Applied Clay Science 146 (2017) 316–324

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Research paper

Deformation characteristics and stress responses of cement-treated expansive clay under confined one-dimensional swelling

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ARTICLE INFO

Keywords:
Expansive clay
Cement-treated soil
One-dimensional compression
Lateral coefficient of earth pressure
Swelling pressure

ABSTRACT

This study presents an investigation of the effects of cement addition to expansive clay on its deformation characteristics and stress responses during swelling. The effects were evaluated by focusing on the unconfined compressive strength, swelling-shrinkage strains under various conditions, and the lateral coefficient of earth pressure during one-dimensional deformation for artificial mixtures of two different clays at three different ratios. The clays used in this study were a Na-montmorillonite bentonite and a non-expansive Bangkok clay, mixed at different proportions to simulate naturally encountered expansive clays with different degrees of swelling potential. The experimental programme involved unconfined compression, areal shrinkage strain by unconfined drying, vertical free swelling strain, and confined swelling pressure tests. The experimental results show that the cement addition led to marked decreases in the areal shrinkage strain and vertical free swelling strain in addition to the obvious improvement of strength and stiffness of soils. The confined swelling pressure test results indicated that the cement had a greater effect in reducing vertical swelling pressure than the lateral swelling pressure of the soils during one-dimensional swelling. The measured lateral coefficient of earth pressure and stress paths of untreated and cement-treated soils and their engineering implications are discussed.

1. Introduction

Expansive soils exhibit significant swelling and shrinkage upon changes in water content and stress conditions. The swelling and shrinkage phenomenon of expansive soils is considered as serious and challenging problems in geotechnical engineering due to the potential damages arising from unpredictable upward movements and large settlement of structures founded on such soils undergoing moisture content fluctuations (Nelson and Miller, 1992; Al-Rawas et al., 2005; Puppala et al., 2013). According to Katti et al. (2002), Ferber et al. (2009), and Mohamed et al. (2013), soils' swelling potential depends mainly on nature and state of soils (i.e., clay fraction, mineralogy, dry density, water content, etc.) determining the amount of water intake. The predominant mineral content in an expansive soil is often montmorillonite, which causes the soil to swell and shrink during wetting and drying (Komine and Ogata, 1999; Radhakrishnan et al., 2014). The swelling and shrinkage movement or a change in swelling pressure of expansive ground does not take place only in the vertical direction (Mohamed et al., 2013; Wang et al., 2015). Expansive soils swell laterally as well as vertically. As reported by Andy (1989) the lateral swelling pressure could be 2–10 times larger than the vertical swelling pressure, depending on the conditions. If these pressures are greater than the foundation resistance or retaining wall capacity, then uplifts, often uneven and differential, and/or horizontal movements will occur. This might cause cracks or damage to structures. Retaining structures, in particular, are normally not designed to endure the enormous swelling pressure.

Recently, measuring and assessing the swelling deformation and pressure are given a particular importance in designing foundations on expansive soils. In evaluating the swelling pressure, some researchers suggest a technique that allows soil to heave until attaining the equilibrium and then apply pressure to bring it back to the original volume (Katti et al., 2002), while other researchers propose zero swelling (constant volume) tests and one-dimensional consolidation tests for predicting heaves in swelling soils (Fredlund, 1969; Basma et al., 1995; Al-Shamrani and Dhowian, 2003; Wang et al., 2012; Rao and Ravi, 2015). However, these methods generally concern only the vertical swelling pressure measurement. There is still no systematic knowledge that allows the designer to predict the lateral swelling pressures on geotechnical structures due to swelling soils (Mohamed et al., 2013).

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http://dx.doi.org/10.1016/j.clay.2017.06.022
Received 22 March 2017; Received in revised form 21 June 2017; Accepted 23 June 2017
0169-1317/

For non-swelling soils, on the other hand, the established theory of earth pressure based on force equilibrium and perfect plasticity may be adopted without a particular need to consider the additional pressure due to the mineral swelling. Therefore, many geotechnical projects opt for excavating and replacing the entire expansive soil or to improve them comprehensively. Much more cost-effective measures would be devised, however, if it is understood how the stress responds during swelling, and how the responses may be altered by more modest means such as adding a limited dose of binding agents such as lime or cement.

The lateral coefficients of earth pressure of different soils under various conditions have been investigated by some researchers; e.g. Katti et al. (2002) on the lateral earth pressure of the expansive black cotton soil, Tian et al. (2009) on the coefficients of earth pressure at rest in thick and deep layers of swelling clay. However, research on the lateral coefficient of earth pressure of expansive soils is still limited in number and scope. This research aims to understand and evaluate the effect of cement addition on curbing the undesirable swelling pressure of expansive problematic soils through a variety of readily measurable mechanical quantities as well as close observation of the effective stress path obtained by more elaborate tests. The investigation mainly focuses on the strength-stress-strain characteristics and the earth pressure responses in expansive soils under one-dimensional swelling with and without cement treatment. The latter is expressed in terms of the lateral coefficient of earth pressure (K_s). Artificial expansive soil specimens were prepared for mechanical testing by mixing a Na-montmorillonite bentonite with non-expansive Bangkok clay at different proportions to observe responses of soils with different swelling potentials. In addition to swelling tests in the specially designed oedometer, a number of more conventional laboratory experiments were performed on both cement-treated and untreated soils. Based on the results from these different tests, this paper presents observations on general effects of cement addition on mechanical responses of expansive soils.

2. Experimental programme

2.1. Materials

The expansive soil specimens tested in this study were artificially prepared by mixing a commercially available Na-montmorillonite bentonite with natural non-expansive Bangkok clay, which is locally found in the central of Thailand. Bangkok clay is a soft marine silty clay, characterised by high water content, low shear strength, and high compressibility (Horpibulsuk et al., 2011; Surarak et al., 2012). Na-montmorillonite has low permeability and marked expansibility due to its stacked-lamellar structure (Por et al., 2015). Bangkok clay is a clay with low swelling potential exhibiting physical and engineering properties similar to those of kaolin, while Na-bentonite is a clay with a very high swelling potential. In this study, the Bangkok clay was firstly air-dried for about one week. It was then crushed and sieved through a No. 40 sieve (425 μm). The mixing proportions between the bentonite and Bangkok clay (in the form of powder) were varied at 40:60, 20:80 and 0:100 by dry weight. Ordinary Portland cement was added at 5% and 10% of the dry soil mixture (i.e. bentonite plus Bangkok clay) by weight. Unless specified otherwise, the mixed soils with and without cement treatment were compacted at the optimum moisture content (OMC) and maximum dry density (MDD) of the untreated states, which were obtained from a modified compaction test (ASTM D1557). The compacted specimens were prepared for the unconfined compression, the vertical free swelling strain and the confined swelling pressure tests after 28 days of curing. The index properties and physical properties of compacted untreated soils were determined by following the ASTM standards, as presented in Table 1. Chemical compositions of materials were analysed by X-ray fluorescence (Bruker AXS, Germany model S4 Pioneer Wavelength dispersive X-Ray Fluorescence [WDXRF] Spectrometry). Table 2 lists the chemical composition of bentonite, Bangkok clay and cement obtained by the X-ray fluorescence (XRF) analysis.

Table 1
Experimental conditions and properties of compacted cement-untreated soils.

Sample notation	BKK:B (%)	Initial state: 100% degree of compaction at modified compacted energy				Index properties			
		OMC (%)	ρ_d (Mg/m^3)	e_0	S_{r0} (%)	LL (%)	PI (%)	G_s (−)	A (−)
BKK100B0	100:0	15.50	1.70	0.55	74	72	41	2.64	0.55
BKK80B20	80:20	16.60	1.67	0.61	73	102	65	2.69	0.92
BKK60B40	60:40	20.50	1.60	0.73	78	191	152	2.76	2.23

Remarks: BKK = Bangkok clay content by weight (%); B = Bentonite content by weight (%); OMC = optimum moisture content (%); ρ_d = dry density of a compacted soil at OMC by a modified compacted energy (Mg/m^3); e_0 = initial void ratio; S_{r0} = initial degree of saturation (%); LL = liquid limit (%), PI = plasticity index (%); G_s = specific gravity; A = activity number.

Table 2
Percentage of chemical composition of bentonite, Bangkok clay and cement obtained from XRF.

Chemical composition	Bentonite (%)	Bangkok clay (%)	Cement (%)
SiO_2	50	63	21
Al_2O_3	19	21	5
FeO	15	8	4
CaO	5	–	65
MgO	3	2	1
K_2O	–	3	1
Na_2O	3	1	–
Others	5	3	4

More details on physical properties of these soils are given by Por et al. (2015).

2.2. Testing methods

The experimental programme is summarised along with the sample notation in Table 3. The experimental programme is consisted of unconfined compression (UC), areal shrinkage strain (ASS), vertical free swelling strain (VFSS), and confined swelling pressure (CSP) tests, as well as the index properties tests. A brief summary of the laboratory procedures and equipment used are presented in the following sections.

2.2.1. Unconfined compression (UC) test

The unconfined compressive strength (q_u) and Young's modulus at half the failure stress (E_{50}) of the untreated and cement-treated soils were obtained by performing conventional unconfined compression tests according to ASTM D2166. The specimens were trimmed to 70 mm diameter and 150 mm height and tested at a loading rate of 0.75 mm/min after the 28-day curing.

2.2.2. Areal shrinkage strain (ASS) test

The soils at different mixing proportions, with and without cement as shown in Table 1, were prepared in the form of powder and then uniformly mixed with water content at the liquid limits (w_L) of the cement-untreated states, and placed in a 120 mm × 20 mm × 5 mm mould. The soil specimens were cured for 28 days in advance to allow the cement hydration. The soil specimens in the mould were then firstly air-dried in a controlled temperature room of 30 ± 1 °C and a relative humidity of 50 ± 2% for 7–10 days to reach a stable moisture content. At this stage, cracks formed in the soil specimens in irregular patterns, as shown in Fig. 1. Image analysis was then performed to determine the area (projected to a plane which included the largest cross-section, 120 mm × 20 mm, of the specimens) of the void increment after air-drying (A_c) and the area of the sample before cracking (A_t). The testing