Stabilization a clay soil by ion injection through electrical field

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Abstract

A program of experiments was conducted to study the use of the electrokinetic technique to transport a stabilizing chemical agent through a clay soil. The experimental tests were undertaken on a clay soil in a special apparatus by applying a constant voltage gradient across the sample to introduce the solution of calcium chloride with different concentrations in the soil. The variations of shear strength across the sample resulting from the electrokinetic process were determined. The experiments were conducted in two groups. In the first group the electroosmosis method was used for soil samples with distilled water. In the second group the electrokinetic technique was applied to the soil to transport the solution of calcium chloride with concentrations 0.25, 0.5, 1.0 and 1.5 Mol/L through the pores of soil. The results showed that the strength of soil is increased for both groups and the amount of increase in the second group is dependent on the concentration of calcium chloride injected to the soil. The injection of this stabilizer also increased the electric current and electro osmotic permeability.

Keywords: electrokinetic, soil stabilization, shear strength

Introduction

Soft soils are known for their high compressibility and low shear strength. In engineering practice, there are three main aspects of behavior of these soils that may be improved. They are strength, volume changes and permeability. There are many in situ techniques for improving the behavior of soft soils. Chemical improvement is a common method that is used in situ for improving the desired behavior of soil. In this method chemical agents such as lime, cement or fly ash are added and mixed with the soil. The improvement of soil is achieved by exchanges of ions and chemical reaction between the soil water system and agent (Miller and Azad, 2000 and Kumar *et al*., 2007). However, these methods are not suitable to improve and stabilize a soil that is beneath an existing structure which may be settling.

Eelectro-osmotic technique is another method that is usually used for improvement of fine grained soils such as silts and clays. This method uses two electrodes that are embedded in soil and by applying an electricity current via these electrodes, the pore fluid moves from the anode to cathode. In other words the movement of water to the soil is prevented from the anode and the water in pores of soil between anode and cathode is drained at the cathode. Consequently the pore fluid pressure is reduced and the mechanical properties of soil such as shear strength are improved (Xue *et al*., 2017 and Gargano *et al*., 2019). Chew *et al.* (2004) and Rittirong *et al*. (2008) reported successful in situ application of this method for projects such as stabilization of slopes and excavations. The implementation of this method of stabilization takes a long time and has some limitations (Alshawabkeh and Sheahan, 2003).

The improvement of soil may be needed for establishment a new project or stabilization of a soil that is located beneath or adjacent to an existing building. Different methods have been proposed such as grouting, freezing, hydrofracture grouting, inducing consolidation by applying surcharge pressure and electro-osmotic consolidation (Xanthakos *et al*., 1994 and Holden, 1997). All of these methods have been shown to result in some degree of ground movement and in some cases they may cause damage to adjacent or overlying structures. Drawing chemical agents through the soil by electro-osmotic flow from anode to the cathode is another method for improvement and stabilization of soil with little or no associated volume change (Segall *et al*., 1980 and Alshawabkeh and Sheahan, 2003). The method of drawing chemical solution into the soil during electro-osmosis was adopted at the end of 1990s for improving the properties of clay soil. Acar and Alshawabkeh (1993) and Probstein and Hicks (1993) examined the transportation of chemical agents in soil under electric potential. They found that the electroosmosis carrying injected ions toward the cathode by mobilizing the pore fluid made changes in the behavior of soil. Ozkan *et al*. (1999), Rogers *et al.* (2003), Alshawabkeh and Sheahan (2003), Mohamedalhassan and Shang (2003), Barker *et al*., (2004), Chien *et al*. (2009), Ou *et al*. (2009 and 2018), Peng *et al*. (2015) Xue *et al.* (2018) and Estabragh et al. (2019) indicated that the chemical improvement under an electrical field (due to the transportation of chemical ions between electrodes) can overcome the problems associated with other methods and achieve appropriate results. This method, known as electrokinetic stabilization (EKS), consists of electroosmosis, eletromigration and electrophoresis. Electroosmose involves the movement of pore water of soil, electromigration includes the movement of ions in pore water and electrophoresis is the movement of soil solids. In a compacted soil, the effect of eletrophoresis is usually negligible (Mohamedelhassan and Shang, 2003). Ozkan *et al.* (1999); Alshawabkeh and Sheahan, (2003) and Asavadorndeja and Glawe (2005) used different chemical stabilizers and electrodes in electrokinetic stabilization (EKS) systems to improve the soil properties. They reported, based on their obtained results, that the EKS can significantly improve the mechanical behavior of clay soils.

A number of researchers such as Ou *et al*. (2009), Chien *et al*. (2009), Abdullah and Al-Abadi (2010) and Tajudin (2012) have conducted electerokinetic tests to improve soils by injecting solution of calcium chloride. Ou *et al*. (2009) and Chien *et al*. (2009) used concentrations of 0.01, 0.1 and 1 of $CaCl_2$ in their work. Abdullah and Al-Abadi (2010) and Tajudin (2012) used concentrations of 1.0 and 1.5 Mol/L respectively. However, they have used a limited range of concentrations of this solution. The aim of this work is to assess the use of EKS for stabilization of clay soils. In this research program, the effect of calcium chloride with different concentrations was investigated by conducting the experimental tests under a constant electrical gradient and time. In each test, solution of calcium chloride with different concentrations was introduced to anode while distilled water was introduced at the cathode reservoirs. In other tests, distilled water was introduced to the anode and cathode reservoirs and the results were used as reference. The obtained results were analyzed and compared.

Materials

Soil, calcium chloride and distilled water were the materials that were used in this work. A brief description of these materials is presented below.

Soil

The soil that was used in this study was a natural clay that was supplied by a local supplier. Laboratory tests were performed on samples of the soil according to ASTM standard to determine its properties. A summary of the physical, mechanical and chemical properties of the soil is presented in Tables 1 and 2. The soil was classified as silt with high plasticity (MH) according to the Unified Soil Classification System (USCS). XRD (X-ray diffraction) tests were conducted on samples of the soil and the results are shown in Fig.1. As shown in Fig.1a the minerals of the soil include quartz, calcite, feldspar (Na, Ca) and feldspar (K). The clay minerals of the soil are Illite, Chlorite and Montmorillonite (Fig.1b).

Calcium chloride

Calcium chloride was selected as a stabilizing material as it is highly soluble in water, inexpensive and safe for environment. Because of these characteristics, it has been used in bench studies and field trials (Rogers *et al*. 2002 and Baker *et al*. 2004). Solutions of calcium chloride were prepared at concentrations 0.25, 0.5, 1.0 and 1.5 Mol/L. The above concentrations were selected in order to collect information about the effectiveness of different concentrations. To prepare a desired solution, the required mass of the calcium chloride was poured to a graduated container and then distilled water was added until the volume reached to 1 liter. It was shaken thoroughly before it was ready to use.

Distilled water

Distilled water was used for preparing the solutions of calcium chloride and for conducting tests without solution of calcium chloride (base tests). The pH and electric conductivity (EC) of water were 7.2 and 0.009 dS/m, respectively.

Apparatus

A schematic diagram of the electrokinetic stabilization testing apparatus that was used in this work is shown in Fig.2. The apparatus was similar to the one that was used by Mohammedalhassen and Shang (2001) Rittirong *et al*. (2008) and Estabragh *et al*. (2016). The main cell, loading frame and D.C. power supply are the main components of the apparatus (Fig. 2). The main cell was in a rectangular tank for holding the soil sample. It was made of nonconductive transparent Perspex sheets to enable monitoring of the deformation of samples during testing and to prevent from short circuiting. The Perspex sheet used was 10 mm thick and the internal dimensions of the tank were 30, 10 and 25 cm length, width and height respectively. Two reservoirs, namely anode and cathode reservoirs, were added on the two sides of main cell as shown in Fig.2. These reservoirs were filled with anolyte and catholyte solutions and the total hydraulic head in them was controlled by adjusting standing tubes through valves. The apparatus included two rectangular electrodes, made from stainless steel with holes of 1 mm diameter. They were vertically positioned in the main cell at a distance of 5 cm from the soil to the main cell. Two sides of the sample in the main cell were covered by two saturated geotextile sheets to prevent from the loss of soil during the test (Kim *et al*. 2009 and Jeon *et al*. 2010 used filter paper and porous stone between soil and electrode compartments). At the bottom of the main cell a number of iridium oxide voltage probes with diameter of 1 mm were placed at distances of 2, 5, 8, and 11 cm from the anode. They were used for measuring the voltage at different times during the test. A loading system consisting of two plates that were connected to each other through an isolated bar, was used to apply load on the soil sample. One of these plates was placed on top of the soil and the other one was at the bottom of the main cell that applied load to the sample. A dial gauge that was installed on the top plate was used to measure the vertical deformation of the sample during testing. The power supplier of D.C. current consisted of a generator that produced various ranges of voltage and was connected to the electrodes through the connections.

Sample preparation

The slurry method was used for preparing the samples for the main tests as in this method there is no apparent detrimental effect on the uniformity of sample (Marto, 1996). A specific amount of air dried soil was weighed and the required volume of distilled water for water content of 5% above the liquid limit was measured and poured in a plastic bowl. The soil was then gradually added and mixed with the water by a hand steer. The prepared mixture was left in the bowl with a plastic cover for about 10 days for uniform distribution of moisture. The strength and water content of the prepared soil was measured by using vane shear apparatus in random points of the soil to ensure the uniformity and homogeneity of the prepared sample. The average values of initial void ratio and shear strength were 1.52 and 0.85 kPa respectively. The prepared sample was poured in the main cell in three layers. Each layer was vibrated for about 5 minutes to remove the air trapped inside the soil. Then a saturated geomembrane was placed on top of the soil in the cell. The level of fluids at the two reservoirs of the main cell was kept constant.

Experimental tests

The experimental tests were divided into two groups: in the first group the anode and cathode reservoirs were fed with distilled water. The purpose of conducting this test was to assess the treatment of soil without any transported ion agent in the soil. In the next group of tests the anode reservoir was fed with calcium chloride solution with desired concentration while the cathode reservoir was fed with distilled water. It was possible to use tap or sea water instead of distilled water for conducting the tests. Tap and sea water usually have different ions that may interact with minerals of clay (e.g., in the form of cation exchange) during sample preparation or testing. These interactions affect the behavior of soil which could make the analysis of results difficult. For this reason, distilled water was chosen for testing as reference solution and samples were prepared using solutions of $CaCl_2$ with different concentrations. The aim of these tests was to evaluate the effect of injection of calcium ions on treatment of soil at different concentrations of calcium chloride.

After placing the prepared soil in the apparatus, both reservoirs were fed with the desired fluids and then, the soil was consolidated in two stages. At the first stage, consolidation was done only by applying a surcharge pressure of 1.0 kPa to the soil sample through a loading plate (as shown in Fig.2) while the level of fluid at the both reservoirs was kept constant. The surcharge pressure was used for consolidation of the very soft slurry sample to prevent the soil from squeezing out of apparatus. The settlement of the sample was recorded by using a dial gauge. The consolidation under the surcharge pressure (preloading stage) was done for a duration of 5 days. After this stage, the second stage of consolidation was performed by maintaining the surcharge pressure and applying an electric current with potential of 50 volts (as suggested by Mitchell and Soga, 2005), keeping the level of fluid in both reservoirs constant (hydraulic gradient was set to zero). During this stage, in addition to measuring the vertical displacements, the volume of outflow of fluid from the cathode was measured. During the test, samples of anolyte and catholyte solutions were taken at every 24 hours using a syringe and kept in small bottles in a controlled temperature room (at 25°C) for pH and EC measurement. pH and EC were determined according to the ASTM D1125-14 and D5464-16 standard respectively.

The total time for the preloading stage and applying electrical current was about 10 days. After completing the test, the surcharge pressure and geomembrane were removed and strength of the soil sample was measured by using a vane shear apparatus. The vane shear test has some limitations, as is not suitable for fissured or unsaturated clay soil and clay soil containing sand or silt. In spite of these limitations it is easy to use and quick for measuring the undrained strength of non-fissured fully saturated clay. The strength was measured at distances of 4, 11, 15 and 26 cm from the anode. After the shearing test, a number of samples were taken from the points where the shearing tests were conducted and the water content and Atterberg limits were determined according to the ASTM D 2216-19 and ASTM D 4318-00 standards respectively. After testing, the pH and EC of the soil were also measured, according to the method that was used by Abu-Hassanein et al. (1996), by taking samples from distances of 4, 12, 19 and 26 cm from the anode. In addition, a number of samples were taken at anode, middle and cathode for conducting scanning electron microscopy (SEM) tests. The samples were scanned under SEM following the method that was used by Tremblay *et al*. (2002).

Results

The results obtained are presented in the following sections.

pH

The variations of pH values against time for distilled water and different solutions of calcium chloride in anode and cathode reservoirs are shown in Fig.3. As shown in this figure, the pH values increased and decreased steadily at cathode and anode reservoirs respectively, until the end of the test when they reached nearly constant values. The results show that the final values of pH for distilled water at anode and cathode are 4.8 and 12.35 respectively but for solution of 0.25 Mol/L calcium chloride they are changed to 4.12 and 12.5 respectively. It is observed from these results (Fig.3) that by increasing the concentration of calcium chloride, the pH is decreased at the anode and increased at the cathode in comparison with distilled water. For example, for the solution of 1.5 Mol/L the values of pH at the end of the test at the anode and cathode reservoirs are 2.42 and 13.36. The trends of variations in pH at both reservoirs are function of CaCl2 concentration. The higher the concentration, the greater is the reduction in pH at the anode and increase in pH at the cathode reservoirs. When a direct current is applied through electrodes that are immersed in fluids at both reservoirs, an electrolysis reaction occurs. During this reaction oxygen and hydrogen are released at anode and cathode which results in the formation of hydrogen and hydroxide ions. They produce acidic and basic fronts at anode and cathode respectively. These reactions result in low and high pH areas near the anode and cathode respectively (Barker *et al.*, 2004).

***EC** (Electrical Conductivity)*

Fig.4 shows the results of variation of EC with time for both reservoirs for different qualities of the used fluid. As shown in this figure, the value of EC for the distilled water is initially 3.5 at both anode and cathode reservoirs but by increasing the time they are increased so at the end of the test, they reach to 17 and 60 dS/m at anode and cathode reservoirs. For solutions of $CaCl_2$, at the start of the test the value of EC at anode is higher while at cathode it is the same as the distilled water. By increasing the time as the test progresses, EC is reduced at the anode and increased at the cathode. This trend is also seen for other concentrations of $CaCl_2$. It is seen from Fig.4 that the rate of reduction of EC at anode is slow but the increase in EC at cathode is relatively rapid. For example, for the solution of calcium chloride with concentration of 1.5 Mol/L the initial values of EC at anode and cathode are 133 and 6.2 dS/m but at the end of the test they change to 128.5 and 77.8 dS/m respectively. It can be said the acid front produced at the anode causes desorption, dissolution and ionization of cationic metals which then migrate toward the cathode. This is resulted in increasing the value of EC at the cathode reservoir. For the solution of calcium chloride, the amount of increase in EC at anode is more than cathode. It can be said the anode reservoir is continuously fed with solution of calcium chloride but when the injected ions enter the space of soil and are transported to cathode, some of them react with existing anions and cause decrease in the value of EC in comparison with the anode reservoir. The increase in the value of EC is dependent on the concentration of $CaCl_2$. The higher the concentration of $CaCl_2$, the higher is the value of EC at both anode and cathode.

Q (*Discharge)*

The amount of fluid that leaves the apparatus (outflow) was measured continuously and the results are shown in Fig.5. The results show that the volume of outflow at the end of the test for the distilled water is 1118 cm^3. The outflow for calcium chloride solution at concentrations of 0.25 and 0.5, are 2070 and 2540 cm^3 but for concentrations 1.0 and 1.5 they are 820 and 560 cm^3 respectively. It is resulted that the volume of outflow is not dependent on the concentration of calcium chloride and does not follow a specific trend.

K_e (electro-osmotic permeability)

The eletcro-osmotic flow rate in soil depends on the coefficient of electro-osmotic permeability (K_e) and the intensity of the applied electric field. The amount of fluid outflow from the cathode due to the application of voltage gradient can be described by an equation similar to Darcy's law (Alshawabkeh *et al.*, 1999)

$$q_e = K_e * E \tag{1}$$

where q_e is the electro-osmotic flow rate, E is the electric field intensity and K_e is electro-osmotic permeability. As it is seen from the above equation, the rate of discharge of fluid from the soil is controlled by K_e and E. It can be said that the discharge of fluid under a specific electric field intensity is dependent on the value of K_e. The values of K_e were calculated based on equation (1). Fig.6 shows the variations of K_e with time for different fluids that were used in this work. As shown in this figure, the order of the curves in this space is similar to the curves of outflow discharge from the cathode reservoir (Fig.5). It is seen from this figure that the curves for 0.25 and 0.5 Mol/L are located above the curve of distilled water while the curves for 1.0 and 1.5 Mol/L are below it. The results show the general trend of reduction in K_e with time but the rate of reduction is more rapid for calcium chloride solutions of 0.25 and 0.5 Mol/L than the solutions with concentrations of 1.0 and 1.5 Mol/L.

I (Intensity of electrical current)

Fig. 7 shows the variation of the intensity of measured electrical current with time for different fluids. It is seen that there is a peak in the value of I at times less than one day of testing, but it is then decreased with increasing the time. The order of the curves in this space is evolved with increasing the concentration of calcium chloride. The final value of I for distilled water is 0.25 A and for concentrations 0.25, 0.5, 1.0 and 1.5 Mol/L of calcium chloride, it is changed to 0.31, 0.38, 0.41 and 0.43 A respectively. The value of *I* is dependent on the amount of existing ions in the pores of soil; at high concentrations more ions exist which results in higher values of *I*. These results are in agreement with the results that were reported by Ou *et al*. (2009).

Consolidation

As mentioned above, consolidation was conducted in two stages: one before applying the electric current and one after that. In both stages, the vertical deformation was measured by recording the data from a dial gauge. The results of both stages are shown in Fig.8. As shown in this figure, the vertical deformation during loading is relatively high in comparison with the deformation due to the applied electric current. The magnitudes of deformation at the initial stage are dependent on the concentration of calcium chloride; so, increasing the concentration induces more deformation. For example, at the end of this stage the values of deformation for distilled water and 1.5 Mol/L calcium chloride solution are 5.132 and 10.378 mm respectively. It is seen from this figure that the changes in the deformation of the sample during the application of voltage gradient is not significant and the deformation curves are nearly straight lines.

Strength

The strength of the treated soil was measured at distances of 4, 11, 18 and 26 cm from the anode. Fig.9 shows the measured strength along the length of soil that was treated with different fluids along with the baseline soil strength before contacting the main test. As shown in this figure, by increasing the distance from the anode the strength is increased and the maximum strength is observed near the cathode. The results also show that by increasing the concentration of calcium chloride solution the strength is increased. For concentration of 1.5 Mol/L the strength near the cathode is nearly 43 kPa but for distilled water it is 8.2 kPa at the same point (showing an increase in strength of about 5 times compared with distilled water as electrolyte). It is seen from this figure that the order of expansion curves is dependent on the concentration of calcium chloride solution.

pH and EC results of soil

Fig.10 shows the variations of pH and EC along the soil sample after testing. As shown in Fig.10a the value of pH at the distance of 4.0 cm from anode is in the acidic range and the degree of acidity at this point is increased by increasing the concentration of $CaCl_2$. The value of pH is increased by increasing the distance from anode and at the distance of 15 cm from anode pH is equal to 7.0 for all used fluids except distilled water. The increasing of pH continues for the distance more than 15 cm. It is observed from this figure (Fig.10a) that the soil at the distance of 15 cm is divided into acidic and basic sections. Fig.10b shows that the value of EC is maximum near the anode (4 cm from anode) for any used $CaCl_2$ solution (except distilled water). The increase in EC at this distance is dependent on the concentration of $CaCl_2$. By increasing the distance from the anode the value of EC is decreased. After the distance of 20 cm EC reaches a nearly constant value.

SEM results

Structure of a soil has a strong influence on its mechanical and physical behavior. Structure of clay soil usually consists of micro and macrostructures. The microstructure is responsible for chemical interaction by minerals of clay. With scanning electron microscopy (SEM) significant information about the structure of soil can be obtained. SEM technique is now widely used for description the behavior of different types of soil (Diamond 1970 and Collins and McGown 1974). Tremblay *et al.* (2002), Cai *et al.* (2006)

and Estabragh *et al*. (2019) used the SEM results for observing the microstructure of soil samples under different conditions. In this work SEM tests were conducted on soil samples near anode and cathode in order to understand how the microstructure of soil is changed due to the injection of ions under electrical field.

Fig.11 shows the SEM results for the soil samples that were taken from around the anode and cathode at the end of the test when the anode reservoir was full of calcium chloride solution with concentrations of 0.5 and 1.5 Mol/L. Fig.11a shows the micrographs of the samples that were taken from the vicinity of the anode when the concentration of injected calcium chloride was 1.5 Mol/L. In this case the particles are plate-like in shape and parallel with each other with large voids between them. As shown in Fig.11b, for the sample around the cathode at the same concentration, the soil particles are flocculated so, the particles paste to each other with some space between them. Fig.11c shows the micrograph of sample taken around the cathode at concentration of 0.5 Mol/L calcium chloride. The pasting of the particles to each other and the structure of the soil is similar to the sample in the vicinity of the cathode at concentration of 1.5 Mol/L.

Discussion

The size of clay particles is very small but their specific surface is very high in comparison with coarser particles. The surface of clay particles carries negative charges but they can be neutralized when the positive ions or exchangeable cations present in the pore fluid of soil are adsorbed to the surface of these particles. The cations are not attracted strongly and if the quality of water is changed, they can be replaced with other cations. Mitchell and Soga (2005) define the quantity of exchangeable cations as the cation exchange capacity (CEC). Cation exchange may change the physical and physicochemical behavior of a soil (Mitchell and Soga, 2005). There are many sources of cation exchange capacity for clay soils such as isomorphous substitution, broken bond at edges and corners of particles due to unsatisfied valances and replacement of hydrogen of an exposed hydroxyl by another type of cation. The isomorphous substitution is one of the major sources of cation exchange. Therefore, when water is added to dry soil, the concentration of cations near the surface of particles is high and they tend to diffuse from the soil to form the same concentration thought. The charge surface and mobile ions in bulk fluid together are termed diffuse double layer (DDL).

Fig.3 shows the changes in the value of pH at anode and cathode when using solution of calcium chloride at anode in comparison with when distilled water is used. These changes are dependent on the concentration of the used calcium chloride. It can be said that when a liquid with ions is used, the electrolysis action is increased and the value of pH decreases in comparison with liquid without ions. The increase in the value of pH can be attributed to the migration of realized ions due to exchange of ions with injected Ca^{+2} in the soil. The variations of EC with time for both reservoirs are presented in Fig.4 for different fluids**.** As shown in this figure, when distilled water is used as electrolyte, the values of EC are changed with time due to the application of direct electric current. The initial value of EC for distilled water changes from 3.5 to 17 and 60 dS/m at anode and cathode respectively.

Fig.5. shows the variations of volume of outflow of fluid from the soil sample during the application of electric current. As shown in this figure, the volume of outflow for solutions of 0.25 and 0.5 Mol/L is increased in but for solutions of 1 and 1.5 Mol/L there is a reduction in the amount of outflow in comparison with distilled water. The results

show that the reduction in outflow is indirectly correlated with concentration of $CaCl_2$. The thickness of DDL layer is dependent on the concentration of existing ions; there is a reduction in the thickness of DDL with increasing the concentration of ions (Van Olphen, 1977 and Mitchell and Soga, 2005). The shrinkage of DDL results in a flocculated structure in the soil. By increasing the concentration of $CaCl_2$ more ions enter the pores of soil and reduce the thickness of DDL which results in a flocculated structure. The higher the concentration of $CaCl_{2,}$ the higher is the degree of flocculation of the soil. In a flocculated structure, the path between spaces is irregular and this is increased with increasing the degree of flocculation. Therefore, when the fluid flows through the mass of soil, the path of flow is not parallel to particles (or some could even be perpendicular to particles) which could provide some obstruction to the path of the outflow. On the other hand, the Ca^{+2} may react with hydroxyl and make sediment between spaces of particles and prevent from outflow of the fluid. The results of K_e (Fig.6) are similar to the results of outflow from the sample.

Fig.7 shows the variations of I with time for different fluids. It is seen from this figure that at the initial stage of the test I is increased and then decreased steadily until the end of the test. The curves are evolved with increasing concentration in comparison with distilled water. At a given time for concentration of 1.5 Mol/L the value of I is more than the other concentrations.

The two stages of consolidation are shown in Fig.8. As shown in this figure, the amount of settlement is increased with increasing the concentration of $CaCl_2$. At the first stage, the applied load was the same for all samples and at the second stage, the applied voltage and its duration were the same. Under similar conditions, the viscosity of pore fluid is important in settlement of soil. When the viscosity is increased, the displacement of particles would be easier in comparison with a solution with lower viscosity which results in greater settlement. Since the viscosity solution of 1.5 Mol/L is more than distilled water and the other concentrations of $CaCl_2$, more settlement is observed for this solution. It is seen from Figs 5 and 6 that the final values of discharge flow and K_e for solution of 1.5 Mol/L $CaCl_2$ is less than 0.5 Mol/L of $CaCl_2$. This trend of variations of discharge flow and K_e is not consistent with the values of final settlement of samples with these concentrations of $CaCl_2$ solution as shown in Fig.8. As it was explained above, the value of settlement is increased with increasing the concentration of $CaCl_2$ due to the increase in the viscosity of the solution. Increasing the settlement causes reduction in the voids between particle and leads to decrease of discharge fluid from the sample and reduction in the value of K_e for the sample with 1.5 Mol/L $CaCl_2$ (Figs. 5 and 6). Fig.9 shows the strength of soil at different distances from anode for different fluids. The maximum strength for each fluid is seen near the cathode. Fig.9 shows that the strength curves evolved with increasing the concentration of $CaCl_2$. The higher the concentration the higher is the strength. The increase in strength at the cathode when the solution is distilled water is due to sedimentation of some salts or cementation between the particles by existing the ions in the space of particles (Rittirong *et al.* 2008). For solutions of $CaCl_2$ the strength is minimum at anode and maximum at cathode. It can also be argued that pozzolanic reactions can occur at alkaline pH. Ou et al. (2018) stated that the injection of calcium chloride solution will cause cementation between the clay particles near the cathode and these mechanisms can increase the strength of soil. They argued that the main mechanism of cementation is due to the pozzolanic reaction in formation of C-S-H

(Calcium Silicate Hydrate) or C-A-H (Calcium Aluminate Hydrate) gel. Fig.10 shows the variations of pH and EC across the length of the soil at the end of the test. As shown in this figure, up to a distance of 15 cm from the anode the pH of the soil is in acidic range and is basic in the rest of the soil. This is changed with the concentration of the calcium chloride solution. As shown in Table 2 the initial value of pH of the soil is 8.0. When the solution of calcium chloride is used, the Ca^{+2} ions are entered the pores of the soil. A number of these cations are replaced with other cations of clay such as H^{+1} by isomorphous replacement. The release of anions causes a drop in the value of pH along this distance from anode in comparison with distilled water. The rest of Ca^{+2} ions are transported to the cathode which react with existing hydroxide ions and produce a basic environment that results in increase in pH. On the other hand the degree of flocculation of soil structure is increased with increasing the concentration of ions (as shown in Fig.11) which results in increase in the strength of the soil. These findings are not in agreement with the results that were reported by Ou *et al.* (2009) and Chien *et al.* (2009). They reported that the strength is maximum at anode and minimum at cathode. This is may be due to the different types of apparatus and different methods of testing. The results of this study showed that by injection the solution of $CaCl_2$ the improvement of soil is limited to the area around of cathode. In order to improve the strength of the soil through the entire length of it after injection the solution of $CaCl_2$ for a specific time the injection should be followed by another chemical solution such as KOH or Na_2SiO_3 as used by Ou *et al.* (2018).

This research study has established that the application of EKS method has potential to be used successfully in field applications and the viability of this technique has been proven in this laboratory study. Successful field applications can be achieved if suitable chemical stabilizers are used together with the appropriate choice of electrode materials and other design considerations.

Conclusion

This paper presented the results from an experimental investigation to study the method of injection of calcium chloride ions into a clay soil using the electrokinetic technique. The experimental tests were conducted under constant electrical voltage with different concentrations of calcium chloride. The results indicated that the injection of calcium chloride causes increase in the value of electric current and electro-osmotic permeability and EC and K_e are increased with increasing the concentration of calcium chloride. The results also showed that the shear strength of clay soil is increased and its compressibility is reduced by injection of these ions. The increasing of strength and reduction of compressibility are depended on the concentration of calcium chloride and for a constant concentration, they increase with increasing the distance from anode.

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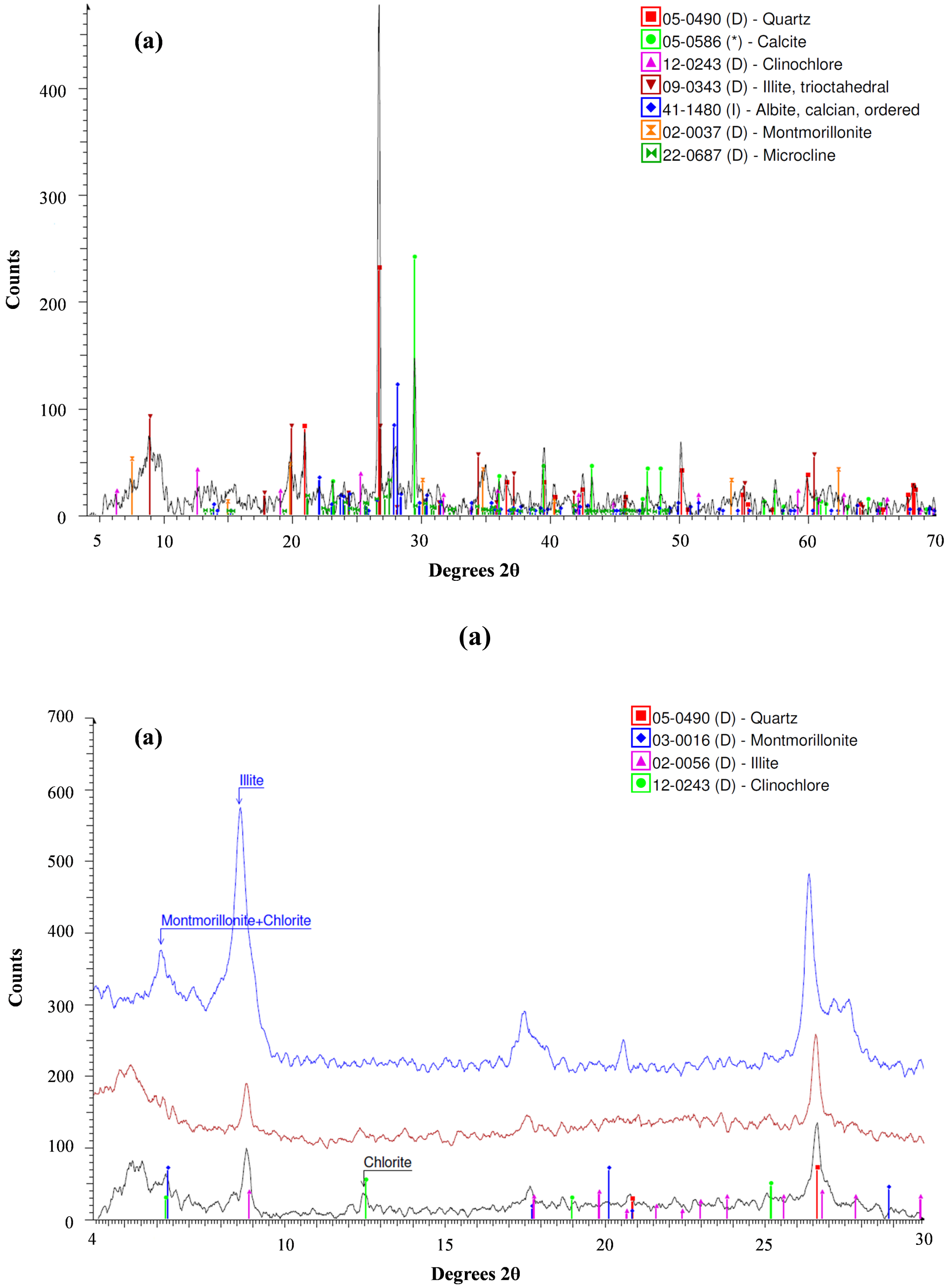


(a)

(b)

Fig.1. X-ray diffraction plots (a) minerals (b) clay mineral of soil

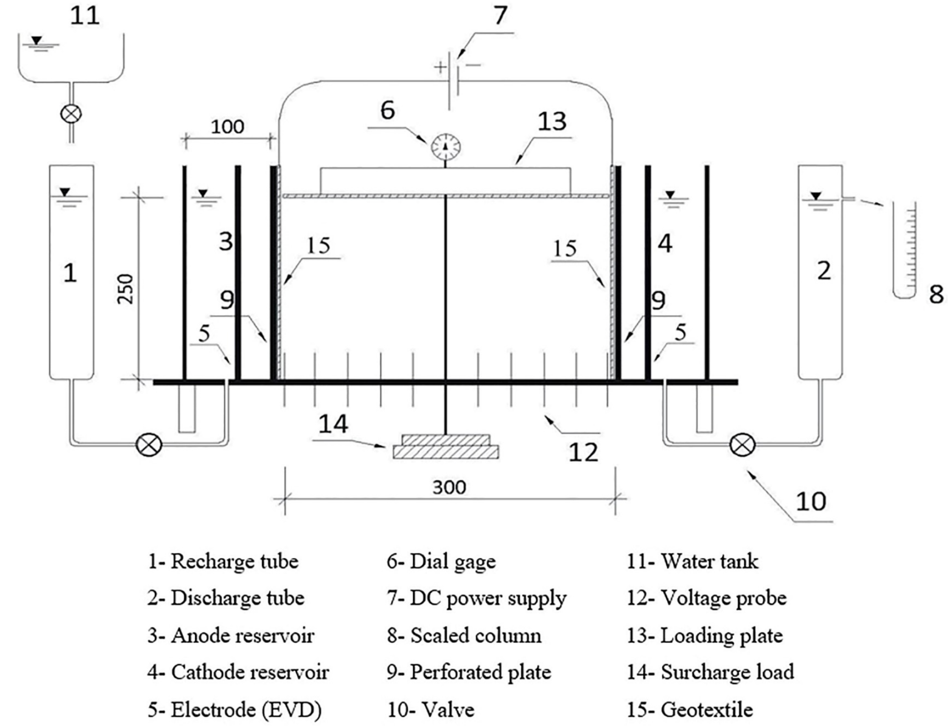


Fig.2. Schematic plan of the test set-up (dimensions in mm)

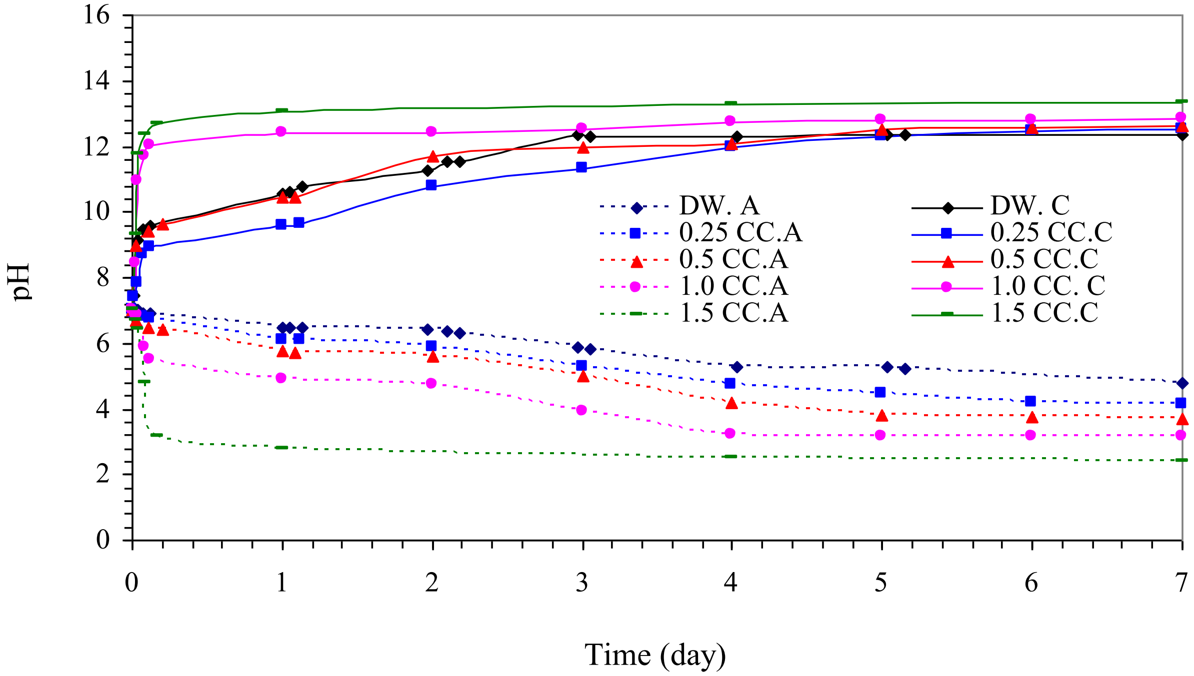


Fig.3. Variations of pH with time. DW=Distilled water, CC= Calcium chloride A=Anode, C= Cathode

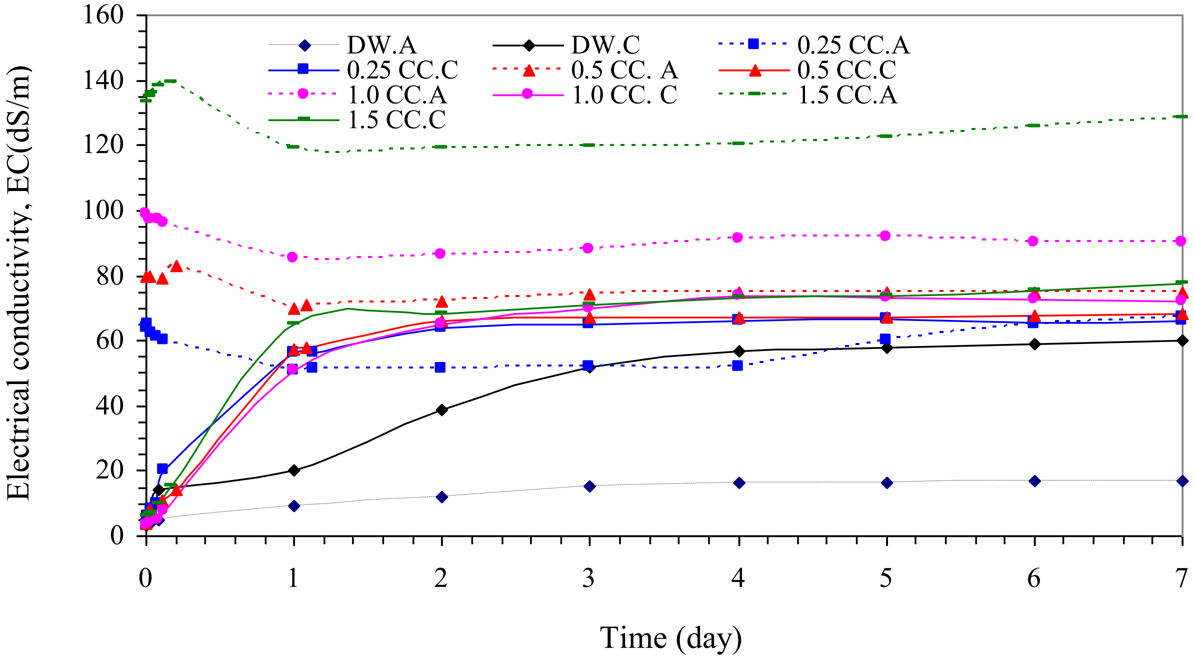


Fig.4. Variations of EC with time. DW=Distilled water, CC= Calcium chloride A=Anode, C= Cathode

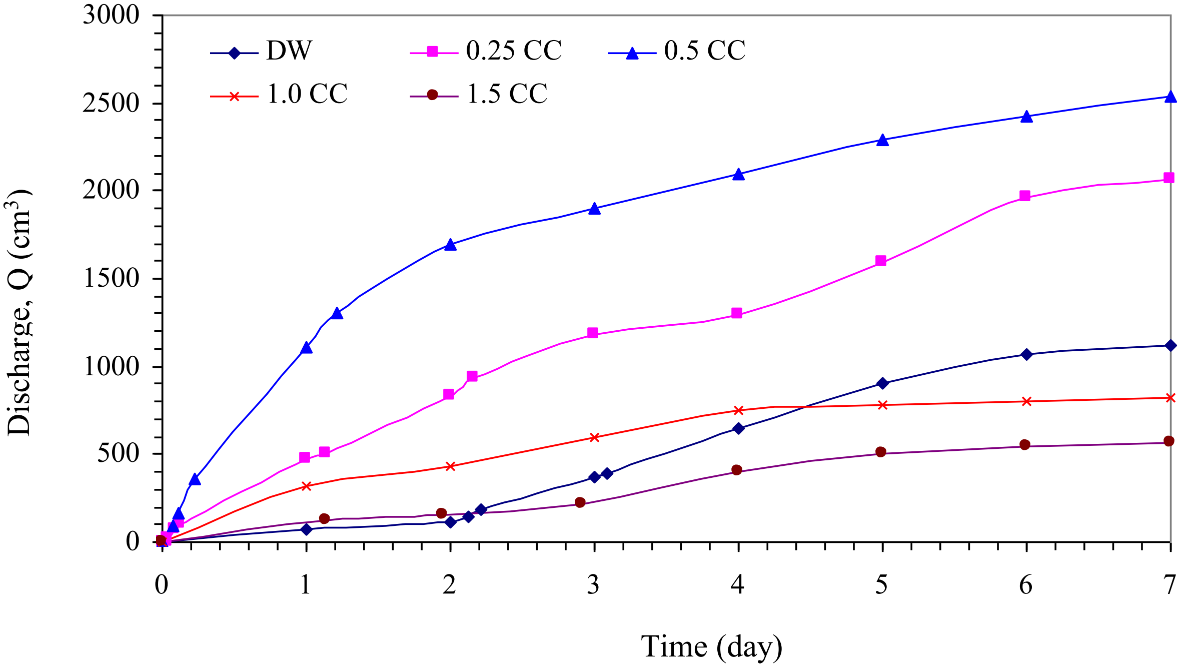


Fig.5. Variations of discharge fluid from cathode with time. DW= Distilled water, CC= Calcium chloride

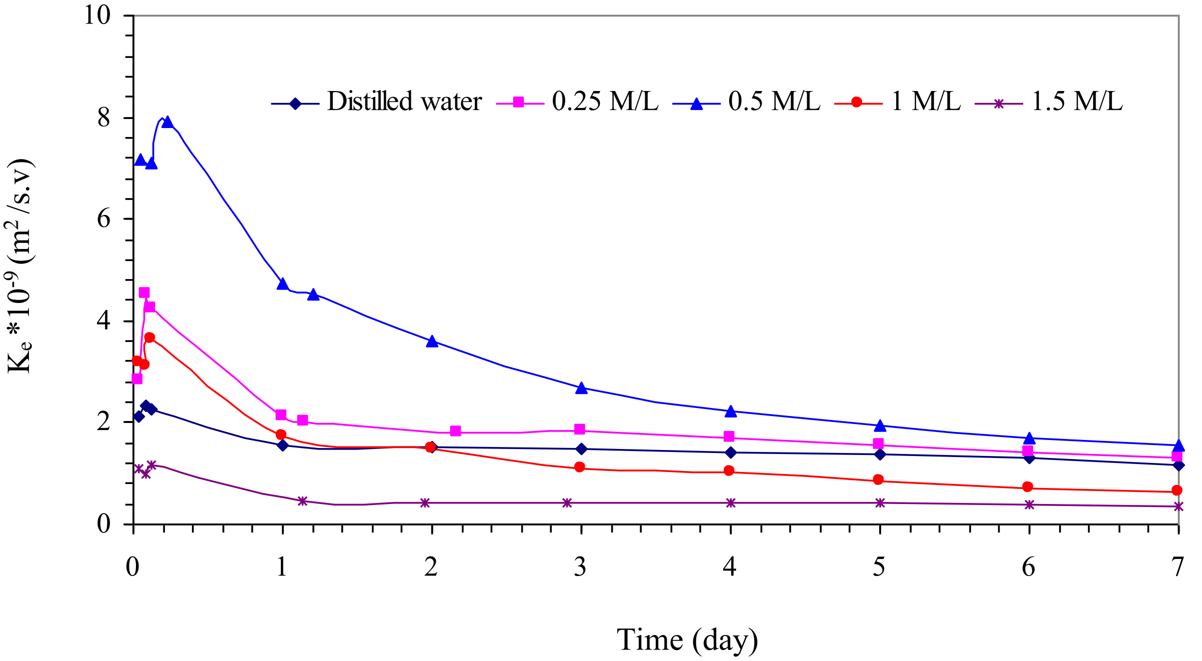


Fig.6. Variations of K_e with time during different tests. DW= Distilled water

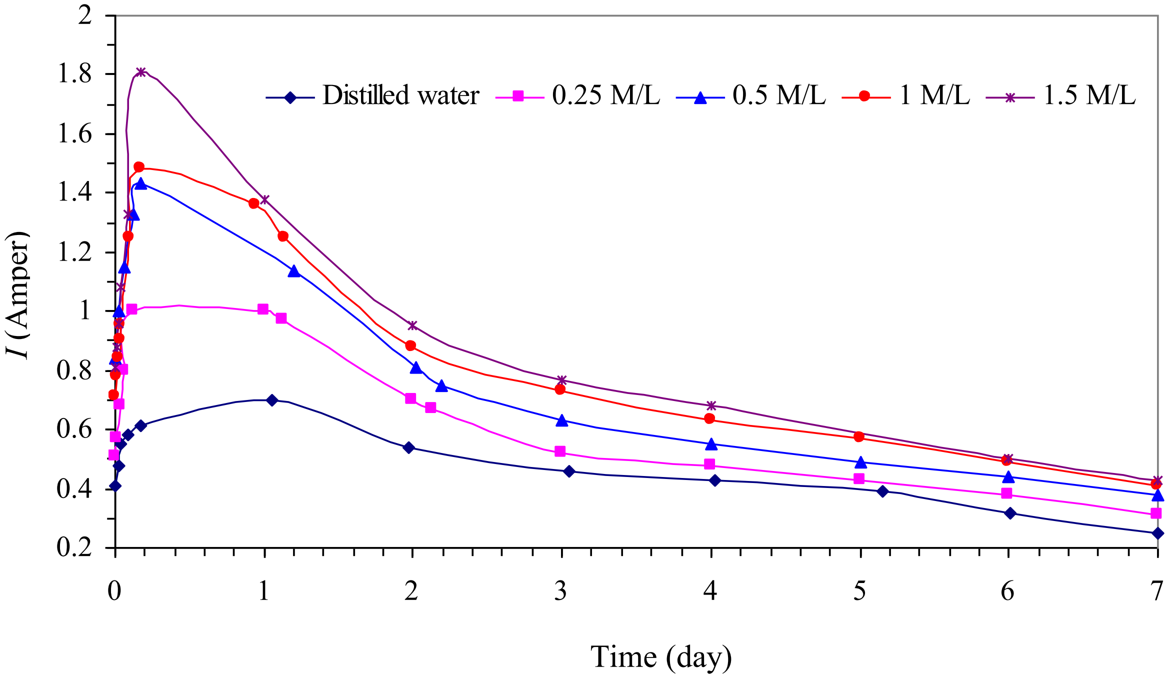


Fig.7. Variation of current intensity with time during different tests. DW= Distilled water

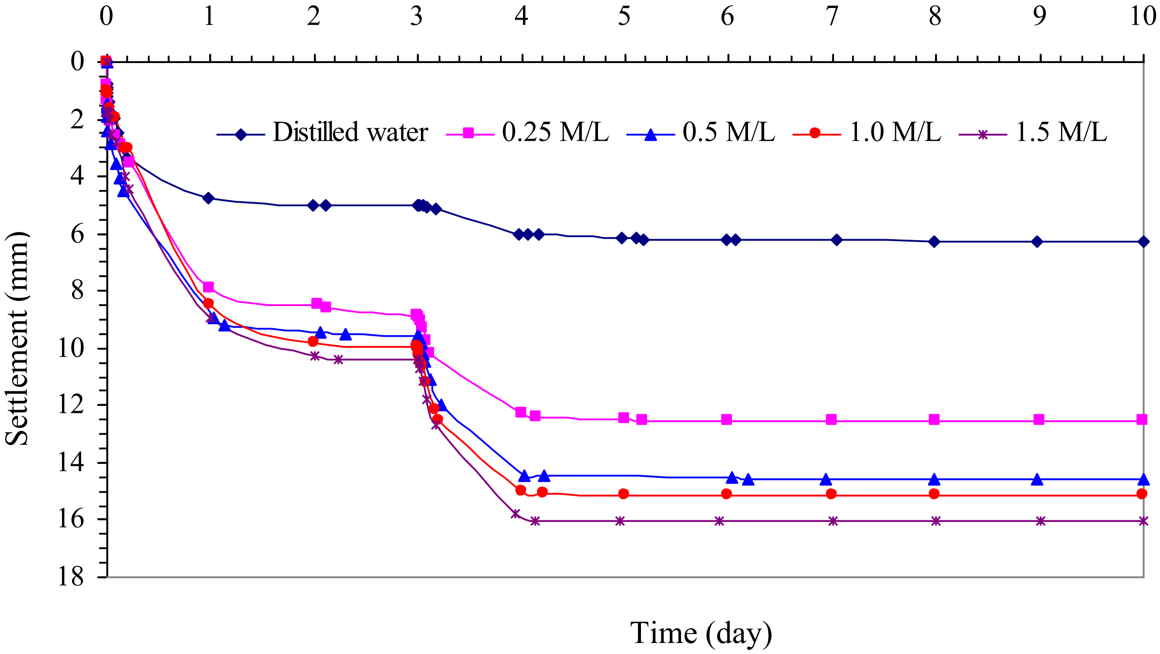


Fig.8. Variation of settlement with time for different fluids

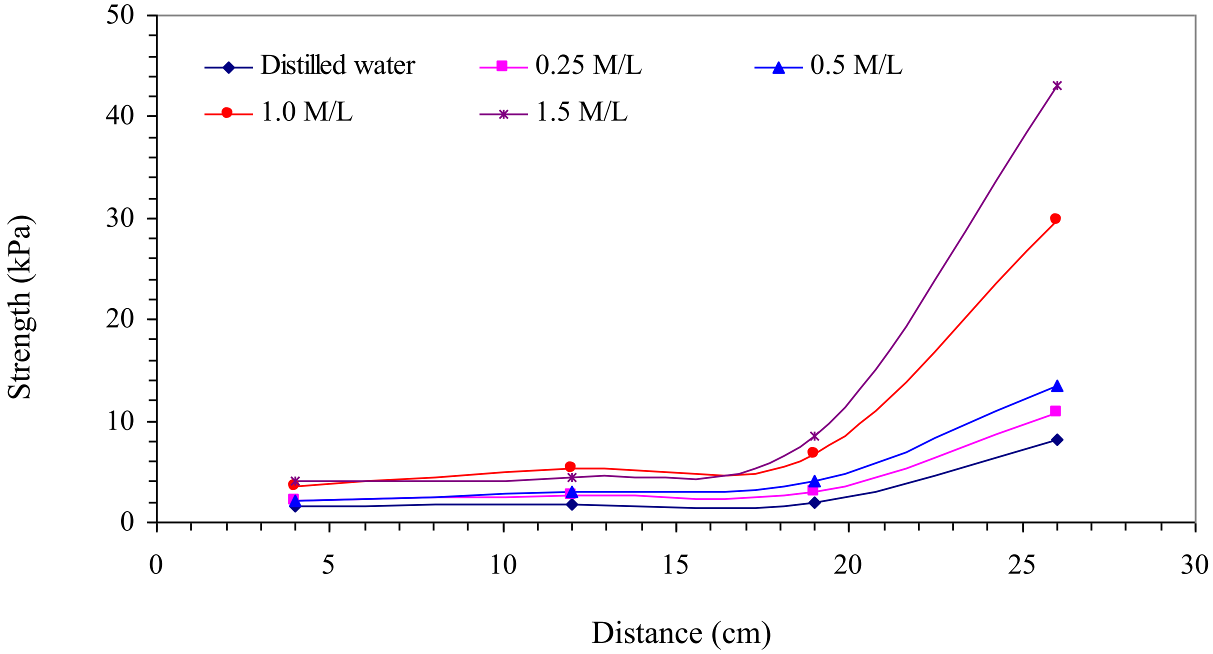
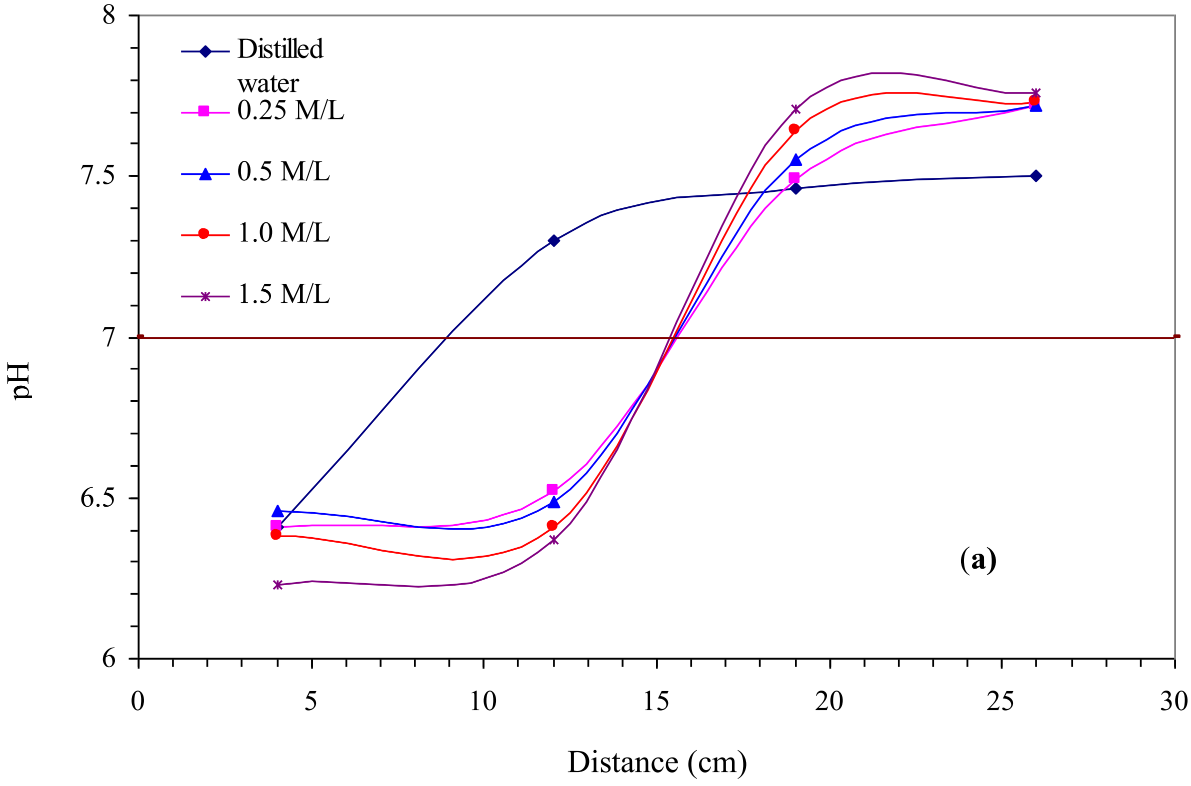


Fig.9. Variation of strength along the soil sample



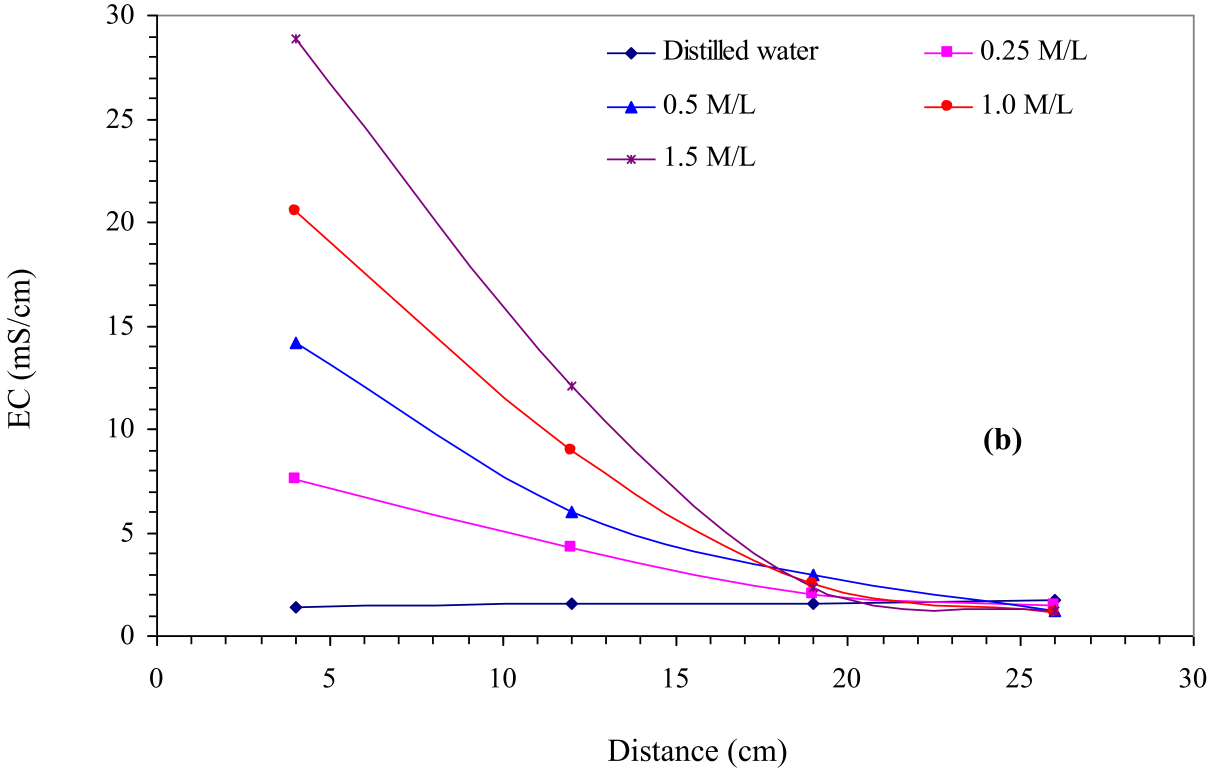
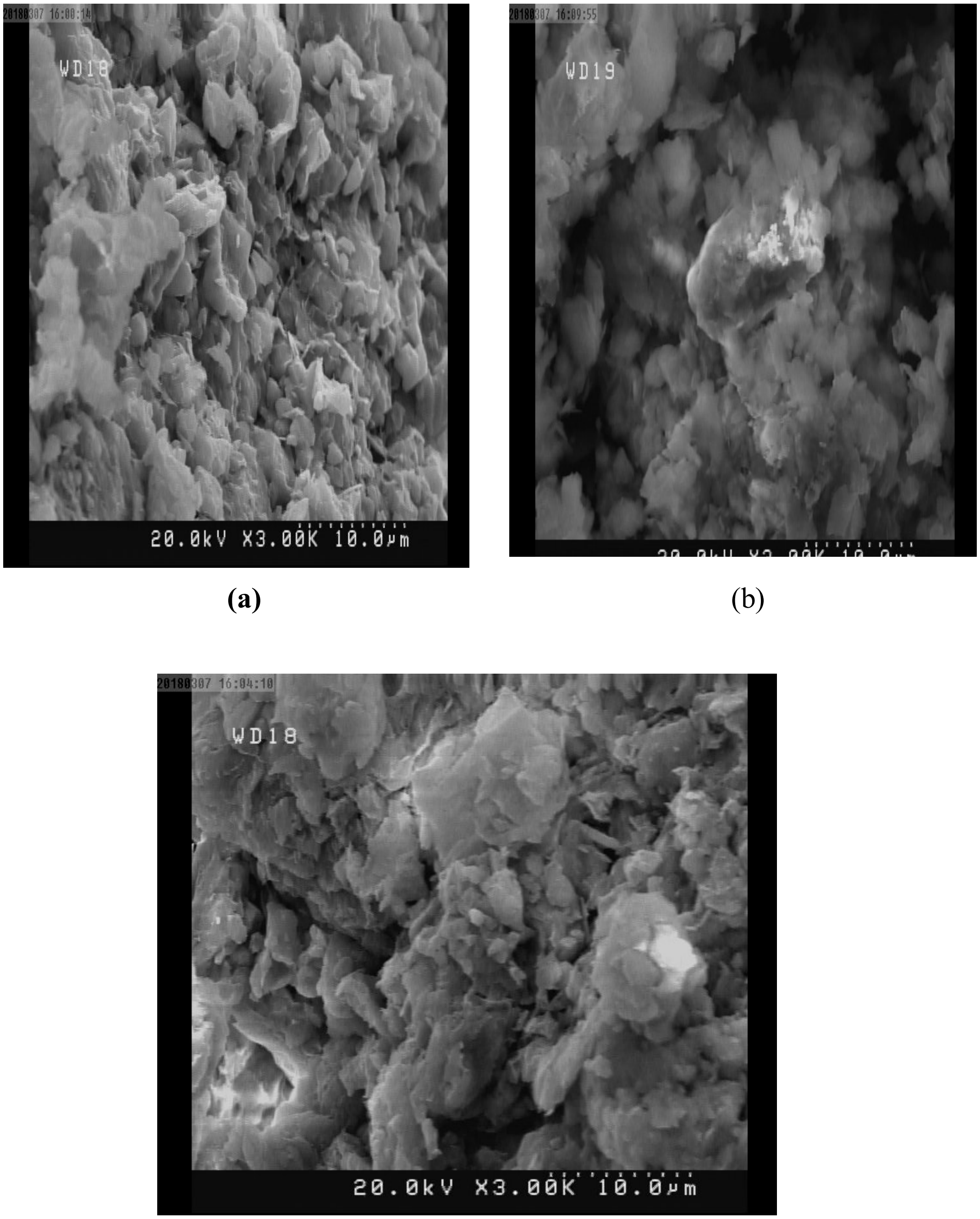


Fig.10. Variations of pH (a) and EC (b) along the soil sample



(a) (b)

(c)

Fig.11. Scanning electron microscope micrograph for Calcium chloride. (a): Cathode, 0.5 M/L, (b): Anode, 1.5 M/L, (c): Cathode, 1.5 M/L

List of Tables

Table 1. Physical and mechanical properties of soil

Property	Standard designation	Value
Specific gravity, G_s	ASTM D 854-10	2.70
Particle distribution		
Gravel (%)		8.0
Sand (%)		27.0
Silt (%)		53.0
Clay (%)		12.0
Consistency limits		
Liquid limit, LL (%)	ASTM D 4318-10	51.3
Plastic limit, PL (%)	ASTM D 4318-10	26.1
Plastic index, PI (%)	ASTM D 4318-10	25.2
Shrinkage limit, SL (%)	ASTM D 427-04	13.0
USCS classification	ASTM D 2487-11	MH
Compaction characteristics		
Optimum water content, *w* (%)	ASTM D 698-07e	16.33
Maximum dry unit weight, γ_{dmax} (kN/m^3)		17.75

Table 2. Chemical composition of soil

Chemical component	Amount	Chemical component	Amount
pH	8.0	Mg^{2+} (meq/L)	10.0
EC* (mmhos/cm)	10.74	Cl^- (meq/L)	60.0
Na^+ (meq/L)	114.0	CO_3^{2-} (meq/L)	0.6
K^+ (meq/L)	0.23	HCO_3^- (meq/L)	4.0
Ca^{2+} (meq/L)	24.0	SO_4^{2-} (meq/L)	83.0
CO_3Ca (%)	10.2	O.C.** (%)	0.11

*- Electrical conductivity
**- Organic content

Notation

E- electrical field intensity

EC- electrical conductivity

EKS- electrokinetic stabilization

I- intensity of electrical current

K_e- electro-osmotic permeability

Mol/L- molecule per liter

Q- discharge

q_{e}- electro-osmotic flow rate