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Research paper

# Mechanism of electro-osmotic chemical for clay improvement: Process analysis and clay property evolution

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ABSTRACT

Electro-osmotic chemical methods were applied in a series of geotechnical studies in which various solutions were injected into clay samples, increasing the undrained shear strength of the clay. Such methods resulted in a series of phenomena and in clay property evolution. In this study the current, temperature, settlement, drainage volume, and electrical potential distribution during the electro-osmotic experiments were monitored as process data, and the electrical conductivity in clay, calcium content, pH, water content, and undrained shear strength after the electro-osmotic chemical experiments were measured as clay property evolution data. Based on the process data, clay property data, and relevant theories, the mechanism of clay reinforcement with electro-osmotic chemicals was comprehensively explained. The development of an electro-osmotic permeability coefficient difference and the permeable drainage boundary condition resulted in a negative pore water pressure distribution shaped as an arch, which resulted in the water content having the same distribution and induced settlement. Because of the gathering of $Ca^{2+}$ and $H^{+}$ near the anode, a chemical cement reaction occurred near the cathode. The electrical potential gradient near the anode was lower than that near the cathode. Because of the chemical cement reaction between $Ca^{2+}$, $OH^{-}$, and $SiO_3^{2-}$, the undrained shear strength near the cathode was much higher than that near the anode. In addition, a coupling analysis of the electro-osmotic chemical process and clay property evolution is presented at the end of the discussion.

## 1. Introduction

Since 1952, Casagrande has used electro-osmosis technology to reinforce soft soil and slopes. A series of successful practical applications have followed to promote electro-osmosis technology (Jones et al., 2017). Lamont-Black et al. (2016) adopted the electro-osmosis consolidation method to improve a roadbed slope. Zou et al. (2017) used an electrically conductive wick drain (ECWD) and automated power supply (APS) to reinforce a Wenzhou soft soil.

In addition, grouting of chemical solutions can produce a cementing material between soil particles to improve soil. Because the permeability coefficient of clay is low, a grouting method on clay via hydraulic pressure will cause fracturing. However, by using the electro-osmotic chemical method one can inject a saline solution into clay and avoid fracturing, and it is a suitable method to improve low permeability soil. Ou et al. (2009) injected saline solutions into a Taipei field test site and found that the electro-osmotic chemical method effectively improved the soil foundation.

Scholars have attempted to inject various solutions into soil using the electro-osmotic chemical method, including saline solutions (Lefebvre and Burnotte, 2002), methacrylate polycations (Pączkowska, 2005), positively charged $SiO_2$@$Al_2O_3$ core-shell nanoparticles (NPs) (Zhang et al., 2017), $CaCl_2$ (Chien et al., 2011), $Al_2(SO_4)_3$ (Mohamedelhassan and Shang, 2003), $Mg(CH_3COO)_2$, $AgNO_3$, and $ZnSO_4$ (Otsuki et al., 2007). Ozkan et al. (1999) injected $Al^{3+}$(0.5 M) (anode chamber solution) and $PO_4^{3-}$(0.5 M) (cathode chamber solution) for 21 days during one reinforcement experiment of kaolin clay. During another experiment, 1 M $H_3PO_4$ solution was concurrently injected into the anode and the cathode for 14 days. Their experimental data showed that the undrained shear strength increased to 500–600% that of untreated kaolin clay, mainly because of the contribution of the cementing material. Asavadorndeja and Glawe (2005) used the depolarization method to balance the pH value of $CaCl_2$ solution in the anode chamber and provide a weak base solution condition, benefiting the pozzolanic reaction in the whole clay sample. Their results showed a 570% increase in the clay undrained shear strength, although the

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water content only changed 5% after 7 days of treatment. Moayedi et al. (2014) used the suspension liquid of Portland cement to reinforce soft soil using the cementing between the soil particles and the Portland cement. Ayodele and Agbede (2017) injected $CaCl_2$ solution into the anode and $H_3PO_4$ solution into the cathode to increase the shear strength of laterite and inferred that the increase in shear strength was caused by the cementing material $Ca_5(PO_4)_3OH_{(s)}$. Keykha et al. (2014) combined carbonate-producing bacteria and electro-osmotic grouting of a $CaCl_2$ solution to produce $CaCO_3$ and then cemented soil particles.

The aforementioned studies inferred or observed a cementing material contribution to an increase in undrained shear strength. In addition, a series of studies investigated the mechanism of soil reinforcement with electro-osmotic chemical methods. Alshawabkeh et al. (2004) explained the electrochemical and mechanical processes of the electro-osmotic chemical method with a $H_3PO_4$ solution based on electro-osmosis flow, ion migration, and the charge flow theory. However, this study showed a lack of settlement data analysis and clay property evolution. Chang et al. (2010) conducted electro-osmotic chemical experiments to reinforce kaolin clay; the experiments lasted 2 h, 4 h, 8 h, 16 h, 24 h, and 120 h. After the electro-osmotic chemical experiments, they measured the pH, water content, shear strength, and calcium content at the different positions. Their results showed that the pozzolanic reaction of $Ca^{2+}$ caused the undrained shear strength to increase near the cathode. Zhang et al. (2016a) used pulse wave potentials to explore the mechanism of soil reinforcement using the electro-osmotic chemical method with a $CaCl_2$ solution, which increased the interconnectivity of the soil particles. They concluded that the interconnectivity of the soil particles was the main reason for the shear strength improvement. Zhang et al. (2016b) closed the cathode and conducted an electro-osmotic chemical experiment using a $CaCl_2$ solution. They found that the ion migration and the water content redistribution led to an improvement in undrained shear strength. Ou et al. (2015) explored a clay mineral changing near the cathode after electro-osmotic injection of $CaCl_2$ from the anode and found that the Ca-hydration products filled the soil voids causing an increase in undrained shear strength. These mechanism studies focused on the evolution of clay property during the electro-osmotic chemical process. However, it is necessary to combine the electro-osmotic chemical process data with the clay property evolution data to explain the electro-osmotic chemical mechanism.

Chien et al. (2010) injected $CaCl_2$ and $Na_2SiO_3$ solutions into clay from the anode for improvement in the undrained shear strength near the anode area. This study conducted electro-osmotic chemical experiments using $Ca(NO_3)_2$ solution (anode chamber solution) and a $Na_2SiO_3$ and NaOH mixture solution (cathode chamber solution), which avoided soil-anode contact blocking. During the electro-osmotic chemical experiments, the current, temperature, settlement, and drainage volume were monitored. To explore the clay property evolution during the electro-osmotic chemical process, the water content, undrained shear strength, pH, electrical conductivity, and calcium content of clay samples were measured following the experiments. From these experimental data, the mechanism of the electro-osmotic chemical method was understood based on the relevant theory.

## 2. Materials and methods

### 2.1. Clay description

Based on the SL-237-1990 standard, the liquid limit and plastic limit of the clay sample were confirmed. According to the Unified Soil Classification System (USCS), the clay sample was low plastic clay (CL). We mixed drying clay and distilled water obtaining a slurry sample with 68% water content, which is much higher than the liquid limit of clay. The salt content of the clay is 0.93% as per the SL-237-1990 standard. X-ray diffraction (XRD) technology was used to investigate the mineral composition of the clay particles using the Biscaye method (Biscaye, 1965), which has been previously successfully adopted (Carretero et al., 2014; Garzón et al., 2016). The clay mineral contains kaolin (67%), illite (14%), and chlorite (15%). To explore its elemental composition, X-ray fluorescence (XRF) was used. All the aforementioned results are shown in Table 1. The grain size distribution (Fig. 1) was obtained with a laser particle analyzer (Malvern AWM2000) using the method in Pieri et al. (2006).

**Table 1**
Physical properties, mineral and chemical composition.

| | |
|---|---|
| **Physical properties** | |
| Water content (%) | 68 |
| Liquid limit (%) | 43.7 |
| Plasticity index | 22.2 (CL) |
| Salt content (%) | 0.93 |
| pH | 6.4 |
| Consolidation water content (%) | 46.4 |
| **Mineral composition (%)** | |
| Kaolinite | 67 |
| Illite | 14 |
| Smectite | 4 |
| Chlorite | 15 |
| **Chemical composition of initial clay(%)** | |
| $SiO_2$ | 59.8 |
| $Al_2O_3$ | 26.0 |
| $Fe_2O_3$ | 5.1 |
| $K_2O$ | 4.0 |
| MgO | 1.5 |
| $TiO_2$ | 0.9 |
| CaO | 0.9 |
| $Na_2O$ | 0.7 |
| $SO_3$ | 0.4 |
| Cl(%) | 0.3 |
| $P_2O_5$(%) | 0.2 |

### 2.2. Electro-osmotic chemical experimental systems

For a comprehensive study of the electro-osmotic chemical mechanism, an electro-osmotic chemical experimental system was designed, which includes an experimental cell and measurement system.

A schematic diagram of the experimental cell is shown in Fig. 2. The experimental cell is composed of plexiglass, which is divided into three chambers by two gates. The anode chamber (60 mm × 50 mm × 100 mm) is connected to a solution tank, which is used to supply the $Ca(NO_3)_2$ solution (1 mol/L). The middle chamber (254 mm × 50 mm × 100 mm) is

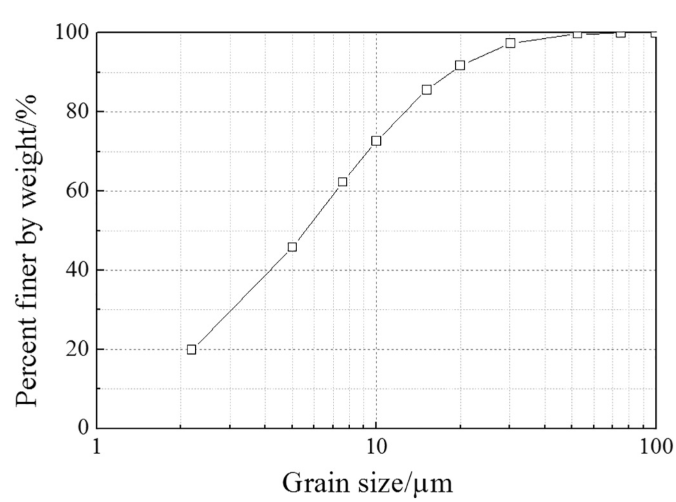


**Fig. 1.** Grain size distribution of clay.