The Influence of Moisture Content, pH and Liquid Limit on Electrokinetic-treated Dredged Marine Sediments Stability by using Calcium Chloride as an Enhancement Agent

Nurul Syakeera Nordin1,2 and Chee-Ming Chan1

1 Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat Johor
2 Research Centre for Soft Soils, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat Johor
Corresponding author: chan@uthm.edu.my

Abstract. Reusing the dredged marine sediment (DMS) that was spawned from maintenance dredging work will reduce its disposal effect towards the environment. Furthermore, reusing the DMS could optimize the storage capacity of existing confine disposal facilities (CDF) and can prolonging its lifespan. Treating the DMS with an adequate pre-treatment is the best way to manage this sediment in sustainable solution. The purpose of this research is to study the influence of moisture content (w), pH and liquid limit (LL) towards the DMS’s stability after treated with electrokinetic (EK) method. Stainless steel plate was used as the electrode, while distilled water (DW) and calcium chloride (CaCl2) were applied as the enhancement agents. The aforementioned enhancement agents are electrically injected into the DMS which causing flow of the solutions through the pores in DMS under 50 V/m of applied direct current. The EK-treated DMS shows increment in strength and it was influenced by w, pH and LL. The dry zone area was created near the anode and wet zone was created near the cathode. The application of CaCl2 create a better result in physical properties of DMS compared to pure systems. The EK-treated DMS hence could be reuse as a geomaterial in construction activities. Largely, EK has significantly improve the quality of DMS even though the strength increase observed was not homogeneous throughout the specimen.

1. Introduction
Mosavat et al. [1] have demonstrated the various effects on the soil due to EK treatment. Figure 1 summarises the chemical changes in the clay with the alteration in the physical and chemical characteristics of the clay soil. In their studies, the authors have investigated the performance of EK towards kaolinite by using stainless steel electrodes. The authors highlight when a direct current (DC) electric potential is applied to soil, it will stimulate the migration of electricity, pore fluid, ions and fine particles. These migrations occurred across the soil towards the oppositely charged electrodes. Henceforth producing a combined effect of a chemical, hydraulic and electrical (CHE) gradient [1-2].

The authors have mentioned there are various complex electrochemical effects regarding the application of electric potential. Those effects are the electrolysis reaction, electric potential difference, electric current flow and leading to production of electrophoresis and electromigration. The electrolysis reaction at the anode and cathode are as equation (1) and (2).
The oxidation process occurred at the anode and it generate an acidic font. While reduction process occurred at the cathode and generating a base font. The standard reduction electrochemical potential ($E_0$) is the measure of the reactants in its own standard states [1][3]. Electrochemical effect creates an electric potential difference that lead to generation of electroosmosis (EO). EO is a flow of pore fluid across the soil profile. It is known as the primary phenomena in EK that responsible for species transport through the porous media [1][4-6].

![Diagram](image.png)

**Figure 1.** Summary mechanisms of EK treatment [1].

In year 2014, Mosavat et al. [1] traces the development of undrained shear strength ($S_u$) towards EK treated soil. In their case study of EK treatment towards kaolinite, the authors identify the strength development at five different normalized distances from anode and at five different time intervals. The $S_u$ was measured directly using a hand vane shear apparatus. In their study, two types of enhancement solution were used to explore the EK performance. These enhancement solutions were permitted through the soil via anode. Two types of enhancement solution are hydrated lime and saline solution. Hydrated lime was selected due to its extensive use as a soil stabilizer and soil treatment agents. The saline solution was prepared by mixed 0.1 N $CaCl_2$ with 1:100 sodium silicate ($Na_2SiO_3$) solutions. The combination of $CaCl_2$ and $Na_2SiO_3$ will result in the formation of hydrated calcium silicate. This mixture is generally used as grouting material. Silicate grouts has demonstrated the advantages in being reliable, safety and ease of use, environmental acceptability and adaptability over a wide range of applications. In their research, the authors claim a change in the electro-osmotic potential occurred across the tank with the
development of differential zeta potential in soil under the influence of the electric field. It is also associated with the changes in soil pH and the changes in the chemical concentrations of the soil pore solution. Jayasekera and Hall [7] mentions the location of wet and dry regions are reliant on the mineralogical properties of the soil. Its properties include the permeability characteristics, clay type and content, diffuse double layer (DDL) characteristics, etc.

2. Experimental work

2.1 Material
The studied material was dredged from Kuala Perlis Jetty, Perlis of Peninsular Malaysia in year 2016. Selection of dredging site was made based on Malaysian Marine Department (Jabatan Laut Malaysia, JLM) dredging schedule. The sediments (figure 2) was dredged at depth 4 to 6 m from sea level using backhoe dredger (figure 3). The properties result of the DMS are reported in table 1. The w is about 240.74 % (3.36 LL), dried in an oven at 100 °C (BS 1377-2:1990:3.2). The particle density ($G_s$) value of DMS is 2.36 Mg/m$^3$, measured using a small pycnometer method (BS 1377-2:1990:8.3). The liquid limit (LL) value is 71.70 % by using a cone penetrometer method (BS 1377-2:1990:4.3). The plastic limit (PL) and plastic index (PI) value for DMS are 40.06 % and 31.64 %, respectively (BS 1377-2:1990:5). The DMS consist of 2.5 % of sand, 80.5 % of silt and 17 % of clay. The DMS was classified in high plasticity silt, MH for its soil classification (Unified Soil Classification System) [8-9].

![Figure 2. DMS](image1.png)  
![Figure 3. Backhoe dredger.](image2.png)

| Table 1. Properties of dredged marine sediments. |
|-----------------------------------------------|
| Natural water content, w (%) | 240.74 |
| LL (%) | 71.70 |
| PL (%) | 40.06 |
| PI (%) | 31.64 |
| $w/LL$ | 3.36 LL |
| $G_s$ (Mg/m$^3$) | 2.36 |
| Particle size distribution (%) | Sand: 2.5 Silt: 80.5 Clay: 17 |
| Soil classification | High plasticity silt, MH |

2.2 EK experimental set-up
The EK cell (figure 4) was made from transparent acrylic plate (15 mm) and was divided into three compartments. Each compartment was separated with perforated walls. The usage of transparent acrylic plate was to prevent short circuiting and monitoring the DMS level during the experiment. Those three compartments are the specimen cell and two electrolyte reservoirs (anode and cathode compartments). The internal dimension for specimen cell and electrolyte reservoirs were 280 × 165 × 413 mm and 40 × 165 × 413 mm, respectively.
Two types of EK experimental setups were erected with different enhancement agents in electrolyte compartment. Those setups were namely as $EK_0$ ($DW$ - $DW$, natural system) and $EK_1$ ($CaCl_2$ - $DW$ system). Each electrolyte reservoir was filled with 1000 mL of catholyte/anolyte. A summary of $EK$ experimental setups is listed in table 2. The experiment was conducted in 14 days. The period was considered from the previous study by Nordin and Ahmad Tajudin [10-11]. In his analysis, the volume of electrolyte used were monitored every 24 hours and the author identifies that the volume was constant after 224 hours (9.3 days). When $EK$ experiment was terminated, the treated specimen was sectioned into six equal parts at each 45 mm from the anode. Those treated specimens were investigated through its w ($BS$ 1377-2:1990:3.2), $S_u$ ($BS$ 1377-7:1990:3), $LL$ ($BS$ 1377-2:1990:4.3) and $pH$ ($BS$ 1377-3:1990:9).

Table 2. The summary of $EK$ experiment.

| Parameters                              | $EK_0$ | $EK_1$ |
|-----------------------------------------|--------|--------|
| Applied voltage (V/m)                   | 50     |        |
| Anode compartment electrolyte           | $DW$   | $1.0M CaCl_2$ |
| Cathode compartment electrolyte         | $DW$   |        |
| Experimental duration                   | 14 d   |        |

3. Results & Discussion

3.1 $EK$ effect on $w$ and $S_u$ variations

The correlation between $w$ and $S_u$ of $EK$ treated $DMS$ is shown in figure 5. The graph presents the intercorrelations of six measurements of $w$ - $S_u$ at different normalized distance from the anode. These data are divided into three zones for analysis. The first zone was 0 – 95 mm (near the anode), second zone 95 – 190 mm (middle area), and third zone was 190 – 280 mm (near the cathode) from the anode. These results indicate decreasing $w$ with increasing $S_u$. It is interesting to note that a wet region was created in the cathode area, while dry region in the anode area. A comparison of these $EK$ phases reveals that the strength development is not homogenous but varies accordingly to the distance from the anode. Another striking result to emerge from the data is the high increment of $S_u$ in $EK_1$. It shows that the application of $CaCl_2$-$DW$ in the $EK$ system has significantly improved the strength of $DMS$ compared to $EK_0$ ($DW$-$DW$).
Figure 5. Variations of $w$ and $S_u$ for EK-treated DMS.

Asavadorndeja and Glawe [12] mentioned in their study that the decrease in $w$ provides some contribution to the increase in strength. In the third zone, the decrease in $S_u$ and increases in $M_c$ are similar in all EK phases. It is encouraging to compare this observation with Liaki et al. [13] who found similar trend of $M_c - S_u$ relationship near the cathode area. The authors claimed that the circumstances are in accordance with classical soil mechanics theory. A high increment of $S_u$ of $E K_1$ is attributed to the introduction of calcium ions into the $D M S$. The injected of calcium ions from the anode were moved into the $D M S$ by electromososis process. The positive performance of calcium ions as the injecting chemical in $E K$ has been proven since 1960s by Esrig and Gemeinhardt. They have investigated the performance of calcium ions in $E K$ stabilization towards an illitic clay. The results showed an improvement in the strength compared at the same water content and it increased more than one order of magnitude [14].

The results corroborate with the postulations of Mosavat et al. [1] who found similar condition in $E K$-treated soil, where the driest region occurred in the first zone and the wettest region occurred in the third zone. It was further claimed that consolidation took place in the anode area, with the reduction in $w$ producing $E K$ cementation effect. Referring to Mosavat et al. [1] and Jayasekera & Hall [7], the location of wet and dry regions is highly dependent on the mineralogical properties of the soil, such as permeability, soil type and diffuse double layer ($D D L$) characteristics.

3.2 Relationship between $w$ and $S_u$

Figure 6 presents the relationship between $w$ and $S_u$ of $E K$-treated and untreated $D M S$. There is a significant positive relationship between strength and moisture parameters of untreated $D M S$ ($R^2 = 0.9892$). These relationship of untreated $D M S$ were measured by using a maintain load test. The untreated $D M S$ was consolidated to a different $w$, henceforth measure its strength by using a laboratory vane shear test. Hence, the exponential line of untreated $D M S$ provides an indication of experimental variability in identifying the processes that affected the strength development in treated $D M S$ [12][14]. This finding corroborates with the ideas of Liaki et al. [13], who proposed that the data that lie above and/or shift to the right of the exponential line denote soil strengthening. Whilst, for data that lie below and/or shift to the left denote soil weakening. The authors declared that the plotted data that lie a small distance away from the exponential line might be attributed to chemical changes arising on the surface of the soil particles (e.g. $D D L$). On the other hand, data lying further away from the exponential line were attributed to chemical reactions occurring in the soil (e.g. compound precipitation).
Most of the plotted data of EK-treated DMS shows an improvement and lie above the exponential line. This study has found that generally right after the termination of EK, the treated DMS near the cathode developed as a wet region compared to other sections. This attributed to the electromomosis process which carried water molecules from the anode towards cathode. The present study confirms previous findings by Liaki et al. [13] in the strength development of EK treated DMS. The strength development in DMS is mainly affected by the DDL. This is due to the small distance of plotted data from the exponential line and it is also reinforced by the pH value of EK-treated DMS. Where, only for the further distance away from the exponential line of plotted data are affected by the precipitation process and required a high pH value (alkaline condition). A further study could assess by increasing the molarity or concentration of chemical used in order to investigate the strength development that affected by the compound precipitation process.

3.3 EK effect on pH and Su variations
The relationship between pH and Su of the EK-treated DMS is presented in figure 7. As can be seen from the figure, pH at the first zone (near the anode) were reported significantly more acidic in all EK phases than the other two zones (middle area & near the cathode). The correlation between pH and Su is suggestive of the strength development being significantly affected by the pH value. The pH in all EK phases displayed increment towards the cathode and remained in alkaline condition near the cathode area. This trend is similar to previous studies where acidic (pH < 7) and alkaline condition (pH > 7) were observed to develop in the anode and cathode regions of EK-treated soil, respectively [12-13].
In 1999, Ozkan et al. [14] reported that acidic soil conditions can cause ionization of soil, dissolution of basic precipitates, desorption of surface cation species into the pore fluid and leading to a flocculated soil structure. The present results corroborate with the findings by Ozkan et al. [14], where the acid front in the anode area recorded the highest strength in the EK-treated DMS. Asavadorndeja & Glawe [12] postulated that the formation of cementing agents in EK stabilization is mainly dependent upon the soil’s pH and the availability of free calcium ions. The application of cations as an enhancement agent and the processes involved explains the ions would migrate into the soil through the processes of electromigration and osmotic advection, hence improving the soil’s strength. One of the mechanisms that provides the greatest contribution in increasing the soil’s strength is precipitation. As mentioned before, DDL is the major mechanism that underscores strength development in DMS compared to precipitation [13]. There are several possible explanations for this result primarily near the cathode area that merely affected by the precipitation. Some authors have speculated that precipitation reaction normally occurred when pH of soil solution more than seven [12]. Henceforth, it shows that the precipitation reaction is limited to the cathode region.

3.4 EK effect on pH and LL variations

Figure 8 shows the relationship between LL and pH relative to distance from the anode. It is clearly indicated that the LL values for EK-treated DMS is pH dependent. Predominantly, the post-EK LL values decreased with increased distance from the anode. At first zone, the LL for EK-treated DMS rose from the untreated DMS value (71.70 %). Second zone two acts as a ‘transition zone’ between the LL and pH, while third zone illustrates the post-EK DMS pH rose from the untreated DMS value (6.80).

According to Liaki et al. [13], the results of an acidic environment and higher LL values near the anode may attributed to flocculation in the DMS structure. Besides, the compression of the DDL may occur as there are more positive ions (i.e. $H^+$) existent by implication from the pH values. Henceforth, this circumstance supporting the finding in $S_u$ value which clarified the higher strength in anode were reinforced by a flocculated structure in EK-treated DMS.
Additionally, the application of stainless steel electrode may have indirectly raised the LL at first zone. This is due to the greater number of higher valency positive ions (i.e. $Fe^+$) emerging into the system near the anode. This could also be affected by the thinning of DDL via cation exchange where the higher valency ions replace the lower valency of ones [13]. In year 1983, Casagrande postulated that the increase in LL mainly near the anode is affected by the electroosmosis process. On the other hand, Mitchell (1993) observed that the increasing cation valence tends to increase the LL of non-expansive minerals. Thus, these findings are corroborates as observed by several past research works that clarified the impact of the type of electrode used. The findings of this result have an important implication to support the physicochemical changes in EK-treated DMS.

4. Conclusions
An EK treatment towards DMS shows an improvement in enhancing its $S_u$. It is also developing the driest and wettest zone in the vicinity of anode and cathode, respectively. The application of CaCl$_2$ as stabilizers create a better result in physical properties of DMS compared to other systems. The grey colour of DMS turns to reddish brown in the vicinity of anode. This is due to the release and migration of iron oxides that affected from EK processes. The iron oxides that adsorbed onto the DMS surface contributed to a cementation effect between sediment particles. This cementing compound has improved the strength of the DMS. The $w$, $pH$ and LL values of EK treated DMS are correspond with the $S_u$ value in all system [15].

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Figure 8. Variations of $pH$ and LL for EK-treated DMS.
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