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Strength mobilization of cement-treated dredged clay during the early stages of curing

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Abstract

Cement-treated marine clays have been widely used as a construction filling material in coastal engineering projects in recent years. The strength mobilization of cement-treated clay in terms of early stages of curing is important because the strength increases during the transportation and the placement to the construction site. In this study, to examine the characteristics of strength for cement treated clays during the early stages of curing, a series of vane shear and unconfined compression tests were carried out with varying water and cement contents for four marine dredged clays. On the basis of the results obtained from the laboratory tests, it was found that the strength mobilization process can be divided into two stages; first stage within 3 days after curing (the early stage of curing) and the second stage 3 days after the curing. Two equations to evaluate strength during early stages of curing were proposed based on the initial water content and specific volume ratio normalized by liquid limit. The equations consisted of coefficient a_1, strength at 1 h curing, and coefficient b_1, strength increment ratio. It was found that the equation based on the specific volume ratio is slightly better in predicting the strength during the early stages of curing than the equation based on normalized water content. It is concluded that the proposed equations are very simple and useful to determine the strength of cement-treated clay during the early stages of curing.

Keywords: Cement-treated clay; Un-drained shear strength; Unconfined compressive strength; Normalized specific volume ratio; Normalized initial water content

1. Introduction

A large amount of soft clayey soils are dredged annually for the maintenance of navigation channels and seaports. These dredged clays are dumped in waste-dumping sites enclosed by seawalls. The lack of dumping site and the high construction cost for closed waste-dumping facility are serious concerns in Japan (Tsuchida et al., 1996; Tsuchida, 1999). In order to solve these problems, dredged clays treated with cement are used as construction material in projects which require low design strength, ranging from 100 kPa to 500 kPa. Cement-treated clay is used as construction filling material, in the backfilling of quay walls, in artificial barrier layers at waste disposal sites, and in submerged embankments. These materials are constructed by either the Pneumatic Flow Mixing Method, where the mixing of clay and cement milk inside the pipeline by means of the turbulent flow generated during transportation, or on special working ships, where the cement-treated clay passes through a transport pipe connected to the construction site (Tsuchida, 1999; Tang et al., 2001; Watabe et al., 2011; Seng and Tanaka, 2011; Watabe and Noguchi, 2011).

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This process requires a considerable amount of time for the material to reach the construction site. The strength of cement-treated clays increases during the transportation and construction stages. In particular, if the cement-treated soil during transport is too stiff, it is difficult to transport the material to the construction site due to the high friction forces acting on the interior wall of the pipe. Moreover, strength mobilization during the early stages of curing is needed to determine the thickness for the placement of cement-treated clay on the slope of artificial barriers and/or submerged embankments as the strength increases with curing time. To our knowledge, there is no available literature to estimate the strength mobilization of cement-treated clays during the early stages of curing.

The basic physical properties of cement-treated clays have been extensively examined by many researchers (Terashi et al., 1979; Uddin et al., 1997; Horpibulsuk et al., 2004). It is well-known that the strength mobilization of cement-treated clay is influenced by many factors, such as the types and quantity of binder (Terashi and Tanaka, 1981; Clough et al., 1981), the mixing methods of admixtures (Omine et al., 1998; Larsson, 2001), the curing conditions (Consoli et al., 2000; Suzuki et al., 2014), and the characteristics of the nature of soils (Kamon et al., 1999). Empirical equations based on various indices have been proposed to predict the strength of cement-treated soils. The indices of these equations include the mass ratio of cement to dried soil (Mitchell et al., 1974; Nagaraj and Miura, 1996; Tan et al., 2002), the cement mass per wet soil volume of 1 m^3 (Terashi and Tanaka, 1981; Tang et al., 2001; Zhang et al., 2013), the water–cement ratio (Suzuki, 1990; Miura et al., 2001), the void ratio (Yajima et al., 1996; Lorenzo and Bergado, 2004), the total water–cement ratio (Miura et al., 2001; Horpibulsuk et al., 2003, 2011; Liu et al., 2008), the yield stress ratio (Kasama et al., 2006, 2007), increments in mass of bound water per unit volume (kg/m^3) or increment in mass of hydration water per unit volume (kg/m^3) (Zhu et al., 2007; Chiu et al., 2008), porosity divided by the volumetric cement content (Consoli et al., 2010, 2011), and the activity number of clay (A) (Sasanian and Newson, 2014). However, even though there are a number of empirical equations available in the literature with various indices proposed by several researchers, since they are derived from data from curing times of more than 3 days, those indices cannot be readily applied to estimate the strength of cement-treated clays in the early stages of curing. The present study aims to estimate the strength mobilization of cement-treated clay during the early stages of curing, i.e. within 3 days after mixing of cement and clay.

To examine the strength mobilization during early stages of curing, a series of laboratory vane shear and unconfined compression tests were carried out under different initial water contents and cement contents for four dredged marine clays. The un-drained shear strength and unconfined compressive strength for cement-treated clay obtained from these tests were then correlated with the initial water content and specific volume ratio normalized by liquid limit. Based on the results, equations to estimate strength during the early stages of curing for cement-treated soils are proposed.

2. Review of previous studies

Previous studies have been mainly focused on the cement treatment by Deep Mixing or Jet Grouting methods on stages of curing for more than 3 days.

Mitchell et al. (1974) proposed a relationship between the unconfined compressive strength of cement treated soils and the curing time, as given in the following equation:

$$q_D = q_{D_0} + K \log\left(\frac{D}{D_0}\right) \tag{1}$$

where, q_D is the unconfined compressive strength at curing after D days, q_{D0} is the unconfined compressive strength at curing after D_0 days, and $K=480\ c$ for coarse-grained soils and $K=70\ c$ for fine-grained soil, and c is the cement content determined by the mass ratio of cement to dried soil.

Nagaraj and Miura (1996), and Yamadera et al. (1997) proposed equations based on the results of unconfined compression tests on clays treated with Portland cement at different water contents, as shown in the following equation:

$$\frac{q_T}{q_{14\ \text{days}}} = a + b\ \ln(D) \tag{2}$$

where q_D is the unconfined compressive strength at curing after D days, $q_{14\ \text{days}}$ is the unconfined compressive strength at curing after 14 days, and a, and b are constants.

Abrams (1918) proposed an equation to evaluate the strength of concrete mixture based on the water/cement ratio. Miura et al. (2001) and Horpibulsuk et al. (2003, 2011) found that the strength development of cement treated clays depends only on the clay–water/cement ratio, w_c/C, and hence modified Abrams' equation, as shown in Eq. (3). The clay–water/cement is defined as ratio of the total water content to the mass of cement to dry mass of soil. The total water content refers to the addition of natural water content of clay and water added to make the cement slurry.

$$\begin{aligned} \frac{q_{(w_c/C)_1,\ D}}{q_{(w_c/C)_2,\ 28}} &= 1.24^{\left[(w_c/C)_2 - (w_c/C)_1\right]}(0.038+0.281\ln(D)) \quad \text{if} \quad LI = 1.0-2.5 \\ \frac{q_{(w_c/C)_1,\ D}}{q_{(w_c/C)_2,\ 28}} &= 1.24^{\left[(w_c/C)_2 - (w_c/C)_1\right]}(-0.216+0.3421\ln(D)) \quad \text{if} \quad LI > 2.5 \end{aligned} \tag{3}$$

where, $q_{(wc/C)D}$ is the unconfined compressive strength of the cement-treated clay to be estimated at clay–water/cement ratio of (w_c/C) after D days of curing, and $q_{(wc/C)28}$ is the unconfined compressive strength of the cement-treated Bangkok clay at clay–water/cement ratio after 28 days of curing. LI refers to the liquidity index of the soil.

Tang et al. (2001) conducted a series of strength tests for 28 marine clay samples treated with cement and proposed a equation considering the water content and the cement content as given in the following equation:

$$q_u = \frac{K(C-C_0)}{\left(G_s w/100+1\right)^2} \tag{4}$$

where K is the strength coefficient, C is the amount of cement: the weight of cement per unit volume, C_0 is the minimum amount of cement required for strength mobilization, and w is the water content of original soils.

Lorenzo and Bergado (2004) found that the ratio of void ratio after curing to cement content, e_{ot}/A_w, effects the total clay water content, the cement content, and curing time on the unconfined compressive strength of cement-treated clay. Based on these relationships, a equation to evaluate the strength with curing time was proposed as shown in the following equation:

$$q_u = Ap_a e^{B(e_{ot}/A_w)} \quad (5)$$

where, A and B are the dimensionless constants, P_a is the atmospheric pressure, e_{ot} is the void ratio after curing time t, and A_w is the cement content. Based on the results presented for soft Bangkok clay mixed with Type I Portland cement, the constants were found to be $A = 10.33$ and $B = -0.046$. Hence, the constant A is affected by the type of admixture (or type of cement), while the constant B, which is basically the slope of the mean function, is affected by the type and mineralogy of the clay.

Liu et al. (2008) introduced the total water–cement ratio, R, which considers the effects of initial water content in original clays and the water–cement ratio in cement mixture to predict the unconfined compressive strength of cemented-clays.

$$R = \frac{M}{100} + \frac{\rho}{(1 + (100/\omega_n))C}$$

$$\frac{q_{u(R,T)}}{q_{u(R1,T28)}} = (-0.019 + 0.31 \ln T)\frac{(1/R) - (1/20.0)}{(1/R_1) - (1/20.0)} \quad (6)$$

where, R is the total water–cement ratio after mixing, M is the water–cement ratio: the ratio of water to cement by mass, C is the amount of cement: the cement mass per unit volume (kg/m^3), and T is the curing time, $q_{u(R,\ T)}$ is the unconfined compressive strength of the cement-treated clay estimated at total water–cement ratio of (R) after T days of curing, and $q_{u(R1,\ T28)}$ is the unconfined compressive strength of the cement-treated clay estimated at total water–cement ratio of (R_1) after 28 days of curing.

Tsuchida and Tang (2012) proposed a equation, in which the gel-space ratio theory of hardened cement paste is considered, to predict the unconfined compressive strength of cement-treated clays, as given in the following equation:

$$q_u = k_c^*(c^* - c_0^*)Y^N \quad (7)$$

where k_c^* is the coefficient of strength increment, c^* is the cement content, c_0^* is the minimum cement content required for strength mobilization, Y is the volumetric solid content (solid particles of cement, and soil), and N is the exponential parameter for the effect of void structure of soil and cement content to all solid material of soil.

As mentioned, many researchers have proposed equations based on various indices to predict the strength mobilization of cement-treated soils through laboratory tests. However, the equations to estimate unconfined compressive strength are based on curing times of more than 3 days. In addition, since the strength of 14 or 28 days is used as a reference, the equations used to evaluate the unconfined compressive strength during the early stages of curing for less than 3 days are not applicable. To our knowledge, there is no equation to determine the unconfined compressive strength of cement treated clays during the early stages of curing based on the water content, cement content, and curing time.

3. Method of study

In this study, dredged clays were collected from four ports: Tokuyama, Mizushima, Hibiki, and Moji. The physical properties, such as the liquid and plastic limits, the ignition loss, and particle density of these clays, are presented in Table 1. Ordinary Portland cement was used as a binder to prepare the specimen of cement-treated clay. The water content was calculated based on the initial water content normalized by the liquid limit for the preparation of specimens. Laboratory experiments, laboratory vane shear test and an unconfined compression test were performed with varying water content, cement content, and curing time, as listed in Table 2. Fig. 1 demonstrates the phase diagram of cement treated clay, in which cement is calculated as solid with soil. In this study, the cement content c^* (%) is defined as the ratio of mass of cement to the mass of solid particles in cement and soil, as shown in

Table 1
Physical properties of dredged clay.

Site	Liquid limit w_L (%)	Plastic limit w_P (%)	Plasticity index I_P	Ignition loss L_i (%)	Particle density ρ_s (g/cm^3)
Tokuyama port	107.6	35.4	72.2	10.02	2.64
Mizushima port	65.3	15.5	49.8	6.6	2.76
Hibiki port	61.2	20.7	40.5	4.2	2.75
Moji port	89.5	29.3	62.0	8.3	2.67

Table 2
Mixing specification and curing time of cement-treated clay.

Site	Normalized water content (w'/w_L)	Cement content, c^* (%)	Curing time
Tokuyama port	1.5, 2.0	2, 4, 6, 10, 15, 20	0, 0.5, 2, 3, 5, 7, 10, 15 (h) 1, 2, 3, 7, 28, 90 (days)
Mizushima port	1.5, 2.0, 2.5	10, 15, 20	0, 0.5, 2, 3, 5, 7, 10, 15 (h) 1, 2, 3, 7, 28, 90 (days)
Hibiki port	1.5	10, 15, 20	0, 0.5, 2, 3, 5, 7, 10, 15 (h) 1, 2, 3, 7, 28, 90 (days)
Moji port	1.5	10, 20	0, 0.5, 2, 5, 7, 10, 15 (h) 1, 2, 3, 7, 28, 90 (days)

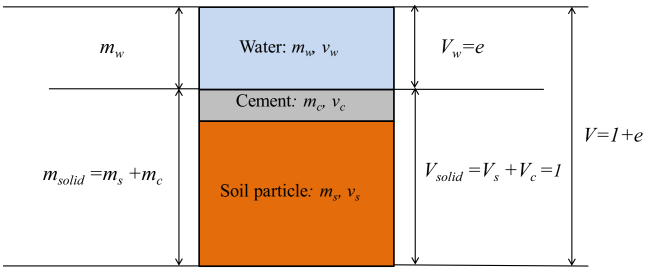

Fig. 1. Phase diagram for cement treated clay.

Eq. (8) and Fig. 1. However, in general, the cement content of cement-treated soil c (%) is defined as the ratio of dry weight of cement to dry weight of soil, as shown in Eq. (9). The main reason for using the definition shown in Eq. (8) and Fig. 1 is to distinguish the strength mobilization due to the effect of solid increment in the treated soil and the chemical reaction by the cement.

$$c^* = \frac{m_c}{m_s + m_c} \times 100\ (\%) \tag{8}$$

$$\mathrm{c} = \frac{m_c}{m_s} \times 100\ (\%) \tag{9}$$

where m_s and m_c indicate the dry mass of cement particles and the clay particles, respectively.

3.1. Sample preparation

To prepare the samples, the dredged clay was passed through a 2 mm sieve to remove shell pieces and other coarse particles. The specimen preparation was carried out as described below.

- Cooling of dredged clay and distilled water: In this experiment, the dredged clay and distilled water were brought to 0–2 °C in order to prevent hardening after mixing due to inhibiting the chemical action of cement while clay and cement are being mixed (Tsuchida et al., 2014).
- Preparation of cement milk: The cement milk was prepared by mixing cement and distilled water. The water–cement ratio of the cement milk was kept to 1:1 by mass ratio of cement and distilled water. When the designed water and cement contents are very high, the mass of distilled water is less than the mass of cement content. In this case, cement milk was prepared as 1:0.5 by the mass ratio of cement and distilled water.
- Mixing of cement milk with dredged clay: After adding the cement milk into the dredged clay, the slurry was thoroughly mixed by means of hand mixer for 2 min. At that time, the designed water content was added to the slurry considering the water content in the cement milk. After that, the slurry was thoroughly mixed for 30 min using vacuum mixer, which can avoid the decrease of water content and chemical reaction, in ice water at 0 °C to prevent hardening due to chemical reaction, as mentioned earlier.
- Specimen preparation for laboratory tests: After mixing, the cement-treated clay was transferred in to a cylindrical mold with dimensions 60 mm × 60 mm for the vane shear test, and a summit mold of 50 mm × 100 mm for the unconfined compression tests. In order to avoid the formation of air bubbles in the mixture, the molds were lightly tapped during the pouring process of each of three layers. After the mold was filled with the mixture, the top of the summit mold and cylindrical mold was sealed by polythene wrap to prevent evaporation. The cylindrical mold of vane shear test was cured under atmospheric pressure at room temperature (20 ± 3 °C,) and the summit mold of unconfined compression test was cured in water at room temperature (20 ± 3 °C). In this procedure, the starting time of curing was set to 30 min after mixing because the time to transfer the mixture into the mold varies depending on the samples.

3.2. Laboratory tests

In this study, two laboratory experiments were conducted: a laboratory vane shear test (LVS test) and unconfined compression test (UC test). Owing to the low shear strength of dredged clays treated with cement immediately after mixing, conventional methods such as tri-axial or unconfined compression tests cannot be carried out. Thus, the laboratory vane shear test was selected to determine the shear strength of cement-treated clays with comparatively low strength. The vane shear apparatus used in this study is the UV-100 made by Seishikou Inc. in Japan. For all the experiments, a vane blade was inserted 2 cm from the surface of the specimen. The equation for calculating the un-drained shear strength is presented in the following equation:

$$c_u = \frac{M}{\pi\left(\left(D^3/6\right) + \left(HD^2/2\right) - \left(d^3/12\right) + \left(d^2La/2\right)\right)} \tag{10}$$

where, M is the measured torque at peak (kg m), D is the diameter of the vane, H is the height of the vane, d is diameter of the vane shaft (2 mm), L is the contacted length of vane shaft, and a is friction coefficient of shaft. Herein, a value of 1.00 was assigned to a. The diameter and the height of the vane were 20 mm and 10 mm, respectively. The shear rate of the laboratory vane apparatus was constant as 6° to 12° rotations per minute. The un-drained shear strength having the higher scatters in range of very low strength was determined through regression analysis to achieve more accurate results.

An unconfined compression test was carried out on the samples with sufficient strength to stand on their own. However, in case of early stages of curing time, the laboratory vane shear tests were conducted for the samples which cannot stand on their own. The purpose of the unconfined compression test is to determine the unconfined compressive strength of the specimens of cement-treated soils. The unconfined compressive strength is the maximum vertical stress that a sample can sustain. The cement-treated samples were compressed at a strain rate of 1% per minute specified by the Japanese Industrial Standards JISA 1216 (JIS A1216, 2008).

4. Data analysis and results

4.1. Formulation of the correction factor

In this study, the un-drained shear strength (s_u) obtained from LVS test was calculated based on the equation; $2s_u = q_u$. The strength of cement-treated clay is presented as either $2s_u$ or q_u. All the data obtained from the LVS and UC tests under different cement contents and water contents are plotted in Figs. 2(a) to 5(a). The vertical dotted lines in Figs. 2(a) to (5) indicate before and after 3 days of curing time. The other dotted lines drawn in the graph indicate the trend of variation of strength development with curing time. A close review of the data presented in Fig. 2(a) reveals considerable differences in the strength values obtained from LVS and UC tests even though the cement content is higher for the same water content. It appears that the strength obtained from LVS test is higher than that obtained from UC test. Kogure et al. (1988) also reported that the strength obtained from laboratory vane shear test is higher than that obtained from unconfined compression and also for direct shear tests on reconsolidated slurry clay. However, the reason for the difference was not known. In our study, it is suspected that this change can be attributed to the difference of failure modes in the LVS and UC tests and disturbance when removing the samples from the mold for UC tests. In the preparation of samples, the top of the

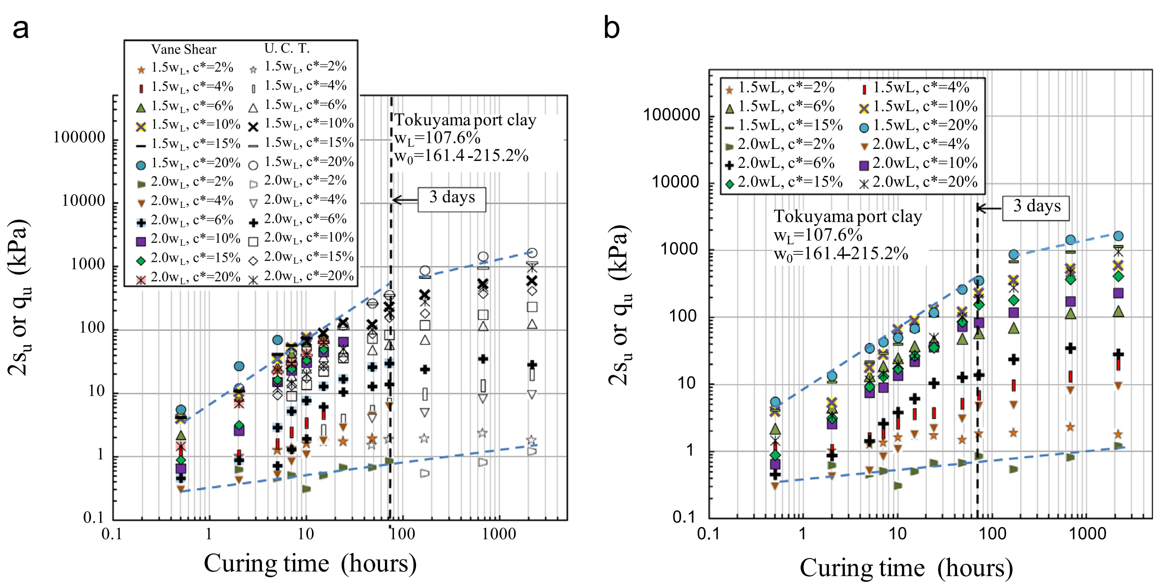

Fig. 2. Relationship between strength mobilization with curing time, ranging from 0.5 h to 90 days, for Tokuyama clay in log–log scale. (a) Before application of correction factor. (b) After application of correction factor.

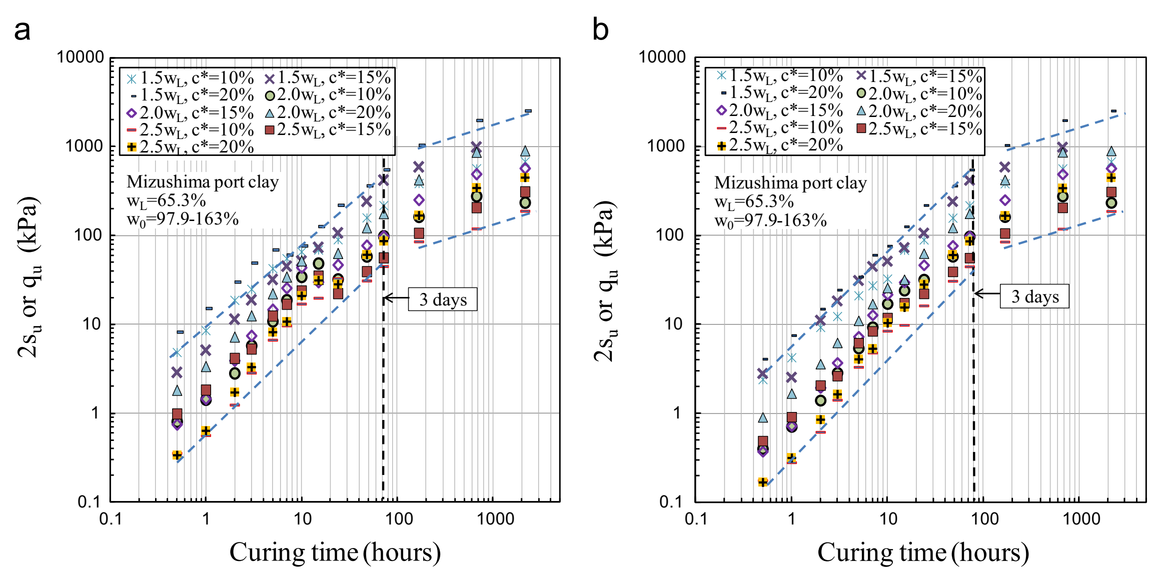

Fig. 3. Relationship between strength mobilization with curing time, ranging from 0.5 h to 90 days, for Mizuahima clay in log–log scale. (a) Before application of correction factor. (b) After application of correction factor.

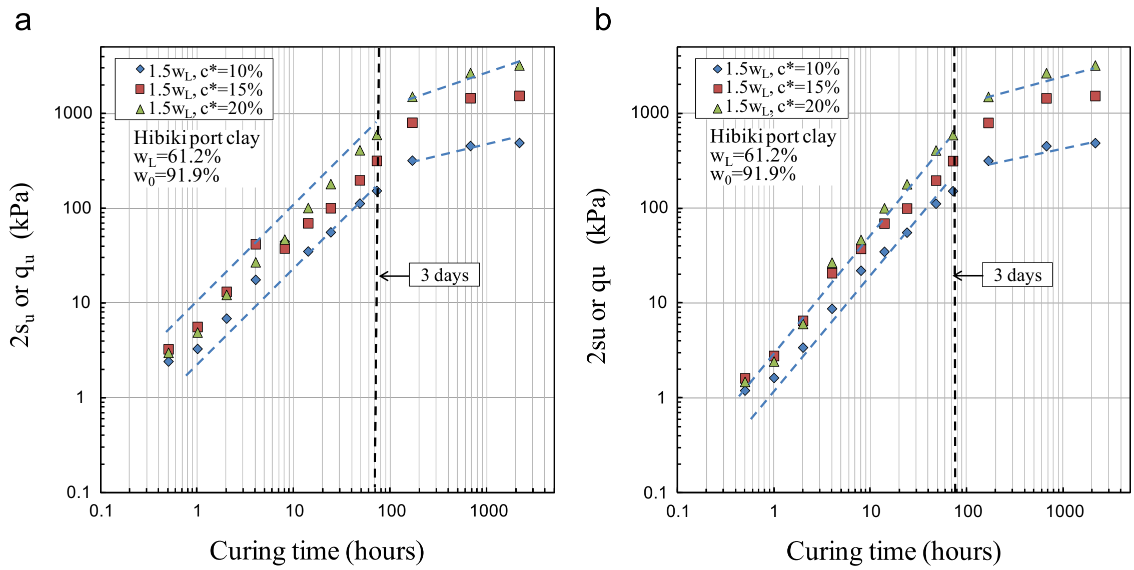

Fig. 4. Relationship between strength mobilization with curing time, ranging from 0.5 h to 90 days, for Hibiki clay in log–log scale. (a) Before application of correction factor. (b) After application of correction factor.

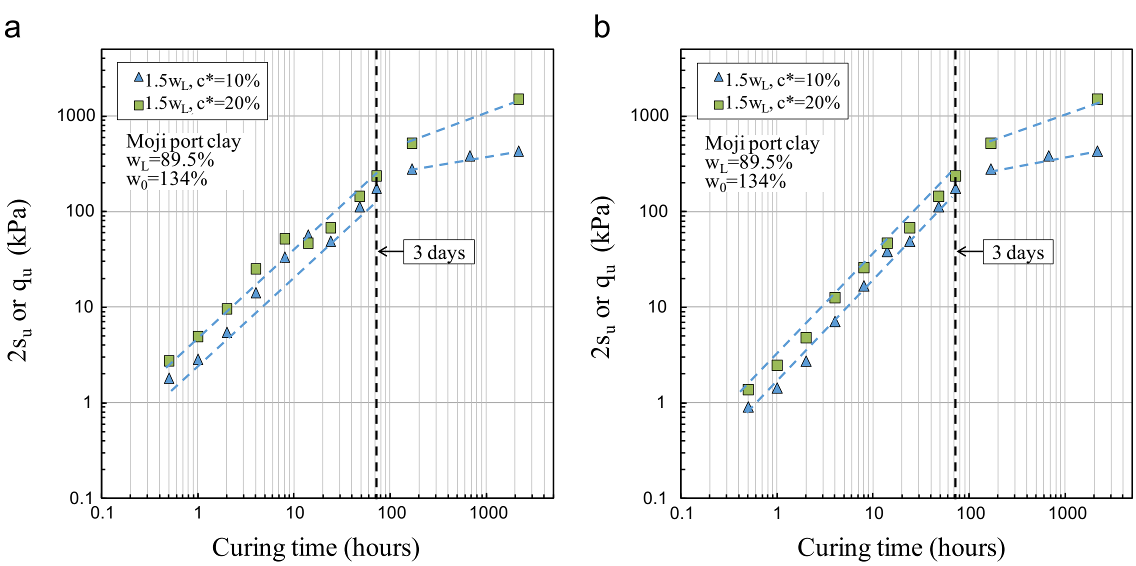

Fig. 5. Relationship between strength mobilization with curing time, ranging from 0.5 h to 90 days, for Moji clay in log–log scale. (a) Before application of correction factor. (b) After application of correction factor.

molds were sealed by polythene wrap to prevent the evaporation of water for both tests. The summit mold which has holes to facilitate the soil sample intact with water was cured at room of temperature of 20 ± 3 °C in water. The mold of the LVS test was cured under an atmospheric pressure at a temperature of 20 ± 3 °C because mold of LVS test made of acryl is difficult to make hole as in the case of summit mold. However, Nader and Chang (1993) showed that the method of curing (either wrapped curing or moisture curing) does not significantly affect the strength development of cement treated soil for up to 7 days. In addition, since the curing time of LVS test used in this study is very short (within 10 h, except in the case of 2% and 4% of Tokuyama clay), the method of curing was considered to have no significant effect on strength development. Since, in our study, both samples were cured at the same temperature, there may be no effect on the strength development even though the method of curing is slightly different.

To determine the difference of strength obtained from LVS and UC tests, the data obtained under the same conditions as the LVC and UC tests were used for Tokuyama clay. However, it was not possible to carry out both tests for all mixing conditions due to experimental limits: the unconfined compression test cannot be carried out if the specimen cannot stand by itself in the early stages of curing. In other words, there are experimental limits according to mixing conditions. The data covers the cement contents of 2% to 20%, water contents of 161.4% to 214% and curing times of 4 h to 3 days. Fig. 6 illustrates a comparison of magnitude for strength, q_u,

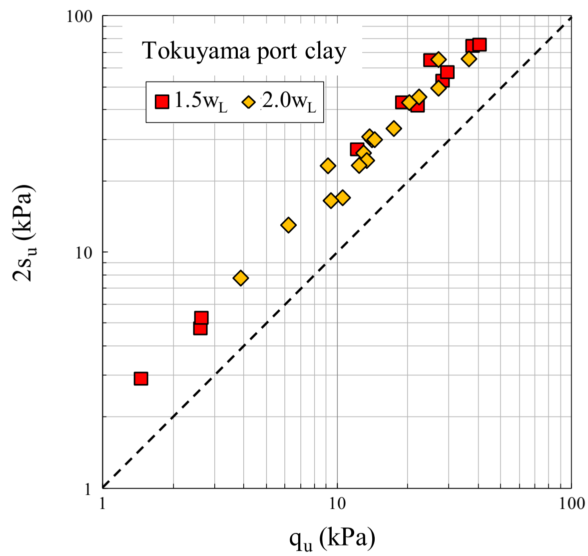

Fig. 6. Comparison of magnitude of strength according to experiment methods.

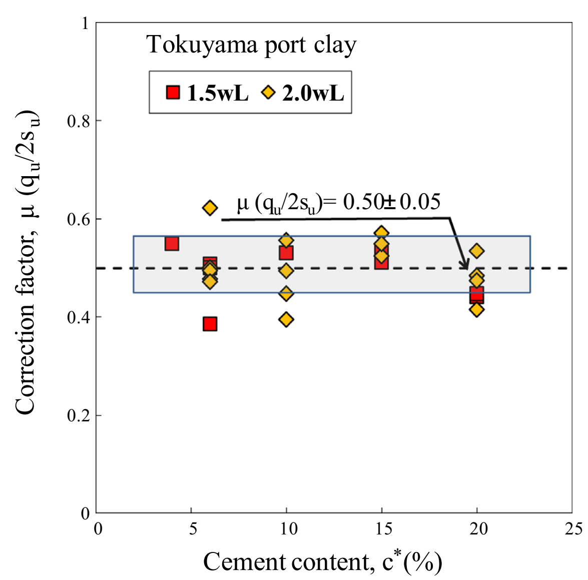

Fig. 7. Correction factor of cement content with different curing time (4 h to 3 days).

obtained from the UC test and $2s_u$, obtained from the LVS test. A correction factor, μ, is proposed as the ratio of unconfined compressive strength for the two times of un-drained shear strength and calculated based on the statistical analysis. The ratio, μ, of unconfined compressive strength, q_u to two times of un-drained shear strength, $2s_u$, was presented with the different cement contents in Fig. 7. The correction factor is shown in the following equation:

$$\mu = \frac{q_u}{2s_u} = 0.50 \pm 0.05 \tag{11}$$

where μ: q_u(UC test)/$2s_u$(LVS test).

It was found that the proposed correction factor is appropriate irrespective of water content, cement content, and curing time.

After correcting the strength by applying the correction factor given in Eq. (11), the comparison of strength mobilization at early stages of curing before and after applying the correction factor for four dredged clays used in this study is plotted in Figs. 2(b) to 5(b). From these figures, it can be seen that the variation of strength increment is consistent irrespective of the laboratory method used. Further, this correction factor can be applied to all cement-treated clays used in this experiment.

4.2. *Strength mobilization of cement-treated dredged clay with curing time*

All clays were mixed with more than 10% cement content (10%, 20%, and 30%) for the laboratory experiments conducted. However, the laboratory experiments were also conducted on Tokuyama clay samples with a cement content of less than 10% (2%, 4%, and 6%). Figs. 2–5 show the relationship between the strength ($2s_u$ or q_u) and curing times, ranging from 0.5 h to 90 days for four cement-treated dredged clays. The strength mobilization changed considerably before and after 3 days of curing for the treated-clays of more than 10% cement content. The strength mobilization within 3 days increased linearly with a high gradient in a log–log scale. The rate of strength mobilization decreased after 3 days. Therefore, the relationship between strength mobilization and curing time can be divided into two stages; the first stage is within 3 days after mixing and the second stage is after 3 days of mixing. For the tests conducted on clays with a cement content of less than 10%, the gradient varies with the cement content; the higher the cement content, the greater the gradient. It is worth noting that the strength mobilization of clay with a cement content of 2% did not changed considerably with curing time. It is considered that the effect of the hydration reaction, which can increase the strength, is small. Many researchers have focused on the equation of strength mobilization for the secondary stage of curing time, i.e. after 3 days. Therefore, the empirical equations available in the literature cannot be readily applied to determine the strength during the early stages of curing.

4.3. *Development of equation to predict the strength during the early stages of curing*

The development of equation for the prediction of strength at early stages is important for many civil engineering projects, which deals with the transport of cement treated soils. As mentioned in an earlier section, the strength increases linearly with time in a log–log scale and therefore, a linear relationship, as shown in Figs. 2(b) to 5(b), is proposed after the application of the correction factor. This can be explicitly presented as in Eqs. (12) and (12′).

$$\ln(q_u \text{ or } 2s_u) = \ln(a_1) + b_1 \ln(t) \tag{12}$$

$$q_u \text{ or } 2s_u = a_1 t^{b_1} \tag{12′}$$

where t is curing time, $2s_u$ or q_u is strength obtained by LVS and UC tests, respectively. a_1 is the strength at 1 h of curing time, and b_1 is the gradient of the graph drawn in the log–log scale. The coefficients, a_1 and b_1, were determined by a regression analysis conducted based on all data. It is well known that water content normalized by liquid limit, w_L, as shown in Eq. (13) can successfully be used as an index to analyze the properties of natural clays. In this study, the initial water content is varied when cement is added to the clay slurry. This index, w'/w_L, was correlated with a_1, the strength at 1 h of curing. The water content is calculated by the mass of water to the mass of solid particles of both soil and cement, as shown in Eq. (14).

$$w_L = \frac{m_w}{m_s} \tag{13}$$

$$w' = \frac{m_w}{m_s + m_c} \tag{14}$$

where m_s and m_c are the mass of soil and cement, respectively, and m_w is the mass of water.

In this study, different types of clays were used to study the effects on strength at 1 h a_1 with normalized water content, w'/w_L. Also, the effect on strength at 1 h a_1 with normalized water content was examined by varying cement contents for selected clay types. To find the relationship between strength at 1 h a_1 and normalized water content according to cement content, Tokuyama port clay was mixed with varying cement content, ranging from 2% to 20%. The same experimental procedure was conducted for the other clays collected from Mizushima, Hibiki, and Moji ports with a cement content varying from 10% to 20%. In addition, to compare the results, the same experimental procedure was adopted for the untreated clays of Mizushima, Hibiki, and Moji ports.

The un-drained shear strength varies with normalized water content for untreated dredged clay, as shown in Fig. 8. On the basis of these results, the un-drained shear strength of untreated dredged clay can be written with the normalized water content as shown in the following equations:

$$\ln(s_u) = 0.16 - 4.80 \ln\left(\frac{w'}{w_L}\right) \tag{15}$$

$$s_u = \exp(0.16)\left(\frac{w'}{w_L}\right)^{-4.8} = 1.17\left(\frac{w'}{w_L}\right)^{-4.8} \tag{15'}$$

Fig. 9 demonstrates the relationship between the strength at 1 h a_1 and water content normalized by liquid limit, w'/w_L, with varying cement content for Tokuyama port clay. To compare with the differences in the strength, $2s_u$, at 1 h of curing for un-treated clays, the strength at 1 h for untreated clays is calculated based on Eq. (15), and is also drawn as in a dashed line in Fig. 9. From the relationship as shown Fig. 9, the logarithm of strength at 1 h a_1 can be expressed with logarithm of normalized water content as given in the following equations:

$$\ln(a_1) = c_1 - c_2 \ln\left(\frac{w'}{w_L}\right) \tag{16}$$

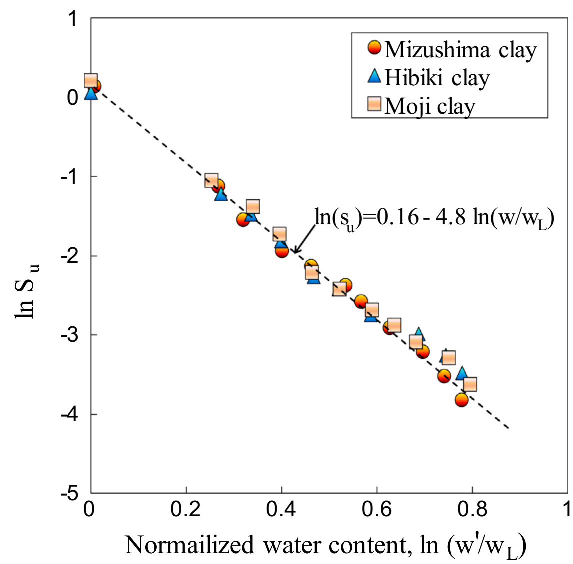

Fig. 8. Variation of un-drained shear strength to normalized water content for untreated clay.

$$a_1 = \exp(c_1)\left(\frac{w'}{w_L}\right)^{-c_2} \tag{16'}$$

where parameter c_1 is logarithm of strength, i.e. $\ln(a_1)$, when the initial water content is equal to the liquid limit. Parameter, c_2 is a gradient of the relationship between the strength and the normalized water content. The strength at 1 h a_1 increases with the cement content. Further analysis of the data reveals that the strength at 1 h a_1 is greater than that of untreated clay under the same normalized water content. Fig. 9(a) to (c) was drawn to elaborate the difference of strength respect to cement content. Three equations can be derived based on the cement content referring to Fig. 9(a) to (c) and are shown in the following equations:

$$a_1 = \exp(1.96)\left(\frac{w'}{w_L}\right)^{-4.80} \quad \text{cement content : } 2-4\% \tag{16.1}$$

$$a_1 = \exp(2.60)\left(\frac{w'}{w_L}\right)^{-4.80} \quad \text{cement content : } 6\% \tag{16.2}$$

$$a_1 = \exp(2.95)\left(\frac{w'}{w_L}\right)^{-4.80} \quad \text{cement content : } 10-20\% \tag{16.3}$$

Eqs. (16.1)–(16.3) were derived keeping c_2 as a constant value to 4.8, the gradient of the relationship between the strength and initial water content of untreated clay, regardless of cement content. It was found that the value of parameter, c_2, for each of cement-treated clays used in this study was also close to 4.8 and, hence this gradient was kept constant for the treated soils to allow for comparisons with the strength increment for untreated clay. Fig. 10 shows the variation of parameter, c_1, for different cement contents. It can be seen that the parameter c_1 gradually increases up to the cement content of 10% and then converges to a constant value. Fig. 11 illustrates the relationship between parameter, a_1, and normalized initial water content for all clay types for more than 10% of cement

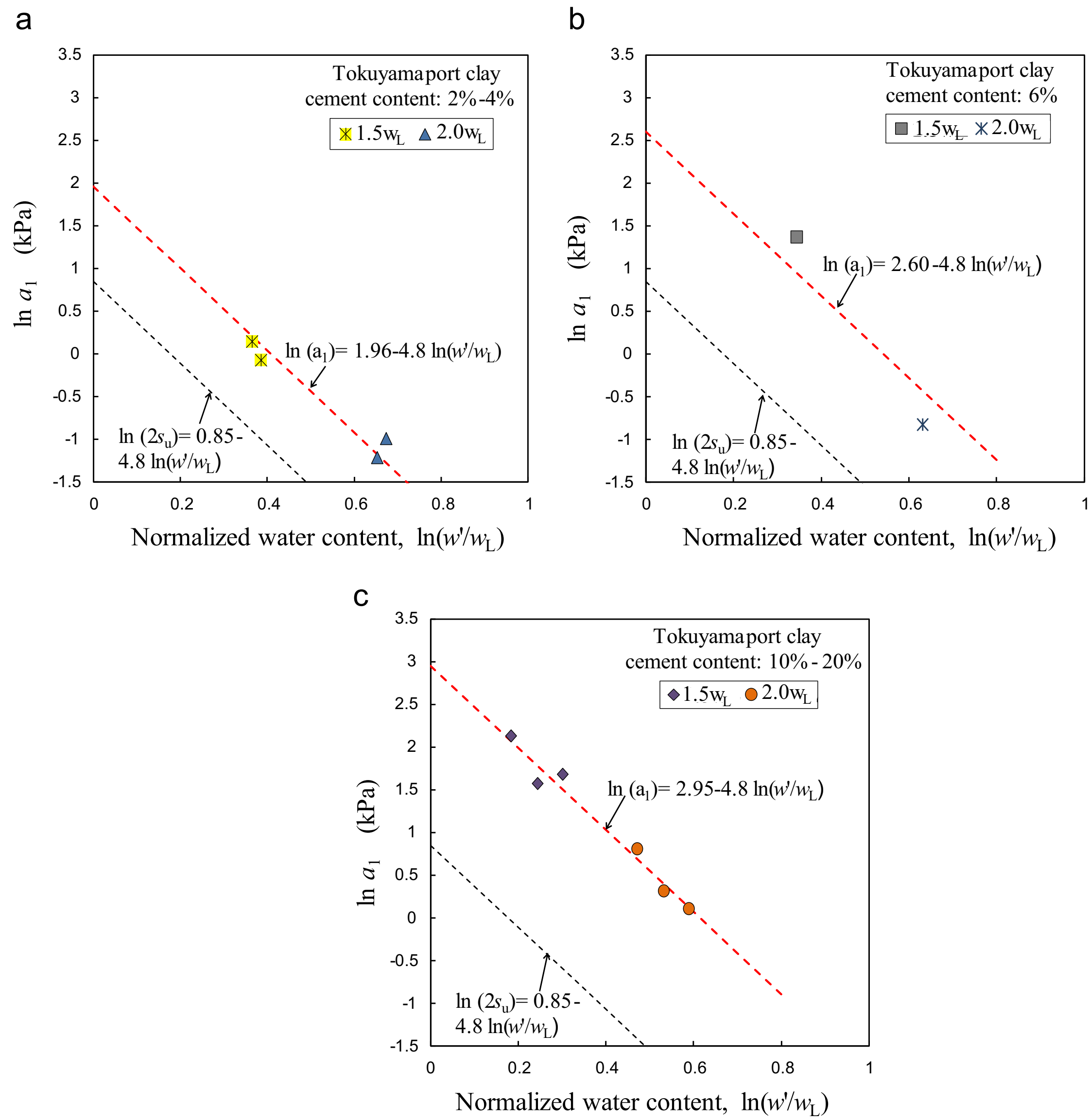

Fig. 9. Relationship between the strength of 1 h curing and normalized water content for different cement contents. (a) Cement content: 2–4%. (b) Cement content: 6%. (c) Cement content: 10–20%.

content. As shown Fig. 11, the strength at 1 h a_1 varies with normalized water content and is different depending on the clay type. The equation of parameter, a_1, and the parameters c_1 and c_2, can be presented for each of clay type, as shown in Table 3. It can be seen that the parameter c_1, differs with clay types. In order to present a unique equation, the strength at 1 h a_1 of all clay types was plotted with normalized water content. The strength at 1 h for all clays is derived in Fig. 11 irrespective of clay types as shown in the following equation:

$$a_1 = \exp(3.00)\left(\frac{w'}{w_L}\right)^{-4.8} \quad \text{All studied clay types} \tag{16.4}$$

Tsuchida et al. (2002) have used the index of specific volume ratio to evaluate the compressive characteristics of marine clays as given in the following equation:

$$I_v = \frac{\ln v'}{\ln v_L} \tag{17}$$

In this study, the specific volume ratio index, I_v, is defined as the ratio of logarithm specific volume ratio (include volume of soil and water only) to the logarithm of specific volume ratio, which includes the volume of cement in addition to the volume of soil and water. The specific volume ratio varies when cement is added to clay slurry. The former is shown in Eq. (18) and the latter is shown in Eq. (19).

$$v_L = \frac{v_s + v_w}{v_s} \tag{18}$$

$$v' = \frac{v_s + v_c + v_w}{v_s + v_c} \tag{19}$$

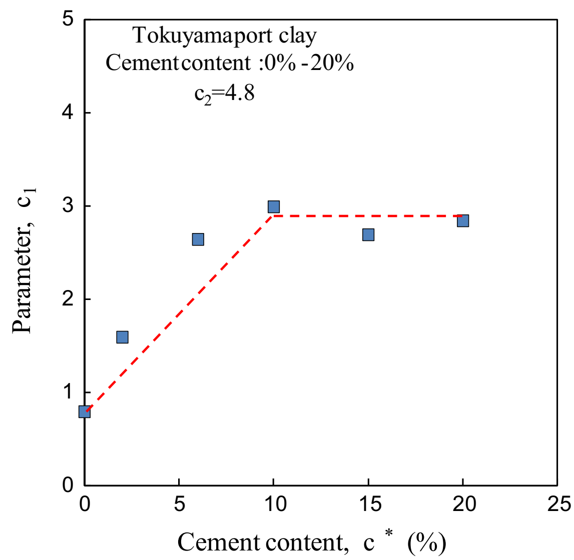

Fig. 10. Variation of parameter c_1, with different cement contents.

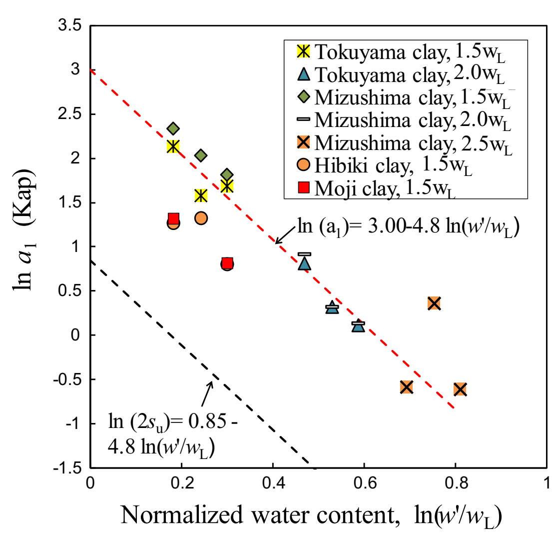

Fig. 11. Relationship between strength for 1 h curing and normalized water content for all clay types.

Table 3
Coefficient a_1 with normalized water content for different clay types.

Site	Liquid limit, w_L (%)	Coefficient a_1, $a_1 = \exp(c_1)(w'/w_L)^{-c_2}$	c_1	c_2
Tokuyama port	107.6	$= \exp(2.95)(w'/w_L)^{-4.80}$	2.95	4.80
Mizushima port	65.3	$= \exp(3.18)(w'/w_L)^{-4.80}$	3.18	4.80
Hibiki port	61.2	$= \exp(2.30)(w'/w_L)^{-4.80}$	2.30	4.80
Moji port	89.5	$= \exp(2.22)(w'/w_L)^{-4.80}$	2.22	4.80

where, v_s and v_c are volume of soil and cement, respectively, and v_w is the volume of water.

The effect on parameter, a_1, with normalized specific volume ratio was examined for different cement contents for selected clay types. To determine the relationship between parameter, a_1, and the normalized specific volume ratio according to the cement content, Tokuyama port clay was mixed with cement, with contents ranging from 2% to 20%. However, the cement content of the other clays collected from Mizushima, Hibiki, and Moji ports varied from 10% to 20%. For comparison purposes, the same experimental procedure was adopted for the untreated clays of Mizushima, Hibiki, and Moji ports. The relationship between the un-drained shear strength and normalized specific volume ratio for untreated dredged clay is shown in Fig. 12. The un-drained shear strength of untreated dredged clay can be written with normalized specific volume ratio as shown in the following equations:

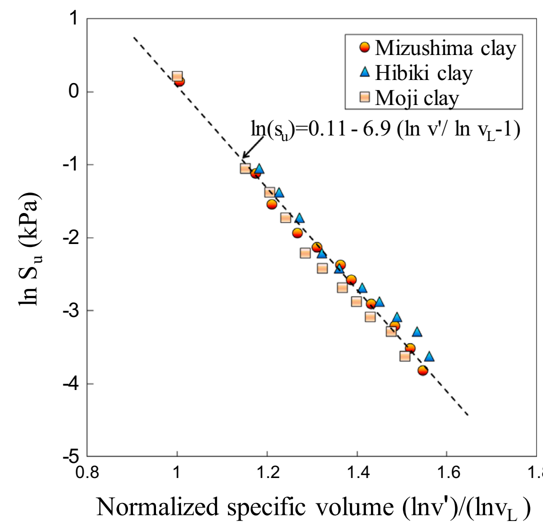

Fig. 12. Relationship between shear strength without cement and normalized volume ratio.

$$\ln(s_u) = 0.11 - 6.90(I_\nu - 1) \tag{20}$$

$$s_u = \exp(0.11)v^{-6.9/\ln(v_L)} = 1.12v^{-6.9/\ln(v_L)} \tag{20'}$$

where, $n = d_2/\ln v_L$, Fig. 13 shows the relationship between the parameter, a_1, and specific volume ratio normalized by liquid limit, v'/v_L, with varying cement content for Tokuyama port clay. To compare with the differences in the strength, $2s_u$, at 1 h of curing for un-treated clays, the strength at 1 h for untreated clays was calculated based on Eq. (20), and is represented as a dashed line in Fig. 13. From this relationship, the logarithm of parameter, a_1, can be expressed with logarithm of specific volume ratio, as shown in the following equations:

$$\ln(a_1) = d_1 - d_2(I_\nu - 1) \tag{21}$$

$$a_1 = \exp(d_1 + d_2)v'^{-n} \tag{21'}$$

where, $n = d_2/\ln v_L$, parameter d_1 is logarithm of strength, i.e. $\ln(a_1)$, when the specific volume ratio is equal to liquid limit. Parameter, d_2 is the gradient of the relationship between the strength and the normalized specific volume ratio. The parameter, a_1, increases with the cement content. Further analysis of the data reveals that the parameter, a_1, is greater than that of untreated clay under the same normalized specific volume ratio. Figs. 13(a) to (c) was drawn to elaborate the difference of

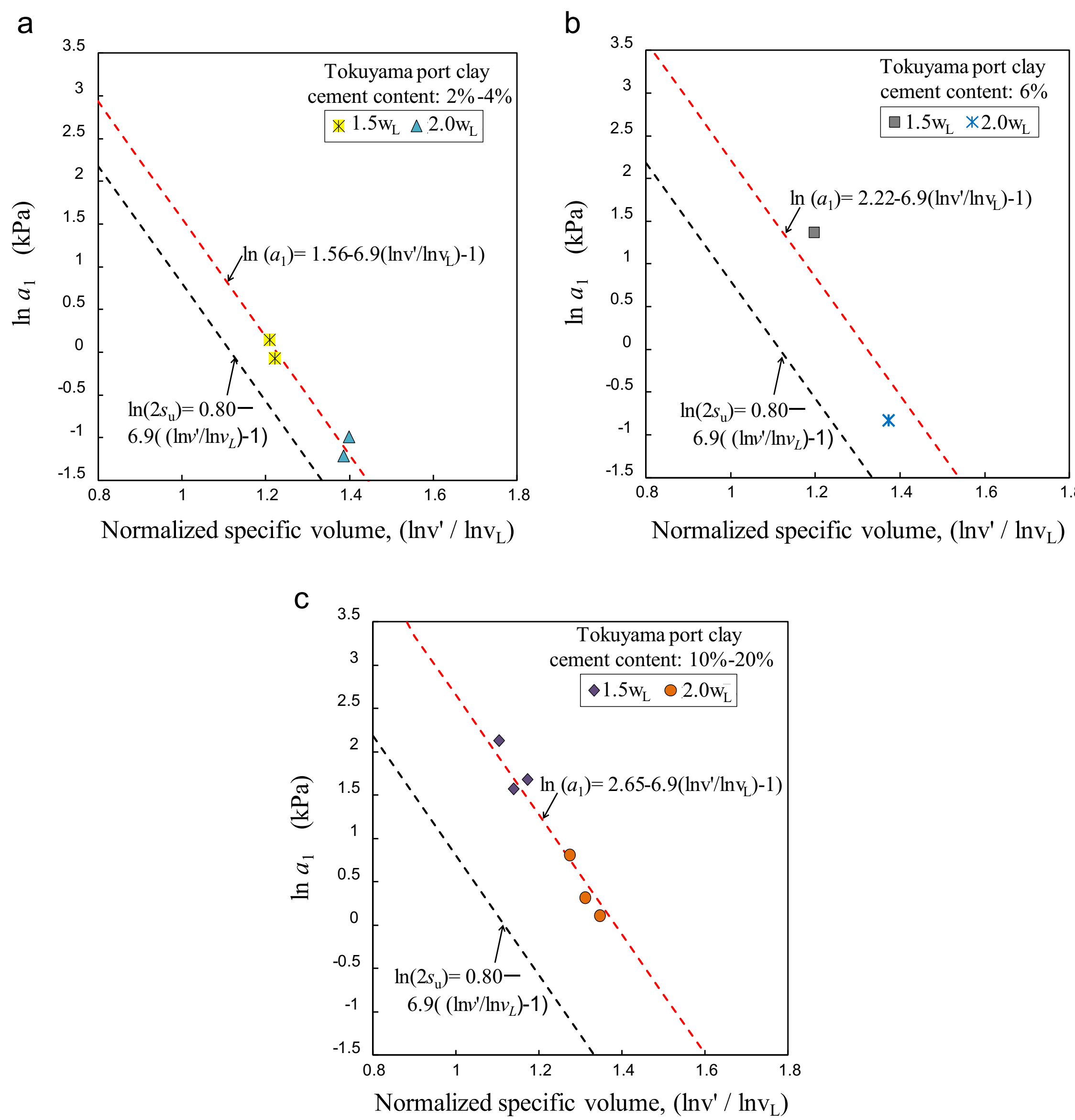

Fig. 13. Relationship between strength for 1 h curing and normalized specific volume ratio for different cement contents. (a) Cement content: 2–4%. (b) Cement content: 6%. (c) Cement content: 10%–20%.

strength respect to cement content. Three equations can be derived based on the cement content referring to Figs. 13(a) to (c) and are shown in the following equations:

$$a_1 = \exp(1.56 + 6.90)\nu'^{-n} \quad \text{cement content}: \; 2-4\% \tag{22.1}$$

$$a_1 = \exp(2.22 + 6.90)\nu'^{-n} \quad \text{cement content}: \; 6\% \tag{22.2}$$

$$a_1 = \exp(2.65 + 6.90)\nu'^{-n} \quad \text{cement content}: 10-20\% \tag{22.3}$$

where, $n = d_2/\ln v_L$

Eqs. (22.1)–(22.3) were derived keeping the value of d_2 constant at 6.9, the gradient of the relationship between the strength and specific volume ratio of untreated clay, regardless of cement content. In addition, it was found that the values of parameter, d_2, for all clays used in this investigation, was close to 6.9, and hence this gradient was kept constant for the treated soils to allow the strength increment for untreated clay to be compared. Fig. 14 shows the variation of parameter d_1 for various cement contents. The parameter, d_1, gradually increases up to the cement content of 10% and then converges to a constant value. Fig. 15 illustrates the relationship between parameter, a_1, and normalized specific volume ratio for all clay types for more than 10% of cement content. It can be seen that the parameter, a_1, varies with normalized specific volume ratio and is different with clay type. The equations of parameter, a_1, and the parameters d_1 and d_2, can be presented for each clay types, as shown in Table 4. The parameter, d_1, is found to be different for all clay types. In order to develop a unique equation, the parameter, a_1, was plotted with normalized specific volume ratio for all clay types. The developed equation is shown Eq. (22.4) and is illustrated in Fig. 15.

$$a_1 = \exp(2.90 + 6.90)\nu'^{-n} \quad \text{All studied clay types} \tag{22.4}$$

It can be seen that the strength at 1 h a_1 can be developed due to reduction of free water content as a result of adding

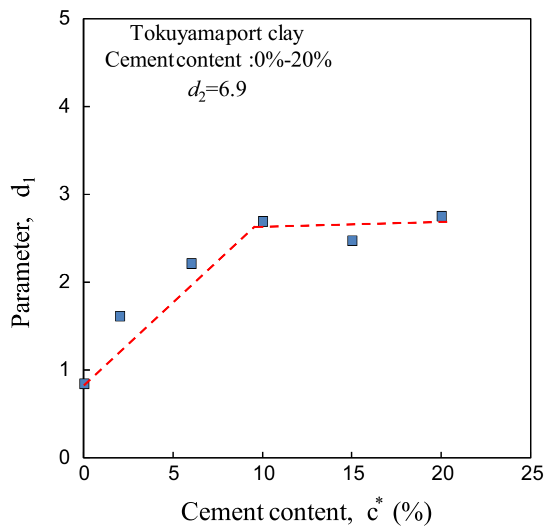

Fig. 14. Variation of parameter d_1, with different cement contents.

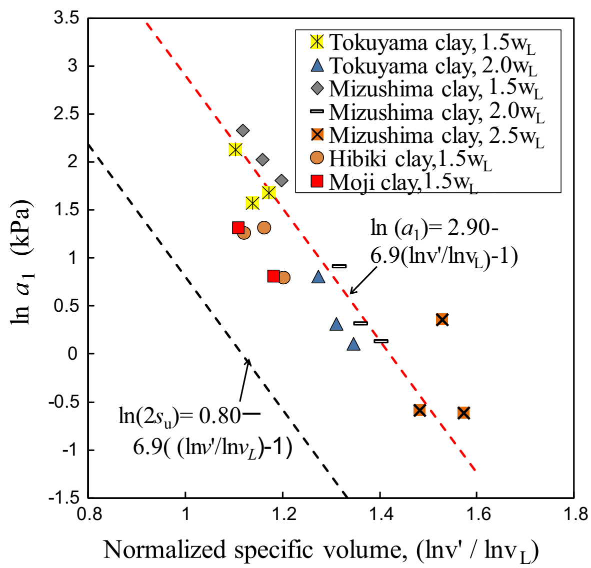

Fig. 15. Relationship between strength for 1 h curing and normalized specific volume ratio for all clay types.

Table 4
Coefficient a_1 with normalized specific volume ratio for different clay types.

Site	Liquid limit, w_L (%)	Coefficient a_1, $a_1=\exp(d_1+d_2)\nu'^{-n}$, where, $n=d_2/\ln\nu_L$	d_1	d_2
Tokuyama port	107.6	$=\exp(2.65+6.90)\nu'^{-n}$	2.65	6.90
Mizushima port	65.3	$=\exp(3.15+6.90)\nu'^{-n}$	3.15	6.90
Hibiki port	61.2	$=\exp(2.24+6.90)\nu'^{-n}$	2.24	6.90
Moji port	89.5	$=\exp(2.08+6.90)\nu'^{-n}$	2.08	6.90

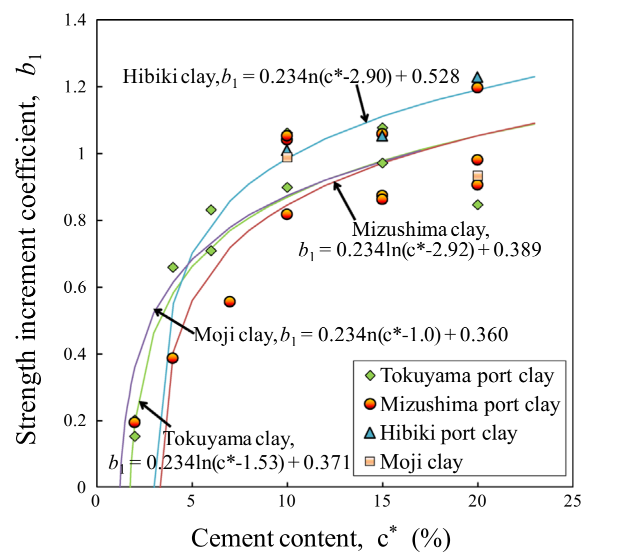

Fig. 16. Strength increment coefficient b_1, with different clay types in initial stages of curing time.

cement content. Since the above formula were derived based on 1 h curing time, the effect of hydration of cement cannot be successfully explained in this study. Therefore, to study the hydration and pozzolanic effect at early stages of curing, more data and analyses are required.

As shown in Eq. (12), the strength increment coefficient, b_1, (gradient of the logarithm of the curing time and the logarithm of the strength in the log–log scale) was correlated with cement content. Fig. 16 shows the relationship between strength increment coefficient and cement content with different clay types at early stages of curing time. In addition, to determine the value of strength increment coefficient, b_1, in more detail, the experiment was additionally carried out with small cement content, 2%, 4%, and 7% for clays sample of Mizushima port. As shown in Fig. 16, the strength increment parameter, b_1, is close to zero when the cement content, c^*, is very small, 2%. Besides, that, the strength increment coefficient b_1, increased with the cement content. The equation on the strength increment coefficient, b_1, can be expressed as shown in the following equation:

$$b_1=e_1\ln\left(c^*-e_2\right)+e_3 \tag{23}$$

where parameters, e_1 and e_3, are strength increment parameters at early stages of curing, and a parameter, e_2, is the minimum cement content for strength mobilization. The parameter, e_1, was kept constant to 0.234. The equations of strength increment coefficient, b_1, and the parameters, e_1, e_2 and e_3, can be presented for each of clay type as shown in Table 5.

The proposed Eqs. (16) and (21) based on normalized water content and normalized specific volume ratio, respectively, can be used to estimate the parameter, a_1, which means strength at 1 h immediately after mixing. In addition, strength increment coefficient, b_1, is proposed with cement content at early stages of curing time, within 3 days. Eq. (24) is obtained by substituting a_1 and b_1 into Eq. (12).

$$q_u=\exp(c_1)\left(\frac{w'}{w_L}\right)^{-c_2}\times t^{e_1\ \ln(c^*-e_2)+e_3} \tag{24}$$

Table 5
Coefficient b_1 with cement content for different clay types.

Site	Liquid limit, w_L (%)	Coefficient b_1, $b_1 = e_1 \ln(c^* - e_2) + e_3$	e_1	e_2	e_3
Tokuyama port	107.6	$= 0.234 \ln(c^* - 1.53) + 0.371$	0.234	1.53	0.371
Mizushima port	65.3	$= 0.234 \ln(c^* - 2.92) + 0.389$	0.234	2.92	0.389
Hibiki port	61.2	$= 0.234 \ln(c^* - 2.90) + 0.528$	0.234	2.90	0.528
Moji port	89.5	$= 0.234 \ln(c^* - 1.00) + 0.360$	0.234	1.00	0.360

$$q_u = \exp(c_1) \times 72^{e_3} \left(c^* - e_2\right)^{e_1 \ln t} \left(\frac{w'}{w_L}\right)^{-c_2} \quad (24')$$

where, c_1 and c_2 are strength parameters normalized to water content related to 1 h curing after mixing with cement. The parameter e_1 is constant, 0.234 and the parameter e_2 is minimum cement content to develop strength. Parameter e_3 is the strength increment coefficient within 3 days.

when $t = 72$ h, Eq. (24′) becomes

$$q_u = \exp(c_1) \times 72^{e_3} \left(c^* - e_2\right)^{e_1 \ln t} \left(\frac{w'}{w_L}\right)^{-c_2} \quad (24'')$$

Subsequently, Eq. (25) can be developed based on Eqs. (12) and (23).

$$q_u = \exp(d_1 + d_2)\nu'^{-n} \times t^{e_1 \ln(c^* - e_2) + e_3} \quad (25)$$

where $n = d_2/\ln v_L$, d_1 and d_2 are strength parameters normalized to specific volume ratio related to 1 h curing after mixing with cement. The parameter e_1 is constant, 0.234 and the parameter e_2 is the minimum cement content to develop the strength. Parameter e_3 is the strength increment coefficient within 3 days. Eq. (25) can be transformed as shown in the following equation:

$$q_u = \exp(d_1 + d_2)\nu'^{-n} \times t^{e_3} \left(c^* - e_2\right)^{e_1 \ln t} \quad (25')$$

when $t = 72$ h, Eq. (25′) becomes Eq. (25″).

$$q_u = \exp(d_1 + d_2) \times 72^{e_3} \left(c^* - e_2\right)\nu'^{-n} \quad (25'')$$

Eq. (25″) is the same form as Eq. (7), which was empirically proposed by Tsuchida and Tang (2012). This is the reason $e_1 = 0.234$ was used as a constant.

$$q_u = k_c^* \left(c^* - c_0^*\right) Y^N \quad (7)$$

$$k_c^* = \exp(d_1 + d_2) 72^{e_3} \quad (26)$$

where, $N = n = d_2/\ln v_L$.

Eq. (26) shows that the coefficient of strength increment k_c^* is determined by 3 parameters d_1, d_2 and e_3, where d_1 and d_2 are strength parameter immediately after mixing with cement and e_3 is the parameter strength increase with time. According to Tsuchida and Tang (2012), the range of N of cement treated marine clays was from 3.9 to 4.9. However in this study, the values of n were calculated by $d_2/\ln v_L$ and ranged from 5.9 to 6.9. Further studies will be necessary to find the reason for this difference. Eqs. (24) and (25) are based on the combination effect of water content, cement content, volume ratio, and curing time for marine dredged clays.

5. Discussion

Two equations, Eqs. (24) and (25), were proposed to determine the strength of cement treated clay at early stages of curing for four dredged clays collected from Tokuyama, Mizushima, Hibiki and Moji ports. The value of the parameters, c_2 and d_2, are close to the gradient of untreated clay for the relationship strength at 1 h of curing and the normalized initial water content and normalized specific volume ratio and were kept at a constant value, 4.8 and 6.9, respectively, for ease of comparing the strength increments with untreated clay. The parameters, c_1 and d_1, are determined by a regression analysis after keeping the gradient at a constant value. The parameters, e_1, e_2 and e_3, are determined by the $b_1 - (c^* - e_2)$ relationship. The $b_1 -$ $(c^* - e_2)$ relationship was obtained assuming the value of e_2, and the coefficient of determination R^2 was calculated. The value of e_2 was determined when the coefficient of determination R^2 was at its maximum. The strength calculated by Eqs. (24) and (25), in which the correction factor was applied to the strength, $2s_u$, measured from LVS test, and measured strength for each of clays are shown in Figs. 17–20. It was observed that the measured strength agreed well with the calculated strength for most of the data. However, some data showed considerable variations of up to twice the measured value. The mean absolute percent error (MAPE) when determining the strength based on normalized initial water content (Eq. (24)) for Tokuyama, Mizushima, Hibiki and Moji clays are 32.83%, 32.36%, 13.07% and 38.19%, respectively. The MAPE in determining the strength based on normalized specific volume ratio (Eq. (25)) for Tokuyama, Mizushima, Hibiki and Moji clays are 28.01%, 34.36%, 12.57% and 37.15%, respectively. The coefficient a_1 can be determined by using two indices, the normalized initial water content and the normalized specific volume ratio, whereas, the coefficient b_1 is determined only by the cement content. Accordingly, the coefficient a_1 calculated by the normalized initial water content and normalized specific volume ratio can be used for determining the accuracy of strength estimation when considering the usefulness of the formulas proposed in this study. The coefficient of determination R^2 based on normalized specific volume is higher than that based on normalized initial water content except for Mizushima port clay. In the case of Mizushima port clay, the R^2 based on the normalized initial water content and the normalized specific volume ratio are 0.899 and 0.892, respectively. Therefore, it was found that the accuracy of proposed formulas is determined by correlating the coefficient a_1 (strength at 1 h of curing). In this study, the coefficient a_1 obtained based on the normalized specific volume ratio is better than that obtained based on normalized water content except for Mizushima port clay.

c_1, c_2, d_1, and d_2 are significant parameters, which determine the strength at 1 h a_1. The parameters c_1 and d_1 change with cement content. The parameters c_1 and d_1 gradually increase

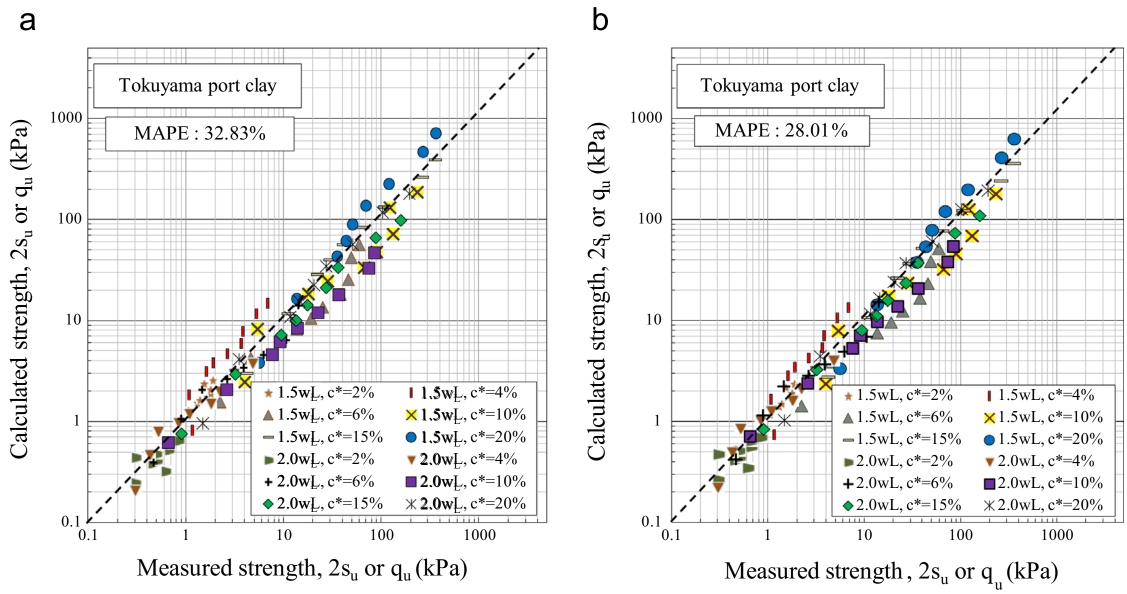

Fig. 17. Comparison of calculated strength and measured strength for Tokuyama port clay in initial stages of curing time. (a) Normalized water content index, w'/w_L. (b) Normalized specific volume ratio index, v'/v_L.

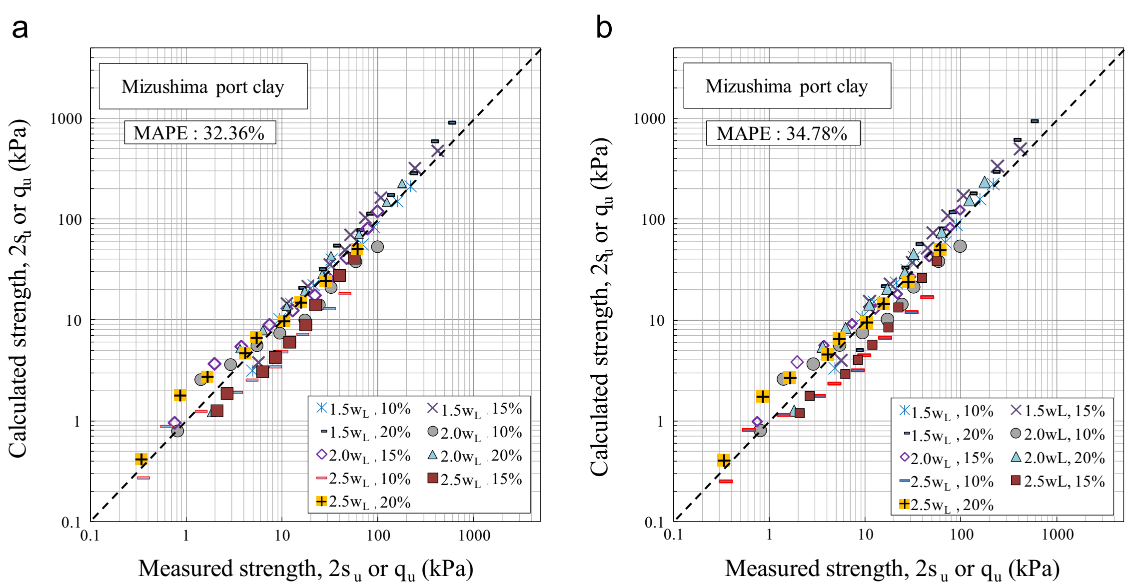

Fig. 18. Comparison of calculated strength and measured strength for Mizushima port clay in initial stages of curing time. (a) Normalized water content index, w'/w_L. (b) Normalized specific volume ratio index, v'/v_L.

up to a cement content of 10% and then converge to a constant value. When the cement content is higher than 10%, strength can be determined based on the constant values of c_1 and d_1. These two parameters are mostly based on the addition of solid content in cement treated soil.

The proposed parameters, c_1, c_2, d_1 and d_2, are initial strength coefficients determining the strength at 1 h of curing after mixing with cement. The parameter, e_1, is the initial strength increment coefficient, 0.234. The parameter, e_2, is the minimum cement content for strength increment. The parameter, e_3, is the coefficient indicating the strength increment within 72 h of curing. The parameter, c_1, ranges from 2.22 to 3.18. In addition, the parameter, d_1, includes the range from 2.08 to 3.15. In cases of parameter, e_2, 1.00% to 2.90% is included as the range. Lastly, the parameter, e_3, ranges from 0.360 to 0.528. It was shown that the proposed parameters, c_1, c_2, d_1, d_2, e_1, e_2, and e_3 within 72 h of curing were not correlated with any specific physical properties, not the liquid limit, plastic limit, plasticity index, ignition loss, or particle density. Fig. 21 and Tables 3–5 show the parameters, c_1, c_2, d_1, d_2, e_1, e_2, and e_3, varies with the liquid limit for the four cement-treated clays. In Fig. 21(a), the parameter, c_1 is 2.66 on average in the liquid limit ranging from 61.2% to 107.6% and the standard deviation is 0.41. Besides that, the average value

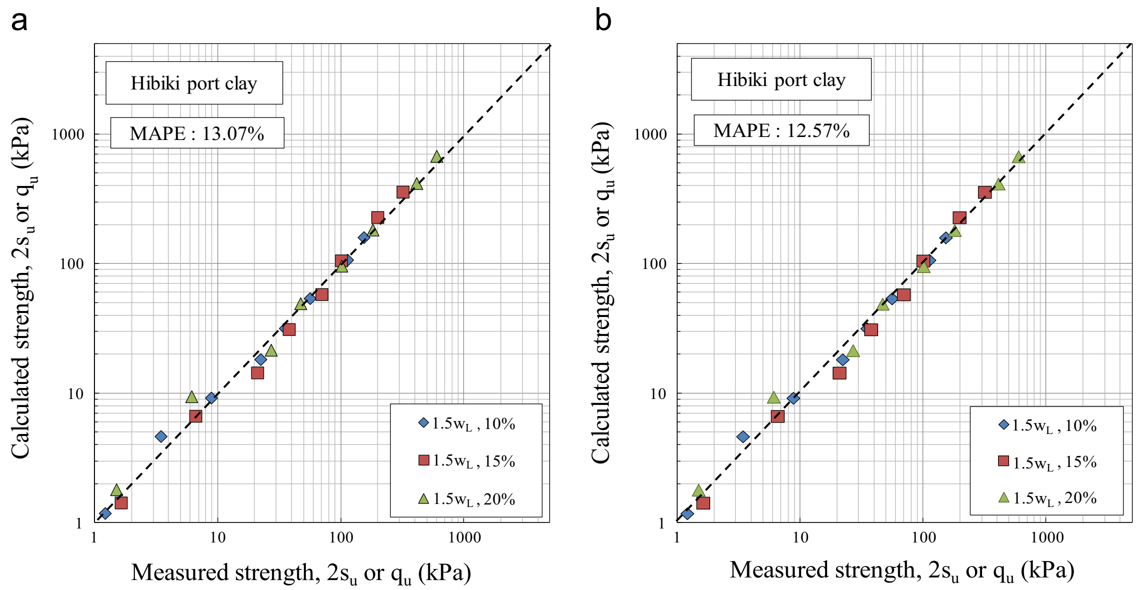

Fig. 19. Comparison of calculated strength and measured strength for Hibiki port clay in initial stages of curing time. (a) Normalized water content index, w'/w_L. (b) Normalized specific volume ratio index, v'/v_L.

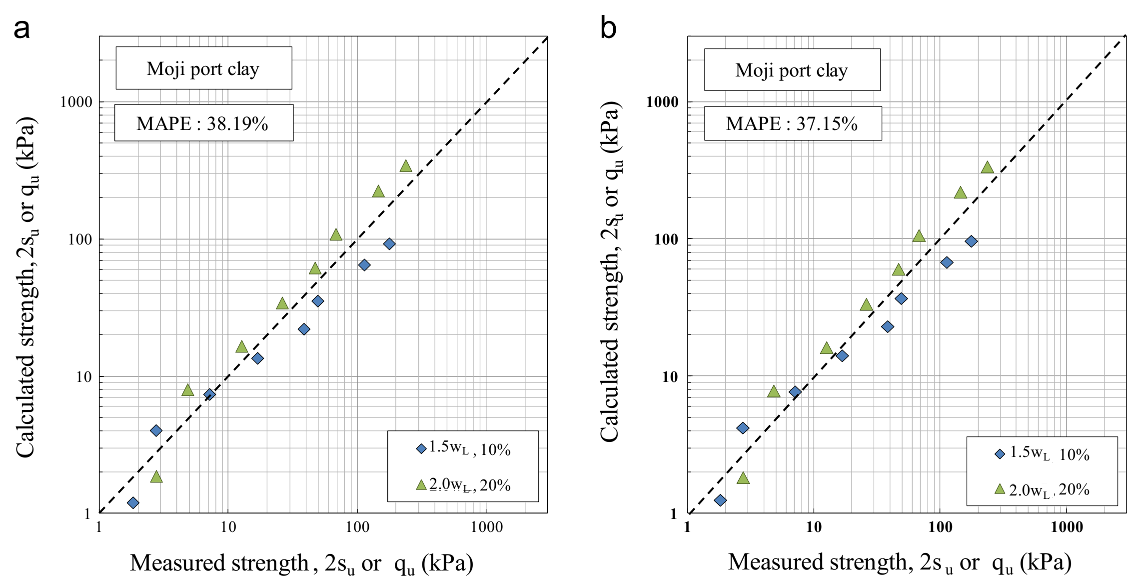

Fig. 20. Comparison of calculated strength and measured strength for Moji port clay in initial stages of curing time. (a) Normalized water content index, w'/w_L. (b) Normalized specific volume ratio index, v'/v_L.

of parameter d_1 shows is 2.53 in the liquid limit ranging from 61.2% to 107.6% with a standard deviation of 0.41. In addition, it was found that the behavior of parameters, d_1 and d_2, with physical properties including the liquid limit, plastic limit and ignition loss were similar to parameters, c_1 and c_2. The average value of parameters, e_2 and e_3, which significantly affect the strength increment, were 0.61 and 0.341 and the standard deviation varied between 0.45 and 0.07 in a range of liquid limits from 61.2% to 107.6%, respectively.

This study focused on understanding the strength mobilization in cement treated clays during the early stages of curing. The design water contents ranged from 91.9% to 215.2%, and the liquid limit ranged from 61.2% to 107.6% for the clays investigated. The cement content varied from 2% to 20%. In addition, it should be noted that the clays used in this study are not terrestrial clay but marine clays dredged from the seabed. Using the developed equations, the strength of cement treated clays can be estimated specially for the range mentioned above. However, to widely use the proposed equation, more experiments for various types of clay, including the physical properties, organic content and mineralogy, are required.

6. Conclusions

In this study, four dredged clays with different water contents and cement contents collected from Tokuyama, Mizushima, Hibiki and Moji ports were investigated. Based on the study, two equations were proposed to determine the

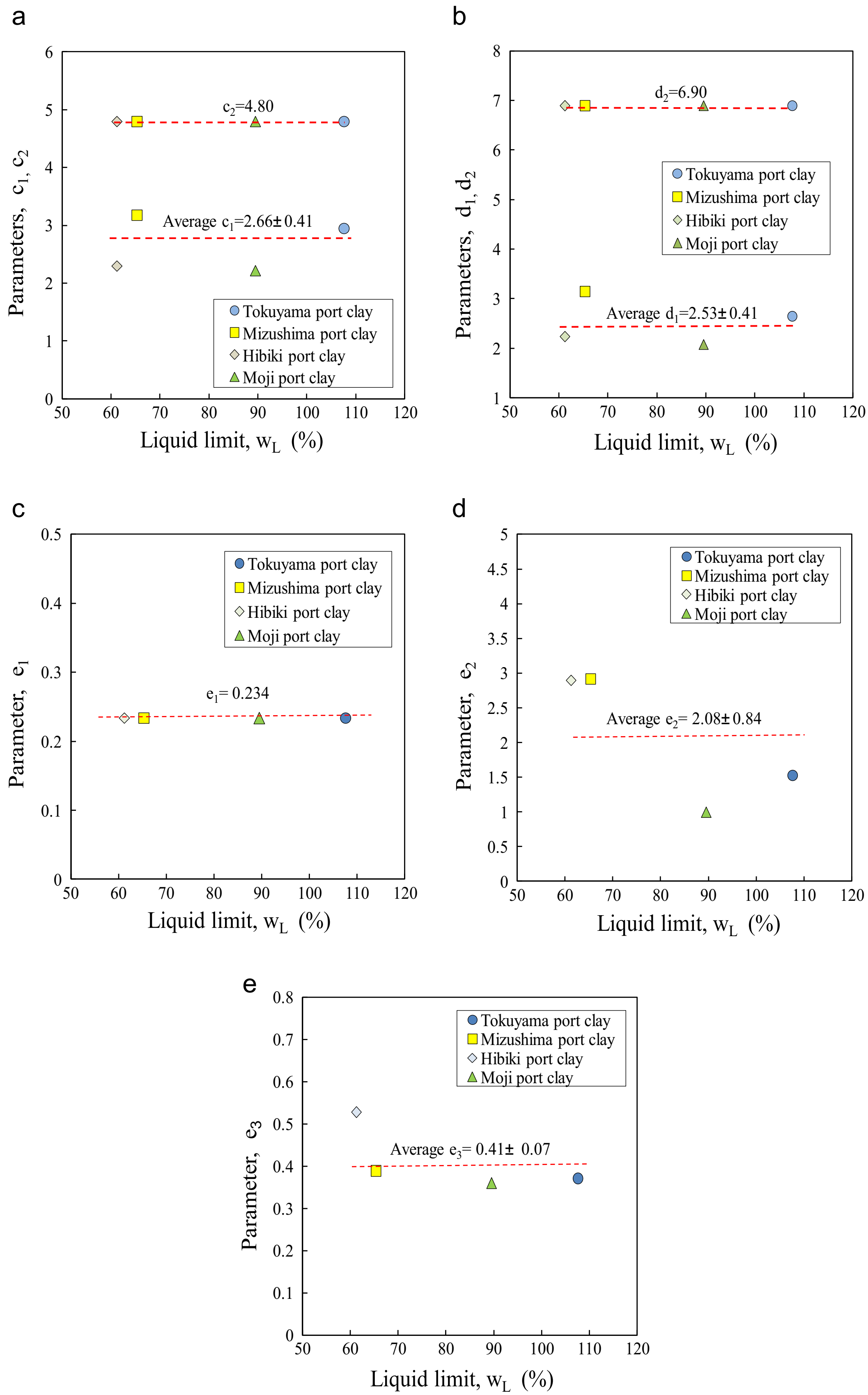

Fig. 21. Relationship between parameters and liquid limit for cement-treated clays. (a) Parameters, c_1 and c_2. (b) Parameters, d_1 and d_2. (c) Parameter, e_1. (d) Parameter, e_2. (e) Parameter, e_3.

strength of cement treated clay at the early stages of curing, in times ranging from 0.5 h to 72 h. In addition, the strength calculated from proposed equations was compared with the strength measured in laboratory vane shear tests and unconfined compression tests. Based on these analyses and their results, the following conclusions can be drawn.

(1) The strength mobilization in cement-treated dredged clays showed clear tendency depending on the curing time. Therefore, the relationship between strength mobilization and curing time can be divided into two stages; the first stage (within 3 days) and second stage (after 3 days).
(2) It was shown that the strength, $2s_u$, obtained from LVS test is greater than that of unconfined compression test. This may be due to the mode of failure according experiment method and the disturbance occurred when the sample removed from the summit mold. The correction factor was proposed based on the data and is illustrated below.

$$\mu = \frac{q_u}{2s_u} = 0.50 \pm 0.05$$

where μ: q_u(UC test)/$2s_u$(LVS test).
(3) Two indices, normalized water content w'/w_L, and normalized specific volume ratio $\ln v'/\ln v_L$, can be used to evaluate the strength at 1 h a_1, of cement treated dredged clays. In addition, the coefficient a_1 is used for determining the accuracy of strength estimation for proposed formulas. In this study, the strength at 1 h a_1 obtained based on normalized specific volume ratio is better than that based on normalized water content except in the case of Mizushima clay.
(4) Two equations were proposed to estimate the strength of cement treated dredged clays as follows.

$$q_u = \exp(c_1)\left(\frac{w'}{w_L}\right)^{-c_2} \times t^{e_1 \ln(c^* - e_2) + e_3}$$

$$\left(\text{Normalized initial water content}, \ \frac{w'}{w_L}\right)$$

$$q_u = \exp(d_1 + d_2)\nu'^{-n} \times t^{e_1 \ln(c^* - e_2) + e_3}$$

$$\left(\text{Normalized specific volume ratio}, \ \frac{\upsilon'}{\upsilon_L}\right)$$

where, $n = d_2 / \ln v_L$.

The strength calculated from the proposed equations were compared with the measured data and good agreement was found for the strength values. Therefore, these equations can be successfully used to estimate strength of cement treated clays for the early stages of curing.

$$q_u = \exp(d_1 + d_2) \times 72^{e_3}\left(c^* - e_2\right)\nu^{-n} \quad (25'')$$

$$q_u = k_c^*\left(c^* - c_0^*\right)Y^N \quad (7)$$

Eq. (25) of normalized specific volume ratio can be transformed as Eq. (25″) when the curing time is 72 h. Eq. (25″) is the same form as Eq. (7), which was empirically proposed by Tsuchida and Tang (2012).

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