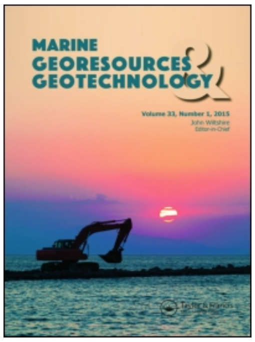

Marine Georesources & Geotechnology

ISSN: 1064-119X (Print) 1521-0618 (Online) Journal homepage: http://www.tandfonline.com/loi/umgt20

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To cite this article: M. Malekzadeh & N. Sivakugan (2017) One-dimensional electrokinetic stabilization of dredged mud, Marine Georesources & Geotechnology, 35:5, 603-609, DOI: 10.1080/1064119X.2016.1213778

To link to this article: http://dx.doi.org/10.1080/1064119X.2016.1213778

Accepted author version posted online: 27 Jul 2016.
Published online: 27 Jul 2016.

MARINE GEORESOURCES & GEOTECHNOLOGY
2017, VOL. 35, NO. 5, 603–609
http://dx.doi.org/10.1080/1064119X.2016.1213778

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One-dimensional electrokinetic stabilization of dredged mud

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ABSTRACT

Reuse of dredged marine sediments for land reclamation is a sustainable method for disposing the large quantities of dredged spoil, accumulating every year worldwide. However, due to their high water content and low permeability, dewatering and self-sedimentation of the material takes a long time to be completed. Therefore, different methods, such as prefabricated vertical drains and vacuum preloading, are used to improve the consolidation properties of the dredged mud at the port of Brisbane. Among these stabilization methods, vacuum preloading is determined as the most effective method to increase the consolidation of the dredged mud. However, clogging during vacuum consolidation is undesirable. Therefore, electrokinetic stabilization draws attention since it is an environmentally friendly and time efficient method to dewater and consolidate dredged mud significantly. The effectiveness of the electrokinetic stabilization depends on the properties of the soil and the electrode configurations. One-dimensional and two-dimensional electrode configurations are the most popular configurations. In this study, the effect of one-dimensional electrode configuration, which is installation of electrodes in arrays of anodes and cathodes on consolidation parameters of dredged mud, is investigated. Based on this study, the dredged mud sediments can be stabilized using one-dimensional electrokinetic stabilization which resulted in improving compression index and coefficient of volume compressibility and reduction of soil plasticity index.

ARTICLE HISTORY
Received 19 April 2016
Accepted 11 June 2016

KEYWORDS
Compressibility; consolidation; dredged mud; electrode configuration; one-dimensional electrokinetic; physiochemical changes

Introduction

Electrokinetic stabilization is one of the promising techniques to improve the properties of soils. Electrokinetic stabilization is the application of electrical current to the soil through the electrodes. Electrokinetic stabilization includes electro-osmosis, electrolysis, electrophoresis, and electromigration which are responsible for changes in soil. Electro-osmosis is the transport of water through the soil from anode to the cathode. Electrophoresis is the movement of charged particles which leads to soil sedimentation and aids in the settlement of soil particles during electrokinetic stabilization. Electro-osmosis occurs as a result of movement of capillary water from the anode to the cathode. In addition to electrophoresis and electro-osmosis, electromigration, which is movement of ions due to the induced electric potential, results in the movement of solute such as salt during the electrokinetic process. Many factors, such as the type of electrode material, electrode spacing and electrode configuration affect the effectiveness of the method due to the chemical reactions that occur as a result of electro-osmosis, electromigration, and electrolysis of the anode during the process. The electrode configuration controls the intensity of the electric field applied to the soil and the changes in the soil properties at the end of electrokinetic stabilization.

Electrokinetic stabilization is one of the environmentally friendly and cost-effective methods that can be used to increase the pile bearing capacity, preventing liquefaction, soil decontamination, and improving strength (Acar and Alshawabkeh 1996; El Naggar, and Routledge 2004; Chen, Tang, and Jia 2007). Electrokinetic stabilization is able to treat wide range of soils. However, its applicability to dredged mud sediments is not investigated in the literature extensively. Therefore, it is crucial to undertake a feasibility study on suitability of the method to improve the method and its applicability for stabilizing dredged mud sediments.

The effectiveness of electrokinetic stabilization is based on the electrode material and its configuration, the effective area which is the treated area by electrokinetic treatment varies depending on the electrode configuration. Two types of electrode configurations are presented in the literature (Alshawabkeh, Yeung, and Bricka 1999). One-dimensional configuration case occurs when the number of anodes and the cathodes are the same. In this case, the spacing between the electrodes is governing the effectiveness of the treatment. Figure 1a shows the effective area between the electrodes when they are placed one dimensionally. In practical applications, a series of anodes and cathodes are installed along a straight line in rows. The other type of electrode configuration is two-dimensional configuration in which there would be more than one cathode for an anode. In this configuration, the acidic environment is created by electrolysis of the anode which produces a larger effective area. This is desirable in a case where cementation near the cathode does not occur due to the presence of organic materials (Asavadorndeja and Glawe 2005). Depending on the type of chemicals in the soil, the high pH near the cathode caused soil cementation in some

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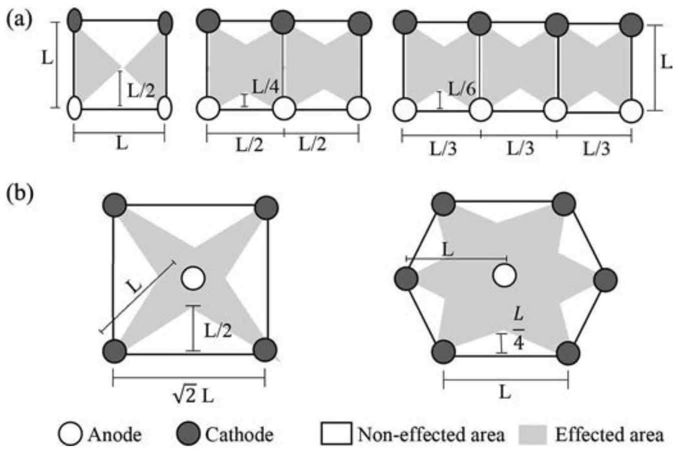

Figure 1. (a) One-dimensional electrode configuration and (b) two-dimensional electrode configuration (Alshawabkeh, Yeung, and Bricka 1999).

cases and resulted in high strength properties of the area near the cathode. However, in other cases, no cementation occurs near the cathode and the strength properties increase mainly near the anode. If that is the case, the effective area can be increased by installing four or more anodes for each cathode, thus creating rectangular or hexagonal configurations such as those shown in Figure 1b.

The affected and nonaffected areas can be explained through the electric field potential which shows by electric exponential and field lines between two identical electrodes and two nonidentical electrodes. To better understand the equipotential and electric field lines, consider the case of seepage in geotechnical engineering. Seepage occurs when there is a head difference between upstream and downstream. Similarly, electrons transfer from one electrode to the other, in this case from anode to the cathode, due to the applied electric potential. Since one electrode has a negative charge and the other has positive charge, the electric field line is from positive pole to the negative pole, and the poles attract each other to equilibrate (Figure 2a). This is similar to the passage of water from upstream with higher head to downstream to the lower head until equilibrium. However, if the polarities are the same, the electrons are repelling each other (Figure 2b). This creates an area that is not affected by the electric field, thus creating a region of soil that cannot be stabilized by electrokinetic treatment. Just like seepage, thousands of exponential lines that are created within the flow region intersecting electric field lines at 90°.

In this study, the effect of the one-dimensional electrode configuration on electrokinetic stabilization of the dredged

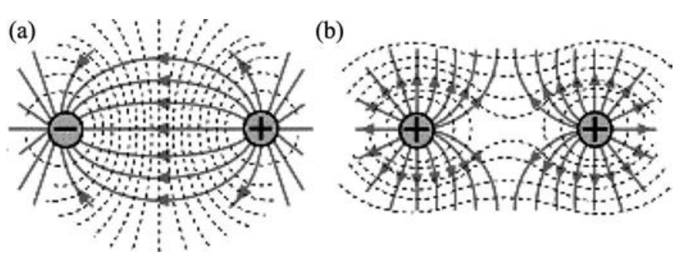

Figure 2. Electric field line and exponential lines. (a) two nonidentical electrodes and (b) two identical electrodes (Ogborn and Whitehouse 2000).

mud to monitor the changes of consolidation parameters and physiochemical properties will be investigated.

Experimental study

Materials

Soil

The soil used in this study is remolded marine sediment taken from the reclamation area that is used for expanding the port facilities in port of Brisbane, Australia. The physical properties of the dredged mud are presented in Table 1. The major and minor minerals existing in the dredged mud are presented in Table 2.

Electrodes

Galvanized steel rod. Hollow galvanized steel with wall thickness of 2 mm and 19 mm inner diameter is cut into smaller rods with a height of 100 mm and is installed into the Perspex glass. The rim of the rod is attached to the base of the Perspex box with silicon. Before installation, the cathode is wrapped with filter paper to avoid the blockage of the perforated holes which are provided to allow the drainage of water from the cathode.

Apparatus and procedure

Setup. The electrokinetic stabilization setup used herein is shown in Figure 3. Two galvanized electrodes are placed in the Perspex box at the distance of 75 mm from each other before the soil slurry is poured. The samples of dredged mud are prepared to 1.35 liquid limit (LL). This water content is chosen since 1.35 LL which is equivalent to 124%, which is half of the water content of the samples that were received from the port initially, since the purpose of the method is to investigate the consolidation parameter of the soil. If the water content is higher, it takes longer time for the sediments to settle, so higher water content just affects the timeframe. However, lower water content results in higher resistivity due to the generation of the heat and cracks in the soil, which results in less effective electrokinetic stabilization. Also during electro-osmosis, as the water content of the soil reduces, desiccation cracks may appear. These cracks reduce the efficiency of the electro-osmosis. It is necessary to know at which water content soil starts to crack. The water content at which the dredged mud starts to shrink, known as desiccation limit, is 1.2 times its plastic limit (Stark, Choi, and Lee 2009). This water content should be taken into consideration to determine the initial moisture content that is appropriate for electrokinetic stabilization. When the buckets of dredged mud are kept in the storage room near the laboratory, the moisture content

Table 1. Physical properties of the dredged sediment.

Property		Standard
Liquid limit (%)	92	AS 1289.3.9.1
Plastic limit (%)	40	AS 1289.3.2.1
Plasticity index (%)	52	—
Linear shrinkage (%)	33	AS 1289.3.4.1
Specific gravity	2.61	AS 1289.3.5.1
Unified soil classification system (USCS)	CH–clay with high plasticity	—

Table 2. Mineralogy of the untreated dredged mud.

Mineral	Chemical composition	Weight (%)
Alunogen	$Al_2(SO_4)^3 \cdot xH_2O$, $5 < x < 16$	<10
Amphibole	e.g., $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	<1
Gypsum	$CaSO_4 \cdot 2H_2O$	<1
Halite	NaCl	<10
Mica	$(K,Ca,Na)(Al,Mg,Fe)_2(Si,Al)_4O_{10}(OH)_2$	<1
Kaolin	$Al_2Si_2O_5(OH)_4$	<1
Potassium feldspar	$KAlSi_3O_8$	<10
Pyrite	FeS_2	<1
Quartz	SiO_2	>50
Sepiolite	$Mg_8(OH)_4Si_{12}O_{30}(H_2O)_{12}$	Possibly < 1
Sodium plagioclase	$NaAlSi_3O_8$	<10

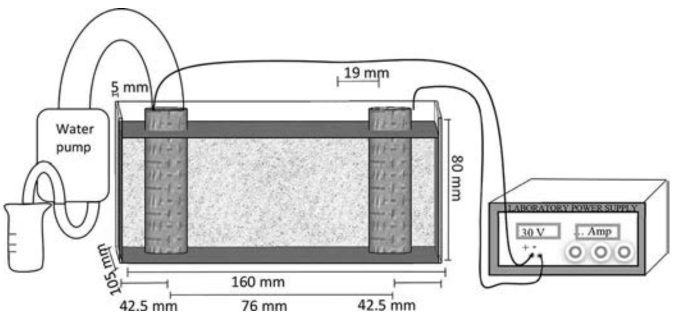

Figure 3. Schematic view of one-dimensional electrokinetic stabilization setup.

reduces. To bring its moisture content to the desired level, the lumps of dried dredged mud are placed into a bucket after measuring its moisture content, then the amount of water to be added to obtain the desired moisture is mixed with the dredged mud using a mixer. Then the prepared dredged material is poured into the Perspex box, and the positive and negative poles of the DC supply are connected to the electrodes, where water flows from the negative pole to the positive pole (cathode) from which it is drained using a mechanical pump.

Once the electric current reaches zero, it indicates that further electrokinetic stabilization cannot be achieved. This is attributed to either the corrosion of the anode, increase in soil resistivity, or the generation of negative pore pressure near the anode which interrupts the current flow through the soil. The corrosion rate of the anode is calculated using the initial and final masses of the anode from the following equation

$$\text{Corrosion rate of anode} = \frac{M_o - M_f}{M_o} \times 100 \tag{1}$$

where M_o is the initial mass of the anode and M_f is the final mass of the anode. The initial mass of the anode is measured as 51.513 g and the final mass is recorded as 44.041 g, resulting in 15% corrosion of the anode.

Figure 4. Generation of cracks during and after electrokinetic stabilization.

Sample preparation for consolidation testing. When the electrokinetic stabilization is finished, samples were taken from the area near the anode and the cathode to measure the moisture content values for preparing samples for consolidation tests under oedometer. When the electric potential is applied to the dredged mud and dewatering starts, the soil starts to cracks (Figure 4 shows the generation of crack within the soil during and after electrokinetic stabilization) which makes it difficult to take undisturbed and whole samples for consolidation. For that reason, remolded samples need to be prepared.

To prepare comparable samples with same density, a soil sampler is used to determine the density of the treated dredged mud. The sampler that is used is an extruder for determination of the dew point of the soils (Figure 5). Once the density and the water contents near the anode and the cathode are known, the consolidation ring of diameter 63 mm is filled and compacted by hand with the amount of soil reaching the measured density to create identical remolded samples. After preparing the soil in the ring, the samples are tested for consolidation in oedometer.

Sample preparation for measuring the changes of soil chemical properties. When the electrokinetic stabilization is finished, two samples are taken. One from the anode and the other from the cathode. The sample preparation used in this study is based on Allan and Hodgins (2003) proposed method; however, the timing is chosen based on the type of soil as 1 hour for mixing instead of 15 min and 24 hours saturation instead of 16 hours. The samples are then put in the oven to dry completely for 24 hours. Then the samples are crushed and pulverized using a pestle. The pulverized sample is passed through sieve number 4.25 mm. Then the mixture is prepared, using a 1:5 soil–water ratio, for chemical testing such as pH, electric conductivity, and salt content. When the mixture is prepared, it is mixed using a magnetic stirrer for an hour. Since dredged mud has low permeability, the mixture is left for 24 hours and then the test is preformed using a microprocessor-based water proof pH/conductivity/temperature tester model 7200. The critical temperature at which electrical conductivity should be measured at is 25°C.

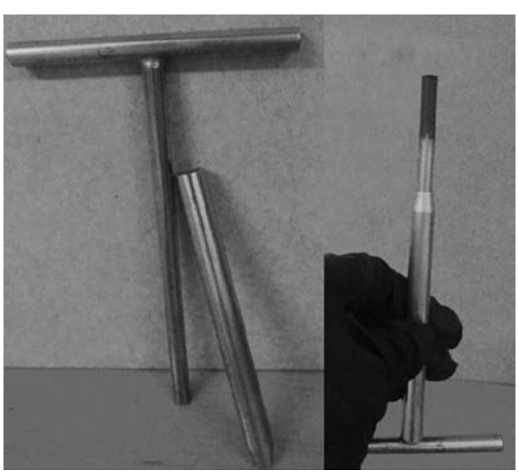

Figure 5. Soil sampler used to measure the soil density.

This model has a temperature compensation which automatically corrects the measurement. The temperature correction is based on the following conversion:

$$EC_{25} = f_t\ EC_t \tag{2}$$

where f_t is a temperature factor that should be determined according to the following relationship, suggested by (Sheets and Hendrickx 1995):

$$f_t = 0.4470 + 1.4034\ e^{-t/26.815} \tag{3}$$

Results and discussion

The result of electrokinetic test presented here is based on the changes of consolidation parameter, compression index, rebound index, variation of electric current and voltage with time, coefficient of volume compressibility, water content, and physiochemical properties of the treated soil in comparison with the nontreated dredged mud.

Variation of electric current and voltage

Once the electrodes are connected to the DC supply, the initial voltage of 16 V is applied. The DC supply used in this study is a cheap, easy to use, and accessible type of DC supply with which neither of voltage or DC supply can be kept constant. To keep the electric current constant, a constant current source is needed, which is not cost effective. Since the resistivity of the soil is changing during the electrokinetic stabilization, the electric current and the voltage are changing as according to the Ohm's law:

$$V = IR \tag{4}$$

where I is the electric current in amperes, V is the voltage in volts, and R is the resistivity of the soil in ohm. Figures 6 and 7 show the variation of electric current and voltage with time. It is shown that the voltage and the electric current reduce with time. The electric current and voltage at any time can be determined from the following equations:

$$I = 0.0091\ \left(t^2\right) - 0.2079\ t + 1.2587 \tag{5}$$

$$V = -0.0772\ t^2 - 0.1247\ t + 16.028 \tag{6}$$

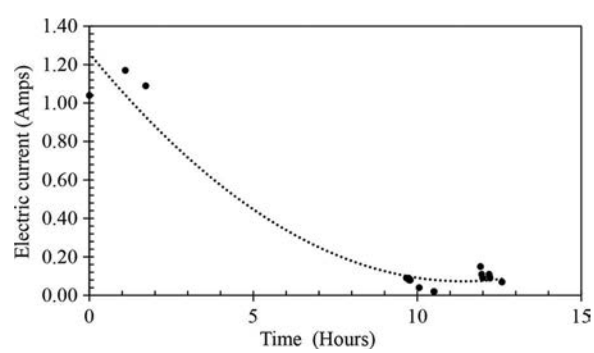

Figure 6. Variation of electric current with time during electrokinetic stabilization.

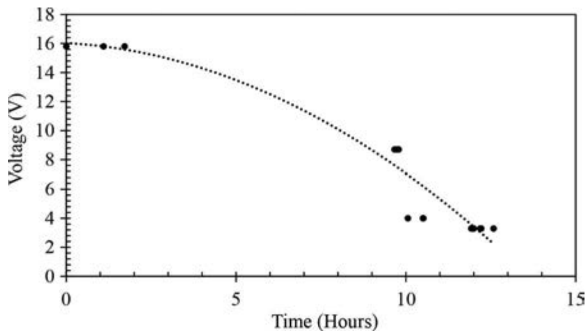

Figure 7. Variation of voltage with time during electrokinetic stabilization.

where I is the electric current, V is the voltage, and t is the time. The coefficient of correlation of the fitted curve for electric current versus time is 96% and for voltage versus time is 92%.

Compression and rebound index

Figure 8 shows the variation of void ratio with effective stress from which the consolidation parameters are determined.

Compression index or soil compressibility shows how much the soil settles due to consolidation. The amount of soil compressibility is determined by compression index. Mitchell (1993) categorized soils into high compressible having a compression index of greater than 0.4, moderate to intermediately compressible with compression index value between 0.2 and 0.4, and low compressible if having a compression index less than 0.2. Table 3 shows compression index, rebound index, and compression and recompression ratio of the treated and untreated dredged mud. It is shown that the compressibility of the untreated dredged mud is determined by Ganesalingam et al. (2011) as 0.560–0.825 which categorizes the dredged mud as a high compressible soil. With the use of electrokinetic treatment, the compressibility of the dredged mud is reduced to 0.446 near the anode and to 0.386 near the cathode, showing a significant improvement in dredged mud using electrokinetic stabilization. The rebound index of the treated dredged mud, which is the slope of the rebound curve in void ratio-effective stress, near the anode and the cathode is 0.079, which is less than the untreated soil. Compression ratio which is $Cc/(1+e_0)$ reduced significantly and showing reduction in plasticity index of the soil. However, the recompression ratio $Cr/(1+e_0)$ increased showing an increase in proportion of recompression deformation.

Table 3. Compression index, rebound index, compression and recompression ratio of the treated and untreated dredged mud.

	Untreated dredged mud*	Electrokinetically treated dredged mud near the anode	Electrokinetically treated dredged mud near the cathode
Compression index (Cc)	0.560–0.825	0.446	0.386
Rebound index (Cr)	0.061–0.095	0.079	0.079
Compression ratio (CR)	0.142–0.210	0.030	0.030
Recompression ratio (RR)	0.014–0.023	0.170	0.148

*Ganesalingam et al. (2011).

Coefficient of volume compressibility

Coefficient of volume compressibility shows how much the volume of the soil changes based on its initial void ratio. Figure 9 shows the changes of coefficient of volume compressibility for the applied effective stresses under oedometer testing. As shown in the figure, the coefficient of compressibility of the dredged mud increases when effective vertical stress of less than 20 kPa is applied to the soil. When the effective stress increases further, the coefficient of compressibility of the soil reduces. This is attributed to the dissipation of pore pressure in the beginning of the experiment. The similar behavior is observed in untreated samples with lower ranges of coefficient of volume compressibility, and this is attributed to the difference between the initial void ratios (Ganesalingam et al. 2011).

The coefficient of volume compressibility for a range of applied effective stresses is determined from the following formula:

$$m_v = \frac{\varepsilon_{vol}}{\Delta\sigma'} = \frac{\frac{\Delta V}{V_0}}{\Delta\sigma'} \tag{7}$$

where ε_{vol} is the volumetric strain per unit increase in stress, V_o is initial volume of the specimen, Δv changes in the volume of the soil, and $\Delta\sigma'$ increase in effective stress that results in the changes of the volume.

Changes of physiochemical properties

The properties of the soil change during and after the electrokinetic stabilization as a result of oxidation and reduction reactions. Oxidation reaction occurs near the anode and the reduction reaction occurs near the cathode. Oxidation results in electrolysis and corrosion of the anode and is defined as

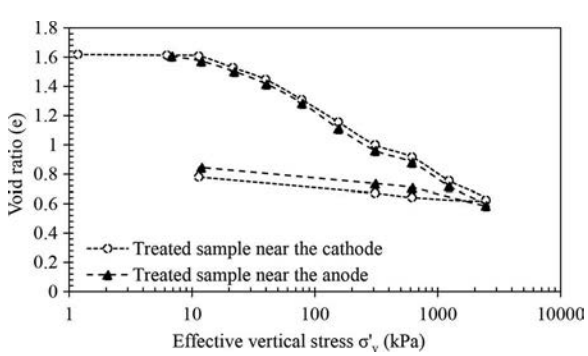

Figure 8. Void ratio versus effective stress of the stabilized dredged mud.

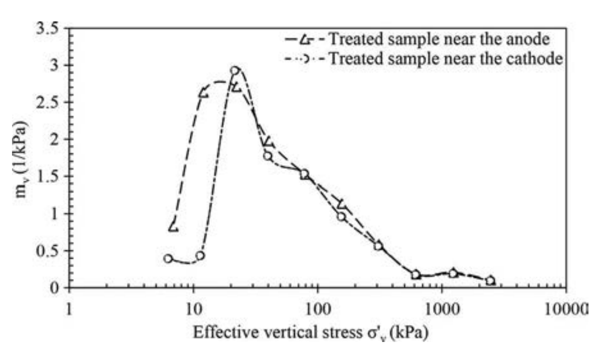

Figure 9. Coefficient of volume compressibility versus effective stress.

the removal of electrons. However, reduction reaction that occurs near the cathode is the addition of electrons to the soil. In electrokinetic stabilization, these are dominant electrochemical reactions which result in the dissolution of water into hydrogen near the anode and generation of hydroxide near the cathode (Alshawabkeh, Sheahan, and Wu 2004). The following reactions are referred as redox reactions:

$$2H_2O - 4e^- = 4H^+ + O_2 \text{ (anode)} \quad (8)$$

$$2H_2O + 2e^- = 2OH^- + H_2 \text{ (cathode)} \quad (9)$$

The reduction of pH is often related to the generation of H^+ ions near the anode and increase in pH is related to the generation of OH^- that reacts with the cations that are migrated from the anode to the cathode (Moayedi et al. 2014).

The cementation in the soil occurs depending on the soil (Asavadorndeja and Glawe 2005) which provides the condition for exchanging cations. Therefore, formation of stabilizing agent depends on the changes of pH during electrokinetic stabilization. Pozzolanic reactions and soil cementation near the cathode occur due to the soil composition and the pH of the soil that create the condition for the reaction to occur. Cementation near the cathode results in an increase in soil strength and changes in Atterberg limits. Jayasekera and Hall (2006) observed that liquid limit and plastic limit increased near cathode (alkaline) but reduced near anode (acidic).

Table 4 shows the changes of electrochemical properties of the soil before and after electrokinetic stabilization. When the pH of the soil reduces, the zeta potential of the soil also reduces. As a result of the reduction of soil zeta potential, the soil double layer reduces and this decelerates the flow of water through the soil. Therefore, electro-osmotic permeability of the soil reduces. It is not mainly the initial pH value of the soil that influences the electrokinetic stabilization, but the buffering capacity which is the ability of the soil to withstand pH fluctuations. Soils with higher buffering capacity have higher organic matter and clay particles (Chappell and Burton 1975) and need more base or acids to raise or alter their pH value. As the presence of organic matter results in cementation near the cathode, the soils that have high buffering capacity are preferable. Cementation near the cathode in dredged mud has not occurred and this shows that dredged mud has low buffering capacity.

Soil salinity affects the electro-osmotic flow by affecting its zeta potential (Mitchell and Soga 2005). Soils with higher zeta potential have higher electro-osmotic permeability. If soil salinity increases, the zeta potential reduces due to the reduction of double-layer thickness. Therefore, electrokinetic stabilization is unlikely to be successful in soils with very high salinity.

During electrokinetic stabilization, the ionic concentration changes due to the electromigration. Therefore, electrical conductivity of the soil varies based on the ionic strength. As a result, each section of the soil may have different values of electrical conductivity. This change of local electric conductivity results in variation of electric potential. The electric conductivity of the soil near the anode is almost equivalent to the electric conductivity of the soil surrounding the cathode. According to Hamed, Acar, and Gale (1991), stability of the anions is observed under alkalinity and the stability of the cations occurs under acidity. Therefore, since the pH of the soil near the anode is low, the insignificant change of electric conductivity shows that the cations near the anode are stable. This is attributed to the presence of cations such as Fe^{3+} that is induced to the soil from the galvanized steel anode. When pH of the clay increases or reduces drastically, soil compositions such as iron, aluminum, and sodium disperse and later precipitate as hydroxides or salt near the cathode and this is the reason for having higher salt content, total dissolved solids, and electric conductivity, which shows the concentration of ions. Pugh (2002) represented a method for prediction of electrical conductivity of natural soils from plasticity index (Figure 10). According to Pugh (2002), changes in electric conductivity of the soil result in changes of plasticity index. Therefore, the plasticity index of the treated soil can be estimated from electric conductivity measurement.

The electric conductivity of the untreated soil is 0.06 S/m dividing the value presented in Table 1 by the distance between electrodes (76 mm). According to the graph, the plasticity index of the soil is estimated to be 52% which is along with the plasticity index found using AS 1289.3.9.1 and AS 1289.3.2.1. Therefore, the plasticity index of the treated soil is estimated as 30% near the anode and 36% near the cathode. The comparison between the plasticity index of the treated and untreated samples shows that electrokinetic stabilization reduces the plasticity index of the dredged mud significantly.

Table 4. Changes of electrochemical properties of the dredged mud.

	pH	EC	Salt content
Near anode	1.98	2.09 mS	1.06 ppt
Near cathode	7.25	2.38 mS	1.19 ppt
Original soil	8.13	4.80 mS	2.90 ppt

ppt, part per trillion.

Amount of dewatering

Dewatering efficiency is defined as the quantity of water drained per unit of electric current which is proportional to electro-osmotic permeability (Jones et al. 2008). The reduction of water content and increase in shear strength near the anode are higher than near the cathode (Mitchell 1993). Dewatering efficiency is based on the amount of water to be removed in comparison with the initial moisture content (W_i) and can be found from the following equation:

$$\text{Dewatering efficiency} = (W_i - W_f)/W_i \quad (10)$$

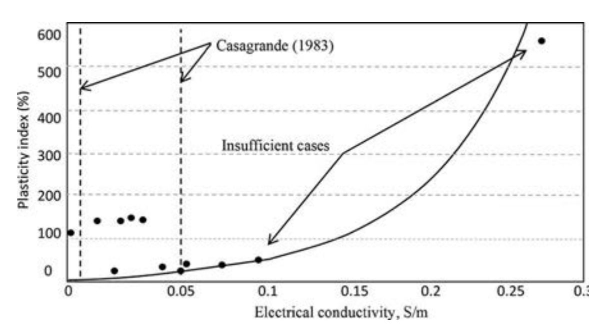

Figure 10. Conductivity versus plasticity index for some natural soils (Pugh 2002).

where W_f is water content of the soil after electrokinetic stabilization.

Fourie, Johns, and Jones (2007) reported 83% water content reduction after application of electro-osmosis dewatering of mine tailings with initial gravimetric water content of 257%. Electro-osmotic consolidation of peat and clayey soils with an average initial water content of 472 and 355% was studied by Kaniraj, Huong, and Yee (2011), which resulted in 100% water content reduction and significant soil improvements. The dewatering efficiency in this study is calculated as 52%. If the dewatering of the dredged mud is more than 50%, the dredged mud will become workable. Therefore, the electrokinetic stabilization reduced the water content of the dredged mud successfully.

Conclusion

An experimental study is performed to investigate the effect of one-dimensional electrode configuration on consolidation properties of the dredged mud as well as changes in its physio-chemical properties. It was concluded that

1. The electrokinetic consolidation increased the compression index of the dredged mud and this shows an increase in strength properties of the soil and as a result, a satisfactory improvement of the dredged mud.
2. The pH of the soil is reduced significantly near the anode showing that the dredged mud has a very low buffering capacity. Due to the high pH and no cementation near the cathode, it is concluded that the soil has no significant amount of organic material.
3. The reduction of coefficient of volume compressibility with the increase in effective stress shows a reduction in electro-osmotic permeability with increasing applied load, and this is attributed to the reduction in void ratio of the soil.
4. The compression index of the soil reduced up to 2.1 times less than the untreated dredged mud. Recompression index reduces up to 1.2 times less than the untreated dredged mud.

In general, the consolidation properties of the dredged mud are improved using one-dimensional electrokinetic stabilization, and this shows a significant improvement in dredged mud and applicability of the electrokinetic stabilization in improving the properties of the dredged mud sediments.

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