

Investigating The Effect of Electro-osmosis On Sandy Soil Near Saturated Conditions

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Abstract- This experiment investigated the effect of electro-osmosis on water and salt movement in soil with potential application in agriculture. A range of voltages were applied for different durations to a sandy soil in an isolated transparent acrylic plastic cell. The tests were performed at voltage gradients 3, 6 and 10 Vcm⁻¹. The measurements included the volume of soil-water extracted from point lysimeters, electrical conductivity of the soil-water, soil-water potential (SWP) and pH value at different voltage gradients. The results showed that the electric field intensity affected the salt distribution from anode to cathode during the application of the direct electric current. Soil-water content was observed rising with increased electric field intensity. The pH of the soil-water has changed due to the effect of electrical field.

Keywords - electro-osmosis; irrigation; electric field in soils

I. INTRODUCTION

Irrigators are increasingly faced with declining water availability and increased competition for water resources. Hence, there is increasing focus on the potential to use more marginal quality (e.g. saline) water for irrigation and to improve irrigation efficiency.

Precision irrigation systems deliver water to only part of the soil surface or root zone. This means that water will move both vertically and laterally from the point of application [1]. However, plant roots remove water from the soil, concentrating salts in the root zone. Hence, in these systems, there is a non-uniform distribution of salt which is inversely related to the soil-water movement and results in the accumulation of salts around the periphery of the wetted zone [2]. This salt accumulation may affect crop water uptake. Root zone salinity is normally managed by the application of additional water to leach the salt out of the root zone. However, in precision irrigation systems, applying excess water may not necessarily translate into deep drainage and leaching of salt below the root zone. Conversely, the application of leaching volumes of water may result in excessive loss of beneficial ions (e.g. nitrate) from the root

zone. Hence, there would be significant benefits in the development of a technique which selectively moves salts either without mass water movement or maintains salts within the root zone against the mass water movement.

The prime aim of this research is to investigate the ability of electro-osmosis to control/promote water in sub-surface soil region for agriculture application. A relevant scope of the research is to investigate the possibility to use the electro-osmosis phenomenon to provide salt control in root zone.

II. ELECTRO-OSMOSIS THEORY AND APPLICATION

When an electrical potential is applied to a column of soil, water particles are forced to move from the anode towards the cathode because of the electrical potential difference between the negatively charged soil surface and the solution [3, 4]. This phenomenon is known as electro-osmosis (EO); a simplified diagram of water movement in a soil is shown in Figure 1.

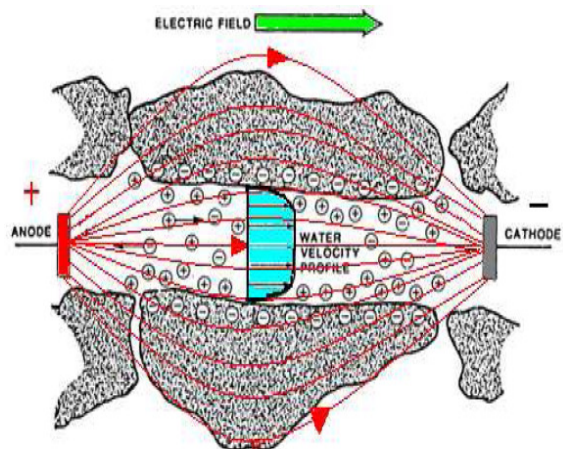


Figure 1 Principle of electro-osmosis through soil capillary.

Several theories are established to describe and evaluate water flow by electro-osmosis [3]. Among those theories, the most commonly accepted theory is

the Helmholtz-Smoluchowski (H-S) model. This theory is based on the assumption that the fluid flow through soil pores is governed by electrical forces causing flow towards the cathode. The volume of electro-osmosis flow through a bundle of capillaries of cross sectional area A under effect of an electrical field E (Vm^{-1}) is determined by the H-S equation.

$$Q = K_e E A \quad (1)$$

Where, Q is the fluid volume rate (m^3s^{-1}), K_e coefficient of electro-osmosis conductivity ($\text{m}^2\text{V}^{-1}\text{s}^{-1}$), E electric field strength (Vm^{-1}) and A cross sectional area (m^2).

Helmholtz-Smoluchowski introduced the K_e as the volume rate of fluid flowing through a unit cross sectional area due to a unit electrical gradient. The rate of electro-osmosis flow is controlled by the K_e of soil. The value of K_e is determined as:

$$K_e = \varepsilon \frac{\zeta n}{4\pi\eta} \quad (2)$$

Where, ε denotes the electrical permittivity ($\text{C}^2\text{N}^{-1}\text{m}^{-2}$) of soil, ζ Zeta potential (V) of soil-pore fluid interface, n soil porosity (unit less), and η viscosity of pore fluid (Nsm^{-2}).

The electro-osmosis phenomenon has found different applications in civil engineering and geotechnical engineering. Casgrande [3] implemented the electro-osmosis technique in civil engineering to improve the engineering properties of soils. The study illustrated that by applying electro-osmosis to fine-grained soil the produced electrical field immediately re-directed the pore water seepage force which resulted in increased soil shear strength. Electro-osmosis has also been effectively implemented to improve the strength of soil [5], increasing the load capacity of friction piles and consolidating and dewatering mine tailings and coal washery [6], [7].

There have been only limited studies into the use of electro-osmosis for moving water and salt in agriculture applications. Kamel [8] investigated the elemental composition in soil and water before and after the application of EO and quantified the volumes of water moved by EO at different heights/depths and voltages. Kamel [8] stated that the application of a current density of 600 mAcm^{-2} and 500V was possible to extract water quantity of $200\text{cm}^3\text{h}^{-1}$ consuming energy of 300Wh when the cathode installed at 20cm from the water surface and with applying 740 mAcm^{-1} and 520V the extracted water from soil was $100\text{cm}^3\text{h}^{-1}$ consuming energy of 385Wh when the cathode placed at 40cm from water surface. Cairo [9] conducted experiments to concentrate and remove nitrates from contaminated soils. The results obtained showed that nitrate concentration in saturated soil tended to increase from anode to cathode after the application of an electrical field as the nitrate solution moved toward the cathode. However, as the soil became unsaturated,

the nitrate started to migrate toward the anode. Cho [10] conducted a lab-scale experiment to investigate the movement and removal of salts in greenhouse soil under an electric field. The water content of the soil sample was approximately 30%. The results showed salt removal efficiency depends on salt type; the highest percentage removed was 81% of nitrates (due to the high solubility) and the lowest percentage was 50%, which was achieved for chloride and sulphate.

This research investigated the effect of applying direct current electric fields to soil and has potential application for the movement of water and salts in agricultural applications. Different voltages with different durations were applied for each test in the lab-scale experiment.

III. METHODOLOGY

The experiment was conducted on an isolated electro-osmosis cell housed in a $820 \text{ mm-long} \times 230 \text{ mm-wide} \times 620 \text{ mm-high}$ container made of transparent acrylic plastic sheet 10-mm thick. The cell was filled with dry sandy soil up to the level of 45 cm and situated in a flat tray filled with a 5-cm high water table. The water in the tray is the only water source to the experiment. The soil surface was open to the atmosphere and evaporation was assumed to be negligible. Holes were fitted in the bottom of the acrylic container in order to enable water to flow into the lower part of the container and keep the soil at the bottom of the container in near saturated conditions. Two 75-cm long and 20-mm diameter stainless steel rods, placed horizontally in the cell at the same vertical plane were used as electrodes. The upper electrode was placed at five centimeters below the soil surface and the lower electrode at the bottom of the container in the near saturated part of the soil. The electrodes were 35 cm apart on a vertical distance. Three tensiometers were installed at different levels between the electrodes to measure soil-water potential. Three point lysimeters were also installed between the electrodes and used to extract soil-water samples (at constant suction) for pH and electrical conductivity (EC) analysis. Glass thermometers were used to measure the temperature of water, air and soil during the test. A $0\text{-}600 \text{ Volt}$ and 0 to 1.7 Ampere DC power supply was used to power the experiment.

A sandy soil was placed into the electro-osmosis cell and allowed to equilibrate for three days before connecting the cell to the DC power supply. The upper electrode was powered as the cathode whereas the lower as the anode so that electro-osmosis water flow was expected to be directed vertically upward from the bottom to the top of the container. Electro-osmosis tests were performed with voltage gradients of 3 Vcm^{-1} for 9 days, 6 Vcm^{-1} for 5 days and 10 Vcm^{-1} for 4 days. The pH, EC and potential of the soil-water were measured as a function of time during these tests.

IV. RESULTS AND DISCUSSION

A. Soil-water extraction

Figure 2 shows the volume of water extracted from soil each 24 h near the cathode using the cup suction during EO operation. Before applying the electrical gradient to the soil sample the amount of the soil-water extracted was about 38 mL. When the power supply was switched on at voltage gradient of 3Vcm^{-1} the volume of water extracted increased consistently, which suggests that the water in soil near the surface (cathode area) is increased due to the application of electric field. After 7 days the power supply was switched off. The volume of water extracted 24 h after switching off was reduced to 11 mL. This data suggests that the electric field induced water to move upwards from the anode toward the cathode during the application of electro osmosis.

Figure 3 shows the volume of water extracted near the cathode when applying voltage gradients of 6 and 10Vcm^{-1} . The results show that the volume of water extracted is increased with higher voltages. As above, once the power supply was switched off the volume of water extracted decreased rapidly. This indicates the electric field has maintained the water near the soil surface (cathode region).

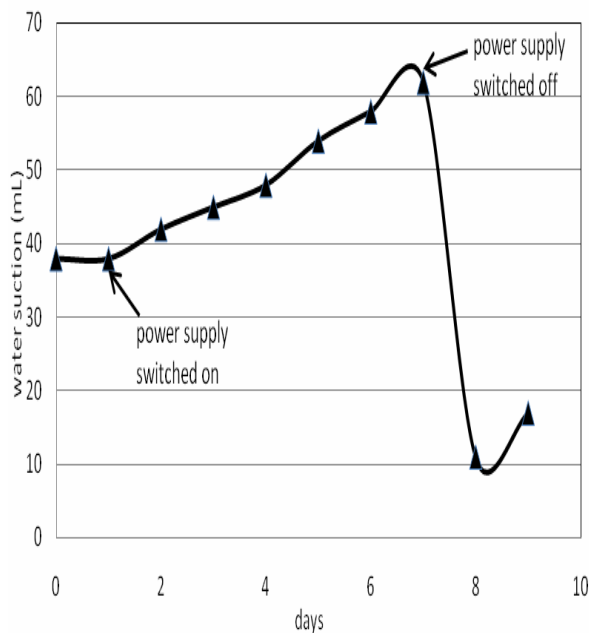


Figure 2 Volume of water extracted from top lysimeter when applying electrical gradient of 3Vcm^{-1}

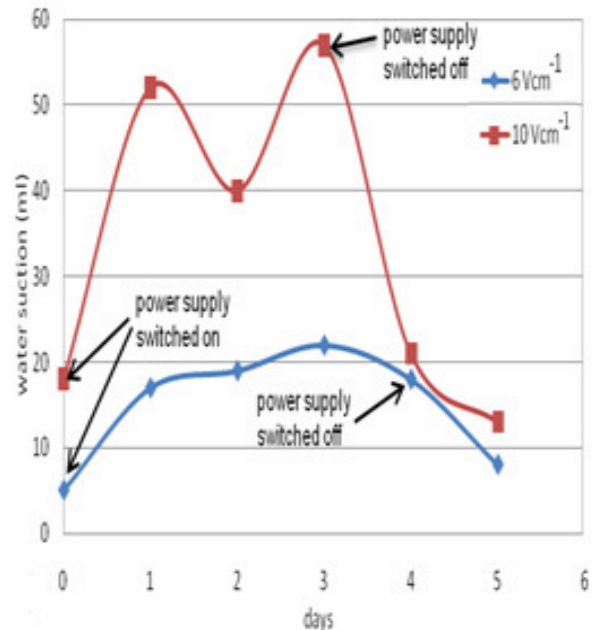


Figure 3 Volume of water extracted from top lysimeter when applying electrical gradients of 6 & 10Vcm^{-1}

B. Soil-water potential SWP

The soil-water potential (SWP) was measured using a hanging water column technique. Figure 4 shows the arrangement of the tensiometers within the soil container at 8, 20 and 31 cm from the ponded water surface at the bottom of the soil. The tensiometers were initially equilibrated with the water surface (10 cm from the bottom of the soil container). After equilibrium, the power supply was switched on at a voltage gradient of 3Vcm^{-1} . The values of SWP during the test are shown in figure 5. The water potential at the cathode decreased to -20 mm in the first 10 h before it increased to reach a plateau of +23 mm within 58 h. Whereas, at the middle tensiometer area the water potential increased to reach 60 mm after 33 h, then decreased to low levels fluctuating around -35 mm. In contrast, at the anode no changes were observed in the first 29 h then the potential reduced to -7 mm before it increased back to reach a plateau of +20 mm.

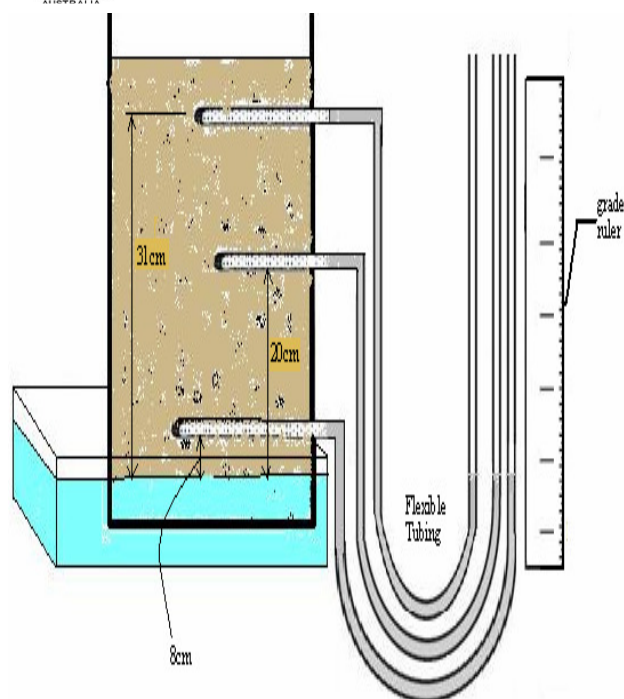


Figure 4 Schematic of hanging water column technique

Figure 6 shows the soil-water potential at sequentially applied voltage gradients of 6 and 10 Vcm^{-1} . The SWP at the anode decreased rapidly to -95 mm in the first 21 h before steadily increasing to reach to -27 mm after 5 days. When an increased voltage gradient of 10 Vcm^{-1} was then applied for 4 days, the SWP increased slightly to reach -20 mm. In contrast, the SWP at the cathode increased slowly to +12 mm when 6 Vcm^{-1} was applied and continued to increase to reach +40 mm when 10 Vcm^{-1} was subsequently applied. The SWP at the middle tensiometer increased to +40 mm during the first 24 h when 6 Vcm^{-1} was applied and then went off the scale 24 h later.

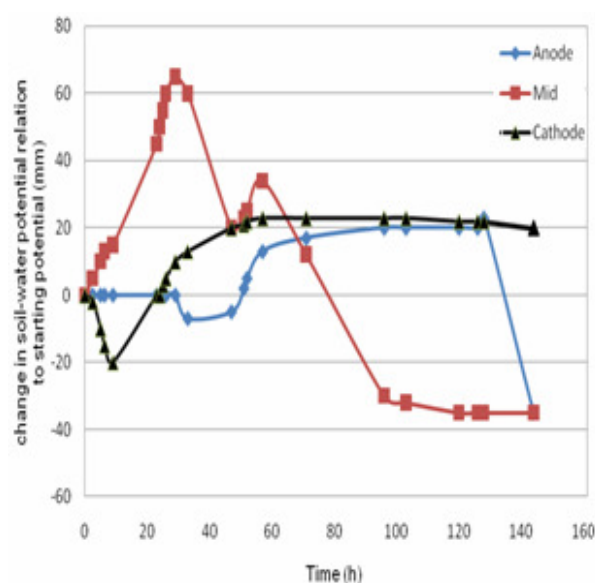


Figure 5 Changes in soil-water potential when applying voltage gradient 3 Vcm^{-1}

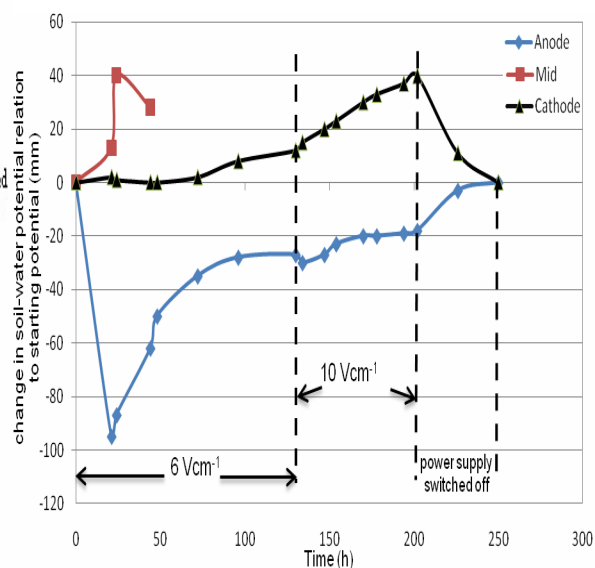


Figure 6 Changes in soil-water potential when applying voltage gradients 6 and 10 Vcm^{-1}

C. Electrical Conductivity

The electrical conductivity (EC) of the soil-water was measured by an EC-meter every 24 h taking suction cup samples. Figure 7 shows the EC of the extracted soil-water during the application of EO. The initial conductivity near the cathode area was 611 μScm^{-1} . The EC decreased steadily to 77 μScm^{-1} with the application of the electrical field for 4 days. Twenty four hours later the EC increased to the level of 121 μScm^{-1} before it decreased further to almost a value of 55 μScm^{-1} . In contrast, in the first 3 days of the test, the EC near the anode increased gradually from a value of 328 to 490 μScm^{-1} before it decreased to reach 193 μScm^{-1} at the end of the EO application. Although it was clear that the overall electrical conductivity of the soil-water decreased, it was unclear whether this was due to the migration of salts or precipitation of salt near the electrodes.

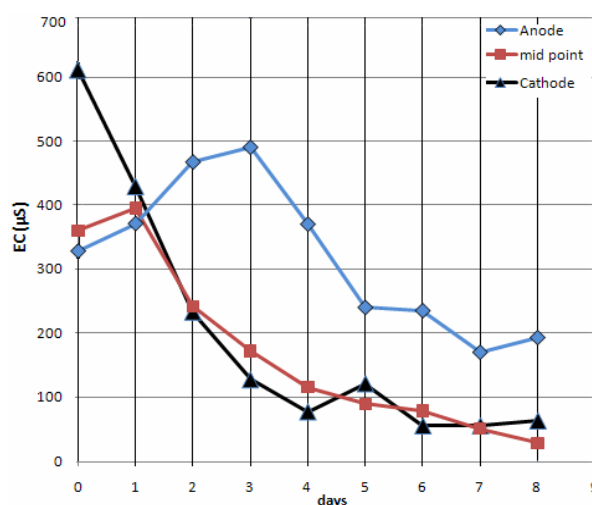


Figure 7 Electrical conductivity of extracted soil-water when applying voltage gradient 3 Vcm^{-1}

D. Soil-water pH

The initial soil-water pH was 7.47 units near the cathode and 7 at the anode. In the first 48 hours of the experiment, the pH increased almost linearly from 7.47 to 7.55 at the cathode and from 7 to 7.3 near the anode. After 72 h, the pH decreased steadily to reach levels of 7.2 near the cathode and 6.46 near the anode. When the power supply was switched off, the soil-water pH rose again to settle at 7.25 near the cathode and 6.6 near the anode at the end of the test as shown in figure 8. From the literature it has been shown that the anode produces H^+ and the cathode OH^- , so the variation of soil pH is most likely attributed to the migration of H^+ to cathode and OH^- to the anode [11],[12].

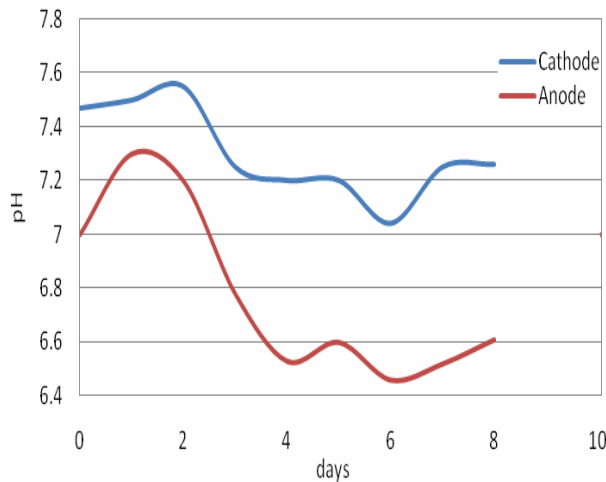


Figure 8 Soil pH when applying electrical gradient of $3Vcm^{-1}$

V. CONCLUSION

The effects of electro-osmosis on water movement in soil was investigated in this study by applying electric field through electrodes in soil and monitor the increase in soil moisture near the soil surface. The extracted water volumes were observed to increase with increased electric field intensity which gives indication that the electro-osmosis could be used to control/maintain water in root zone. The results showed that the electric field intensity affected the salt distribution reference from the anode to the cathode during the application of the direct electric current. The observed salt movement was different to the mass water movement. The pH of the soil-water was changed due to the effect of electrical field.

VI. REFERENCE

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