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Evaluation of the influence of salt concentration on cement stabilized clay by electrical resistivity measurement method

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ABSTRACT

The influence of salt concentration on the cementation process of cement stabilized clay is studied using the electrical resistivity measurement. The clay with various sodium chloride salt concentrations was prepared artificially and stabilized by Ordinary Portland cement with different contents. A series of electrical resistivity tests and unconfined compressive strength tests of cement stabilized clay specimen after curing for 28 days were carried out. The electrical conductivity and pH value of pore fluid of the cement stabilized clay were also measured, and the microstructure of the samples was investigated by a scanning electron microscope. The results indicate that a high salt concentration has a detrimental effect on the unconfined compression strength of cement stabilized clay and results in a low electrical resistivity. A good linear relationship between the unconfined compression strength and the electrical resistivity of cement stabilized clay was observed. A unique exponential func'tion well adapts electrical resistivity values with cement content and salt concentration. The porosity-salt concentration/cement content ratio is an appropriate parameter to assess the electrical resistivity of the cement treated salt-rich soil investigated. The electrical resistivity measurement can be used as a non-destructive and both time and cost effective method to evaluate the quality of cement stabilized soft clays in practice.

1. Introduction

Due to increased urbanization and industrialization, foundation soils with suitable geotechnical properties are not easily available. There is a growing demand for construction on soft soil ground, which is characterized by high plasticity, high water content and void ratio, low strength and high compressibility. For such soils, deep mixing is a popular method for improving the strength. In the deep mixing method, powder cement or slurry cement is injected into the natural soil at the required depth and a blade is pushed into the ground to mix the soil and cement. Many deep mixing projects have demonstrated that the method has obvious advantages, such as easy and rapid installation and relatively small vibration. More importantly, it can effectively reduce the settlement and increase the stability of soft ground (Broms and Boman, 1975; CDIT, 2002; Han et al., 2002; Liu and Hryciw, 2003). Many researchers have performed experimental studies on the fundamental mechanical properties and engineering behavior of cement stabilized soils (Miura et al., 2001; Horpibulsuk et al., 2003; Terashi, 2003; Lorenzo and Bergado, 2004; Larsson et al., 2005). However, very limited studies have been conducted to reveal the effect of salt concentration on the strength of cement stabilized soils, so the characteristics of the cement stabilized clay with high salt concentration were still not clear. An adequate understanding of the mechanism of salt concentration influence on the cement hydration process and pozzolanic reactions is also necessary for a successful deep mixing ground improvement project in salt rich soft clay.

The engineering properties of cement stabilized clay were traditionally studied using standard penetration test and the unconfined compression strength (UCS) test method in China. Some limitations were pointed out, such as the time and cost ineffective and destructive disadvantages (Liu et al., 2008). The use of resistivity measurement has been shown to be an effective tool for characterizing soil and porous rock in geotechnical engineering practice recently due to its economical, non-destructive, and relatively non-invasive advantages (Fukue et al., 1999; Liu et al., 2008; Bryson and Bathe, 2009). The applicability of the electrical resistivity method has been validated by in situ resistivity cone penetration test or laboratory model investigation. Literatures show that electrical resistivity can be used to investigate the mechanical properties of soils (Archie, 1942; McCarter, 1984; Samouëlian et al., 2005; Bryson and Bathe, 2009; Russell and Barker, 2010; Seladji et al., 2010), to trace the spatial characteristics of solute transport in natural soils (Andrew et al., 1996; Damasceno and Fratta, 2006), and to monitor and delineate contaminants in the subsurface (Yoon and Park, 2001; Grellier et al., 2007). Genelle et al. (2012) reported that electrical

Abbreviations: UCS, unconfined compression strength; SEM, scanning electron microscope; CAH, calcium alluminate hydrate; CSH, calcium silicate hydrate.

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resistivity tomography was a good means of detecting defects and heterogeneity in the landfill cover material both when it was put in place and subsequently. For the cementitious materials, Taylor and Arulanadan (1974), Tashiro et al. (1994), and McCarter et al. (2003) observed the electrical responses of the cementitious hydration systems using an alternating current impedance spectroscopy. Li et al. (2003, 2007) and Xiao and Li (2009) used a noncontact electrical resistivity measurement method to understand the cement hydration mechanism and to correlate electric resistivity to concrete setting time. Miao et al. (2003) and Liu et al. (2008) studied electrical resistivity of laboratory prepared soil–cement admixtures and indicated that it had a good relationship with unconfined compression strength. Sirieix et al. (2002) and Lataste et al. (2003) verified the electrical resistivity measurement allowing the detection, location, and characterization of cracks in concrete. However, very few studies have been conducted on the effect of salt concentration on the electrical resistivity of cement stabilized clay.

This study focused on the effect of salt concentration on the electrical resistivity characteristic of the cement treated clay. For the purpose of obtaining a clear mechanism understanding of the effect of salt concentration on the electrical resistivity of cement stabilized clay, microstructure analysis is also conducted. In summary, the scope of the current investigation is (1) to identify the effect of salt concentration on the electrical resistivity of cement stabilized clay; (2) to correlate the electrical resistivity to the parameters of cement stabilized salt-rich soil; and (3) to understand the mechanism with the microstructure analysis.

2. Materials and method

2.1. Materials

2.1.1. Soil sample

Lianyungang marine clay used in this investigation was obtained from Liezikou bridge construction field, Guannan Prefecture, Jiangsu Province, China. Clay was sampled at 2.0 m depth under the ground surface. Properties of the Lianyungang marine clay samples are shown in Table 1. The clay has a high plasticity with a liquid limit of 58.7% and a plastic limit of 33.8%. The total salt concentration and ignition loss are quite high, with values of 46.16 g/L and 16.5%, respectively. The clay fraction (<0.005 mm) and silt fraction (0.075–0.005 mm) are 43.7% and 53.5%, respectively, which indicates that the Lianyungang marine clay is composed of silt and clay fractions. Table 2 presents the chemical analysis results of pore water of Lianyungang marine clay. The result shows that the dominant salt composition in the pore water is sodium chloride. To investigate the mineral composition of the soft soil, a compositional analysis was performed to obtain chemical compositions of the soft soil, as listed in Table 3. Tables 1 through 3 indicate that the Lianyungang marine clay not only has high water content, high void ratio, and high compressibility, but also contains much higher contents of sodium chloride salt (Liu et al., 2011).

2.1.2. Cement

Ordinary Portland cement type I was used to investigate the effect of cement content (the ratio of cement weight to weight of the dry soil, termed as a_w) on the strength of stabilized clay. The chemical composition of cement is listed in Table 4.

2.2. Test method

2.2.1. Unconfined compression strength test

In order to investigate the effect of salt concentration, the clays were treated to eliminate the salt by the wash method (Xing et al., 2009). The wash method was applied as follows: the Lianyungang marine clay from the construction field was air-dried, crushed down, sieved, and dipped in distilled water for 24 h. Salt in the soft soil was cleaned out after cleaning for 5 times. After that, a different content of sodium chloride salt was added into the washed soil and mixed thoroughly for 10 min by a miniature mixing machine. Their sodium chloride salt concentration (the ratio of sodium chloride salt weight to weight of the dry soil, termed as C_s) was 2.5%, 5.0%, 7.5% and 10.0%, as listed in Table 5.

The clay was then mixed with 10, 15 and 20% cement by mass of dry soil. In order to eliminate the effect of difference in water content, the samples were prepared to be at the same water content of 70% (i.e. 1.2 times liquid limit) by adding the distilled water in clay. All samples were compacted by hand vibrating to eliminate the entrapped air. The samples, cured at temperature about 20 °C and humidity of 95%, were 50 mm in diameter and 100 mm in height. The unconfined compression tests were conducted on specimens at curing periods of 28 days according to the procedure of ASTM D2166-06. In order to compare with the strength of undisturbed Lianyungang marine clay, unconfined compression test of undisturbed natural soft clay was also performed according to the same procedure.

2.2.2. Electrical resistivity test

Before the UCS test, the electrical resistivity of the cement treated clay specimen was measured using the Gwinstek LCR-816 apparatus with a plate two-electrode method. Two copper electrodes, with a diameter of 50 mm and thickness of 2 mm, were placed on the top and at the bottom of the cylinder specimens during the measurement of the electrical resistivity. A vertical pressure of 5 kPa was applied on the copper probes to make a well contact condition between the copper electrodes and specimens. This pressure was found to have a negligible effect on the shear strength of the samples. All of the measurements of the electrical resistivity were performed under the controlled temperature of 20 ± 2 °C.

The schematic of this test method is shown in Fig. 1, and the electrical resistivity of specimen, ρ (Ω·m), is calculated based on the following equation:

$$\rho = \frac{\Delta U}{I} \cdot \frac{S}{L} \tag{1}$$

in which ΔU = the electrical voltage applied to the soil (V), I = the electrical current (A), S = the cross-section area (m^2) through which electrical current conducts, and L = the length (m) of the cement-stabilized clay specimen parallel to the electrical current.

It has been found experimentally (Arulanandan, 1991; Rinaldi and Cuestas, 2002) that the electrical resistivity of soil depends on the frequency range at which they are measured. At high frequencies, variations in the electric field for clayey soils cause ions to be released from

Table 1
Properties of Lianyungang marine clay.

Water content (%)	Density (g/cm^3)	Special gravity	Void ratio, e	Liquid limit (%)	Plastic limit (%)	Plasticity index
58.3	1.679	2.72	1.681	58.7	33.8	24.9

Particle size distribution, %			pH	Total salt concentration (g/l)	Organic matter (%)
Sand (>0.075 mm)	Silt (0.075–0.005 mm)	Clay (<0.005 mm)			
2.8	53.5	43.7	7.8	46.16	1.1