

## **Stabilization of clay soil with polymers through electrokinetic technique**

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### **Abstract**

In this work the effect of migration of two polymers, namely polyethylene oxide (PEO) and sodium carboxymethyl cellulose (CMC) with concentrations of 2, 4 and 6 g/L on improvement of a clay soil is investigated through a program of experimental tests. The tests were conducted in a special apparatus under the voltage of 50 volt and over a period of 7 days. During each test, the values of pH and EC in the two reservoirs, discharge fluid from the cathode reservoir were measured at different time intervals. At the end of each test the strength of soil was measured across the length of sample. SEM tests were also carried out at the end of the test on the samples. The results showed that both polymers caused significant increase in the settlement and undrained shear strength of the soil but the maximum strength was obtained at concentration of 4 g/L. At this concentration the values pH and EC at the cathode reservoir were about 13 and 48 dS/m for both polymers. The SEM results revealed that the increase in strength is due to the covering of the particle surfaces and penetration of the polymer between the spaces of soil particles.

Key words: Electrokinetic, polymer, distilled water, clay soil, settlement, strength

## **Introduction**

One of the challenges of geotechnical engineering is to improve the physical and mechanical properties of the problematic soils. These soils may be used as foundation material or as material for construction work. Improving the physical and mechanical properties of a soil will improve its performance such that it will be able to support the applied loads without risk of failure or excessive deformation. The selection of an appropriate method for soil improvement or stabilization is dependent on the type and nature of the soil. Soil stabilization methods can be divided into those that are applicable to non-cohesive soils and those for cohesive soils. In the present work, only the techniques that are used for improving the cohesive soils are considered.

The stability of buildings is dependent on the soil on which they are founded. In cases where soft clay soil forms a large area of a town or city and there is a lack of suitable soil, the improvement of this kind of soil should be considered before any design and construction of buildings. One of the soil improvement methods is to use surcharge or preloading to increase the strength and limit the settlement of the soil. However, this method takes a long time to achieve the desired behaviors (Charles & Watts, 2002). In order to decrease the time, it is possible to increase the weight of the surcharge but it may cause sudden failure of the ground. Another method for decreasing the time of

improvement is installation of vertical drains and it can be used for surface and deep soils. Chemical techniques are also used for improving the behavior of cohesive soils. In these methods usually calcium ions are produced in the mass of soil based on the agents such as lime or cement (Bahar et al.; 2004 and Al-Rawas et al.; 2005). These chemical methods have been used satisfactory for many decades. Recently new compounds have been introduced that when mixed with cohesive soils, they could undergo reactions to yield a solidified material. It has been found that organic chemicals can be mixed with soil where polymerization reactions bind the soil particles together (Brown et al.; 2004). Some researchers such as Ajayi-Majebi et al. (1991), Bolander (1999) and Tingle & Santoni (2003) examined the use the resin as an additive agent for stabilization of soils. Bolander (1999), Tingle & Santoni (2003) and Estabragh et al. (2011 and 2013) investigated the effect of different resins on the strength of soil. They reported that adding the desired resin can increase the tensile strength and unconfined compressive strength of cohesive soil. Rauch et al. (2002), Katz et al. (2001) and Inyang et al. (2007) also conducted a series of laboratory experiments to evaluate the effects of polymers on treatment of clay soils. Pore water can have an important influence on the stability of soils. The strength and stability of soil are dependent on the effective stress and hence, on the change in pore water pressure. Dewatering is a technique of improving soil behavior by reducing pore water pressure and water content (Casagrande, 1952 and Bjerrume et al., 1967). In practice, for safe and economic design of electro-osmotic projects in the field, some information about design parameters is required. Parameters such as  $K_e$  (electro-osmosis permeability),  $K_h$  (hydraulic permeability),  $E$  (electric field intensity) and  $\rho$  (energy consumptions) can be determined through a set of laboratory experiments (Shang & Mohamedelhassan, 2001).

Another problem that engineers may be faced is how to improve the soil under a founded building. The above methods can not be used for this case as they may lead to settlement of buildings. Al-Shawabkeh & Sheahn (2003) proposed the freezing, hydrofracture grouting and electroosmotic consolidation for such cases. Using these methods may cause considerable movement of the ground and can be a potential cause of damage to the adjacent and overlying structures. Rogers et al. (2003), Al-Shawabkeh & Sheahn (2003) and Barker et al. (2004) suggested that, to overcome this problem, it is possible to use chemical improvement under an electrical current. In this method the chemical ions are transported between two installed electrodes and the desired improvement is achieved. This type of stabilization is known as electrokinetic stabilization and involves the use of electrokinetics to draw stabilizing chemicals through the soil. In this technique, by applying a direct current (DC) under a specific gradient an electrical field is provided across the mass of soil through two electrodes to facilitate the migration of stabilizing agents into the soil. Rogers et al. (2003) stated that this method is suitable for soils with low permeability and can be used without any excavation of soil and for improving the soil beneath a foundation.

This method of soil improvement was adopted at the end of 1990s. Ozkan et al. (1990) studied the use of electrokinetics for injection of ions of aluminium and phosphate to stabilize kaolinite and they reported increase in strength up to 50-60%. Lefebre & Burnette (2002), Mohamedal Hassan & Shang (2003), Alshawabkeh & Sheahan (2003), Alshawabkeh et al. (2004), Otsuki et al. (2007), Chien et al. (2009), Ou et al. (2009) and Abdullah & Al-Abadi (2010) also reported that injection of ionic solutions to soil under an electric voltage can improve the strength of soft clay soil. In this technique the cations in a

saline solution may migrate in clay soil under the electric field. The cationic ions may cause cation exchange on clay particles which can cause a change of clay structure and lead to improvement of the soil. Paczkowska (2005) examined the injection of a polymer to a clay soil by this method and found it is effective in increasing the strength parameters of the clay soil.

In recent years, special attention has been paid to the polymer materials for use in civil engineering projects. This is because of their suitable properties such as tightness, good aging stability; resistance to gasoline, organic solvents and strong inorganic acids and bases (Paczkowska, 2005). Paczkowska (2005) showed that by using a polymer the amount of outflow of water could be about 3.5-3.85 times more than using distilled water. To achieve the desired strength, it is possible to reduce the duration of treatment or increase distance between the anode and cathode both of which would reduce the cost of treatment. Although some research works have been done on the treatment of clay soils by injection of ions under electrical field, but treatment of clay soil by injection of polymer materials is relatively rare, except the research work reported by Paczkowska (2005). The research work by Paczkowska (2005) is limited to one type of polymer material and the measured data is limited to liquid flow in and out of soil, electrical current and water content. The focus of this work is to study the effects of different polymers and determine the optimum concentration of the used polymers. In this work two types of polymer were selected. Injection tests were conducted at different concentrations and the values of pH, EC (Electrical Conductivity),  $K_e$  (Electro-osmotic permeability) and strength of the treated soil were measured during or at the end of the tests. The effects of the two polymers were compared with each other and with distilled water and the best concentration for field work

was recommended. The experimental procedures and results are presented in the following sections.

## **Materials**

The main materials that were used in this work were soil, water and polymers. A brief description of the materials is presented below.

### *Soil*

The soil used in the testing program was a fine grained soil comprising 10% sand, 56% silt and 34% clay. Laboratory tests to determine specific gravity, liquid limit (LL), plastic limit (PL), shrinkage limit (SL), grain size distribution and compaction characteristics were conducted according to the ASTM standards. Tables 1 and 2 summarize the various physical, mechanical and chemical properties of the soil. The soil can be classified as clay with low plasticity (CL) according to the Unified Soil Classification System (USCS). XRD (X-ray diffraction) tests were also conducted on the samples of this soil. Based on the XRD tests, the minerals of the soil include quartz, calcite, feldspar (Na, Ca) and feldspar (K). The results also show that the clay minerals of the soil are illite, chlorite and montmorillonite.

### *Water*

Drinking water was used for conducting the tests. It had a pH of 7.0, Cl content of 1.7 meq/L and Ca-Mg content of 9.1 meq/L.

### *Polymer*

Two different types of polymer were used in this work. They were polyethylene oxide (PEO) and Sodium carboxymethyl cellulose (CMC). These polymers were used by Inyang et al. (2007) for controlling the volume change of an expansive soil. Selected of these

polymers was based on their high aqueous solubility, medium to high biodegradability, low toxicity (or nontoxicity) and low cost.

a- *Polyethylene oxide (PEO)*

Polyethylene oxide (PEO) is a polymer with chemical formula  $(-\text{CH}_2\text{CH}_2\text{O})_n-$  that is obtained by polymerization of ethylene oxide. It is commercially available over a wide range of molecular weights. PEO with different molecular weights has different applications and physical properties (e.g. viscosity) due to the chain length effects. It is in liquid or low melting solid state depending on its molecular weight. Therefore, it is a compound with many applications from industrial manufacturing to medicine. It has low toxicity and is a water soluble polymer. The PEO used in this research was a white powder with melting point 65-67°C. Its bulk density and particle size were 0.3 to 0.5 kg/L and 1000  $\mu\text{m}$  respectively. The PEO used had a low molecular weight (200000 g/mol) with neutral charge.

b- *Sodium carboxymethyl cellulose*

Sodium Carboxymethyl cellulose (CMC) is a plant based “green” and inexpensive natural polymer consisting of glycopyranose units with non-toxic, biocompatible, and biodegradable nature (El-Newehy et al., 2016). Due to being water soluble, CMC possesses both carboxylate and hydroxyl groups

The pure Sodium Carboxymethyl cellulose is white or milk white fibrous powder or particles and tasteless. It is soluble in water but insoluble in organic solvents. Its chemical formula is  $[\text{C}_6\text{H}_7\text{O}_2(\text{OH})_2\text{OCH}_2\text{COONa}]_n$  and its viscosity is within 25-50 Pa.s. It is a non-toxic and aqueous solution and is neutral or alkaline. Sodium Carboxymethyl cellulose is

used for producing sodium salt, as well as ammonium and aluminum salts. The CMC that was used in this work had a molecular weight of 80000 g/mol with negative charge.

Solutions with concentrations of 2, 4 and 6 g/L of these polymers were examined in this work. To prepare a desired solution, the required mass of the polymer 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.

### **Apparatus**

Based on the considerations reported by previous researchers, an apparatus was designed and made for this work, similar to the one used by Rittirong et al. (2008) and Mohammedalhasan & Shang (2001). The apparatus consists of a main cell, loading frame and D.C. power supply as shown in Fig. 1. The main section of the apparatus is the cell that consists of a rectangular tank (with length, width and height of 30, 10 and 30 cm respectively) that holds the soil sample. It was made of Plexiglas plates with 1 cm thickness. Two reservoirs, namely anode and cathode, were added on the two sides of the main cell and were connected to the cell through perforated Plexiglas sheets as shown in Fig. 1. The reservoirs were filled with fluid and the total hydraulic head in them was controlled by adjusting two identical standing tubes through valves. Two electrodes made of stainless steel sheets (also used by Paczkowska, 2005) were added to allow the liquid to pass easily. The electrodes were rectangular in shape and had holes with 1 mm diameter. They were placed vertically at a distance of 5 cm from the soil in the main cell. Geotextile sheets were used between soil and electrode compartments to prevent from loss of soil (Jeon et al. 2010 and Kim et al. 2009 used filter paper and porous stone between soil and electrode compartments). These sheets were saturated (by submerging in the same liquid as the one



used in the anode and cathode reservoirs) and then placed on the two sides of sample. Being saturated, the sheets could not absorb the pore water from the sample and sample remained in saturated condition. A number of voltage probes were installed at the bottom of the cell at distances 0.15, 0.3, 2, 3, 5, 8 and 11 cm from the anode. The diameter of the probes was 1 mm and they were made from iridium oxide (as used by Rittirong et al., 2008). These probes were used to measure the voltage in certain time intervals during the progress of the test. A loading system was designed to apply the desired load to the soil sample (see Fig.1). It consists of a plate that is placed on top of the sample and is connected to another plate at the bottom of cell through a bar coated with a foam material that is isolated against electrical current. The load was applied through the bottom plate to the sample. A dial gauge was mounted on the top plate for measuring the vertical deformation due to consolidation. 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**

A specific amount of air-dried soil was mixed with water to bring its water content to 5% above the liquid limit. The soil was mixed by hand steer for about 1 hour until a smooth condition was achieved. This mixture was kept in a plastic bowl with closed lid for about 10 days for uniform distribution of water content. The strength of the prepared soil was measured by using shear vane apparatus in random points of the soil. The prepared soil sample was placed at three layers in the main cell and each layer was subjected to 5 minutes of vibration. During vibration the small air voids that were formed while placing the soil in the main cell were disappeared by vibration. After that a saturated geomembrane was

placed on top of the soil to create horizontal flow condition. The level of fluid was kept the same in the anode and cathode reservoirs at two sides of the soil in the main cell.

### **Experimental tests**

The experimental tests were conducted in two groups: in group 1 the anode and cathode reservoirs were filled with distilled water while in group 2 the anode reservoir was filled with desired polymer solution and the cathode reservoir with distilled water. The procedures for both groups were as follows.

After placing the sample of soil in the main cell the anode and cathode were filled with desired fluid and then a surcharge pressure of 1.0 kPa was applied to the soil via the loading plate. The level of fluid was kept constant at both reservoirs and consolidation was recorded using a dial gauge. The consolidation settlement stopped after about five days. This consolidation stage under the surcharge pressure will be referred to as preloading consolidation stage. Osmosis consolidation was carried out after the preloading consolidation stage by keeping the fluid levels constant in the anode and cathode reservoirs. Therefore, the hydraulic gradient between the two reservoirs was set to zero. The osmosis consolidation was enforced by applying a D.C. current through the soil. During the test the changes in vertical deformation were measured using a dial gauge and the changes in volume of the sample were determined by measuring the volume of discharge fluid that flowed out from the cathode reservoir. In addition, the values of pH and EC of the fluid in both reservoirs were measured during the test. The total time for the consolidation stage was about 10 days for different voltages. The tests were conducted in a temperature control room at 20-22°C. The temperatures of both reservoirs during the test were measured from time to time and were nearly the same. It was not realized that during the injection of

polymer materials to the soil they were decomposed and changed to toxic gas. When the test was completed the surcharge load and the geomembrane were removed. After that the undrained shear strength of soil was measured by using shear vane apparatus. This was performed at the distances of 4, 11, 18 and 26 cm from the anode. A number of samples were also taken from these points after the strength tests for determination of water content and Atterberg limits.

At the end of each test scanning electron microscopy (SEM) tests were performed on the samples that were taken from at the anode, middle and cathode in order to observe the microstructure of the samples in different conditions. The samples were scanned under SEM following the method that was used by Tremblay et al. (2002).

## **Results**

The results obtained are discussed in the following sections.

### ***pH***

Fig.2 shows the variations of pH at the anode and cathode reservoirs for different fluids during the tests. The results show that the initial values of pH for distilled water and all polymer solutions at anode and cathode reservoirs are nearly the same (i.e. pH=7) . During the test by increasing the time, the values of pH at the anode decreased for all fluids but they increased at the cathode. At the end of the test, the value of pH at cathode for distilled water was 12.4 but for the other solutions it was more than 13.3. This shows that the effect of these solutions in creating an alkaline environment is more than distilled water. At the end of test, the value of pH at anode was 4.8 for distilled water. However, for the different solutions of CMC and PEO the values of pH decreased from initial values but there was no specific trend with increasing the concentration. The value of pH for anode reservoir at

concentration 4 g/L was less than the other concentrations for both polymers. Comparing the results of pH at cathode for both polymers indicates that the value of pH for PEO nearly the same as CMC. In other words, the effect of both polymers solutions is important in creating basic in cathode reservoir.

#### *EC (Electrical Conductivity)*

The variations of EC with time at the anode and cathode reservoirs during the tests are shown in Fig.3. The results show that during the tests, the values of EC for both anode and cathode increased from their initial values by increasing the time. For example the initial values of EC for distilled water at anode and cathode were 1.37 and 1.16 dS/m respectively and they are changed to 17 and 60 dS/m at the end of the test. This trend of variations is also seen for CMC solution with different concentrations. The initial values of EC at concentration of 2 g/L CMC at anode and cathode were 4.58 and 2 dS/m respectively but at the end of the test they changed to 11.03 and 36.8 dS/m. The results show that by increasing the concentration of CMC the values of EC at anode were increased and the amount of increase is dependent on the concentration of CMC. This trend of variation was also observed for oxide with concentrations of 2 and 4 g/L of PMC but at concentration of 6 g/L a decrease in value of EC is observed in comparison with the other concentrations.

#### *Q (Discharge)*

Fig.4. shows the variations of cumulative discharge of fluid from the cathode reservoir at different times during the test. As shown in this figure the total volume of discharge of distilled water at the end of the test was 1118 cm<sup>3</sup> but for solution of CMC it changed to 1015, 2659 and 2110 cm<sup>3</sup> at concentrations of 2, 4 and 6 g/L respectively. It is seen that for concentrations of 4 and 6 g/L the discharge of fluid was nearly twice the distilled water

and the maximum discharge of fluid was at concentration of 4 g/L. The volume of discharged fluid for solution of PEO had no specific trend; at the concentrations of 2, 4 and 6 g/L the final volumes of discharge were 925, 3010 and 890 cm<sup>3</sup> respectively. The maximum volume of discharge for PEO was also at concentration of 4 g/L.

**$K_e$**  (electro-osmotic permeability)

The amount of discharge of fluid from the soil can be defined by the following relationship (Mitchell, 1993):

$$Q = K_e * E * A \quad (3)$$

where  $Q$  is the electro-osmotic flow rate,  $A$  is the cross sectional area normal to the direction of flow,  $E$  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 from the obtained data based on equation (3). Fig.5 shows the variations of  $K_e$  with time for each of the used solutions. As shown in this figure, the value of  $K_e$  decreased with time for all solutions. The value of  $K_e$  at the end of the test with distilled water was 1.18E-09 m<sup>2</sup>/s.v but for other solutions its value was more than distilled water. For example for CMC with concentration of 2 g/L the value of  $K_e$  was 5.35E-09 m<sup>2</sup>/s.v. and it decreased with increasing the concentration of CMC. The value of  $K_e$  for the solution of PEO was more than distilled water but its maximum value was at concentration of 6 g/L (4.48E-09 m<sup>2</sup>/s.v.).

**$I$**  (Intensity of electrical current)

The results of variations of current intensity with time are shown in Fig.6 for different solutions. As seen in this figure, the intensity of current is decreased with increasing the

time. The intensity of current for the distilled water reached 0.27 ampere (A) at the end of test but for the CMC and PEO its value changed with concentration of solution. For the CMC solutions, the intensity of current was 0.11, 0.39 and 0.36 A at concentrations of 2, 4 and 6 g/L respectively. The value of  $I$  was 0.09, 0.4 and 0.1 A for concentrations of 2, 4 and 6 g/L of PEO respectively. It is resulted that for both polymers the value of  $I$  is increased until concentration of 4 g/L then there is a reduction in the value of it.

### ***Consolidation***

The vertical settlement of soil was measured for all samples using a dial gauge before, during and after application of the electric current. Figs 7a and b present the variations of vertical settlement during the two stages of testing. It is seen from Fig.7a and b that the settlement at the end of the first stage (consolidation under surcharge pressure) was not the same for distilled water and polymer solutions. During the second stage (osmotic consolidation by applying electric current) the total settlements were 1.32, 1.57 and 1.63 mm for CMC with concentrations of 2, 4 and 6 g/L (Fig.7a). These values for the same concentrations of PEO were 1.1, 1.18 and 0.91 mm respectively (Fig.7b). It is observed from these figures that during the application of electrical current, most of the settlement occurred in the first day of testing.

### ***Strength***

At the end of each test the strength of the soil was measured at distances 4, 11, 18 and 26 cm from the anode (Fig.8). The results show that the undrained shear strength generally increased by increasing the distance from the anode. When the solution was distilled water, the strengths at distances of 4, 11, 18 and 26 cm were 1.6, 1.8, 2.0 and 8.2 kPa respectively. Also, when the solution of CMC or PEO was used, the strength increased with increasing

the distance from the anode. For the CMC solution with concentration of 2g/L, the strength was less than distilled water while for the CMC solutions with concentrations 4 and 6 g/L the strength was higher in comparison with distilled water. For the CMC with concentration of 4 g/L, the strength at distance of 26 cm from the anode was nearly four times the strength with distilled water. The results show that for the CMC solutions, the highest strength was at concentration of 4 g/L and lowest at concentration of 2 g/L. Similar results were also obtained for the PEO solutions at different concentrations. For the PEO solutions, the highest strength was seen at concentration of 4 g/L and lowest at concentration of 6 g/L.

### ***SEM results***

Figs.9a and 9b show the SEM results for the soil samples that were taken from around the anode and cathode at the end of test when the anode reservoir was full of distilled water. As shown in Fig.9a the soil particles were plate-like in shape and parallel with each other with large voids between them. It is seen from Fig.9b that the pores between the particles were reduced in comparison with Fig.9a and they made a denser mass of soil. Figs. 10a, b and c show the micrographs of the samples that were taken from the vicinity of the cathode (26 cm from the anode) at the end of the tests for concentrations of 2, 4 and 6 g/L PEO. As shown in Fig.10a the particles were nearly parallel to each other but for the concentrations of 4 and 6 g/L they were less parallel and the spaces between them were reduced in comparison with concentration of 2 g/L (Fig.10a). Fig.11 a and b show the micrographs for the soil with CMC solution with concentrations 2 and 6 g/L. It is seen that by increasing the concentration of CMC, the contact between particles was increased which resulted in increase in strength of the soil.

### ***Discussion***

Applying a direct electrical current via electrodes produces electrochemical reactions such as oxidation at the anode and cathode. The reactions produce an acid front and oxygen at anode and a base front and hydrogen gas at cathode. The presence of  $H^+$  in the anode causes the value of pH to decrease and the liquid adjacent to the anode gets acidic, but in the cathode it changes to alkaline. Fig. 2 shows the variations of pH in the fluid that electrodes were immersed in. The initial value of pH was about 7 in all tests. During each test, the value of pH in the anode decreased leading to an acidic front while it was increased in the cathode resulting in a basic front. When distilled water was used, the final values of pH were 4.8 and 12.4 at the anode and cathode respectively. However, for different concentrations of CMC or PEO solutions the values of pH at anode and cathode were less than 4.13 (final value of the pH for distilled water) and more than 13.3 respectively. It can be concluded that the solutions of polymers produce ions that help to increase the intensity of acidic and basic fronts in the tests. The results indicate that at concentration of 4 g/L, both polymers produced more acidity around the anode than the other concentrations (i.e. 2 and 6 g/L). It is resulted that more ions are produced at this concentration of used polymers.

Variations of electrical conductivity (EC) of fluids at anode and cathode reservoirs during the tests are shown in Fig.3. As shown in this figure the initial values of EC for distilled water at anode and cathode reservoirs were 1.37 and 1.16 dS/m respectively. This initial value for the solutions of CMC changed to 4.58, 7.58 and 11.7 in the anode reservoir for concentrations of 2, 4 and 6 g/L. The increase of EC can be the result of accumulation of dissolved ions, particularly in the cathode reservoir. As it was discussed earlier, the decrease of pH in the anode creates an acidic front which moves from the anode to the



cathode. Solution of this polymer in water produces some ions that increase the EC. The value of EC was increased with increasing the concentration the CMC. This polymer is an anionic kind because of the carboxylate components. These components are solved in water and produce Na and COO ions that cause increase in the value of EC at the anode. The value of EC was also increased at both reservoirs during the tests. When distilled water was used at anode and cathode, the values of EC increased from their initial values. For example, for distilled water the final values of EC were 17.0 and 60.0 dS/m at the anode and cathode respectively. At the end of test, these values were changed to 11.03 and 36.8 for 2 g/L solution of CMC. A similar trend of variation was seen for the solutions of 4 and 6 g/L where the magnitude of EC at the anode reservoir was a function of concentration of this polymer.

The final values of EC for PEO were less than that the values that were obtained for CMC. PEO is a nonionic and neutrally charged polymer. When it is solved in water, it may obtain charges or become protonated which increases the value of EC in comparison with distilled water. Rosen (1989), Edwards et al. (1994) and Ko et al. (1998) have also shown that the nonionic surfactant may obtain charges during solution in water. The results also show that the final values of EC for both reservoirs were increased and at concentration of 4 g/L the values of EC were higher than the other concentrations. It can be concluded that by the applying the electrical current this polymer produces ions that cause increase in the value of EC at both reservoirs.

As shown in Fig.7 the deformations at the end of stage 1 (consolidation under surcharge pressure) for CMC and PEO solutions were more than distilled water. This difference is due to the viscosity of polymer solutions that is higher than the distilled water which can

facilitate the deformation of particles under the applied loads. The results indicate that the soil deformations at the end of first stage of consolidation have no specific trend in comparison with the used polymer solutions. As it is seen from Fig.7, the settlement at the end of stage 1 for both polymers at concentration of 2 g/L is more than those at concentrations 4 and 6 g/L. It can be said that the penetration of polymers in the soil fills the voids between the particles, covers their surfaces and prevents from their displacement during the test. For the soil with CMC solutions the rate of settlement during the second stage of consolidation is relatively high until 20 hours after which the trend becomes smooth for distilled water and different concentrations of CMC. A similar trend can be seen in Fig.7b for the PEO solutions at different concentrations. The results show that during the second stage of consolidation, the defamations for CMC solutions at concentrations 2, 4 and 6 g/L are 1.32, 1.57 and 1.63 mm but for PEO at these concentrations they are 1.1, 1.18 and 0.91 mm respectively.

The trend of variations of volume of discharge flow (Fig. 4) shows that the flow rate is higher during a short period of the time at the start of application of electric current to the soil sample, but it is reduced until it reaches a constant value. The total outflow of distilled water was 1118 cm<sup>3</sup> but for 2, 4 and 6 g/L CMC solutions it was changed to 1015, 2659 and 2110 cm<sup>3</sup> respectively. These values were 925, 3010 and 890 cm<sup>3</sup> for PEO solutions at concentrations 2, 4 and 6 g/L respectively. The results indicate that the maximum outflow occurred at concentration of 4 g/L for both polymers but it decreased at concentration of 6 g/L. At concentration of 2 g/L of both solutions, the volume of outflow from the soil was less than distilled water. At concentration of 4 g/L, the structure of the soil was flocculated which facilitated the discharge of fluid from the soil. However, at concentration of 2 g/L

the degree of flocculation was less than that at concentration of 4 g/L, so the discharge of fluid was decreased. At concentration of 6 g/L CMC the discharge of fluid decreased in comparison with 4 g/L. This may be due to the accumulation of polymer in the voids of soil and blocking of the pathway of fluid which led to reduction of outflow of fluid from the soil. The results of discharge fluid due to the concentration of PEO are similar to the CMC solution. For PEO, the discharge fluid at concentration of 4 g/L was more than 2 and 6 g/L. The difference in the discharge fluid at the same concentration for the two polymers can be attributed to the different physical and chemical properties of the two polymers. Dewatering and treatment are dependent on the volume of water that flows out of the soil (cathode reservoir). The results showed that at concentration of 4 g/L both polymers caused more water to flow out of the sample (about 2-3 times more than water) and the greatest strength was achieved at this concentration. In practice, for safe and economic design of treatment projects in the field, some information about design parameters is required. Therefore, it is necessary to conduct a set of laboratory tests on soil samples to determine the required design information such as the best concentration of polymer. In the field, if improved strength of soil is required by dewatering, it is possible to reduce the duration of treatment or increase the distance between cathode and anode both of which would result in cost saving.

The electrokinetic permeability,  $K_e$  decreased and nearly approached to zero at the end of the test (Fig. 5). The value of  $K_e$  for the soil with CMC solutions was a function of its concentration; it decreased by increasing the concentration. However, the same trend was not observed for the PEO solutions. This can be attributed to the difference of properties of the two polymers. These results are consistent with the results that were reported by

Mohamedelhassan & Shang, (2001) and Rittirong, et al., (2008). According to the model of Helmholtz & Smoluchowski (H-S model), the value of electro-osmosis permeability ( $K_e$ ) is independent of pore size of soil (in contrast with hydraulic permeability ( $K_h$ ) which varies with pore size), but it depends on the electric field intensity. As shown in Fig.5, the values of  $K_e$  decreased with increasing the treatment time. The changes of  $K_e$  are dependent on the variations of pH and reduction of water content. Shang (1997) indicated that the value of  $K_e$  is dependent on the zeta potential. The variation of zeta potential is a function of pH changes. Since the values of pH are not the same along the sample therefore, the zeta potential is not constant and this leads to the reduction of  $K_e$ . The discharge of fluid from the cathode is decreased by reduction of  $K_e$ .

During the tests, the values of electrical current,  $I$ , initially increased in all tests, and then decreased until it reached a constant value. These results are in agreement with the results that were reported by Ou et al. (2009) for injection of solution of  $\text{CaCl}_2$  into a clay soil. The final values of  $I$  for the CMC solutions at concentrations of 4 and 6 g/L were more than distilled water. For PEO solutions, there was no particular trend for variations of  $I$  with time.

As shown in Fig.8, when the electrokinetic technique is used for soil improvement using distilled water or a solution of polymer, the shear strength of the soil is increased. The results show that the improvement is dependent on the distance of soil from the anode; the strength is increased by increasing the distance from the anode. When distilled water is used, the increase in shear strength in the vicinity of the cathode is about five times that in the vicinity of the anode. The value of pH is high around the cathode and the soil is an alkaline condition. Under this condition, the transported ions from anode form a cementing

material that pastes the particles together with strong bond and this leads to increase in the shear strength of the soil. The micrograph in Fig.9b shows that the particles are pasted to each other and form a coagulated structure which increases the strength of the soil. These results are consistent with the results reported by Micic et al. (2002), Alshawabbeh & Sheahn et al., (2003), Burnotte et al., (2004) and Rittirang et al., (2008). The effect of polymer solutions on improving the strength of the soil is similar to distilled water; by increasing the distance from the anode the degree of improvement is increased (Figs10 and 11). As the polymers migrate from the anode towards the cathode, they penetrate between the sheets of minerals of clay and cause a cation exchange between them which leads to formation of a link or bond between the sheets increasing the strength of the soil (Paczkowska, 2005). Lagaly et al. (2006) explained the intercalation condition in the adsorption of organic compounds by the clay soils. They stated that in the process of penetration of organic molecules into the interlayer space of clay minerals (intercalation) the intercalated guest molecules can be displaced by other suitable molecules. The interlayer cations can be exchanged by various types of other suitable molecules. The cation exchange can make strong links between sheets of clay soil because the organic cations are covalently attached to the polymer chain. The results show that, for both polymers, the maximum strength is seen in the vicinity of the cathode. As it is seen from Fig.8 the strength for different concentrations of polymers is increased with increasing the distance from the anode. Comparison of the amount of increase in strength at cathode for different polymer solutions shows that maximum strength is obtained at concentration of 4 g/L for both polymers. Perhaps the high value of pH is effective in linking the sheets of clay by penetration of polymer. As mentioned above, PEO is a nonionic and neutrally

charged polymer. When it is solved in water, it may obtain charges or become protonated and this causes increase in the value of pH in comparison with distilled water. Rosen (1989), Edwards et al. (1994) and Ko et al. (1998) have also shown that nonionic surfactants may obtain charges during solution in water. This can link the sheets and form bond between them. When CMC is solved in water, it produces Na and COO ions that are important in adsorption of polymer to the sheets of clay. Comparing the results for different concentrations of polymer indicates that maximum strength is obtained at concentration of 4 g/L. At concentration of 2 g/L the amount of polymer that contributes to the penetration and exchange of ions is not significant. At concentration of 6 g/L a certain amount of polymer contributes to ion exchange but the rest of it remains between the pore space of the particles and at the contact of particles which is an important factor in reduction of the strength of the soil.

Electrokinetic technique is usually used for cohesive soils. When a soil is treated by injection of materials, the degree of treatment is dependent on many factors such as the type of injected material and the type of minerals of the clay soil. In this work a clay soil with low plasticity was used. The tests can be performed on other clay soils with different minerals to study the interaction of injected material and strength of treated soil.

### **Conclusion**

Stabilization of a clay soil through electrokinetic technique was studied by injection of two different types of polymer. The following conclusions can be drawn from the results obtained in this study:

- The negative and neutral polymers cause decrease and increase in pH values at anode and cathode in comparison with distilled water. The final values of EC are

- increased at the anode and cathode by injection of both polymers. These variations are dependent on the concentration of the used polymer.
- The outflow of fluid from the soil is observed when polymer is injected but the maximum discharge is observed for concentration of 4 g/L of polymer.
  - The strength of soil is increased by using polymer solutions. For a given concentration of polymer the amount of increase in strength is dependent on the distance from the anode. The maximum strength is observed around the cathode for both polymers at concentration of 4 g/L.
  - For field applications, it is possible to achieve the desired strength at reduced cost, reduced duration of treatment or increased distance of anode and cathode

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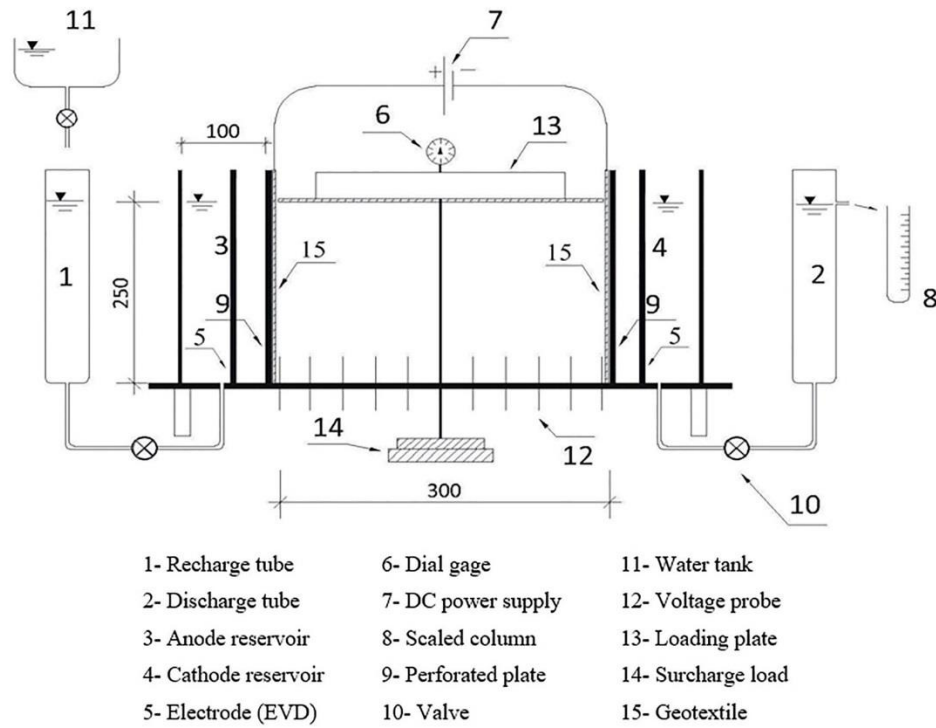
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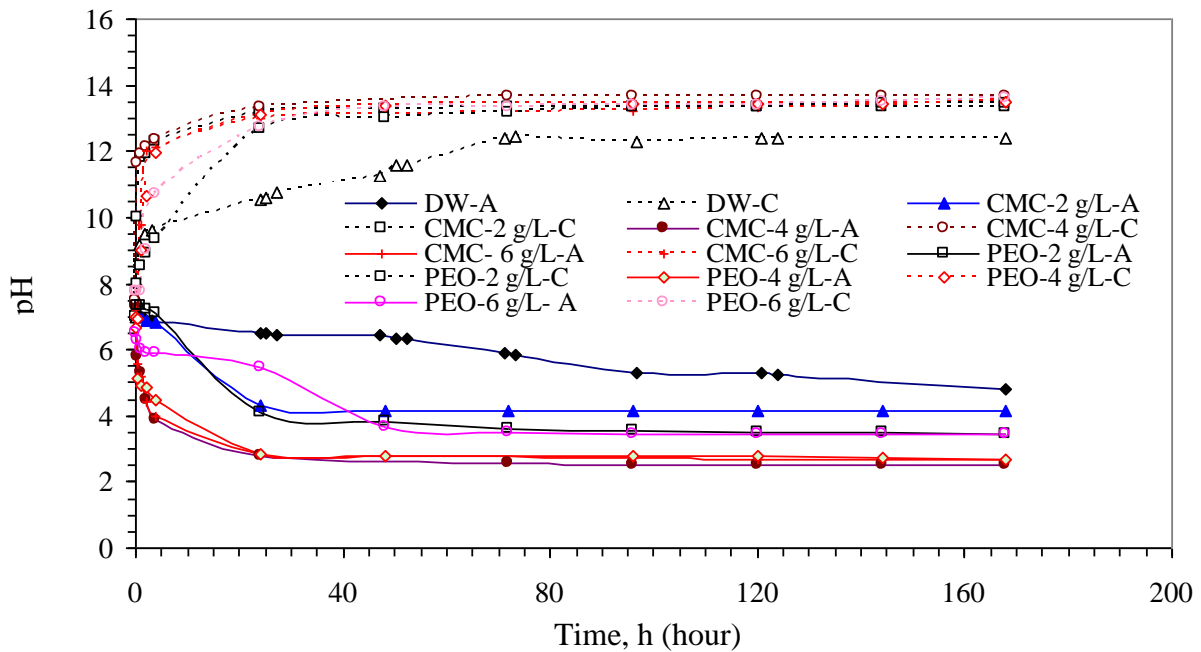
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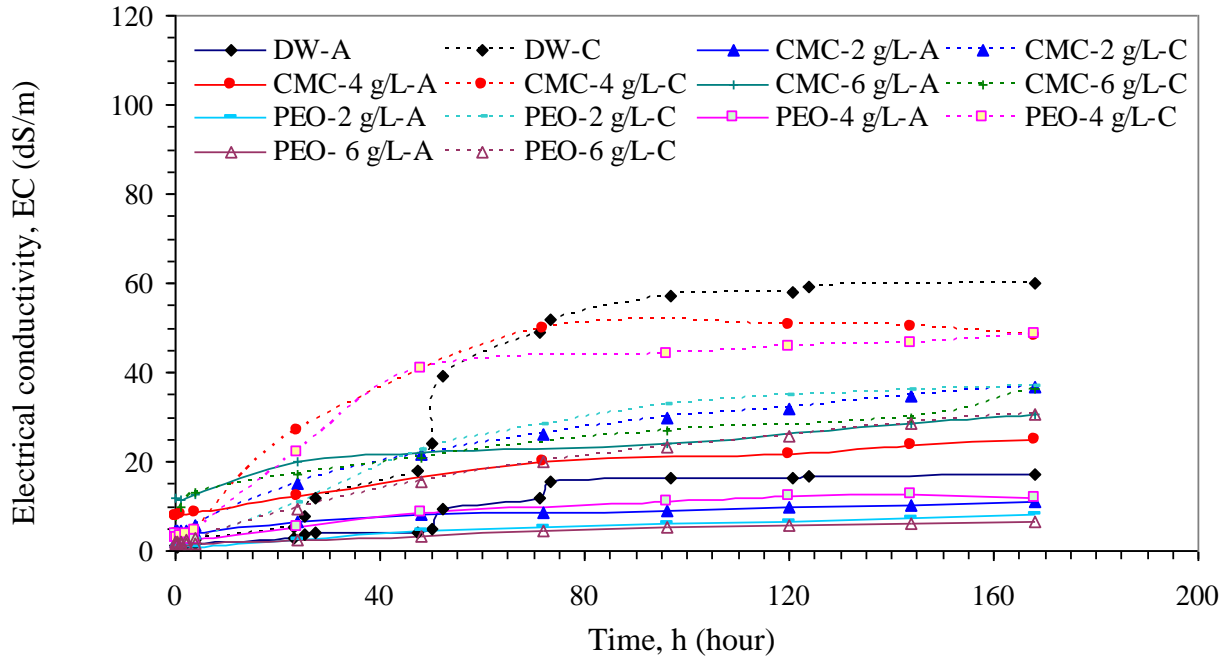
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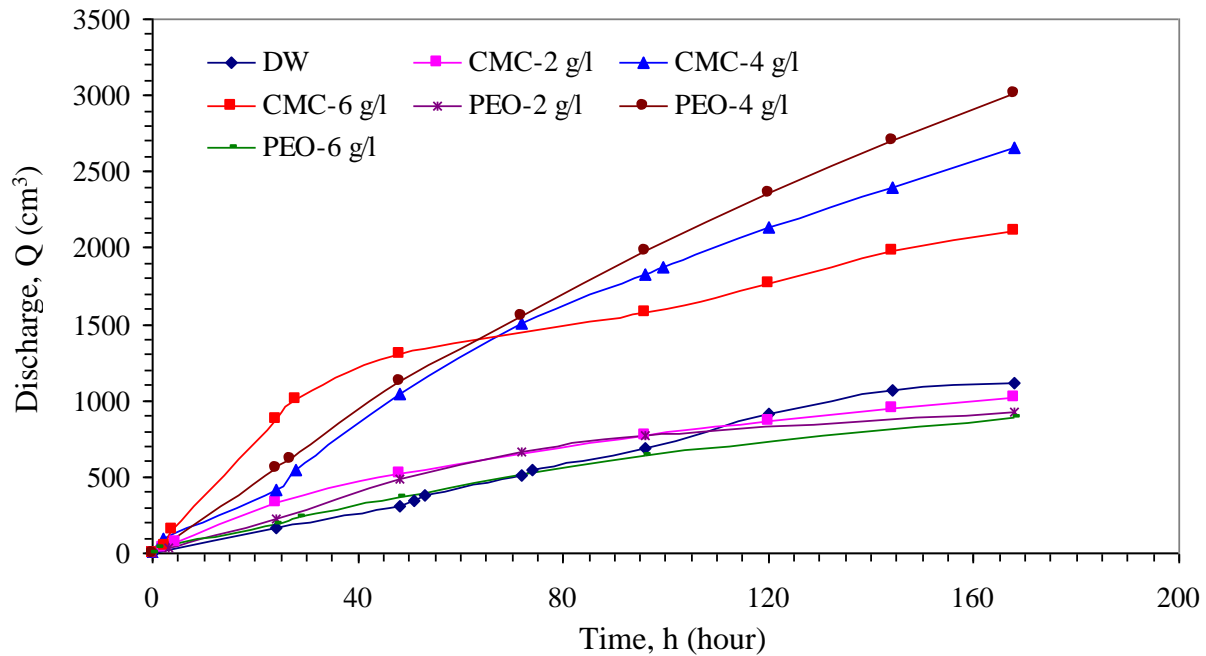
**Fig.1.** Schematic plan of the test set-up (dimensions in mm)



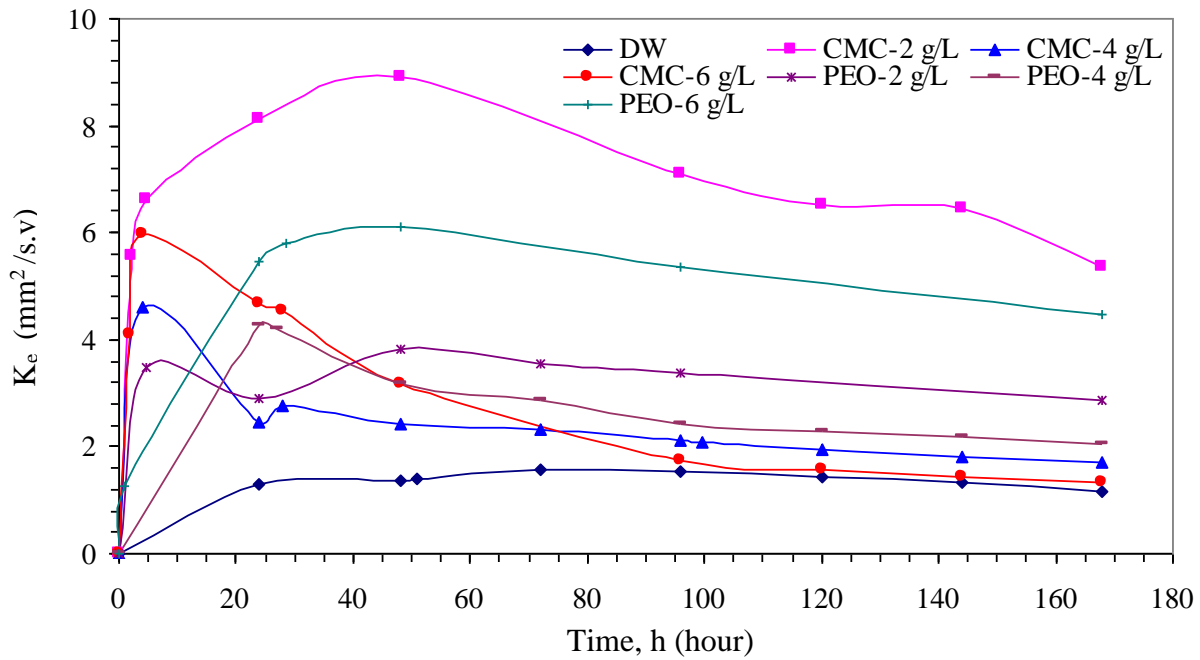
**Fig.2.** Variations of pH with time. DW=Distilled water, A=Anode, C= Cathode



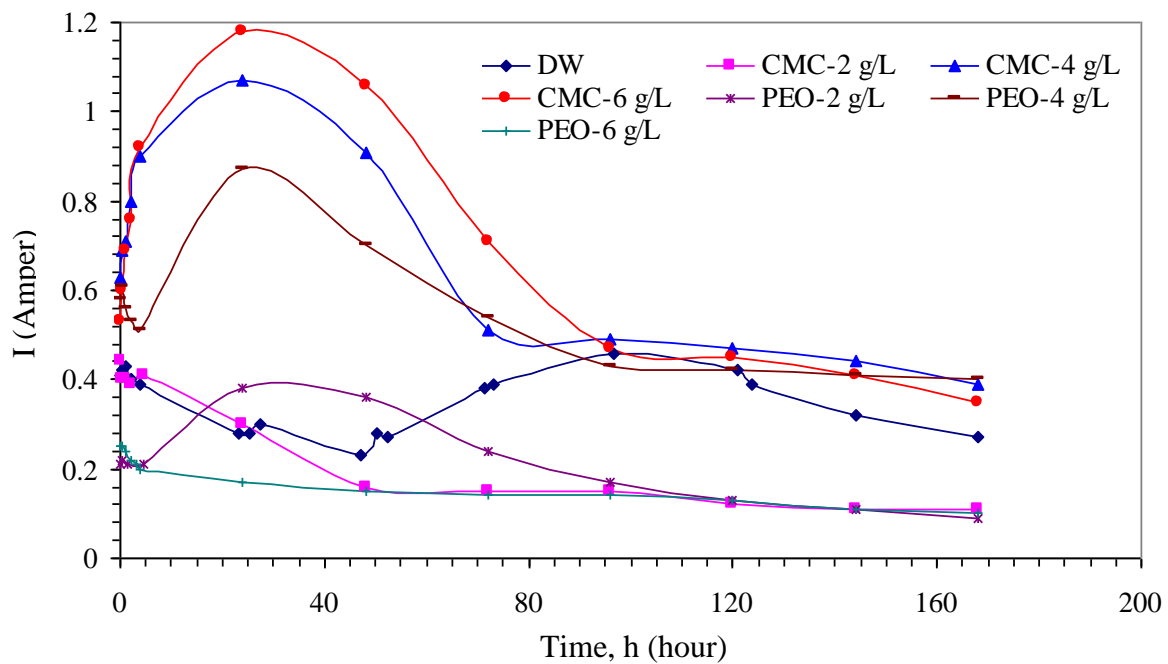
**Fig.3.** Variations of EC with time. DW=Distilled water, A=Anode, C= Cathode



**Fig.4.** Discharge fluid of cathode with time. DW= Distilled water

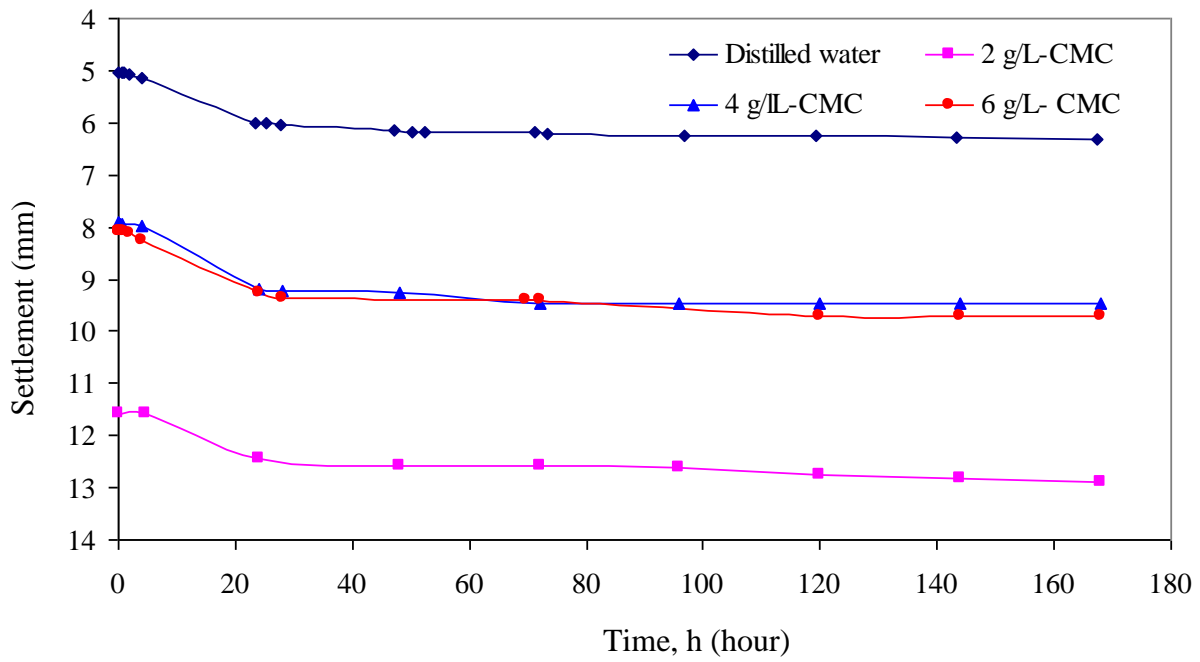


**Fig.5.** Variations of  $K_e$  with time during different tests. DW= Distilled water

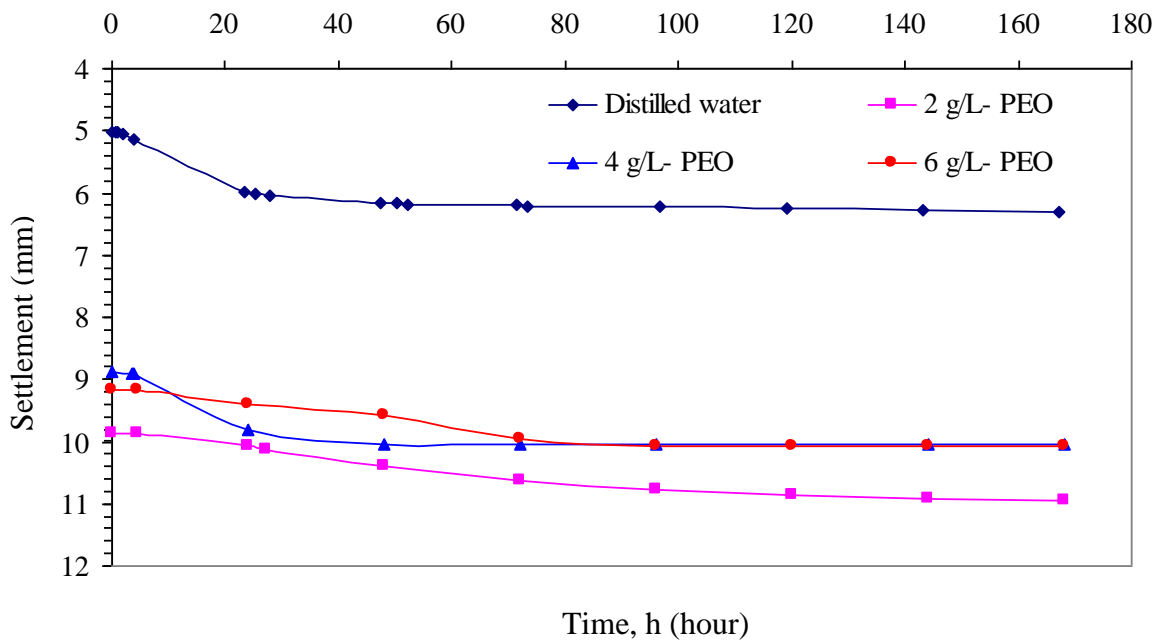




**Fig.6.** Variation of current intensity with time during different tests. DW= Distilled water

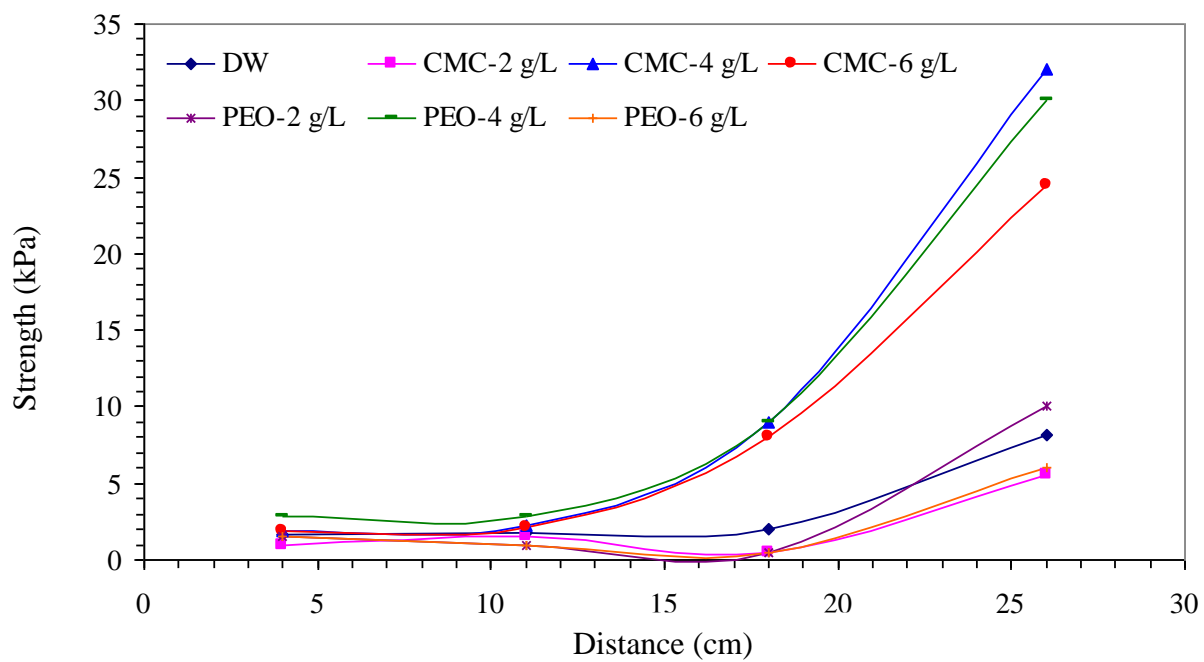


(a)

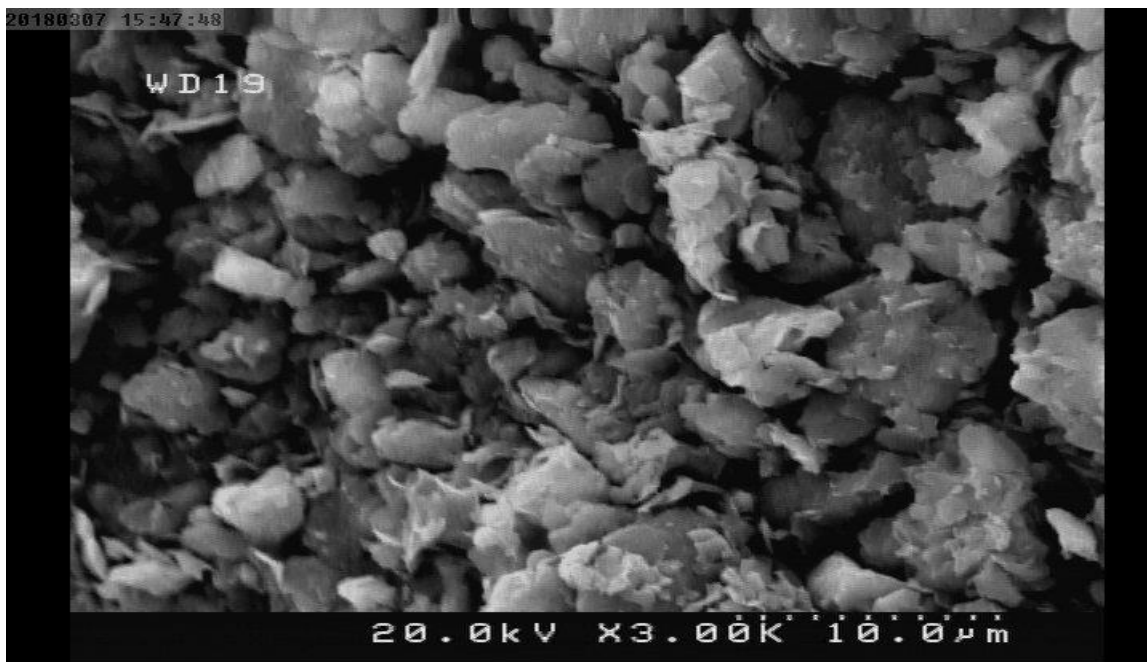


(b)

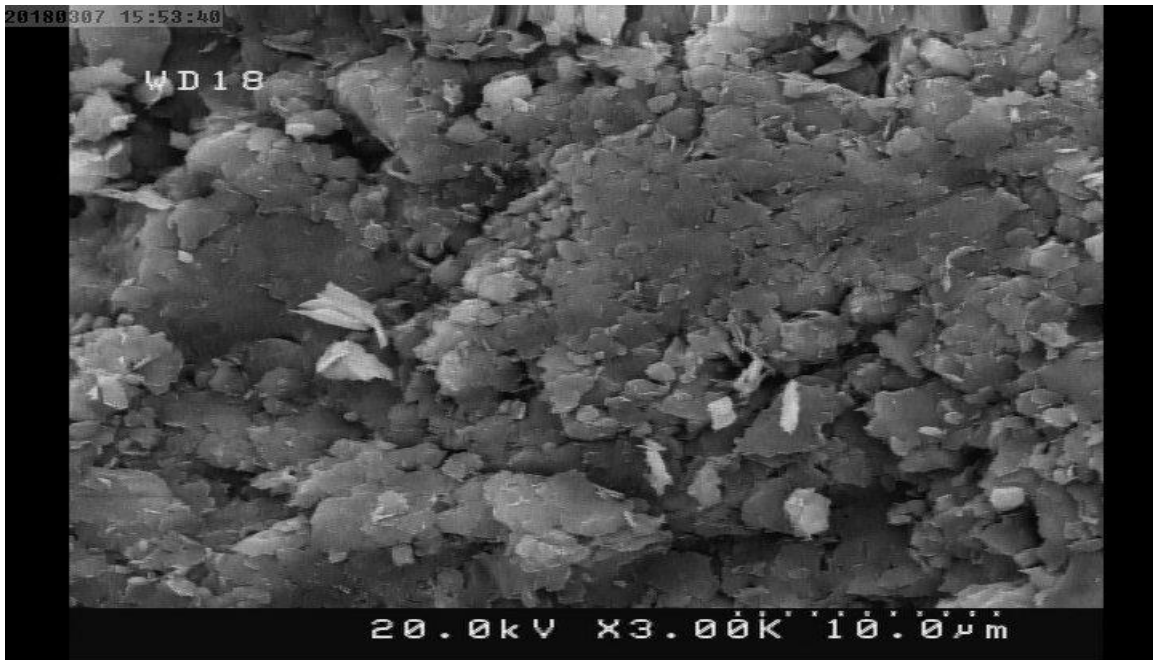
**Fig.7.** Settlement with time, a: CMC solution, b: PEO solution



**Fig.8.** Variation of strength along the sample

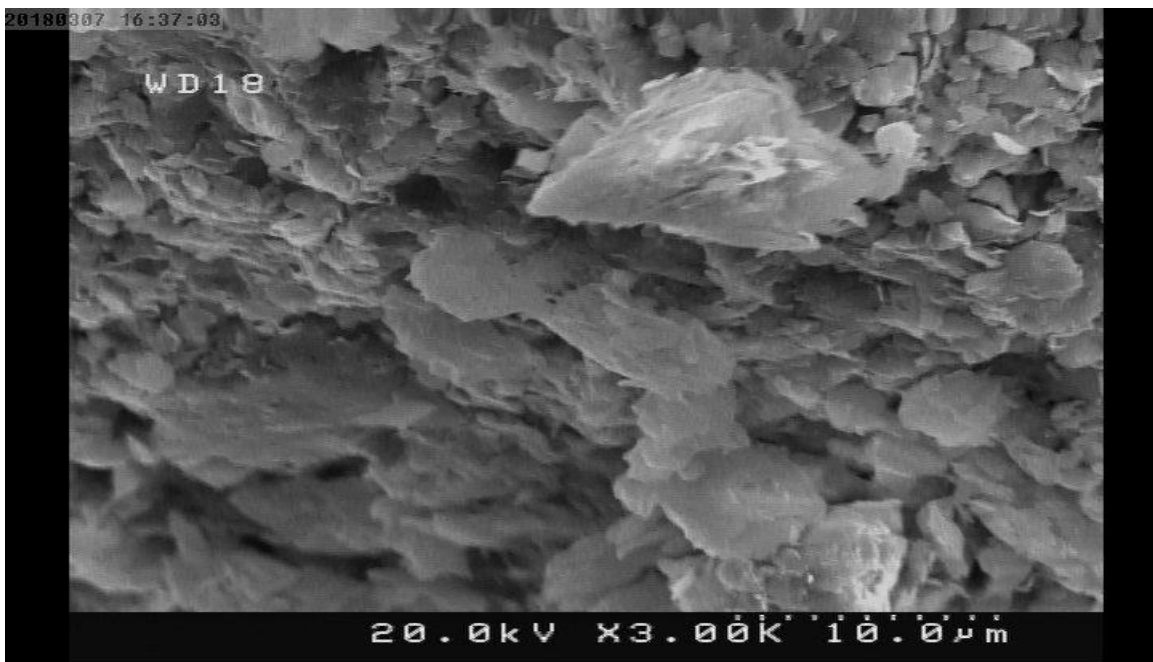


(a)- Anode

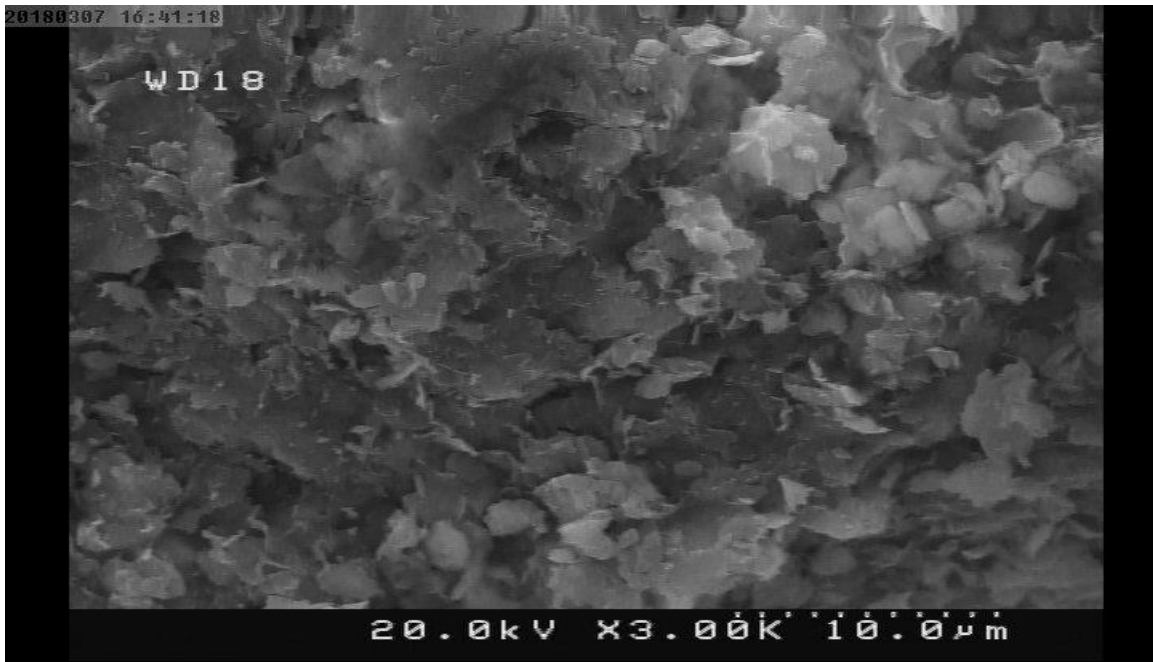


(b)- Cathode

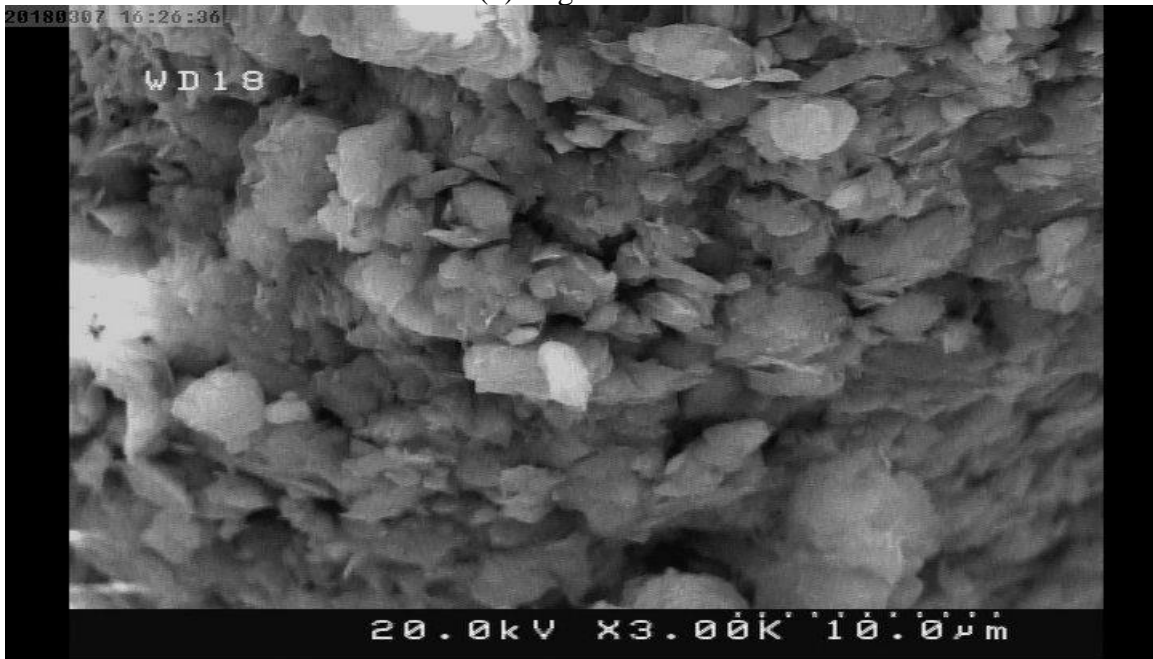
**Fig.9.** Scanning electron microscope micrograph for distilled water. (a): anode, (b): cathode



(a)- 2 g/L PEO

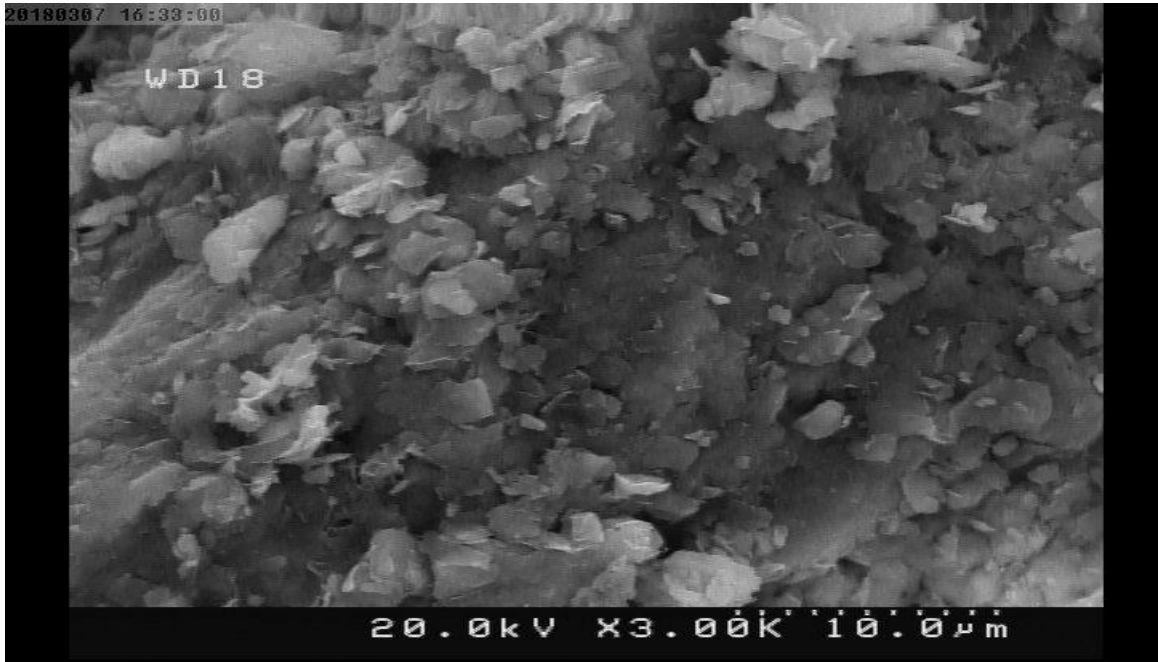


(b)- 4 g/L PEO

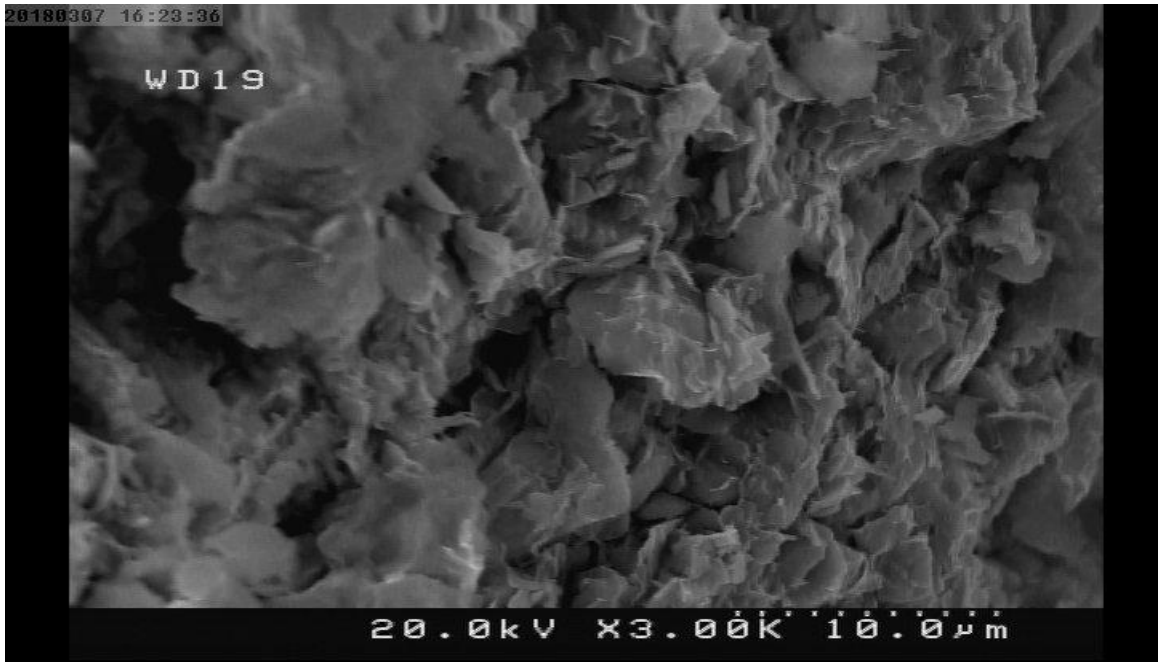


(c)- 6 g/L PEO

**Fig.10.** Scanning electron microscope micrograph for PEO solution. at cathode (a): 2 g/L, (b): 4 g/L, (c): 6 g/L



(a)- 2 g/L CMC



(b)- 6 g/L CMC

**Fig.11.** Scanning electron microscope micrograph for CMC solution. at cathode. (a): 2g/L.  
(b): 6 g/L

**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	53.3
Plastic limit, PL (%)	ASTM D 4318-10	26.1
Plastic index, PI (%)	ASTM D 4318-10	27.2
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	Amount	Chemical component	Amount
pH	8.0	Mg <sup>2+</sup> (meq/L)	10.0
EC <sup>a</sup> (mmhos/cm)	10.74	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. <sup>b</sup> (%)	0.11

a-Electrical Conductivity

b- Organic content

