the mold was then vibrated and tapped at the lower part with a hammer. After filling the mold with the mixture, the top of the mold was sealed with high polymer film to prevent change in water content. The test conditions for cement-treated sandy soils are shown in Table 4. It should be noted that the results of undrained triaxial compression shear tests for cement-treated Akita sand and Rokko Masado were originally reported by Zen et al. (1990).

All of the test specimens were cured for 27 days in a humid room under atmospheric pressure at a temperature of 20±3°C. After curing, a series of isotropic consolidation and undrained triaxial compression shear tests were performed according to JGS-0523 (JGS, 2000). The top and bottom of the specimen were lubricated by a rubber membrane sheet smeared with a silicone grease. Drainage was allowed at the top surface of the specimen. The

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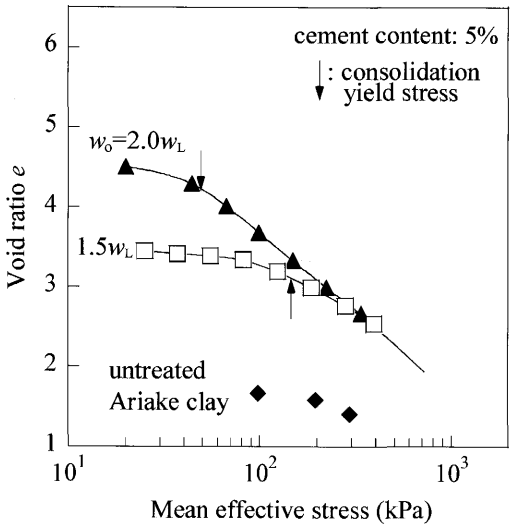
excess pore water pressure was measured at the bottom of the specimen. For cement-treated Ariake clay, a slitted-filter was placed around the cylindrical surface of the specimen to facilitate radical drainage of the specimen. External dial gage and double tube burette were used to measure the axial displacement and the volume change of the specimen with an accuracy of 0.1% of the initial height and volume respectively. In order to raise the degree of saturation of specimen in the isotropic consolidation test and triaxial compression test, a partial vacuum of 60 kPa was applied in the specimen set-up process to draw out pore air keeping an initial effective confining pressure constant, and then de-aired water was drowning from the bottom of the specimen. A back pressure of 198 kPa was maintained for 24 hours before starting the consolidation process. These careful treatments were used to ensure full saturation of specimen, and achieved B-values in excess of 0.95 in all cases. Isotropic consolidation test was carried out using incremental loading. Each consolidation step was terminated after confirming the completion of consolidation by using the $3t$-method (JGS, 1999) together with the measurements of excess water pressure at the base of each specimen. The specimens were then sheared at an axial compression rate of 0.05%/min for cement-treated Ariake clay and 0.1%/min for the cement-treated sandy soils, respectively.

ISOTROPIC CONSOLIDATION

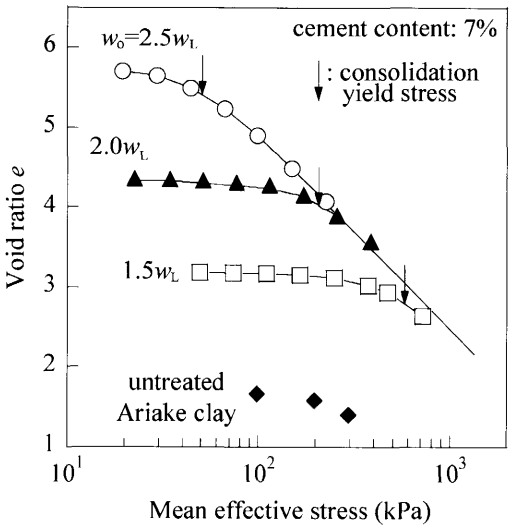
The e-ln p' relationships of cement-treated and untreated Ariake clay are shown in Fig. 1. The consolidation data indicate well defined yield points, p'_y, for each of the cement-treated specimens although none were subjected to compaction or preloading. For a given cement content, an unique Normal Consolidation Line (NCL) can be obtained irrespective of the initial void ratio (water content). This consolidation characteristic is similar to that of cohesive soil. Yajima et al. (1997) had reported similar experimental results for cement-treated Yoneyama clay. In addition, the compression index of the NCL, $\lambda = (-de/d\ln p')$, increases with cement content while the reference void ratio, e_0, which is the void ratio at unit p', increases with the cement content. Based on these observations, strength properties of cement-treated soil should be evaluated in two rejoins, pre-yield ($p' < p'_y$) and post-yield or normally-consolidated ($p' \geq p'_y$). The pre-yield region is referred to "quasi-overconsolidation" in this paper as there is no mechanical pre-consolidation of specimens.

The relationship between p'_y (obtained by the Casagrande method) and cement content is shown in Fig. 2. It is observed that the yield stress increases exponentially with the cement content, but decreases with increasing initial water content.

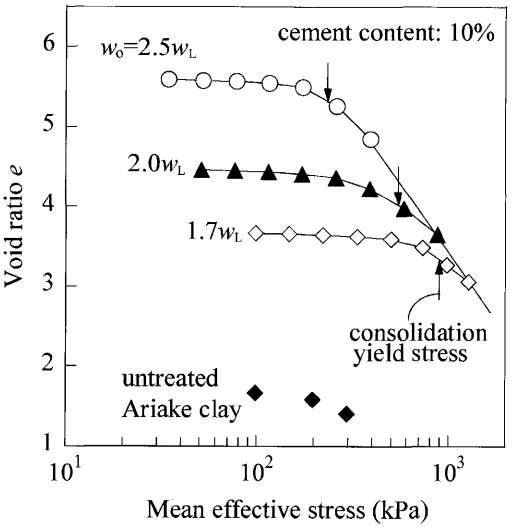
The e-ln p' relationships of untreated and cement-treated sandy soils (i.e. Akita sand, Rokko Masado and Toyoura sand) are shown in Fig. 3. The e-ln p' curves of cement-treated Akita sand and Rokko Masado undergo



(a) cement content 5%



(b) cement content 7%



(c) cement content 10%

Fig. 1. Isotropic consolidation of cement-treated Ariake clay

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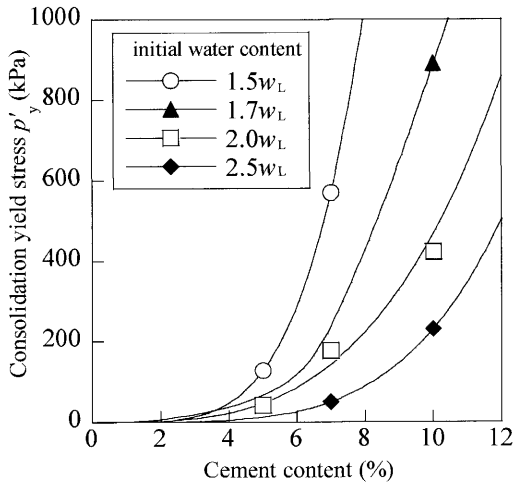
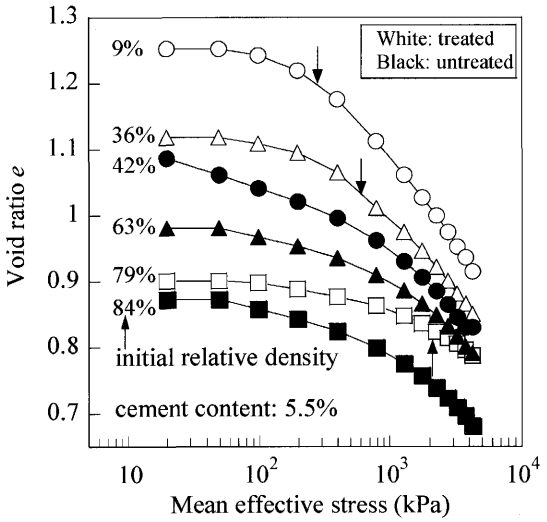


Fig. 2. Effect of initial water content and cement content on consolidation yield stress of cement-treated Ariake clay

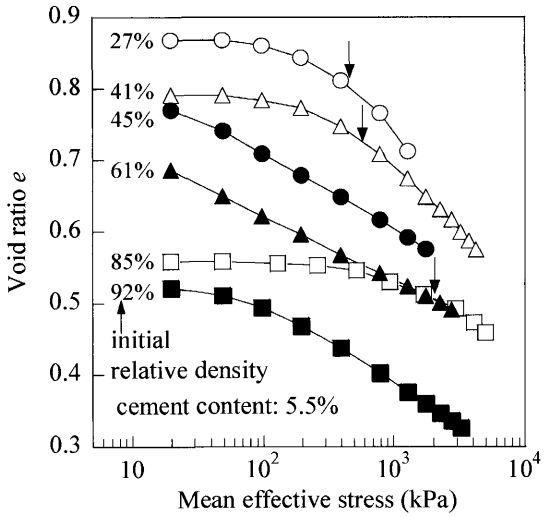
swell changes in void ratio compared to their untreated counterparts, and also show well-defined consolidation yield stresses. As a result, the stress state of cement-treated Akita sand and Rokko Masado, can also be divided into normal consolidation and quasi-overconsolidation regions. The cement-treated Toyoura sand shows similar behaviors at low initial relative density, but can not be distinguished from the untreated specimens at median and high initial relative density. In dense cases, consolidation yielding of cement-treated sandy soil is related to the degradation of the cementation and to the breakage of soil particles (Been and Jefferies, 1985; Pestana and Whittle, 1995; Miura et al., 1984). In comparison, the soil particles of Rokko Masado and Akita sand are quite fragile, and cementation is effective in preventing the breakage of soil particle at low pressures. Yielding (Figs. 3(a) and (b)) is then probably associated with degradation of cementation.

Figure 4 summarized the relationships between initial relative density and consolidation yield stress p'_y in order to evaluate the change of consolidation yielding stress with the variation of density for these sandy soils. The figure also includes data of Dog's Bay sand and Quiou sand (Kwag et al., 1999; Yasufuku et al., 1999) which are typical crushable carbonate sands. It can be seen that the consolidation yield stress of cement-treated and untreated sandy soils have very similar relations of relative density in spite of the difference of soil mineralogy except for medium dense and dense Toyoura sand. Moreover, p'_y of cement-treated sandy soil can be formulated by an exponential function of relative density. The relationship between initial relative density and p'_y of the three cement-treated sandy soils with cement content of 5.5% was very similar to that of the two untreated carbonate sands (Dog's Bay sand and Quiou sand). It is partly because carbonate generated by the chemical reaction of cement and water has the same chemical composition of carbonate sand.

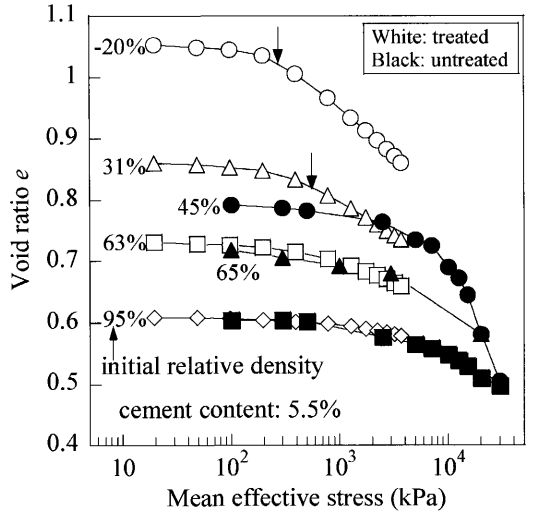
Figure 5 shows the value of Λ ($=1-\kappa/\lambda$) as a function



(a) Akita sand, cement content 5.5%



(b) Rokko Masado, cement content 5.5%



(c) Toyoura sand, cement content 5.5%

Fig. 3. Isotropic compression behavior of cement-treated sandy soils

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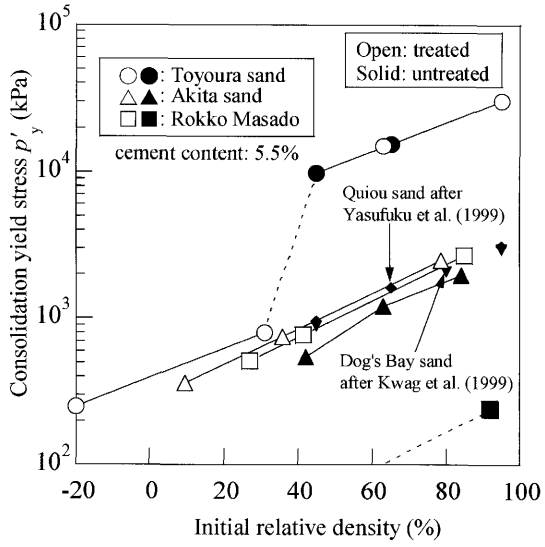


Fig. 4. Consolidation yield stress and initial relative density

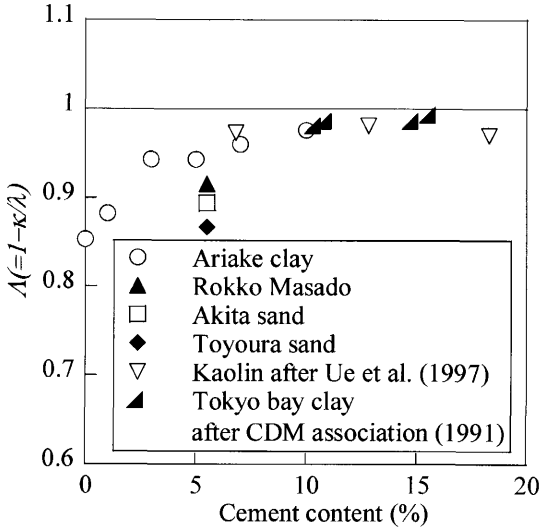


Fig. 5. Effect of cement content on compression properties at pre- and post-yielding

of cement content in order to evaluate the change of stiffness at the yield stress. It is noted that λ and κ are the inclination of e-ln p' in normal consolidation and quasi-overconsolidation regions, respectively. The data are compared with prior studies for cement-treated Kaolin and Tokyo Bay clay (Ue et al., 1997; CDM association, 1991). It was observed that Λ gradually increases toward 1.0 in proportion to cement content, which confirms the high stiffness of cement-treated soil for stresses $p' < p'_y$. In addition for specimens with same cement content, the Λ of cement-treated clayey soils was slightly larger than those of cement-treated sandy soils used in this study.

UNDRAINED SHEAR STRENGTH

Effective Stress Path and Introduction of Cementation Parameter

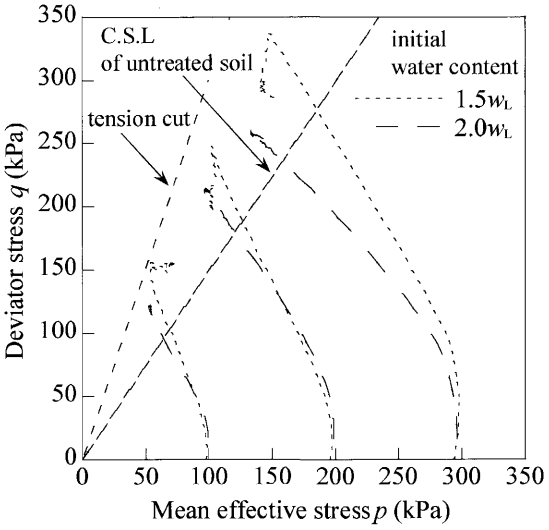
Figure 6 shows the effective stress paths for undrained shearing of cement-treated Ariake clay specimens consolidated into normally consolidated stress range ($p' > p'_y$). The critical state line of untreated Ariake clay ($M = 1.49$) was also shown by a dotted straight line. The results show the effective stress paths for the same cement content and confining pressure seemed to be identical irrespective of the initial water content (with the exception of tests of $p' = 300$ kPa, Fig. 6(a)). The peak deviator stress, q_{max}, occurs at an obliquity (q/p') substantially higher than the critical state line of untreated clay. The difference between these "failure" states and the critical state line of untreated Ariake clay increases with increasing cement content.

Figure 7 summarizes the failure states (p'_f, $q_f = q_{max}$) for normally consolidated cement-treated Ariake clay. It can be seen that the failure envelope for a given cement content is parallel or slightly steeper than the CSL of untreated Ariake clay in confining pressure up to 294 kPa. Clough et al. (1981) and Zen et al. (1990) have previously found that the inclination of failure envelope was almost the same or slightly larger than that of untreated soil, and the up-ward shift of failure envelope was caused by the cementation effect based on the results of triaxial compression shear tests for cement-treated sandy soils. Gouvenot (1997) also reported same experimental outcome for chemically grouted sandy soil. On the other hand, Lambe (1960) and Ue et al. (1997) had presented data which show that both of cohesion intercept and inclination of failure envelope increased with increasing cement content. Therefore, it was commonly expected that the apparent cohesion of cement-treated soil would increase with cement content, however, it was unclear how the frictional strength would be affected by cementation. One possible reason for different effects on the frictional strength is that cement mixing not only generates cementation between soil particles, but also supplies fine grains to the untreated soil through very fine particles in the cement agent. To a first approximation, the current suggests that cement-mixing affects only to apparent cohesion of undrained shear strength.

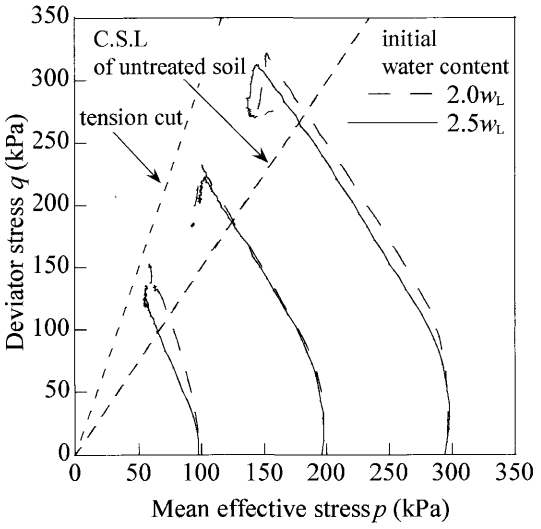
Assuming that failure envelope of cement-treated soil in p'-q space is parallel to that of untreated soil, the apparent cohesion can be characterized by an equivalent tensile stress, p'_r, in Fig. 8. It can be seen that p_r increases linearly with cement content for the experiment reported in this study. Schnaid et al. (2001) proposed a similar approach for interpreting drained triaxial compressions shear tests on cement-treated sandy soil.

The effective stress paths for undrained shearing in the quasi-overconsolidation region are shown in Fig. 9. The data are normalized by the consolidation yield stress p'_y. It can be seen that the initial effective stress paths for $q/p' = 0.2$–0.4 are approximately vertical suggesting that the soil can be treated as an elastic material (no shear-

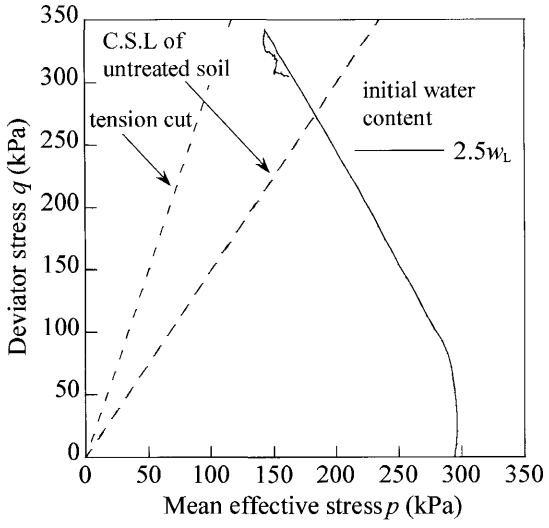
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(a) Ariake clay, cement content 5%



(b) Ariake clay, cement content 7%



(c) Ariake clay, cement content 10%

Fig. 6. Effective stress paths for normally consolidated specimens of Ariake clay ($p'_c > p'_y$)

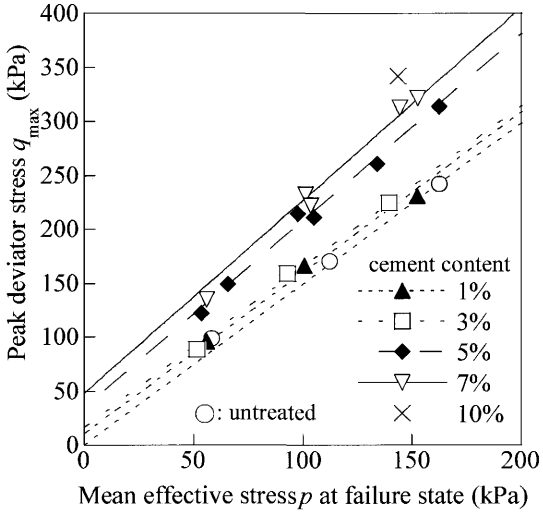


Fig. 7. Failure state in normally consolidated state

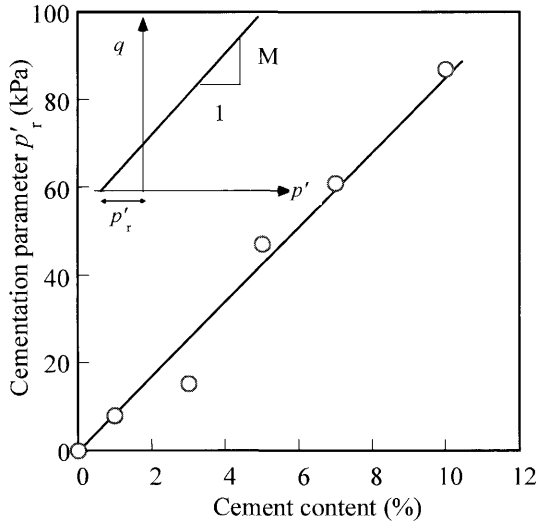


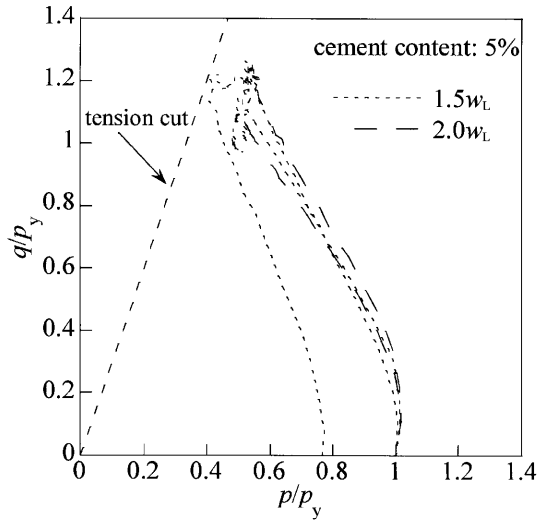
Fig. 8. Cementation parameter p'_r and cement content

induced pore pressures). The effective strength envelope is bounded by the tension cut-off and by the response of the normally consolidated samples. The characteristics are very similar to undrained shear behavior of mechanically overconsolidated cohesive soil specimens.

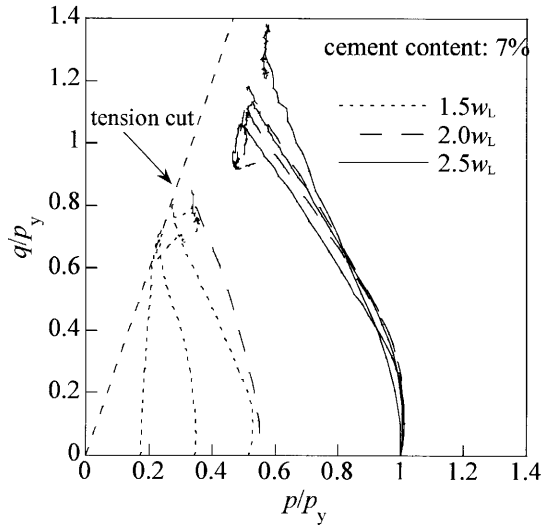
Undrained Shear Strength in Terms of Confining Pressure

Figure 10 shows the relationship between the undrained shear strength s_u ($=q_{max}/2$) of cement-treated Ariake clay and the consolidation pressure, p'_c, in the normally and quasi-overconsolidated regions. The failure envelope in normally consolidated region is estimated by connecting the failure state in the consolidation pressures $p'_c > p'_y$. The undrained shear strength ratio concludes, $s_u/p'_c = 0.4$–0.45. The undrained strength of quasi-overconsolidated specimens has a much less increase by p'_c. There is a significant influence of the initial water content on the undrained shearing to quasi-overconsolidated

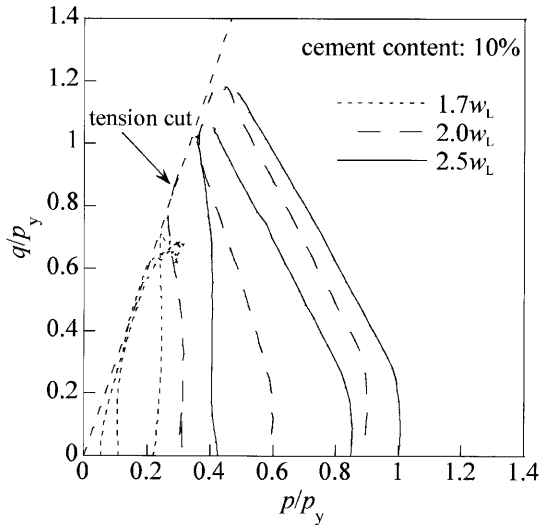
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(a) Ariake clay, cement content 5%

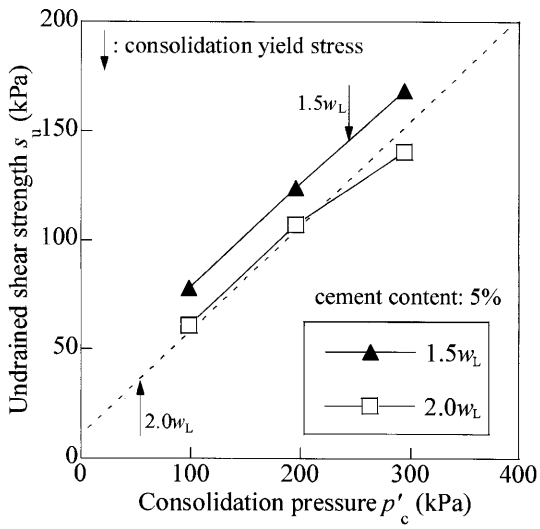


(b) Ariake clay, cement content 7%

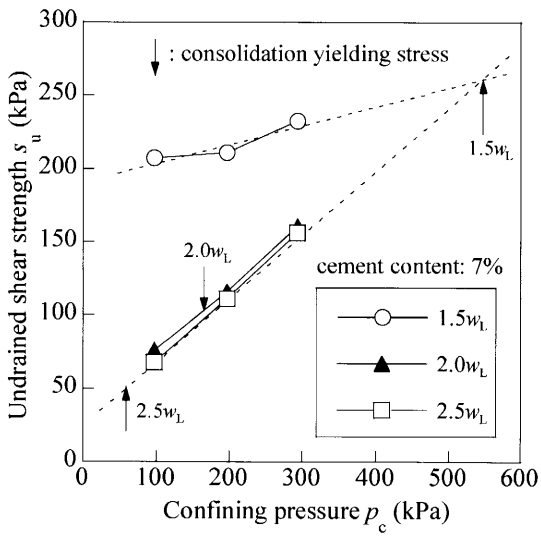


(c) Ariake clay, cement content 10%

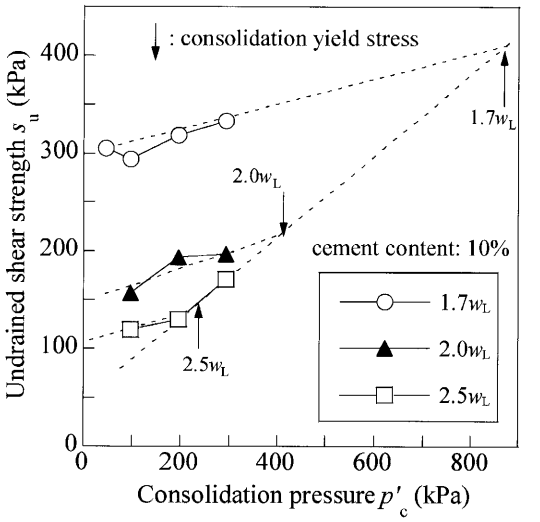
Fig. 9. Normalized effective stress paths in quasi-overconsolidated Ariake clay



(a) cement content 5%



(b) cement content 7%



(c) cement content 10%

Fig. 10. Effect of consolidation pressure and initial water content on undrained shear strength of cement-treated Ariake clay

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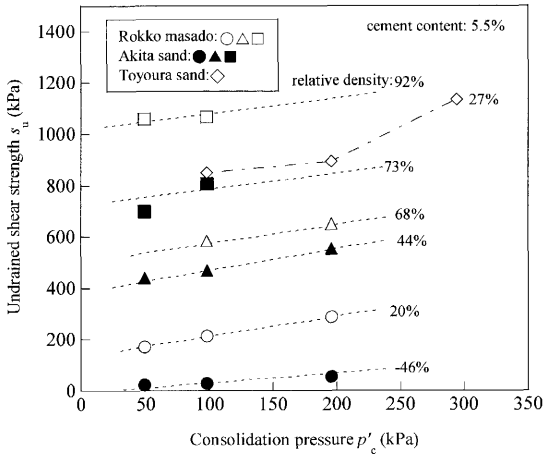


Fig. 11. Undrained shear strength and consolidation pressure for sandy soils (after Zen et al., 1990)

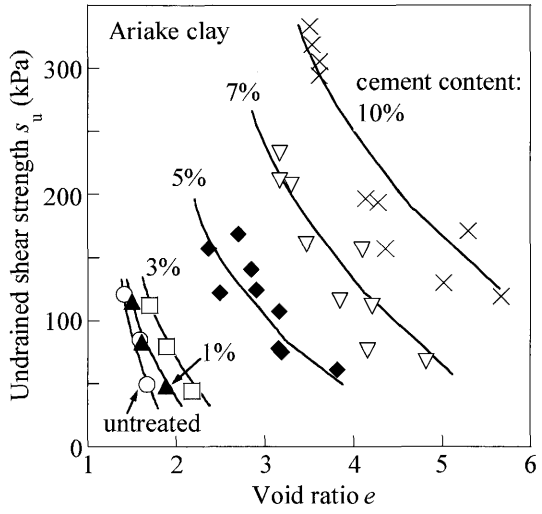


Fig. 12. Effect on void ratio on undrained shear strength of cement-treated Ariake clay

specimens. From these experimental findings, it can be emphasized that the undrained shear strength of cement-treated Ariake clay should be evaluated as a function of confining pressure together with cement content. Tatsuoka and Kobayashi (1983) have also reported similar experimental results from undrained triaxial compression tests on cement-treated Tokyo Bay clay (cement content = 8–20%). Their experiments correspond to quasi-overconsolidated state. Terashi et al. (1980) and Yajima et al. (1997) have presented the failure envelope of cement-treated Kawasaki clay (cement content = 10% and the $w_i = 200\%$) and Yoneyama clay (cement amount $= 100\ \mathrm{kg/m^3}$ and $w_i = 75\%$) which formed a bilinear curve as the function of confining pressure is similar to results shown in Fig. 10.

Figure 11 summarizes the relationship between undrained shear strength s_u and consolidation pressure for cement-treated Akita sand, Rokko Masado and Toyoura sand. It was observed that s_u slightly increased with confining pressure and the failure envelope shifted to upper-side with increasing relative density. It can be emphasized that the stress states of cement-treated Akita sand, Rokko Masado and Toyoura sand were considered to be in the quasi-overconsolidation region because of the prior observation that $p'_c < p'_y$. Matsuoka and Sun (1993) showed similar experimental results for tests on cement-treated Toyoura sand (cement content = 5.3–14.3%) at consolidation pressures up to 10 MPa.

Undrained Shear Strength in Terms of Void Ratio

Figure 12 illustrates the effects on cementation on undrained strength as a function of the initial void ratio for Ariake clay. Although there is some scatter in the test results, especially at high cement content (7%, 10%), there is a well-defined correlation showing that s_u increases with decreasing void ratio. When combined with the experimental observations in the previous section, the undrained strength-dependency of cement-treated soil clay should be evaluated as a function of void ratio, consolidation pressure and cement content.

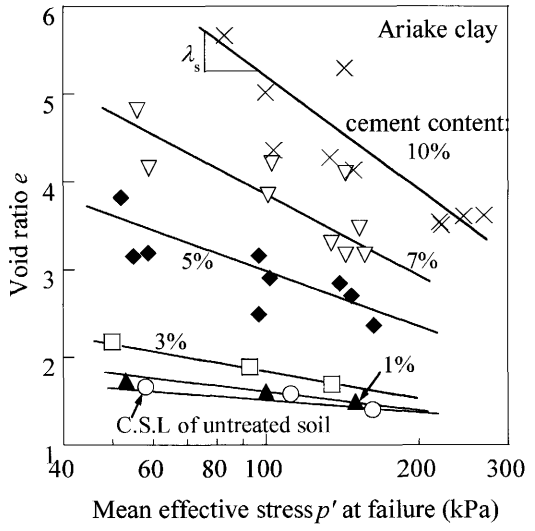


Fig. 13. Critical state and failure lines of cement-treated Ariake clay

The relationship between void ratio and mean effective stress at failure is shown in Fig. 13 and compared with results for the critical state line of untreated Ariake clay. It can be observed that the failure state of cement-treated soil in e-ln p' space was located above the critical state line of untreated clay and the difference between cement-treated soil and untreated soil increases with the cement content. Moreover, the slope of the failure state lines, λ_s (Fig. 13), increases with cement content and the failure state lines appear to converge towards the untreated CSL as mean effective stress increases. However, cement content is a key parameter controlling undrained shear strength at low consolidation pressure.

PRIMAL FACTOR ON THE STRENGTH

This section considers a simplified approach to describe the shear strength of cement-treated soils. Prior results introduced a reference tensile stress, p'_r (Fig. 8), to

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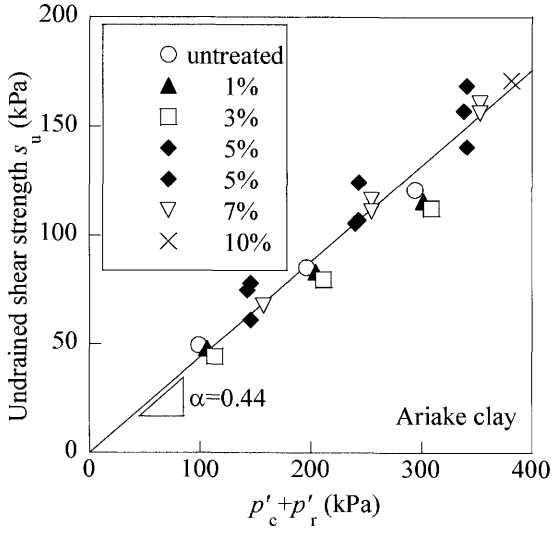


Fig. 14. Rearranged Fig. 7 by changing the horizontal axis of $(p'_c+p'_r)$

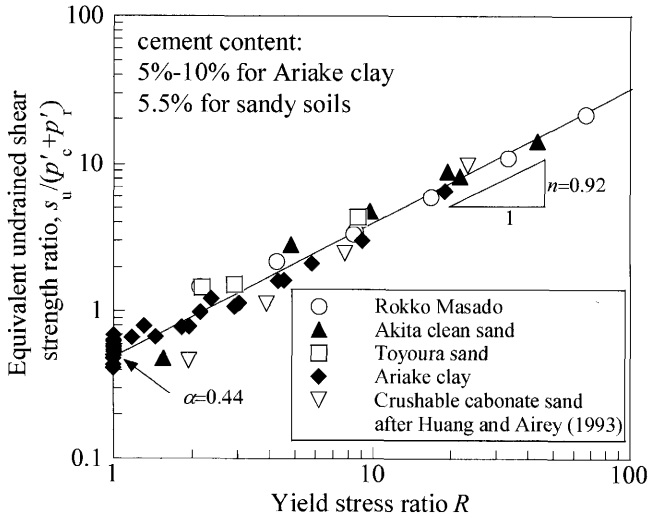


Fig. 15. $s_u/(p'_c+p'_r)$ and yield stress ratio

characterize changes in cohesion of the soils due to the cement content. Figure 14 replots the undrained shear strength of normally consolidated cement-treated Ariake clay as a function of $p'_c+p'_r$. The results show a linear relation independent of cement content and initial water content:

$$\frac{s_u}{p'_c+p'_r}=\alpha\cong 0.44 \tag{1}$$

where α is the equivalent undrained strength ratio of normally consolidated Ariake clay and $(p'_c+p'_r)$ is referred to as "cementation-enhanced" consolidation pressure.

The undrained shear strength property in quasi-overconsolidated region was examined by replotting the equivalent undrained strength ratio, $s_u/(p'_c+p'_r)$ as a function of the yield stress ratio, R, defined by:

$$R=\frac{p'_y+p'_r}{p'_c+p'_r} \tag{2}$$

This yield stress ratio is equivalent to the overconsolidation ratio for cases where $p'_r=0$.

Figure 15 shows that $s_u/(p'_c+p'_r)$ is strongly related to the magnitude of R irrespective of the initial water content and cement content. Moreover, the relationship between $s_u/(p'_c+p'_r)$ and R can be formulated using an exponential function (similar to the SHANSEP relation, Ladd and Foott, 1974):

$$\frac{s_u}{p'_c+p'_r}=\alpha\times R^n \tag{3}$$

where $n=0.92$ is the gradient of the function plotted in ln $s_u/(p'_c+p'_r)$-ln R space. Equation (3) is very similar to the undrained strength evaluation for cohesive soil in overconsolidated region (Mitachi and Kitago, 1976; Murthy et al., 1982; Mayne, 1980).

The test results of Akita, Rokko Masado, Toyoura and crushable carbonate sand (Huang and Airey, 1993) are also plotted in Fig. 15 by assuming $p'_r=0$. The relationship between $s_u/(p'_c+p'_r)$ and R for cement-treated sandy soil can also be expressed by the same exponential function and parameter ($\alpha=0.44$, $n=0.92$) as cement-treated Ariake clay. These results suggest that the equivalent undrained shear strength ratio of cement-treated soils can be estimated independent of the soil type, initial density (water content) and cement content. The prior results from isotropic consolidation confirm that yielding of cement-treated sandy soils can be determined as a function of the cement content and initial relative density. Accordingly, it is supposed for one of the reason that soil type was not influential in determining yield stress ratio for at least cement-treated sandy soils, although the correlations of consolidation yield stress of cement-treated sandy soil and clayey soil should be clarified in future study.

From previous considerations about Fig. 15, it is concluded that cementation parameter p'_r and yield stress ratio R are primal factors influencing the undrained shear strength of cement-treated soils. In other words, p'_r and R are parameters that characterize the effect of cementation and initial soil density on the undrained shear strength. Especially, the yield stress ratio R was important in estimating the undrained shear strength of in-site cement-treated soil at low range of consolidation pressures and mixing at high cement content.

CONCLUSIONS

Paper has evaluated the factors influencing the strength of cement-treated soils based on results of isotropic consolidation and undrained triaxial shear compression tests. The following conclusions are obtained:

(1) Cement-treated soil has a normally consolidated line in e-ln p' space that is dependent on the cement content similar to the consolidation characteristics of cohesive soil. The consolidation yield stress increases with the increasing cement content and formation density of the specimen.

(2) The undrained shear strength of cement-treated soil

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can be evaluated by dividing the stress state into normally consolidated and quasi-overconsolidated regions irrespective of the difference of soil type. The undrained shear strength slightly increases with the increasing confining pressure under the quasi-overconsolidation and then increases at constant rate in the normally consolidated state.

(3) A new parameter p'_r (Fig. 8) representing the cementation effect is proposed to represent the cohesive component of shear strength. Yield stress ratio, $R=(p'_y+p'_r)/(p'_c+p'_r)$, represents quasi-overconsolidated stress state. The equivalent undrained shear strength ratio of cement-treated soils, $s_u/(p'_c+p'_r)$, can be evaluated as an unique function of the yield stress ratio, R.

(4) The general relation for undrained shear strength, Eq. (3), appears to represent the behavior for a wide range of cement-treated soils with plotted parameters α and n.

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NOTATION

q: deviator stress
p': mean effective stress
p'_y: consolidation yield stress
Λ: $=1-\kappa/\lambda$
λ: inclination of normally consolidated line in e-ln p' space
κ: inclination of quasi-overconsolidated line in e-ln p' space
q_{max}: peak deviator stress for the undrained triaxial compression test
p'_r: cementation parameter
s_u: undrained shear strength ($s_u=q_{max}/2$)
p'_c: confining pressure at undrained triaxial compression test
α: inclination of failure envelop in normal consolidation in p'-q space
$p'_c+p'_r$: cementation-enhanced consolidation pressure
R: yield stress ration
n: gradient in ln $s_u/(p'_c+p'_r)$-ln R space
$s_u/(p'_c+p'_r)$: undrained shear strength ratio

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