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Electrokinetic Stabilisation Method of Soft Clay in Pure System using Electrokinetic Geosynthetic Electrode

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Abstract. Electrokinetic stabilisation (EKS) method has the ability to solve the problems of soft highly compressibility soil. This study will present the results from an experimental study of EKS on soft soils using inactive kaolinite clay, inert electrode and distilled water (DW) as a pure system mechanism before any chemical stabilisers being used in this research. Therefore, this will provide a baseline study to improve the efficiency of EKS approach. The test model was using inert electrode of Electrokinetic Geosynthetic (EKG) developed at the Newcastle University to apply a constant voltage gradient of 50 V/m across a soil sample approximately 400 mm. Distilled water was used at the pore electrolyte fluid compartments supplied under zero hydraulic gradient conditions for the periods of 3, 7 and 14 days. Throughout the monitoring, physical and chemical characteristics were measured. Results from the monitoring data, physical and chemical properties of the pure system showed the development of pH gradient, the changes of electrical conductivity and chemical concentrations with regards to the distance from anode and treatment periods due to the electrochemical effects even though there was no chemical stabilisers were introduced or released from the degradation of electrodes.

1. Introduction

The use of electrokinetic in geotechnics for dewatering (electrosmosis) and stabilisation of low permeability soil was initiated by Casagrande in 1930s [1, 2]. It has demonstrated that a large reduction in water content will increase the shear strength of the soils due to the electrosmosis effect by electrical gradient. Since then, electrosmosis has been successfully implemented in the field for various geotechnical applications including stabilisation of slope [3, 4], embankment [5], improve friction pile capacity [6, 7], and electrosmotic strengthening of soft sensitive clay [8, 9]. More recently, numerous field applications include electrosmotic consolidation technique combine with vertical drain [10, 11] and new innovative geosynthetic electrodes [12, 13]. Where electrosmosis has proved successful, it usually has been as a result of using the process to introduce a chemical into the soil, either through anode solution or by direct electrolyte replacement. This improves the stability of the soil either by cation exchange occurring in the clay mineral content, or by cementitious material being deposited in the pore space [14]. This adaption of electrosmosis is known as electrokinetic stabilisation (EKS).

The application of deep chemical ground improvement using the EKS method has the potential to overcome problems of soft highly compressibility soil. This technique can enhance the strength and



reduce compressibility of a wide range of soils so it has the potential to treat soils anywhere in the world. Chemical stabilisation of clay soils using calcium-based stabilisers [15], such as lime and cement has been practiced routinely over many decades. In some cases, these methods are not suitable to stabilise soil under existing structure [16, 17]. It is expected that chemical improvement of soils in situ using electrokinetic stabilisation will play a very important role in the future not only as an alternative method for problematic soil whether under existing foundation or as part of a new development.

Previous research by Liaki [16, 18] conducted at the University of Birmingham, successfully proved the concepts and established the practical possibilities of improving the classical chemical modification and stabilisation reactions in situ [19, 20]. At the same time this work also has overcome the problems caused by electrode degradation. However, further investigations is still needed to assess what happens when appropriate selected chemical stabilisers are added to clay soils, both when mixed and then transported using electric currents. For that reason, the present study developed a new approach to treat soft clay soils in order to modify and improve their properties. By providing a better understanding of the 'pure' relatively inert system, which has no chemical introduced, will provide a baseline study to improve the efficiency of EKS approach when applied to soft compressible soils. Thus this technique has the potential to enhance key strength and stiffness gain under foundations to ensure this is controlled in the most efficient way.

2. Experimental Programme

2.1 Materials and Sample Preparations

An experimental programme was conducted to assess the efficiency of EKS when applied to soft clay soils. The original physical and chemical properties of clay soil were investigated first through laboratory programme following appropriate British Standard as shown in Table 1. Then, a laboratory investigation of EKS approach was carried out using the electrokinetic test methods developed at the University of Birmingham. Commercially available EKG electrodes were used to prevent the degradation of electrode that requires replacement during the treatment. In order to avoid the complexity of the system with different clay minerals and chemical changes that associate with coupled flows, pH gradient and electrolysis and redox reactions, a relatively 'pure' and inert form of kaolin was used in this study supplied by WBB Devon Clays. In addition, kaolin soil has been selected in this study because of its low activity, low adsorptive capacity and high electro-osmotic transport efficiency compared with other clays. A DC power supply obtained by Thurlby Thandar Instruments (model TS3022S) was used to supply power to the electrodes. A constant voltage gradient of 50 V/m was used for all electrokinetic treatments for 3, 7 and 14 days so that the effects of electric current with time could be assessed.

Table 1 Properties of English China Clay

Particle Size Distribution :	
Silt	49 %
Clay	51 %
Atterberg Limit :	
Liquid Limit	60 %
Plastic Limit	34 %
Permeability :	
Falling Head Test	2.2×10^{-8} m/s
Oedometer Test	2.6×10^{-10} m/s
Average specific gravity (G_s) :	2.63
Compression index (C_c) :	0.365
pH value :	5.1
Conductivity :	19.6 μ S/cm
Surface Area :	8 – 10 m ² /gm

The slurry sample was prepared by mixing the clay soils with deionised water to achieve 90% water content. The water content of slurry has been chosen based on 1.5 time liquid limit (LL) to produce homogeneous sample. Approximately, 10.66 kg of deionised water was poured into the mixer bowl and then 11.84 kg of dry English China clay was gradually added to ensure consistency of mixing. The slurry sample was then mixed using Hobart mechanical mixer and blended thoroughly for 30 minutes. Two mixtures of slurry samples need to be filled into the tank with the total amount of soil and water was 23.68 and 21.32 kg, respectively, achieving a water content of 51 % for all test samples.

The initial height of the slurry is 386 mm for all test samples. The load was applied to consolidate the slurry sample until it reached a final height of about 271 mm using hydraulic jack to achieve moisture content of 51%. The first consolidation pressure was set at approximately 10 kPa for about 24 hours to prevent soil particle migration via the drainage. The subsequent surcharge pressures were gradually increased in four increments over a 4 days period until a final height was reached. After consolidation thin solid plastic walls were removed at both ends of soil compartment and the gaps left were then inserted by the EKG electrodes. The soil samples were reconsolidated under the same loading as the last consolidation (67.9 kPa) for about 24 hours before the loading was released upon EKS testing. Subsequently, the electric current were turned and monitored throughout the test durations. This was performed to make sure a good contact between soils and electrodes. Physical and chemical properties of the treated soil were carried out along the soil profiles that were divided into eight sections from anode to cathode.

2.2 Electrokinetic Stabilisation Test Setup

The EKS model apparatus consisted of a tank made of non-conductive material which was PVC-U sheet to prevent short circuiting. The PVC-U sheet has 12 mm thick with internal dimensions of 450 x 220 x 550 mm. The tank consisted of main compartment of internal dimension 370 x 220 x 550 mm to locate soil samples for treatment and two small compartments that had internal dimension of 40 x 220 x 550 mm to supply the distilled waters (DW) into the soil. A schematic diagram of the EKS testing model is shown in Figure 1.

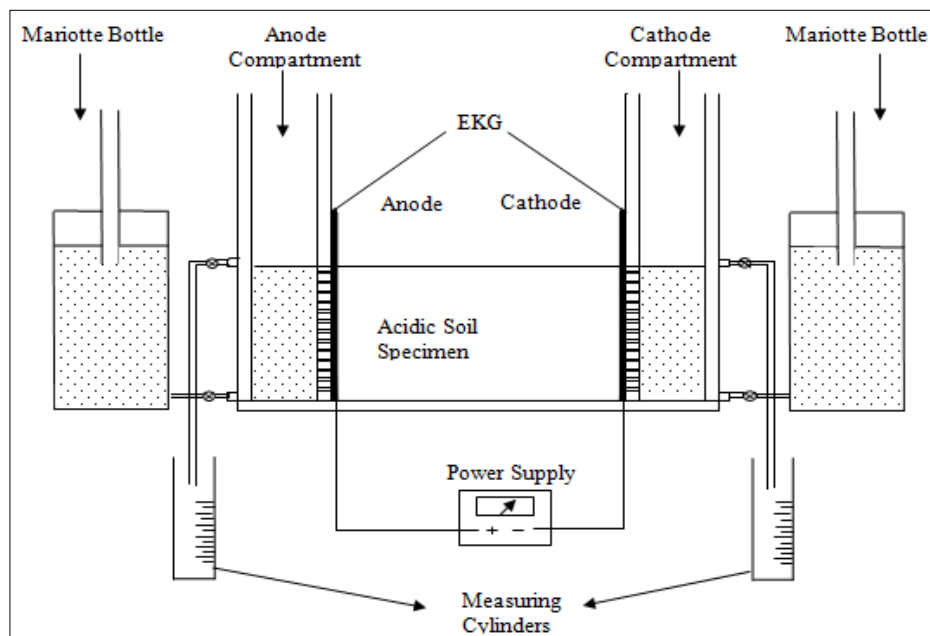


Figure 1. Schematic Diagram of EK Stabilisation Testing Mode

3. Results and Discussions

3.1 Monitoring Data

Figure 2 shows the monitoring of electric current for 3, 7 and 14 days of DW-DW system. It has been observed that electric current of those 3 different periods shows similar trend except for the 14 days treatment period which has lower value of about 9 mA at the beginning of the test, compared with 3 days and 7 days treatment periods which were with values of 12 and 13 mA, respectively.

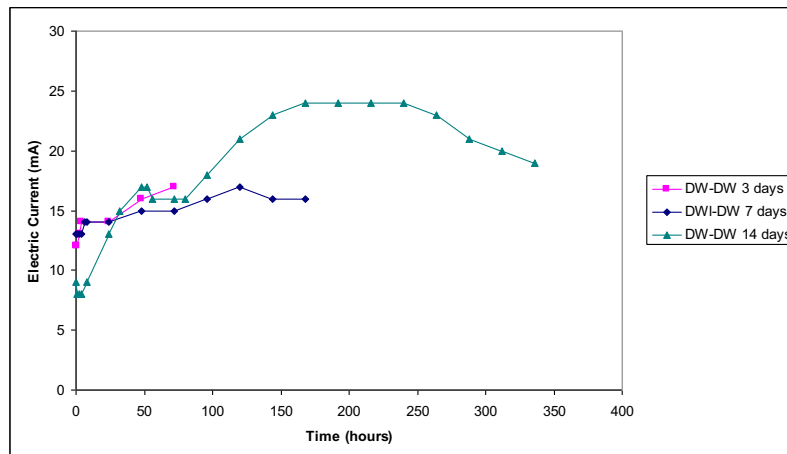


Figure 2. Electric Current of DW-DW system with time

After the 24 hours duration of EKS testing, the electric current values for the 3, 7 and 14 days treatment periods were reached at about 13 to 14 mA. The value of record current maintained these values, with similarly seen until 96 hours with both 7 days and 14 days tests. However, after this time for the 14 days test current rose, peaking at around 170 hours at 24 mA before dropping over the last 4 days (96 hours) to a value of 19 mA. The current trend in this pure system was attributed to the electrochemical effects in the clay-water electrolyte system which varied across the samples with time, thus affected the current profiles during tests.

The electric current variations with treatment time for the same type of electrode are comparable with [16] as seen in Figure 3 who reported that the current initially increased at about 14 mA, while it then dropped within the first 100 hours of treatment, as resistant of the materials increased and the voltage was set at the constant level. However, it was observed a large variation especially at the beginning which reported by Liaki [16] with different treatment time. This was due to the soil electrode contact which varied upon insertion of electrode during sample preparation which caused large variation especially at the beginning which found by Liaki [16].

Therefore, the improvement of the procedures and design configuration made for the current research has overcome the problem related to the soil-electrode interfaces. It should be noted that after the consolidation thin solid plastic walls were removed at both ends of the soil compartment, the gaps left were then inserted by the EKG electrodes. In order to make sure a good contact between soils and electrodes, the soil samples were subjected to load under the same loading of the last consolidation for about 24 hours before electric current were turned on.

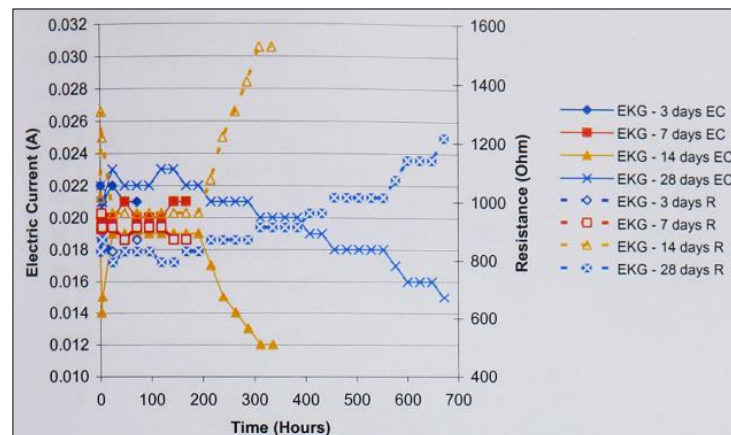


Figure 3. Electric Current of DW-DW system with time [16]

3.2 Physical and Chemical Analysis

In order to determine whether the application of EKS method results were caused by electrochemical process and were not caused by the variation of water content, the relationship between undrained shear strength and variation of water content was performed using the same preparation samples as the main experimental programme for comparison purposes and eliminated the variability of the results caused by different sample preparation, e.g. using consolidation method. The results of this relationship were then plotted in Figure 4 combining the control line together with the EKS results of DW-DW system. The data points located above the control or shifted to the right of the control line indicates an area of soil strengthening, whereas the data points located below the control line or shifted to the left of the control line indicates an area of soil weakening.

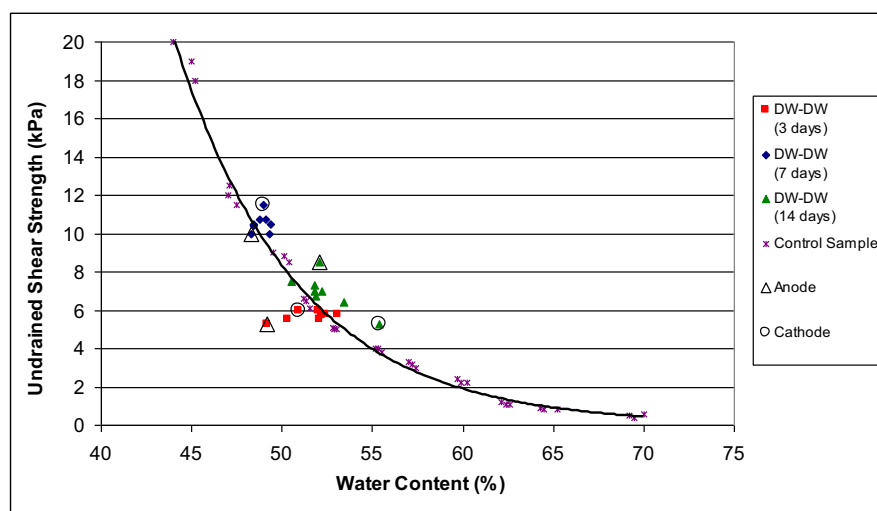


Figure 4. Relationship between undrained shear strength and water content of DW-DW system

In general as seen in Figure 4, most of the data points for DW-DW for 3, 7 and 14 days treatments lie essentially along the control line except for a few data points near to the anodes and cathodes. This was due to the electrochemical reactions taking place at the anode and the cathode that caused the changes of acid or alkaline environment respectively. Thus, results in soil strengthening or weakening during electrokinetic treatment.

It can be seen that the data points near the anode and the cathode for the 3 days test shift away below the control line, whilst the remainder of the data do not change much. The soil weakening for this short term duration test near the anode can be attributed to electrolysis of water generates oxygen gas that causes cavitations. While, hydrogen gas generation at the cathode may contribute to the soil weakening. Since only distilled water supplied at both electrodes, therefore no higher valence of ions to replace the lower valence ions into system were present and only hydrogen ions and hydroxide ions were released from electrolysis product. Small changes of pH values near the anode from pH 5.1 to pH 4.8 and at the cathode from pH 5.1 to pH 5.3 (see Figure 5) indicate that the electrolysis of water was still in the early stage and limiting the contribution to significantly increasing the soil shear strength near both electrodes. During the early stages of the treatment, there was not much release of hydrogen ions and hydroxide ions from electrolysis of water to change the pH environment near both electrodes.

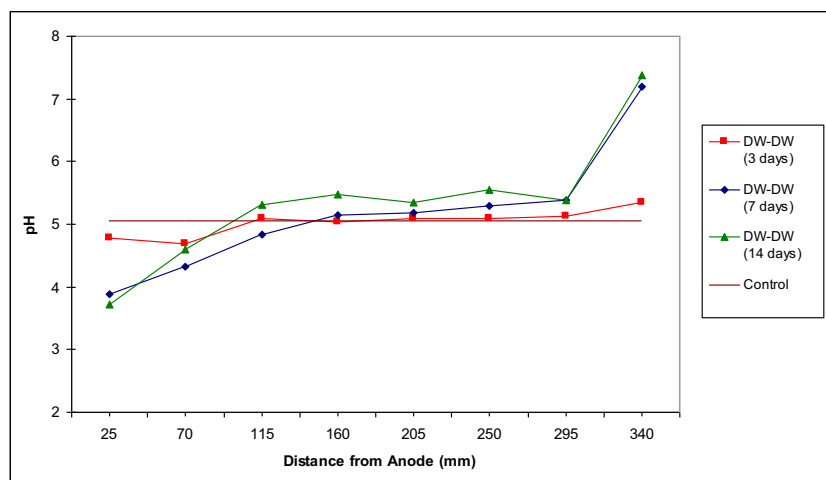


Figure 5 pH of DW-DW system with distance from anode

The test for 7 days showed that the data points close to the anode lie slightly below the control line whilst the rest of the values towards the cathode are slightly shifted away, above the control line. This shows that the values increasing towards the cathode due to the electrochemical processes that change the soil properties after a certain time which in this case was over 7 days of treatment period. At the anode, even though the data point was slightly away from the control line, there was a sign of improvement when compared with the data points of the 3 days test near the anode; these had shifted further away from the control line. At the cathode, the data point of 7 days test (340 mm from the anode) showed the greatest improvement. This can be explained by electromigration process that caused the positive ions (from the soil itself) to migrate towards the cathode and then precipitated when the alkaline environment started to develop at the cathode. This was supported by the pH results for the 7 days test with pH value at the cathode to change to a pH of 7.4 created an alkaline environment near the cathode (see Figure 5). It also suggested that hydroxide ions released from electrolysis product may react with cations within the pore fluid to form metal hydroxide gels, thus changed the soil properties near the cathode. Precipitation normally occurs in alkaline environment to form cementing compound that bind soil particles together resulted in soil strengthening. According to Asavadorndeja and Glawe [17], precipitation happens when pH value raise above pH 7. In this case the migration of hydrogen ions across the soil may change the pH at the cathode.

Data points for DW-DW for the 14 days treatment also showed similar trend as the 7 days treatment except for data points in the proximity of the anode. According to Liaki [16], the data points in the proximity of the anode shifted away, above the control line due to the establishment of physical mechanism under acidic environment, thus changes the soil structure and the arrangement of the clay fabric. Since no cations such as calcium or iron were introduced into the system, therefore the abundance

of hydrogen ions caused the changes of the pore fluid in clay-water electrolyte system which results in the changes of soil structure of the soil. This was supported by the pH values at the anode which decreased from pH 5.5 to pH 3.72 to form acidic environment (see Figure 5).

Therefore, the use of distilled water as an electrolyte will not affect the soil shear strength for short term duration but in fact caused soil weakening at the anode area for the 3 days test. The shear strength showed significant change for a longer term duration as demonstrated by the 14 days test. The trend was similar with the results from [16] for the 3, 7 and 14 days tests as seen in Figure 6. However, the 28 days of treatment period conducted by Liaki [16] has significantly increased the soil shear strength at the cathode but did not much change at the remainder of the samples.

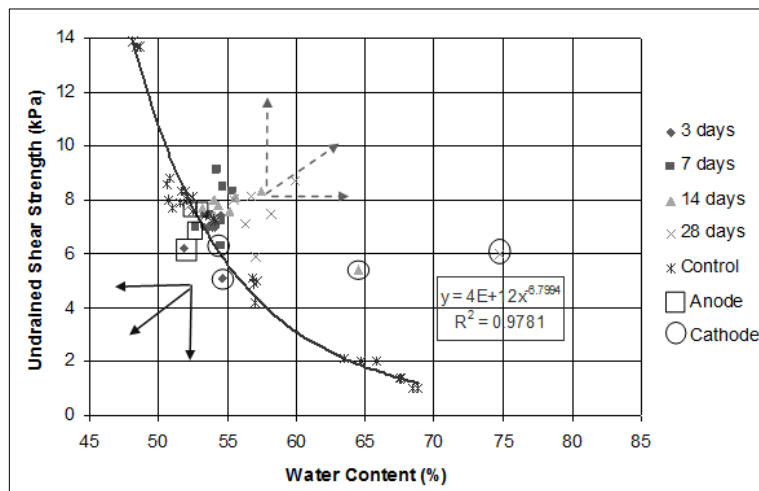


Figure 6. Relationship between undrained shear strength and water content of DW-DW system [16]

The pH values of the 7 and 14 days tests were increased to about pH 7.2 and 7.4, respectively. The rest of pH values for 7 and 14 days tests were consistent at the mid-point of soil sample from 115 mm to 295 mm away from anode. The results of pH values were consistent with the results from [16] indicating that the electrolysis processes produce a large pH gradient across the soil sample due to the production of hydrogen and hydroxide ions at the anode and cathode areas, respectively.

Figure 7 shows the results of electrical conductivity for all test periods of DW-DW system. The results show greater variation of electrical conductivity values across the soil samples. However, all the values are above the control value ($19.6 \mu\text{S}/\text{cm}$). The highest value of $134.5 \mu\text{S}/\text{cm}$ recorded at 70 mm from anode for the 14 days test while the lowest value is close to the control value at 295 mm from the anode for the 7 days test. There was significantly an increased in the electrical conductivity at the anode area due to the high acid environment which caused dissolution of certain chemical compound and clay minerals. Certain ions, i.e. Al, Fe and Si ions from dissolution process and hydrogen ions from electrolysis process were released into the pore fluid under an acid environment resulted an increase in ionic strength between the clay particles and migrate towards the cathode. However, in alkaline pH environment the solubility of these ions were reduced due to the precipitation of metal hydroxides to bind the clay particles, thus reduce the ionic strength of the pore fluid. The solubility of ions in the pore fluids and electrolysis process are the main contributors to the variation of electrical conductivity values across the soil samples. In addition, this has also contributed to the decrease in electric current with time as seen in Figure 2.

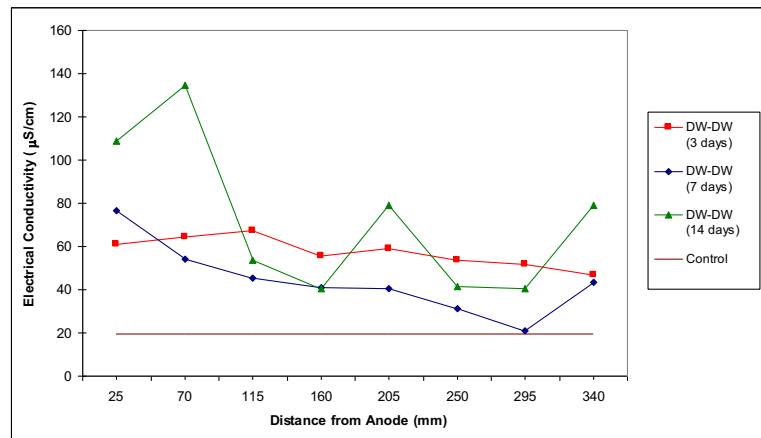


Figure 7. Electrical conductivity of DW-DW system with distance from anode

Figure 8 to 10 show the variations of metal concentration of DW-DW system from anode to cathode. The Fe values for all DW-DW tests as shown in Figure 8 are generally lower than of the control sample. For all the test period experiments a similar trend from anode to cathode was observed. The highest Fe concentration value of 1787 mg/kg was recorded at 250 mm away from anode. Since there is no source of Fe introduced into the system, the lower values of Fe concentration were due to some of the Fe migrated from anode to cathode and were drained out through the cathode. The Fe ions which adsorbed on the clay surface or as part of chemical compound in the natural clay were released in the pore fluid. During the electrokinetic process, these ions were migrated towards the cathode and will precipitate under high alkaline environment or otherwise will flush out through the cathode chamber. In contrast, the results of Fe concentrations from Liaki [16] showed a slight increase in Fe concentration across the soil samples even though there was no source of Fe ions introduced into the system. This was probably due to the steel corrosion occurred at the bottom edge of EKG electrodes if not sealed properly after it was cut or exposed during the insertion of the electrode after consolidation stage. Therefore, the current research has used an epoxy resin to prevent such phenomena from happening. The corroded EKG was observed during the trial test using silicon which was proposed by Liaki [16] to cover the expose steel at the bottom edge of the EKG electrodes. In order to be assured that the EKG electrodes did not corrode, the EKG electrodes were weighed before and after the EKS testing and no significant weight loss was found to affect the results of Fe concentration in this study.

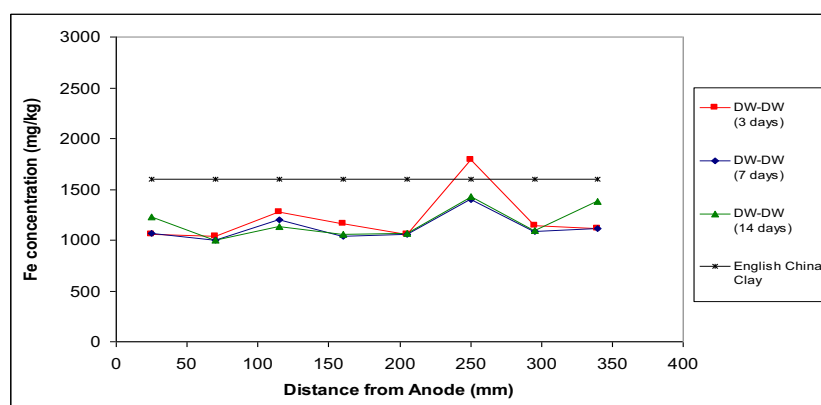


Figure 8. Fe concentration of DW-DW system with distance from anode

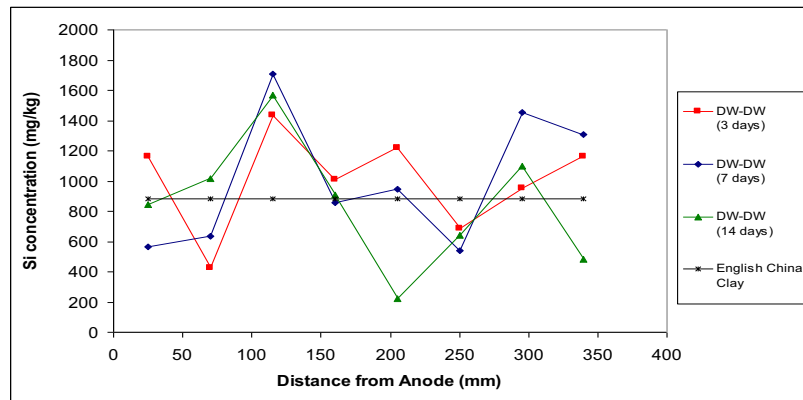


Figure 9. Si concentration of DW-DW system with distance from anode

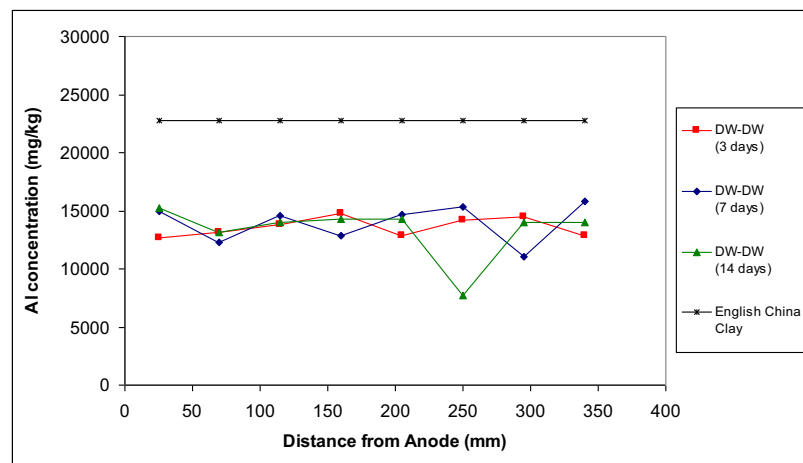


Figure 10. Al concentration of DW-DW system with distance from anode

The Si values in Figure 9 were fluctuated across the soil samples. Therefore, it was suggested that the solubility of Si ions were varied and complex with the electrochemical process during the EKS treatment. There were no results of Si concentration presented by Barker [18] to compare with the current results. Liaki [16] has reported that Si ions were not analysed due to a significant variance of unacceptable ranges were found. Similarly, the low solubility of Si ions on Oxford clay was also observed by Liaki [16] which affects the variability of Si concentration. Figure 10 show the Al values are generally lower than of the control sample. This trend is similar with the result from Liaki [16] however no explanation was given to explain this trend. In addition, this trend is also similar and consistent with the Fe concentration results. An extreme pH condition developed across the soil samples caused dissolution of Al ion.

4. Conclusion

The result presented and discussed in this study is comparable with the previous study performed by others [16,21]. However, the improved version of the procedures and design considerations [19,21] has been made to solve the problem faced by Liaki [16] and to achieve the objectives of this study before any chemical stabilisers were introduced into the system. The results from monitoring data, physical and chemical analysis showed that there are several important mechanisms relating to the electrochemical effects and these can be drawn from this study using a pure system. The key conclusions made are:

- i. The electric current profiles were influenced by the ionic concentration of the pore fluid within the soil matrices. Therefore, the addition of distilled water at both anode and cathode had caused increased of the electric current at the beginning of the test, but then a decrease with treatment time indicated that a high resistivity zone was formed due to precipitation of metal hydroxide at the cathode from the clay mineral itself and pore fluid. Thus this caused the fluid flow to become minimally decreasing the electric current across the system.
- ii. The soil weakening for the 3 days test near the anode and cathode can be attributed to electrolysis of water. At the anode, the production of oxygen gas caused cavitation whereas hydrogen gas generation at the cathode due to the development of gas bubbles which affected the arrangement of soil particles. These phenomena was supported by the small changes of pH values near the anode from pH 5.1 to pH 4.8 and at the cathode from pH 5.1 to pH 5.3 which indicated that the electrolysis of water was still in the early stage and limiting the contribution to significantly increasing the soil shear strength near both electrodes.
- iii. The test for 7 days showed a greater soil improvement towards the cathode due to the electrochemical processes that changed the soil properties. This can be explained by electromigration process which caused the positive ions (from the soil itself) migrating towards the cathode and then precipitated when the alkaline environment started to develop at the cathode as proven by other researchers[16,20,21,22]. While at the anode, there was a sign of improvement when compared with the data points of the 3 days test near the anode due to the acidity environment that changed the properties of clay soil. This was validated by the pH values at the anode which decreased from pH 5.5 to pH 3.72 to form acidic environment.
- iv. Data points for DW-DW for the 14 days treatment also showed similar trend as the 7 days treatment except for data points in the proximity of anode.
- v. The solubility of ions in the pore fluids and electrolysis process were the main contributors to the variation of electrical conductivity values across the soil samples.
- vi. There was significantly an increased in the electrical conductivity at the anode area due to the high acid environment which caused dissolution of certain chemical compound and clay minerals thus increased the solubility of ions in pore fluid. In alkaline pH environment the solubility of these ions were reduced due to the precipitation of metal hydroxides to bind the clay particles, thus reduced the ionic strength of the pore fluid.
- vii. The reduction of Fe and Al concentration along the soil profiles has confirmed the released of these ions from clay lattice into the pore fluid due to the variations of pH environment across the soil samples. During the electrokinetic process, these ions were migrated towards the cathode and precipitated under high alkaline environment or otherwise flushed out through the cathode compartment.

The baseline study of the pure system in this study is important for the analysis of results when using a chemical test. This was observed from the results of monitoring data, physical and chemical properties of the pure system which caused e.g., the development of pH gradient, the changes of the electrical conductivity, and chemical concentrations with regards to the distance from anode and treatment periods due to the electrochemical effects. This electrochemical effect will occur during the EKS testing even though there was no chemical stabiliser were introduced or released from the degradation of electrodes.

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