Technical Report

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Reclamation by CaO Improved Soil

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Abstract

"CaO-improved soil" suits with construction material of reclamation, because of its strength and aseismicity. In this study, we examined soil characteristics, and reclaimed artificial ground made of dredged soil and steelmaking slag by using pipe mixing method for the first time. From the result of the survey, 1) Long term consolidation settlement of "CaO-improved soil" is shorter than sand, "CaO-improved soil" is not liquefaction. 2) Designing of mix propotion of "CaO-improved soil" is as same as cement stabilization. 3) Unit weight and short-time strength were useful for predicting sustained strength. 4) Strength of cone and surface wave velocity were useful for assessing ground strength.

1. Introduction

In Japan—a small island country surrounded by the seas, the reclamation of land from the sea has long been conducted at various parts of the country to create land areas for airports and industrial facilities. Land reclamation work requires huge volumes of soil. As an example of effective utilization of dredged soil, the cement-improved dredged soil is used as a material for land reclamation in the Chubu International Airport Artificial Island Construction Project, and in several others. The major requirements of any material for land reclamation are as follows: the material should have the prescribed strength and earthquake resistance, there should be an established method of mixing design for the material, the quality of work executed using the material can be managed properly, and the land reclaimed using the material meets the prescribed performance requirement. The CaO-improved soil has good strength development property and liquefaction resistance. Therefore, we considered that it could effectively be used as a material for land reclamation. In this report, we shall verify the usefulness of CaO-improved soil as a material for land reclamation from the standpoint of the properties of the soil and the methods of mixing design, work quality management, and reclaimed land evaluation, based on the results of land reclamation work executed by Nagoya Works of Nippon Steel & Sumitomo Metal Corporation.

2. Properties of Soil

2.1 Short-term consolidation characteristic

With the aim of evaluating the consolidation characteristic of CaO-improved soil, we performed a consolidation test using specimens (each being 10 cm in diameter and 4 cm in height) prepared from CaO-improved soil obtained by mixing dredged soil and CaO in a mini-plant placement test using the in-pipe mixing method, which was collected before the placement. The water content in percent of dry weight of the dredged soil was adjusted to 1.6 wL (water content = 118.4%, fine grain content = 75.3%, liquid limit wL = 74%), and the mixing ratio of CaO was 30 vol%.

The consolidation test was done at five different levels of strength. An example of the test result is shown in **Fig. 1** [1] and the relation between unconfined compressive strength and consolidation yield stress is shown in **Fig. 2** [1]. Like cement-solidified soil, the CaO-improved soil also shows a yield point and the relation $P_c = 1.25\,q_u$ between consolidation yield stress P_c and unconfined compressive strength q_u.

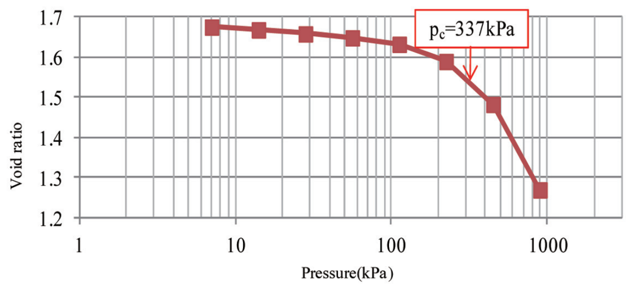

Fig. 1 Experiment of consolidation [1]

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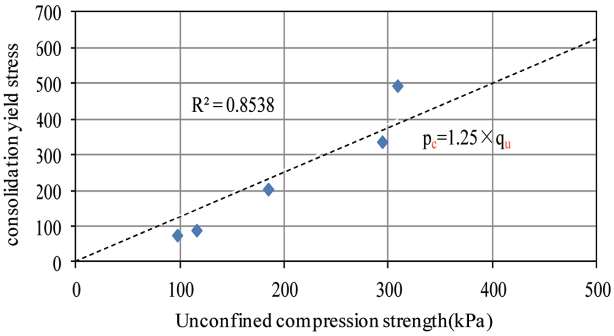


Fig. 2 Relationship between consolidation yield stress and unconfined compressive strength [1]

Table 1 Ratio of second coefficient of consolidation and compressive index of CaO-improved soil [1]

		Ratio of duration time and finish time of first consolidation	
		$t/t_p = 10$	$t/t_p = 100$
Load of consolidation	0.5 p_c	0.0029	0.0012
	1.0 p_c	0.0106	0.0028
	1.5 p_c	0.0092	0.0028

2.2 Long-term consolidation characteristic

In the case of a clayey ground, there is a fear that its consolidation will continue over years after a load is applied to it from above, causing the structure built on top of it to sink. With the aim of grasping the long-term consolidation and settling behavior of CaO-improved soil, we performed a long-term consolidation test and obtained the amount of creep deformation due to secondary consolidation. The water content in percent of dry weight of the dredged soil was adjusted to 1.4 wL (water content = 124.6%, fine grain ratio = 88.7%, liquid limit = 89%) and the mixing ratio of CaO was 25 vol%. **Table 1** [1] shows the values of C_a/C_c, the ratio of secondary consolidation coefficient to compression index, obtained from the results of the long-term consolidation test. While the C_a/C_c of alluvial clay is generally in the range 0.03 to 0.04,[2] the C_a/C_c of CaO-improved soil is 0.0012 to 0.0106, less than one-tenth that of alluvial clay. Thus, it can be seen that the CaO-improved soil is a material, which is hardly consolidated in the long run.

2.3 Dynamic characteristics

With the aim of grasping the liquefying characteristic of CaO-improved soil, we performed a cyclic triaxial test. The water content in percent of dry weight of dredged soil was adjusted to 1.4 wL (water content = 124.6%, fine grain ratio = 88.7%, liquid limit = 89%), and the mixing ratio of CaO was 25 vol%.

The test results are shown in **Fig. 3** [1]. As the cyclic loading is continued, the excess pore water pressure increases. However, the excess pore water pressure ratio does not reach 1.0. It cyclically increases and decreases during application of the load. With respect to the change in strain, an axial strain occurs and increases as the number of loading cycles is increased. Even so, unlike “clean sand” having a uniform grain size distribution, the CaO-improved soil does not show a sharp increase in strain.

Next, the relation between cyclic shear stress ratio and cyclic loading stress times is shown in **Fig. 4** [1]. As a reference, the figure also shows the results obtained with Rokko decomposed granite,

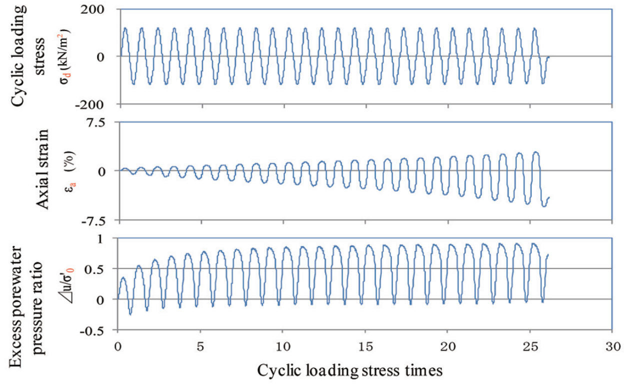


Fig. 3 Result of cyclic undrained triaxial test [1]

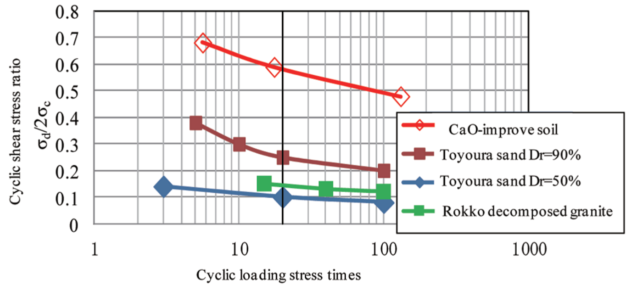


Fig. 4 Relationship between cyclic shear stress ratio and cyclic loading stress times [1]

which liquefied extensively during the Great Hanshin-Awaji Earthquake in 1995, Toyoura sand (relative density Dr = 50%), which is often used in a liquefaction test, and compacted Toyoura sand (Dr = 90%). Compared with Rokko decomposed granite and Toyoura sand (Dr = 50% and 90%), the CaO-improved soil is much higher in cyclic shear stress ratio. From the above test results, it is considered that the CaO-improved soil is a material that does not liquefy.

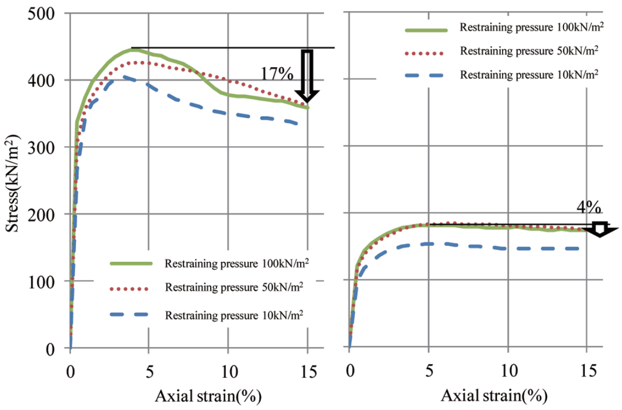
2.4 Softening behavior after peak strength is attained

As the CaO improver contained in CaO-improved soil is a granular material, there is a possibility that the shear band that occurs after the peak strength is reached, increasing in width and causing the soil behavior to change. Therefore, we performed a consolidated undrained shear test and studied the stress–strain relation for CaO-improved soil, which differs in the maximum grain size of CaO improver (25 mm and 5 mm). The water content in percent of dry weight of dredged soil was adjusted to 1.6 wL (water content = 142.4%, fine grain ratio = 97.9%, liquid limit = 89%), and the CaO improver mixing ratio was 25 vol%.

Figure 5 [1] shows the test results for CaO improver with the maximum grain size of 5 mm and 25 mm. From the figure, it can be seen that the stress in the CaO-improved soil reaches a peak at an axial strain of about 4% and that the decline in strength after reaching the peak is small when the maximum grain size of CaO improver is 25 mm.

2.5 Permeability

The approximate values of permeability coefficients of different types of soil are shown in **Table 2**. The permeability coefficients of CaO-improved soil obtained by a consolidation test are shown in **Fig. 6**. From the figure, it can be seen that the permeability coefficient of CaO-improved soil is in the range 10^{-7}–10^{-6} cm/s, between those of silt and clay.



(a) Max grain size : 5mm (b) Max grain size : 25mm

Fig. 5 Relationship between stress and strain of CaO-improved soil [1]

Table 2 Coefficient of permeability of soil

	Sand	Silt	Clay
Coefficient of permeability (cm/s)	10^{-2}	10^{-5}	10^{-7}

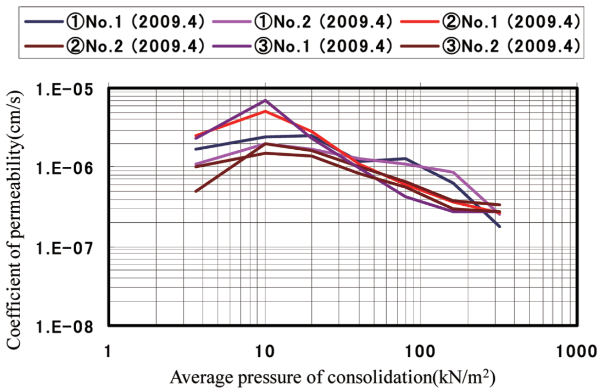


Fig. 6 Coefficient of permeability of CaO-improved soil

3. Outline of Execution of Reclamation Work

CaO-improved soil as a material for land reclamation was applied for the first time in reclamation work in the public water surface north of Tokai Motohama Pier of Nagoya Works of Nippon Steel & Sumitomo Metal. The work was executed in the east area (Apr.–May 2012; about 30000 m^3) and in the west area (Mar.–Sep. 2013; about 410000 m^3) separately. In this report, we shall describe the reclamation work executed in the east area. The plan of the work site is shown in **Fig. 7** and the cross section of the work site is shown in **Fig. 8**.

For mixing CaO improver in dredged soil, the in-pipe mixing method suitable for pressure feeding of soil over long distance and the speedy execution of large-scale work was adopted. **Photos 1–3** [2] show scenes of the work being executed.

Dredged soil and CaO improver were measured as described below. First, the operator of the backhoe on the pressure feeding vessel secures a fixed volume of dredged soil from the soil carrier paying attention to the level of soil input previously marked on the inside of the bucket of the backhoe. Next as shown in **Photo 4** [2], the operator cuts out a certain portion of CaO improver from the belt conveyer

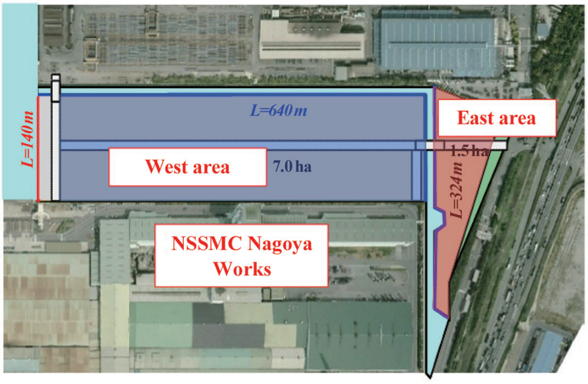


Fig. 7 Plan of reclamation work

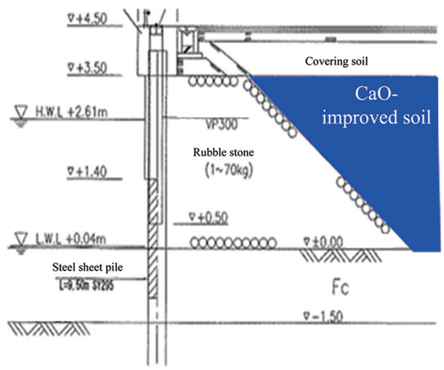


Fig. 8 Cross section of reclamation work

Photo 1 Air pressure type transfer vessel [2]

Photo 2 Location of reclamation [2]

and measures the weight thereof so that the volume ratio of dredged soil to CaO improver becomes 75:25 in the bucket. Then, the weighed materials are put into the hopper of the pneumatic feeder vessel and mixed in a pipe (800 mm in inside diameter) as they are pressure-fed over a distance of 300 m. After the mixture is kept temporarily in a storage tank by a slowdown cyclone installed within the reclamation site, it is subjected to the secondary pressure feeding

Photo 3 Situation of pouring [2)]

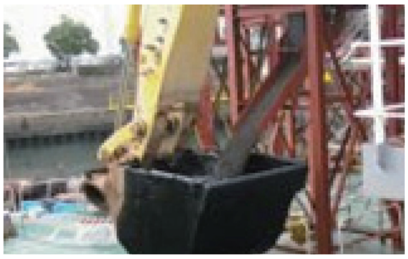


Photo 4 Situation of measuring steelmaking slag [2)]

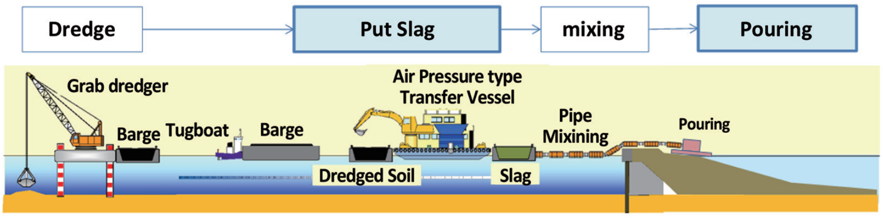


Fig. 9 Flow of reclamation work [2)]

and placement by a concrete pump (**Fig. 9** [2)]). Concerning the qualities of water (pH and SS concentration) in the neighboring sea area, they were measured once a day during execution of the work along the line demarcating the work site. It was confirmed that the measured values were well under those specified by the applicable environmental regulations.

4. Materials

The dredged soil was collected from two points in the neighborhood of Nagoya Port. The CaO improver used was of grain size equivalent to CS-20 specified in JIS A 5001. The physical properties of those materials are shown in **Table 3** [2)], and the grain size distribution of each of the materials is shown in **Fig. 10** [2)]. It can be seen that the dredged soil in area A contained large proportions of silt and clay, whereas the dredged soil in area B consisted mainly of sand. In the FY 2009 Environmental Technology Verification Project (ETV Project) of the Ministry of Environment, it was prerequisite that CaO-improved soil to be used in an actual sea area should meet the specifications for benthic sediments.[3)] It was confirmed that the above materials were compatible with the applicable standards.

5. Method of Mixing Design

5.1 Concept of mixing design

The basic concept of mixing design for CaO-improved soil is based on the technical manual of the in-pipe mixing and consolidation method. **Figure 11** [4)] shows the relation between design strength q_{uck} and percent defective. With the horizontal axis representing unconfined compressive strength q_u and the vertical axis representing frequency n, the strength distribution becomes normal. Here, the ratio of samples whose strength is lower than the design strength q_{uck} to all the samples collected from the work site is defined as the percent defective. According to the above manual, the percent defective cannot exceed the tolerable limit.

The equation used for mixing design is given below. Indoor target strength q_{ul} relative to design strength q_{uck} is calculated with consideration given to strength ratio β, coefficient α related to percent defective, and variation coefficient v. In the indoor mixing test, the minimum mixing ratio of CaO improver that meets the calculated indoor target strength q_{ul} is selected.

Table 3 Physical properties of dredged soil and steelmaking slag [2)]

			Unit	Dredged soil Area A	Dredged soil Area B	Steelmaking slag
Soil density		ρs	g/cm^3	2.644	2.648	3.04
Consistency	Liquid limit	wL	%	109.8	58.5	-
	Plastic limit	wP	%	38.5	31.9	-
	Plasticity index	IP	-	71.3	26.6	-
Grain size distribution (%)	Grabel	-	%	0.14	12.44	75.1
	Sand	-	%	13.8	53.60	22.7
	Silt	-	%	70.2	20.00	2.2
	Clay	-	%	15.9	13.96	
	Max grain size	-	mm	9.5	26.0	25
Wet density		-	g/cm^3	1.303	1.636	-
Ignition loss		Li	%	11.6	8.5	-
Natural water content		w0	%	171.3	73.3	5.2
Natural water content/ liquid limit		w0/wL	-	1.56	1.25	-

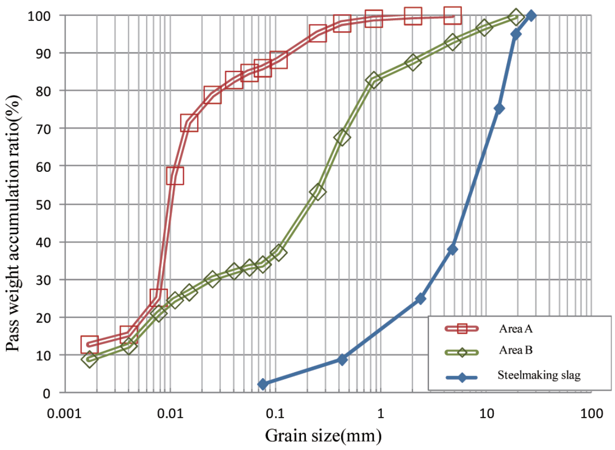


Fig. 10 Gradation curve [2)]

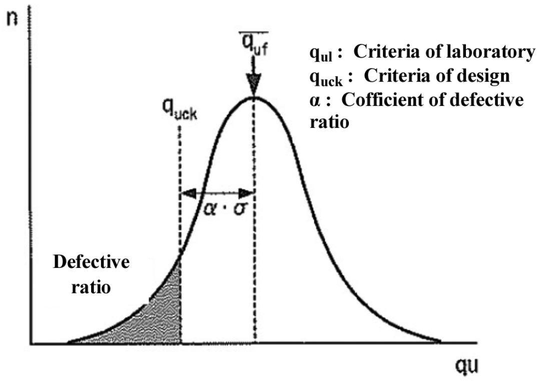


Fig. 11 Relationship between criteria and defective ratio [4)]

$$q_{ul} = \frac{q_{uck}}{\beta\,(1 - \alpha v)} \tag{1}$$

In order to decide the mixing ratio for the CaO-improved soil to be used in the work, we previously collected samples of dredged soil from the appropriate areas and subjected them to an indoor mixing test. The design strength q_{uck} of the ground of the work site is 30 kN/m^2. Here, in accordance with the technical manual of the in-pipe mixing and consolidation method, the tolerable limit of percent defective in the mixing design is set at 25%. In addition, based on the results of a preliminary field test [5)] of CaO-improved soil, the field (underwater) average strength/indoor target strength β and the variation coefficient α of strength in placement in water are set as $\beta = 0.63$ and $\alpha = 0.23$. Substituting them in Equation (1), the indoor target strength q_{ul} becomes 60 kN/m^2.

When placing the CaO-improved soil by the in-pipe mixing method, it is necessary to check the material fluidity and segregation characteristic during pneumatic feeding in order to secure good workability. Although there are no definite standards for material fluidity, the cylinder flow value (JHS A 313) in the range 90–110 mm is used as a general yardstick.

5.2 Results of mixing test

In the preliminary mixing test, dredged soil from area A that accounts for more than 90% of the total area of the work site was used. The water content in percent of dry weight of the original dredged soil was 1.56 wL. However, on the assumption that the water content would vary from day to day during execution of the actual work, the water content of dredged soil was varied between 1.4 wL and 1.8 wL in the mixing test. Here, the mixing ratio of CaO improver is the proportion of the volume of CaO improver to the total volume of CaO-improved soil including dredged soil. Since the generally adopted mixing ratio is 30%, we tested a mixing ratio of 30% ± 5%. After the CaO-improved soil was aged in a constant-humidity room, it was subjected to an unconfined compressive strength test. The criterion applied in the test was whether or not the indoor target strength q_{ul} = 60 kN/m^2 was attained within 3 months after the mixing.

Figure 12 [2)] shows the results of the unconfined compressive strength test mentioned above. The measured strengths are plotted by liquid limit ratio and by number of days of aging. It can be seen that with a mixing ratio of 30% or 35%, the target could be attained in 28 days. Even with a mixing ratio of 25%, indoor target strength q_{ul} = 60 kN/m^2 could be attained by 84 days of aging. Thus, it was confirmed that the required strength could be obtained when the mixing ratio was in the range 25% to 35%.

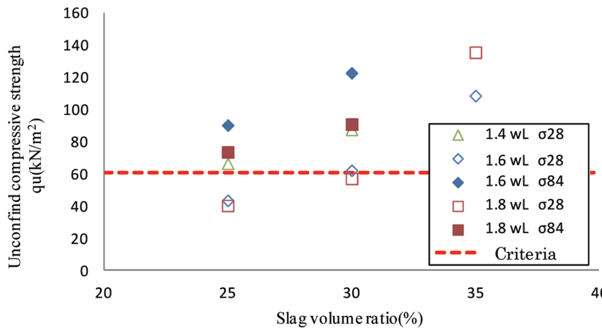


Fig. 12 Unconfined compressive strength of laboratory [2)]

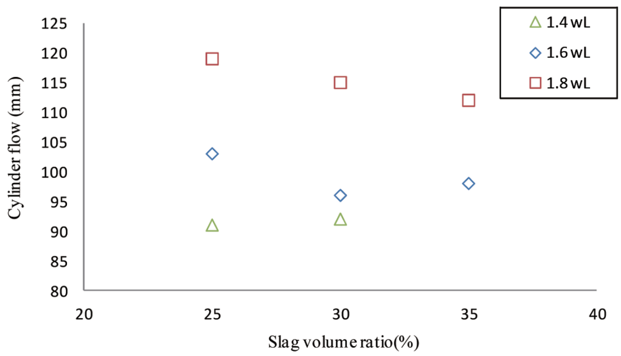


Fig. 13 Cylinder flow test of laboratory [2)]

Figure 13 [2)] shows the relation between the mixing ratio of CaO improver and the flow value of CaO-improved soil obtained by the mixing test. In all the test cases, the flow value was in the range 90–120 mm, nearly the same as specified in JHS A 313, and the phenomenon of material segregation was not observed at all.

Based on the above test results, we selected the CaO improver volume ratio of 25% as the basic mixing ratio in the execution of work.

5.3 Results of work execution

(1) Strength

Since the strength ratio β of CaO-improved soil in water is 0.63 [5)], the field target strength relative to design strength q_{uck} = 30 kN/m^2 becomes 30/0.63 = 48 kN/m^2. **Figure 14** [2)] shows the distribution of unconfined compressive strength (28 days of age) in the execution of 15-day work using CaO-improved soil at site. The average strength at site was 114 kN/m^2, indicating that the field target strength could be attained. Of a total of 15 soil samples 28 days of age, only two samples showed compressive strength lower than 48 kN/m^2. As the percent defective is 2/15 × 100 = 13%, we could confirm that it was well below the tolerable limit of percent defective (25%) set during the mixing design.

(2) Workability

Figure 15 [2)] shows the measured flow values and pressure gradients, together with those given in literature. [4, 5)] In the present work execution, the initial water content in percent of dry weight of dredged soil varied between 0.4 wL and 1.6 wL in area A and between 0.5 wL and 1.5 wL in area B. As a result, the flow value of CaO-improved soil widely varied between 82 mm and 156 mm. However, no troubles in soil feeding occurred during the period of work execution.

In addition, it was found that the pressure gradient decreases as

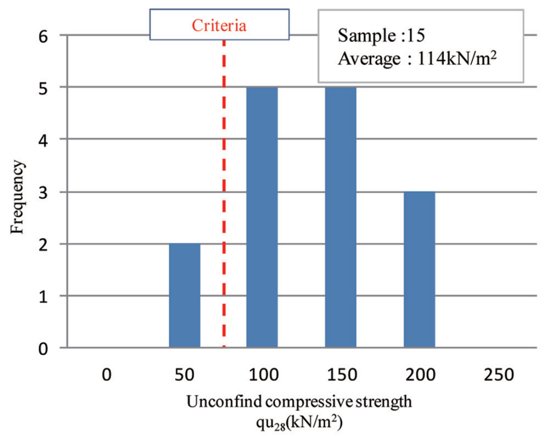


Fig. 14 Histogram of unconfined compressive strength in site [2)]

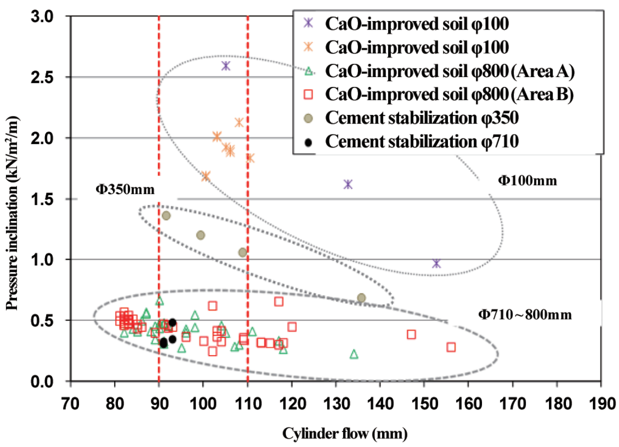


Fig. 15 Relationship between cylinder flow and pressure inclination [2)]

the diameter of the pipe for pneumatic feeding of soil is increased; moreover, the pressure gradient with a 800 mm-diameter pipe used in the present work is not very different from the pressure gradient when cement-stabilized soil was fed through a 710 mm diameter pipe; further, the relation between flow value and pressure gradient, obtained with CaO-improved soil is similar to that obtained with cement-stabilized dredged soil of clay or sand.

Thus, we demonstrated that even for Cao-improved soil, it is possible to implement mixing design using a method similar to the one that is applied to cement-stabilized soil.

6. Method of Work Quality Management

6.1 Relation between short-term and long-term strength of CaO-improved soil

The major problem involved in work management on a day-to-day basis is to establish a technique to control and evaluate uncertain factors such as the variation of water content of dredged soil at the work site to secure the design strength of material. To that end, it is necessary that there be means of speedily predicting the material strength and feeding back the relevant data to the work site as required and thereby securing the desired work quality. It has been reported that in soil improvement using a cement-based stabilizer, the quality of work was managed by predicting the long-term soil strength based on the short-term soil strength.[4)] In this connection, we attempted to clarify if similar quality management could be applied to CaO-improved soil as well.

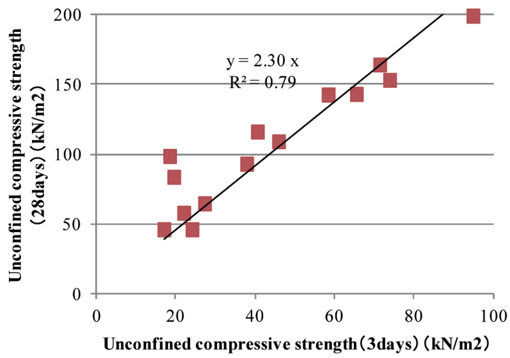


Fig. 16 Relationship between age of 3 days and 28 days of unconfined compressive strength [2)]

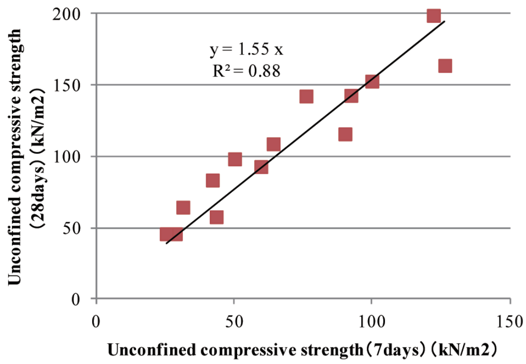


Fig. 17 Relationship between age of 7 days and 28 days of unconfined compressive strength [2)]

CaO-improved soil collected in a storage tank during 15 days of field work was first aged at the site and then subjected to an unconfined compressive strength test (material age: 3, 7, and 28 days). The test results are shown in **Figs. 16** [2)] and **17** [2)]. The initial water content in percent of dry weight of dredged soil varied markedly, between 0.4 wL and 1.6 wL in area A, and between 0.5 wL and 1.5 wL in area B. Therefore, the strength of CaO-improved soil varied widely. However, there was a strong correlation y = 2.30x (R^2 = 0.79) between the 3-day-old material and the 28-day-old material and y = 1.55x (R^2 = 0.88) between the 7-day-old material and 28-day-old material. Thus, it was found possible to accurately predict the long-term strength from the short-term strength. The implication is that predicting the long-term strength from the short-term strength can be one method of quality control of CaO-improved soil.

6.2 Relation between wet density and strength of CaO-improved soil

As mentioned in 6.1, it was found possible to estimate the long-term strength of CaO-improved soil from the short-term strength of the soil. If the strength of CaO-improved soil can be predicted in the earlier stages of its placement, it helps to implement proper management of the amount of CaO improver input. Therefore, we tackled the development of a method for evaluating the soil strength on the day of soil placement.

The higher the water content ratio of CaO-improved soil, the smaller becomes the strength of the soil. The density of seawater is 1.03, which is smaller than the dry density of CaO improver (3.04) and the soil particle density of dredged soil in area A (2.648) or area

B (2.644) (see Table 3). Therefore, the higher the water content ratio, the smaller becomes the wet density of CaO-improved soil. Then, the authors considered if it would become possible to express the variation of strength due to the day-to-day change in water content ratio by measuring the wet density of CaO-improved soil.

Figure 10 shows the relation between unconfined compressive strength (material: 28 days of age) and wet density (daily average), obtained during 15-day work. The wet density was measured before the secondary pressure feeding of soil, and the unconfined compressive strength was obtained by subjecting CaO-improved soil collected and aged at the work site to an unconfined compressive strength test. The initial water content ratio of dredged soil varied widely, between 0.4 wL and 1.6 wL in area A and between 0.5 wL and 1.5 wL in area B. Therefore, the variation of wet density of CaO-improved soil widened. Even so, the wet density showed a positive correlation with the soil strength.

The variation of wet density is ascribable, at least in part, to the variance in mixing ratio of CaO improver. With the aim of grasping the condition of variation of CaO improver mixing ratio, we measured the variance in wet density of batches of CaO-improved soil placed from the same soil carrying barge. Figure 11 shows an example of wet density distribution obtained with 20 samples of CaO-improved soil collected in five hours, four samples per hour. The water content ratio of dredged soil was 30.3%. The coefficient of variation of wet density is 0.011, suggesting that the variance in CaO improver mixing ratio is insignificant. Thus, in the case of CaO-improved soil, it was considered possible to confirm the difference in strength development due to the variation of water content ratio of dredged soil by measuring the wet density of CaO-improved soil.

The implication is that it should be possible to predict the degree of attainment of the target strength of CaO-improved soil by measuring the short-term strength and wet density of the soil.

7. Evaluation of Reclaimed Land

As a rule, the design strength of reclaimed land is controlled in terms of the unconfined compressive strength. In the case of CaO-improved soil, however, it has been known from previous studies that soil samples can hardly be collected from considerable depths of water, although it is possible to collect the PVC pipes laid out for the placement of soil and block samples near the surface of water.[6] Therefore, we tackled the evaluation of reclaimed land using a combination of the cone penetration test, which permits examining the land in depth direction, and the surface wave probing technique, which permits evaluating the entire land.

7.1 Evaluation of reclaimed land in depth direction

For reclaimed land 16 000 m^2 in area, we performed an electrical static cone penetration test at five points twice—one month and three months after the land was reclaimed. **Figure 18**[2] shows the cone-tip resistance values converted in terms of unconfined compressive strength using $q_c = 12.1 \times q_u$ obtained by a preliminary field test.[5] The vertical axis represents depth (m), or distance from the top of CaO-improved soil. Here, a comparison with the design strength of 30 kN/m^2 reveals that the target strength was attained in the entire depth of the land. In addition, it was confirmed that the results of an unconfined compressive strength test of block samples performed at two points were almost the same as the results of the cone penetration test.

7.2 Evaluation of entire reclaimed land

Figure 19[2] shows the results of surface wave probing of reclaimed land carried out three months after completion of the reclamation work. The section 0 to 1 m in depth consists of ordinary cover soil and the section 1 to 6 m in depth consists of CaO-improved soil. The unconfined compressive strength, q_u, of the ground is estimated from the S-wave velocity, V_s, obtained by the surface wave probing method. Using cement-stabilized soil, Kusumi et al.[7] proposed the following equation expressing the relation between V_s and q_u.

$$q_u = 1.0 \times 10^{-5} \cdot V_s^{1.872} \qquad (2)$$

The measured value of V_s for the ground consisting of CaO-improved soil was 150–200 (m/s). Substituting the measured value of V_s in Equation (2), the estimated value of q_u is 120–200 (kN/m^2), which indicates that the design strength 30 kN/m^2 is attained in horizontal direction as well. Note that the range of estimated values of q_u obtained above agrees well with q_u = 130 (kN/m^2) obtained by block sampling.

From the facts described above, we could confirm by the static cone penetration test and surface wave probing method that the entire reclaimed land has attained the target strength.

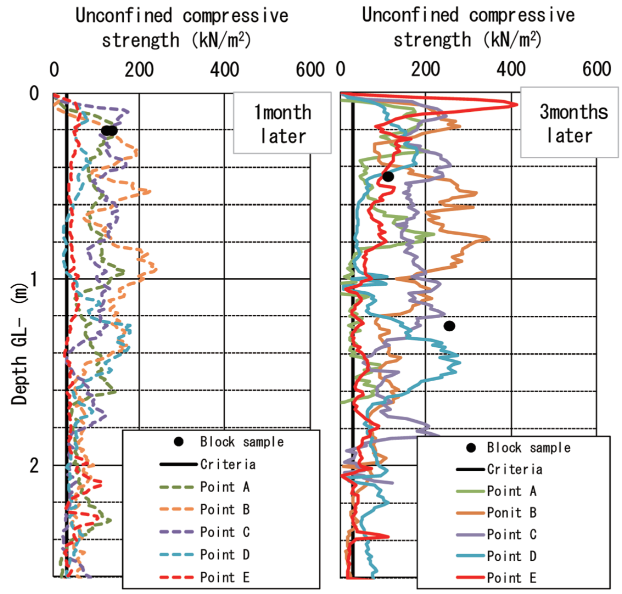


Fig. 18 Distribution of depth strength[2]

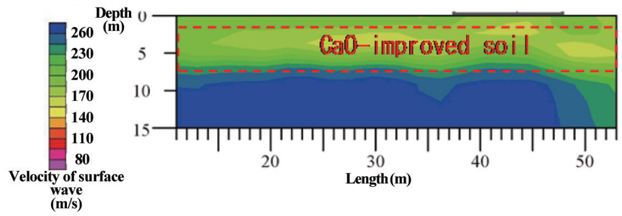


Fig. 19 Result of surface wave method[2]

8. Conclusion

Concerning the usefulness of CaO-improved soil as a material for land reclamation, we obtained the following knowledge.

1) With respect to its characteristics, CaO-improved soil has a high secondary consolidation coefficient to compression index ratio and a high cyclic shear stress ratio. Therefore, it is considered that CaO-improved soil is a material, which has good resistance to the long-term settlement due to consolidation and

which does not liquefy.

2) With respect to the mixing design method, the mixing design for CaO-improved soil can be implemented in the same way as for cement-stabilized soil.
3) With respect to the method of work management, it is possible to predict the degree of attainment of the target strength by measuring the short-term strength and wet density of the soil. This method is considered a useful means of work quality management.
4) With respect to the evaluation of reclaimed land, based on the results of a cone penetration test and surface wave probing in the field, we confirmed that the reclaimed land has attained the target strength.

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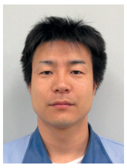

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