

## **Stabilization of a clay soil by injection of different ions**

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## **Stabilization of a clay soil by injection of different ions**

### **Abstract**

In this work the effects of calcium and magnesium ions on stabilization of a clay soil was studied by conducting a set of laboratory tests. A special apparatus was employed for performing the tests under constant voltage and time. During the tests, solutions of calcium chloride ( $\text{CaCl}_2$ ) or magnesium chloride ( $\text{MgCl}_2$ ) with different concentrations were injected to the soil samples. The electro-osmotic and electrokinetics methods were used for stabilization of the soil and the results were compared with each other. In the electro-osmotic technique distilled water was used as pore fluid but in the electrokinetic method,  $\text{CaCl}_2$  or  $\text{MgCl}_2$  solutions with various concentrations were injected to the pore of soil samples. The results revealed an increase in strength of the soil in both methods. In the electrokinetic method, the amount of increase in strength was a function of concentration of the used solution. The results also indicated that solution of  $\text{CaCl}_2$  is more effective in increasing the strength, discharge flow and electro-osmotic permeability than  $\text{MgCl}_2$  solution at various concentrations. In addition, the variations of these properties are a function of concentration of used solution.

Keywords: environment, geotechnical engineering, land reclamation

## **Introduction**

Soft clay soils are from the group of problematic soils as they generally have low shear strength and also experience excessive settlement under loading (Shang *et al.*, 2004). Construction and buildings founded on soft soils may lead to excessive settlement and stability problems. Therefore, the mechanical behaviors of these soils should be improved before using them as construction or foundation materials. Preloading can be used to improve the behavior of soft soils before using for civil engineering projects but it may require a long time to achieve the final settlement (Charles and Watts, 2002). It is possible to apply larger preload; although it takes less time to reach the final settlement, but it could lead to failure of the soil. If the time and the availability of materials for stabilization are limited, there are other methods for stabilization such as preloading with installation of vertical drains or chemical stabilization. In chemical stabilization, agents such as lime or cement have been used as the stabilizing materials over many decades. This method of stabilization results in increase in stiffness and shear strength and decrease in plasticity and potential of swelling of soils. The improvement of soil by these methods is achieved through exchanges of ions and chemical reaction between the soil water system and used agent. However, these methods cannot be used for improvement of soils that are located under existing buildings because of risk of settlement. Other techniques such as artificial freezing, electroosmotic consolidation or hydro-fracture grouting can be used to improve the behavior of soils under existing structures (Alshawabkeh and Sheahan, 2003). However, using these suggested methods may result in considerable movement or damage to adjacent buildings. To overcome these limitations for stabilization of soils, several researchers have suggested the use of

Electrokinetic Stabilization (EKS) method (e.g., Rogers *et al.*, 2003, Alshawabkeh and Sheahan, 2003, Barker *et al.*, 2004, Chien *et al.*, 2009, Ou *et al.*, 2009 and 2018, Peng *et al.*, 2015, Xue *et al.*, 2018, Gargano *et al.*, 2019 and Estabragh *et al.*, 2019 and 2020). In this method chemical ions are transported, under an electrical gradient, between two electrodes that are embedded in soil mass which leads to improvement in behavior of soil. In this method an electrical field is created across the soil by applying a direct current under a voltage gradient through a pair of electrodes that are embedded in the soil. This facilitates the transport of chemical ions across of soil mass. This technique does not have the limitations of the above-mentioned methods such as the need for excavation or mixing of chemical agents with soil on site (Rogers *et.al.*, 2003). The EKS method includes electroosmosis, electromigration and electrophoresis processes. Electroosmosis is the uniform movement of pore water from the anode toward the cathode, electromigration consists of transportation of ions in pore water and electrophoresis involves the movement of solid particles of soil. Usually, electrophoresis is not very effective in compacted soils (Mohamedelhassan and Shang, 2003). Alshawabkeh and Sheahan (2003) and Asavadorndeja and Glawe (2005) used this method with different chemical stabilizers and electrodes for stabilization of soil and reported that this method can improve the properties of soil. Improvement of soil behavior by injection of solution of  $\text{CaCl}_2$  to soil by the EKS method has been investigated by some researchers (e.g., Chien *et al.*, 2009, Abdullah and Al-Abadi, 2010, Tajudin, 2012 and Estabragh *et al.*, 2020) who have reported acceptable results. Chien *et al.* (2009) used  $\text{CaCl}_2$  and  $\text{NaCl}$ , whereas Kamarudin *et al.* (2011) used  $\text{CaCl}_2$ ,  $\text{AlCl}_3$ , and  $\text{H}_3\text{PO}_4$ , and Nordin *et al.* (2013) used  $\text{Ca}^{2+}$  and  $\text{SiO}_3^{2-}$  ionic solutions for stabilization of soft soils. Their results showed

that using of this method can successfully improve the soil behavior. Several investigations have indicated that using calcium as stabilizing agent for treatment of soils, especially expansive soils that include much sulfate, may lead to a new heave distress problem instead of mitigating it (Puppala et al., 1999). This is called sulfate induced heave (Mitchell, 1986). Puppala et al. (2005) stated that the occurrence of sulfate induced heave is due to the presence of sulfate in natural soil and usually occurs when lime or cement is used as stabilizing agent. Therefore, an agent without calcium may be used for stabilization of soils with sulfated without any problem.  $MgCl_2$  as a stabilizer can be replaced by  $CaCl_2$ . It is used on roads to control dust and humidity and minimize coarse particles scattering. Therefore, the use of  $MgCl_2$  is becoming more common because of its potential to improve the mechanical behavior of problematic soils (Turkoz et al., 2014). However, studies on the use of the  $MgCl_2$  for stabilization of clay soils in the EKS method are rare in the literature.

### **Aim of this work**

Recently, a number of researchers have studied the use of  $MgCl_2$  for stabilization of clay soils (e.g., Turkoz *et al.*, 2014 and Latifi *et al.*, 2015). They have reported that the use of  $MgCl_2$  can successfully improve the geotechnical behavior of soil including potential of swelling and strength characteristics. A survey of literature reveals that the stabilization of clay soils by injection of  $CaCl_2$  has been studied under different conditions (e.g., different concentrations) but stabilization a clay soil by using  $MgCl_2$  through the electrokinetic technique has not been reported. In this work the effect of  $MgCl_2$  and  $CaCl_2$  with different concentrations are studied through a program of experiments under

constant electric gradient and time. The results are analyzed and compared with each other at different concentrations for different solutions.

## **Materials**

The materials used in this work are clay soil, calcium chloride, magnesium chloride, and distilled water. They are described briefly in the following sections.

### *Soil*

The soil used in this experimental work was a clay soil and was bought from a local supplier. The soil was sourced from around the Karaj city which is located 20 km west of Tehran (Capital of Iran) at foothills of Alborz Mountains. Laboratory tests were conducted (according to the ASTM standard) on the soil to determine its physical and mechanical properties. The mechanical, physical and chemical properties of the soil are summarized in Tables 1 and 2. The soil was classified as silt with high plasticity (MH) based on the Unified Soil Classification System (USCS). Fig.1 shows the results of X-ray diffraction (XRD) tests that were performed on the samples of the soil. The results indicate that the soil is composed of quartz, calcite, feldspar (Na, Ca) and feldspar (K) minerals (Fig.1a). The clay minerals of the soil include Illite, Chlorite and Montmorillonite (Fig.1b).

### *Magnesium chloride (MgCl<sub>2</sub>)*

MgCl<sub>2</sub> is a hygroscopic salt and soluble in water. It is commonly used for road pavement and stabilization of road materials. It is also used for controlling dust and humidity to prevent from scattering the coarse particles and formation of ice (Thenoux and Vera, 2002). Due to its common usage, it has a considerable potential for improving the behavior of soil and hence has drawn the attention of researchers around the world (Latifi

*et al.*, 2015).  $MgCl_2$  solution has no damaging effects on cement, asphalt, plants or living creatures (Goodrich *et al.*, 2009). Because of these properties it is considered as a stabilizing agent in this research work.

#### *Calcium chloride ( $CaCl_2$ )*

$CaCl_2$  is used as a stabilization material because it is safe for the environment, highly soluble in water and cheap in price. It has been successfully applied in bench and field trial tests (Rogers *et al.*, 2002 and Barker *et al.*, 2004). Because of these properties it is chosen for soil stabilization in this work.

#### *Distilled water*

Distilled water was used for conducting the electroosmotic tests (as reference tests, without solution of calcium chloride or magnesium chloride). It was also used for making the desired solutions of calcium chloride or magnesium chloride. The distilled water had a pH of 7.2 and EC (electrical conductivity) of 0.009 dS/m.

According to the literature, a number of researchers (e.g., Abdullah and Al-Abadi, 2010 and Tajudin 2012) used solutions of  $CaCl_2$  with concentrations of 1.0 and 1.5 mol/l in their work respectively. In this work the concentration of 0.125, 0.25 and 0.5 mol/l were considered because they were close to the used concentration and allow comparison between the obtained results with the findings of previous researchers. Also, the same concentration was selected for  $MgCl_2$  to allow comparison with  $CaCl_2$ . To prepare the desired solutions, the required amount of magnesium chloride or calcium chloride was weighted and poured into a large glass graduated beaker. Then distilled water was added until the volume reached to 1 liter. It was then mixed thoroughly by shaking to achieve a uniform solution, ready to be used.

## **Apparatus**

Fig.2 shows a schematic diagram the experimental apparatus used in this research. It is similar to the apparatus that was previously used by researchers such as Mohammedalhasen and Shang (2001), Rittirong *et al.* (2008) and Estabragh *et al.* (2014). It consists of the main cell, loading frame and D.C. power supply. The main cell is a rectangular tank with internal dimensions of 39 cm (length), 19 cm (width) and 25 cm (height). It was made of 10 mm thick transparent perspex sheets. Perspex was chosen as it is nonconductive and prevents from short circuiting the current during the test. The main cell is used for holding the soil sample during the test. Two reservoirs, so called anode and cathode reservoirs, were added at the two sides of the main cell (Fig.2). They were filled with desired solutions (namely anolyte and catholyte solutions). The method of control of the hydraulic head in the two reservoirs was similar the method that was used by Rittirong *et al.* (2008) and Mohammedalhasen and Shang (2001). The reservoirs were filled with the desired fluid and the total hydraulic head in them was controlled by adjusting two identical standing tubes through valves (Fig.2). Two electrodes (rectangular in shape) made of stainless steel were installed in the apparatus. They were perforated with holes with diameter of 1mm. The electrodes were placed vertically in the apparatus and their distance from the main cell was 5 cm. These perforated electrode plates allowed the free flow of ionic solutions in the soil block. Two sides of soil sample were covered by two sheets of saturated geotextile to ensure that soil was not lost during the test. Other researchers have used filter paper and porous stone between soil and electrode compartments to prevent from the loss of soil (e.g., Kim *et al.*, 2009 and Jeon *et al.*,



2010). A number of voltage probes were installed at the bottom of the main cell at distances of 2, 5, 8 and 11 cm from the anode to measure the voltage throughout of soil at specific times during the test. A loading system was added to the apparatus to allow application of load on the sample in the main cell. It consisted of two plates, one placed on the top surface of the sample and one at the bottom of the main cell, through which the load was applied on the sample. The two plates were connected by an isolated bar.

The vertical displacement of sample was measured during test by a dial gauge that was placed on the top plate. A generator was used to produce D.C. current at different voltages for the electrodes. The discharge flow of fluid through the soil was collected via the outlet flow into a graduated container and its volume was measured at different times during the test. The tests were performed at a nearly constant temperature (i.e. 25°C) in a temperature controlled room.

### **Sample preparation**

Slurry samples were prepared for the main test as used by Estabragh *et al.* (2019). The following procedure was followed for preparing the samples for testing.

Air dry soil was weighed and mixed with the required volume of water to achieve a water content 5% higher than the liquid limit. The soil and water were then thoroughly mixed by hand steer. The mixture was moved to a plastic bowl and a plastic sheet was used to cover its surface. This mixture was kept in this condition for about 10 days for uniform distribution of moisture in the soil mass. To ensure homogeneity and uniform distribution of moisture, a number of samples were taken randomly and their water content and shear strength (by using a vane shear apparatus) were determined. The prepared slurry samples were poured in the main cell in three layers. Vibration was used for each layer in the cell

to remove air trapped inside the soil. Then the top surface of the soil in the main cell was covered by a saturated geomembrane sheet while the level of distilled water in both reservoirs was kept constant. The soil was left for three days to ensure its homogeneity.

### **Experimental tests**

The main aim of this program of testing was to assess the influence of transportation of calcium and magnesium ions at different concentrations on stabilization of a clay soil and comparing with the results for the two ions.

The program of experimental tests included three groups of tests as shown in Table 3. In the first group distilled water was used to fill the reservoirs of the apparatus. The aim of this test was to study the stabilization of the soil by electro osmotic method in the absence of any agents. For tests in group 2 or 3 the anode reservoir was filled with solution of  $\text{CaCl}_2$  or  $\text{MgCl}_2$  with different concentrations (0.125, 0.25 and 0.5 mol/l) while for both cases, distilled water was used for filling the cathode reservoir (Table 3).

The following procedure was followed for conducting a test:

An external surcharge pressure of 1 kPa was applied, as preloading, through the loading plate on the top of the sample in the main cell while both reservoirs were full of distilled water. Then the sample was allowed to consolidate for 7 days while the displacement of soil was monitored from readings the dial gauge that was mounted on the sample. Therefore, at this stage, the settlement of the sample occurred only under surcharge pressure. This stage was done because in the in situ soil is not in the form of slurry. In addition, the application of surcharge pressure on the soil sample during the EKS testing was also depended on the depth of insertion of the electrodes in the soil (Tajudin, 2012). This procedure of testing (using preloading) is similar to the work of Tajudin (2012). He

stated that the amount of preloading before EKS testing is dependent on the depth of insertion of the electrodes in the soil. After completion of the settlement, the anode reservoir was filled with solution of  $\text{CaCl}_2$  or  $\text{MgCl}_2$ . Then a 50 volt electric current (as suggested by Mitchell and Soga, 2005) was applied to the soil that was under the pressure of 1 kPa and the level of fluids was kept the same in both reservoirs. This stage lasted 7 days and during this stage both the settlement of sample and volumetric discharge flow from the cathode reservoir were measured. During the test, samples were taken from the fluids in both reservoirs every 24 hours, using a syringe. The samples taken were poured in small plastic bottles and stored in a cabinet at constant temperature of  $25^\circ\text{C}$ . Then the pH and EC of these samples were determined. At the end of the test, the external load and geomembrane cover were taken off from top of the soil and a shear vane apparatus was used to determine the shear strength of soil. The strength of soil was measured at different distances from the anode (i.e. 4, 12, 19 and 26 cm). Then the moisture content and consistency limits were measured on the samples that were taken from the same positions where the strength was measured. A number of soil samples were also taken from the soil mass at distances of 4, 12, 19 and 26 cm from anode for determination the pH and EC. Furthermore, SEM (Scanning Electron Microscopy) tests were also conducted on a number of samples taken from the main cell from around the anode, cathode and middle of the soil sample.

## **Results**

In this section, the results obtained from the experiments are presented.

### *pH and EC of reservoirs*

Fig. 3 shows typical results of variations of pH with time for both anode and cathode reservoirs that were filled with distilled water and calcium chloride solution at different concentrations. It is seen from the results that the pH is decreased and increased steadily with time at the anode and cathode reservoirs respectively until they reach to a nearly constant value. The figure also shows that when distilled water is used in both reservoirs, the final values of pH reach to 4.66 and 12.6 at anode and cathode reservoirs respectively. For the calcium chloride solution at concentrations 0.125, 0.25 and 0.5 mol/l, the values of pH in the anode reservoir at the start of the tests are 2.8, 1.98 and 1.83 respectively. At the end of the test the values of pH in the cathode reservoir reach 12.35, 12.3 and 12.2 for concentrations 0.125, 0.25 and 0.5 mol/l of this solution. It is seen that the variations of pH at the anode are function of calcium chloride concentration; increasing the concentration causes reduction in the value of pH at the anode reservoir in comparison with distilled water. The results also show that the value of pH at the cathode reservoir is nearly 12.3 for distilled water and different concentrations of CaCl<sub>2</sub> solution. It can be said that, in the range of used concentrations of calcium chloride, the value of pH at the cathode reservoir is independent of the concentration of CaCl<sub>2</sub>.

Fig.4 illustrates typical changes of EC with time when the anode and cathode reservoirs are filled with MgCl<sub>2</sub> solutions at different concentrations and distilled water along with the results for distilled water. At the start of the test, the value of EC for distilled water is around 1.3 dS/m in both reservoirs. However, it changes with time and at the end of the test, the values of EC reach 5.3 and 2.4 dS/m at the anode and cathode reservoirs respectively.

For  $\text{MgCl}_2$  solution at concentration of 0.125 mol/l, the values of EC at the start of the test are 10.1 and 2.28 dS/m at the anode and cathode reservoirs respectively. By increasing the time, the values of EC at both reservoirs are increased but the rate of increasing in the cathode is more than the anode. The final values of EC at the end of this test reach to 22.1 and 29.8 dS/m at the anode and cathode reservoirs. For concentrations of 0.25 and 0.5 mol/l the trend of variations of EC is not the same as that of 0.125 mol/l. At these concentrations the values of EC are increased from the initial values but the final values in the anode are more than the cathode reservoir (contrary to 0.125 mol/l). It is also seen from Fig.4 that the values of EC at the end of the test for concentration of 0.25 Mol/L are 55.5 and 30.2 dS/m at the anode and cathode reservoirs respectively. Similar results are seen for concentration of 0.5 mol/l. Therefore, according to the obtained results, for the concentrations used, the variations of EC are not a function of concentration.

*Q (discharge) and  $K_e$  (electro-osmotic permeability)*

Fig.5 shows the measured volume of discharge fluid from cathode reservoir together with the calculated  $K_e$  with time at various concentrations of  $\text{CaCl}_2$ . The results show that at the end of test, the volume of fluid for distilled water is 1118  $\text{cm}^3$  but it is increased to 1820, 3482 and 3530  $\text{cm}^3$  for concentrations of 0.125, 0.25 and 0.5 mol/l of  $\text{CaCl}_2$  solution respectively. Fig.5 presents the measured volume of discharge fluid from the cathode reservoir together with the calculated  $K_e$  with time at various concentrations of  $\text{CaCl}_2$ . The results show that at the end of test, the volume of discharge fluid for distilled water is 1118  $\text{cm}^3$  but it is increased to 1820, 3482 and 3530  $\text{cm}^3$  for concentrations of 0.125, 0.25 and 0.5 mol/l of  $\text{CaCl}_2$  solution respectively. Fig.5 reveals that, in the range

of concentrations of CaCl<sub>2</sub> used, the volume of discharge flow from the soil is increased with increasing the concentration of CaCl<sub>2</sub>. By increasing the concentration from 0.125 to 0.25 mol/l, the discharge flow is increased by 1662 cm<sup>3</sup> but when the concentration is further increased from 0.25 to 0.5 mol/l, the change in discharge volume is only 48 cm<sup>3</sup>. Therefore, the rate of increase in discharge flow it is reduced by increasing the concentration of CaCl<sub>2</sub> solution. The value of  $K_e$  was determined according to the equation that was suggested by Alshawabkeh *et al.* (1999), as:

$$q_e = K_e * E \quad (1)$$

Where  $q_e$  is the electro-osmotic flow rate,  $E$  is the electric field intensity and  $K_e$  is electro-osmotic permeability. The above equation shows that, for a specific electrical intensity, the variation of rate of outflow is directly proportional to the value of  $K_e$ . Fig.5 also shows the changes in the value of  $K_e$  during the tests for different concentrations of CaCl<sub>2</sub>. The results also indicate that the values of  $K_e$  decrease with time, so at the end of the tests, the values of  $K_e$  for 0.125, 0.25 and 0.5 mol/l reached to  $1.61*10^{-9}$ ,  $1.64*10^{-9}$  and  $1.86*10^{-9}$  (m<sup>2</sup>/s-v) respectively. These results show that the variations of  $K_e$  with time are in opposite trend of discharge flow from the soil.

$I$  (Intensity of electrical current) and  $R$  (Resistance)

Fig.6 illustrates the changes in the values of  $I$  and  $R$  with time for distilled water and CaCl<sub>2</sub> solutions at different concentrations. The results show that the value of  $I$  decreased with time for all used solutions. It is seen from this figure that the curve of distilled water is located at the bottom and that of the CaCl<sub>2</sub> solution with concentration 0.5 mol/l at the top with final values of 0.07 (distilled water) and 0.28 (0.5 mol/l) ampere. As shown in this figure, the trend of variations of  $R$  with time is the opposite of the trend of  $I$ . In other

words, the value of  $R$  is increased by increasing the time. The value of  $R$  at the end of test for distilled water is 192.6 ohm and for different solutions of  $\text{CaCl}_2$  is nearly the same (i.e. 185.7 ohm).

### *Strength*

The shear strength of stabilized soil was measured at the distances of 4, 12, 19 and 26 cm from the anode. Fig.7 shows typical results of the measured strength of soil improved with distilled water and with different concentrations of  $\text{MgCl}_2$  solution at these distances along the soil. It is seen that the maximum shear strength is achieved at the distance of 26 cm from the anode (around cathode). The maximum value of shear strength for distilled water is 8.2 kPa. For the solutions of  $\text{MgCl}_2$ , the shear strength is dependent on the concentration of  $\text{MgCl}_2$ ; for concentrations 0.125, 0.25 and 0.5 mol/l of  $\text{MgCl}_2$  the values of strength are 17, 18 and 22.4 kPa at distance of 26 cm from the anode respectively.

### *Soil water content and Atterberg limits*

Fig.8 shows the water content of the soil after testing at different distances (4, 12, 19 and 26 cm) from the anode. As shown in this figure, the water contents of the samples for all tests are located below the control line (the control line shows the water content of the soil before testing). The results show that by using distilled water in anode and cathode reservoirs, the water contents at 4 and 26 cm from the anode are 47 and 48.8% respectively. This indicates that water content around the cathode is more than around the anode. The variations of water content when the anode reservoir is filled with  $\text{MgCl}_2$  or  $\text{CaCl}_2$  solution with different concentrations are shown in this figure. It is seen that the water content for each concentration at the anode is slightly less than the cathode. For example for  $\text{MgCl}_2$  at concentration of 0.125 mol/l, the water contents at 4 and 26 cm from the anode are 39.7 and 42.8 % respectively. It is also seen from this figure that by

increasing the concentration the water content is reduced around the anode and cathode. For the  $\text{CaCl}_2$  solution the water content at the same distance and concentration is less than the  $\text{MgCl}_2$  solution (Fig.8). For the  $\text{CaCl}_2$  solution at each concentration, the water content at the cathode is also more than the anode.

The values of the liquid limit (LL) and plastic limit (PL) after the test for different solutions at different distances from the anode are shown in Fig.9 along with the control lines (values of LL and PL before testing). For distilled water the values of LL and PL near the anode (4 cm) are 47.5 and 25.9% but around the cathode they are changed to 53.4 and 29.8 % respectively. It is seen that their values are increased around the cathode (26 cm). Similar changes in the Atterberg limits are also observed when the solutions of  $\text{CaCl}_2$  and  $\text{MgCl}_2$  with different concentrations are used as anode reservoir. It is seen that at the cathode, increasing of LL and PL is directly proportional to the concentration of solution in anode reservoir.

#### *pH and EC of soil*

At the end of each test the values of pH and EC along the soil were determined on the samples that were taken at the distances of 4, 12, 19 and 26 cm from anode (Fig.10). Fig.10a presents the values of EC and pH along the soil after stabilization by distilled water and solutions of  $\text{CaCl}_2$  at different concentrations. The results indicate that the value of pH is nearly 6 at the distance of 4 cm from the anode and it reaches to 7 at the distance of 12 cm from the anode. This indicates that by increasing the distance from the anode the value of pH is increased. The variation of pH from 12 cm to 19 cm is not significant but after 19 cm, the increasing trend of pH continues and it reaches to 8 at distance of 24 cm from the anode. The variations of EC along the length of the soil are



not the same as pH; around the anode (distance of 4 cm) the value of EC is maximum and then it decreases by increasing the distance (except for distilled water). Fig.10b shows a similar trend for changes of pH and EC along the length of soil when  $MgCl_2$  solution with different concentrations is used for soil stabilization.

### *SEM results*

The effect of transported ions on the microstructure of the soil was studied by performing SEM tests on samples of stabilized soil. Figs.11 and 12 show the images that were obtained for samples at different concentrations for  $MgCl_2$  and  $CaCl_2$  respectively. As shown in these figures, the shape of particles around the anode are plate-like with large spaces between them without any bonding but in the vicinity of the cathode, the particles are pasted together through bonding that is produced from sediments or cementitious materials with agglomerated and flocculated structure. It is seen that by increasing the concentration, the degree of pasting of particle through bonding and the degree of flocculation are increased around the cathode and around the anode the size of voids is decreased. Comparison between the results in Figs.11 and 12 shows the degree of pasting of denseness of particles is more for the  $CaCl_2$  solution than the  $MgCl_2$  solution, for each value of concentration.

## **Discussion**

The surfaces of clay minerals contain negative charges. This is as a result of isomorphous substitution and exchange of high valency with low valency atoms. Due to their negative charge, the minerals of clay can attract cations and positively charge section of water molecules that surround the particles. A layer of water is strongly bonded to the surface of clay mineral which is termed diffuse double layer (DDL). The concentration of cations

is the highest at the surfaces of clay minerals and it decreases exponentially by increasing the distance from the clay surface.

The chemical behavior of pore fluid can also influence the structure of clay soil (Mitchell and Soga, 2005). Changes in chemical quality of pore fluid can occur in different ways such as change in the concentration of pore fluid or the valence of the ions that exist in pore fluid.

The ions in the DDL can be replaced with the ions absorbed on the surface of clay particles. This substitution of ions is termed as ion exchange. The exchange ion has an important influence on the behavior of clay soil. Many factors such as ion size and its valency influence on the exchange of one type of cation by another type. The total amount of exchangeable cations is called cation exchange capacity (CEC). Fig.13 shows that when distilled water or a solution of  $MgCl_2$  or  $CaCl_2$  is used at anode reservoir (cathode is filled with distilled water in all cases) the initial values of pH at anode and cathode reservoirs are decreased and increased respectively. During the stabilization of soil by the electrokinetic method, the applied electrical field produces a number of ions that change the value of soil pH due to the electrochemical reactions at the boundaries of electrodes. Therefore, the hydrogen and hydroxyl ions ( $H^+$  and  $OH^-$ ) are generated at anode and cathode respectively (Acar and Alshawabkeh, 1993). At this stage an acidic front is developed at anode that will move to the cathode through the soil. In contrast, the production of  $OH^-$  produces a basic region at cathode that will move toward the anode by migration and diffusion. It can be said that producing the acidic and basic regions and their advancement toward the cathode and anode influence the initial pH of soil sample (see Fig.10). It is seen from Fig. 13 that when distilled water is used in the anode

reservoir, the final value of pH (pH=4.6) is more than the pH of CaCl<sub>2</sub> or MgCl<sub>2</sub> solution in this reservoir but in the cathode, the difference between the final values of pH is not significant. When the solution of CaCl<sub>2</sub> or MgCl<sub>2</sub> is used, the exchange ions of Ca<sup>+2</sup> and Mg<sup>+2</sup> produce H<sup>+1</sup> ions. This results in an increase in the number of H<sup>+1</sup> ions at the anode reservoir in comparison with distilled water and leads to reduction in the value of pH. When the concentration of CaCl<sub>2</sub> is increased, there is a reduction in the value of pH. This is because with more Ca<sup>+2</sup> ions, more H<sup>+1</sup> ions are produced which increases the degree of acidity in the anode reservoir. For the MgCl<sub>2</sub> solution, a reduction in the value of pH is observed at the anode reservoir. However, no definite relationship is observed between the reduction of pH and concentration of MgCl<sub>2</sub>. The results obtained in this work are in agreement with those presented in Hamed *et al.* (1991) and Estabragh *et al.* (2020). It can be said that the initial pH of soil is under the influence pH of two reservoirs. Fig.10 shows that the pH of soil in the vicinity of the anode is changed to acidic condition and degree of acidity is related to the concentration of the used solution. This may be due to the movement of acidic front from anode to the soil which changes the pH of soil to acidic. In other words, cations that are transported to the soil mass from the anode reservoir are exchanged with cations on clay minerals and the produced H<sup>+1</sup> ions decrease the initial pH of soil. This figure (Fig.10) also shows the pH of the soil is increased when the distance from anode is increased. When the calcium chloride or magnesium chloride solution is used, the Ca<sup>+2</sup> or Mg<sup>+2</sup> ions are moved to the spaces of soil particles and some of them are substituted with other cations such as H<sup>+1</sup>. Some of OH<sup>-</sup> ions are moved to the cathode under the electrical field due to diffusion and electromigration and this plays an important role in increasing the pH of the soil.

Therefore, it ( $\text{OH}^-$ ) may be transported the formed basic front from cathode to the anode is effective in increasing the pH in this region of soil. The rest of the released  $\text{Ca}^{+2}$  or  $\text{Mg}^{+2}$  ions enter the cathode region, react with hydroxyl ions and increase the value of pH in soil, producing a basic environment. These results are consistent with the results that were published by Mohamedelhassan and Shang (2003) and Tajudin (2012).

Fig.14 shows the final value of EC for the different solutions used for stabilization of the soil. The total amount of dissolved ions in water can be estimated by measuring the value of EC. This figure shows that for both solutions, the values of EC at the anode reservoir are more than distilled water and they increase with increasing the concentration of the used solution. For the  $\text{CaCl}_2$  solution, when the concentration of  $\text{CaCl}_2$  is increased, the values of EC at the cathode reservoir are decreased. A similar trend is found for the variations of EC for  $\text{MgCl}_2$  solution with different concentrations. This can be explained as follows. When the  $\text{Ca}^{+2}$  ions enter the soil from the anode reservoir, majority of them are exchanged with other ions on the clay minerals or act with other released anions in soil. The rest of them move to the cathode reservoir. The amount of these actions may be less for  $\text{Mg}^{+2}$  than  $\text{Ca}^{+2}$  and cause increasing of EC at cathode. The changes of EC at both reservoirs can influence on the initial value of EC for soil in the main cell. The value of EC for the soil in the vicinity of anode is increased for each solution and it is decreased by increasing the distance from anode (see Fig.10). Similar findings have been reported by other researchers (e.g., Mohamedelhassan and Shang, 2003 and Tajudin, 2012).

Fig.15 shows the final results of outflow of the fluid from the sample for distilled water and  $\text{CaCl}_2$  and  $\text{MgCl}_2$  solutions at various concentrations. The results show that, for each of used solutions, when the concentration of the solution is increased, the volume of

discharge flow is also increased. The results also indicate that, at a constant concentration, the volumetric discharge of the  $\text{CaCl}_2$  solution is more than  $\text{MgCl}_2$  solution. This can be attributed to the changes in the initial form of the soil structure because of the cation exchange between clay and the solution. The thickness of DDL is reduced by cation exchange and the amount of reduction is increased by increasing the concentration of existing ions in the solution (Van Olphen, 1977 and Mitchell and Soga, 2005). The shrinkage of DDL leads to the formation of flocculated structure in soil and the degree of flocculation is increased with concentration. When the structure of soil becomes more flocculated, the void spaces between soil particles are increased and hence the outflow of fluid is increased. The  $\text{MgCl}_2$  solution also changed the structure of the soil to flocculated form due to the exchange of cations. The form of structure (orientation of particles and voids between them) that is made by  $\text{MgCl}_2$  solution at the same concentration as the  $\text{CaCl}_2$  solution is not the same (as shown in Figs.11 and 12) and hence the discharge flow of the fluid from soil is reduced. The orientations of particles relative to each other are important in the flow of fluid in the soil. The arrangement of particles due to  $\text{MgCl}_2$  solution could be perpendicular to the direction of flow of fluid, obstructing the flow and hence reducing the discharge fluid from the soil in comparison the  $\text{CaCl}_2$ . Another reason for reduction of fluid flow from the soil with  $\text{MgCl}_2$  solution (in comparison with  $\text{CaCl}_2$  solution) could be the reduction the pores between particles. This is because during the testing, acidic and alkaline conditions are created in the vicinity of anode and cathode respectively. The acidic front advances towards the cathode and basic front migrates from the cathode to anode. The movement of the acidic front is faster than the basic front. On the cathode side, chemical action occurs between hydroxide ions, the injected ions and

other metallic ions. The produced materials precipitate and clog the pores between particles, resulting in reduced flow of fluid from the soil mass.

Fig.16 shows the variations of  $K_e$  for distilled water, and  $\text{CaCl}_2$  and  $\text{MgCl}_2$  solutions at different concentrations. It is seen that the trend of variations of  $K_e$  is similar to the variation of discharge fluid from the soil. It can be said the outflow of fluid from the sample is related to the value of  $K_e$  and hence, changes of  $K_e$  can change the amount of outflow of fluid. These findings are in agreement with those of discharge fluid from the soil samples (Fig.15). These results are also in agreement with the results that were presented by Mohamedelhassan and Shang (2001) and Rittirong *et al.*, (2008).

The results show that the values of  $I$  is increased in the initial stage of the tests and then it is decreased with time until it reaches to a nearly constant value (see Fig.6). These results are in agreement with those published by Ou *et al.* (2009) for stabilization a clay soil with  $\text{CaCl}_2$  solution. Fig.17 shows the final values of  $I$  at the end of test for different solutions. The results show that there is increasing in the value of  $I$  when the concentration of both fluids is increased. For a specific concentration, the value of  $I$  for  $\text{CaCl}_2$  solution is less than  $\text{MgCl}_2$  solution. It can be said that the value of CEC for different ions is not the same for a specific mineral of a clay soil. In other words, the CEC of  $\text{Mg}^{+2}$  may be less than  $\text{Ca}^{+2}$  ions for this soil. Therefore, a number of  $\text{Mg}^{+2}$  ions may remain between particles and cause increase in the value of  $I$ .

Fig. 7 shows that for a specific fluid, the improvement of soil is increased by increasing the distance from the anode; it is minimum at the anode and maximum at the cathode.

Fig.18 compares the values of soil strength in the vicinity of cathode for different solutions at different concentrations. It is shown that the shear strength of the soil with

CaCl<sub>2</sub> solution is more than MgCl<sub>2</sub> solution at different concentrations and by increasing the concentration, the effect of CaCl<sub>2</sub> on the shear strength is more than MgCl<sub>2</sub>. The outflow of fluid from the soil is important in increasing the strength because the pore water pressure is reduced leading to increase in the effective stress. As shown in Fig.15, the outflow of fluid due to CaCl<sub>2</sub> at a specific concentration is more than MgCl<sub>2</sub>. The solubility of CaCl<sub>2</sub> in water at 20°C (74.5 g/100 cc water) is more than MgCl<sub>2</sub> (54.3 g/100 cc water) and solution of CaCl<sub>2</sub> produces more ions in comparison with MgCl<sub>2</sub> resulting in higher values of  $I$  at different concentrations. It can be said that the exchange ions and reaction of Ca<sup>+2</sup> are more than Mg<sup>+2</sup> because of the difference in their solubility. The results in Fig.10 reveal that in the vicinity of cathode the value of pH is high and therefore soil is in alkaline condition. Pozzolanic reactions may occur in alkaline conditions which produce cementation materials. Ou *et al.* (2018) suggested that cementation is due to pozzolanic reactions and Calcium Silicate Hydrate (C-S-H) or Calcium Aluminate Hydrate (C-A-H) gel. Therefore, the movement of injected ions from anode to cathode is effective in forming the cementing materials. The formed materials paste the particles to each other by a strong bond which increases the strength of the soil (Fig.12). The properties of the cementing materials formed from the MgCl<sub>2</sub> or CaCl<sub>2</sub> solution is not the same. It appears that the cementitious materials formed with the CaCl<sub>2</sub> solution are more effective in increasing the strength of the soil than the materials that are formed with the MgCl<sub>2</sub> solution. Some researchers such as Micic *et al.* (2002), Alshwabbeh and Sheahn (2003), Burnotte *et al.* (2004) and Rittirang *et al.* (2008), reported that cementation occurs during electroosmotic stabilization of soil between particles, particularly around the cathode. The produced cementitious material is not as strong as the cementation that is produced by injection of ions such as Ca<sup>+2</sup> or Mg<sup>+2</sup>.

The results show that injection of calcium and magnesium ions can improve the properties of a clay soil. For field applications of the electrokinetic method, more information from laboratory tests is needed. It is suggested, as a further work, that different tests on different types of soil with different agents should be conducted and a database should be prepared for field works.

### **Conclusion**

This work presented a study on the improvement the properties of a clay soil through EKS technique by using calcium chloride and magnesium chloride at different concentrations. The tests were conducted under constant electrical voltage and time. The obtained results are summarized as follows:

- Both  $\text{CaCl}_2$  and  $\text{MgCl}_2$  solutions can increase the values of  $K_e$ ,  $I$ ,  $Q$  and shear strength of soil in comparison with distilled water. The amount of increase in these parameters is function of concentration of the used solution. For a specific concentration of solution, the value of strength is increased by increasing the distance from the anode.
- In general, calcium chloride is more effective than magnesium chloride in improving the mechanical properties of clay soil, at least in the range of concentrations used in this study.
- More studies are needed to be performed by this method to get a better understanding of the effects of numerous physicochemical processes that are involved during the test. This could lead to the development of a proven method of in situ stabilization of soils. This could also provide a suitable method that can be used for stabilization of soils under existing structures without any adverse affect on the ground



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## **List of Tables**

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**Table 2.** Chemical composition of soil

**Table 3.** Characteristics of different tests

**Table 1.** Physical and mechanical properties of soil

Property	Standard designation	Value
Specific gravity, $G_s$	ASTM D 854-10	2.70
<i>Particle distribution</i>		
Gravel (%)		8.0
Sand (%)		27.0
Silt (%)		53.0
Clay (%)		12.0
<i>Consistency limits</i>		
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	CL
<i>Compaction characteristics</i>		
Optimum water content, $w$ (%)	ASTM D 698-07e	16.33
Maximum dry unit weight, $\gamma_{dmax}$ (kN/m <sup>3</sup> )		17.75

**Table 2.** Chemical composition of soil

Chemical component	Value	Chemical component	Value
pH	8.0	Mg <sup>2+</sup> (meq/l)	10.0
EC* (dS/m)	0.74	Cl <sup>-</sup> (meq/l)	60.0
Na <sup>+</sup> (meq/l)	114.0	CO <sub>3</sub> <sup>2-</sup> (meq/l)	0.6
K <sup>+</sup> (meq/l)	0.23	HCO <sub>3</sub> <sup>-</sup> (meq/l)	4.0
Ca <sup>2+</sup> (meq/l)	24.0	SO <sub>4</sub> <sup>2-</sup> (meq/l)	83.0
CO <sub>3</sub> Ca (%)	10.2	O.C.** (%)	0.11

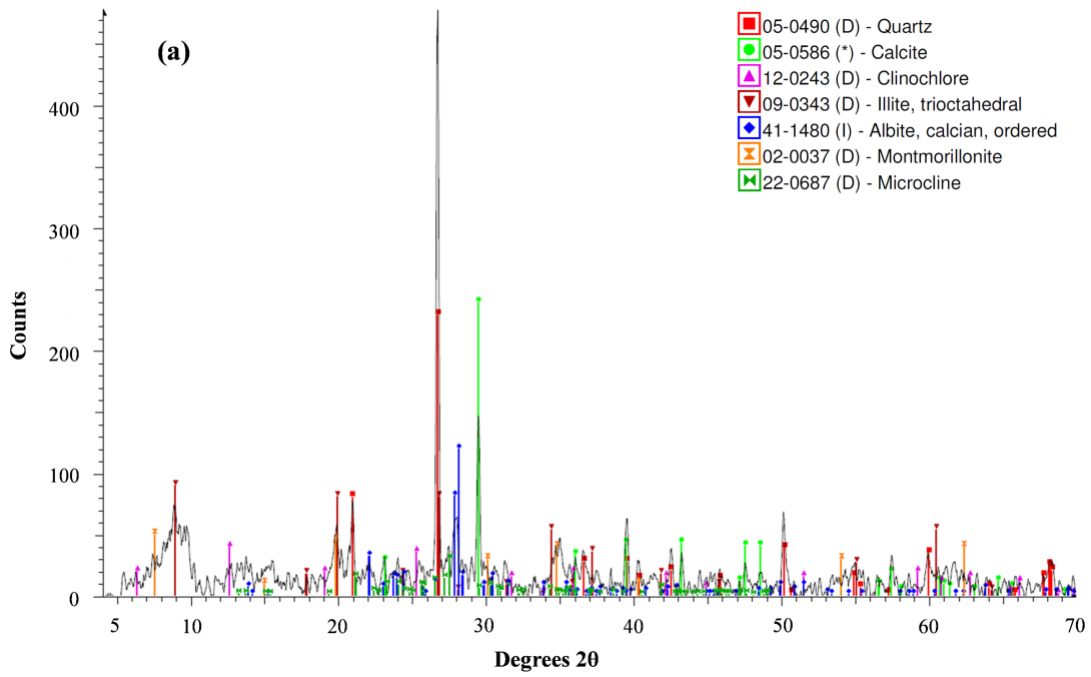
\*- Electrical conductivity

\*\*- Organic content

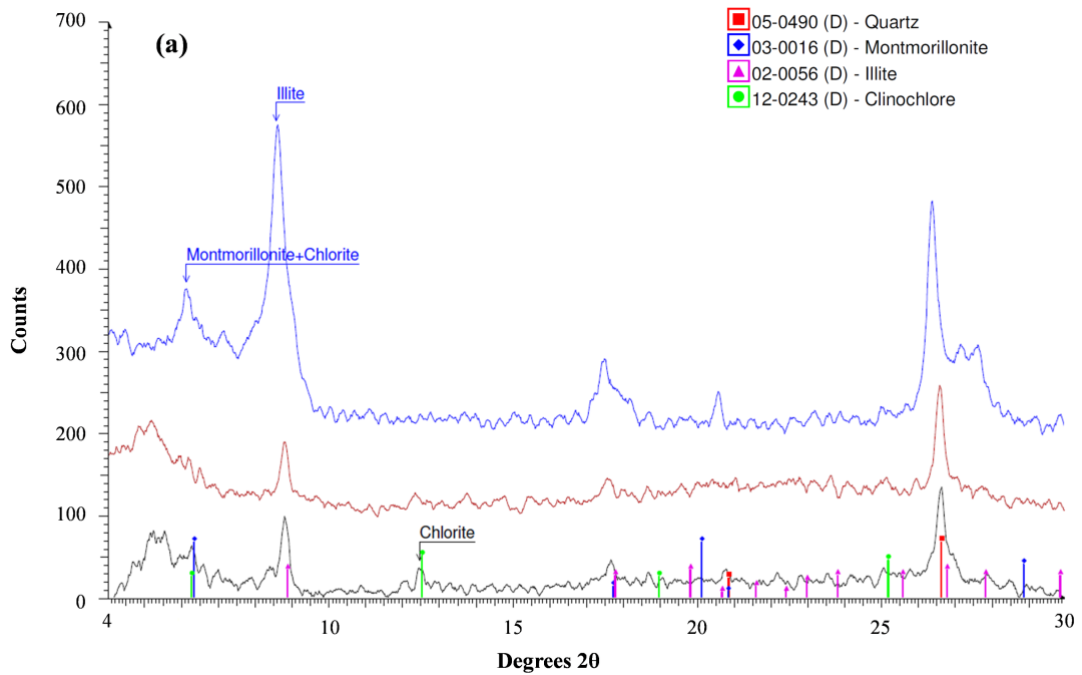


**Table 3.** Characteristics of different tests

Group No.	Test No.	Stabilizer fluid	Concentration (mol/l)	Anode reservoir	Cathode reservoir
1	1	Distilled water	-	Distilled water	Distilled water
2	2	CaCl <sub>2</sub>	0.125	CaCl <sub>2</sub>	Distilled water
	3	CaCl <sub>2</sub>	0.25	CaCl <sub>2</sub>	Distilled water
	4	CaCl <sub>2</sub>	0.50	CaCl <sub>2</sub>	Distilled water
3	5	MgCl <sub>2</sub>	0.125	MgCl <sub>2</sub>	Distilled water
	6	MgCl <sub>2</sub>	0.25	MgCl <sub>2</sub>	Distilled water
	7	MgCl <sub>2</sub>	0.5	MgCl <sub>2</sub>	Distilled water

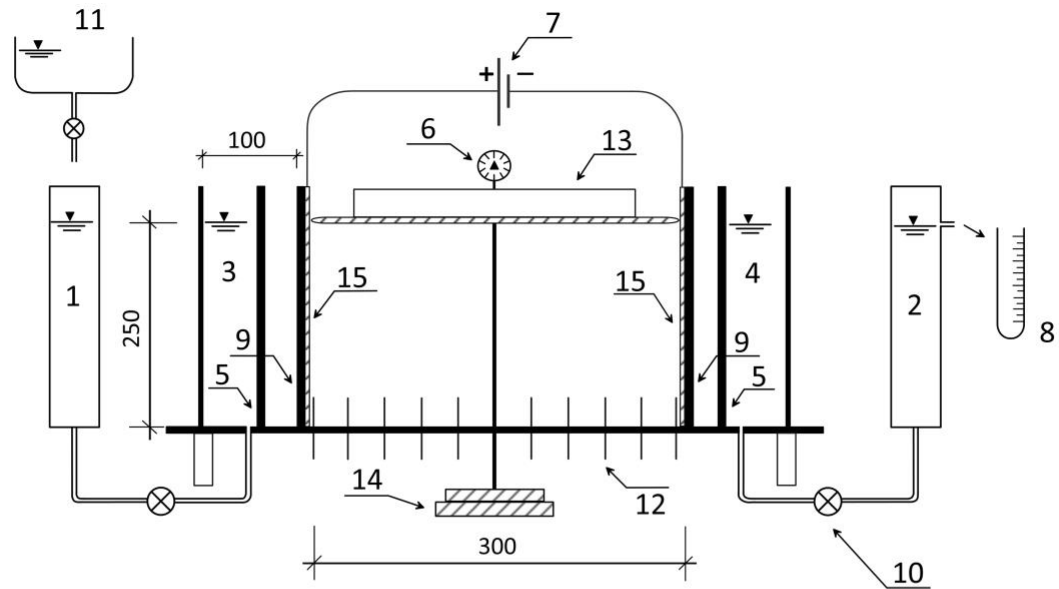


(a)



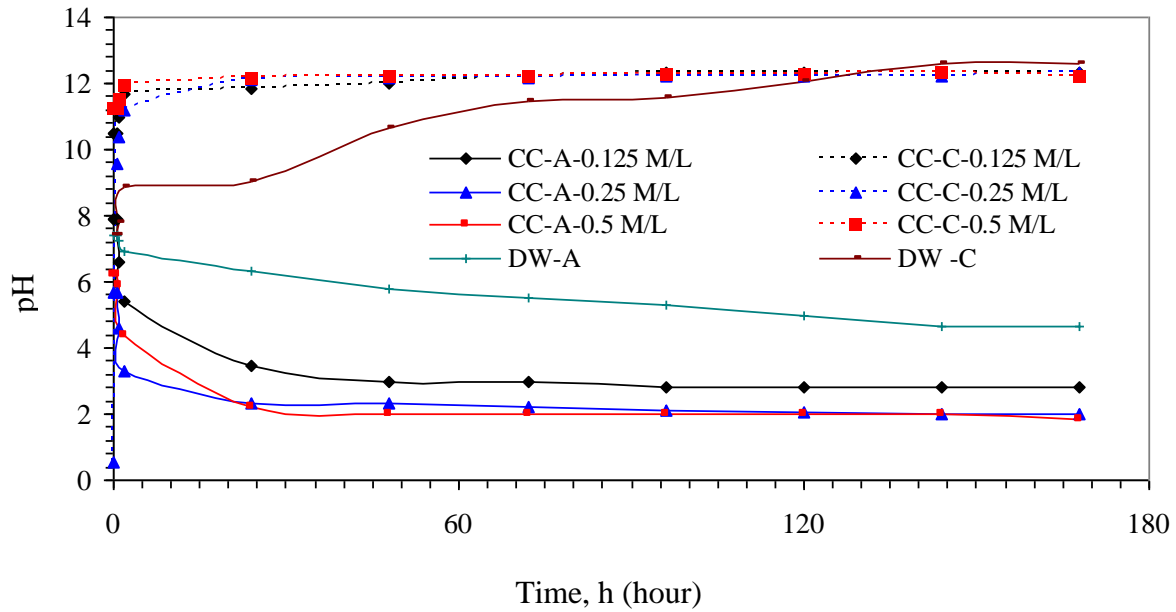
(b)

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

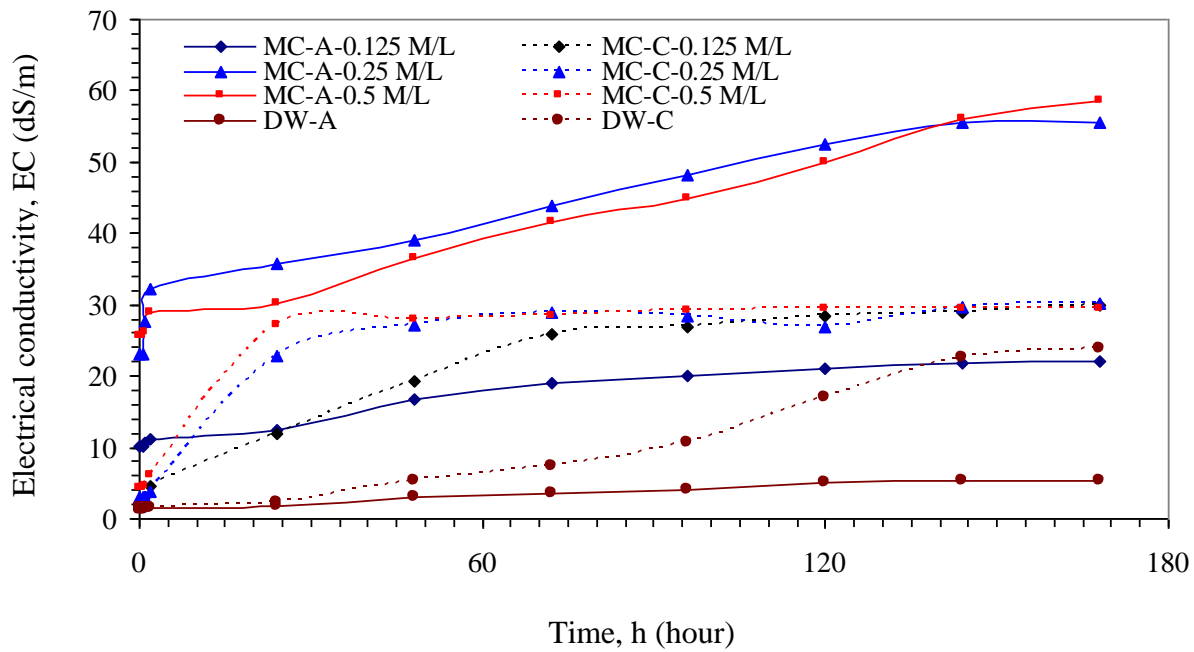


- |                      |                     |                    |
|----------------------|---------------------|--------------------|
| 1- Recharge tube     | 6- Dial gage        | 11- Water tank     |
| 2- Discharge tube    | 7- DC power supply  | 12- Voltage probe  |
| 3- Anode reservoir   | 8- Scaled column    | 13- Loading plate  |
| 4- Cathode reservoir | 9- Perforated plate | 14- Surcharge load |
| 5- Electrode (plate) | 10- Valve           | 15- Geotextile     |

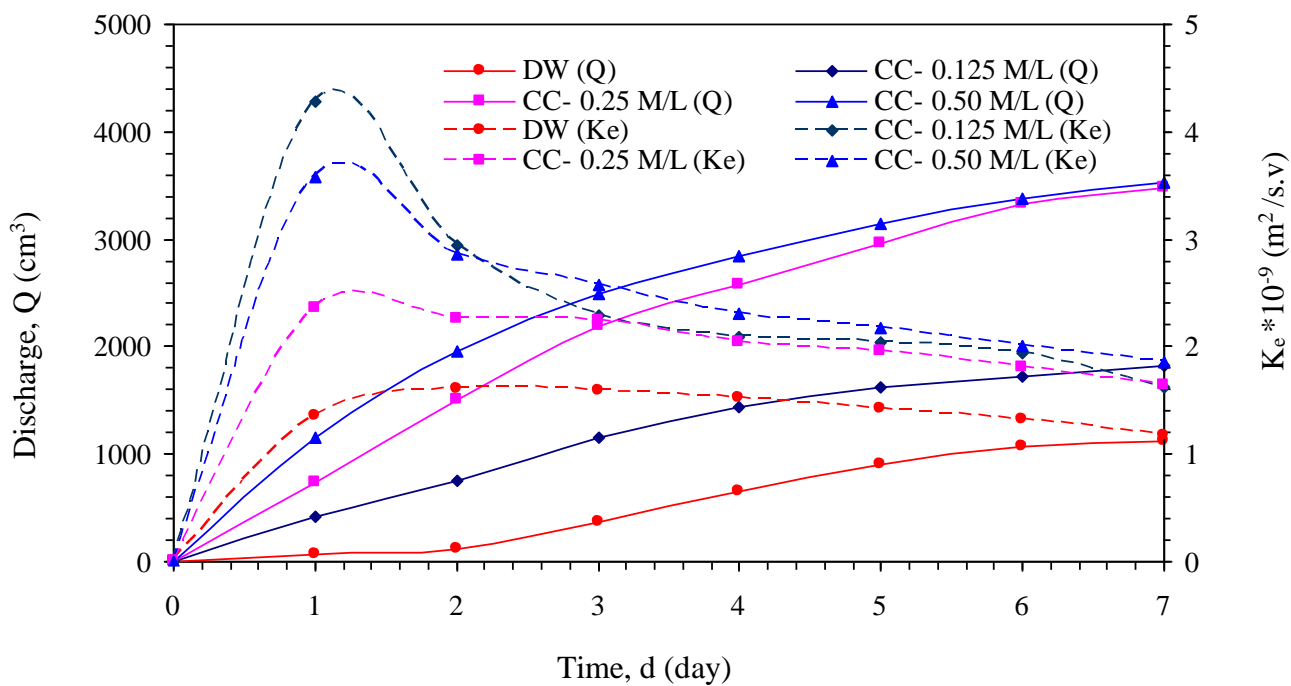
**Fig.2.** Schematic plan of the test set-up (dimensions in mm)



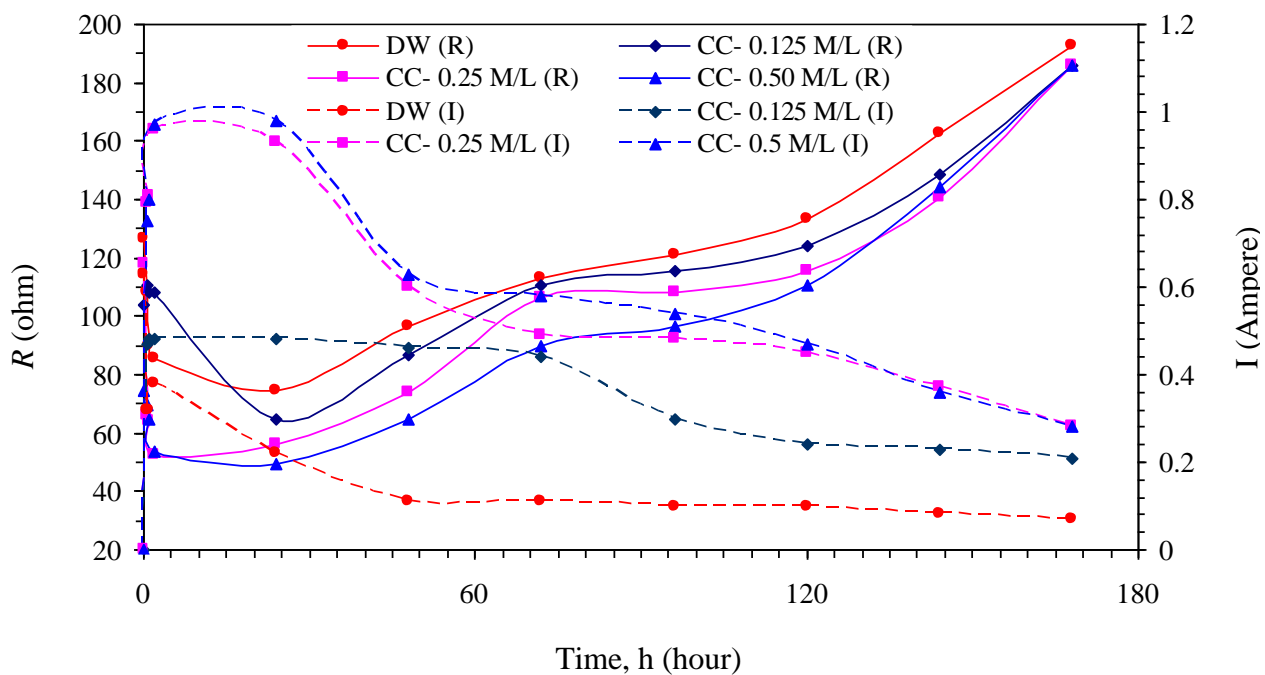
**Fig.3.** Variations of pH of two reservoirs with time. CC= CaCl<sub>2</sub>, DW.= Distilled Water, A=Anode, C= Cathode



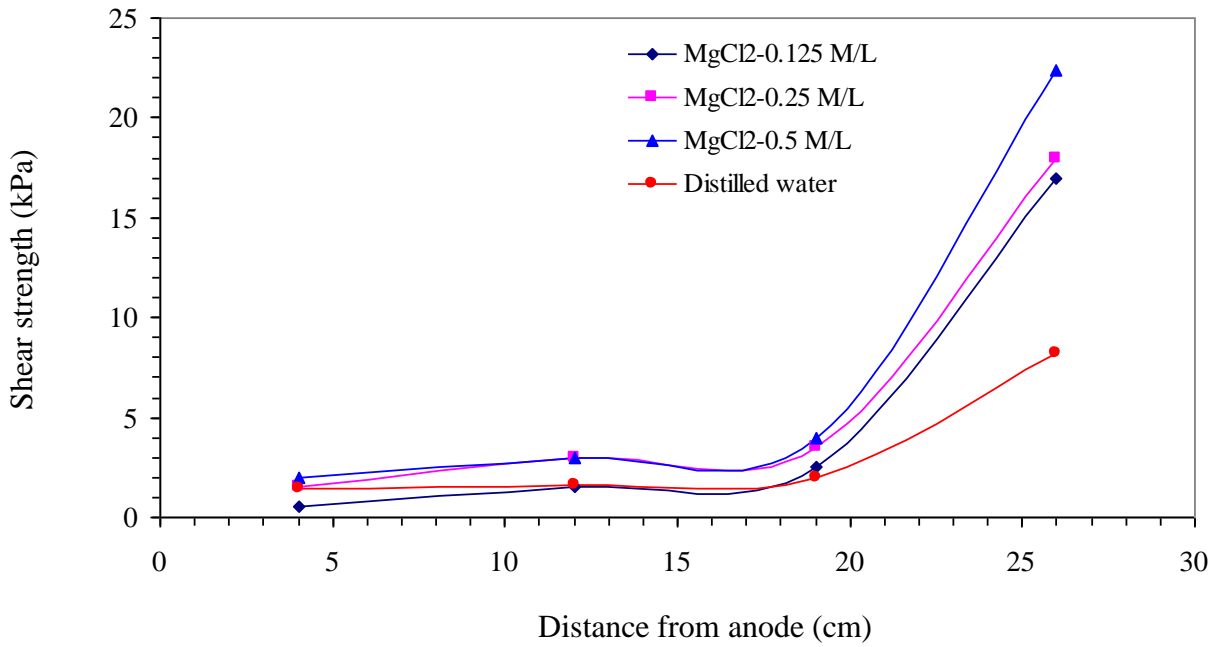
**Fig.4.** Variations of EC of two reservoirs with time MC= MgCl<sub>2</sub>, DW= Distilled Water, A=Anode, C= Cathode



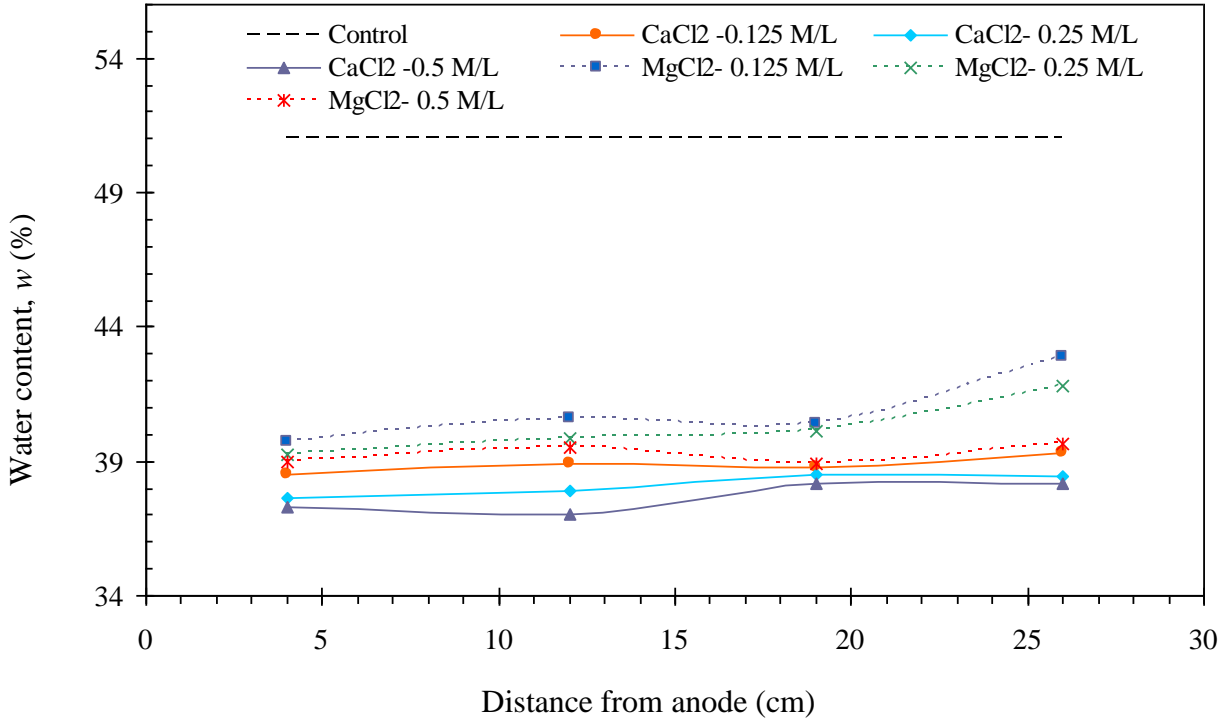
**Fig.5.** Variations of fluid discharge and  $K_e$  with time for solutions of  $\text{CaCl}_2$  at different concentrations. DW=Distilled Water, CC=  $\text{CaCl}_2$



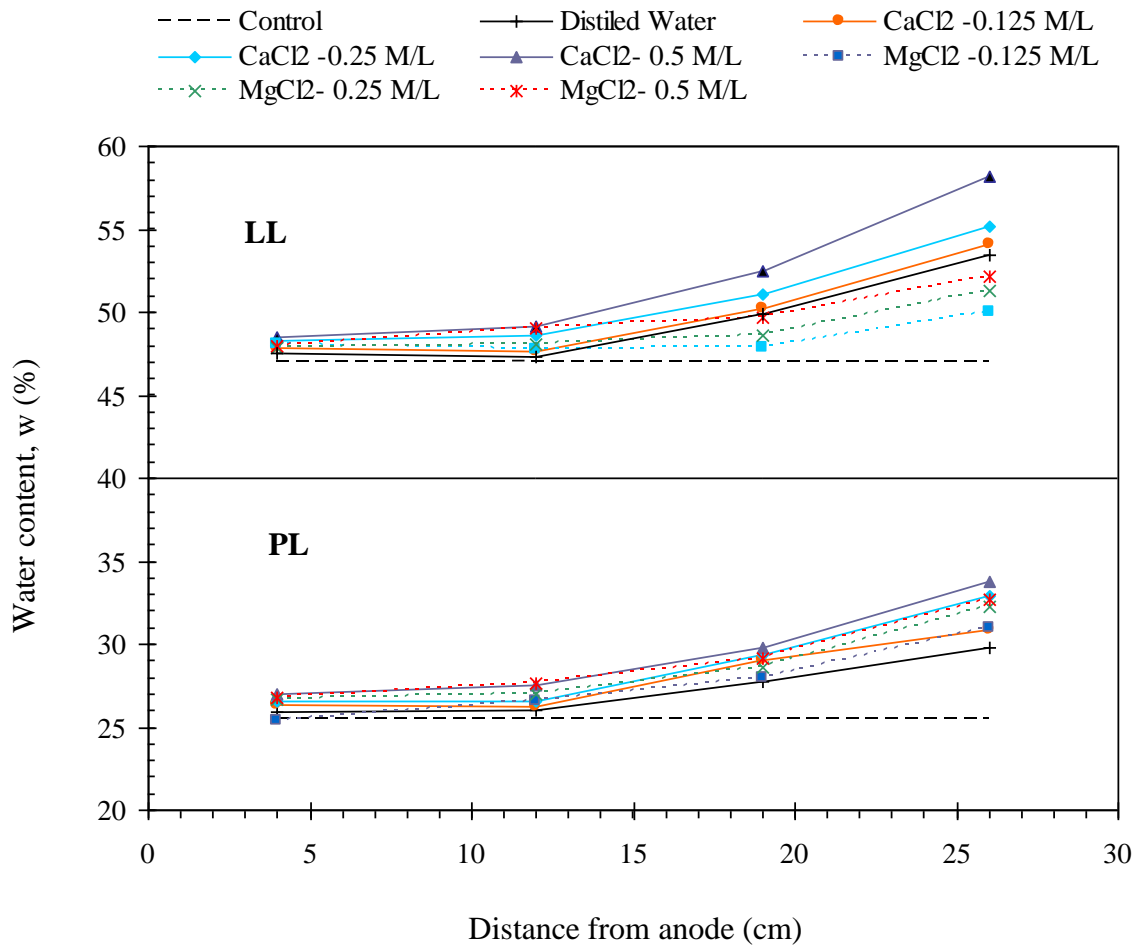
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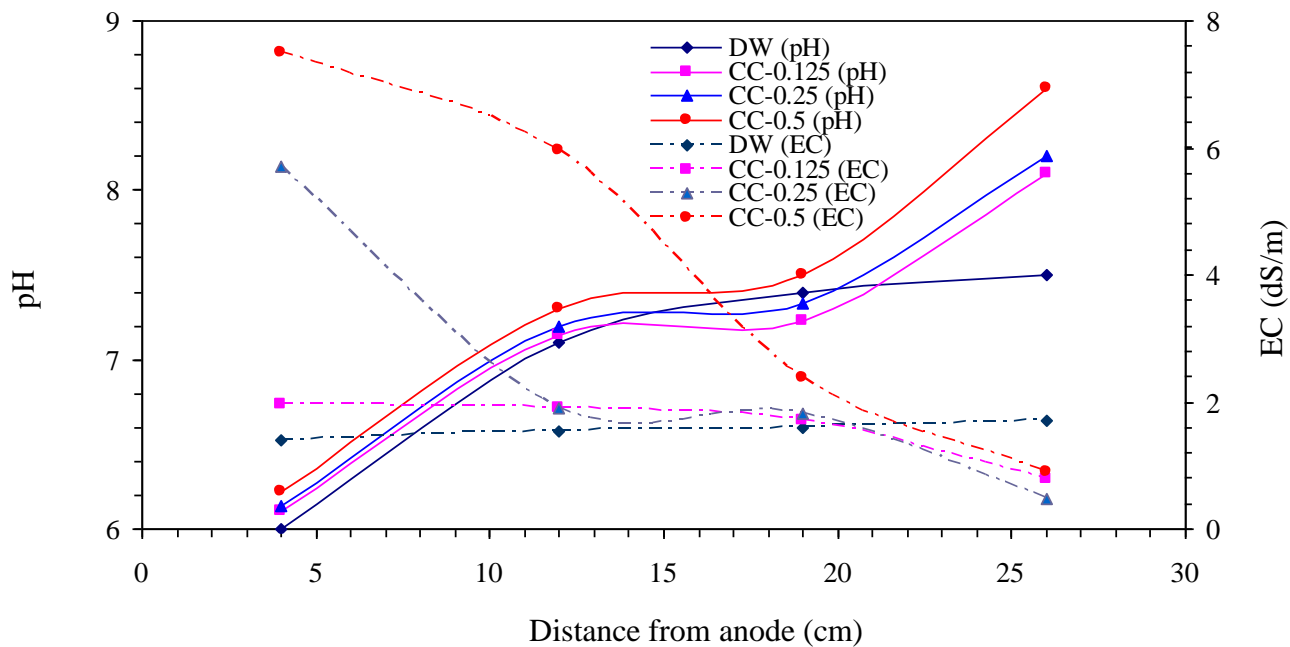
**Fig.7.** Variations of shear strength along the soil sample with distance from anode



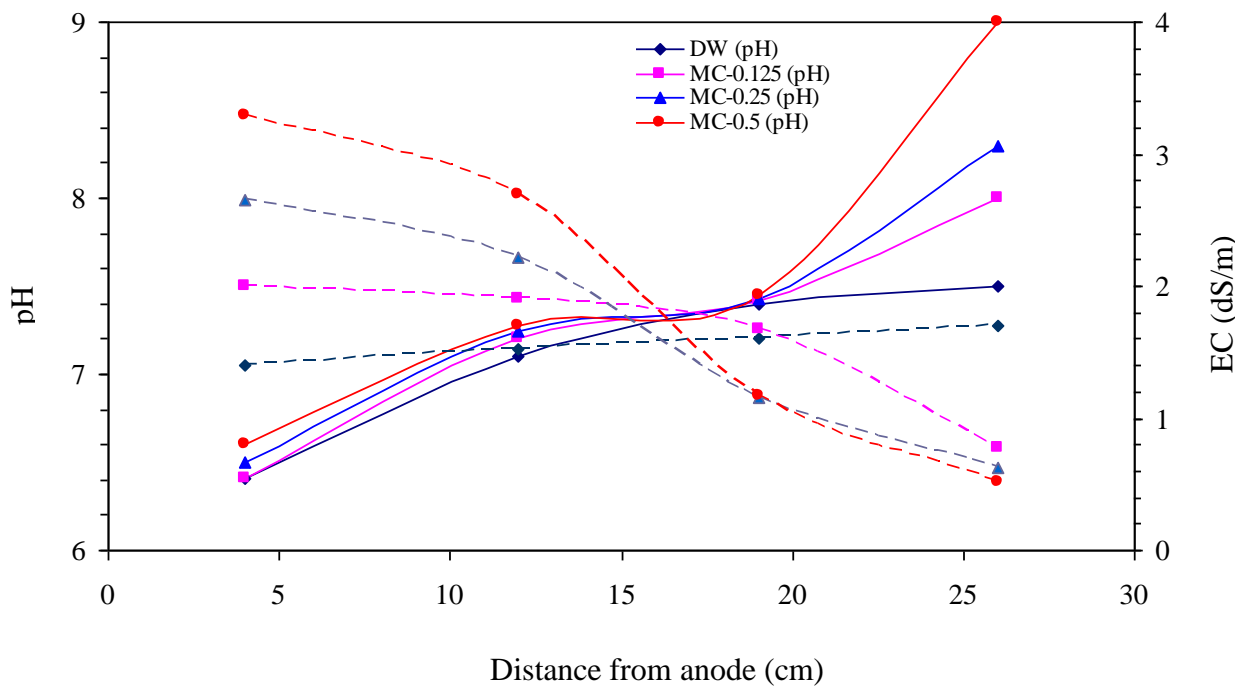
**Fig.8.** Variations of water content after each test along the soil sample with distance from anode.



**Fig.9.** Variations of LL (liquid limit) and PL (plastic limit) after each test along the soil sample with distance from anode.



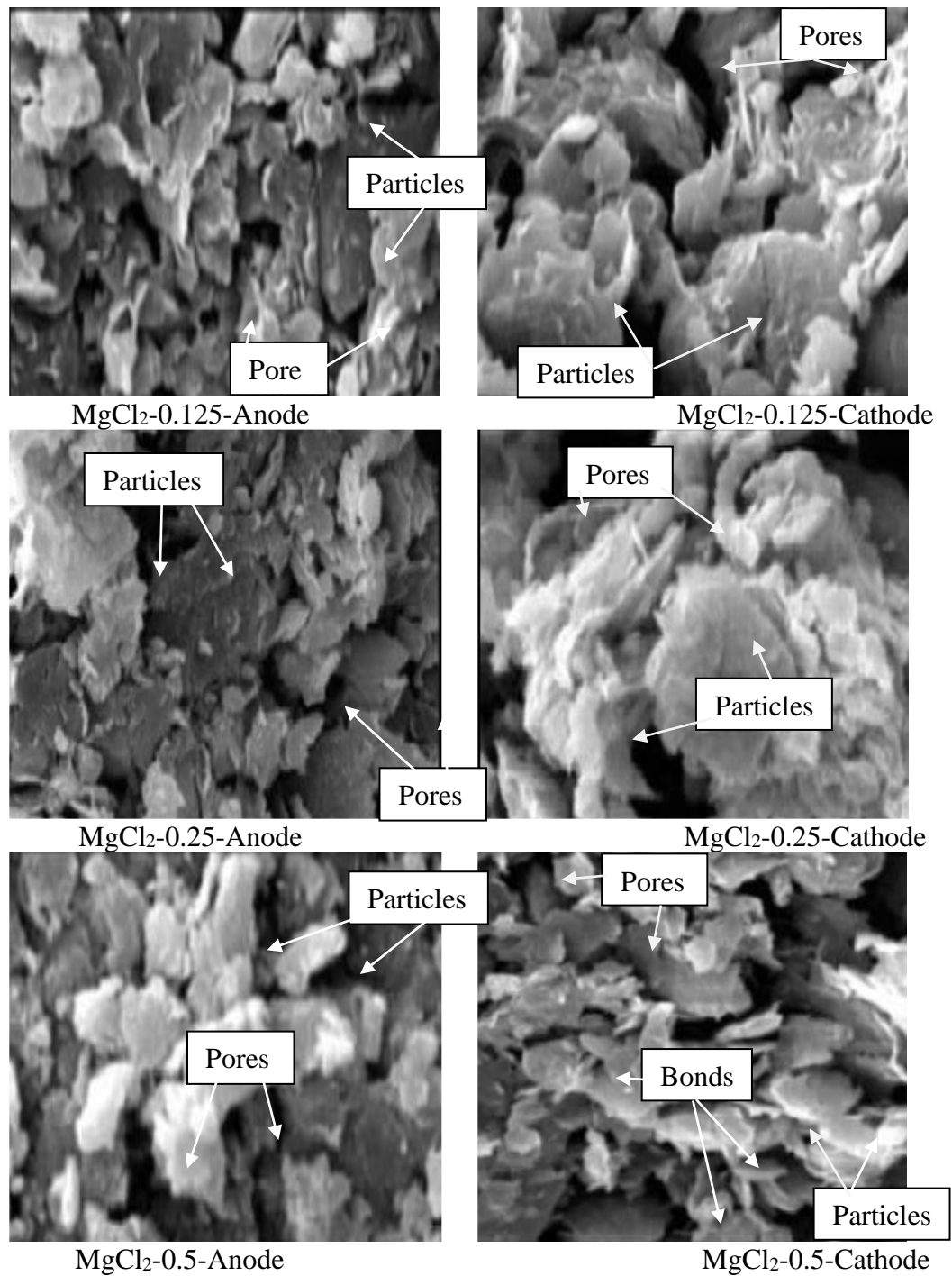
(a)



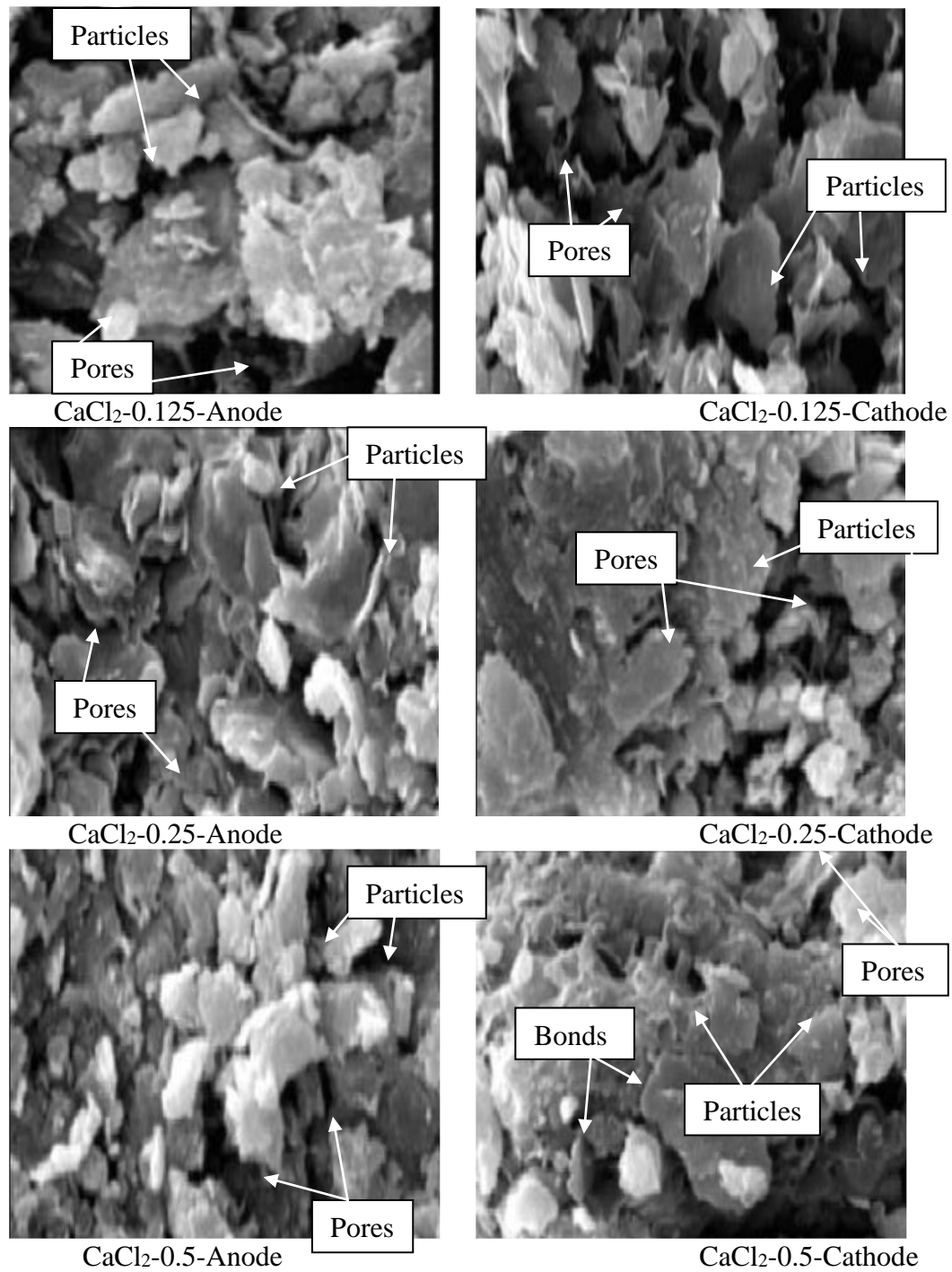
(b)

**Fig.10.** Variations of pH and EC along the soil sample with time and with distance from the anode for different solutions at different concentrations (a) CaCl<sub>2</sub> (b) MgCl<sub>2</sub>. DW= Distilled Water, CC= CaCl<sub>2</sub>, MC= MgCl<sub>2</sub>.

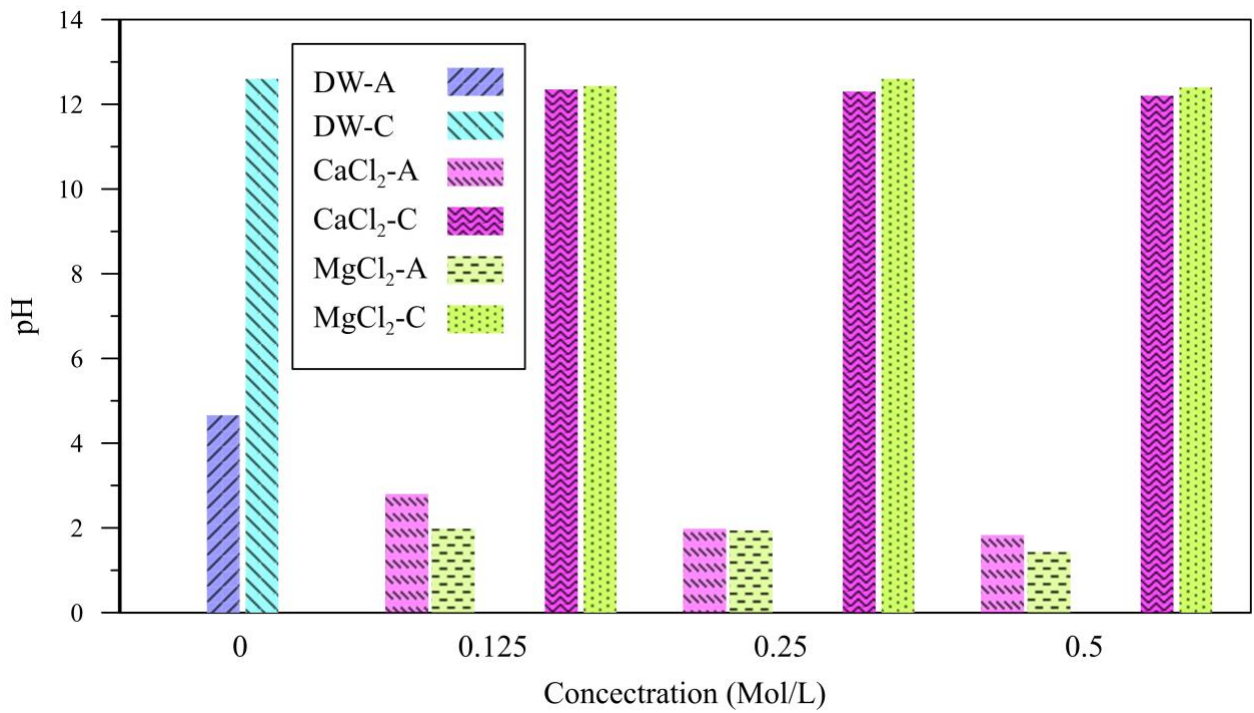




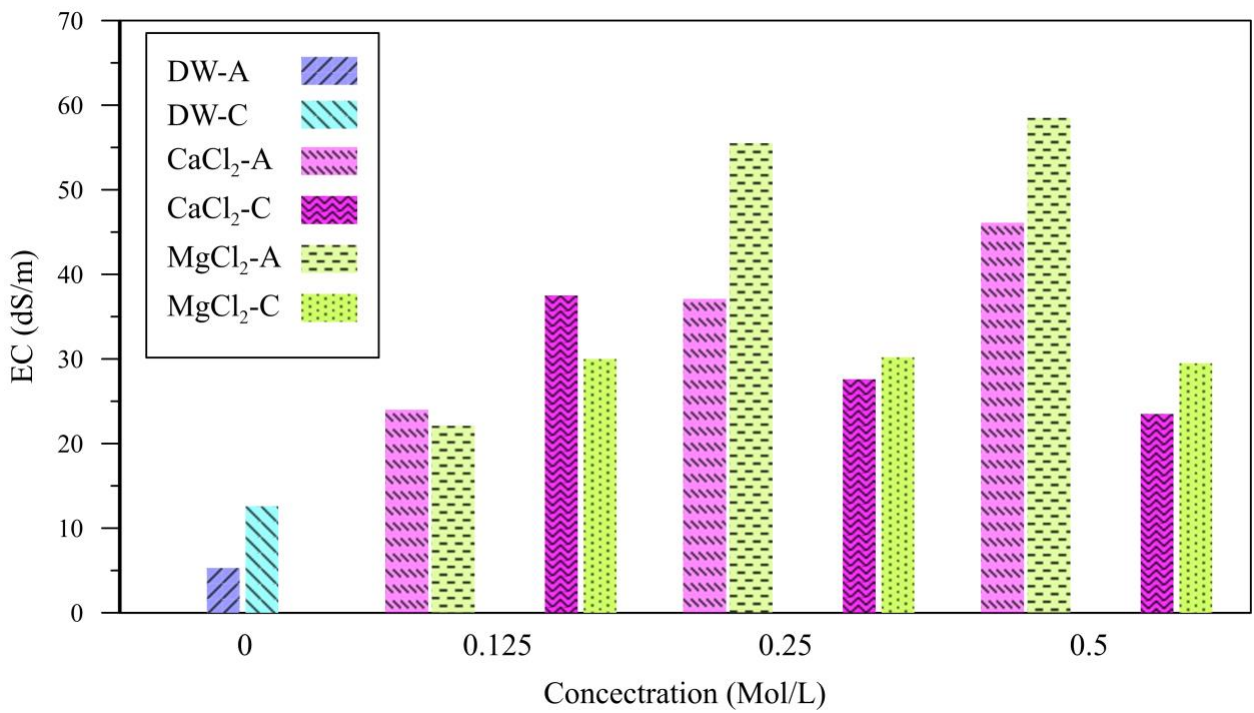
**Fig.11.** Scanning electron microscope micrographs for MgCl<sub>2</sub> solution at anode and cathode for different concentrations



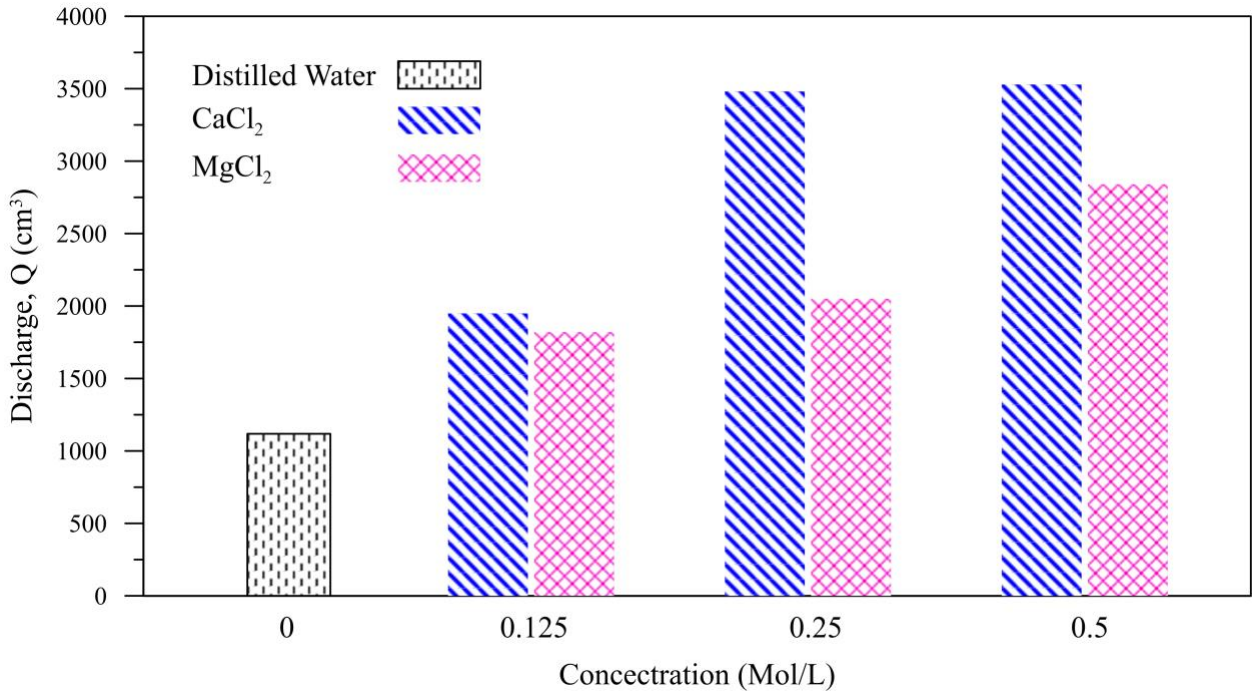
**Fig.12.** Scanning electron microscope micrographs for CaCl<sub>2</sub> solution at anode and cathode for different concentrations



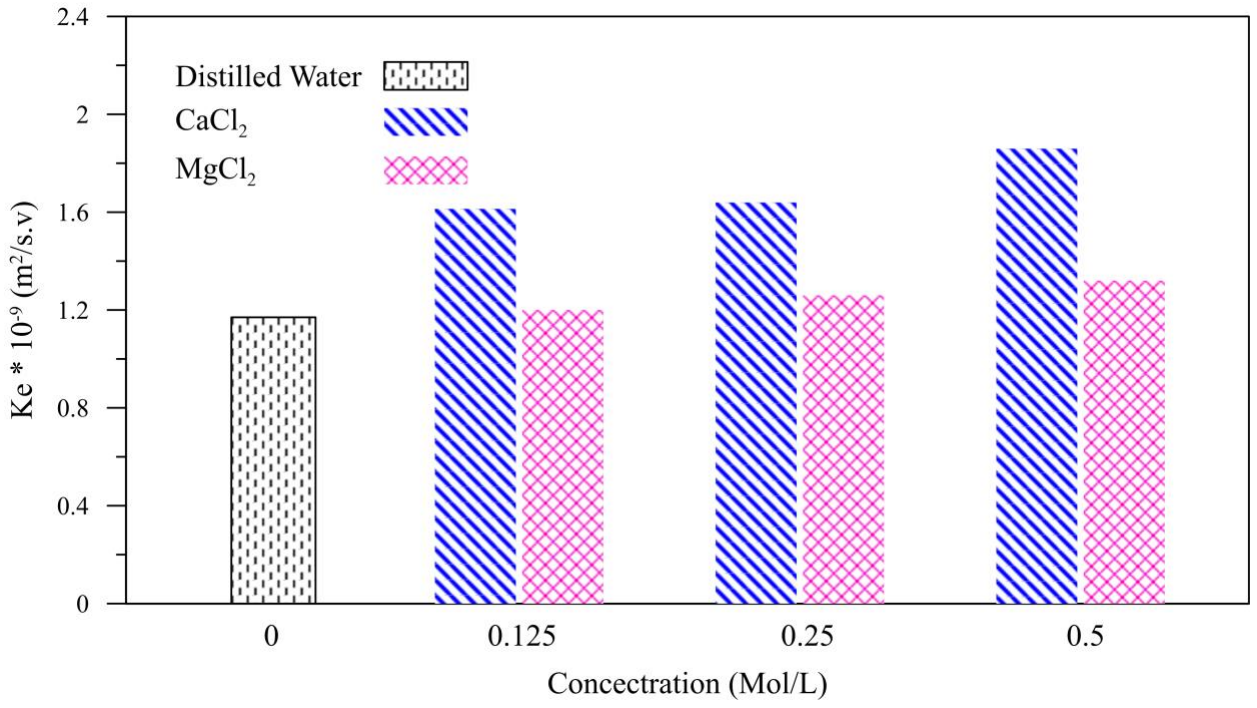
**Fig.13.** Comparison the values of pH at end of each test for different solutions



**Fig.14.** Comparison the value of EC at end of each test for different solutions

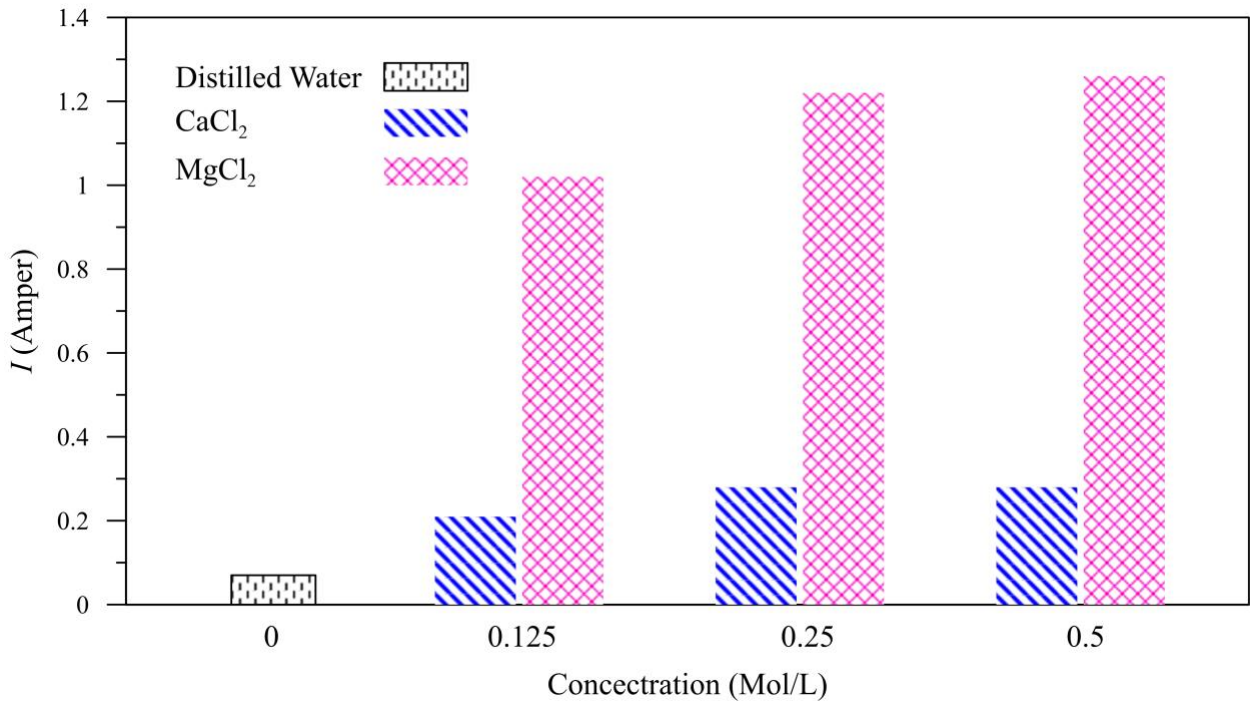


**Fig.15.** Comparison flow discharge at the end of each test for different solutions

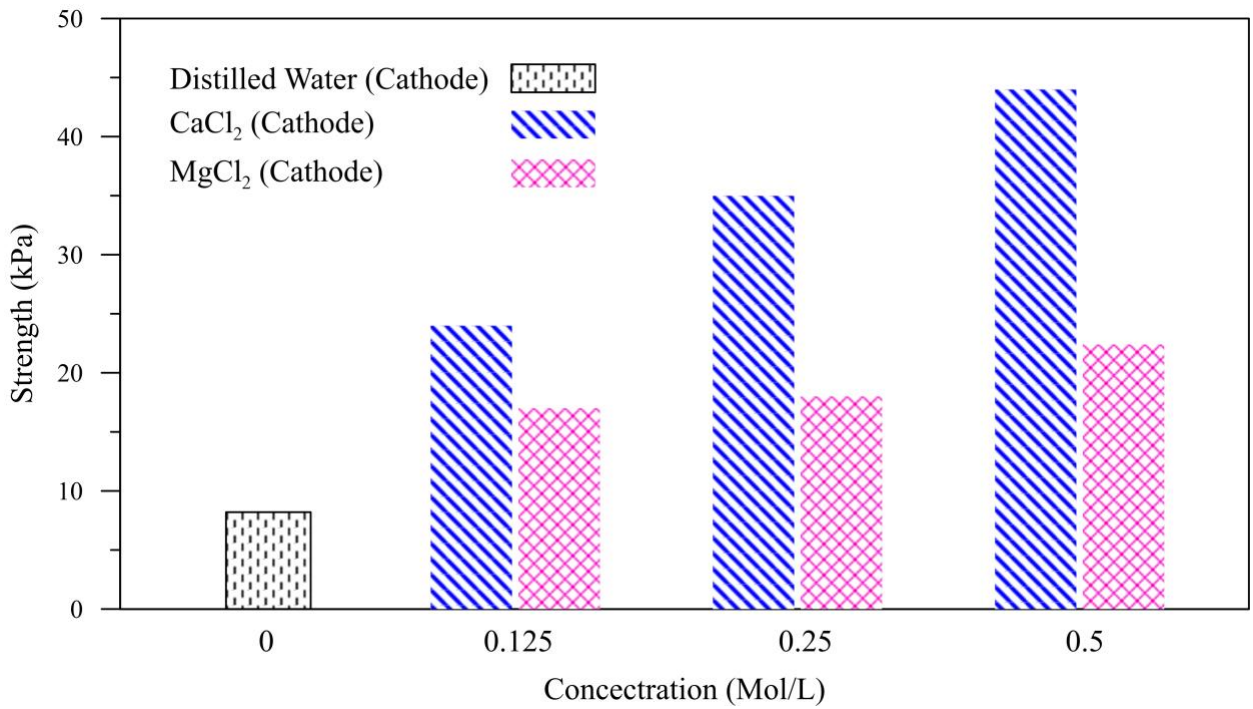


**Fig.16.** The values of  $K_e$  at end of each test for different solutions





**Fig.17.** Final values of I for different solutions



**Fig.18.** The values of measured strength of improved soil at cathode for different solution