IGC-2018
Indian Geotechnical Conference
Indian Institute of Science, Bengaluru | 13-15 December 2018

Electro-osmosis: A review from the past

Amal Azad Sahib[1],Bushra I[2], Rejimon G[3]
[1]*Assistant Professor in Civil Engineering, TKM College of Engineering, Kollam (Currently Research Scholar, IIT Madras)*
[2]*Formerly Professor in Civil Engineering, TKM College of Engineering, Kollam*
[3]*Instructor in Electrical and Electronics Engineering, TKM College of Engineering, Kollam*

ABSTRACT

Electro-osmosis is a powerful technique, as a means of dewatering soils of high compressibility and moisture content. Electro-osmosis is an established technique and has been investigated by many researchers as long as a century ago.

The treatment factors that contribute to the effectiveness of electro-osmotic consolidation are: type of electrode, voltage gradient, polarity reversal, current intermittence, and duration of treatment. Copper, mild steel and stainless steel in different shapes and forms have been used as electrodes. Electrokineticgeosynthetics (EKG) used in electro-osmotic consolidation applications provide electrokinetic function in addition to the filtration and drainage functions. The EKG electrodes are less susceptible to corrosion due to the polymeric cover or treatment against corrosion. Even though most studies claim the effectiveness of this technique, the procedure is not widely accepted in the industry due to the risks and costs involved. This paper aims to review the suitability of this technique on soils around the world. Also, this paper looks closely into the properties of the soil that make it ideal for the success of this technique. With reference to Indian soils, the results of electro-osmosis studies on Kuttanad clay, are presented

1 INTRODUCTION

From its inception since 1949, electro-osmosis is recognized as a technique that holds vast potential to improve water-logged clayey soils (Casagrande, 1949;Gray and Mitchell, 1967;Golenko, 1971; Chappel and Burton, 1975;Wan and Mitchell, 1976; Gray and Somogyi, 1977;Lo et al., 1991;Shang and Masterson, 2000;Hamir et al., 2001;Chew, et al., 2004; Rittirong et al., 2008). Though the efficiency is highly questionable based on the parameters trialed for various soils, researchers around the world continue to bring out theories that influence the efficiency of this technique.

Electro-Osmosis is unison of many mechanisms such as electrophoresis, dielectrophoresis, electrokinetic migration and electrochemical hardening. In an electrokinetic dewatering process, the two phases that dominate are electrophoretic sedimentation and electro-osmotic consolidation (Shang, 1997). Electrophoresis is the phenomenon by which negatively charged ions (in this case clay) are attracted to positively charged electrode (anode). The movement of water, under a DC potential, from positive (anode) to negative electrode is termed as electro-osmosis.

Electro-osmosis (EO) is the most useful of the electrokinetic processes activated with EKG because it holds the potential to overcome the limitations of very slow and in some cases effectively zero hydraulic flow in fine-grained, low permeability materials such as silts and clays.

2 SOIL PARAMETERS GOVERNING EO

Electro-osmosis is fundamentally governed by the cation-anion distribution and water-ion distribution. The better the co-ion (the ions in the external solution phase, a few of which invade the internal solution phase) exclusion, less affected is the electro-osmotic flow by salinity increases in pore water. Co-ion exclusion can be enhanced by a fixed charge density or cation exchange capacity and low water content. Active clays with high exchange capacity such as illitic and bentonitic soils can effectively exclude co-ions even at high salinity but low concentration of water itself reduces the amount of water moved per unit electrical charge. Inactive clays such as silty and kaolin clays with low exchange capacity at high water content and low salinity would ensure a high electro-osmotic transport but with increase in salinity, the co-ion exclusion falls off rapidly thus reducing the electro-osmotic efficiency (Gray and Mitchell, 1967).

Whereas hydraulic permeability is related to grain size, electro-osmotic permeability is effectively independent of grain size. This means that electro-osmosis can result in flow rates 100 to 10,000 times greater than hydraulic flow in fine-grained materials. In the absence of knowledge about the clay mineralogy, a particle size distribution curve can be used to estimate the proportion of clay that may be present. Absence of clay does not necessarily indicate the lack of potential for electro-osmotic flow. Electro-osmotic flow has been reported in materials such as quartz powder, rock flour, ochre and alum sludge, and in sewage streams including those comprising humic, anaerobic digested, surplus activated and primary sludges. The key factors are the origin and magnitude of the negative surface charges and the salinity of the pore water which would act to compress the double layer and thus minimise the effectiveness of the surface charge. (Jones et al, 2011)

The Electro-osmotic flow, qe, produced by an applied electric field is given by the expression,

$$q_e = k_e i_e A \qquad (1)$$

where k_e is the electro-osmotic conductivity, i_e is voltage gradient and A is cross-sectional area

The electro-osmotic flow velocity, v_e, is given by the expression,

$$v_e = \frac{D\xi\Delta E}{4\pi\eta\Delta L} \qquad (2)$$

wherev_e = electro-osmotic flow velocity, in centimeters per second, ΔE = applied voltage, in volts, ΔL = electrode spacing, in centimeters, η = viscosity, in centipoises,D = dielectric constant of the soil water, and ξ = Zeta potential in volts

Shang (1997) discusses the influence of Zeta potential on the electro-osmotic permeability. By using the Stern–Gouy model, zeta potential can be measured and the effectiveness of a soil type to electro-osmosis evaluated.

Typical electrode and electrolyte properties

Malekzadeh et al. (2017) conducted EK tests using polyaniline coated galvanized steel electrodes. It was found that a 5 V application gave an improvement comparable to soil stabilized by uncoated electrodes with 30 V application; but a 30 V application did not give a proportionate improvement as the coating disintegrated at this voltage gradient.

Xue et al. (2015) tested on Dalian marine sludge using three electrode types and found Iron electrodes to be most effective compared to Copper and Aluminium for this particular soil. This has been concluded based on the gradual decline of voltage and current, the corrosion loss for Iron was consistent with values calculated using Faradays law. The strength improvement was attributed to a cementing action near the anode. The reason for the excess corrosion loss in the other two electrodes was assumed to be due to salinity and acidity. This could have been better supported with pH and conductivity measurements for this soil, which have not been mentioned in the paper. Also the same could be compared to treatments using painted or galvanized electrodes.

Citeau et al. (2011) conducted EK tests on a biscuit factory sludge, with varying conductivity (or salinity) and pH. They concluded that conductivity values around 0.3 mS/cm and slightly acidic pH of 5.3 gave the best results for EK treatment.

Soil cementation due to electrokinetic treatment which has a phenomenal role in the strength improvement is reported to be closely related to the electric field intensity, which in turn is controlled by the electrode layout and applied voltage (Mohamedelhassan et al., 2005; Rittirong et al., 2007). Rittirong et al. (2008) investigated the effects of the electrode configuration based on the electric field analysis of large-scale electrokinetic tests on model caissons embedded in calcareous sand. The pull out resistance of the caissons increased by 90 % and it was concluded that increased electric field intensity on the exterior of the caisson, lowered electric field intensity on the interior and embedding the central electrode below the bottom of caisson can optimize the method.

Chen and Murdoch (1999) conducted EK field tests on illite-smectite clays of Cincinnati, Ohio. A mesh made from Titanium, coated with metal oxides, 3.1 X 3.4 m was used as the upper anode. The lower electrode, was hydraulic fracture filled with granular graphite, 2.5 m radius. Using an average gradient of 20-31 V/m and current 42- 57 A resulted in a total 2-4 L/ hr infiltration, 0.6-0.8 L/hr of drainage due to electro-osmosis alone. The pH of soil reduced near the anode and slightly increased near the cathode, the migration of pH was slower than similar fronts in laboratory experiments.

Chew et al. (2004) used electrokineticgeosynthetics (EKG) in lab and field trials on Singapore marine clay. 8 m deep soft clay underlying an 18 m sand fill was subjected to EO treatment using EK drains for two weeks showing ten-fold reduction in time to achieve the strengths compared to conventional PVDs. The total energy consumption was reported as 1.8 kWh/m3. Further an emphasis is laid on high conductance of the EVD, insulation of the shoes and provision of polarity reversal.

Rittirong et al. (2008) conducted a similar field trial on soils of Sarawak, Malaysia to stabilize an access road, the total treatment area being 560 m X 4 m on each side of the existing road. It was divided into sections of 28 m X 4 m each for individual power supply. The electrification period was 20 h daily for five days in each section. Five power supplies were circulated over the treatment area. The total treatment period for the entire area was 14 days. Electro-osmotic flow was found to have ceased in 3 days of the power supply, though polarity reversal procedures were systematically followed. The gas generated at the soil/electrode interface is believed to have acted as an electrical insulator that increases the electrical resistivity which probably diminished the effectiveness of the electrokinetic treatment. The energy consumption was 0.7 kWh/m^3. Table 1 gives a comparison of the power consumed in various EO field trials.

Table 1 Energy consumption in field tests

Project	Electrode material	W (kWh/m3)	Reference
Stabilisation of excavation	Steel	17	Bjerrum et al. (1967)
Stabilisation of shipyard embankment	Steel	0.5	Chappell and Burton (1975)
Slope stability at Kootenay River	Steel	6.7	Wade (1976)
Field test of strengthening sensitive clay	Copper	6.4	Lo et al. (1991)
Improvement of steel pile groups	Steel	1	Milligan (1994)
Tuas land reclamation	EVD	1.8	Chew et al. (2004)
Sarawak road construction	EVD	0.7	Rittirong et al. (2008)

Intermittent current, a two-step procedure-electrophoretic consolidation by top cathode-bottom anode condition and electro-osmotic consolidation by top anode-bottom cathode condition, reversing polarity immediately after electrophoresis, reducing time of electro-osmotic consolidation are some measures to reduce energy consumption (Shang, 1997)

3 RESULTS FROM EO STUDIES ON KUTTANAD CLAY

Kuttanad Clay has gained much significance as a very soft soil with low bearing capacity and large compressibility values. The water logging nature has rendered the area uninhabitable, especially during severe monsoons. The monsoons of 2018 have been particularly the most disastrous in the last 30 years. The authors attempted electro-osmotic studies in the laboratory using Copper rods (Amal and Bushra, 2014) and Copper sheets (Amal et al., 2017) on Kuttanad soil. A 60 V/m application on a 30 cm X 30 cm test tank with 20 cm spacing of electrodes produced 20 kPa undrained shear strength when copper rods were used and 20-25 kPa when copper sheets covering the entire area was used(Fig. 1). This indicates that using intermittent electrodes (rods) would suit more than energy intensive electrode sheets.

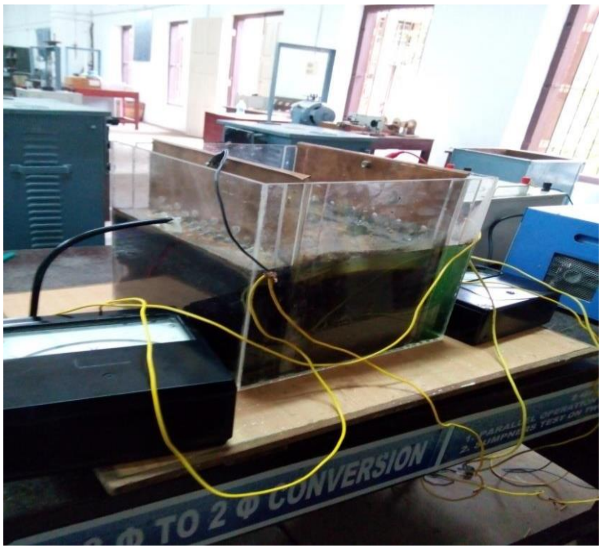

Fig.1 Electro-osmotic set-up 30*30 cm

In the 30 cm X 30 cm mould, when the voltage gradients were varied in independent trials, keeping the spacing between electrodes fixed at 20 cm, there is a clear increase in the rate of improvement (Table 2). The shear strength for 120 V/m treated samples were about 1.3 times and 2.5 times more than the 60 V/m and 20 V/m treated samples. Therefore, it may be inferred that for smaller contact areas, a higher voltage gradient would yield better results whereas for larger contact areas, the optimum voltage gradient need not be a higher value.

Even though the strength improvement is higher for higher voltage gradients in 30*30 mould, the water drained at the cathode reduces slightly with increase in voltage gradient. It may be inferred that the reduction in water content for higher voltages was accelerated due to heating, in addition to the drainage of water at the cathode. As can be seen from Fig. 2, the percentage of water drained by Electro-Osmosis (EO) to the total water drained by self-consolidation and EO is around 42 % for 20 V/m EO whereas it falls to around 32 % for 120 V/m EO. The rate of heating of soils with increased potential gradients seems to be an interesting aspect to be investigated.

Table 2 Results of tests conducted for different voltage gradients on 30 cm X 30 cm mould (20 cm electrode spacing)

Voltage gradient (V/m)	Water collected (ml)		Shear strength @ anode before EO (kPa)	Shear strength @ anodeafter EO (kPa)	I* (A)	P* (kWhr/ m^3)
	After SS*	After EO				
20	105	78	2.2	18.3	0.08	0.56
40	64	34	1.1	21.8	0.1	1.4
60	295	165	2.1	27.3	0.8	17.1
80	300	190	2.9	28.3	1	28.4
100	282	152	1.1	31.5	1.2	42.6
120	172	85	2.4	41.3	2.1	89.6

*SS- Self stabilization, I – Current, P- Power consumed

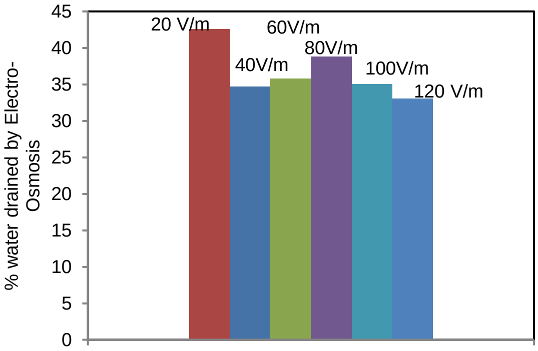

Fig.2 Percentage water drained by Electro-osmosis

Table 3 Results of tests conducted for different voltage gradients on 90 cm X 90 cm mould

Spacing of electrode (cm)	Voltage gradient (V/m)	Shear strength@ anode before EO (kPa)	Shear strength @ anode after EO (kPa)	I (A)	P (kWhr/ m^3)
20	60	2.9	158.4	2.6	6.2
	120	3.6	170.3	5.1	24.2
40	60	3.6	105.7	3.2	15.2
	120	3.9	93.4	6.5	61.6
60	60	2.6	92.5	3	21.3
	120	2.9	83.5	6.4	91
80	60	3.4	90.7	4.1	38.9
	120	3.6	130.9	8.7	165

Table 3 shows the results from tests on a90 cm X 90 cm mould using 60 V/m and 120 V/m for different spacings of electrodes (sheets). The strength improvement for all the combinations are commendable but considering power loss, the voltage gradient of 60 V/m seems more reliable compared to 120 V/m.

The pH of Kuttanad soil in untreated form was 3.7. Table 4 shows the values of pH of the soil after Electro-osmotic treatment. It is observed that near anode, the soil remains acidic and lower than 3.7 and near cathode; there is slight increase in the pH though it remains in the acidic range. However this aspect corrodes the electrode material and hence deters electro-osmosis process. This is evident from the observations of immense power consumption. In field trials this aspect has to be carefully handled.

Table 4 pH measurements after EO trials

Voltage Gradient (V/m)	pH	
	Near Anode	Near Cathode
20	3.2	4.3
40	3.3	4.
60	3.4	3.7
80	3.4	3.8
100	3.2	3.9
120	3.1	4.1

While testing the pH of the Kuttanad soil, the values obtained clearly indicated that the soil is acidic in nature and after the Electro-osmotic stabilization process, its acidity seems to be increasing. This led to the thought that the soil can be used as a battery electrolyte which can replace the present electrolytes that are not at all eco – friendly. Hence an earth battery was prepared by using 1.89 kg of soil in liquid form having 66% water and by using copper sheet as anode and aluminium sheet as cathode in a box of 20x15x7 cm, total weight of cell was 3.5kg (Fig 3). The potential gradient in between the electrodes were measured with a multimeter. Initially from the cell, a potential difference of 0.75V was obtained i.e; without using concentrated Sulphuric Acid. Later, along with the soil, concentrated Sulphuric Acid was added by varying amounts starting from 15% to 30% by an increment of 5%. While adding 30% of Sulphuric acid, 3.48V was obtained which was comparatively higher than that of the commonly used batteries.

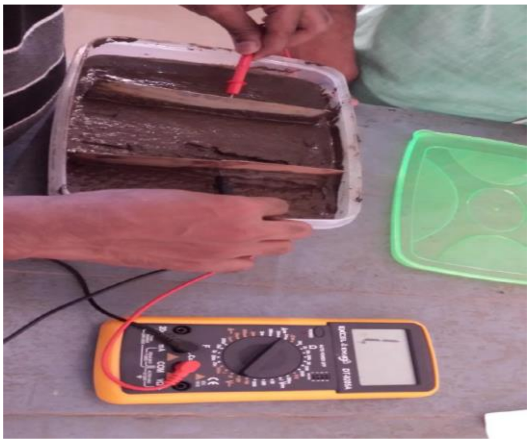

Fig.3 Earth Cell

Table 5 Earth cell results

Concentration of Sulphuric Acid (%)	Voltage Obtained(V)	Current Obtained (mA)
0	0.75	40
15	2.1	110
20	2.7	155
25	3	160
30	3.5	186

It is observed from Table 5 that as the concentration of sulphuric acid increases voltage obtained also increases. Usually a small AA Battery has 1.5V and maximum current output of 1400mA and has a weight of 23g. Lead acid battery has 12.0V and maximum current output 8A (with 38% of Sulphuric Acid) which has a weight of 4kg and size of 15.1 x 9.8 x 9.4 cm. As compared to these batteries the use of Kuttanad soil as a battery electrolyte is limited since the voltage and current obtained are not substantial compared to the size of the cell.

4 CONCLUSIONS

In order to successfully implement the Electro-osmotic technique on field, it is essential to conduct laboratory tests to determine a specific design standard considering various parameters such as pH, type of minerals, salinity, material and type of electrodes, electrode configuration, and voltage gradient. Overall, the effectiveness of this technique can be determined from Zeta Potential values of the soil that give an indication of the electro-osmotic permeability.
With respect to Kuttanad soil, the effectiveness of the technique using two arrangements i) rods ii) sheets were evaluated. Both gave similar strength improvement, power consumption being less for the rods, hence making them more effective.Kuttanad soil that was tested here was already acidic and EO reduced the pH further (near the anode), thus corroding the electrodes and deterring the process.

References

1. Amal, A.S. and Bushra, I. (2014). Suitability of electro-osmosis in Kuttanad Clay. Indian Geotechnical Conference, Kakinada, India
2. Amal, A.S., Bushra, I and Rejimon, G. (2017).Electro-Osmosis Studies OnKuttanad Clay. 6th Indian Young Geotechnical Conference, pp.495-498
3. Bjerrum, L., Moum, J. &Eide, O. (1967). Application of electro-osmosis to a foundation problem in a Norwegian Quick Clay. Geotechnique,17, No. 3, 214–235.
4. Casagrande, I. (1949). Electro-osmosis in soils. Géotechnique, 1(3): 159–177.
5. Chappell, B.A. and Burton, P.L. (1975) Electro-osmosis Applied to Unstable Embankment.*Journal of Geotechnical Engineering Division*, ASCE, 102(GT8), pp. 733-740
6. Chew, S.H., Karunaratne, G. P., Kuma, V.M., Lim, L.H., Toh, M.L. and Hee, A.M. (2004). A field trial for soft clay consolidation using electrical vertical drains. *Geotextiles and Geomembranes*, 22, 17–35
7. Citeau, Morgane& Larue, O &Vorobiev, Eugene. (2011). Effect of electrolytes content on the electro-osmotic dewatering of agro-industrial sludge. Proceedings of the 11th International Congress on Engineering and Food. May 22-26, Athens, Greece.
8. Colin J.F.P. Jones, John Lamont-Black, Stephanie Glendinning (2011) Electrokineticgeosynthetics in hydraulic applications. Geotextiles and Geomembranes. 29 (4), pp 381-390
9. Golenko, N.A. (1971). Electro-Osmotic and Hydraulic flow in soils with a varying

porosity.*Fundamenty i MekhanikaGuntov*, No.1, pp.23-25

10 Gray, D.H. and Mitchell, J.K (1967). Fundamentals Aspects of Electro-osmosis in Soils.*Journal of Soil Mechanics and Foundation Division, ASCE* 93(SM6), pp.209-236

11 Gray, D.H. and Somogyi, F. (1977). Electro-Osmotic Dewatering with Polarity Reversals.*Journal of Geotechnical Engineering Division, ASCE* (GT1),pp.51-54

12 Hamir, R.B., Jones, C.J.P.F. and Clarke, B.G. (2001). Electrically Conductive Geosynthetics for Consolidation and Reinforced Soil.*Geotextiles and Geomembranes*. Vol.19, pp.455-482

13 Jiann-Long Chen, and Larry Murdoch(1999). Effects OfElectroosmosis On Natural Soil: Field Test. J. Geotech. Geoenviron. Eng., 1999, 125(12): 1090-1098

14 Lo, K.Y., Ho, K.S. and Inculet, I.I. (1991). Electro-Osmotic Strengthening of soft, sensitive clays.*Canadian Geotechnical Journal* 28, pp.62-63

15 Malekzadeh,M.,SivakuganN., KazumO., Mathan B.(2017). Effect of polyaniline-coated galvanized steel electrodes on electrokinetic sedimentation of dredged mud slurries. Canadian Geotechnical Journal, 54, pp 1150-1157

16 Milligan, V. (1994). First application of electro-osmosis to improve friction capacity: three decades later. Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi, India, Vol. 5, pp. 1–5.

17 Mohamedelhassan, E., Shang, J. Q., Ismail, M. A. & Randolph, M. F. (2005). Electrochemical cementation of calcareous sand for offshore foundations. International Journal of Offshore and Polar Engineering, 15, No. 1, 71–79.

18 Rittirong, A., Douglas, R. S., Shang, J. Q. and Lee, E. C. (2008).Electrokinetic improvement of soft clay using electrical vertical drains. *Geosynthetics International*, 15(5), 369-381.

19 Rittirong, A., Shang, J. Q., Ismail, M. A. & Randolph, M. F. (2007). Effect of electric field intensity on electro-cementation of caissons in calcareous sand. International Journal of Offshore and Polar Engineering, 17, No. 1, 74–79.

20 Shang, J.Q. (1997). Electrokinetic dewatering of clay slurries as engineering covers. Canadian Geotechnical Journal.34 (1), pp 117-133

21 Shang, J.Q. and Masterson, K.L. (2000). An Electro kinetic Testing Apparatus for Undisturbed Soils under in-situ Stress Conditions.*Geotechnical Testing Journal, ASTM*, Vol.23,No.2,pp. 215-224

22 Wade, M. H. (1976). Slope stability by electro-osmosis. In Proceedings of the 29th Canadian Geotechnical Conference, Vancouver, Canada, section 10, pp. 44–66.

23 Wan, T. and Mitchell, J.K. (1976). Electro-Osmotic Consolidation of Soils.*Journal of Geotechnical Engineering Division, ASCE*, 102(GT5), pp.473-491

24 ZhijiaXue, Xiaowei Tang, Qing Yang, Yong Wan & Gang Yang (2015). Comparison of Electro-Osmosis Experiments on Marine Sludge with Different Electrode Materials. Drying Technology, 33:8, 986-995.