Soils and Foundations 2014;54(5):1018–1026

HOSTED BY

ELSEVIER

CrossMark

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

Modeling compression behavior of cement-treated zinc-contaminated clayey soils

Yan-Jun Du[a,1], Suksun Horpibulsuk[b,*], Ming-Li Wei[a,1], Cherdsak Suksiripattanapong[b], Martin D. Liu[c]

[a]*Institute of Geotechnical Engineering, Southeast University, China*
[b]*School of Civil Engineering, Suranaree University of Technology, Thailand*
[c]*Faculty of Engineering and Information Sciences, The University of Wollongong, Australia*

Available online 16 October 2014

Abstract

In this paper, the compression behavior of cement-treated soil with various cement contents and zinc concentrations is presented and modeled by the destructuring framework and the concept of the Intrinsic Compression Line (ICL). The void ratio of a cement-treated sample with Zn contamination is the sum of the void ratio sustained by the intrinsic soil fabric (destructured void ratio) and the additional void ratio due to cementation. The compression index at the pre-yield state, C_s, increases as the Zn concentration increases or as the cement content decreases. At the post-yield state, the additional void ratio is inversely proportional to the effective vertical stress. The rate of reduction in the additional void ratio is controlled by the destructuring index, b. The values for b and yield stress are mainly dependent upon the degree of cementation, which is controlled by the cement content and the Zn concentration. Based on a critical analysis of the test data, a practical (simple and rational) method for assessing the compressibility of cement-treated soil with various Zn concentrations is suggested. The proposed predictive method is useful not only for quickly determining compression curves, with acceptable errors, but also for examining the results of tests on cement-treated zinc-contaminated soil.

Keywords: Cement-treated soil; Compression curve; Contaminated soil; Destructuring

1. Introduction

Recently in China, a large number of chemical plants have been relocated from major cities to suburban areas due to revised industrial policies which aim to reduce the environmental impact caused by the insufficient control of discharged wastes from such plants. Most of the original sites are rich in heavy metals such as zinc, lead, chromium, and copper (Chen et al., 2011). These soils contaminated by heavy metals are not only hazardous to the environment and human health, but also lead to a reduction in the bearing capacity of foundations (Khan et al., 2004). For these reasons, it has become necessary to adopt effective and economical remediation technologies to treat the soils contaminated by heavy metals.

Solidification/stabilization (*S/S*) is a widely used remediation technology, which involves mixing the contaminated soils

*Corresponding author. Tel.: +66 44 224322; fax: +66 44 224607.
E-mail addresses: duyanjun@seu.edu.cn (Y.-J. Du), suksun@g.sut.ac.th (S. Horpibulsuk), weimingli830716@sina.com (M.-L. Wei), cherdsak_2526@hotmail.com (C. Suksiripattanapong), martindl@uow.edu.au (M.D. Liu).
[1]Tel.: +86 25 83793729; fax: +86 25 83795086.
Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2014.09.007
0038-0806/

with additives to reduce the contaminant leachability and to improve their mechanical properties by physical and chemical means (Chen et al., 2011; Du et al., 2012a, 2012b, 2013, 2014a, 2014b). Solidification can encapsulate the soils contaminated by heavy metals in a monolithic solid with high structural integrity and enhanced mechanical properties, such as unconfined compressive strength (Chen et al., 2009; Du et al., 2012a, 2012b).

Studies in literature have proven that the types and the concentrations of heavy metals considerably affect the strength of cement-based solidified/stabilized contaminated soils (Chen et al., 2011; Du et al., 2012a, 2012b, 2013; Mulligan et al., 2001; US EPA, 2004). Previous works have shown that the presence of zinc oxides retards the cement hydration, resulting in a reduction in strength of cement-based materials (Chen et al., 2009; Stegemann and Buenfeld, 2002; Zhou et al., 2009). The retardant effect is attributed to the precipitation of calcium zincates ($Ca[Zn(OH)_3H_2O]_2$) due to the interaction between zinc and cement components (mostly in the form of tricalcium silicate, C_3S), which wrap around the cement particles (coating effect) and form a barrier between the cement particles and water (Yousuf et al., 1995; Du et al., 2012a, 2013). As a result, the formation of cementitious products, such as calcium silicate hydrates (CSH), is suppressed and this causes a reduction in strength.

Most researchers have merely focused on the effect of the types of heavy metal and the concentration levels on the development of strength in the cement-treated zinc-contaminated soils (Chen et al., 2011; Du et al., 2012b, 2013, 2014a, 2014b), while studies on the compression behavior of cement-treated soils contaminated by heavy metals are very limited.

Burland (1990) proposed the concept of an Intrinsic Compression Line (ICL) based on numerous oedometer tests on reconstituted clay at initial water contents of 1.0 to 1.5 times the liquid limits (mostly 1.25 times). He also proposed the concept of a sedimentation compression line (SCL) for natural sedimentary clays. The effect of the soil structure (fabric and bonding) on the compression characteristics of natural structured clays was successfully assessed by comparing the location of the oedometer compression curves of structured soils to the ICL and SCL in a semi-logarithmic diagram of the void index (I_v) versus the compression stress (p, kPa). The concept has been shown to be powerful for analyzing and assessing the compression behavior of reconstituted clays (Horpibulsuk et al., 2011c; Liu et al., 2013).

Chiu et al. (2009) investigated the effect of the cementation structure on the compression behavior of cement-treated sludge by referring to the ICL. Tremblay et al. (2001) evaluated the influence of the organic content on the compression characteristics of lime-treated natural sedimentary clays with reference to the ICL and SCL. Horpibulsuk et al. (2004) proposed a generalized compression line for cement-treated soils using the ICL as a framework. Based on the ICL concept, Liu and Carter (1999 and 2000) proposed a destructuring framework to predict the compression curves of various structured soils. Their method has been extended to predictions of the compression curves for natural structured Bangkok clay with various degrees of sample disturbance (Horpibulsuk et al., 2007), cement-treated clay (Horpibulsuk et al., 2010; Suebsuk et al., 2011) and cellular lightweight cemented clay (Horpibulsuk et al., 2013).

To the authors' knowledge, only a very limited number of studies have been done on the applicability of the ICL concept and the destructuring framework for modeling the compressibility behavior of cement-treated soils contaminated by heavy metals. The compressibility behavior is an important issue for the deformation analysis of geotechnical structures and for the theoretical modeling of the soil behavior (e.g., Burland, 1990 and Horpibulsuk et al., 2010). Accordingly, the objectives of this study are (1) to investigate the influence of the zinc concentration and the cement content on the compression characteristics (consolidation yield stress σ'_y and compression index at pre- and post-yield states) of cement-treated zinc-contaminated soil; (2) to estimate the compression curves of cement-treated soil at various degrees of cementation, i.e., cement contents and Zn concentrations; and (3) to propose a practical (simple and rational) method for assessing the compression curves of cement-treated soil at various degrees of cementation.

2. Materials and methods

2.1. Testing materials

The soil used in this study was collected from Lianyungang City of Jiangsu Province in China. The natural water content was 45% and the specific gravity was 2.72. The liquid and plastic limits were 55% and 26%, respectively. The soil consisted of 4.8% sand, 69.5% silt, and 25.7% clay. Based on the Unified Soil Classification System (USCS), the soil was classified as high plasticity clay (CH). The grain size distribution was measured using a laser particle size analyzer. The main clay mineral compositions were a illite-smectite mixed layer mineral, illite, and kaolinite (Liu et al., 2011). The dominant ions in the soil pore water were sodium and chloride (Liu et al., 2011). Locally produced cement was used as a binder. The major chemical compositions of the cement were 49.18% calcium oxide (CaO), 26.01% silica (SiO_2), and 10.61% aluminum oxide (Al_2O_3). Based on ASTM C150, the cement was classified as Portland cement Type I. In this study, zinc (Zn) was selected as the target heavy metal because it is commonly encountered at contaminated sites in China (Chen et al., 2011; Du et al., 2012a). A zinc nitrate ($Zn(NO_3)_2$) solution, which was used to make the artificial zinc-contaminated soil, was prepared by dissolving the zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$) powder (Analytical Reagent grade) in the distilled water. The reason for choosing nitrate is that it is inert for cement hydration (Cuisinier et al., 2011).

2.2. Sample preparation and testing methods

To prepare the cement-treated zinc-contaminated soil samples, oven-dried soil was firstly mixed thoroughly with a predetermined volume of $Zn(NO_3)_2 \cdot 6H_2O$ solution to reach the initial water content of approximately 60%. Cement