Journal of Applied Mechanics Vol.12, pp.413-420 (August 2009) JSCE

Elasto-plastic description of mechanical behavior on treated soils of the dredged soil of Nagoya Port

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In order to effectively use the huge amount of dredged soil (DS) as geomaterials, four kinds of stabilizers are used to improve the properties of DS. The mechanical behavior of the treated soils are studied through the experiment and simulated by using SYS Cam-clay model. In order to interpret the effect of the stabilizers on the behavior as the action of the soil skeleton structure, the mechanical behavior of the treated soils is simulated by using the same elasto-plastic parameters as DS. The simulation result indicates that the treated soils can be in initial highly structured state and heavy overconsolidated state with slow decay of structure and slow loss of overconsolidation. Only the mechanical behavior for steel slag-treated soil can be simulated by using new elasto-plastic parameters because the grain size ranges wider and the weight proportion is more than other stabilizers.

Key Words: *dredged soil, treated soil, elasto-plastic behavior, soil structure*

1. Introduction

The dredged soil (DS) of about 1.3 million m^3 is annually generated in Nagoya Port and it is cannot be used directly as a geomaterial because of its low strength and high water content. Most of the soil is reclaimed on Nagoya Port Island (PI), which is a temporary storage of the dredged soil since 1975. PI has now reached its acceptance capacity and will be expanded again even though it has been expanded three times in history and it now has come to 257 ha in area and 25m in depth. How to densify and use this huge amount of DS is important for maintaining the function of PI, consuming industrial waste and finding new kinds of geomaterials.

For DS in deep layer in PI, with the development of consolidation and the discharge of pore water, the volume reduced and the water content decreased to a certain extent compared with the soil in shallow layer, which is newly reclaimed on PI. For DS in deep layer with lower water content, it is possible to be used as "compaction material" after further treatment or improvement.

To effectively use DS in deep layer in PI, some kinds of stabilizers are used to improve the mechanical properties of the soil. In this study, the treated soils were made by mixing with some kinds of stabilizer, like blast furnace cement (CS) and gypsum neutral soil stabilizer (GS), or some kinds of industrial by-products, like steel slag (SS) and paper sludge (PS). The treated soils were studied through a series of laboratory tests to investigate their compression and shearing behaviors.

It is important to choose a proper mixing method for mixing DS with stabilizers. In this study, "Crushing and mixing procedure"[1] was used to homogenously mix these stabilizers with DS, which is difficult to be mixed with other materials by conventional method. After mixing, the mixtures were compacted to make the specimen for laboratory tests.

To describe the elasto-plastic responses of DS and the treated soils, Super/subloading Yield Surface Cam-clay model[2,3] (SYS Cam-clay model) was adopted. The responses can be interpreted based on the concept of decay of structure and loss of overconsolidation.

2. Properties of the dredged soil and stabilizers

2.1 Properties of the dredged soil

DS used in this study consists mainly of SiO_2 and Al_2O_3, of which the percentages are 67% and 17% respectively. Also the physical properties are set out in Table 1. The grain density of DS used here is 2.64g/cm^3, and the current water content about 40%, which is prepared to be the same value as the one in the deep

Table 1 Physical properties of the dredged soil

Grain density	ρ_s[g/cm^3]	2.639
Natural water content	w_n[%]	35~40
Liquid limit	w_L[%]	57.0
Plastic limit	w_P[%]	29.6
Plastic index	I_P[%]	27.4
Clay proportion	[%]	35.1
Silt proportion	[%]	34.2
Sand proportion	[%]	30.7
Aver. grain diameter D_{50}	[mm]	0.011
pH		8.0

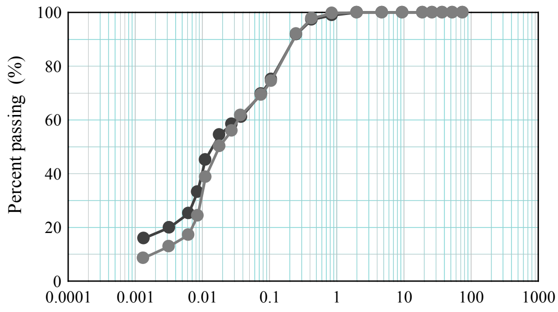

Fig. 1 Grain size distribution of DS

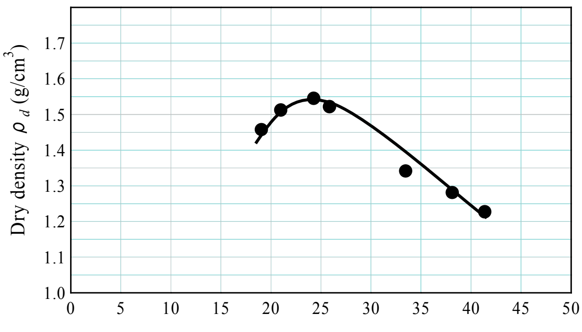

Fig. 2 Compaction curve of DS

layer in PI. The current water content is between the plastic limit of 29.6% and liquid limit of 57.0%.

Figure 1 shows the grain size distribution curves. The weight proportions of clay, silt and sand in DS are 35.1%, 34.2% and 30.7% respectively. Therefore, it can be classified to be a kind of clay-like geomaterial. For this kind of fine-grained dredged soil, it is difficult to compact with high water content[4].

Figure 2 is the compaction curve of DS. Test method for soil compaction using a rammer, the calling name A-a, was performed on DS in accordance with JIS Designation A 1210 1999. Because the optimum water content w_{opt} is 24.3%, which is much less than its current water content, it is very difficult to compact DS. Figure 3 shows the unconfined compression test result. The unconfined strength q_u of DS is less than 20kPa, which does not satisfy the basic strength of 50kPa for construction geomaterial. In Fig. 3, w, ρ_t, ρ_d and v are water content, wet density, dry density and specific volume respectively.

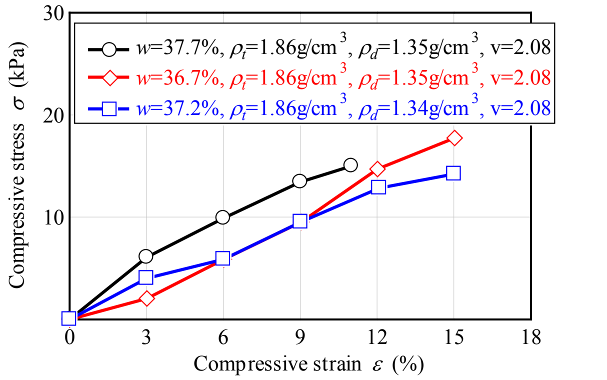

Fig. 3 $\sigma - \varepsilon$ curve in unconfined compression test of DS

Table 2 Main compositions of stabilizers

CS	[%]	GS	[%]	SS	[%]	PS	[%]
CaO	54.98	SO_3	32.56	CaO	40	SiO_2	31.4
SiO_2	25.41	CaO	30.7	Fe_2O_3	11	Al_2O_3	27.3
Al_2O_3	8.26	SiO_2	13.8	SiO_2	10	CaO	16.6
MgO	3.32	Al_2O_3	3.19	f-CaO	7.1	MgO	10.8

Figure 2 implies that two methods may be available to increase the strength of DS. One is to reduce the water content; and the other is to mix DS with some kinds of stabilizers. For the former method, when the water content is reduced to optimum water content, the unconfined strength would be much higher due to high density of soil. In this study, the latter method is adopted, which can not only highly promote the strength but also improve its mechanical properties.

2.2 Properties of four kinds of stabilizers

In this paper, four kinds of stabilizers were used, which were blast furnace cement B (CS), gypsum neutral soil stabilizer (GS), steel slag (SS) and paper sludge (PS). The essences of soil improvement effect by using stabilizer can be classified to "chemical effect" and "physical effect".

Chemical effect is that the chemical compositions in stabilizer react with the water in soil, where the effect is not only to reduce the water content in soil but also to generate new chemical material in hydration reaction, such as calcium hydroxides and gypsum stiffening hydrates, which have higher strength. The main chemical compositions are set out in Table 2.

Besides the reduction of water content due to adding stabilizer into DS, the change of physical properties is the other reason of improvement effect, which is mainly about "coarse grain affection"; On the contrary for the fine-grained stabilizers, like CS, GS and PS, the affection is not obvious. However for coarse-grained stabilizer like SS, its physical property is important in soil treatment.

One of the characteristics of physical properties of the SS is

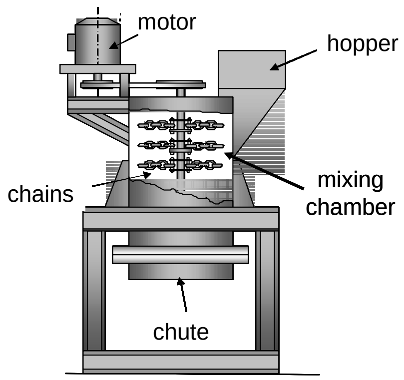

Fig. 4 Chain rotary crusher-mixer[1)]

that the grain size of SS varies in a wide range from 0.075mm to 37.5mm. And the grain size of some SS is like gravel, which is totally different from the fine particle of DS or other kinds of fine-grained stabilizers like CS. The grains with the size larger than 2mm occupied 40%~95% of total weight; while for DS, as shown in Fig. 1, there is no particle with the size over 2mm. Therefore, the grain distribution of the mixture of SS is different from DS.

3. Preparation of specimen and determination of optimum weight proportion

In this study, to guarantee the quality of the treated soil, the aim strength is set 7-day-curing strength of 100kPa, which corresponds to the standard strength of the 3rd type of construction geomaterial defined by Ministry of Land, Infrastructure and Transport of Japan (MLIT, Japan). In order to determine the optimum weight proportion of stabilizers for the aim strength, where the weight proportion is defined as the ratio of the weight of stabilizer to total weight of treated soil, the unconfined compression test were carried out. In each kind of treated soils, stabilizer was mixed with DS at the weight proportions of 10%, 20%, 30% and 40%.

"Chain rotary crusher-mixer"[1)] shown in Fig.4 was used to mix DS with stabilizers homogeneously. The center of the mixing chamber (diameter 500mm, height 700mm) is occupied by a rotary shaft armed with 3 banks of four chains each, for a total of 12 chains in all. The operation of the motor sets the chains rotating at high speed in a horizontal orbit, generating a force that pulverizes the soil material fed in from the hopper. After being homogeneously mixed with any additives used, it is finally discharged through a chute. The rotation speed of the chains varies from 0 rpm to 900 rpm, and is freely adjustable to control the percussive force for the material to be pulverized.

In this machine, soil is crushed and mixed with air to turn the dewatered sludge into an aggregate of clay granules in a non-saturated state. For this kind of "clay pebble", the water content is easy to decrease, and therefore the assembly can be compacted to high density[5)]. In this case, after crushing and mixing under a rotation speed of 500rpm, the treated soils are immediately compacted in the mold to make the specimen with curing period of 0 days, 7 days and 28 days. Therefore, the water content of the treated soils decreases due to the hydration reaction by these stabilizers.

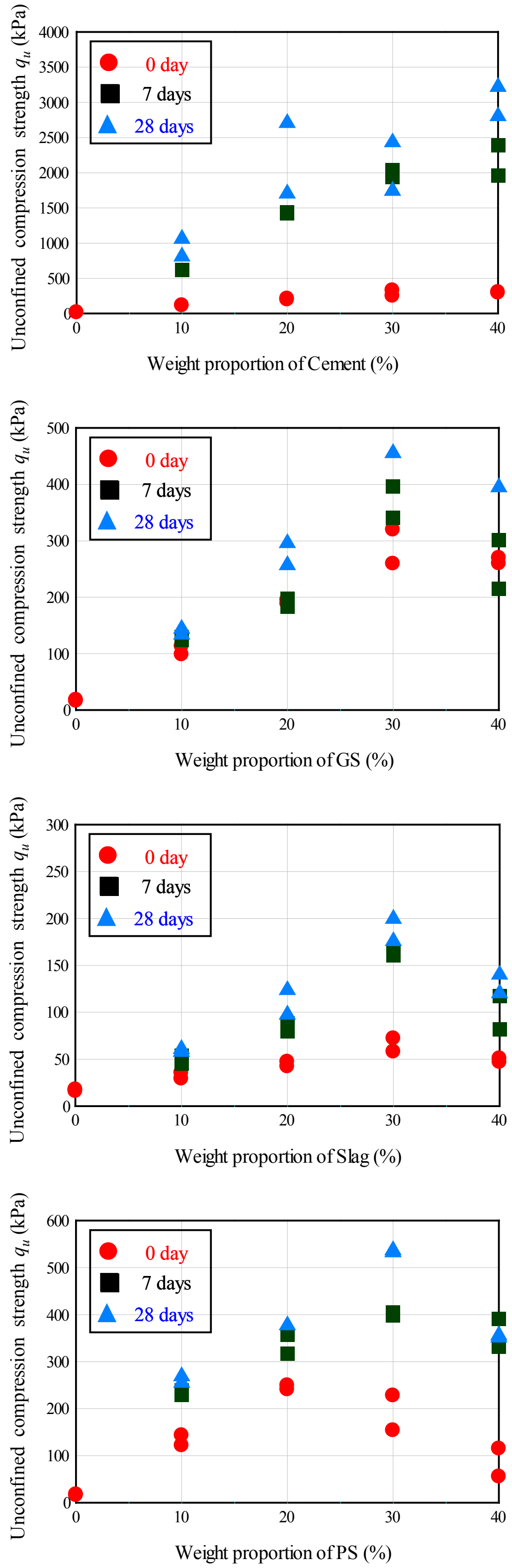

Fig. 5 Unconfined compression test results of the treated soils with different weight proportions of stabilizers

Table 3 Optimum weight proportions of stabilizers

Stabilizer		Weight proportion (%)
Cement	(CS)	2
Gypsum neutral soil stabilizer	(GS)	10
Steel slag	(SS)	30
Peper sludge	(PS)	10

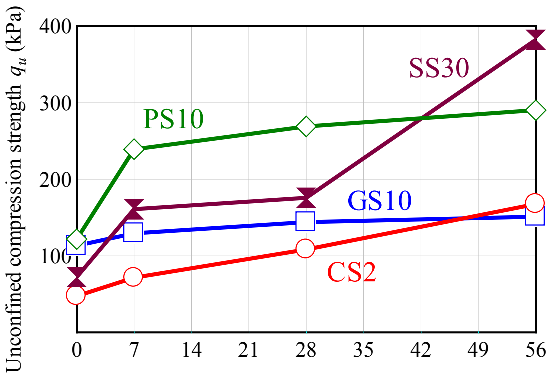

Fig. 6 The effect of curing period on unconfined strength

The unconfined compression test results of treated soils are shown in Fig. 5, where the weight proportion of 0% corresponds to the situation of DS. For the compaction process, the mold, of which the size is 5.0cm in diameter and 10.0cm in height, was used and the compaction energy was adopted to obtain the same compaction curve as the standard compaction test (JIS Designation A 1210 1999) of the treated soil. Although the aim of the test is to determine the optimum weight proportion, Fig. 5 also shows the effect of the weight proportion on the 7-day-curing strength. Each optimum proportion can be determined as shown in Table 3. For the cement (CS), by linearly interpolating relationship between the unconfined compression strength q_u and the weight proportion, the optimum weight proportion of 2% can be determined. The four kinds of treated soils are renamed as follows; Cement-treated Soil (CS2), Gypsum neutral soil stabilizer-treated Soil (GS10), Slag-treated Soil (SS30) and Paper sludge-treated Soil (PS10).

The effect of curing period on unconfined strength is shown in Fig. 6. After obvious increase of strength in 7 days, for all of stabilizers, the increase speed was much slower during the following 21 days from 7th day to 28th day. In the last period between 28th days and 56th days, for GS10 and PS10 there were almost no increase in the strength; while for CS2, there was about 80% of strength growth, and for SS30 the ratio was more than 200%.

4. Compression and shear behavior through laboratory tests for DS and the treated soils

In order to comprehend not only the unconfined compression strength q_u but also the mechanical behavior of the treated soils, the oedometer test and triaxial compression test were carried out by using the specimen with 28 days of curing period. The reason why the specimen with 28 days of curing period was used in the tests is to obtain the stable mechanical behavior because the stabilization has progressed to some extent. However, it should be noticed that the stabilization continue to progress and the strength still has increase potential as shown in Fig. 6.

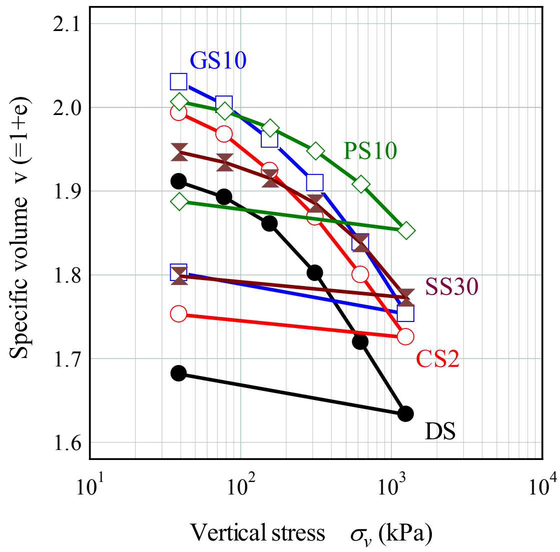

Fig. 7 Oedometer test results

4.1 Compression properties - the oedometer test

In this test, vertical stress σ_v was applied on specimens from 39.4kPa to 1255.7kPa, and then unloaded to 39.4kPa in accordance with JIS Designation A 1217: 2000. Figure 7 illustrates the oedometer test results on DS and four kinds of treated soil (CS2, GS10, SS30 and PS10). In Fig. 7, the initial specific volumes of all treated soils are larger than that of the dredged soil. For GS10 and CS2, their changes in specific volume from 39.4kPa to 1255.7kPa of loading are 0.25 and the compressibility is almost the same as the dredged soil. It implies that 10% gypsum neutral soil stabilizer and 2% cement hardly improved the compression property of the soils. While for SS30 and PS10, the changes in specific volume are much smaller, which are 0.17 and 0.15, respectively. It suggests that 30% steel slag and 10% paper sludge greatly improved the compressibility of the dredged soil. In other words, the slope of the compression line of GS10 and CS2 are almost the same as the one of the dredged soil; while for SS30 and PS10, there are obvious changes in the slope compared with the dredged soil.

4.2 Shear properties - the undrained triaxial compression test

After 24 hours isotropic consolidation, the triaxial tests started at the shearing speed of 0.014mm/min under two different constrained pressures, which are 98.1kPa and 294.3kPa respectively. Figure 8 shows the undrained triaxial test result of DS. Figures 9 to12 show the comparative test results of DS and different kinds of treated soils, in which different mechanical response in triaxial test can be found[6].

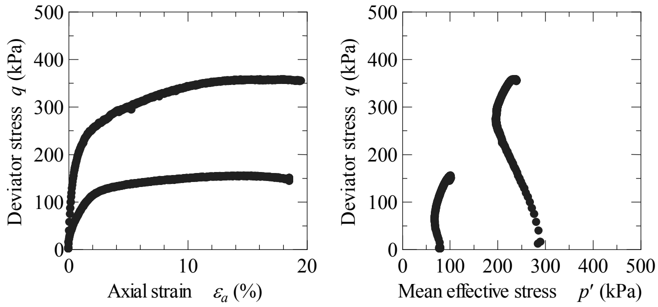

Fig. 8 Undrained triaxial test result on the dredged soil

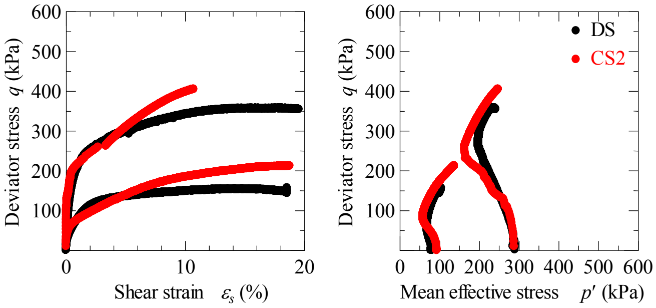

Fig. 9 Undrained triaxial test results of CS2

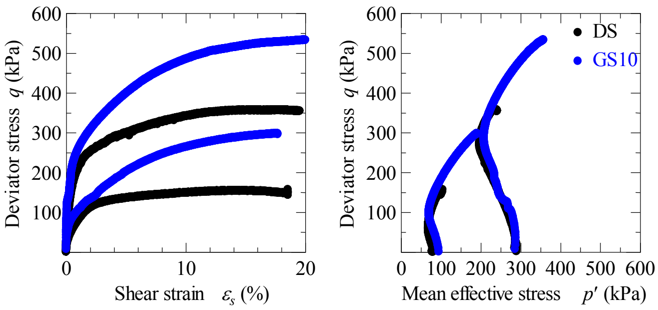

Fig. 10 Undrained triaxial test results of GS10

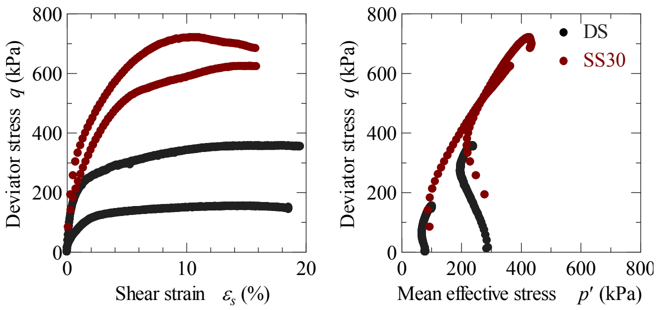

Fig. 11 Undrained triaxial test results of SS30

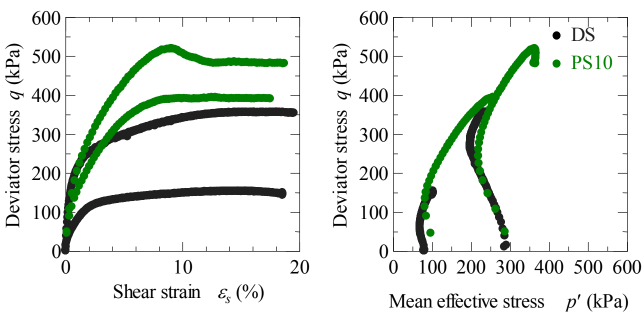

Fig. 12 Undrained triaxial test results of PS10

As shown in Figs. 9 and 10, the deviator stresses q - the axial strain ε_a curve of CS2 is almost as same as the curve of DS within the axial strain of about 2%, however at the larger strain of about 2%, the curve of CS2 is slightly larger then the curve of DS. While the q - ε_a curve of GS10 is much larger than the curve of DS at the larger strain of about 2%. For effective stress path of both of the treated soils, after the mean effective stress p' decreases, the part of that the q increases with the increase in p' is larger than that of DS. That shows that the improvement effect of CS and GS on the mechanical properties of DS.

Figures 11 and 12 show another type of deformation behavior compared with Figs.9 and 10. For the behavior corresponding to high confining pressure of 294.3kPa, CS2 and GS10 as well as DS exhibit no softening behavior as shown in Figs.9 and 10, while SS30 and PS10 shows softening behavior after the axial strain comes to about 10%. Although the behavior wasn't observed in detail, the shear band may appear in the specimen. For the low confining pressure of 98.1kPa, the deviator stress of SS30 and PS10 in hardening behavior was larger than the one of CS2 and GS10.

5. Elasto-plastic interpretation of the mechanical behavior of DS and the treated soils by using SYS Cam-clay model

5.1 Calculation results of the treated soils with the same elasto-plastic parameters as DS

To interpret the mechanical properties of these four kinds of treated soils, the simulation results of CS2 and SS30 were chosen as the typical treated soils in this section. The light lines in Figs. 13 to 15 are simulation results of DS, CS2 and SS30 by using the SYS Cam-clay model[2), 3)]. The model describes the mechanical behavior of these natural deposited clays/sands, which are mostly found in structured, and usually also in overconsolidated states with more or less a condition of anisotropy by introducing the concept of skeleton structure. The constitutive laws in the model are introduced three evolution laws; the first one describes decay/collapse of soil structure, the second loss of overconsolidation, and the third evolution of anisotropy. The degree of the structure is expressed by the similarity ratio between the Cam-clay yield surface and the superloading surface as R^* ($0 < R^* \leq 1$), while the overconsolidation by the similarity ratio between the subloading and superloading surfaces as R ($0 < R \leq 1$). With ongoing plastic deformation, the soil structure decays, that is R* closes to 1, while the overconsolidated state of the soil becomes normally consolidated state, that is R closes to 1 under these evolution laws. The details of the SYS Cam-clay model can be found in the references 2) and 3).

In order to interpret the improvement effect of stabilizer on the mechanical properties based on the concept of soil skeleton structure, especially decay of structure and loss of overconsolidation, the elasto-plastic parameters of the treated soils used were as same as that of the dredged soil. From the simulation results that shows good agreement with the

Table 4 Elasto-plastic parameters and evolution parameters

Elasto-plastic parameter		Evolutional parameters			
Compression index $\tilde{\lambda}$	0.15		(DS)	(CS2)	(SS30)
Swelling index $\tilde{\kappa}$	0.02	m	1.5	0.15	1.0
Critical state constant M	1.4	a	0.3	0.18	0.8
NCL intercept N	2.15	b	1.0	1.0	5.0
(at $p' = 98.1$kPa)		c	1.0	0.1	0.1
Poisson's ratio ν	0.3	c_s	0.3	0.3	0.3

m: Degradeation parameter of overconsolidation state
a, b, c, c_s: Degradeation parameter of structure

Table 5 Initial conditions

< Oedometer test >	DS		CS2		SS30	
σ'_{v0}(kPa)	39.2		39.2		39.2	
v_0	1.91		1.99		1.95	
$1/R_0$	7.9		20.8		15.6	
$1/R_0^*$	1.6		7.0		4.0	
< Triaxial test >	**DS**		**CS2**		**SS30**	
p'_0(kPa)	98.1	294.3	98.1	294.3	98.1	294.3
v_0	1.92	1.77	1.79	1.84	1.64	1.61
$1/R_0$	3.4	1.8	7.3	3.9	14.3	5.0
$1/R_0^*$	1.6	1.5	2.0	5.0	1.5	1.5

σ'_{v0}(kPa) : Vertical effective stress
p'_0(kPa) : Confining stress
v_0 : Spesific volume
$1/R_0$: Overconsolidation ratio
$1/R_0^*$: Degree of structure

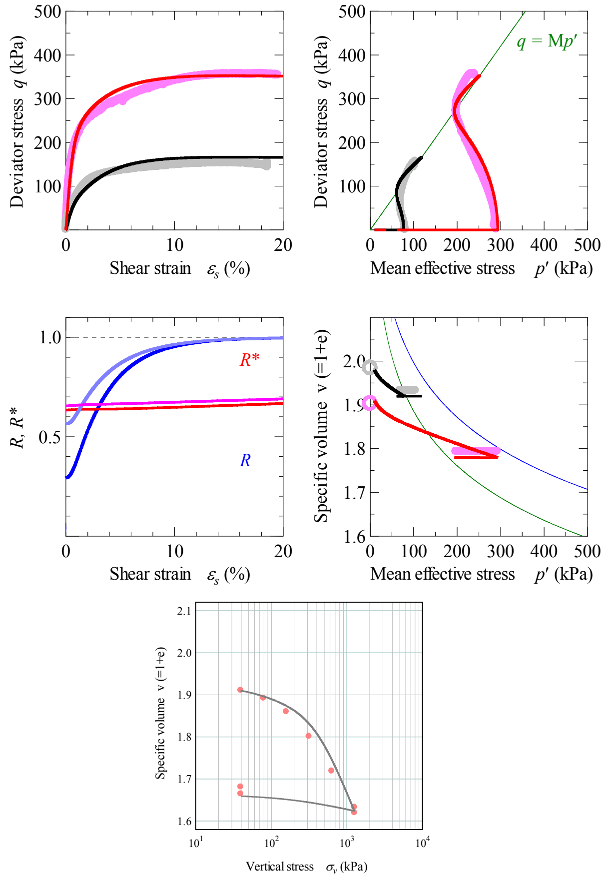

Fig. 13 Simulation result of the dredged soil

experimental results, the improvement effect of stabilizer on the mechanical behavior can be explained by the initial values, which means the initial soil structure and initial overconsolidation ratio and the evolution parameters, which means the change of the soil skeleton structure on the mechanical behavior. The parameters and initial values were determined by reproducing the shear behaviors in triaxail compression tent and the compression behavior in oedometer test. These soil constants are shown in Table 4 and Table 5.

Figure 13 illustrates the simulation results of DS. The calculation results can be in good agreement with the experimental results of both triaxial compression test and oedometer test. From the calculation results, DS is lowly structured and lightly overconsolidated state. As shown in the relationship between R , R^* and ε_s in Fig.13, it is judged that the decay of soil structure is slow, while the loss of overconsolidation is relatively fast. The previous study [2), 3)] indicates that at the same plastic deformation, for clay, it is easier to lose overconsolidation than to decay structure, while for sand, the decay of structure is faster than the loss of overconsolidation. Therefore, DS behaves like typical clay rather than sand.

Figure 14 shows the calculation results of CS2. The calculation results can also be in good agreement with the experimental results. From the calculation results, CS2 specimen is highly structured and heavily overconsolidated state, in which

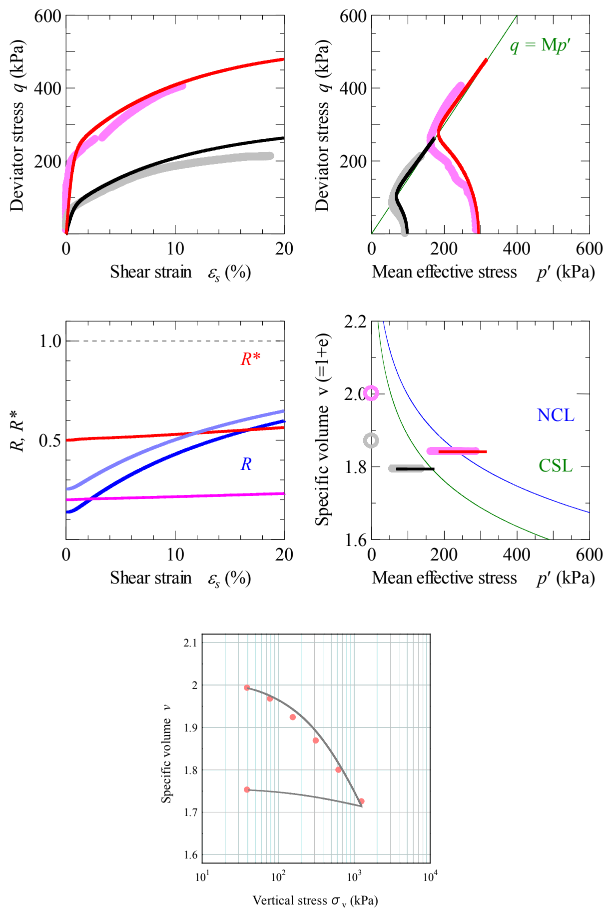

Fig. 14 Simulation result of CS2

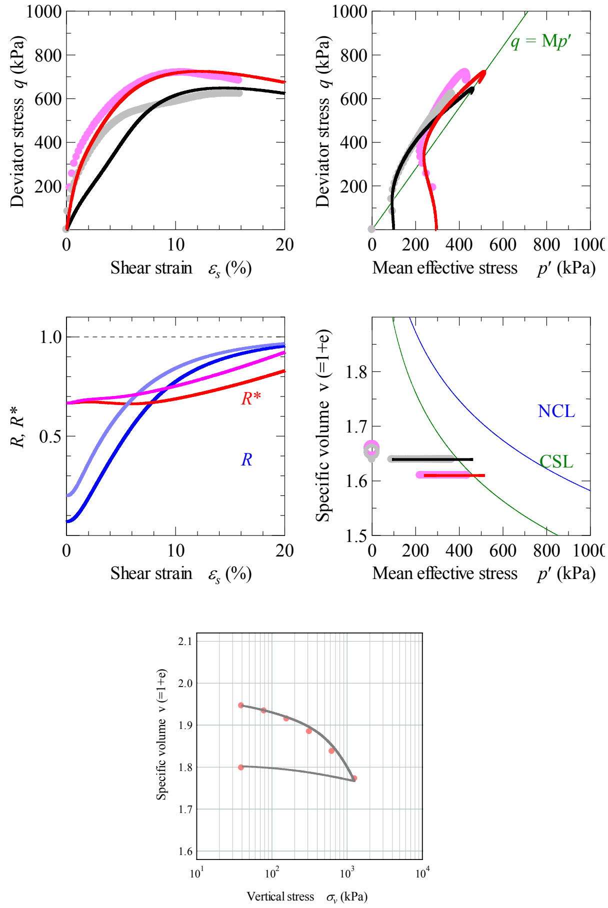

Fig. 15 Simulation result of SS30

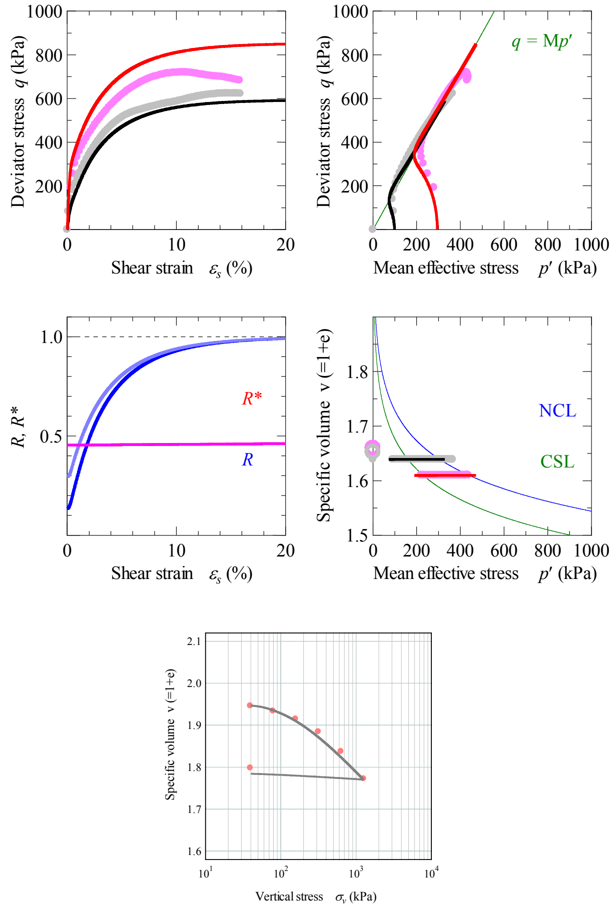

Fig. 16 Simulation result of SS30 with new elasto-plastic parameters

the initial values are different from the one of DS. For CS2 the structure decays slowly, and the overconsolidation looses more slowly than DS. The slow decay of the structure makes CS2 hard to exhibit the softening behavior, while the slow loss of overconsolidation brings that the q increases with the increase in p' for the effective stress path largely. These actions of the soil skeleton structure make the strength of CS2 large.

Figure 15 shows the calculation results of SS30. The q - ε_s curve at high confining stress, especially the softening behavior was simulated to the experimental result well, while the curve at low confining stress wasn't simulated to the stiffness at the small shear strain and no softening behavior at the large shear strain. For the effective stress paths, the effective stress of the experimental result does not seem to close to the critical line of DS, which means that the critical state parameter M may not be the same as the one of DS.

5.2 Simulation result of SS30 using new elasto-plastic parameters

As shown in Fig.15, the situation results of SS30 by using the same elasto-plastic parameter as DS was not good agreement with the experimental results. This is mainly because SS30 has highest weight proportion of stabilizer in four kinds of treated soils and the grain size of SS is much larger than any other stabilizers. In this section, the mechanical behavior will be calculated by using the new elasto-plastic parameters, which is different from the one of DS.

Table 6 New parameters of SS30

Elasto-plastic parameter				
Compression index	$\tilde{\lambda}$	0.08		
Swelling index	$\tilde{\kappa}$	0.005		
Critical state constant	M	1.8		
NCL intercept at $p' = 98.1$kPa	N	1.73		
Poisson's ratio	ν	0.3		
Evolutional parameters				
Degradeation parameter of overconsolidation state				
	m	0.5		
Degradeation parameter of structure	a	0.01		
	b	0.5		
	c	1.0		
	c_s	0.3		
Initial conditions		Triaxial test		Oedometer
Vertical effective stress	σ'_{v0}(kPa)			39.2
Confining stress	p'_0(kPa)	98.1	294.3	
Spesific volume	v_0	1.64	1.61	1.95
Overconsolidation ratio	$1/R_0$	7.4	3.4	3.7
Degree of structure	$1/R^*_0$	2.2	2.2	25.0

Figure 16 shows the simulation result of SS30 using new elasto-plastic parameters, which is listed in Table 6. Compared with Fig. 15, the simulation result shows much better agreement with the experimental results. As shown in Table 6, the elasto-plastic parameters as well as the initial values are different from the ones in Tables 4 and 5. The low compression property can be explained by changing λ from 0.12 to 0.08 and κ from 0.02 to 0.005. The latter part of the effective stress path can be illustrated by changing of the critical state constant M, from 1.4 to 1.8. With regard to the initial values, the change of N, specific volume at p'=98.1kPa on NCL, from 2.0 to 1.73 brings high initial degree of structure and lightly overconsolidation ratio as shown in Table 6. For evolution law of SS30, the soil structure decays slowly while overconsolidation looses relatively fast.

6. Conclusions

In this study, the strength, the compression and shear behaviors of DS and the treated soil were studied through a series of laboratory tests. In order to interpret the effect of the stabilizers on the behaviors as the action of the soil skeleton structure on the behavior, Super/subloading yield surface Cam-clay model was adopted to describe the deformation behavior. The main results in this study can be summarized as follows:

1) In this study, to guarantee the quality of the treated soil, the aim strength is set 7-day-curing strength of 100kPa. Through the experiment, the optimum weight proportions of stabilizers are determined as follows; for cement (CS), gypsum neutral soil stabilizer (GS), steel slag (SS) and paper sludge (PS), they are 2%, 10%, 30% and 10% respectively. All of these four kinds of stabilizers can improve the dredged soil (DS), of which the unconfined strength is about 20kPa.
2) For the simulation results, DS was lowly structured and lightly overconsolidated state, and the decay of soil structure was slow, while the loss of overconsolidation was relatively fast. Based on the previous study, DS are regarded as the typical clay rather than sand.
3) The elasto-plastic responses of CS2, GS10 and PS10 were well simulated by using SYS Cam-clay model with the same elasto-plastic parameters as DS. The initial value indicated that these three kinds of treated soils were in high-structured heavily-consolidated state. And the evolution parameters indicated that these stabilizers changed DS to be new kinds of materials with slow rate in both decay of structure and loss of overconsolidation.
4) For SS30, considering the high weight proportion of SS and the affection of the coarse grain of SS, the new elasto-plastic parameters were adopted to simulate the experimental results better. The result with new parameters is different from the result with the same elasto-plastic parameters as DS. The compression and swelling indices decreased from 0.12 to 0.08 and from 0.02 to 0.005, respectively. The critical state constant M rose from 1.4 to 1.8. According to the new simulation result, SS30 was also with higher initial degree of structure and overconsolidation ratio compared with DS.

Acknowledgement

The authors would like to thank Geolabo-Chubu for providing the undrained triaxial compression test data of slag-treated soil and PS-treated soil.

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(Received: April 9, 2009)