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Engineering behavior of cement-treated marine dredged clay during early and later stages of curing

Gyeongo Kang [a], Takashi Tsuchida [b,*], A.M.R.G. Athapaththu [b]

[a] Department of Civil and Environmental Engineering, Graduate School of Engineering, Hiroshima University, 1-4-1, Kagamiyama, 739-8527 Higashi-Hiroshima, Hiroshima, Japan
[b] Institute of Engineering, Hiroshima University, 1-4-1, Kagamiyama, 739-8527 Higashi-Hiroshima, Hiroshima, Japan

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ABSTRACT

Dredged clay has been re-used as a construction material, backfilling of quay walls, artificial barrier layers of waste disposal sites, and submerged embankments by proper treatment with cement. However, strength development of cement-treated clay has not been fully understood during very early and later stages of curing. In this study, vane shear and unconfined compression tests were conducted to examine the strength development of cement-treated clay under different stages of curing time, ranging from 0.5 h to 90 days. On the basis of the results, the strength development was found to be changed before and after 3 days of curing and it can be clearly divided into two stages depending on curing time; early stage ($t < 3$ days) and later stage ($t > 3$ days). The strength at 1 h curing was determined based on two indices, initial water content and specific volume of cement-treated clay normalized by water content and specific volume at liquid limit. In addition, the strength increment coefficients in early and later stages were obtained by cement content. Based on strength at 1 h curing and strength increment coefficients, two equations were developed to estimate the strength during early and later stages of curing. With the development of the formula, it is possible to determine the strength of cement-treated clays at any stage of curing.

1. Introduction

Clayey soils and mud are annually dredged in maintenance of ports and navigation channels. Dredged soils have potential negative effects on environment by the contaminants, such as organic matter and heavy metal. Owing to this, dredged soils must be classified as waste and disposed to designated waste facility. The disposal of dredged soils in designated facilities consumes considerable time and possesses economical constraints. In general, dredged soils exhibit low shear strength, high compressibility, and high natural water content higher than its liquid limit. Recently, dredged clays have been widely re-used as construction materials, filling and reclamation materials, artificial barrier layers, and submerged embankments, by proper treatment with cement (Chiu et al., 2008; Xing et al., 2009; Watabe and Noguchi, 2011). Although cement-treated soils are extensively used for many purposes, the strength development is not well known during very early and later stages of curing.

Over the past few decades, the engineering properties of cement-treated soils have been reported by many researchers (Miura et al., 2001; Horpibulsuk et al., 2003; Chew et al., 2004; Lorenzo and Bergado, 2004; Kasama et al., 2006, 2007; Zhu et al., 2007; Consoli et al., 2011; Sasanian and Newson, 2014). The solidification process of cement-treated clays is influenced by hydration and pozzolanic reactions, and interaction between the resulting hydrates and soil particles (Lambe and Whitman, 1979; Taylor, 1997; Kim and Do, 2012). The hydration reaction occurs between ordinary Portland cement and water within about 24 h (Xing et al., 2009). The pozzolanic reaction usually occurs among hydrated lime and silica and alumina from clay minerals in dredged soil. Researchers, i.e. Cheriaf et al. (1999) and Kim and Do (2012), reported that pozzolanic activity begins at 28 days. Further study is needed to determine strength development of cement-treated clays during the setting process in very early stages of curing within 24 h. This includes immediately after mixing, during transportation and placing of cement at the construction site. The setting process is a stage when primary hydrates are generated by reacting cement particle consisting of clinkers with water. After finishing the setting process, the strength of cement-treated soils increases over time. It is called "hardening".

The empirical equations proposed based on various indices have been used to predict the strength of cement-treated soils, as shown in Table 1. These indices include: 1) ratio of void ratio (after-curing) to cement content, 2) increment in mass of bound water per unit volume and increment in mass of hydration water per unit volume, 3) yield stress ratio, 4) ratio of porosity divided by the volumetric cement content, 5) activity number with cement–water ratio, and 6) volumetric solid content with cement content. However, these empirical formulas,

* Corresponding author.
E-mail addresses: geokasjb@hiroshima-u.ac.jp (G. Kang), ttuchida@hiroshima-u.ac.jp (T. Tsuchida), rasika@hiroshima-u.ac.jp (A.M.R.G. Athapaththu).

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Table 1
Empirical formulas for prediction of strength for cement-treated soils.

Testing method	Formula	Parameter	Reference
Unconfined compression test, q_u	$q_u = Ap_a e^{B(e_{ot}/A_w)}$	A and B: dimensionless constants P_a: atmospheric pressure e_{ot}: void ratio after curing time, t A_w: weight ratio of cement to dried soil (cement content)	Lorenzo and Bergado (2004)
Unconfined compression test, q_u	$q_u = 39.5(\Delta m_{hw} - 0.76)$ $= 9.5(e^{0.013\Delta m_{bw}} - 1)$ $a_c < a_{c0}$ $q_u = 0.14\Delta m_{hw}^{2.39}$ $a_c > a_{c0}$	Δm_{bw}: increment in mass of bound water per unit volume Δm_{hw}: increment in mass of hydration water per unit volume a_c: cement content per unit volume a_{c0}:threshold cement content per unit volume	Zhu et al. (2007)
Undrained triaxial compression shear test, s_u	$\frac{s_u}{p_c' + p_r'} = \alpha \times R^n$	$p_c' + p_r'$: cementation-enhanced consolidation pressure α: inclination of failure envelop in normal consolidation in p'-q space R: yield stress ratio	Kasama et al. (2007)
Unconfined compression test, q_u	$q_u = [5.45 \times 10^7(\omega) - 5.37 \times 10^8] \times [\frac{\eta}{(C_{iv})^{0.35}}]^{-3.60}$	ω: molding water content η/C_{iv}: porosity (η) divided by the volumetric cement content (C_{iv})	Consoli et al. (2010 and 2011)
Laboratory vane shear test, s_u	$\frac{c_{u,28\ days}}{P_a} = 125.24\beta^2 + 7.47\beta + 0.42$	β: parameter activity number with cement–water ratio ($A^{2.7} \cdot c/w$)	Sasanian and Newson (2014)
Unconfined compression test, q_u	$q_u = k_c^*(c\text{-}c_0^*)Y^N$	k_c^*: strength increment factor c^*: cement content c_0^*: threshold cement content Y: volumetric solid content N: exponential parameter on void structure of cement-treated clay	Tsuchida and Tang (2015)

which evaluate the strength of cement treated soils, are only available for data after 3 days and therefore, a study is required to estimate the strength during early ($t < 24$ h) and later ($t > 24$ h) stages of curing.

In this study, the strength development of cement-treated dredged clays was explored at different curing times ranging from 0.5 h to 90 days. A series of laboratory vane shear and unconfined compression tests was carried out on marine dredged clay mixed with various proportions of cement and water contents. Based on the results, two formulas for estimating the strength of cement-treated dredged clays during early and later stages of curing were proposed based on the strength at 1 h of curing and strength increment coefficients. In addition, the formula proposed based on specific volume was transferred to the same format of that proposed by Tsuchida and Tang (2015) based on volumetric solid content. Applicability of developed formulas were verified based on previous literature.

2. Sample preparation and laboratory tests

2.1. Sample preparation

Dredged clays were collected from Mizushima, Hibiki, Moji, and Tokuyama Ports in Japan, as shown in Fig. 1. The physical properties such as liquid limit, plastic limit, plasticity index, ignition loss, and particle density are summarized in Table 2. The ordinary Portland cement

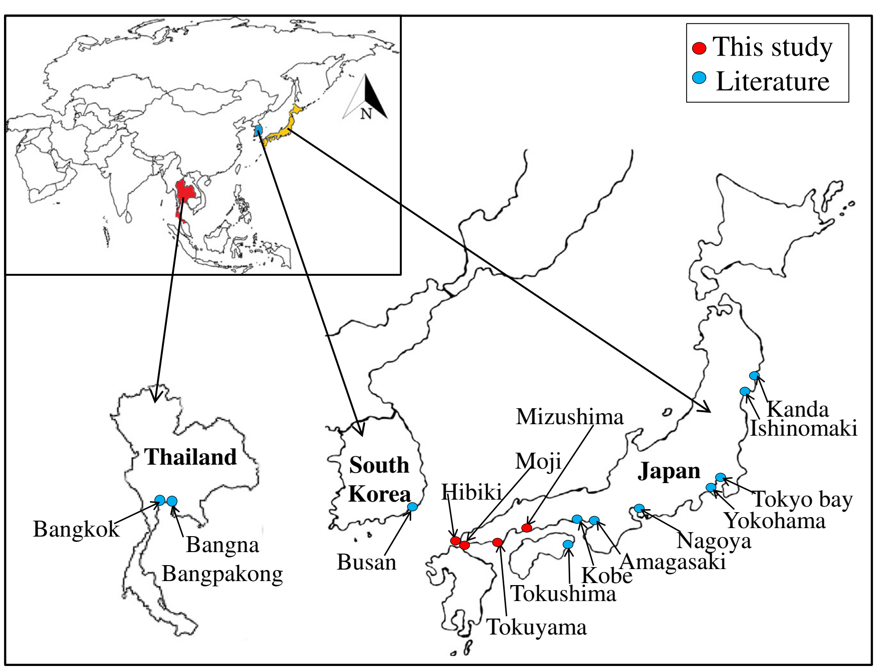

Fig. 1. Collection places of clays analyzed in this study.