Effect of Various Parameters on Electrokinetic Dewatering of Saturated Clay

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Abstract. Electrokinetic dewatering is an effective method to remove water from saturated clay having low hydraulic conductivity. This performs better than other dewatering methods like sand drains, prefabricated vertical drains, vacuum dewatering etc. In electrokinetic dewatering low intensity direct current is applied across the soil layer through electrodes, thereby accelerating the flow due to changes in physio-chemical processes. In the present study, a series of laboratory experiments were performed on saturated clay collected from Lunawada region of Gujarat to study the effect of various parameters on electrokinetic dewatering. A water tight wooden box (40 cm x 40 cm x 30 cm) was used to perform the experiments. Hollow circular stainless steel tubes (length = 25 cm and inner diameter = 1.9 cm) were used as electrodes. Perforations with diameter of 5 mm were provided on electrodes at regular intervals to allow and collect water from surroundings during the experiments. Efficiency of electrokinetic dewatering was studied under variations of voltage, electrode spacing and pH. Water collected at cathode was removed manually from top at cathode and the quantity was measured. The results confirm that dewatering efficiency increases with an increase in voltage as water flows under greater electric gradient at higher potential difference. The decrease in centre to centre spacing between anode and cathode causes overlapping of electric field which enhances dewatering efficiency. Decrease in pH of soil causes soil to be more acidic in nature that results in less dewatering efficiency. Further, cracking patterns near anode for each series of experiments was also studied to enhance the understanding of electrokinetic dewatering. It is confirmed from the experiments that Electrokinetic dewatering is greatly influenced by voltage, electrode and pH. Other parameters like electrode pattern, type of soil, type of electrodes, etc. can also be evaluated for better understanding of Electrokinetic dewatering.

Keywords: Electrokinetic dewatering; Direct current; Stainless steel electrodes; Polarity reversal

1 Introduction

It is a challenging task for geotechnical engineers to provide safe and economical design of foundations resting on weak/poor soil. Stability and settlement problems for constructions on such weak soils make it mandatory to improve the soil. There are many methods of ground improvement that have been performing good in the field including chemical stabilization, surface and deep soil treatment techniques, preloading with installation of vertical drains etc. Each method has some limitations due to which it is not applicable for a particular soil. Electrokinetic dewatering is one of the best methods to remove water from soil effectively. It is the application of electric current to the soil through electrodes that are inserted into the saturated soil. Water transfers from anode to cathode via electro-osmosis. The amount of the water drained out from cathode will be equal to the soil consolidation if additional water or solution is not injected into soil through anode. Reuss (1809) first reported Electro-osmosis. The flow of water through the soil or porous medium is induced by electrical energy that causes due to the thermal or hydraulic gradient. For consolidating different types of soils, electrokinetic stabilization is an innovative method. This also includes soils that possess very high initial water contents in the form of slurry. Although there are various potential applications of electrokinetic stabilization, most of the studies have focused only on soil dewatering, desalination, decontamination and electro-osmotic consolidation. More recently, numerous field applications like electro-osmotic consolidation technique combined with vertical drains and new innovative geosynthetic electrodes found to give best results.

Electrokinetic stabilization is the process of chemical grouting and electro-osmosis. It is most effective method for strengthening of soft clay. Electrokinetic stabilization suits for weak clayey soils which have low hydraulic conductivity and require strengthening (Azhar et al., 2017). Electrokinetic application is affected by certain factors like soil type, zeta potential, pH, temperature, water content, soil salinity, electrical resistivity and conductivity, type of electrodes. Soil with high organic content exhibits a better response to electro-osmotic consolidation. Higher the negative zeta potential, the water has greater tendency to flow through soil mass. Zeta potential is inversely proportional to the applied voltage. Soil pH greater than or equal to 7 gives better electrokinetic consolidation. When temperature is high; it causes a loss of electric contact between soil and electrodes. If soil salinity increases zeta potential reduces and this can reduce the electro-osmotic flow. Methods to improve efficiency of electrokinetic consolidation are intermittent current, polarity reversal and anode depolarization method (Malekzadeh et al., 2016). The value of current decreases and pH increases as time passes when dredged sediment was treated by electrokinetics (Reddy et al., 2006).Laboratory experiments conducted using actual dredged sediments obtained from the Indiana Harbor to determine the extent of electro-osmosis and consolidation using Graphite electrode and ionic flocculent. It was observed that with ionic flocculent higher final dewatering is observed.

The traditional methods can be applied on soils which have low to medium plasticity index as given by international standards. But, where the improvement is needed most fine-grained soils are excluded because these pose the greatest problem for the undesirable properties of soil (Abdullah et al., 2010). In dewatering by electrokinetics, shorter pumping interval resulted in more volume of water draining out due to reduction in water head in the drainage pipe. There was 44-46% decrease in the drained volume of water in the test with polarity reversal. The reduction in water content was more in test beds with cement columns compared to those with lime columns. Lime and cement columns had an influence on the undrained strength (Kaniraj and Yee, 2011). Electro-osmosis method combined load with cathode vacuum drainage in the cathode could drain away more water in less time and achieve more settlement, and the ultimate rate of outflow of water is 1.4 times as large as that in traditional electro-osmosis test. It was recorded that after the electro-osmosis method combined load with cathode vacuum drainage in the cathode conducted, the undrained shear strength of soil is higher; besides, the water content is lower and undrained shear strength is about 1.8 times of soil strength consolidated by the traditional electro-osmosis. It was observed that the soil settlement in horizontal direction of electro-osmosis method combined load with cathode vacuum drainage in the cathode is more uniform than that of traditional electro-osmosis and electro-osmosis method combined load (Liu et al., 2016). Jeyakanthan et al. (2011) presented a design of an electro-osmotic Tri-axial testing apparatus suitable for electro-osmotic treatment of high plasticity black clay and for measuring electro-osmotic permeability and generated pore-water pressure, as well as a testing procedure that accounts for the contribution of electro-chemical changes in the improvement of soil properties. Experimental apparatus was modified from a Standard Tri-axial apparatus. The flow rate depends on the coefficient of electro-osmotic permeability which varies with the void ratio and different voltage gradients. The strength improvement due to electro-osmotic treatment is due to electro-osmotic consolidation and electrochemical changes (ex. cementation, bonding, changes in soil properties due to electro-osmosis. Laboratory study was carried out by Flora et al. (2016) on fine grained dredged sediment (one from the port of Gaeta, and the other one from the Basento River). It was observed that reduction of void ratio and the speeding up of the dewatering process due to the beneficial effect of the electric field is striking for the Basento material, while Gaeta material obtained minor effect. So, the finer and more plastic material is sensitive to the application of the electric field. Further, study is necessary to analyze effect of different potential gradients, orientation of electrodes, and variation of pH. To increase the productivity of this method, techniques like intermittent current, polarity reversal and anode depolarization must be checked for its applicability. The aim of this study is to evaluate the use of electrokinetic dewatering in soft clay and examine the effect of various factors like potential difference, spacing, pH and reversal of polarity on electrokinetic dewatering.

2 Materials used in the Present Study

2.1 Soil

The material used in the present study is obtained from Lunawada region of Gujarat state. Series of laboratory tests were performed to know the various properties of soil like; specific gravity, Atterberg's limits, particle size distribution, compaction characteristics, etc. (Table 1). Soil used for the experiments was first of all oven dried for 24 hours. Lumps of clay was broken in to smaller sizes using wooden hammer. Soil passing through 4.75 mm sieve was separated and used to perform experiments. Moisture content of soil for all the experiments was kept equal to its liquid limit by adding distilled water and it was mixed properly and poured in the box.

Table 1. Physical properties of soil

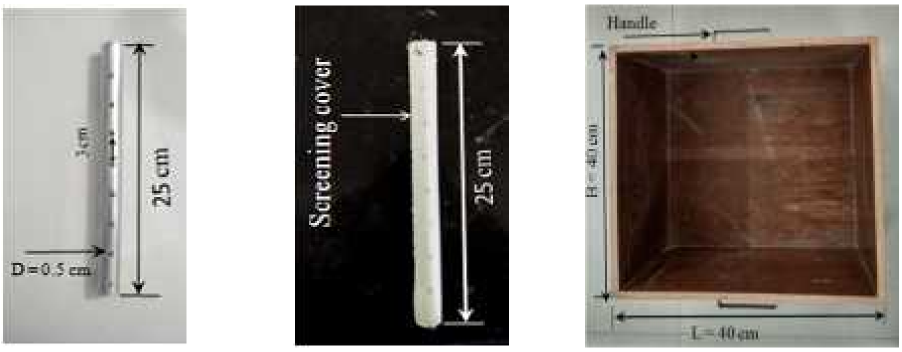
Property	Value	Unit
Specific Gravity (G_S)	2.45	-
Liquid Limit (LL)	38	%
Plastic Limit (PL)	24	%
Shrinkage Limit (SL)	21.94	%
Plasticity Index (PI)	14	%
Maximum Dry Density (MDD)	1.68	gm/cm^3
Optimum Moisture Content(OMC)	19.14	%

2.2 Electrodes

For providing potential difference metal electrodes were used. On the basis of review on the most popular used metal electrode by Malekzadeh et al. (2016) stainless steel electrodes were decided (Fig. 1a). Stainless steel electrodes are less susceptible to corrosion compared to copper, aluminium and other steel electrodes. Copper and aluminium electrodes cause the contamination of soil. Compared to titanium electrodes, stainless steel electrodes are less costly. Electrode was prepared by cutting the stainless steel pipe in pieces of length 25 cm. There were 8 electrodes prepared of same length; the diameter of electrode was 1.9 cm (0.75 inch). As collection of water was done from electrode itself so 5 mm holes were drilled on electrodes using drill machine. Total numbers of holes on each electrode were 24; Holes were made on each electrode in staggered pattern. To avoid clay particles entering in to the electrode along with water, electrodes were covered with cotton cloth along the length and at bottom (Fig. 1b). Total area of electrode was 70.88 cm^2 and effective area of each electrode was 66.17 cm^2.

3 Procedure to Perform Electrokinetic Dewatering

The setup for electrokinetic dewatering and dimension of box and electrodes was designed. It requires DC supply for performing electrokinetic dewatering. The setup was prepared for performing the electrokinetic dewatering with dimensions of box 40 cm x 40 cm x 30 cm (Fig. 1c) considering reference of Fourie et al. (2010) who performed electro-osmotic dewatering on clay. The box was prepared using wooden sheet with two metal handles for better handling. For providing water tightness to the box, water proofing gel was applied on inner surface area of box. The water tightness was checked by filling the water in it for 24 hours to observe if any leakage is present.

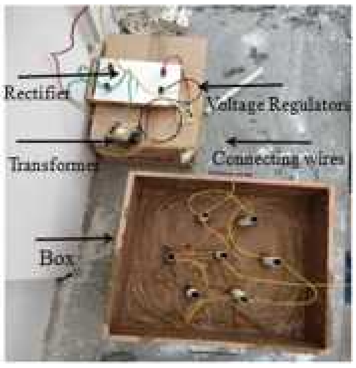


a) Electrode with perforations b) Electrode with filter c) Wooden box

Fig.1. Details of test box and electrode preparation

For providing various DC voltages various electric supplies were needed. A transformer (12V, 3A) was used to step down the AC voltage. Rectifier was used to convert the AC voltage to DC voltage. Breadboard and voltage regulators 7809, 7812 and 7806 were used to regulate the voltage. A syringe of 20 ml connected with tube was used to collect water manually from electrodes. Length of tube was sufficient to reach the bottom of electrodes (Fig. 2a). After making all the arrangements for electrokinetic dewatering the prepared soil was poured in the box. Configuration of electrodes was decided to be hexagonal as reported by Glendinning et al. (2007). Total seven electrodes were used in this study, out of which 6 were anodes and 1 was cathode (Fig. 2b). The water collected at cathode is pumped out manually at each hour by syringe and tube for 24 hours. As it was not possible to collect water continuously for 24 hours manually, so it was collected for first six hours and last 6 hours. The experiments were performed to study four factors; i) effect of potential differences, ii) effect of spacing between electrodes, iii) effect of polarity reversal and iv) effect of different pH of soil. Summary of the test series is provided in Table 2.

a) Syringe with capillary to draw water



b) Experimental setup

Fig. 2. Experimental setup for electrokinetic dewatering

Table 2. Summary of series of experiments

Series	Parametric study	Group of tests with test legends	Parameters varied for the tests	Parameters maintained constant
A	Effect of voltage	EKD-1,EKD-2,EKD-3 & EKD-4	Voltage = 1.2V,1.5V,1.7V and 10V	c/c spacing= 12 cm, Anodes-6,Cathode-1
B	Effect of spacing of electrodes	EKD-1,EKD-5 and EKD-6	c/c spacing = 10cm 12 cm and 14cm	V = 1.2V and Anodes-6,Cathode-1
C	Effect of polarity reversal	EKD-4 and EKD-7	Anodes - 1 & 6 Cathodes -1 & 6	V = 10V and c/c spacing= 12cm
D	Effect of pH	EKD-4,EKD-8 and EKD-9	pH =8.5 and 8.0	V= 10V, c/c spacing = 12cm,Anodes-6, Cathode-1

4 Results and Discussions

4.1 Effect of potential difference (Series - A)

Series of experiments were performed at different voltages. Based on availability of voltage regulators it was decided to perform experiments at voltages 1.2, 1.5, 1.7 and 10. Figure 3 shows variation in volume of water collected at various time intervals for different potential differences. It was observed that with the increasing potential difference amount of water collected increases. Volume of water collected at cathode increases with increase in potential difference because at higher potential difference water flows under high electric gradient.

The width and length of cracks were determined by using Image J software. In this, a known distance of electrode inner diameter (19 mm) is marked by a straight line and the scale is set in ‘Image J’ Software (2019). This procedure is repeated for each and individual figure. Once a scale is set in ‘Image J’ Software then unknown distances can be determined easily. Figure 4 depicts the cracks observed near anode after 24 hours of dewatering. For 1.2 voltage, crack width of 1.18 mm was observed (Fig. 4a) and for 1.5 voltage it was 1.3 mm (Fig. 4b). However, crack width of 2 mm was observed for 1.7 voltage (Fig. 4c) and 3.05 mm for 10 voltage (Fig. 4d). It can be clearly seen that for higher voltage difference, the length as well as width of the crack were on the higher side as compared to low voltage difference.

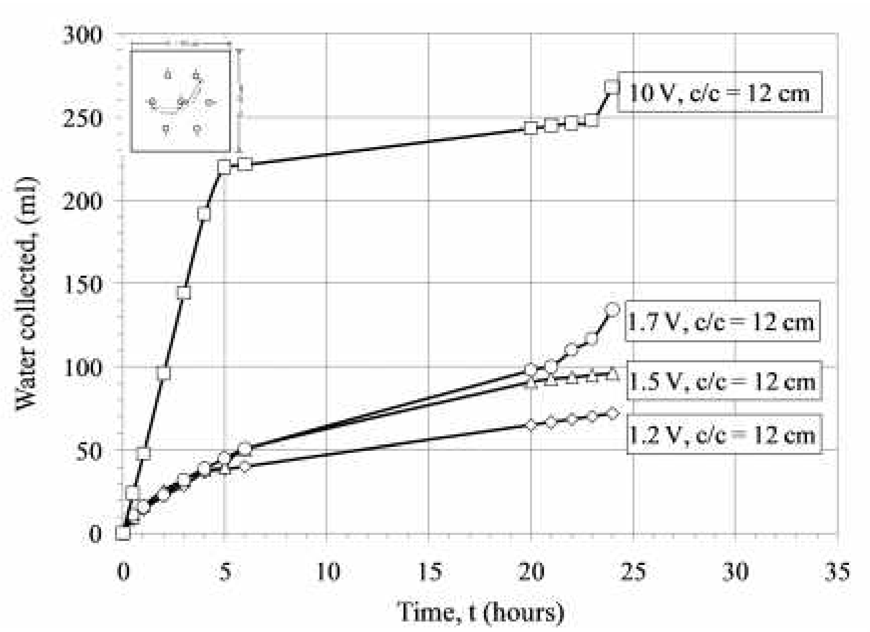
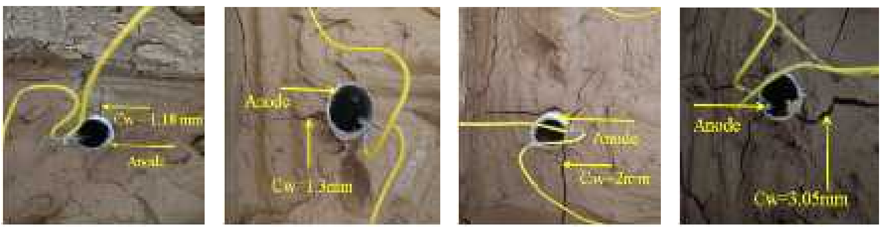


Fig. 3. Water collected at various time intervals



a) V = 1.2V b) V = 1.5V c) V = 1.7V d) V = 10 V

Fig. 4. Cracks observed after 24 hours at anode for various voltages

4.2 Effect of various spacing of electrodes (Series - B)

Experiments were performed by varying centre to centre distance between anode and cathodes by 100mm, 120mm and 140mm respectively. A hexagonal configuration, 6 anodes and 1 cathode was used. Potential difference of 1.2Volt was kept constant for all the experiments in series B. Volume of water collected at cathode with various time intervals for different centre to centre spacing of anode and cathodes is shown in Fig. 5. It was observed that, with the decreasing centre to centre distance between anode and cathode, collection of water increases because electric field of electrodes overlaps more and thus resulting in more draining of water.

Cracks were observed at anodes after 24 hours electrokinetic dewatering for different spacing of electrodes (Fig. 6). For c/c spacing of electrodes equal to 140 mm, maximum crack width of 1.05 mm was observed (Fig. 6a) and when c/c spacing of electrodes equal to 120 mm was maintained, maximum crack width of 1.15 mm was noticed (Fig. 6b).Further, maximum crack width of 2.45 mm was found out for c/c spacing of electrodes equal to 100 mm (Fig. 6c). The width of crack was observed to be high for shorter spacing between anode and cathode. It is due do quick and maximum removal of water from anode to cathode.

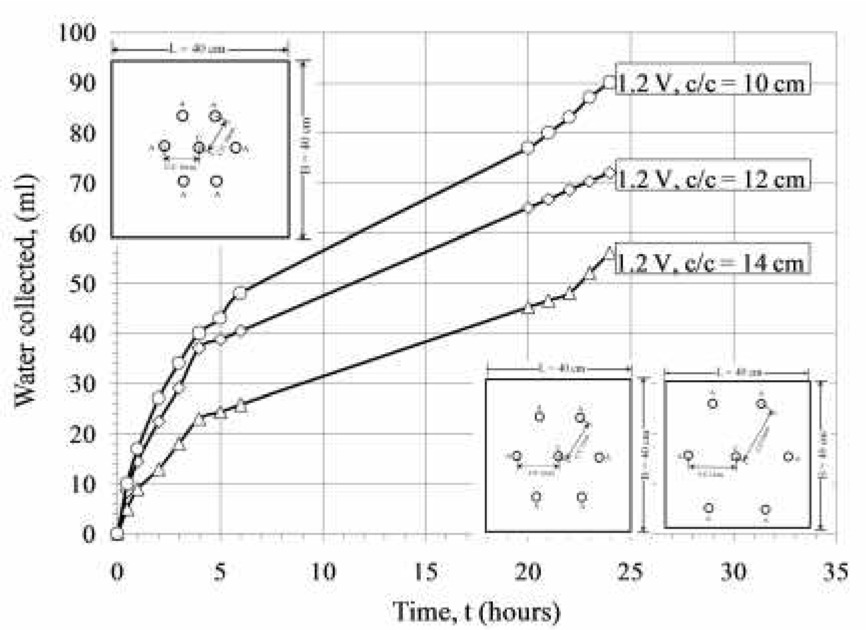
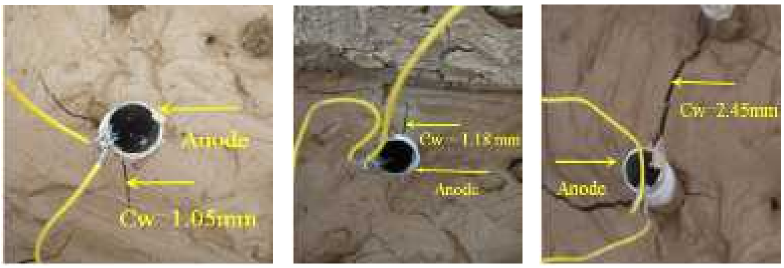


Fig. 5. Water collected at various time intervals



a) c/c =140 mm b) c/c = 120 mm c) c/c = 100 mm

Fig. 6. Cracks observed after 24 hours at anode for various spacing pattern

4.3 Effect of polarity reversal (Series - C)

Experiments were performed by changing the number of anodes and cathodes. First experiment was performed using 6 anodes and 1 cathode. Cathode was kept at the centre of box and anodes were placed at equidistant from cathode. Anodes were placed in hexagonal pattern and at distance 120mm from cathode. Second experiment was performed using 6 cathodes and 1 anode. Anode was kept in centre of box and cathode was placed at equidistant of 120mm. The voltage for both the experiments was kept constant as 10V.

Volume of water collected at different time intervals for two configurations; (i) Case1:6 cathodes and 1 anode, (ii) Case 2:1 cathode and 6 anodes are shown in Fig. 7. It can be clearly seen that for case 1 (6 cathodes and 1 anode), water collected is less as compared to case 2 (1 cathode and 6 anodes). It is because water moves from anode to cathode with high gradient when numbers of anodes are more. Water molecules will get highly charged due to overlapping of electric field.

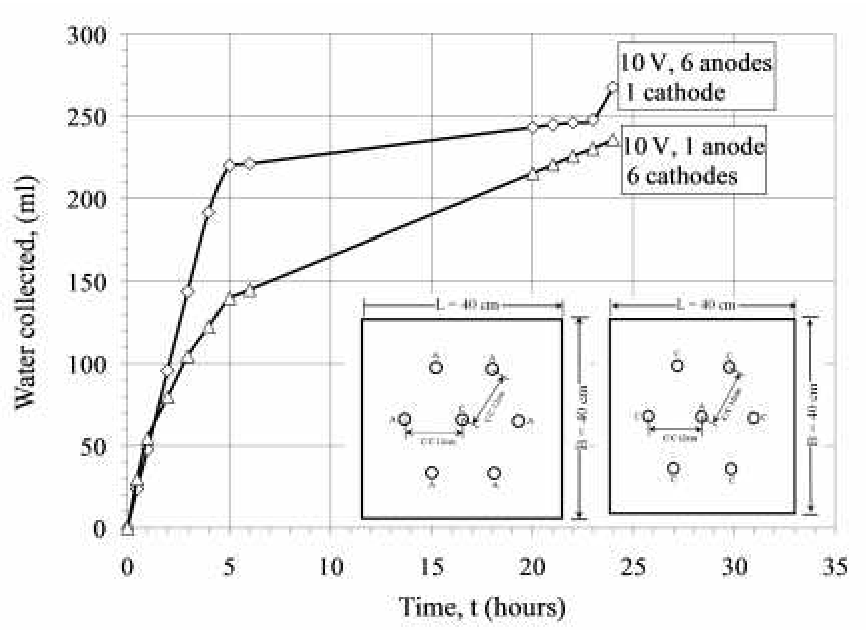


Fig. 7. Water collected at various time intervals

4.4 Effect of various pH of soil (Series - D)

The electrokinetic dewatering tests were performed on different value of pH of soil like 9.5, 8.5 and 8.0. Soil pH was changed by mixing sulphuric acid. First a trial was made for changing the pH of soil on 100 gm and then based on calculations, sulphuric acid was added to the soil for changing its pH as per guidelines provided by IS2720 (P-26) 1987. Soil pH was measured using pH meter. For measuring the pH of soil, 30 gm of soil was taken and mixed with 75ml of distilled water using glass rod and then pH was measured. As can be seen from Fig.8, total volume of water collected at various time intervals decrease with increase in pH of the soil. This confirms that the value of pH of soil should be kept high to remove water from soil at a higher rate.

Figure 9 shows images obtained at anode after 24 hours of electrokinetic dewatering for different pH values of soil. Maximum crack width of 3.05 mm was observed at anode when pH of soil was 9.5 (Fig. 9a) and 1.82 mm for soil with pH of 8.5 (Fig. 9b). However, when pH of soil was maintained to be 8, maximum crack width was obtained to be 1.4 mm only (Fig. 9c). The width of crack was observed maximum when pH of soil was maintained on the higher side. Rate of dewatering increases with increase in pH of soil.

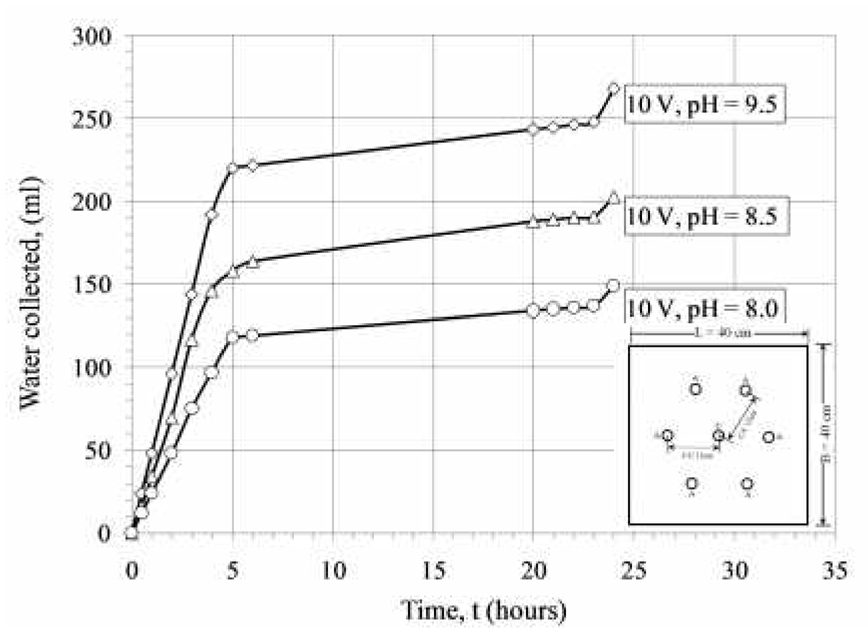
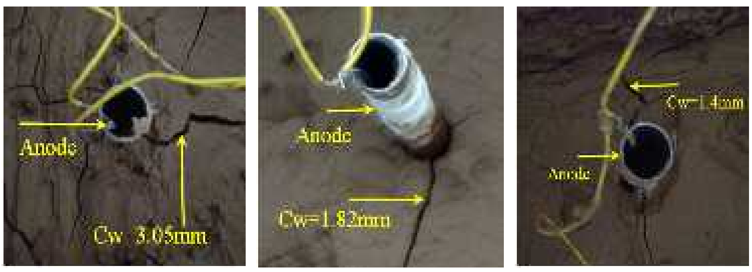


Fig. 8. Water collected at various time intervals



(a) pH = 9.5 b) pH = 8.5 c) pH = 8.0

Fig. 9. Cracks observed after 24 hours at anode for various pH values of soil

5 Conclusions

Different series of experiments were performed to study the influence of various parameters on the performance electrokinetic dewatering. Based on the results obtained from experiments, the following conclusions can be drawn.

1. Amount of water collected at cathode increases with increase in voltage difference for constant spacing and configuration of electrodes. It is because at higher potential difference water flows under greater electric gradient. Width of cracks developed at anode increases with increase in voltage difference because

maximum quantity of water is moving from anode to cathode when voltage difference is high.

2. It was found that amount of water collected at anode decreases with decrease in pH of soil, for constant spacing of electrodes, configuration of electrodes and voltage. Width of cracks developed at anode decreases with decrease in pH of soil.
3. By varying spacing of electrodes it was found that amount of water collected at anode increases with the decrease in spacing. It is due to overlapping of electric field of two electrodes which results in more draining of water. The width of cracks increases with decrease in spacing that causes more draining of water from anode to cathode.
4. For constant voltage and spacing of electrodes, polarity reversal gives reduction in water collection. It is because water moves from anode to cathode and with 6 anodes more water will move towards the cathode. In second case water from 1 anode moves towards 6 cathodes so water collection is less. Width of cracks developed at anode decreases after reversing the polarity.

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