Elasto-plastic description of mechanical behavior of silt improved by lime

Description du comportement mécanique d'un matériau géotechnique composé de “kira”, sable siliceux sous-produit de l’industrie céramique mélangé à de la chaux

M. Nakano and E. Yamada
Department of Civil Engineering, Nagoya University, Nagoya, Japan

ABSTRACT

Mechanical tests were carried out on compacted specimens of Kira converted into pebble form by crushing and mixing with lime with the objective of effective utilization of fine particle silica sand Kira, which is a by-product of the ceramics industry, as a geomaterial. Furthermore, the mechanical behavior was reproduced using the SYS Cam-clay model, which describes the mechanisms of the soil skeleton structure (structure, overconsolidation, and anisotropy), and was explained based on the concept of skeleton structure. The following are our major conclusions for the present research.

1) Fine particle silica sand Kira is a silty sand with a silt fraction of about 65%. The undrained shear behavior of Kira produced from the slurry state resembles the shear behavior of sand. Furthermore, by reproducing the mechanical behavior using the SYS Cam-clay model, we found that the rate of loss of overconsolidation with shear was about the same as the rate of decay/collapse of the soil structure.
2) By reproducing the mechanical behavior of the improved soil obtained by mixing lime into Kira without temporary storage using the SYS Cam-clay model, we found that mixture of lime into Kira changed the evolution rule parameters and slowed the rates of decay/collapse of structure and loss of overconsolidation. Curing had no effect on the evolution rule parameters, raised the initial degree of structure, and increased the initial overconsolidation ratio.

RÉSUMÉ

Nous avons effectué des essais mécaniques sur ce matériau expérimental compacté constitué de “kira”, un sable siliceux sous-produit de l’industrie céramique que nous avons au préalable broyé puis mélangé à de la chaux pour en faire des granulés, dans le but d’étudier son utilisation optimale en tant que matériau géotechnique. Nous avons reproduit son comportement mécanique selon le modèle SYS Cam-clay qui décrit les dynamiques de la structure squelettique du sol (structure, surconsolidation, anisotropie) et interprété les résultats selon le concept de structure squelettique. Les conclusions sont les suivantes.

1) Le sable siliceux “kira” est un sable limoneux dont la proportion en limon attend 65%. Son comportement en cisaillement non drainé suite à sa transformation à partir de son état de boue est semblable à celui du sable. La reproduction de son comportement mécanique selon le modèle SYS Cam-clay nous a permis d’établir que la vitesse de perte de la surconsolidation et de dislocation de la structure du sol due au cisaillement est aussi de grandeur comparable à celle du sable.
2) La reproduction du comportement mécanique des sols améliorés sans stockage temporaire selon le modèle SYS Cam-clay montre la modification du paramètre évolutionnel suite au mélange à de la chaux ainsi que le ralentissement de la dislocation de la structure du sol et de la perte de la surconsolidation. En ce qui concerne la récupération, et avec le même paramètre évolutionnel, une structure initiale élevée correspond à un taux de surconsolidation initial supérieur.

Keywords :improvement by lime, geomaterial, compaction

1 INTRODUCTION

Many different technologies for improving surplus soil and effectively using it as a geomaterial have been proposed to date (JGS, 2003). However, the criteria for soil classification (The public works research institute, 2004) in the criteria for use of surplus soil mainly classify improved soil using the moisture content and cone index as indices, so the objectives of most of the proposed technologies have been improvement of the ease of handling and strength only. However, with the shift towards performance-based design of soil structures in the near future, it is likely that understanding not only the index of strength but also the mechanical behavior of improved soil will become indispensable.

Our research to date has included technologies for non-chemical crushing, air-mixing, and compacting of dewatered sludge obtained by filter pressing surplus soil to achieve further volume reductions. In conclusions, the principle based on soil mechanics to make dewatered sludge easier to handle and achieve large volume reductions is to change from consolidation material to compaction material through mechanical description of compaction and shear behavior (Nakai et al., 2005).

The subject of the present research was not surplus soil, but silica sand “Kira” (65% silt, 30% clay), which is a by-product of the ceramics industry. The mechanical properties of improved soil to which quicklime was added as a stabilizer were measured in laboratory tests, and the mechanical behavior of the soil was described based on elasto-plasticity mechanics, with the objective being effective utilization of the material as a geomaterial with guaranteed properties.

The Kira used was a by-product of manufacture and collection of silica sand, which is used as a raw material for glassmaking. Kira is produced at a rate of about 15% of the quantity of silica sand produced. At present, most Kira must be disposed of as waste, and problems in regard to disposal of Kira have the potential to cause a decline in local industries in Aichi Prefecture, which is the largest area of natural silica production in Japan. This research describes the mechanical behavior of Kira improved soil, but it is not limited to reproducing and explaining a specific improvement process on a specific material. The ability to reproduce and describe the mechanical

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-558

behavior of soils that have previously been difficult to describe, such as silt and soils mixed with lime, can be applied to description of the mechanical behavior of improved soils derived from soils that have also previously been difficult to describe, such as dredging soils, problem soils, and intermediate soils. The results of the present research, which was conducted to assure the quality of improved soil, are considered to be important as they indicate effective scenarios for effective utilization of surplus soil, construction waste, and industrial waste as geomaterials, which is a common challenge in geotechnical engineering throughout the world.

2 PHYSICAL AND MECHANICAL PROPERTIES OF SILTY SAND KIRA

2.1 *Physical properties and composition of fine particle silica sand Kira*

Fine particle silica sand Kira is produced as a by-product of producing silica sand. Its main constituent is quartz (SiO_2), but it also contains mica and feldspar. Its soil particle density is 2.65, and as shown in the grain size accumulation curve in Fig. 1, it is about 70% silt and is classified as silt (ML) according to the method of classification of geomaterials for engineering purposes. In the silica sand production process, namely, in the process of crushing, screening, and removal of iron from the silica sand raw material, silica sand Kira is produced during purification with clear water. Therefore, the initial moisture content of Kira is high, so normally, Kira is compression dewatered to moisture content of 35% using a high pressure filter press in order to produce dewatered sludge of Kira.

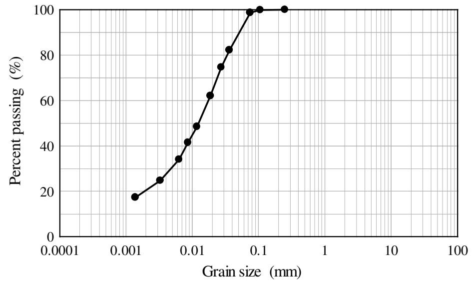

Figure 1. Grain size accumulation curve of Kira

Kira is composed of about 70% SiO_2 and nearly 20% Al_2O_3. During the production process, the Kira passes through a selection process, so it is uniform in terms of quality aspects, such as grain size and composition. As it is originally separated from natural strata, it does not contain harmful substances, such as heavy metals, so it is a resource that can be safely used from the point of view of the ground environment.

2.2 *Mechanical properties of fine particle silica sand Kira*

2.2.1 *Compaction characteristics*

Dewatered sludge of Kira was naturally dried, and compaction tests conforming to the A-a compaction method were carried out using a rammer in accordance with JSF T711-1990. The optimum moisture content w_{opt} was 21%, and the maximum dry density $\rho_{\max}$ was $1.56\,\mathrm{g/cm^3}$. When dewatered sludge of Kira is produced, the moisture content is about 35%, so it is not possible to produce specimens using the impact load of a rammer during compaction. The dewatered sludge of Kira was obtained by static compression in a high pressure filter press, and the Kira maintained its shape despite being unstable.

2.2.2 *Unconfined compressive strength*

Unconfined compression tests were carried out on samples in the following two states: at the optimum moisture content of the obtained compaction curve and the state in which the dewatered sludge of Kira was produced. The specimens were 5.0 cm in diameter and 10.0 cm high and were produced by compaction. However, the dewatered sludge of Kira was produced by static compaction. Figure 2 shows the compressive stress-compressive strain relationship. The unconfined compressive strength when the dewatered sludge of Kira was produced was about 25 kPa, and in this state, Kira cannot be used as a geomaterial. On the other hand, the unconfined compressive strength of the Kira adjusted to the optimum moisture content exceeded 100 kPa, so it is a material that can be used to a certain extent in soil structures.

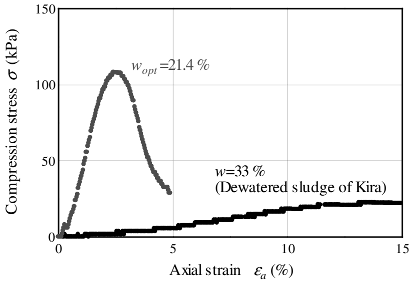

Figure 2. Results of unconfined compression test

2.2.3 *Consolidation characteristics–standard consolidation test results*

Figure 3 shows the standard consolidation test results for silica sand Kira. The two specimens used were Kira in a slurry state with high initial moisture content and compacted Kira with a moisture content of about 30%. The slurry specimen reached the initial state of the compacted specimen as a result of loading and unloading, indicating that the compacted specimen was overconsolidated soil. For both specimens, the coefficient of permeability at each loading stage varied but was about 10^{-6} cm/sec.

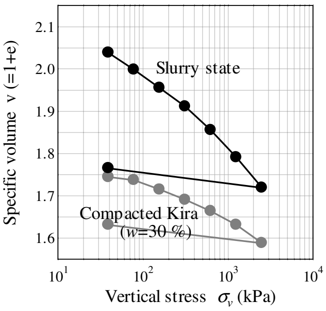

Figure 3. Compression line of slurry state and compacted Kira

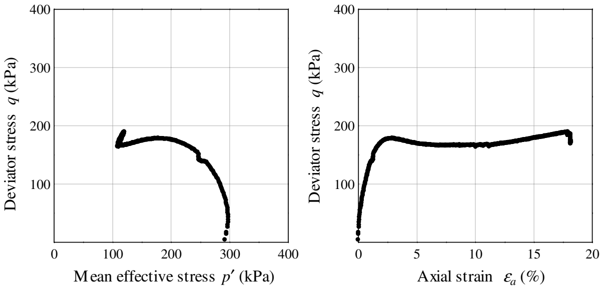

Figure 4. Undrained shear test of slurry state

2.2.4 *Shear characteristic –triaxial compression test result*

Figure 4 shows the triaxial compression test result of the slurry specimen. The specimen was subjected to undrained shear at a constant confining pressure after consolidation under isotropic stress of 294 kPa. The deviator stress q increased along with shear and was followed by a small amount of softening and then further hardening. The effective stress path showed a rise in q as the mean effective stress p' decreased, followed by a decrease in

q. Both p' and q then increased again. This behavior resembled that of medium dense sand.

3 MECHANICAL CHARACTERISTICS OF KIRA IMPROVED BY CRUSHING, MIXING WITH LIME, AND COMPACTION

In the unimproved dewatered sludge state, silica Kira does not make a good geomaterial, so some kind of improvement is necessary. Two methods of improvement can be considered. One method is reduction of the moisture content to the optimum moisture content followed by compaction; the other method is mixture of a stabilizing material in with dewatered sludge of Kira. Here, we have attempted to improve the material itself by mixing it with lime.

In the method of mixing Kira with lime, the dewatered sludge material was first crushed using a chain rotary crusher-mixer (Ninomiya et al., 2002, hereafter referred to as a crusher-mixer) while simultaneously adding lime to it to produce a Kira assembly of "soil pebbles," which was an aggregate uniformly mixed with lime; it was then allowed to stand in this state (temporary storage). After temporary storage, the Kira assembly of soil pebbles was compacted using a rammer (compaction energy of $E_c = 674.5$ kJ/m^3), specimens (hereafter referred to as improved soil) were produced, and the specimens were then cured for 28 days. Here, lime was mixed in at the rate of 3% of the dried weight of Kira, and the effect of the number of days of curing on the mechanical behavior was investigated.

3.1.1 *Effect of number of days of curing on the compression characteristics*

Figure 5 shows the standard consolidation test results for improved soil without curing and with curing for 28 days; in both cases, the specimens were not put in temporary storage. As the number of days of curing increases, the compressibility reduces and the apparent consolidation yield stress increases. This suggests that curing causes the improved soil to become overconsolidated.

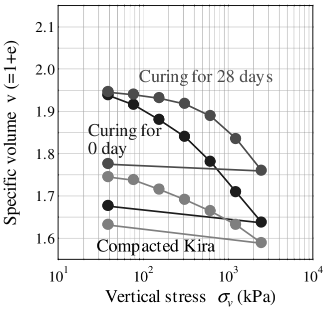

Figure 5. Effect of curing on the compression characteristics

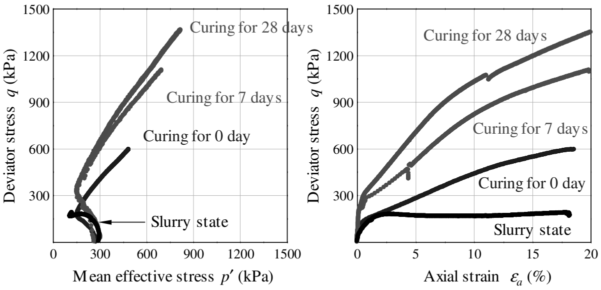

Figure 6. Effect of curing on the undrained shear behavior

3.1.2 *Effect of number of days of curing on shear characteristics*

Figure 6 shows the triaxial compression test results for the improved soil at 0, 7, and 28 days of curing and for the material in a slurry state. The initial rigidity increased as the number of days of curing increased, and the maximum deviator stress increased. For the effective stress path (p'-q diagram), p' decreased and then increased, and the amount of hardening of q subsequently increased as the number of days of curing increased. Curing affected both the strength and deformation behavior.

4 UNDERSTANDING THE EFFECT OF IMPROVEMENT OF KIRA DUE TO CRUSHING, MIXING WITH LIME, AND COMPACTION BASED ON THE SYS CAM-CLAY MODEL

The effect of improvement on the mechanical behavior of the improved soil, in particular the effect of curing, was examined based on the elasto-plastic constitutive model Super/subloading yield surface Cam-clay model (Asaoka et al., 2000, 2002, hereafter referred to as the SYS Cam-clay model), which takes into consideration the concept of soil skeleton structure. This model is capable of explaining the differences in the mechanical behavior of sand, intermediate soil, and clay using elasto-plasticity mechanics by taking into consideration the skeleton structure, in other words, the evolution of soil structure, overconsolidation, and anisotropy. In accordance with plastic deformation, loss of overconsolidation proceeds faster than decay/collapse of soil structure in clay, and decay/collapse of soil structure proceeds faster than loss of overconsolidation in sand, as described in the literature. Soil structure indicates the differences in the void ratio of the compression line of naturally deposited clay and the compression line of the same clay remolded, in other words, the bulkiness, and is indicated in the model by the index of soil structure $1/R^*$ (the larger the value of $1/R^*$ the more highly structured the soil is). By adjusting the evolution rule for structure and overconsolidation in this way, it is possible to differentiate sand from clay and to explain the differences in the mechanical behaviors of the two. Figure 7 shows the results of reproducing the mechanical behavior of unimproved Kira. The material constants and initial values determined in this manner are shown in Tables 1 and 2. Although the initial rigidity of q-ε_s is large, the standard consolidation test results are expressed well. In the R, R^*-ε_s diagrams, R is the inverse of the overconsolidation ratio. These results show that, for unimproved Kira, the rates of loss of overconsolidation and decay/collapse of structure are about the same, depending on the shear deformation. Figure 8 shows the results of reproducing the mechanical tests for improved soil. Tables 1 and 2 show the initial values of the determined evolution rule parameters and the number of days of curing. Table 1 shows that the elasto-plastic parameters of improved soil are the same as for unimproved Kira, so the focus is on the differences in the evolution rule parameters. It can be seen that decay/collapse of structure is reduced by mixing Kira with lime and that loss of overconsolidation slows. This can be confirmed in the R, R^*-ε_s diagrams in Fig. 8. Furthermore, Table 2 shows that as the number of days of curing increases, the specific volume remains unchanged, the initial degree of structure is higher, and the overconsolidation ratio increases. This corresponds to the increase in the apparent consolidation yield stress from the standard consolidation test. The "strength" of the improved soil is large compared with the unimproved Kira because the improved soil acquires a high degree of structure and a heavy overconsolidation ratio, the structure does not collapse easily, and the overconsolidation is lost slowly, although the specific volume remains unchanged. Thus, the behavior, in which q and p' in the latter stage of shearing in the effective stress path increase as the number of days of curing increases, is considered to be caused by the hardening with plastic expansion due to loss of overconsolidation becoming dominant because the overconsolidation ratio increases as curing progresses.

Table 1. Elasto-plastic parameters and evolution rule parameters

Elasto-plastic parameter		Evolution rule parameters		
			Unimproved	Improved
Compression index $\tilde{\lambda}$	0.15	m	0.3	0.18
Swelling index $\tilde{\kappa}$	0.02	a	2.0	0.02
Critical state constant M	1.4	b	0.01	1.0
NCL intercept N	2.15	c	1.5	1.0
(at $p' = 98.1$kPa)		c_s	0.9	0.9
Poisson's ratio ν	0.3	b_r	0.05	0.05
		m_b	0.5	0.5

m: Degradeation parameter of overconsolidation state
a, b, c, c_s: Degradeation parameter of structure
b_r: Evolution parameter of β
m_b: Limit of rotation

Table 2. Effect of curing on initial condition

	Slurry	Curing period		
		0day	7days	28days
Spesific volume v_0	2.04	1.90	2.02	2.01
Mean effective stress p'_0(kPa)	39.2	39.2	19.6	19.6
Overconsolidation ratio $1/R_0$	20.2	48.2	243.7	338.4
Degree of structure $1/R^*_0$	10.0	1.1	14.0	18.0
Degree of anisotropy ζ_0	0.0	0.0	0.0	0.0

5 CONCLUSIONS

Mechanical tests were carried out on specimens of Kira compacted and converted into pebble form by crushing and mixing with lime with the objective of effective utilization of fine particle silica sand Kira as a geomaterial. Furthermore, the mechanical behavior was reproduced using the SYS Cam-clay model, which describes the mechanisms of the soil skeleton structure (structure, overconsolidation, and anisotropy), and was explained based on the concept of skeleton structure. The following are our conclusions for the present research.

1) The unconfined compressive strength of dewatered sludge of Kira with a moisture content of 35% is about 25 kPa, so Kira cannot be directly used as a geomaterial in soil structures such as embankments, etc.
2) Fine particle silica sand Kira is a silty sand with a silt fraction of about 65%. The undrained shear behavior of Kira produced from the slurry state resembles the shear behavior of sand. Furthermore, by reproducing the mechanical behavior using the SYS Cam-clay model, we found that the rate of loss of overconsolidation with shear was about the same as the rate of decay/collapse of the soil structure.
3) By reproducing the mechanical behavior of the improved soil obtained by mixing lime into Kira without temporary storage using the SYS Cam-clay model, we found that mixture of lime into Kira changed the evolution rule parameters and slowed the rates of decay/collapse of structure and loss of overconsolidation. Curing had no effect on the evolution rule parameters, raised the initial degree of structure, and increased the initial overconsolidation ratio.

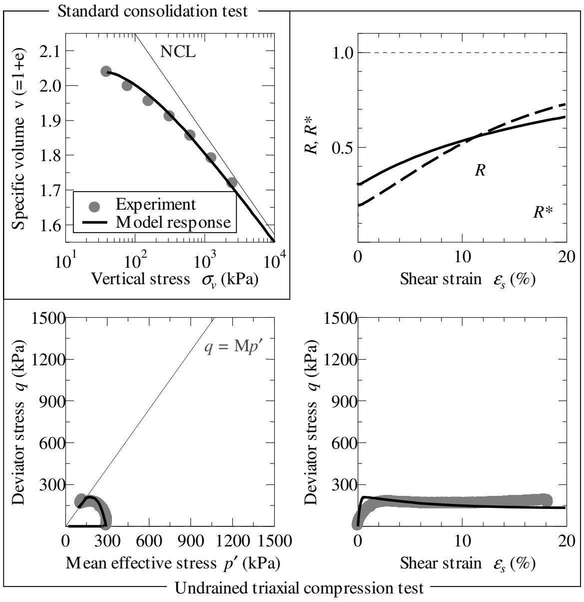

Figure 7. Reproduction of the mechanical behavior of slurry test specimens by the SYS Cam-clay model

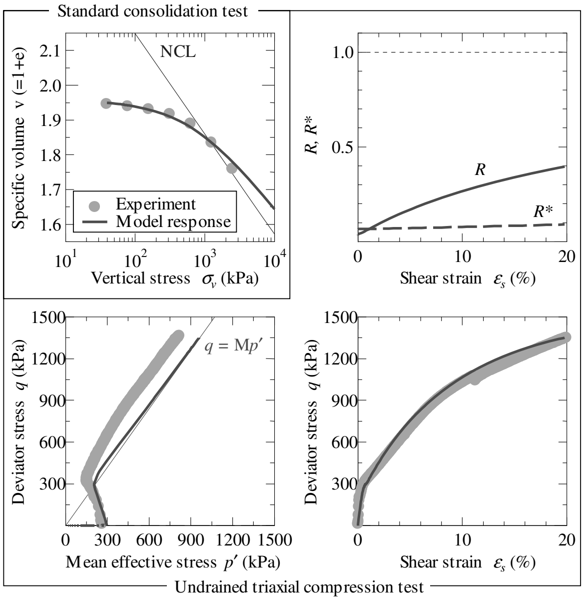

Figure 8. Reproduction of the mechanical behavior of improved soil at 28 days of curing by the SYS Cam-clay model

REFERENCES

Asaoka, A. et al. 2000. Superloading yield surface concept for highly structured soil behavior, S&F, 40(2), 99-110.

Asaoka, A. et al. 2002. An elasto-plastic description of two distinct volume change mechanics of soils, S&F, 42(5), 47-57.

JGS. 2003. Recycling technology in geotechnical engineering -case studies using recycling material-, Tsuchi-to-Kiso, Vol.51, No.6, pp.1-30 (in Japanese).

Nakai, K. et al. 2005. Densification/compression by compaction of a granular geomaterial changed by crushing dewatered sludge with air, 16th ICSMGE, Osaka, pp.2307-2310.

Ninomiya, K. et al. 2002. Example in use of an industrial method for pre-mixing of soils using a rotary crushing and mixing procedure. JSCE, Proc. of 1st Symposium for Civil Engineering Construction Technology, pp.225-232 (in Japanese).

The public works research institute. 2004. Technical manual for effective utilization of surplus soil (in Japanese).