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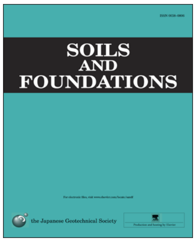

Estimation of compressive strength of cement-treated marine clays with different initial water contents

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Abstract

A formula to estimate unconfined compressive strength of cement-treated marine clays is proposed. The formula has a form similar to the gel–space ratio theory. In the proposed formula, the strength of cement-treated soil is given by volumetric solid content, strength increase coefficient due to cement, exponential parameter *N* representing the effect of the void structure of soil and cement content in respect to the solid material of soil. The formula was adapted to the results of laboratory strength tests of cement-treated soils made of six dredged marine clays with different levels of initial water content. The strengths estimated by the proposed formula agreed with the measured strengths fairly well, using the parameter $N=3.5$–4.6. The formula was applied to the strength estimate of foam- and bead-treated soils made from dredged marine clay, using the parameter $N=2.1$–2.5. The applicability of the proposed formula was examined with the results of strength tests carried out for the design of cement-treated soil for the construction of D runway at Tokyo's Haneda Airport. Seven samples collected in the construction sites were mixed with different amounts of cement and the different levels of initial water content. On fitting the proposed formula to the results of all the data, the proposed formula estimates the measured strength well. On comparing the estimates with those using a conventional formula based on the water–cement ratio, the proposed formula generated better-fit estimates.

Keywords: Cement-treated soil; Marine clay; Unconfined compressive strength; Dredged soil; Port and harbor

1. Introduction

With rapid development and growing industrial and human settlement in coastal areas, there is rising demand for raw materials for coastal development projects. These materials are increasingly difficult to supply. At the same time, there is a need to re-use or dispose of large quantities of dredged soils that are generated in port and navigation dredging works (Port and Bureau, 2006). One treatment process that has been widely used to improve soft clayey soils is the cement mixing method. In 2001–2002, 7 million m^3 of cement-treated soil, made by mixing clay dredged in Nagoya Port with cement slurry, was used as filling material for the Central Japan International Airport (Satoh, 2003). In the expansion of Haneda Airport, completed in 2010, some 49 million m^3 of dredged soils from the navigation channel of Tokyo port were used as filling material, after being mixed with cement slurry by pneumatic mixing (Iba et al., 2009; Watanabe et al., 2009). In addition, nearly 8 million m^3 of dredged clay was mixed with cement and air-foam to create a foamed lightweight soil (Watabe and Noguchi, 2011). Dredged soft clay is also used as an

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intermediate protection layer for cut-off sheets in offshore disposal structures (Watabe et al., 2000, 2001), suggesting that there are potential benefits of using cement-treated dredged soils. Kasama et al. (2006, 2007) conducted a series of high-pressure dewatering experiments on cement-treated soils and reported that dewatered soils may show large compressive strengths nearly equivalent to that of concrete. This means that cement-treated soils are not limited to geomaterial uses but could also be used as tiles or bricks. Udaka et al. (2013) and Tsuchida et al. (2014) reported that after proper preconsolidation, dredged clay with a small amount of added cement shows compressibility behavior similarly to undisturbed natural clay, which has bonding structure formed during long years of sedimentation. Although cement treatment techniques are used for many purposes, in general, knowledge of strength-developing mechanisms is not extensive, and the cement industry has not seen major progress in the design of mixtures for cement-treated soil for nearly 40 years (Japan Cement Association, 2012).

In practical engineering, it is desirable to know the amount of cement required for the improvement of a particular soil before implementing the treatment process. A series of laboratory tests is performed to determine the amount of cement required in a mix in order to achieve the expected strength.

Unconfined compressive strength q_u of cement-treated soil is easily related with water content w of the original soft soil and cement content C in volumetric expression. Some approaches can be quoted as below (Miyazaki, 2003; Miyazaki et al., 2003).

$$q_u = a\,w + b \tag{1}$$

$$q_u = a/\left(W/C\right)^x + b \tag{2}$$

$$q_u = a\,C/w^x + b \tag{3}$$

Eq. (1) is a linear relationship between unconfined compressive strength and water content. Whenever cement content is changed, the parameters a and b involved in Eq. (1) have to be amended. Such a correlation is regarded as of no practical use. Eq. (2) is based on the idea of estimating compressive strength by means of the water–cement ratio, (W/C). Eq. (3) expresses that unconfined compressive strength increases with cement content and decreases with water content in an exponential form. Kida et al. (1977) introduced a modified water–cement ratio $(W/C)'$ where the waster was defined as that being subtracted under the pF-value of less than 3 from the treated soil. In Eqs. (2) and (3), water content and cement content are regarded as two factors governing unconfined compressive strength, but the amount of soil particles is not reflected explicitly. Lee et al. (2005) studied the strength and modulus of marine clay–cement mixture with high cement content and concluded that water–cement ratio alone cannot account for the variation in the strength and the influence of the soil–cement ratio must be also included. Recently, the mechanical properties of cement-treated clays with high water content have been extensively investigated by Horpibulsuk (2001) and Horpibulsuk et al. (2003, 2004, 2011) with the approach using the water–cement ratio as shown in Eq. (2). Sasanian and Newson (2014) carried out the extensive parametric study on the behavior of cement-treated clay and showed that the higher the activity number, the higher the strength of the clay at a given cement–water ratio.

Based on many laboratory tests of saturated dredged clays obtained from various ports around Japan, Tang et al. (2001), Miyazaki (2003) and Miyazaki et al. (2003) proposed an empirical prediction of unconfined compressive strength with cement content and specific volume v of dredged clay, where v is defined as $v = G_s w/100 + 1$, i.e., the ratio of total volume of soil to the volume of soil particles. Eq. (4) expresses the correlation among unconfined compressive strength q_u, cement content C, and specific volume v.

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

where v is specific volume of clay, G_s is specific gravity of soil particles, w is initial water content after cement is mixed (%), C is cement content per 1 m^3 of cement-treated soil (kg/m^3), C_0 is threshold of cement content for strength gain of treated soil (kg/m^3) and K is coefficient of strength gain (kN/kg m).

Eq. (4) reflects that the greater the cement content and the lower the water content, the higher the strength of a treated soil. Fig. 1 shows application examples of Eq. (4) to clayey soils. By properly assigning parameters of strength coefficient K and threshold C_0, unconfined compressive strength q_u can be predicted with fair precision with respect to different curing periods. The correlation coefficient R between predicted unconfined compressive strength q_u^* and measured strength is evaluated ranging from 0.911 to 0.992. There is an interesting tendency for the threshold C_0 not to change with curing periods as the same cement-treated soil. This fact supports the validation of Eq. (4).

The important variable C is given by cement content per 1 m^3. Whenever water content changes, the ratios of both cement to soil particles and cement to pore water are implicated in that change. This means that the expression of cement content C is harder to give an explicit definition.

Referring to the opinion of gel–space ratio theory for cement paste in concrete engineering, the authors modified Eq. (4) to arrive at a new strength prediction based on the ratio of cement weight to soil particles c and the volumetric solid content Y of treated soil. Here, the volumetric solid content Y is equivalent to the inverse of specific volume v, the volume ratio of solidity particles to whole volume of cement-treated soil. In this paper, it is shown that unconfined compressive strength can be predicted with coefficient of strength k_c by the characteristics of individual soil, effective cement adding ratio $(c - c_0)$, and volumetric solid content Y in exponent form as Y^N.

2. Prediction of unconfined compressive strength in terms of volmetric soild content for cement-treated soils

As expressed in Eq. (4) by Miyazaki et al. (2003), the variables of cement content C and C_0 are presented in a unit of kilograms per m^3 (kg/m^3) of cement-treated soil. The factor of coefficient of strength gain K is presented in a unit of kN/kg m.

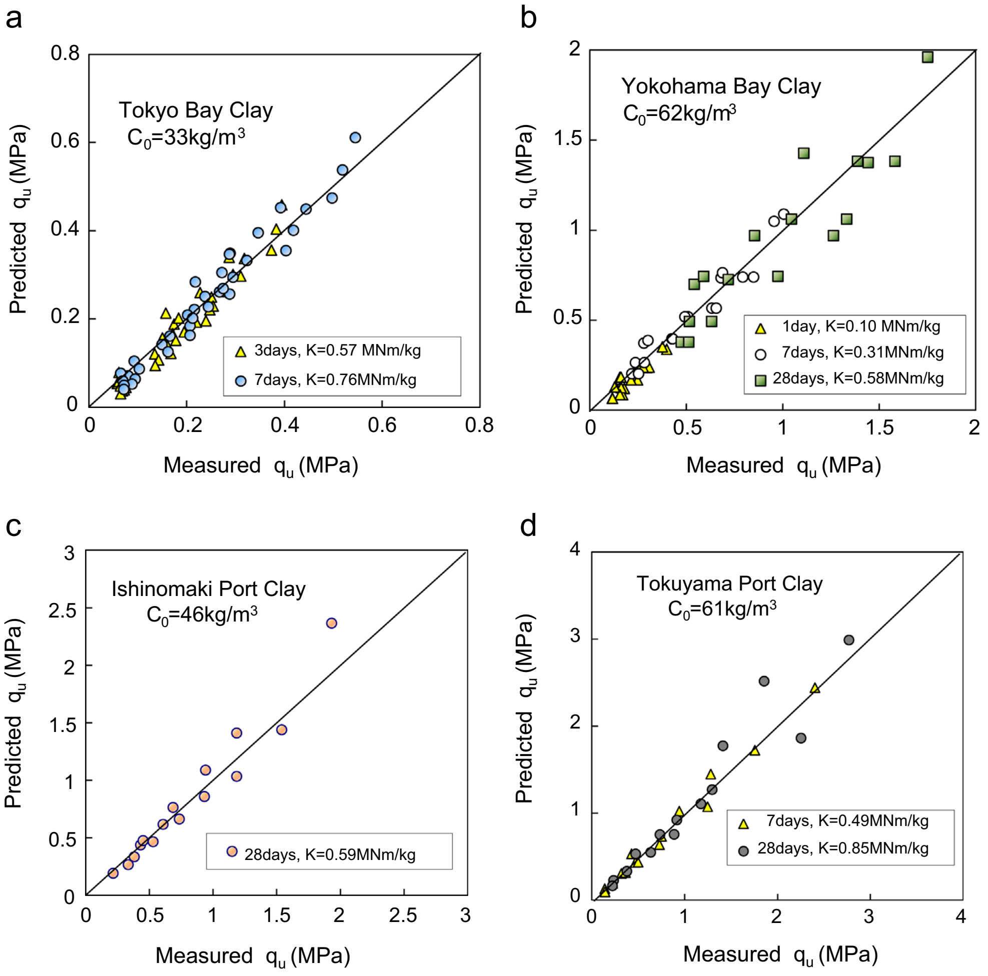


Fig. 1. Comparison between measured strength and predicted strength by Eq. (4). (a) Tokyo Bay Clay, (b) Yokohama Port Clay, (c) Ishinomaki Port Clay and (d) Tokuyama Port Clay

Since cement content C changes with the water content of clay, it is preferable to present it as a mass ratio c of cement added to soil particles. Instead of cement content C, the mixed cement in 1 m^3 can be replaced with the relation of Eq. (5) or Eq. (6). The definitions of C and c are illustrated in Fig. 2.

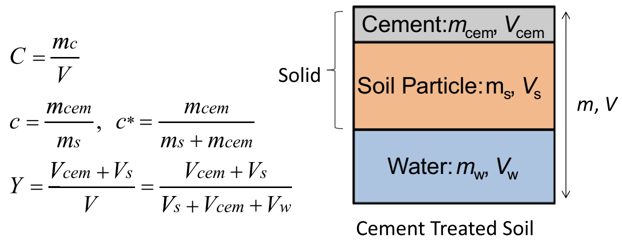
$$c = \frac{C}{1000} \times \frac{v}{\rho_s} \times 100\ (\%) \tag{5}$$

$$C = \frac{10c\rho_s}{v} \tag{6}$$

By substituting Eq. (6) into Eq. (4), we obtain the relation of Eq. (7).

$$q_u = \frac{10G_s\rho_w \times K(c - c_0)}{v^3} \tag{7}$$

where ρ_s is density of soil particles (g/cm^3), ρ_w is density of water (g/cm^3) and G_s is specific gravity of soil particles given by $G_s = \rho_s/\rho_w$. c is weight ratio of added cement to soil particles (%) and c_0 is threshold of c (%) similar to the definition of C_0.



$$C = \frac{m_c}{V}$$

$$c = \frac{m_{cem}}{m_s}, \quad c^* = \frac{m_{cem}}{m_s + m_{cem}}$$

$$Y = \frac{V_{cem} + V_s}{V} = \frac{V_{cem} + V_s}{V_s + V_{cem} + V_w}$$

Fig. 2. Definition of parameters.

In Eq. (7), the term of $10G_s\rho_wK$ is redefined as Eq. (8).

$$k_c = 10\ G_s\rho_wK = 10\rho_sK \tag{8}$$

Thereby, Eq. (7) can be simplified as Eq. (9).

$$q_u = \frac{k_c(c - c_0)}{v^3} \tag{9}$$

k_c is also a coefficient of strength gain (kN/m^2) having the same unit as unconfined compressive strength q_u. A comparison between Eqs. (4) and (9) shows there are different expressions for added cement weight. As previously mentioned, perhaps the term of cement content C (kg/m^3) by cement weight per 1 m^3 is not a fundamental variable, because water content usually changes for a given soil. However, the added cement ratio c(%) used in Eq. (7) depends on soil particles, and may not vary when water content changes. In other words, cement content C is a complicated term that reflects not only the solid phase but also the fluid phase in soils, and added cement ratio c is a simple term that reflects the solid phase only. The latter will not be affected by changes in water content.

In Eq. (9), specific volume v is usually defined as the ratio of solid volume (soil particles) to whole volume (pores and soil particles) of soils, and can be given in Eq. (10).

$$v = \frac{V_s + V_v}{V_s} \tag{10}$$

Here V_s and V_v are volumes of soil particles and pores, respectively. Since void ratio e is defined as the volumetric ratio of pores to soil particles, $e = V_v/N_s$, specific volume v is related to void ratio e as in Eq. (11).

$$v = 1 + e \tag{11}$$

Assuming that clay is saturated, V_v in Eq. (10) can be replaced by volume of water in soil V_w. Substituting Eq. (10) into Eq. (9), the prediction equation can be rewritten as in Eq. (12).

$$q_u = k_c(c - c_0)\left(\frac{V_s}{V_s + V_w}\right)^3 \tag{12}$$

The third term in Eq. (12), powered by 3, is just the volumetric solid content of cement-treated soil, an inverse of specific volume defined in Eq. (10). Therefore, the unconfined compressive strength of cement-treated soil can be predicted to be in proportion with the effective added ratio $(c - c_0)$ of cement to soil particles and with the volumetric solid content powered by 3.

In cement-treated soil, the solid phase includes the soil particles and cement particles. Here we define volumetric solid content Y as shown in Eq. (13) and Fig. 2, in which the volume of added cement is also taken into consideration.

$$Y = \frac{V_s + V_{\text{cem}}}{V_s + V_{\text{cem}} + V_w} \tag{13}$$

where V_{cem} is volume of cement added.

It is known that some pore water will be consumed due to the hydration of cement; that part will precipitate from the liquid phase to the solid phase. Because it is difficult to accurately estimate cement hydration progress, the amount of water used in hydration was not taken into account in this study.

Powers (1958) proposed a gel–space ratio theory to predict compressive strength of cement paste in concrete engineering. In general, in gel–space ratio theory, the compressive strength of cement paste $S(X)$ is given by gel–space ratio X with the following formula (Sakai et al., 1998, 2004).

$$S(X) = S_0 X^N \tag{14}$$

$$X = \frac{V_{\text{hydrates}}}{V_{\text{hydrates}} + V_{\text{pore}}} \tag{15}$$

where V_{hydrates} is volume of hydrates and V_{pore} is volume of pore in cement paste. X is gel–space ratio, defined as the ratio of volume of hydrates to the whole volume of the cement paste. $S(X)$ is developed compressive strength of cement paste and S_0 is intrinsic compressive strength when the cement paste is wholly saturated by cement and hydrates, which is believed to vary with cement type and the composite phase of hydrates. N is a parameter reflecting the pore structure within the cement paste.

Eq. (15) indicates that compressive strength is proportional with gel–space ratio powered by N. The parameter N expresses the dependence of compressive strength on the porosity of the hardened bulk. Powers (1958) evaluated it to be 3.0 for paste of ordinary Portland cement. Sakai et al. (1998, 2004) further analyzed the property of strength development for cement paste that was added with blast furnace slag powder at replacement rate of 20% and 50%. They reported that the gel–space ratio model is valid, and that the parameter N decreases from 3.0 for Portland cement to 2.5, 2.9 for blast furnace slag powder. On the basis of the composite phase model, the decrease in N was explained by the change in pore structure.

Eq. (14) gives the definition of gel–space ratio X as volume of hydrates (including un-hydrated cement) to whole volume of hydrates and pore within the hardened bulk. Eq. (13) gives the definition of volumetric solid content Y in this study. Because these two definitions are based on a similar concept, it seems reasonable to regard gel–space ratio and volumetric solid content as equivalent to each other, even though the effect of partial cement hydrate is not considered in Eq. (13). If the partial cement hydrate was accounted for, the volumetric solid content by Eq. (13) would be a little larger. The parameter N in Eq. (12) for cement-treated soil and in Eq. (15) for cement paste coincides at around 3.0.

Because the cement is included in the solid, we use the new definition of cement content c^* instead of c in Eq. (5) as shown in Fig. 2. Note that c^* is mass ratio of added cement m_{cem} to sum of the masses of soil particles m_s and added cement m_{cem} and it is given in Eq. (16).

$$c^* = \frac{m_{\text{cem}}}{m_s + m_{\text{cem}}} \tag{16}$$

Added cement rate c^* is a ratio of mass of cement to total mass of mixture. c_0^* is a threshold of added cement rate; it is also an initial cement volume necessary for cement-treated soil to start hardening. Added cement ratio c^* used before and added cement rate introduced here are correlated by Eq. (17). Thus, $(c - c_0)$ could be called “effective added cement rate.”

$$c^* = \frac{c}{1 + c} \tag{17}$$

By replacing k_c, $(c - c_0)$ and $1/v$, strength increasing factor k_c^*, effective added cement rate $(c^* - c_0)$, and volumetric solid content Y in Eq. (9), which was deduced from the empirical prediction of unconfined compressive strength proposed by Miyazaki et al. (2003), Eq. (9) becomes a very simple strength prediction formula shown as Eq. (18).

$$q_u = k_c^*(c^* - c_0^*)Y^3 \tag{18}$$

where k_c^* is a coefficient, a strength increasing factor with effective added cement rate $(c^* - c_0)$.

From the similarity with Eq. (14) of gel–space theory in concrete engineering, Eq. (18) is generalized as Eq. (19).

$$q_u = k_c^*(c^* - c_0^*)Y^N \tag{19}$$

In the following section, we verify the applicability of Eq. (18) to six different marine clays obtained from coastal areas. Furthermore, we examine the generalized form of Eq. (19) to the same clays by analyzing the optimum value for parameter N for individual cement-treated soil.

3. Applicability of proposed strength prediction for various Japanese marine clays

Based on tests conducted under different properties of cement with marine clay collected in seaports in Japan, we assessed the applicability of Eqs. (18) and (19). Fig. 3 and Table 1 show the site and the index properties and mixing condition of dredged marine clays, respectively.

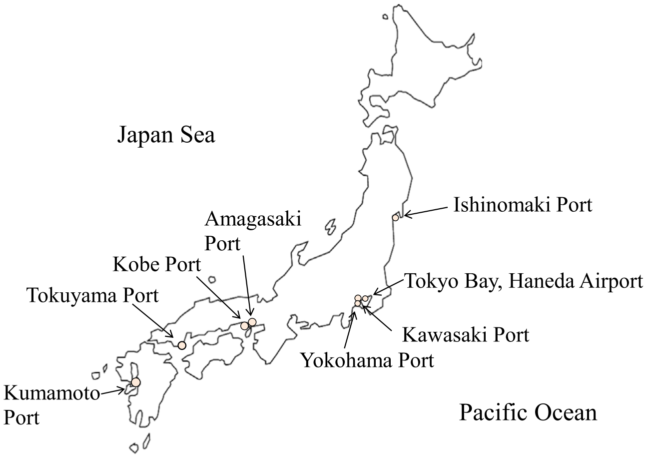


Fig. 3. Sites of marine clays used in this study.

The cement-treated soil is made by adding soil, water, and cement mix into the mixer. In this study, the water content of each clay soil was arranged to three to five levels between the liquid limit w_L and twice the liquid limit $2w_L$, considering the variability of in-situ dredged clay. For Kobe Port Clay and Tokuyama Port Clay, the cases of water content $3w_L$ and $4w_L$ were included, respectively. Three to five levels of cement content were arranged between 45 kg and 175 kg per 1 m^3 of clay slurry.

In the practice of cement treatment, the cement is mixed with soil as a powder or cement slurry, which is usually arranged with 100% water–cement ratio. In laboratory mixture experiments, after the water content of clay was carefully arranged, the necessary amount of cement—which was a powder or cement slurry—was mixed with the soil. Table 1 shows the added cements per 1 m^3 of clayey soil with arranged water content. Parameter C in Eqs. (4)–(6) denotes the cement content for 1 m^3 treated soil, and when a cement slurry was mixed with the clay soil, the water involved in cement slurry was calculated as a part of water contained in the clay soil.

3.1. Study of applicability of equation derived from Miyazaki et al. (2003)

Eq. (18), the equation derived from Miyazaki et al. (2003), can be transformed as follows.

$$q_u Y^{-3} = k_c^*(c^* - c_0^*) \tag{20}$$

By calculating $q_u Y^{-3}$ from the measured strength and the mixture condition and plotting to the cement content c^*, the parameters k_c^* and c_0^* were determined by fitting the linear relationship as suggested in Eq. (20) with the method of least square. The fitting was carried out for each curing time and the

Table 1
Properties and mixing condition of dredged marine clays.

Dredged clays	Range of water content for mixing (%)	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Ignition loss, L_i (%)	Particle density, ρ_s (g/cm^3)	Added mass of cement content per 1 m^3 of clay (kg/m^3)	Water–cement ratio of cement slurry (%)	Curing time (days)	Number of strength tests
Tokyo Bay Clay	179.0–250.0	124.9	35.9	8.8	2.668	40, 50, 60, 70	100, 150, 200	3, 7, 28	27
Yokohama Port Clay	76.1–120.0	61.8	29.8	5.7	2.680	90, 110, 130	120	1, 7, 28	18
Tokuyama Port Clay	120.0–250.0	77.0	34.4	10.7	2.683	80, 120, 160	Powder	7, 28	15
Ishinomaki Port Clay	118.0–198.0	119.9	34.3	12.2	2.674	60, 70, 80, 90, 120	Powder	28	15
Amagasak Port Clay	119.3–179.9	100.2	32.0	9.1	2.614	75, 125, 175	100	3, 7, 28	36
Kobe Port Clay	136.4–220.5	71.4	30.5	8.7	2.646	50, 70, 90, 110	120	7	12
Kawasaki Port Clay	130	55.4	25.2	5.0	2.688	40, 70, 100, 130	Powder	7, 28	32
Kumamoto Port Clay	127.0–211.0	70.4	33.4	7.0	2.692	50, 100, 150, 200	Powder	7, 28	32

average of values of c_0^* was determined as the representative value of the clay. With the representative value of c_0^*, k_c^* was re-determined by the fitting for each curing time. Using the determined c_0^* and k_c^* with Eq. (18), the unconfined compressive strengths q_u were calculated and compared with the measured strengths.

Fig. 4 shows the q_uY^{-3} versus c^* relationship for Tokyo Bay Clay, the data of which were the same as in Fig. 1(a). As shown in Fig. 4, the data for both 3 days of curing and 7 days of curing reveal a linear relation between q_uY^{-3} and c^*. The coefficients of determination R^2 were 0.847 for 3 days of curing time and 0.906 for 7 days of curing time. Fig. 5 shows the comparison of measured unconfined compressive strengths q_u of Tokyo Bay Clay with the strengths calculated by Eq. (18), where the parameters k_c^* and c_0^* were estimated by the method of least squares. As shown in Fig. 5, the strengths coincide fairly well, but discrepancy was found when the strengths were larger than 400 kPa.

The results for Yokohama Port Clay, Ishinomaki Port Clay, and Tokuyama Port Clay – presented in Fig. 1(b)–(d), respectively – were analyzed in a similar way. The results are presented in Figs. 6–8(a). In Fig. 7(a) the initial water content w_0 of clay was shown to consider the effect of different w_0. As shown in these figures, in all three clays, there is a linear relation between the normalized strength q_uY^{-3} and the cement content c^*. The parameters k_c^* and c_0^* were estimated by the method of least squares. Figs. 6–8(b) show good agreements between measured unconfined compressive strengths and strengths calculated by Eq. (18). However, in Tokuyama Port Clay and Tokyo Bay Clay, there were some differences in the range of greater strengths. Considering these findings, the differences are large when the water content is small and the volumetric solid content Y is large, suggesting that the effect of Y on the strength of cement-treated soil is not appropriately estimated by Eq. (18).

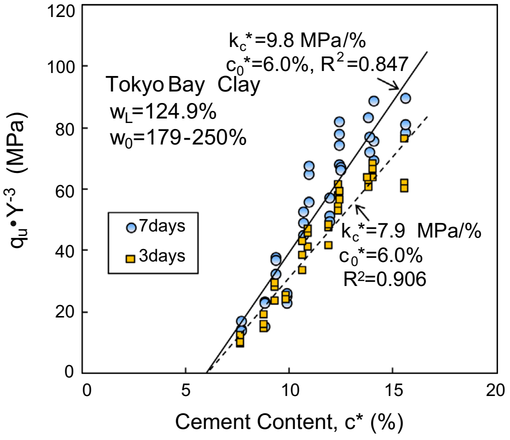


Fig. 4. Cement content and normalized strength, $q_u \bullet Y^{-3}$ (Tokyo Bay Clay).

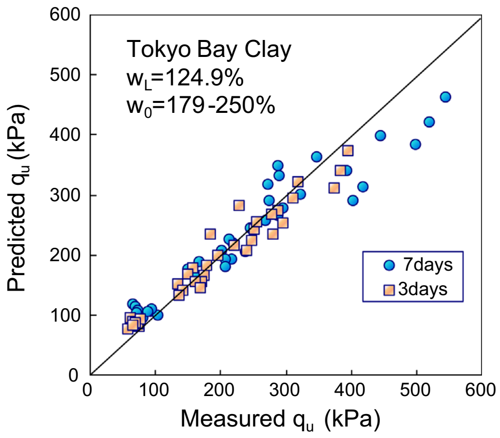


Fig. 5. Comparison between measured unconfined compressive strengths and strengths calculated by Eq. (18) (Tokyo Bay Clay).

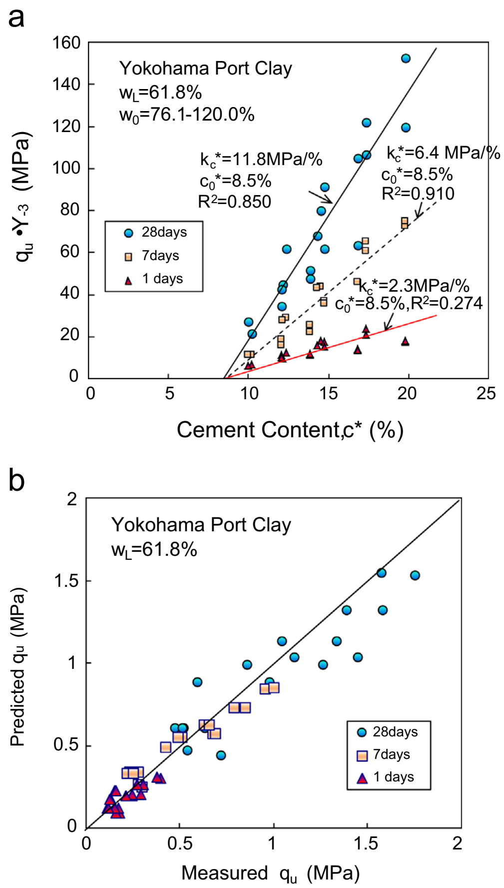


Fig. 6. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-3}$ (Yokohama Port Clay). (b) Comparison between measured unconfined compressive strengths and strengths calculated by Eq. (18) (Yokohama Port Clay).

Reviewing the results of Ishinomaki Port Clay in Fig. 7(a) and (b), where the initial water content samples are shown, there are some differences among the linear $q_uY^{-3}-c^*$ relation dependent on the initial water content. Similarly, Figs. 9 and 10 show the effects of the initial water content of Tokyo Bay on the strength after curing for 7 days, and the initial water content of Tokuyama Port Clay on the strength after curing for 28 days. In both clays, the linear $q_uY^{-3}-c^*$ relations were slightly different with the initial water content, and the larger the initial water content, the smaller the normalized strength q_uY^{-3} at the same cement content c^*.

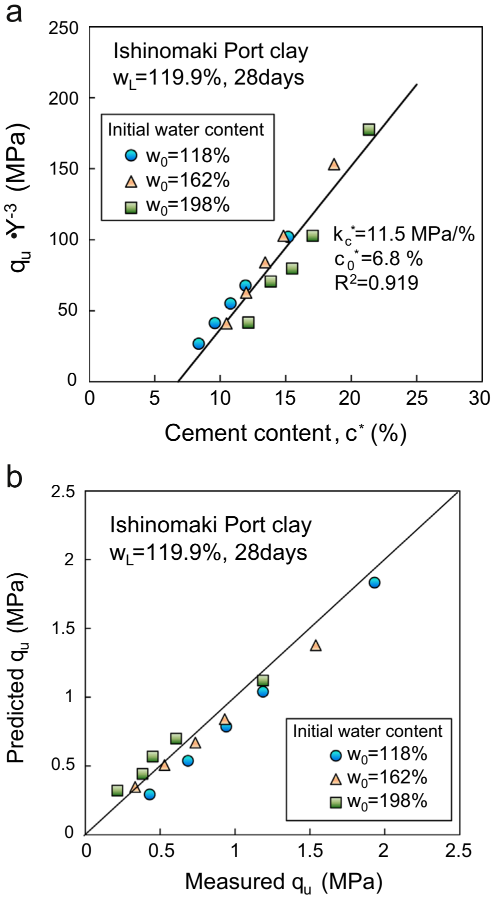


Fig. 7. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-3}$ (Ishinomaki Port Clay). (b) Comparison between measured unconfined compressive strengths and strengths calculated by Eq. (18)(Ishinomaki Port Clay).

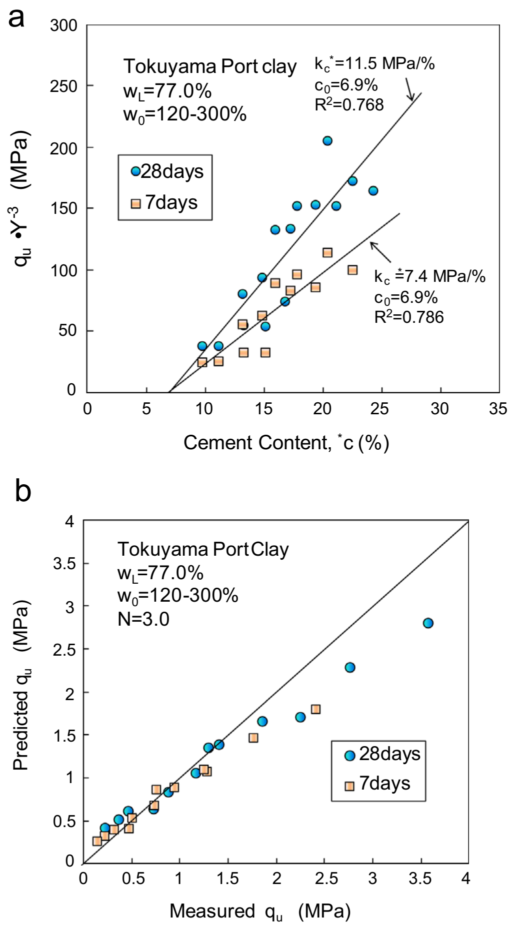


Fig. 8. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-3}$ (Tokuyama Port Clay). (b) Comparison between measured unconfined compressive strengths and strengths calculated by Eq. (18) (Tokuyama Port Clay).

3.2. *Study of applicability of the equation generalized from the gel–space theory of concrete engineering*

We examined the applicability of Eq. (19), which was obtained by generalizing Eq. (18) from the similarity with gel–space theory of concrete engineering. Eq. (19) can be transformed as follows.

$$q_u Y^{-N} = k_c^*(c^* - c_0^*) \qquad (21)$$

For each data set, the $q_u Y^{-N} - c^*$ relationship was obtained by assuming the value of N, and the coefficient of determination R^2 was calculated. The value of N was determined when the coefficient of determination R^2 was at its maximum. The fitting was carried out for each curing time and the representative values of N and c_0^* were determined as the average of those of different curing times. Using the representative values of N and c_0^*, the parameter k_c^* was re-determined by the fitting for each curing time.

Fig. 11(a) shows the $q_u Y^{-N} - c^*$ relationship of Tokyo Bay Clay, where N=4.3, as the coefficient of R^2 was at its maximum (0.937 for strength cured in 7 days, 0.935 for strength cured in 3 days). These values of R^2 for strength cured in 7 days increased substantially from 0.847 with fixed N=3.0 to 0.937 with fittest value of N. Fig. 11(b) is the comparison of measured unconfined compressive strengths q_u and strengths calculated by Eq. (19). The agreement between the measured

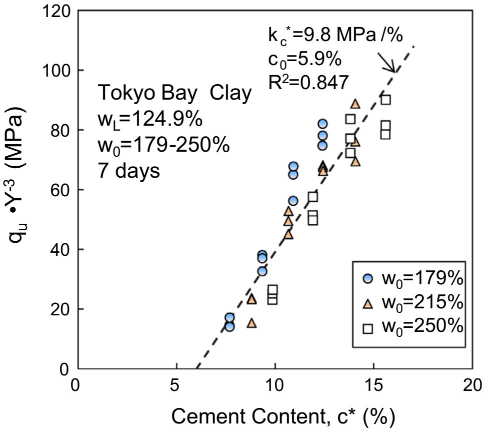


Fig. 9. Effect of initial water content on $c^* - q_u \bullet Y^{-3}$ relationship (Tokyo Bay Clay).

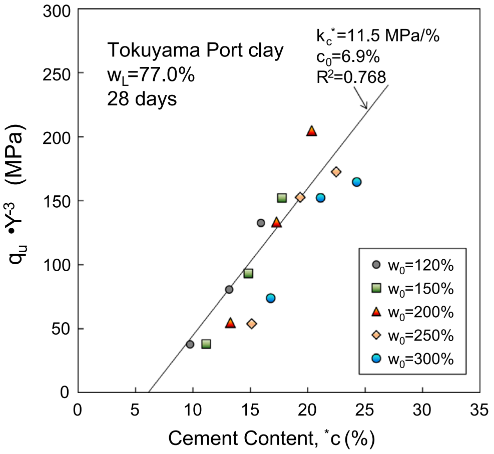


Fig. 10. Effect of initial water content on $c^* - q_u \bullet Y^{-3}$ relationship (Tokuyama Port Clay).

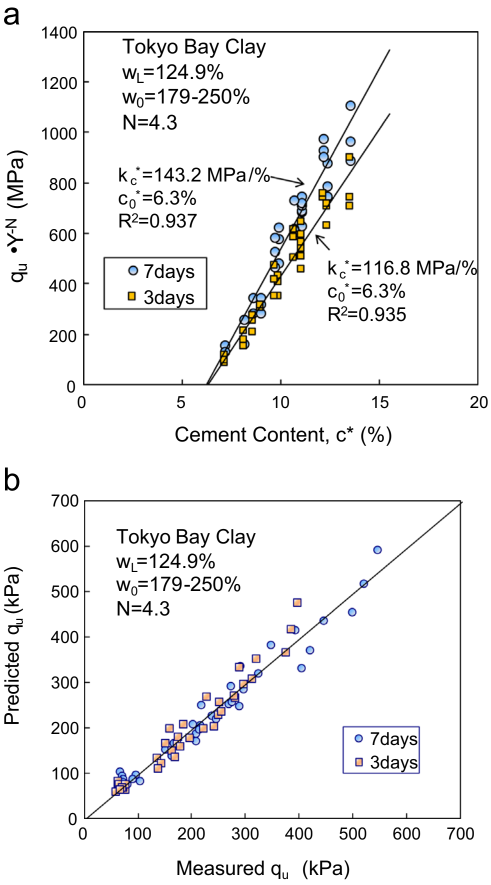


Fig. 11. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Tokyo Bay Clay). (b) Comparison between measured unconfined compressive strengths and calculated strengths (Tokyo Bay Clay).

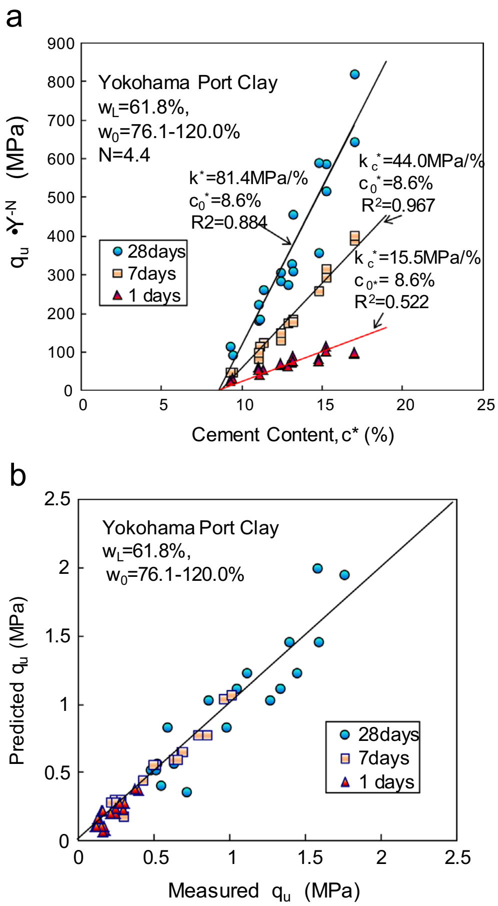


Fig. 12. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Yokohama Port Clay). (b) Comparison between measured unconfined compressive strengths and calculated strengths (Yokohama Port Clay).

and calculated strengths was significantly improved from the result of $N=3.0$ shown in Fig. 5, especially in the range of greater strengths.

Fig. 12(a) and (b) shows the results for Yokohama Bay Clay. The coefficient of determination R^2 was the greatest when $N=4.4$. Similarity to Tokyo Bay Clay, R^2 for strengths increased from the results of $N=3.0$. The increases of R^2 were from 0.850 to 0.884 for 28 days curing time and from 0.910 to 0.967 for 7 days curing time. The agreement between measured and calculated strengths also improved.

Figs. 13–16(a) and (b) show the results for Ishinomaki Port Clay, Tokuyama Port Clay, Amagasaki Clay, and Kobe Port Clay. These clays showed the best fit of linear $q_uY^{-\mathrm{N}}-c^*$relations when the values of N are 3.9, 4.0, 3.9, and 4.1, respectively. The values of R^2 increased from 0.919 to 0.956 in Ishinomaki Port Clay and from 0.768 to 0.920 in Tokuyama Port Clay comparing with Figs. 7 and 8(a). The measured and calculated strengths agreed fairly well for all four clays.

Fig. 13(a), Figs. 17 and 18 show the effect of initial water content for Ishinomaki Port Clay, Tokyo Bay Clay, and Tokuyama Port Clay, where $q_uY^{-N}-c^*$relations are shown with the initial water content of each clay. Comparing with Fig. 7(a), Figs. 9 and 10, the linear $q_uY^{-\mathrm{N}}-c^*$ relation dependency on the initial water content is much smaller. These results show that, by determining the value of N for each clay by the least square method, Eq. (19) can be applied to predict the strength of cement-treated clays independent of the initial water content.

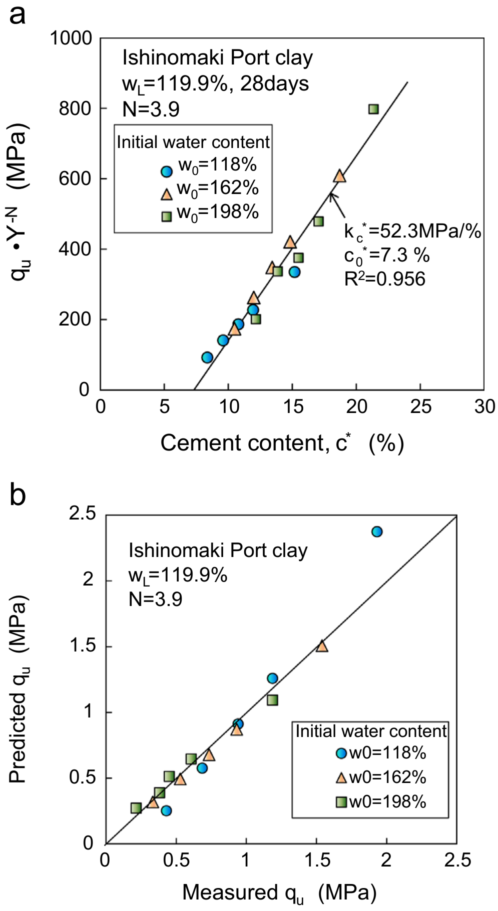


Fig. 13. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Ishinomaki Port Clay). (b) Comparison between measured unconfined compressive strengths and calculated strengths (Ishinomaki Port Clay).

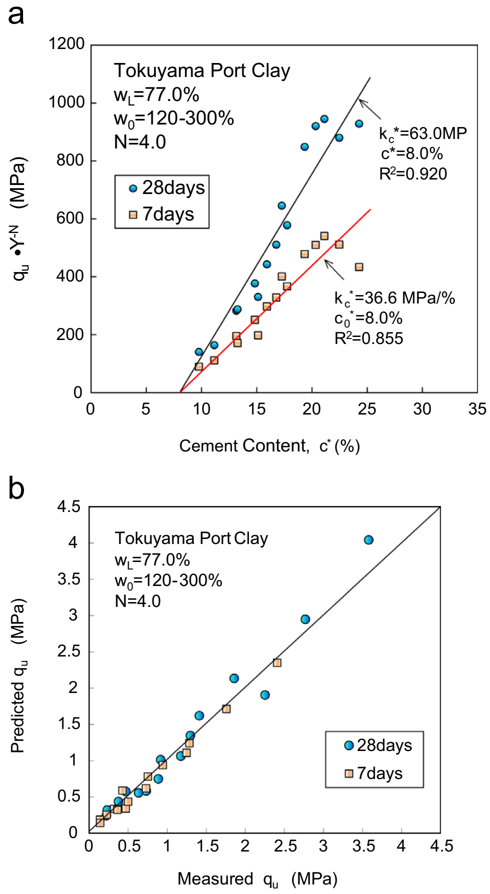


Fig. 14. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Tokuyama Port Clay). (b) Comparison between measured strength and predicted strength (Tokuyama Port Clay).

As mentioned above, it was found that the strengths of cement-treated marine clays can be presented independently of the initial water content by Eq. (19) where the parameters N, k^*, and c_0^* are determined by the analysis of the mixture proportion test. The value of N was ranging from 3.9 to 4.4 for the six marine clays.

3.3. Applicability of the generalized equation to lightweight treated soil made of marine clays

One beneficial use of dredged clay in port and harbor areas is called the method of lightweight treated soil obtained by mixing cement and lightening materials such as air-foam or expanded polystirol beads. This method was used for the first time in the restoration following the Great Hanshin Earthquake of 1996. Since then, approximately 1.4 million m^3 of lightweight treated soils were applied in port harbor or airport projects (Tsuchida et al., 1996, 2001, 2007). Recently, in the expansion project of D runway at Tokyo's Haneda Airport, dredged clay from waterway renewal was beneficially used as base material. As the structure of D runway consisting of the area of landfill and the area of landing pier, the lightweight treated soil was diluted and mixed with cement and air-foam, and cast at the boundary between the two areas to reduce the earth pressure (Watabe and Noguchi, 2011). A quantity of 792 thousand m^3 was used in this project.

Lightweight treated soil, mixed with lightening material such as air-foam or expanded polystyrol beads, has a smaller volumetric solid content than the usual cement-treated soils. In this section, we verify the applicability of Eq. (19) for lightweight soil that includes compressible, lightweight material. For the lightweight treated soil, the volumetric solid content Y was calculated as

$$Y = \frac{V_s + V_{\mathrm{cem}}}{V_s + V_{\mathrm{cem}} + V_w + V_{lwt}} \tag{22}$$

where V_{lwt} is volume of lightweight material such as air-foam or expanded polystyrol beads.

Fig. 19(a) and (b) give the results of Eq. (19) for a proportional test of air-foam-mixed lightweight treated soil based on Tokyo Port Clay. The water content of the dredged clay was initially arranged to 278% and 360%, and a volume ranging from 0 to 384 l of air-foam per 1 m^3 was mixed with the clay slurry. The density of the mixture varied from 0.74 g/cm^3 to 1.34 g/m^3. In this figure, parameter N was determined as 2.4 when the coefficient of determination was at its maximum based on the least square

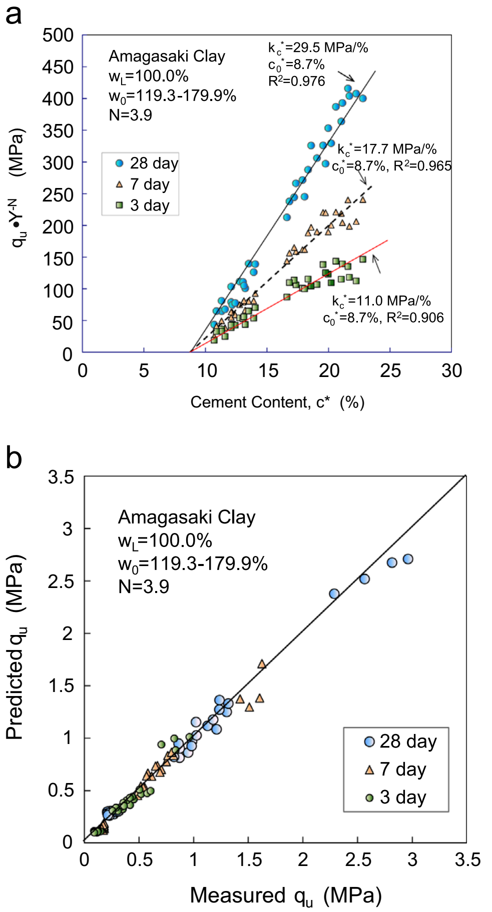


Fig. 15. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Amagasaki Clay). (b) Comparison between unconfined compressive strengths and calculated strengths (Amagasaki Clay).

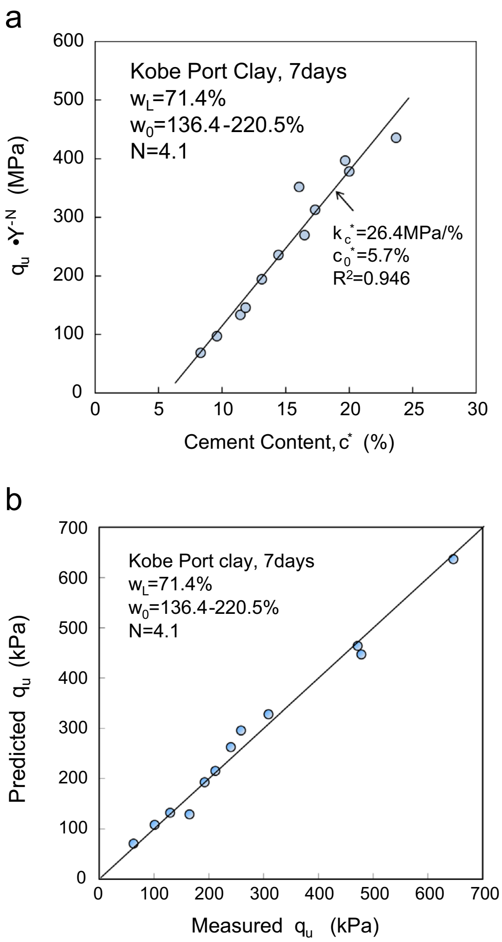


Fig. 16. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Kobe Port Clay). (b) Comparison between unconfined compressive strengths and calculated strengths (Kobe Port Clay).

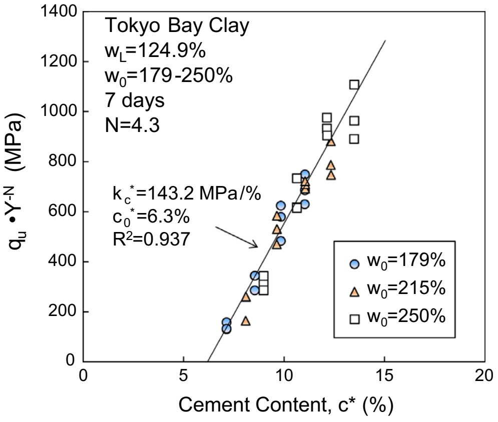


Fig. 17. Effect of the initial water content on $c^* - q_u \bullet Y^{-N}$ relationship (Tokyo Bay Clay).

method. Analyses based on Eq. (19) gave a correlation coefficient $R^2 = 0.937$, implying the measured unconfined compressive strength agreed with the calculated strengths fairly well.

Fig. 20(a) and (b) illustrate the same application to Kumamoto Port Clay (Tsuchida et al., 2001; Satoh et al., 2001). In this case, the initial water content of dredged Kumamoto Port clay was from 127% to 211%, and the volume of mixed air-foam was from 150 to 291 l per 1 m^3. The parameter N at 2.5 yielded a correlation coefficient R^2=0.863 and 0.895 at its maximum for 28 days and 7 days curing time, respectively. These values are a little smaller than those of most cement-treated soils, or light-weight treated soil based on Tokyo Port (dredged) Clay.

Fig. 21(a) and (b) show the application of Eq. (19) to Kawasaki Port Clay, where expanded polystyrol beads were used as lightening material. Parameter N at 2.1 yielded maximum correlation between $q_u Y^{-N}$ and c*, with a correlation coefficient $R^2 = 0.897$.

From the applications above, it can be said that Eq. (19) is valid also to lightweight treated soil, which is characterized by a relatively small value of volumetric solid content. There is a tendency that parameter N in Eq. (19) becomes smaller than 3.0. For usual cement-treated soils, parameter N ranged between 3.5 and 4.5, whereas for lightweight treated soils, it decreased to between 2.1 and 2.5. This difference may be due to the different microstructures of pores in these two type of cement-treated soils. More studies are needed to find the effect of microstructures on parameter N.

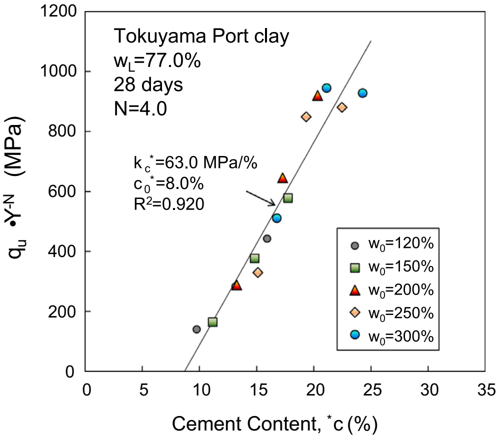


Fig. 18. Effect of the initial water content on $c^* - q_u \bullet Y^{-N}$ relationship (Tokuyama Port Clay).

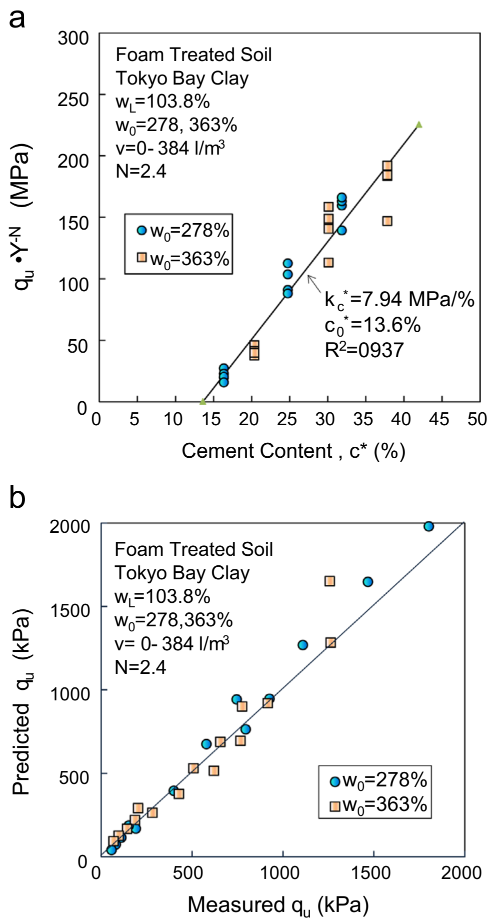


Fig. 19. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Foam-treated soil, Tokyo Bay Clay). (b) Comparison between measured unconfined compressive strengths and calculated strengths (Foam-treated soil, Tokyo Bay Clay).

3.4. Application of the generalized equation to the mixture proportion test results of Tokyo Bay Clay for the construction of D runway at Tokyo's Haneda Airport

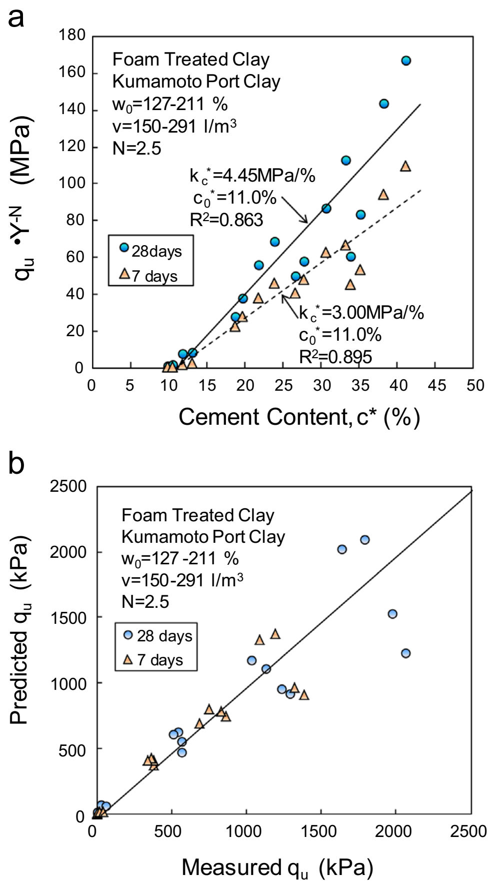


Fig. 20. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (Foam-treated soil, Kumamoto Port Clay). (b) Comparison between measured unconfined compressive strengths and calculated strengths (Foam-treated soil, Kumamoto Port Clay).

In the construction of D runway at Tokyo's International Haneda Airport, 4.9 million m^3 of cement-treated soil was used as a filling material. The clays were supplied by dredging a navigation channel of Tokyo Port and by replacing the clay soil with sand for the construction of revetments. The cement-treated soil was prepared by pneumatic mixing (Iba et al., 2009; Watanabe et al., 2009). To determine the volume of added Portland blast-furnace cement type B, a series of strength tests were carried out with the different mixing conditions, using seven soil samples collected in the construction sites. In this section, we examine the applicability of Eq. (19) to the results of these strength tests.

Table 2 shows the soil properties and conditions of the strength tests for the seven clay samples. As shown in Table 2, the liquid limit of samples ranged from 85.4% to 173.4%, and hence, all the clays were high-plastic clays. For each clay, the fitting based on Eq. (19) was carried out, and the parameters N, k_c^*, and c_0^* were determined as shown in Fig. 22. Although the values of N were different among the samples, the coefficients of determination were high for all the samples. Fig. 23 shows the comparison between the measured strength $q_{u(\text{mes})}$ and calculated strength $q_{u(\text{cal})}$ based on Eq. (19). The following regression relation was obtained.

$$q_{u(\text{cal})} = 0.994 q_{u(\text{mes})}, \quad (R^2 = 0.943) \tag{23}$$

In Fig. 22, the fitting was carried out for each sample. However, in practice, the properties of in-situ clay to be mixed with cement to prepare cement-treated soil often have significant variability. It is common for the liquid limit or particle size properties of dredged clay to be different from those of soil samples used for the mixture proportion. Considering the variability of in-situ clays, it is not realistic to determine the necessary cement content based on the result of mixture proportion tests for each soil sample. It is better to consider all the samples as one group and to determine the necessary cement content for that one group. Accordingly, using all the results of mixture proportion tests for all seven samples, the fitting to Eq. (19) was carried out and the parameters N, k_c^*, and c_0^* were determined as shown in Fig. 24(a). As shown in Fig. 24 (a), the parameter N was 3.6 when the R^2 was 0.882 at its maximum. Fig. 24(b) shows the comparison between the measured strengths $q_{u(\mathrm{mes})}$ and the calculated strengths $q_{u(\mathrm{cal})}$, and the relation of both was given as:

$$q_{u(\mathrm{cal})} = 0.978 q_{u(\mathrm{mes})}, \quad \left(R^2 = 0.873\right) \tag{24}$$

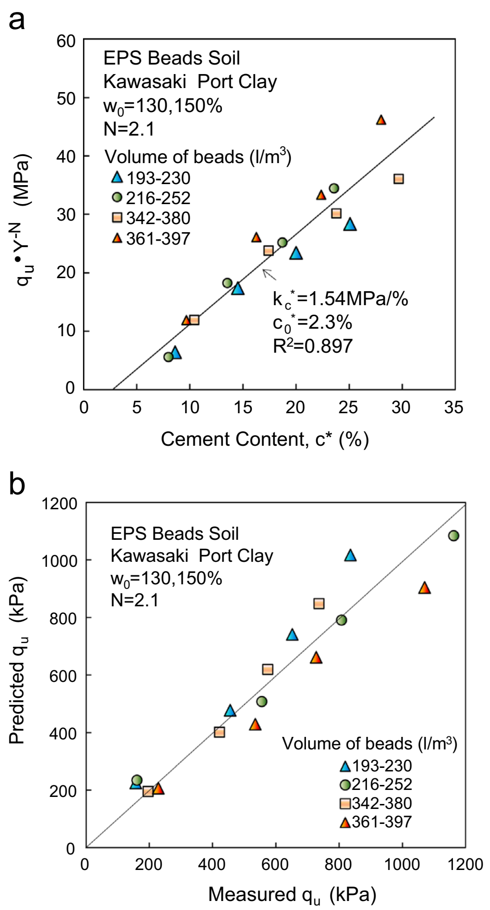


Fig. 21. (a) Cement content c^* and normalized strength $q_u \bullet Y^{-N}$ by Eq. (19) (EPS Beads Soil, Kawasaki Port Clay). (b) Comparison between measured strength and predicted strength (EPS Beads Soil, Kawasaki Port Clay).

This agreement is not as good as the agreement with Eq. (23), in which the fittings were carried out individually for all seven samples. However, the fitting reflected in this equation, considering the samples as one group, has enough accuracy for typical engineering practice.

As mentioned in the introduction, the formulas using water–cement ratio are commonly used to determine the necessary volume of cement for cement-treated soil. As an example of an equation of water–cement ratio, we examined the fitting to Eq. (2) for the data considering the seven samples as one group. Fig. 25(a) shows the relationship between water–cement ratio and unconfined compressive strength, where parameters a, b, and x in Eq. (2) were determined as shown in Fig. 25(a). By changing the value of b, it was found that the coefficient of determination R^2 was at its maximum when $b = 20$ kPa. The unconfined compressive strength q_u (kPa) was given by the following equation.

$$q_\mathrm{u} = 188,000\left(W/C\right)^{-2.57} + 20 \tag{25}$$

Fig. 25(b) is the comparison between the measured strengths $q_{u(\mathrm{mes})}$ and the strengths calculated by Eq. (25), $q_{u(\mathrm{cal})}$. The relationship of unconfined compressive strengths was given as follows.

$$q_{u(\mathrm{cal})} = 0.900 q_{u(\mathrm{mes})}, \quad \left(R^2 = 0.714\right) \tag{26}$$

It is clearly shown that the strengths calculated by Eq. (19) in this study agreed with the measured strengths much better

Table 2
Properties and mixing condition of dredged Tokyo Bay Clay in Haneda D runway project.

Name of samples	Range of water content for mixing (%)	Liquid Limit, w_L (%)	Particle density, ρ_s (g/cm^3)	Ignition loss, L_i (%)	Organic content (%)	Cement content per 1 m^3 (kg/m^3)
Sample A	223.3–303.4	125.4	2.690	10.9	3.6	60–120
Sample B	242.4–320.6	117.8	2.667	11.6	4.6	60–120
Sample C	172.8–236.6	85.4	2.656	8.2	3.5	60–120
Sample D	307.2–412.0	173.4	2.557	14.0	6.6	60–120
Sample E	224.0–314.1	102.3	2.642	9.4	3.9	60–120
Sample F	175.3–272.0	112.7	2.607	9.9	4.0	60–120
Sample G	222.9–314.4	129.8	2.587	11.2	5.6	60–120

*Portland blast furnace cement type B was used.
(Cement milk).

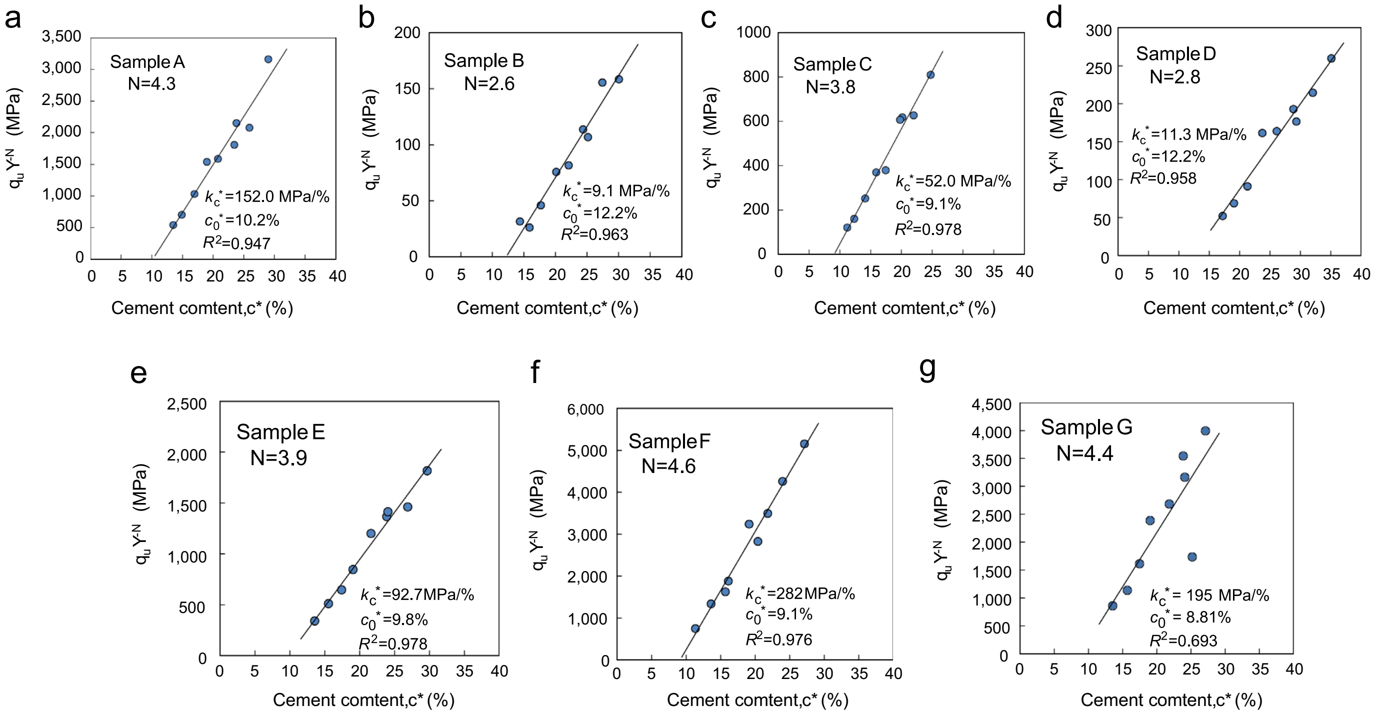


Fig. 22. Determination of parameters c_0^*, k_c^*, and N for Eq. (19) for seven samples of Tokyo Bay Clay.

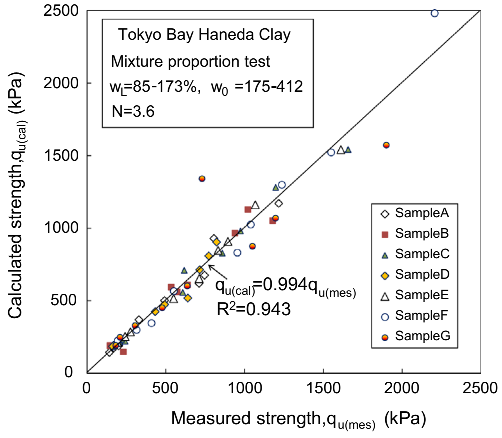


Fig. 23. Comparison between measured strength and predicted strength.

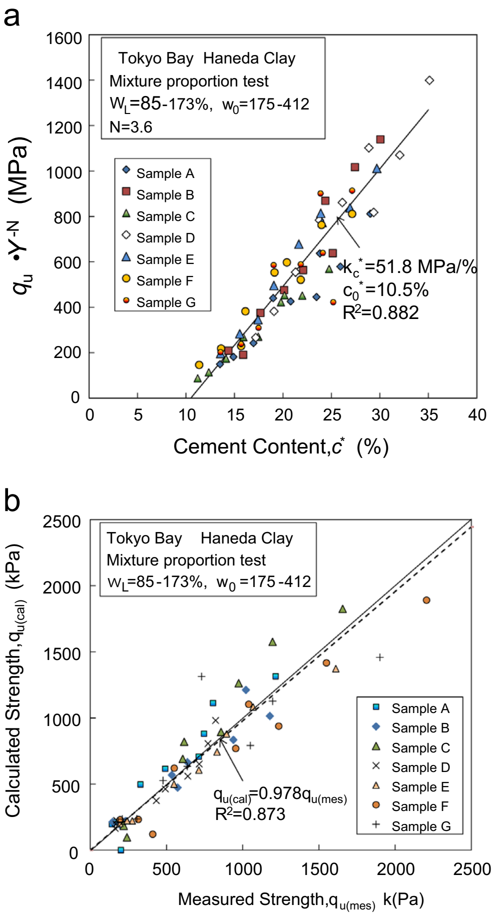


Fig. 24. (a) Determination of parameters c_0^*, k_c^*, and N for Eq. (19) for for seven samples of Tokyo Bay Clay. (b) Comparison between measured unconfined compression strengths and strengths calculated by Eq. (19).

than those calculated by Eq. (25), the conventional equation using the water–cement ratio.

4. Discussion

4.1. Relationship between parameters in the generalized equation with liquid limit of clay

As mentioned above, it was found that the generalized equation Eq. (19), which is proposed from the similarity with the gel-pore ratio theory, can be used to estimate the strengths of cement-treated soil and lightweight treated soils made from marine clays.

The relationship between two parameters N, c_0^* in Eq. (19) and the liquid limit of clay were presented in Fig. 26(a) and (b), where the data of 6 marine clays shown in Figs. 4–18, 3 lightweight

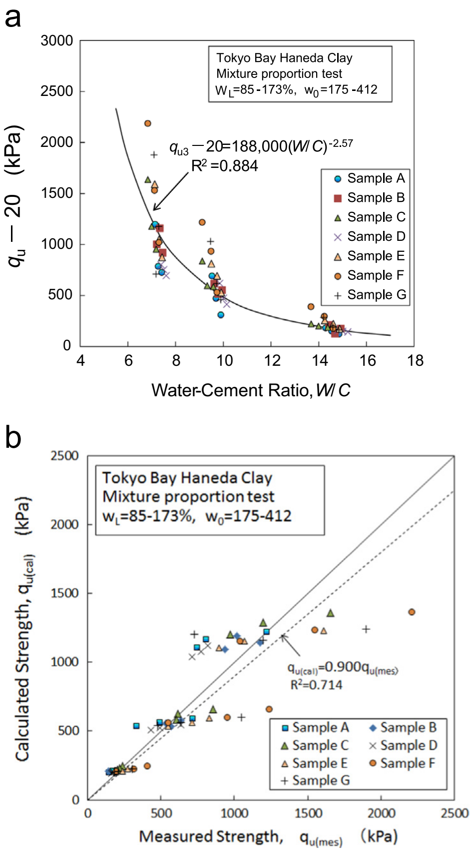


Fig. 25. (a) Determination of parameters for Eq. (2) for seven samples of Tokyo Bay Clay. (b) Comparison between measured unconfined compression strengths and strengths calculated by Eq. (25).

treated soils and 7 samples of Tokyo Bay Haneda Airport are plotted. As shown in Fig. 26(a), the parameter N of lightweight treated soils and sample B and D of Tokyo Bay Haneda Airport were less than 3.0, while N for other clays ranges from 3.8 to 4.6. It is considered that the lightweight treated soil shows small N value due to its structural feature made by air-foam or expanded polystirol beads. The samples B and D from Tokyo Bay Haneda Airport show large ignition loss. Tremblay et al. (2002) showed that the existence of organic material such as humic acid reduced the strength mobilization of cement treated soils. The smaller N value may be due to the presence of organic materials. in the samples B and C. The parameters N and c_0^*, as in Fig. 26(a) and (b), showed no significant relationship with liquid limit of clay. The parameter k_c^* in Eq. (19) means the strength property with increment of cement. As the direct comparison of k_c^* is difficult for soils with different N values, the strength $k_c^*Y^N$ in Eq. (19) when $Y=0.25$ (void ratio e is 3.0) is compared with the liquid limit of clay in Fig. 26(c). As in Fig. 26(c), the strength $k_c^*Y^N$ was also clearly related to the liquid limit. More studies are necessary to determine the physical meanings of the parameters in Eq. (19) and the relationship with the index parameters of soil.

4.2. Relationship between the generalized equation and water–cement ratio theory in concrete and cement milk

Here, we consider the applicability of Eq. (19) to concrete. Fig. 27(a) shows the relationship between the normalized strength q_uY^{-N} and the cement content c^*. In Fig. 26(a), the data from standard mixing proportions of concrete, with slump from 8 cm to 12 cm and water–cement ratio from 39% to 65%, were used, and the volumetric solid content and cement content c^* were calculated from Eqs. (13) and (16). As shown in Fig. 26(a), when $N=3$, the coefficient of determination was the maximum and $R^2=0.984$, and the parameters k_c^* and c_o^* were determined as 5.30 MPa/% and 5.55%. Using Eq. (19), the strength of concrete q_u (kPa) was shown as:

$$q_u = 5,300(c^* - 5.55)Y^3 \tag{27}$$

Fig. 27(b) shows the comparison between the measured and calculated unconfined compressive strengths. As shown in Fig. 27(b), the agreement is very good. It can be said that Eq. (19) can be used for the estimation of concrete. However, in the concrete with standard mixture proportions, the volumetric solid content Y does not change very much. In the case of Fig. 27(a) and (b), the range of Y is from 0.764 to 0.784, which means that the difference of Y is almost negligible. Accordingly, in concrete, the differences of Y in Eq. (19) is not very sensitive to the strength, and the strength is mainly determined by cement content c^* or the water–cement ratio, because the volume of water is almost constant. It can be said that Eq. (19) can be used

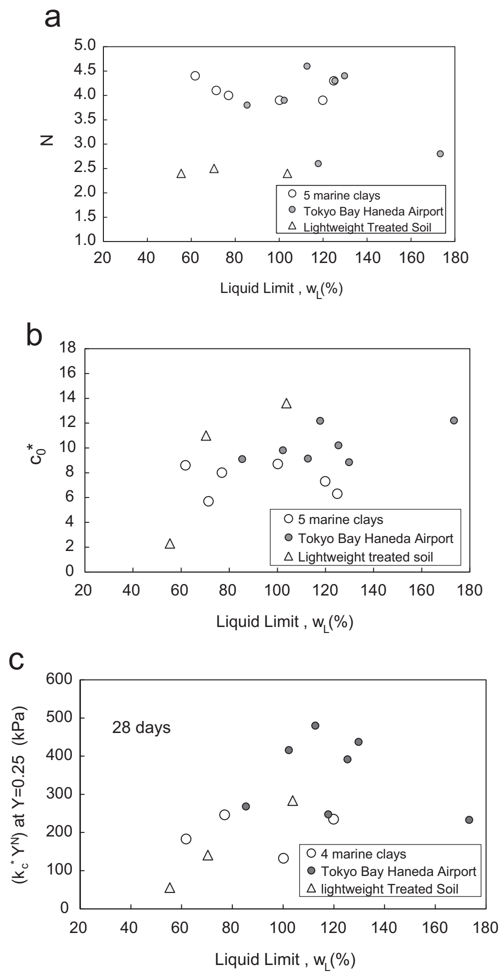


Fig.26. (a) Parameter N with liquid limit of clay. (b) Parameter c_0^* with liquid limit of clay. (c) $k_c^*Y^N$ at $Y=0.25$ with liquid limit of clay.

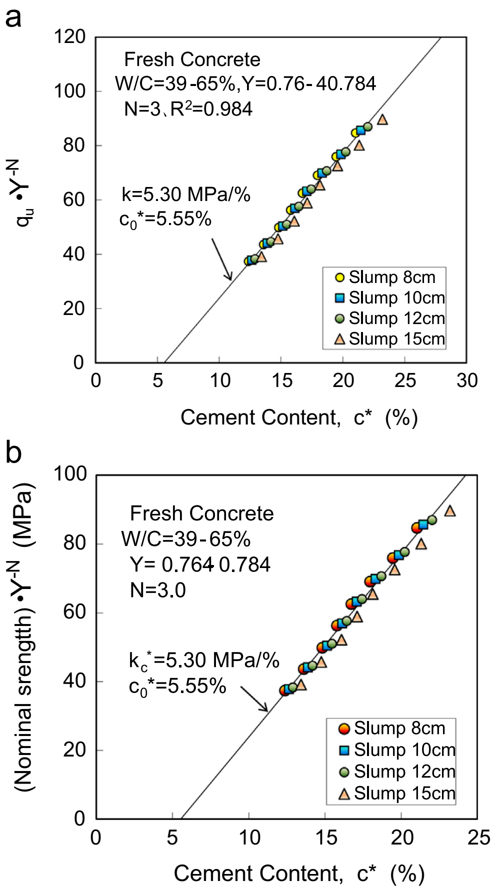


Fig. 27. (a) Cement content c^* and normalized strength relation of concretes with standard specified mixture proportion. (b) Comparison between measured strength and predicted strength by Eq. (19) (Concretes with standard specified mixture proportion).

for concrete, but in the standard mixture proportion, the strength of concrete is mainly determined by the cement content.

Next, the applicability of Eq. (19) to cement milk without aggregate was examined. As the cement milk does not contain any solids except cement, the cement content c^* is almost 100%. Eq. (19) is shown with a constant K as follows.

$$q_u = K \times Y^N \tag{28}$$

The $q_u - Y$ relationship for ordinary Portland cement with marine water and fresh water fits best when $N=3.5$ and k is 1197 MPa. The $q_u - Y$ relationship for blast furnace Portland cement fits best when $N=3.1$ and K is 968 MPa with fresh water and 672 MPa with marine water. The comparison between the measured and unconfined compressive calculated strengths is shown in Fig. 28. As shown in the figure, the agreement was good, and it was found that Eq. (28) can be used to predict the strength of cement milk.

When the cement milk consists of cement and water, Eq. (28) is transformed using water–cement ratio as follows.

$$q_u = K \frac{1}{\left\{1 + \left(\frac{w}{c}\right)\frac{1}{G_c}\right\}^N} \tag{29}$$

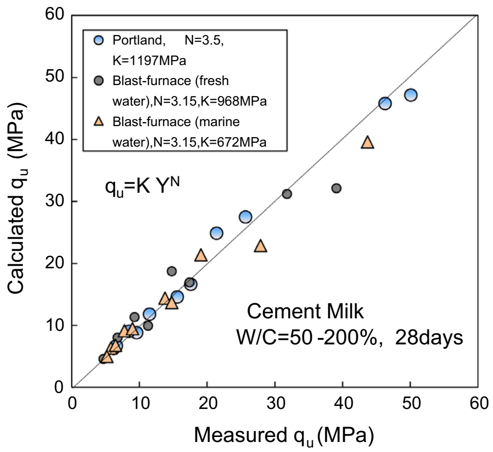


Fig. 28. Comparison between measured strength and predicted strength by Eq. (28) (Cement milk).

where (w/c) is water–cement ratio and G_c is specific gravity of cement. Accordingly, in the case of cement milk, Eq. (19) indicates that the strength is determined by the water–cement ratio.

Thus, although Eq. (19) is proposed to show the relationship between the strength of cement-treated soil, added cement rate and the volumetric solid content for cement-treated soil, it can be used to estimate the strength of concrete and cement milk.

5. Conclusion

In this study a new formula to estimate the strength of cement-treated clay using dredged marine clays was proposed. The applicability of the formula for cement-treated clays and lightweight treated soils was examined. The conclusions are summarized as follows.

(1) A new formula to estimate the strength of cement-treated soil was presented, based on an empirical equation presented by Miyazaki et al. (2003) and the gel–space theory. The formula is shown as:

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

where Y is the volumetric solid content, including mass of added cement.

(2) The fitting of the proposed formula to six marine clays was evaluated. The value N was determined when the coefficient of determination was at its maximum for the linear $q_u - Y^{-\mathrm{N}}$ relation based on the least square method. It was found that the proposed formula fit the experimental data for mixture proportion tests of all the soils with greater values of coefficient of determination. The measured unconfined compressive strengths for all six soils agreed fairly well with the strengths calculated by the proposed formula. The values of N ranged from 3.5 to 4.6.

(3) The proposed formula is applicable to foam-treated soil and beads-treated soil. The values of N determined by the fitting were from 2.1 to 2.5, and the difference from 3.5 to 4.6 of cement-treated soil may reflect the structures of lightweight treated soils.

(4) The applicability of the proposed formula was examined by comparing calculated results with the results of strength tests carried out for the design of cement-treated soil for the project of D runway of Tokyo's Haneda Airport, in which seven samples collected in the construction sites were mixed with different amounts of cement and different levels of initial water content. The proposed formula estimates the measured strength of cement treated soil fairly well. On comparing these with estimates using a conventional formula based on water–cement ratio, the proposed formula was clearly a better fit.

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