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Research paper

Influence of voltage and temperature on electro-osmosis experiments applied on marine clay

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ABSTRACT

A series of electro-osmosis experiments were conducted to explore the effect of voltage and temperature on the electro-osmosis properties of marine clay, including current, average consolidation degree, horizontal shrinkage, shear strength, water content, and anode corrosion. As shown for the resistivity of marine clay, the temperature increased when the electro-osmosis phenomenon occurred. From mechanical and electro-chemical point of view, this study explained the differences in the average consolidation degree and horizontal shrinkage under various experimental conditions. Although a voltage loss appeared due to the anode corrosion, the high voltage and temperature were still found beneficial for the reduction of the soil water content and the increase of shear strength. Furthermore, the electro-osmosis effect at high voltage included the contribution of joule heating.

1. Introduction

The disposal of the marine clay generated from the development of coastal cities and the breakneck construction of ports is a challenge. Most marine clays not only contain a certain amount of water and salt but also have a low permeability. Several methods exist to decrease the marine clay moisture content. The dewatering effect of the vacuum method is limited because the maximum negative pore water pressure that can be applied is less than −80 kPa. In addition, the vacuum conditions are very difficult to control (Peng et al., 2013). The preloading method applied to decrease the soil water content is time-consuming (Sun et al., 2014) and it results in limited improvement. In comparison, the advantages of electro-osmotic method are obvious. This method has a high dewatering capacity, even for soil with small particle sizes (Jones et al., 2011). The principle of this method is to drive the pore water from the anode to the cathode when an electrical field is applied. Consequently, an electro-osmosis water flow is formed by direct current. Parallel, the electrophoresis of negatively-charged clay particles towards the anode is significant in slurry because of the consistency but it is not obvious in clay-rich soil (Alshawabkeh et al., 2004).

Electro-osmosis had been successfully used in many drainage applications on different materials, such as clay-rich soil (Estabragh et al., 2014; Karunaratne, 2011; Lefebvre and Burnotte, 2002), sewage sludge (Citeau et al., 2011), wastewater sludge (Olivier et al., 2015), activated sludge (Olivier et al., 2014; Saveyn et al., 2005), dredger (Sun et al., 2014), and marine sludge (Xue et al., 2015). A number of scholars studied the influence of operational parameters on the effect of electro-osmosis. Mahmoud et al. (2011) combined voltages (10 to 50 V) with pressures (200 to 1200 kPa) as experimental parameters to conduct electro-osmosis experiments on the wastewater sludge. Lee et al. (2007) designed an electro-osmosis filter press and then employed different voltages, durations, and loading pressures in the treatment of wastewater sludge. They discovered that voltage and loading pressure had a positive correlation with dry content. In other words, the higher these two parameters were, the higher the dry solid content was. Parallel, other authors investigated the electrode impact by testing different anode types and their placement. Yoshida and Okada (2006) found that the insertion of anode into sludge and by keeping it vertical with the cathode, could improve the electro-osmosis effect. Yu et al. (2010) applied a stainless steel cathode with a small pore size on the basis of a comparison with the effect of filter cloth placed on the cathode to dewater activated sludge. Xue et al. (2015) compared the effects of three anode materials and found that iron performed better than copper and aluminum while Mohamedelhassan and Shang (2001) found that copper was the best materials among copper, iron and graphite. Wu et al. (2015) reported also that copper exhibited the best performance for electro-osmosis in bentonite. In addition, Citeau et al. (2011) investigated the influence of salt, pH, and polyelectrolytes on the electro-osmosis of sewage sludge and several authors (Ou et al., 2015; Peng et al., 2015) tested an injection of saline solution during electro-osmosis to increase the shear strength of clay. All the results demonstrated that

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appropriate anode, electrode placement method, and electro-osmosis conditions have to be chosen adequately and such parameters usually depend on the material properties.

To explore the phenomenon of electro-osmosis, different voltages may be tested in electro-osmosis experiments with various loading pressures (Mahmoud et al., 2011; Pham-Anh et al., 2012). Furthermore, an obvious increase in temperature during electro-osmosis experiments is usually observed when the tested material presents low electrical resistivity (Navab-Daneshmand et al., 2015) such as silty clay (Chen et al., 2002). The electrical resistivity of clay may vary with water content, saturation, temperature, and liquid limit (Kibria and Hossain, 2012). Navab-Daneshmand et al. (2015) studied the impact of joule effect (heating) by controlling the anode temperature during the electro-osmosis phenomenon in biosolids. In practical electro-osmosis engineering, we always have to face different temperatures in-situ. However, influence of initial environmental temperature on the effect of clay electro-osmosis has not been investigated in the studies.

Based on the above-mentioned factors, this study aimed first to explain how the operational conditions (voltage and temperature) affect the electro-osmosis process in marine clay at various loading pressures. In particular, the influence of experimental temperature on the electro-osmosis of marine clay was investigated. The current and electrical resistivity were measured under three voltages and three temperatures. They reflected the changes in the electro-chemical properties of clay which influenced also the average degree of consolidation (the consolidation curve), the horizontal shrinkage, the water content, the shear strength, and the anode corrosion. Such parameters were measured during or after the experiments conducted under the different tested operational conditions. This study tried to explain the observed experimental phenomena through chemical, electrical, and mechanical theories.

2. Materials and methods

2.1. Description of marine clay

The tested marine clay was collected from Dalian reclamation project site (Dayao Bay). Based on the SL237 standard (1999), the basic properties of clay are shown in Table 1.

The marine clay pH (measured in a suspension with a clay: water ratio equal to 1:5) was found at 7.72 and the grain-size distribution of marine clay in was determined using the methods proposed by Pieri et al. (2006). Fig. 1 shows that the <2 μm fraction (associated to clay) corresponded to 17.3%.

Table 1
Basic properties of remoulded marine clay.

Properties	Values
Water content/%	60
Liquid limit/%	40
Plastic limit/%	21
Plastic index/%	19
Color	Grey
pH	7.72
Salt content	1.29%
Carbonate content	13.27 g/kg
SiO_2	59.1%
Al_2O_3	18.4%
Fe_2O_3	9.43%
K_2O	3.84%
Na_2O	2.49%
MgO	2.07%
Cl	1.34%
CaO	1.11%
Illite	88 ± 1%
Chlorite	7.2 ± 2.5%
Kaolinite	4.1 ± 1.8%
Smectite	0.8 ± 0.7%

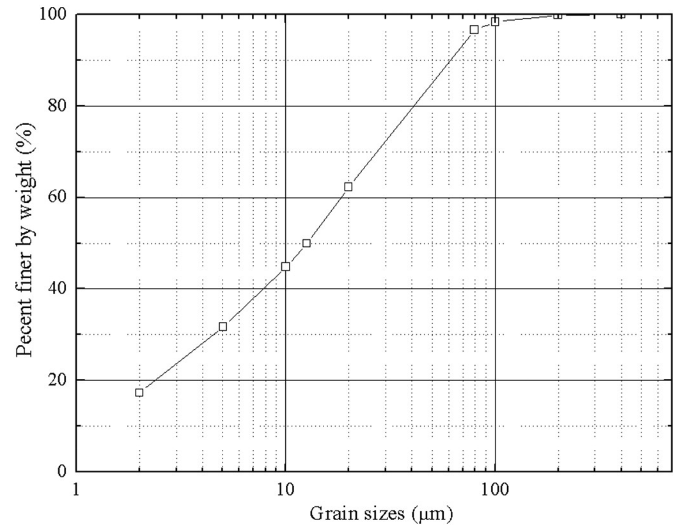

Fig. 1. Particle size distribution of marine clay.

The mineralogical composition of the fine particles (<2 μm) was identified by X-ray diffraction powder with a BRUKER-AXS-D8-Advance powder diffractometer using Cu Kα radiations and the mineralogical composition analysis was determined using the methods proposed by Biscaye (1965) applied in previous studies by Dolinar et al. (2007), Carretero et al. (2014), and Garzón et al. (2016). Illite was the main clay mineral present in the clay fraction and it represents around 88% of the fine particles. The amount of chlorite was 7.2%, and the proportion kaolinite was close to 4.1% and smectite was <2%. The liquid limit and plastic limit of marine clay corresponded to 40% and 21% respectively, indicating that the marine clay belongs to the clay scope (CL) according to the Unified Soil Classification System. To explore the chemical composition of the tested marine clay and to provide a reference for other similar applications, this paper adopted XRF analysis. The Table 1 shows that the material contained calcium, sodium, chloride and sulphur. These ions contribute to the salt content of clay determined by the SL237-063-1999.

2.2. Experimental apparatus

An in-house apparatus based on previous studies was designed and manufactured, as shown in Fig. 2. This apparatus had three parts: a loading pressure device, a circuit system, and a clay sample cell. The pressure device, which is a modified odometer cell, can supply loading pressures from 12.5 kPa to 200 kPa. The circuit system was composed by a power supply, electric wire, and an ammeter. The power supply could provide a voltage of 0 to 60 V and a current of 0 to 5 A. The ammeter had an accuracy within 0.0001 A.

The clay sample cell comprised a pressure plate, a plexiglass tube, geotextile, and two electrodes. The pressure plate, which was used to press the clay sample, was 40 mm thick and had a 79 mm diameter. A

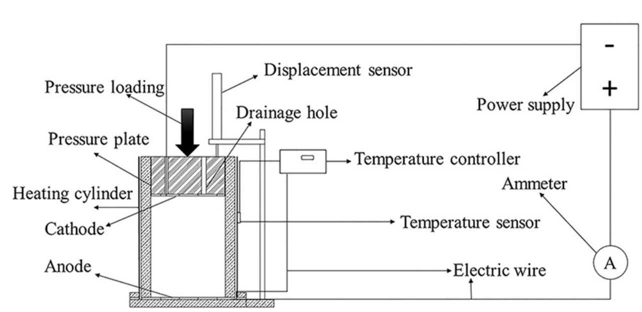

Fig. 2. Apparatus diagram.