Effect of dredge soil on the strength development of air-foam treated lightweight soil

Effets des sols de dragage sur le développement de la résistance des sols mélangés à de l'air

Kataoka S.
Hakodate National College of Technology, Hakodate, Japan

Horita T.
Kobe University, Kobe, Japan

Tanaka M.
Port and Airport Research Institute, Yokosuka, Japan

Tomita R., Nakajima M.
Koa Kaihatsu Corporation, Chiba, Japan

ABSTRACT: In this study, the unconfined compression strength, q_u, and the elastic shear modulus, G, from bender element test, were in detail examined in the laboratory by using the air-foam treated lightweight soil samples made from several kinds of soil. From the results of these tests, the values of the q_u and the G with curing period were different to the kinds of soils into the air-foam treated lightweight soil samples. In addition, it was found that the development of the q_u and the G were related to the increase / growth of the ettringite produced at the time of the reaction of hydration of the concrete. On the other hands, it has been shown that the relations between the q_u and the G are nearly proportional, and that this tendency remains always the same, whatever is the type of soil.

RÉSUMÉ : Dans cette étude, la résistance en compression simple, q_u, avec le module d'élasticité de cisaillement, G, du critère de l'élément bender, était en détail examinés en laboratoire à l'aide de l'air sous forme d'échantillons de sol traités légers fabriqués à partir de plusieurs types de sols. A partir des résultats de ces tests, les valeurs de la q_u et le G avec période de cure étaient différents des types de sols dans l'air sous forme d'échantillons de sol traité légers. En outre, il a été constaté que le développement de la q_u et le G sont liés à l'augmentation / la croissance de l'ettringite produite au moment de la réaction d'hydratation du béton. Dans le cas contraire, il a été montré que les relations entre la q_u et le G sont presque proportionnelle, et que cette tendance reste toujours le même, quel que soit le type de sol.

KEYWORDS: air-form treated lightweight soil, unconfined compression strength, elastic shear modulus.

1 INTRODUCTION

Air-foam treated lightweight soil is a ground material prepared by adding and mixing in a cement-type stabilizing agent and air foam made by a surfactant or animal-protein foaming agent to a source soil such as dredged soil and surplus construction soil. In recent years, there has been an increase in the number of construction projects using air-foam treated lightweight soil for the purpose of reducing earth pressure and containing land subsidence. This new type of ground material for harbor and airport construction that offers added value such as light weight, safety, and recyclability is called Super Geo-Material (SGM) (e.g. Thuchida et al. 1996).

When SGM is employed for a construction site, the required strength of the mix proportion is obtained by multiplying the design strength by an overdesign factor, and a mix proportion test is conducted in advance to determine the amount of stabilizing agent and air foam to be added to the source soil of which the moisture content has been adjusted with water. In some cases where the physical properties of the source soil are expected to vary from one sampling location to another, a mix proportion test is conducted in advance for each representative sampling location to adjust the amount of additives. Naturally, some variations are found in the strength of the soil samples (Nagatome et al. 2010). In fact, when the unconfined compression test and the bender element (BE) test were conducted on a large number of SGM samples taken from the same construction site and to which an equal amount of the stabilizing agent had been added, the unconfined compressive strength, q_u, varied from one sample location of the source dredged soil to another, albeit within the expected range of the design. It was confirmed that there is a high correlation between the shear wave velocity, V_s (or shear modulus, G) and q_u (Kataoka et al. 2011).

This study focused on the properties of the source soil within SGM. Six different types of source soil were used to prepare SGM in a room environment. The unconfined compression test and the BE test were conducted to examine the impact of curing time on the strength and stiffness of the soil. In addition, the microscopic structure of the specimens was observed using a Scanning Electron Microscope (SEM) in order to visually examine how the internal structure of SGM changed with the curing time.

2 SAMPLE PREPARATION AND TESTS PERFORMED

Table 1 shows the physical properties of the source soils used to prepare the SGM specimens. Six types of source soil were used: two types of dredged soil taken from the construction site of the Tokyo International Airport expansion project, one from the area where the odor of what was suspected to be hydrogen sulfide, biological decay and the like (hereafter "Tokyo Bay A") was relatively weak and the other from the area where the same odor was very strong (hereafter "Tokyo Bay B"); dredged soil taken from Kobe Port (hereafter "Kobe"); surface soil taken from a few meters below the seabed of the Sea of Okhotsk (hereafter "Okhotsk"); Kasaoka Clay; and Kuni-bond. The latter two are commercially available products. When liquid limit, w_L, a criterion used for the mix proportion design, was examined, the six types of source soil could be categorized as follows: Tokyo Bay A and B and Kobe, which had an approximately equal level of liquid limit; Kuni-bond, which had a higher w_L than the aforementioned three types; and Okhotsk Seabed Sediment and Kasaoka Clay, which had a lower w_L. While there were almost no differences between Tokyo Bay A and B in physical properties such as w_L and grain size composition, a major difference was observed in the pH level of pore water.

To prepare SGM specimens, seawater taken from Hakodate was used as the mixing water, blast furnace cement B as the stabilizing agent, and air foam (with a density of 0.05g/cm^3) prepared with hydrolyzed animal protein using the pre-foaming method as the foaming agent. These ingredients were then mixed with each of the source soils that had been passed through a sieve of 425μm and the resulting mixtures were put into plastic molds with a 5cm diameter and a 10cm height. With the top sealed by a plastic wrap, the mixtures were then cured in the air until the prescribed curing ages were attained. Table 2 shows the flow values of the specimens after the water content, *w,* of the source soils used to prepare the SGM specimens for this study was adjusted by sea water (hereafter "Adjusted Soil") and after the stabilizing agent and the air foam were mixed in. The required wet density and the amount of stabilizing agent added were respectively kept constant at ρ_t=1.1 g/cm^3 and 75 kg/m^3, with the water content ratio of the Adjusted Soil at 285%, equivalent to 2.5 w_L of Tokyo Bay A and B. While Tokyo Bay A, B and Kobe had similar w_L values, the flow value of Tokyo Bay B was slightly higher than those of the other two after the stabilizing agent was added to the specimens. In addition, the water content ratio of 285% was approximately five times higher than the already low w_L of Kasaoka Clay, causing its flow ability to rise. As a result, its flow value after the stabilizing agent was added exceeded the size of the acrylic plate (of 66 cm per side), which was used for the flow value measurement.

The SGM was taken out of two cylinders per specimen on each of the prescribed curing days to conduct the unconfined compression test and the BE test. In the BE test, bender elements were inserted in pairs at both vertical and horizontal ends, and the shear wave velocity was measured in both vertical and horizontal directions against the soil (V_{vh} , V_{hh}). From these values and the wet density of the specimens, ρ_t, the elastic shearing modulus ($G_{vh}=\rho_t\times V_{vh}^2$, $G_{hh}=\rho_t\times V_{hh}^2$) was obtained. An internal observation of the SGM specimens was made using an SEM on each of the prescribed curing days to examine the correlation between the strength development and the microscopic structure.

Table 1. Sample preparation

samples	Tokyo Bay A	Tokyo Bay B	Kobe	Okhotsk	Kasaoka Clay	Kuni-bond
ρ_s (g/cm^3)	2.62	2.70	2.64	2.56	2.71	2.70
w_L (%)	114.7	112.4	108.2	85.6	55.4	133.1
L_i (%)	10.4	11.5	9.7	7.2	8.2	7.8
pH	7.7	3.4	7.9	7.6	7.5	-
Grain size distribution (%)						
Sand	2	8	0	6	7	6
Silt	27	21	31	47	33	65
Clay (2~5μm)	38	32	33	23	16	16
Clay (~2μm)	33	39	36	24	44	12
clay mineral	Qtz Pl Ill Chl Sme	Qtz Pl Gp Ill Chl Kln	Qtz Pl Ill Chl Sme	Qtz Pl Ill Chl Sme	Qtz Pl Ill Sme Kln	Qtz Pl Sme

Table 2. Water contents and flow values of the SGM specimens

samples	Tokyo Bay A	Tokyo Bay B	Kobe	Okhotsk	Kasaoka Clay	Kuni-bond
w (%)	285 (2.5w_L)	285 (2.5w_L)	285 (2.6w_L)	285 (3.3w_L)	285 (5.1w_L)	285 (2.1w_L)
Frow value (cm)						
Adjusted soil	47.5	58.0	49.0	64.0	66.0 ~*	57.0
SGM	19.0	27.5	21.0	36.0	66.0 ~*	39.0

$*$: 66.0 ~ shows 66.0 over

3 RESULTS AND DISCUSSIONS

3.1 *Strength and Shear modules of the SGM specimens*

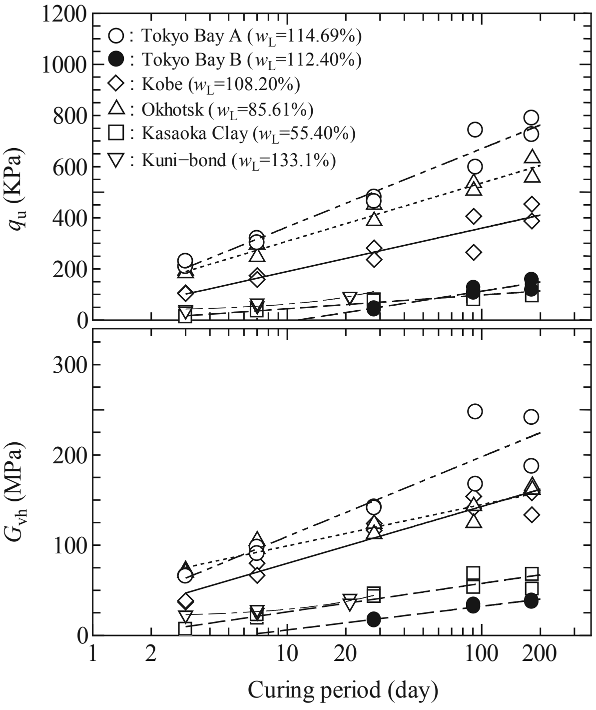

Figure 1. Variation of q_u and G_{vh} with the curing periods

Figure 1 shows the changes to the q_u and G_{vh} levels of the prepared specimens with the elapse of curing days. From the results, q_u and G_{vh} of all specimens showed a linear increase in the semi-log graph. However, a substantial degree of variability was observed from one source soil to another in the soil strength measured on the same curing day even though the mixing conditions, such as the cement quantity per unit volume and the w of the Adjusted Soil were identical. In particular, among the three types of dredged soil (Tokyo Bay A , Tokyo Bay B and Kobe) that shared almost identical physical properties such as w_L, the q_u level of Tokyo Bay B was much lower than the other two. It is suspected that the composition of the pore water was suppressing the strength development of Tokyo Bay B, given that its pH level was lower than those of the other two specimens. On the other hands, the w_L levels of Okhotsk and Kasaoka Clay were lower than those of the aforementioned three types of dredged soil. While Okhotsk showed large q_u and G_{vh} values, comparable to those of Tokyo Bay A, Kasaoka Clay had very low q_u and G_{vh} values, similar to those of Tokyo Bay B. The factors causing the large q_u and G_{vh} values of Okhotsk are suspected to be the large volume of silt in the soil. The small q_u and G_{vh} values of Kasaoka Clay are believed to be caused by the material separation that occurred after the cement and air foam were mixed in because of the high w ratio of the Adjusted Soil of 285 %, about 5 times greater than its w_L. The decrease in the strength of Kasaoka Clay is also likely to have resulted from its clay mineral components since the pore water composition probably did not play a role, as it likely did for Tokyo Bay B.

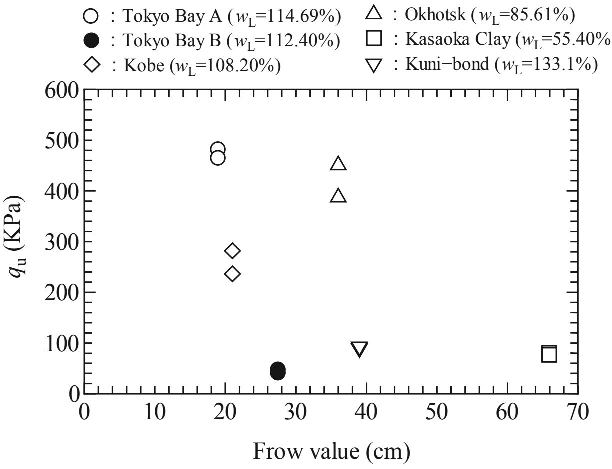

Figure 2. Relationship between flow values of the SGM and q_u (curing period of 28 day)

Figure 2 shows the relationship between the flow values of the SGM specimens and q_u on the curing period of 28 day. While it was believed that there is some relationship between flow values and soil strength, the lower q_u value of Tokyo Bay B than that of other specimens suggests that there is some relationship between the strength and the low pH level of Tokyo Bay B.

Figure 3 shows the relationship between G_{vh} and q_u. It is evident from the graph that there is a strong correlation between G_{vh} and q_u obtained from all the SGM specimens, with an approximately linear relationship between the two variables in each one of them. A previous study showed there is a linear relationship between q_u and Young's modulus in the small strain range of cement-treated sand, while another study demonstrated that there is a linear relationship, as it was found in this study, between the elastic shear modulus and the stiffness of cement-treated soil where cohesive soil was used as the source soil (Shibuya et al. 2001, Seng and Tanaka 2011). Based on these results, the relationship obtained in this study is believed to be a characteristic common to cement-treated soil. While changes to G_{vh} and q_u with the increase of curing days varied greatly from one soil type to another, it was confirmed that the relationship between the variables fell within a certain range, regardless of the type of source soil used. From this it can be concluded that in air-foam treated lightweight soils, where the amount of cement additive and the required ρ_t are approximately the same, the relationship between G_{vh} and q_u is approximately the same, regardless of the type of source soil.

Figure 4 shows the relationship between G_{vh} and G_{hh} obtained from the shear wave velocity propagating in horizontal and vertical directions. The slope is virtually uniform, regardless of the number of curing days and the soil type. However, the slope is smaller than that of natural clay deposits compacted to K_0 (Kawaguchi et al. 2008). Thus, a relatively uniform distribution of nearly spherical air foam inside SGM (Watabe et al. 2004) and a relatively loose (random) state in which the source soil has stabilized are believed to have made SGM an isotropic material in terms of stiffness.

3.2 *Micro structure observation of the SGM specimen*

The microscopic structure of SGM was observed using the SEM in order to examine the factors affecting the strength development of the SGM specimens from the changes to the internal structure with the passage of curing time.

Photos 1 show the internal structures of Tokyo Bay A, on the curing period of 3 (1a) and 182 days (1b), and Tokyo Bay B, on the curing period of 28 (2a) and 182 days (2b). It is observed that on the Tokyo Bay A, needle-like ettringite crystals were formed by the hydration process of the cement on the curing period of 3 day (see 1a), which was characterized by a higher level of strength. The photos also show how the needle-like crystals spread throughout the entire specimen by the 182 day (see 1b) and filled the void space. In the other hands, the ettringite in Tokyo Bay B were observed on the 28 and 182 day (see 2a, b), more void space was observed in the specimen's inner structure and the bonding of crystals did not seem very prevalent. The evidence raises the possibility that the formation, growth, and bonding of ettringite crystals play a major role in the development of the strength and stiffness of SGM.

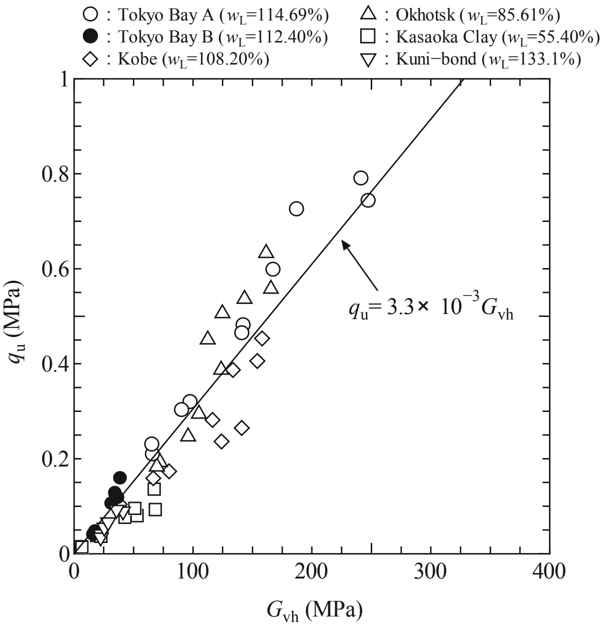

Figure 3. Relationship between G_{vh} and q_u

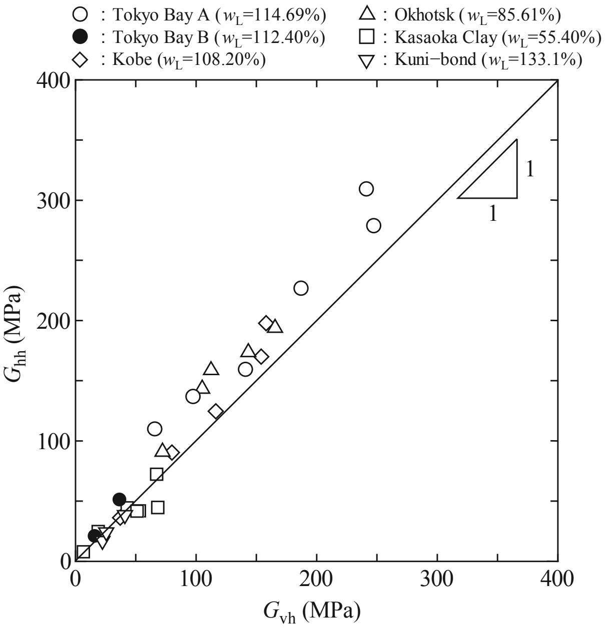

Figure 4. Relationship between G_{vh} and G_{hh}

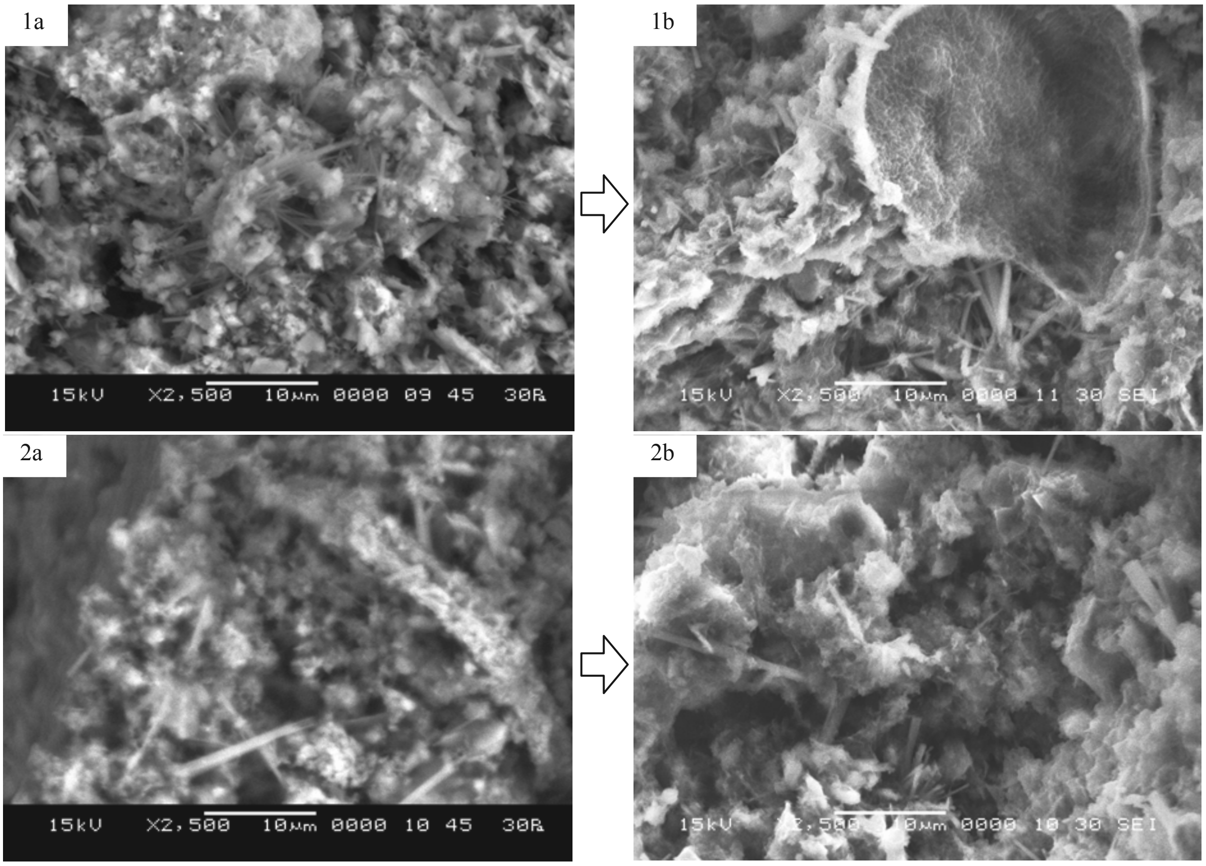

Photo 1. SEM observation of the Tokyo Bay A and B. Curing period of the Tokyo Bay A are 3 (1a) and 182 (1b) days, and curing period of the Tokyo Bay B are 28 (2a) and 182 (2b) days.

4 CONCLUSIONS

In this study the unconfined compression test, the BE test, and observations of the internal structure using an SEM were conducted on SGM specimens prepared with six different types of source soil to examine how different source soils would impact the strength development of SGM. The findings are summarized as follows:

- It was inferred that while the strength and stiffness of the SGM specimens increased with the elapse of curing days, there is a very large variation in their actual levels due to the mineral components and the constituents of pore water contained in the source soil used. In addition, it became clear that the SGM strength cannot be estimated from the flow values of the specimens.
- In SGMs with an approximately equal amount of cement additive and comparable target wet density, the strength and stiffness have a linear relationship as is the case in other cement-treated soil, and their slopes are approximately the same regardless of the soil type.
- The slope obtained from G_{hh} and G_{vh} is characterized by an approximately 1:1 relationship, showing that the air foam in the specimens makes SGM a very isotropic material in terms of stiffness.
- The observations of the internal structure of SGM using the SEM on the predetermined curing days suggested the possibility that the increase, growth, and bonding of needle-like ettringite crystals, formed by the hydration process of the cement, were a major factor contributing to the development of the strength and stiffness of the SGM specimens.

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6 REFERENCES

Kataoka, S., Kawaguchi, T., Horita, T., Tanaka, M., Sakaiya, T. and Shibuya, S. 2011. Unconfined compression strength and elastic shear modulus of air-form treated lightweight soil. *Proc. of the 5th International Symposium on Deformation Characteristics of Geomaterials,* 2, 682-686.

Kawaguchi, T., Yamashita, S., Kataoka, S., Shibuya, S. and Kawajiri, S. 2008. Inherent and induced anisotropy of three natural sedimentary clays reflecting on the elastic shear modulus. *Proc. of the 4th International Symposium on Deformation Characteristics of Geomaterials,* 1, 575-579.

Nagatome, T., Mitarai, Y., Yamatoya, R., Kotou, T. and Noguchi, T. 2010. Unprecedented large scale of rapidly construction work of light weight soil with air form for Haneda D-runway Construction Project (Part 1: Validation of field mixing condition). *The 45th Annual Conference of JGS,* 2093-2094. (in Japanese)

Seng, S. and Tanaka, H. 2008. Properties of cement-treated soils during initial curing stages. *Soils and Foundations,* 51 (5), 575-579.

Sibuya, S. Mitachi, T. and Ozawa, H. 2001. Time/stress-history dependency of deformation-strength characteristics of cement-mixed sand. *Journal of JSCE,* 687 (III-56), 249-257. (in Japanese)

Tuchida, T., Okumura, T., Takeuchi, D. and Kishida, T. 1996. Development of light-weight fill from dredging. *Proc. of the 2nd International Congress on Environmental Geotechnics,* 1, 415-420.

Watabe, Y., Itou, Y., Kang, M.S. and Tuchida, T. 2004. One-dimensional compression of air-form treated lightweight geo-material in microscopic point of view. *Soils and Foundations,* 44 (6), 53-67.