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Electro-osmotic strengthening of silts based on selected electrode materials

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Abstract

Electro-osmosis is considered promising in effectively strengthening silts. This has been an urgent issue for engineers as large volumes of silts are being generated each year and need to be properly disposed. Electrode material is one of the key elements for the electro-osmosis technique. Inconsistent results have been reported in the existing literature on common electrode materials. To clarify these discrepancies and to optimize the electrode material, laboratory tests were performed with four common materials, namely, iron, graphite, copper and aluminum, under three levels of voltage gradient. Observations were performed from the perspectives of the electro-osmotic effect and the ionic strength. As for the former perspective, the electro-osmotic effect was denoted by the drainage, the water content and the effective potential. The graphite electrode was found to perform better at high potentials than iron or copper. The copper electrode exhibited a rapid decrease in the effective potential and current. As for the latter perspective, contents of *Fe*, *Cu* and *Al* were detected in the drainage and soils. Aluminum ions were demonstrated to have higher migration capacities than iron or cupric ions. Further analysis determined that electro-osmosis relies on ions in the original soils instead of those generated by electrode reactions. In conclusion, iron is recommended as the preferable electrode material for electro-osmosis. The performance of different electrode materials is directly reflected by the voltage loss rather than by the ion migration process. The voltage loss can be attributed to various factors, such as corrosion, electrochemical passivation, gas evolution, decomposition and electrochemical potential. The results of this paper provide deep insight into the influence of the electrode material on the electro-osmotic process.

Keywords: Electro-osmosis; Silt; Electrode material; Voltage loss; Ion migration process

1. Introduction

Electro-osmosis is known as the process of water moving from the anodes to the cathodes for colloid in the presence of electric fields. Electro-osmosis was first studied by Reuss in 1809. Previous researchers have reported the applications of electro-osmosis to numerous projects, such as contaminant removal (Andrew and Ronald, 1993), foundation reinforcement (Bjerrum et al., 1967; Lo et al., 1991), embankment stabilization (Fetzer, 1967; Wittle et al., 2008) and pile capacity improvement (Naggar and Routledge, 2004; Soderman and Milligan, 1961). Among these applications, electro-osmosis displays remarkable superiority in strengthening fine-grained soils, such as silts, with high efficiency, where conventional methods, for example, pre-loading or vacuum loading, have less favorable effects especially in terms of how much time they consume. The fundamental reason for these distinguished behaviors lies in the fact that electro-osmotic permeability coefficients for various types of soils are around the magnitude order of 10^{-5} $cm^2/(s\ V)$, while hydraulic permeability coefficients have a wide range from 10^{-1}–10^{-9} m/s (Cassagrande, 1949). Therefore, the reinforced effect of electro-osmosis is independent of the soil particle size, and this method is considered to be a favorable

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and promising technique for the disposal of fine-grained soils, especially silts. Currently, electro-osmosis is receiving growing attention with the overall background of more prosperous mining, dredging and reclaiming projects which are generating massive amounts of silts. It will require a vast amount of space to deposit these silts and years to hydrate them if left untreated. Thus, proper management is required before any construction work begins.

The electrode material is one of the crucial factors for electro-osmosis (Shang and Lo, 1997). A number of researches have been devoted to this topic. Pioneering work was initiated from a comparison of commonly used electrodes, such as iron, copper, graphite and aluminum (Burton and Clifford, 1992; Mohamedelhassan and Shang, 2001; Lockhart, 1983). Metal electrodes were found to have inevitable corrosion, which greatly affects the electro-osmotic efficiency and leads to energy dissipation (Kalumba et al., 2009), while graphite resolves during electro-osmosis. These deficiencies directly restrict the widespread use of the electro-osmosis technique (Glendinning et al., 2008). To eliminate the corrosion problem, several novel electrodes were developed, among which electrokinetic geosynthetics (EKG) electrodes, initially proposed by Jones (2004), firstly raised the most concerns. Effective for mitigating corrosion and improving electro-osmotic effects as it is, multiple doubts still exist with EKG and it will demand further improvements (Glendinning et al., 2007; Hu et al., 2005). Other types of electrodes, such as prefabricated vertical drains (PVD) (Abiera et al., 1999; Bergado et al., 2003) and electric vertical drains (EVD) (Chew et al., 2004; Karunaratne et al., 2004) have also aroused interest.

In particular, previous comparisons of common electrode materials have achieved quite inconsistent results. Lockhart (1983) investigated the effects of iron, copper and graphite electrodes on the current and solid content during electro-osmosis. He found that for *Cu* kaolinite, copper electrodes performed better than iron electrodes, which in turn were better than graphite electrodes. No such variation was found in his previous work on Na kaolinite. Burton and Clifford (1992) compared graphite and iron electrodes on the basis of flow rate and power consumption. Graphite was reported to have an average flow rate of half that of iron with the same energy consumption. Mohamedelhassan and Shang (2001) tested the voltage loss for six pairs of electrodes. Fewer losses were observed for metallic anodes (steel and copper) than for graphite anodes. Bergado et al. (2003) used graphite and copper electrodes with prefabricated vertical drains (PVDs) to explore the electro-osmotic consolidation of Bangkok clay. The results based on both small and large model tests indicated that graphite electrodes yielded a higher magnitude of settlement and a faster rate of consolidation. These authors claimed graphite as being a more effective electrode material. However, Mohamad et al. (2011) obtained no appreciable discrepancy in the electro-osmotic effects of steel, copper or aluminum electrodes through laboratory tests. Thus, distinguished results have been obtained in the preceding researches.

Moreover, researchers have proposed various interpretations for the distinguished performances of the electrodes of concern. Mohamedelhassan and Shang (2001) discovered that the electrochemical potential constitutes the primary cause of discrepancies in the loss in interface voltage observed in their experiments with respect to graphite and iron electrodes. Further evidence was presented by the fact that the electrochemical potentials of graphite and iron are -0.44 V and 1.18 V, respectively. A lower potential signifies stronger reducibility and higher activity of the material, implying a greater tendency for the electrode reactions to occur. From this perspective, the electrochemical potential seems to provide reasonable explanations for the consequences obtained by Mohamedelhassan and Shang (2001). Nevertheless, other researchers have acquired results that are barely consistent with those of Mohamedelhassan and Shang (2001). Lockhart (1983) demonstrated that the performance of a certain electrode varies with different types of clay. Lockhart (1983) attributed the best performance of copper electrode for *Cu* kaolinite to the occurrence of reversible electrochemical half reactions of Cu/Cu^{2+}-kaolinite-Cu^{2+}/Cu, with the cathode reactions being $Cu^{2+}+2e \rightarrow Cu$. As for Na kaolinite, Lockhart (1983) stated that the lack of difference in electro-osmotic effects with iron, copper or graphite was due to the more difficult cathode electrolysis reactions, namely, $2H_2O+2e \rightarrow H_2+2OH^-$. Burton and Clifford (1992) summarily mentioned that iron anodes affect the water-movement efficiency through iron oxidation, dissociation and precipitation. Evidently, great uncertainty still exists regarding how electrode materials actually affect the electro-osmotic process.

Most of the investigations concerning electrode materials have based their conclusions on direct observations of the electro-osmotic effect. Few studies have considered the ion migrating process, which was proved to be the governing force of electro-osmosis (Gray and Mitchell, 1967). Different materials have various electrode reactions and generate various ions. These ions undoubtedly will enter into the soil mass and can play a significant role in promoting electro-osmosis. Observations in this aspect may help in the understanding of the preceding conflicts, which are the starting point of this study. More importantly, studies from this perspective can further reveal the electro-osmotic mechanism in terms of the ion migration process.

In this paper, several laboratory experiments were conducted using the four above-described electrode materials on remolded Hangzhou silt. The objective of this paper is to provide deep insights into the influence of electrode material on the electro-osmotic process. Observations were performed from the perspective of the electro-osmotic effect and the ionic strength. As for the former perspective, the performance of each material was investigated from the viewpoints of drainage, water content and effective potential. As for the latter perspective, the elemental contents of *Fe*, *Cu* and *Al* in the drainage and soil were detected in order to evaluate the migration process of relevant ions due to electrode reactions. The results were also compared with the published literature. Interpretations of distinguished behaviors and inconsistencies are provided on the basis of an overall comparison and analysis.