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Strength and stiffness of cement-treated marine dredged clay at various curing stages

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HIGHLIGHTS

- q_u development of cement-treated clay with curing time is similar to G_0 development.
- A trend of development of q_u and G_0 changes before and after 3 days of curing time.
- q_u and G_0 can be correlated with the normalized specific volume of cement treated clay.
- A new equations to estimate the q_u of cement-treated clay are proposed.

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ABSTRACT

This paper evaluates the unconfined compressive strength (q_u) and stiffness (G_0) of marine dredged clay treated by ordinary Portland cement. Although the cement-treated marine dredged clays have been used as filling materials for construction or reclamation, many of previous studies were more applicable to soft foundation improvement methods such as deep cement mixing and jet grouting. This study aims to investigate how the q_u and G_0 of cement-treated marine dredged clay vary with water and cement contents at various curing times and to observe the relationship of the q_u and G_0. A series of unconfined compression and bender element tests were carried out for cement-treated Tokuyama dredged clay with different values of water and cement contents at various curing times, ranging from 5 h to 90 days and the relationship between the q_u and G_0 was examined. Specific volume normalized by that at liquid limit were applied to facilitate parametric study. The study revealed that the behavior of q_u with curing time are closely similar to that of G_0, and a trend of development of q_u and G_0 change before and after 3 days of curing time. The q_u and G_0 can be correlated with the normalized specific volume. The q_u and G_0 exhibits a linear relationship for the curing time. Based on these results, the empirical equations for estimating q_u are proposed using G_0 estimation equations and the relation between q_u and G_0. In addition, the applicability of formulas based on the relation of q_u and G_0 was evaluated using the relation of G_0 and secant modulus (E_{50}). It was confirmed that the G_0 can successfully describe the improvement effect of cement-treated marine dredged clay and can be used to effectively predict the q_u using the proposed formulas.

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1. Introduction

Every year in Japan, large amounts of clayey sediment soil that are deposited on the bottom of the sea are dredged to maintain ports and waterways [21]. Since disposal is costly and it is increasingly difficult to find suitable sites to dispose the dredged clayey soils, effectively recycling the dredged clay is a major issue. Recently, dredged clay has been reused as a reclamation material through proper treatment with ordinary Portland cement using the pneumatic flow mixing method or special working ship, where the cement-treated clay transfer through a pipeline connected to the construction site [26,34,31,15]. In addition, mixtures in which lightweight materials, Air-form or EPS, and cement are added into dredged clay have been used as a construction filling material in the backfill of quay walls [30,33].

Although the properties of cement-treated soil have been extensively examined by many researchers, these have been focused on mainly the properties of materials employed in deep mixing (DM) or jet grouting (JG) Methods [28,32,19,12]. DM or

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JG methods improve the soil of construction site that the water contents are relatively moderate, and curing time is longer than one week [23]. On the other hand, marine dredged clays have high water content about 1.2 to 1.5 times much larger than their liquid limits because in-situ water contents of normally consolidated marine clays are close to the liquid limit and they absorb some water in the process of dredging and the transportation [22,26,33]. We must monitor or predict the strength from just after mixing with cement to consider a fluidity and workability of cement-treated clay from placing equipment of pneumatic flow method or special working ship to placement point of reclamation or filling.

Traditionally, the strength of cement-treated clay has been evaluated through laboratory tests, such as the unconfined compression test and the triaxial compression test. These laboratory tests require a number of specimens at different curing times, and thus a great deal of time and cost is necessary. Hence, we considered a non-destructive bender element test, which measures the shear velocity of a single specimen, as an alternative to monitor strength development with various curing times. A bender element installed in the cap of a triaxial cell was first used as a transducer for measurement of the small-strain shear modulus of specimens in the geotechnical engineering field by Shirley and Hampton [24]. Some studies were conducted to investigate the correlation between the small-strain shear modulus or shear wave velocity determined by bender element tests and the strength of cement-treated soils [3–5,7,2,23]. In spite of the previous studies, there is no evaluation for the strength and shear modulus for the cement-treated marine dredged clay, and research to date has not suggested clear correlations to estimate strength based on the shear modulus at various curing times, ranging from 5 h to 90 days.

This study was aimed at quantifying the unconfined compressive strength (q_u) and stiffness (G_0) of cement-treated Tokuyama Port dredged clay at various curing times, ranging from 5 h to 90 days, as well as assessing the use of specific volume normalized by that at liquid limit as determination parameter to evaluate the q_u and G_0. A formula for estimating the q_u was proposed based on the correlation between G_0 and q_u. The applicability of strength estimation formulas proposed from the relation of q_u and G_0 was evaluated using the relation of G_0 and secant modulus (E_{50}).

2. Methods and procedures

Dredged clay collected in the Tokuyama Port was used in experiments to determine the engineering properties of cement-treated clay. The physical properties, such as liquid and plastic limits, ignition loss, and specific gravity of Tokuyama clay are summarized in Table 1. Tokuyama clay is typical of marine clays in Japan, which have low strength, high water content, and high compressibility. Ordinary Portland cement ($\rho_c = 3.15 g/cm^3$) was used as a binder in this study. The unconfined compression and bender element tests were performed with different initial water contents and cement contents at various curing times, as listed in Table 2. The initial water content of the cement-treated clay was set to 1.5 and 2 times the liquid limit considering the actual condition of a water content of marine dredged clays used in port and airport construction projects. Furthermore, the cement content was defined as the ratio between the mass of cement and the total solid mass, which includes the soil and cement particles, as follows:

Table 2
Mixing specifications and curing times of cement-treated clays.

Normalized initial water content (w'/w_{LL})	Cement content, c^* (%)	Curing time
1.5, 2.0	10, 20, 30	5, 7, 10, 15 (h) 1, 2, 3, 7, 28, 90 (days)

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

where m_s and m_c are the dry mass of soil and cement, respectively. Hence, the cement content defined in this study needs the more cement amount than that determined from the cement content (c) in which only the soil mass appears in the denominator of the equation ($c = m_c/m_s$) to meet same cement content. The main reason for using this definition is to confirm the development of G_0 and q_u due to the reduction of water content in accordance with an increase in the cement content at the very early curing time immediately after mixing with cement. In other words, it is likely to distinguish the both effects of increased solid content by the cement particles and the chemical reaction by the cement. The curing time was set from 5 h to 90 days to observe the behavior of cement-treated clay corresponding to short-term and long-term curing times.

2.1. Sample preparation

The samples of cement-treated clay were prepared by following the standard of test on stabilized soils in the Japanese Geotechnical Society (JGS 0821-2009), except for the mixing method. Before preparing the samples, the dredged clay was sifted through a 2-mm sieve to remove shell pieces and other coarse particles. Cement undergoes a hydration reaction, which starts the hardening of cement-treated clay, accompanied by a sudden temperature rise shortly after mixing with water. Hiramoto et al. [10] reported that the initial hydration reaction can be delayed by maintaining a low temperature during mixing after reducing the temperature of the material to 0–2 °C. In this experiment, the temperatures of the dredged clay and distilled water were controlled to 0–2 °C to prevent hardening of the cement during mixing caused by the hydration reaction. Hence, the effect of strength increase by the addition of cement particles and chemical reaction, immediately after mixing, can be considered by retarding hydration reaction of cement during mixing time. Cement milk was prepared by mixing cement and distilled water. The mass ratio of cement/water of the cement milk was kept to 1:1. However, when the little water due to much cement had to be added, i.e. $c^* = 20$ and 30% for 1.5 w'/w_{LL}, cement milk was prepared at a cement/water mass ratio of 1:0.5. After adding the cement milk into the dredged clay, the slurry was thoroughly mixed by means of a hand mixer for 2 min. At that time, the designated amount of water was added to the mixture, taking into consideration the water content of the cement milk. After that, the slurry was thoroughly mixed for 30 min using a vacuum mixer, which can avoid the decrease in water content by preventing contact with air, on ice water at 0–2 °C to maintain a low temperature. After mixing, the cement-treated clay was poured into a cylindrical

Table 1
Physical properties of dredged Tokuyama clay.

Liquid limit w_{LL} (%)	Plastic limit w_P (%)	Plasticity index I_P	Ignition loss L_i (%)	Specific gravity G_s (g/cm^3)
107.6	35.4	72.2	10.02	2.64

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