ELECTRO-OSMOTIC HEAD AND FLOW REVERSAL IN SATURATED SOILS

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Fredrick Warner Wheaton

1965

ABSTRACT

ELECTRO-OSMOTIC HEAD AND FLOW REVERSAL
IN SATURATED SOILS

by Fredrick Warner Wheaton

The drainage and irrigation of soils has become increasingly important as the demand for food increases with increasing population. Electro-osmosis shows promise of becoming a new tool by which drainage and irrigation, particularly on heavy soils, can become faster, easier and cheaper.

Investigations were carried out to determine if a reversal in the direction of flow of water due to an applied electric potential occurred in a saturated clay and loam soil. The electro-osmotic head developed under saturated conditions due to a 20 volt potential applied across a soil plug 1 1/2 inches in length was studied for a clay, a sand, and a loam soil.

No flow reversal was found to occur in clay when a potential of 15 and 20 volts was impressed across a soil plug 1 1/2 inches in length. The soil plug was subjected to electro-osmosis for an extended period of time but a flow reversal failed to occur.

The electro-osmotic head developed in sand was zero due to the high hydraulic conductivity of sands. With clay and loam soil the head developed depended on the void ratio, the hydraulic conductivity, the electro-osmotic permeability, and the applied voltage. The electro-osmotic head was found to increase rapidly initially and then slowly dropped when clay soil was used. When loam soil was used the head rose rapidly during the first few hours but the rate of increase became nearly zero after this.

Changes took place in the soil characteristics due to the passage of an area of high ion concentration through the soil. The source of these ions was electroytric erosion of the anode.

Approved E J Monson
Major Professor

Date Aug 30, 1965

Carl W. Hall

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By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1965

ACKNOWLEDGMENTS

I am deeply indebted to my major professor, Dr. C. J. Mackson, (Agricultural Engineering) for his time, guidance, and helpful suggestions which made the completion of this manuscript possible.

I would like to extend my thanks to Mr. E. H. Kidder (Agricultural Engineering) and Dr. M. Fox (Statistics) for serving on my guidance committee and for their helpful suggestions.

To Mr. R. Z. Wheaton (Agricultural Engineering) I would like to extend a special thanks for his able assistance with photography.

I would also like to express my sincere appreciation to Dr. M. M. Mortland (Soil Science) for his helpful suggestions and comments.

Fredrick W. Wheaton

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INTRODUCTION

The phenomena of electro-osmosis, a process of forcing a liquid to flow through a porous medium by an electric potential being impressed across it, has been known to exist since well before the turn of the century. However, it was not until the 1900's that soil was used as the porous medium. Casagrande (1948a) found that when an electric current was passed through soil, water was removed and some consolidation took place.

Casagrande's discoveries stimulated further research. Most of these investigations were directed toward dewatering and consolidation of soil and led to the development of a procedure for stabilizing wet clay and silt soils at construction sites.

Crowther and Haines (1924) used electro-osmosis to reduce the draft of a plow. Mackson (1962) using a model plow moving at 2.5 feet per minute reduced the friction draft by 80 per cent.

Cross (1963) used electro-osmosis to reduce the moisture content of poultry excrement.

Preliminary investigations showed that when a clay sample was subjected to electro-osmosis for an extended period of time a negative electro-osmosic head developed.

If the sign of the charge carried by the clay particles changes during electro-osmosis this negative head would be expected since the direction of flow of water would reverse.

This investigation was designed to determine if the direction of flow of water in clay will reverse when the application of electro-osmosis is continued for an extended period of time. The head which can be developed by electro-osmosis in three soil types under saturated conditions will also be determined. The aim of these studies is to investigate the feasibility of using electro-osmosis for irrigation and drainage of soil. If an electric potential can sustain a head of water it can be used to draw moisture from water sources below which plants roots can reach. However, if the direction of flow of water changes with time when soil is subjected to an electric potential, drainage could occur when irrigation is expected. This could be a costly mistake.

If electro-osmosis could be used for irrigation heretofore unavailable ground water sources might become available to plants. Initial installation costs would decrease for a permanent irrigation system since wires rather than pipes would be used. Such a system could also be employed for drainage if a current carrying conduit was used for one electrode. This configuration would allow the system to be switched from a drainage system to an irrigation system by simply reversing the polarity of the electrodes.

OBJECTIVES

1. To determine if the direction of flow of water will reverse in a clay and a loam soil after electro osmosis has been applied to the soil for an extended period of time.
2. To determine the electro-osmotic head that can be developed under saturated conditions for three soil types under a potential of 20 volts.

LITERATURE REVIEW

The phenomena known as electro-osmosis has been explained on the basis of two theories. The first was known as Helmholtz's double layer theory and the second was called the ion theory. Winterkorn (1947), Casagrande (1948), Vey (1949), Collins (1961) and other investigators based their work on the double layer theory. Geuze (1948) was the only investigator who favored the ion theory. The two theories are explained by Maclean and Rolfe (1945) as follows:

1. The explanation is based on the fact that an "electric double layer" is set up at almost any boundary between two phases of matter, which results in a difference of potential being set up between any two phases in contact. In the case of wet soil, the water phase will be positively charged and the soil particles negatively charged. When an electric field is applied to the wet soil, the soil and water tend to move in opposite directions, but on account of the immobility of the soil particles, only the water moves.

2. Positive ions attached to the clay particles are liberated when voltage is applied and subsequently migrate to the cathode under the influence of the electric field. Each ion acts as a nucleus to a number of molecules of water. When the ion reaches the negative electrode, it gives up its charge and deposits the water it has carried with it.

Casagrande (1948b) took the following formula from Freundlick (1926) to describe the flow of water through soil due to electro-osmosis. When an electric double layer was present at the soil water interface:

$$Q = \frac{E\ D\ R^2 \delta}{4\ \nu\ L} \tag{1.1}$$

where

Q = quantity of liquid moved in unit time through single capillary of radius R and length L

R = radius of capillary

D = dielectric constant of double layer

E = potential difference applied

ν = coefficient of viscosity of liquid

δ = electrokinetic potential difference between bound and free parts of double layer

L = distance between electrodes

Casagrande (1948b) realized the limitations imposed on this expression by the assumption of a single straight capillary of constant radius. To overcome this limitation he developed the following equation to describe flow through a prism of saturated soil:

$$Q_e = \frac{E\ D\ \delta}{4\ \nu}\ q\ A \tag{1.2}$$

where

Q_e = quantity of liquid moved in unit time through a prism of soil

A = cross-sectional area of soil prism in contact with electrodes

q = related to pore water and pore space through which water moves

All other terms are the same as for equation 1.1.

Casagrande (1952) by suitable mathematical manipulation was able to show that equation 1.2 could be expressed as:

$$Q_e = k_e \; U \; A \tag{1.3}$$

where

$U = \frac{E}{L}$ = electrical potential gradient

Q_e = electro-osmotic flow

K_e = electro-osmotic permeability

A = total cross sectional area of N straight capillaries

E and L are the same as in equation 1.1

This equation is more useful since it eliminates the δ, R and D terms which are difficult to determine. This equation is also very similar to Darcy's law (equation 1.4) for hydraulic flow.

$$Q_h = K_h \; V \; A \tag{1.4}$$

where

K_h = hydraulic permeability

V = hydraulic gradient

A = cross sectional area of soil

Q_h = hydraulic flow

The result of equation 1.3, Casagrande (1948a) found, was that the electro-osmotic flow was independent of pore size. It depended only on the void ratio. Winterkorn (1947) and Vey (1949) also found this to be true. Therefore, as Winterkorn states,

> . . .for the same surface-chemical character of the soil, the same liquid, and the same temperature, the amount of liquid moved in unit time and unit cross section under the same potential should be the same for sands, silts, and clays, as long as their porosity is the same.

Rarely are the surface-chemical character and the porosity of sands, silts, and clays similar; hence, the amount of liquid yield from each of these soils is usually not identical for the same potential difference. Winterkorn (1947) found that the electro-osmotic permeability constant (k_e) varies with moisture content and the applied potential. Casagrande (1948a) indicated that the electro-osmotic permeability constant depended on porosity and zeta potential of the soil. However, he found that the quantity of flow of water was nearly constant for all soil materials and the electro-osmotic permeability constant could be approximated by 5×10^{-5} cm/sec/volt/cm. He finds this value to be a useful average for most soils, but when working with bentonite he found variations in the electro-osmotic permeability constant of 2×10^{-5} to 12×10^{-5} cm/sec/volt/cm.

Maclean and Rolfe (1945) found a linear relationship existed between the quantity of electricity consumed (in coulombs) and the quantity of water removed up to the point where the soil resistance began to increase rapidly (Figure 1).

Maclean and Rolfe (1945) also found that a linear relationship existed between the quantity of electricity required to remove a given quantity of water and the clay content of the soil (Figure 2). They found that the amount of water expelled per 1000 coulombs of electricity was greatest for sandy soils and least for clay soils.

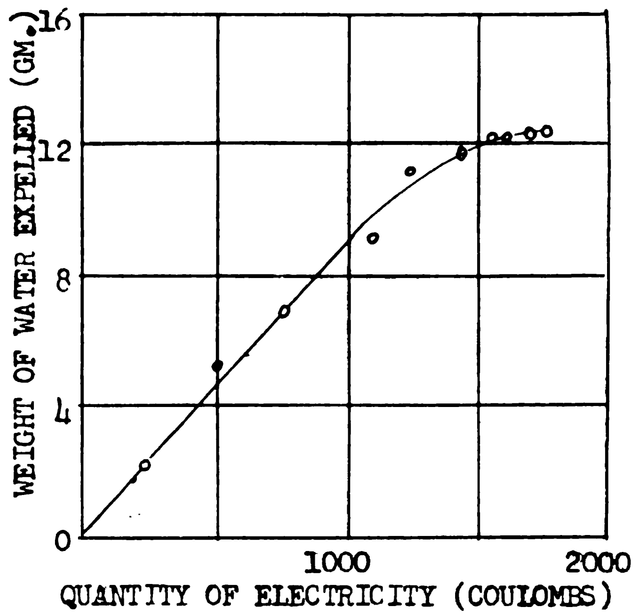


Figure 1. Relation between weight of water expelled and the quantity of electricity used for Harmondsworth brickearth.

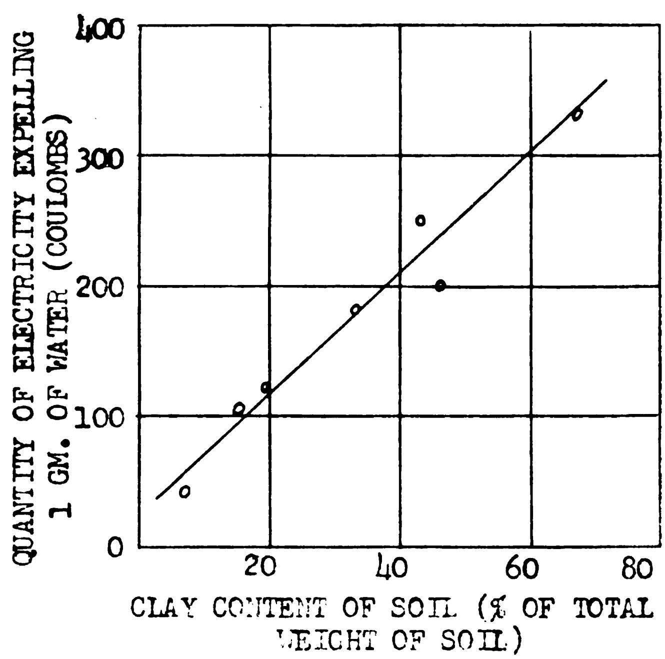


Figure 2. Relation between quantity of electricity required to expell 1 gm. of water from a soil and the clay content of the soil.

From Helmholtz's theory Casagrande (1948a) developed the following equation to express the pressure developed due to electro-osmosis in a single capillary:

$$P = \frac{2\,\delta\,E\,L}{\pi\,R^2} \tag{1.5}$$

P = pressure

δ = zeta potential of soil

E = voltage between electrodes

L = distance between electrodes

R = radius of capillary

Vey (1949) derived an equation to express the pressure in a group of equal sized capillaries with uniform cross section.

$$P = \frac{2\,(1 + e_o)\,\delta\,E\,L}{\pi^2\,e\,R^4} \tag{1.6}$$

e_o = initial voids ratio

e = voids ratio corresponding to pressure P

Other terms as defined in equation 1.5.

The difficulty with equation 1.5 and 1.6 is two fold. First, they are idealized conditions for soil capillaries since straight capillaries of uniform cross section rarely if ever exist in soils, and secondly, the zeta potential and the radius of the capillaries are difficult to determine. However, Casagrande (1948a) found good experimental agreement with equation 1.5 until the soil reached a certain percentage of colloidal material. Above this percentage cracks developed in the soil which allowed freer passage of water and the equations no longer described the pressure developed.

Geuze (1948) attempted to minimize these problems by rewriting equation 1.3 in differential form as follows:

$$dQ_e = K_e\ U\ A\ dt \tag{1.7}$$

Q_e = electro-osmotic flow

K_e = electro-osmotic permeability

U = electrical potential gradient

A = cross sectional area of soil

t = time

He then wrote a similar equation for hydraulic flow given by:

$$dQ_h = K_h\ V\ A\ dt \tag{1.8}$$

dQ_h = hydraulic flow

K_h = hydraulic permeability

V = hydraulic gradient

He also reasoned that the gradients could be expressed as follows:

$$V = \frac{h}{L} \tag{1.9}$$

$$U = \frac{E}{L} \tag{2.0}$$

where

h = hydraulic head

E = potential difference applied

L = distance between electrodes

If flow due to electro-osmosis was in one direction and hydraulic flow was in the opposite direction through the same soil, then at some point an equilibrium must be reached and would be described by equating Q_e and Q_h to flow at any time.

$$Q_e - Q_h = (dh)\ F \qquad (2.1)$$

F = cross section of tube where water is collected

After substitution of the expression from equation 1.7 for Q_e and the expression from equation 1.8 for Q_h the above equation becomes:

$$\frac{dh}{dt} = \frac{(K_e\ E - K_h\ h)\ A}{F\ L} \qquad (2.2)$$

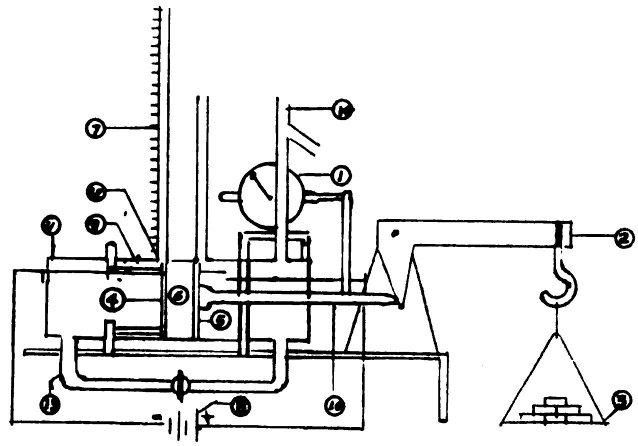
After solving for h the solution of the equation 2.2 is:

$$h = \frac{K_e}{K_h}\ E\ \frac{\exp \frac{K_h\ A\ t}{F\ L} - 1}{\exp \frac{K_h\ A\ t}{F\ L}} \qquad (2.3)$$

Therefore the maximum head should be realized at $\frac{dh}{dt} = 0$ which from equation 2.2 can be seen to be:

$$h_{max} = \frac{K_e}{K_h}\ E \qquad (2.4)$$

From equation 2.3 Geuze (1948) was able to see that the maximum head should occur at t = infinity. However, when testing this theory with peaty clay soil in an electro-smometer (Figure 3) he found the following curve (Figure 4) to describe the results. This does not agree with his original



1. Dial gauge
2. Cantilever
3. Loading-platform
4. Negative electrode
5. Positive electrode
6. Soil sample
7. Piezometric tube
8. Accumulator
9. Glass cylinder
10. Plunger
11. Brass cyclinder caps
12. Hard rubber
13. Connecting tube with stopcock
14. Filling tube with constant head

Figure 3. Electrosmometer.

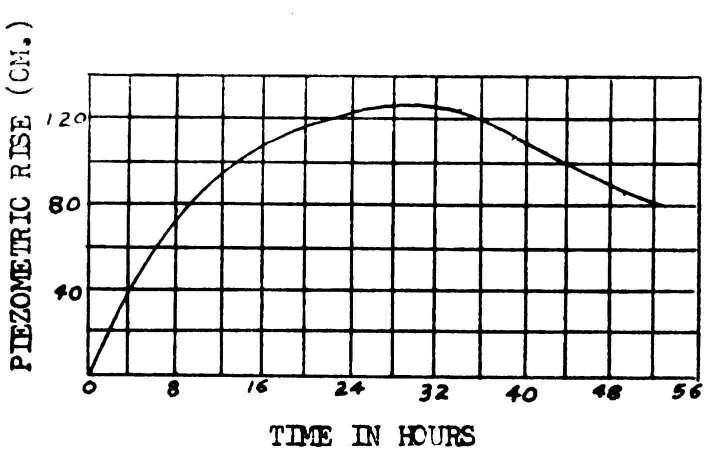


Figure 4. Electrosmometer test for peaty clay soil.

theory. The curve indicates that K_e decreases after a certain time but he found that K_h did also. This meant that K_e decreased even more rapidly. Possible reasons given by Geuze to explain this are as follows:

1. Anode cupric--ions which went into the solution had a strong flocculating power on the negatively charged colloidal soil particles.
2. The cupric (positive) ions may cause the formation of insoluble copper compounds depending on the composition and acidity of the soil solution.

Jacobs (1957) found that various ions were removed from soil by electro-osmosis at different rates. Potassium and sodium were removed much more rapidly than calcium.

Rollins (1956) found the flow rate due to electro-osmosis varied with the type of ions used to saturate the clay particles. Clay saturated with any base had higher flow rates than did hydrogen saturated clay. Flow rates were found to be in the following order when clays were saturated with each of these ions: Al>Na>Ca>Fe>H. Rollins (1956) also found a concentration of hydrogen ions developing around the cathode as electro-osmosis proceeded.

Piaskowski (1957) found electrical energy consumption depended on the per cent clay fraction and the mineralogical character of the soil. Casagrande (1948a) stated that the amount of current passing through one square centimeter of soil depends largely on the grain size of the soil--the smaller the particle size the greater the current.

Marwick (1947) reported that practical applications of electro-osmosis in Germany during World War II include: stabilizing soft silt with sand veins for construction of U-boat pens, stabilizing loam resting on rock for a railroad tunnel and stabilizing a railroad grade where four feet of sand rested on soft silt. Richardson (1953) reported using electro-osmosis to eliminate seepage from the Saginaw River into the excavation area for the Consumers Power Company power plant at Essexville, Michigan. At this same location, electro-osmosis was able to maintain a water head twenty feet above ground level.

Cross (1963) summed up the factors effecting electro-osmosis in soils as follows:

1. Amount of electric current
2. Bulk density of the material
3. Joule heating
4. Acidity of the speciman
5. Time
6. Distance between electrodes
7. Moisture content of the specimen
8. Design of and material in the cathode
9. Anode material
10. Hydraulic gradient
11. Variability of soil-electrode contact.

THEORETICAL DISCUSSION

The explanation offered by Maclean and Rolfe (1945) indicates two possible explanations for the phenomenon of electro-osmosis. One is given by the ion theory and the other by the electric double layer theory. However, upon critical examination of the two theories it appears that these are not different theories but two ways of explaining the same theory.

The double layer theory proposes that two layers of charge of opposite sign are set up at any boundary where two phases of matter are in contact. The origin of these charges was explained by van Olphen (1963) as follows:

> Imperfections within the interior of the crystal lattice of the particle may be the cause of a net positive or a net negative lattice charge. Such a net charge will be compensated by the accumulation of an equivalent amount of ions of opposite sign in the liquid immediately surrounding the particles, keeping the whole assembly electroneutral.

Maclean and Rolfe (1945) further state that when an electric field was applied to the double layer the layers tend to move in opposite directions but in a soil-water system only the water moves because of the immobility of the soil.

The ion theory as given by Maclean and Rolfe (1945) states that:

> Positive ions attached to the clay particles are liberated and subsequently immigrate to the cathode under the influence of the electric field. Each ion acts as a nucleus to a number of molecules of water. When the ion reaches the negative electrode it gives up its charge and deposits the water which it carried with it.

Van Olphen (1963) indicated ions form the charge making up the double layer and Maclean and Rolfe (1945) stated that movement of one layer of the double layer relative to the other was responsible for the occurrence of electro-osmosis. However, Maclean and Rolfe (1945) also attributed electro-osmosis to ion movement in the ion theory. Therefore, if van Olphen's explanation is accepted, movement of one layer of the double layer is a movement of ions and is the same phenomenon as ion movement in the ion theory. The conclusion clearly pointed out by the above discussion was that the electric double layer theory and the ion theory are not separate theories but one theory stated in two forms.

DESCRIPTION OF APPARATUS

The apparatus (Figure 10) used in this investigation was a modification of the electrosmometer (Figure 3) used by Geuze (1948).

The main chamber (Figure 5) was made from 3 inch outside diameter plastic tubing with 3/16 inch wall thickness. In one end of the tube on the inside surface three 1 x 3/4 x 1/4 inch pieces of plastic (electrode support blocks) were glued 120 degrees from each other. They were placed such that the 3/4 inch dimension was in the radial direction and the 1 inch dimension was in the axial direction. These served to support the electrode and allowed space for electrical connections between the electrode and the end of the chamber. This end of the chamber was closed by gluing a circular plastic plate (bottom cover plate) 3 inches in diameter and 1/4 inch thick to the end of the chamber (Figure 10). Holes were then drilled through the main tube wall (Figure 10) to allow vent tube, head tube, supply tube and bypass tube to be connected to the main tube. Two plastic ears (Figure 6) were glued 180° apart on the outside of the main tube. A saddle (Figure 7) was constructed to fit over each of these and was bolted to the ears by a 1/4 x 1 inch stove bolt. A 1/4 x 2 inch machine bolt was welded to

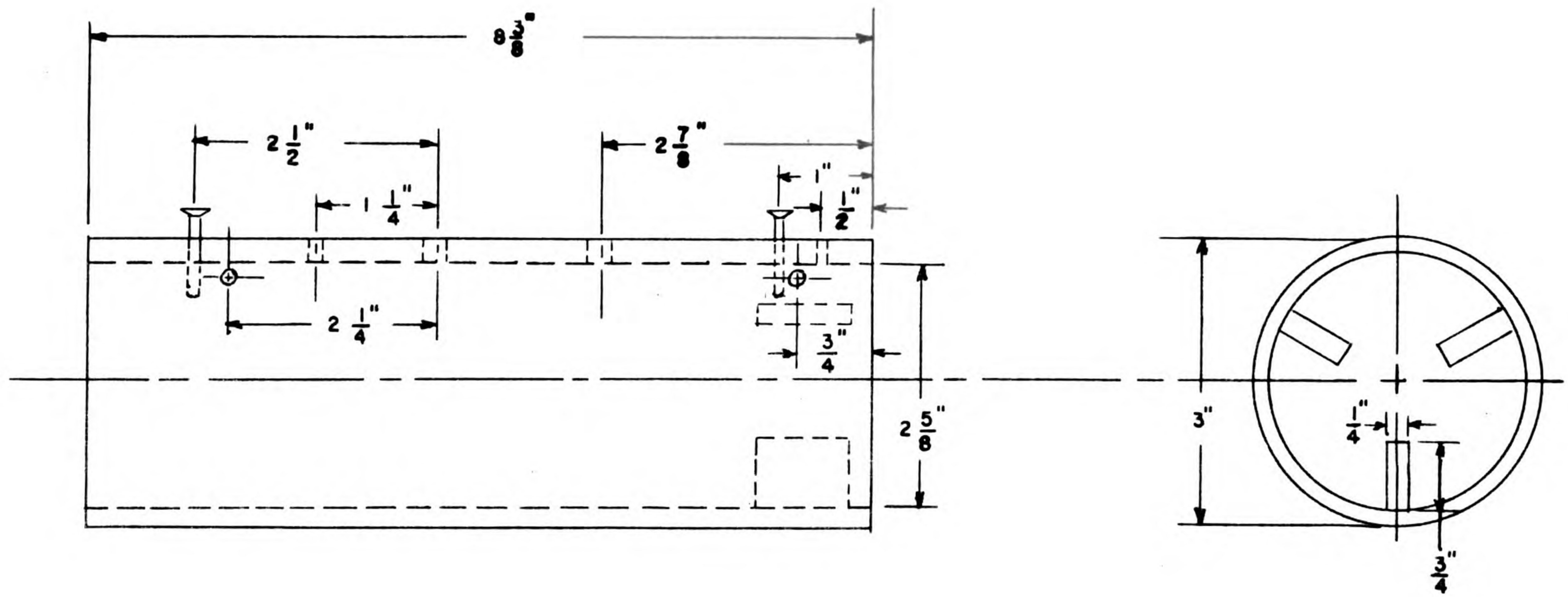


Figure 5. Detail of main tube with electrode support blocks.

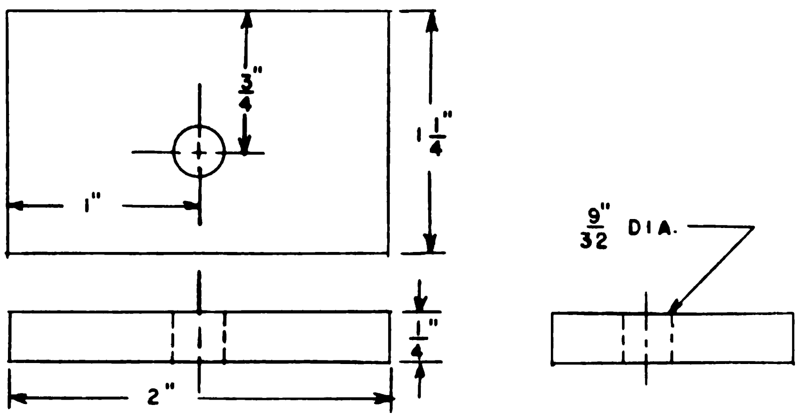


Figure 6. Plastic ear construction detail.

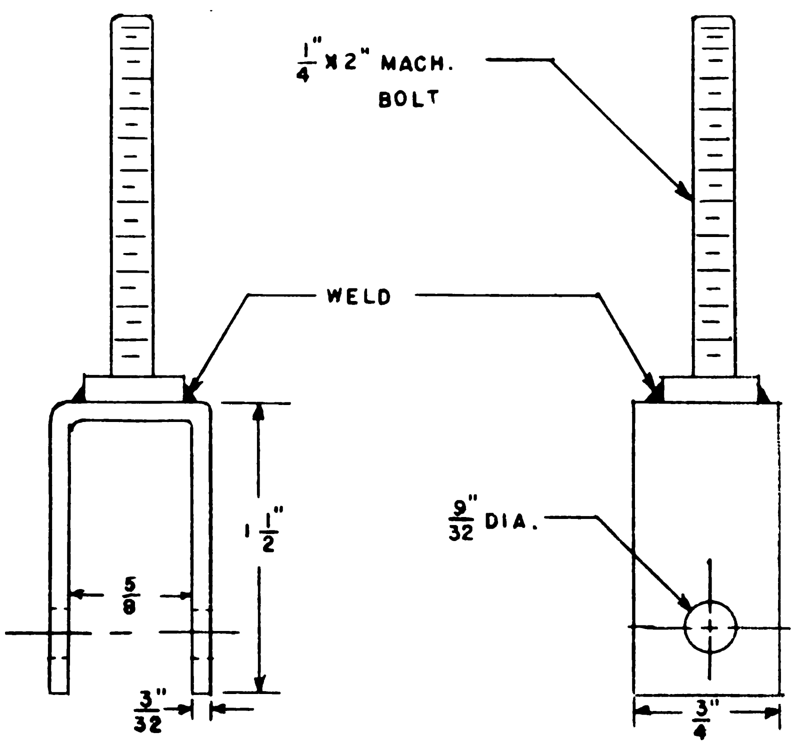


Figure 7. Construction detail of saddle.

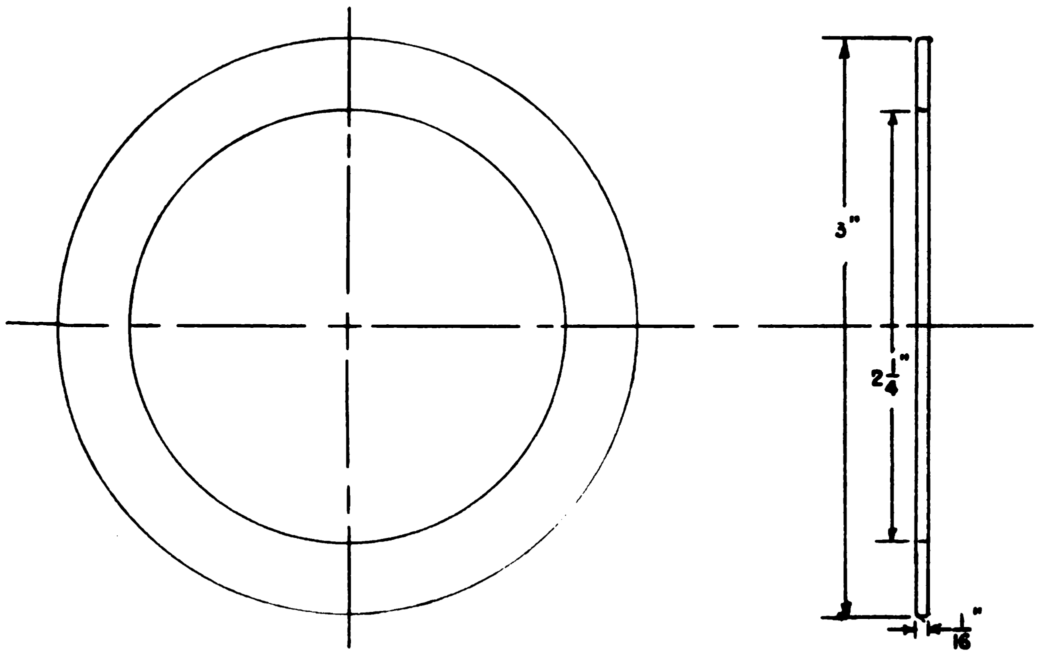


Figure 8. Detail of rubber cover gasket.

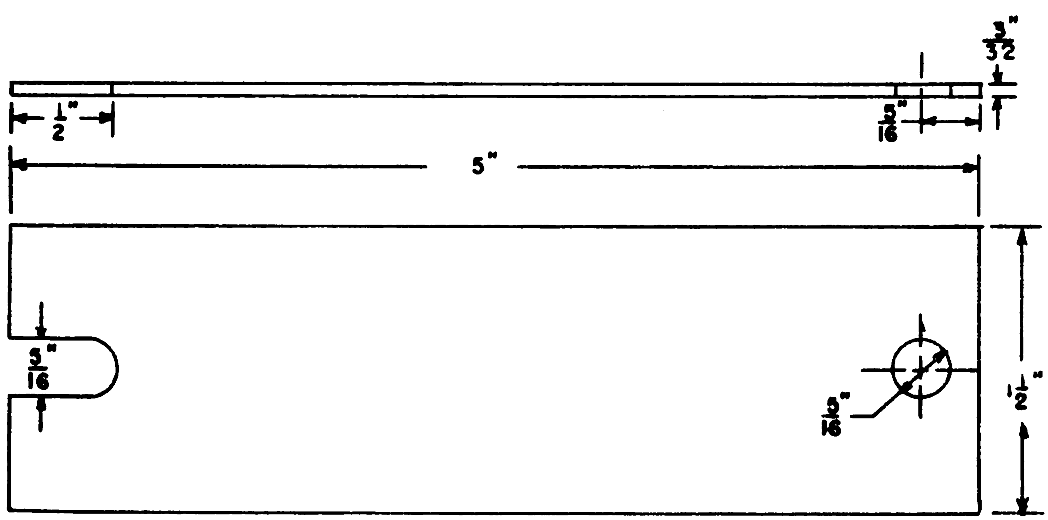


Figure 9. Detail of cover plate.

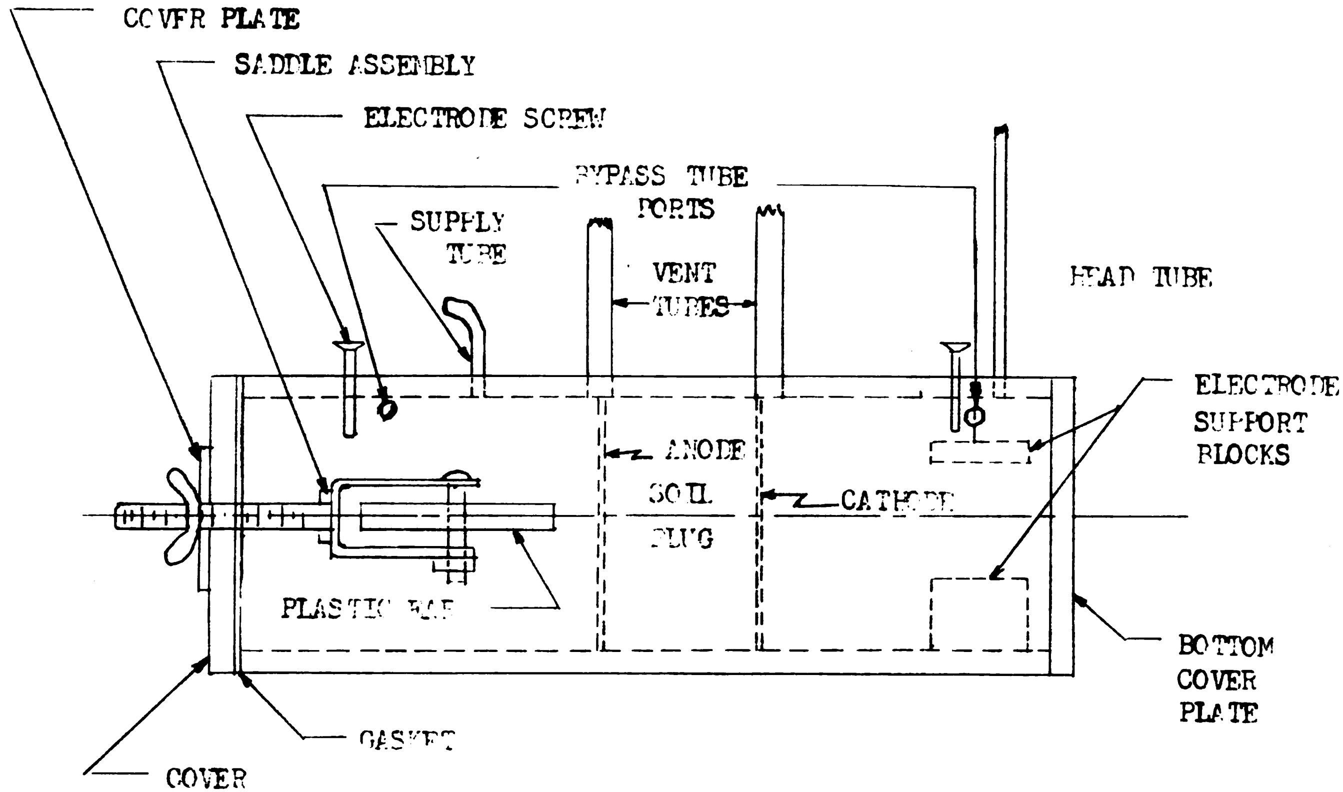


Figure 10. Schematic of assembled apparatus.

the top of the saddle. This assembly was used to tighten the cover on the main tube and provided pressure between cover and main tube.

The cover was made of a circular plastic plate 1/4 inch thick and 3 inches in diameter. On one side of the cover a rubber gasket (Figure 8) was glued with weather stripping glue. A cover plate (Figure 9) was placed across the top of the cover and attached to the saddle assembly. By tightening the wing nut on each saddle assembly the cover was sealed against the end of the main tube. Figure 10 shows the assembled parts.

A constant hydraulic head was supplied by a large container filled with water which was connected by rubber tubing to the inlet port of the main tube. The bypass tube connected the water chambers which were located at each end of the main tube and separated in the center by the soil plug. A valve in the tube allowed this passage to be opened or closed as desired. This permitted rapid equalization of hydraulic pressure on both sides of the soil plug (Figure 11).

Vent tubes were located directly above each electrode (Figure 10) to allow gas bubbles to escape. These were made of 1/4 inch (I.D.) plastic tubing except for one on the anode side which was made of 1/8 inch (I.D.) plastic tubing. (The 1/8 inch diameter tubing was found to work satisfactorily except water was sometimes forced out of it by gas bubbles.

A 1/4 inch tube eliminated this problem.) The vent tubes on the anode side were approximately 24 inches long and those on the cathode side were at least 5 feet long. The longer tubes were needed on the cathode side because the electro-osmotic head developed there.

The 1/8 inch (I.D.) plastic head tube was located on the cathode side of the soil plug. The lower end was extended below the water surface to prevent gas bubbles from entering the tube. The upper part of the tube was fastened to a vertical support and a carpenter's rule was fastened beside it. This provided a scale which facilitated reading the water head in the tube.

The first electrodes used were made of a piece of copper window screen 2-1/2 inches in diameter. These were replaced by solder-coated copper window screen. Finally a piece of 24 gauge stainless steel sheet metal 2-1/2 inches in diameter with 5/64 inch diameter holes drilled arbitrarily through it was used. The reason for these changes will be discussed later.

In order to get the electrical current to the electrodes, a 1/8 x 1 inch flat head brass screw was threaded through the main tube wall near each end (Figure 10) of the main tube. Wires connected the point end of the screws to the electrodes. Power was supplied to the head end of these screws from the D.C. power supply. Each of the three chambers used was connected in series with a calibrated milliammeter so current flow through each chamber could be read.

Contact was maintained between the soil and the electrodes by a spring placed between the anode and the cover. This maintained a pressure on the anode of 2.6 pounds per square inch.

A spacer was placed between the cathode and the electrode support blocks to hold the soil plug in the desired position.

PROCEDURE

The electrical connections inside the tube were made and the spacer and cathode were placed in the tube. Soil was then placed on top of the cathode to a depth of 1-1/2 inches with the main tube in a vertical position. The soil was dampened with tap water and tamped tightly in place to prevent leaks from occurring between the soil and the inner wall of the tube. The anode and spring were placed on top of the soil and pressed down manually. The electrical connections were then made inside the tube for the anode. The cover and cover plate were placed on the main tube and a water tight seal was created by tightening the wing nuts on the saddle assembly (Figure 11).

After placing the main tube in a horizontal position the bypass tube, vent tubes, and head tube were connected to the main tube. The inlet tube was then connected to the main tube and tap water was allowed to enter the water chamber on the anode side of the soil plug. By opening the valve in the bypass tube the water chamber on the cathode side of the soil plug was also allowed to fill. This valve was kept open until the hydraulic head on both sides of the soil plug were equal. The valve in the bypass tube was then closed.

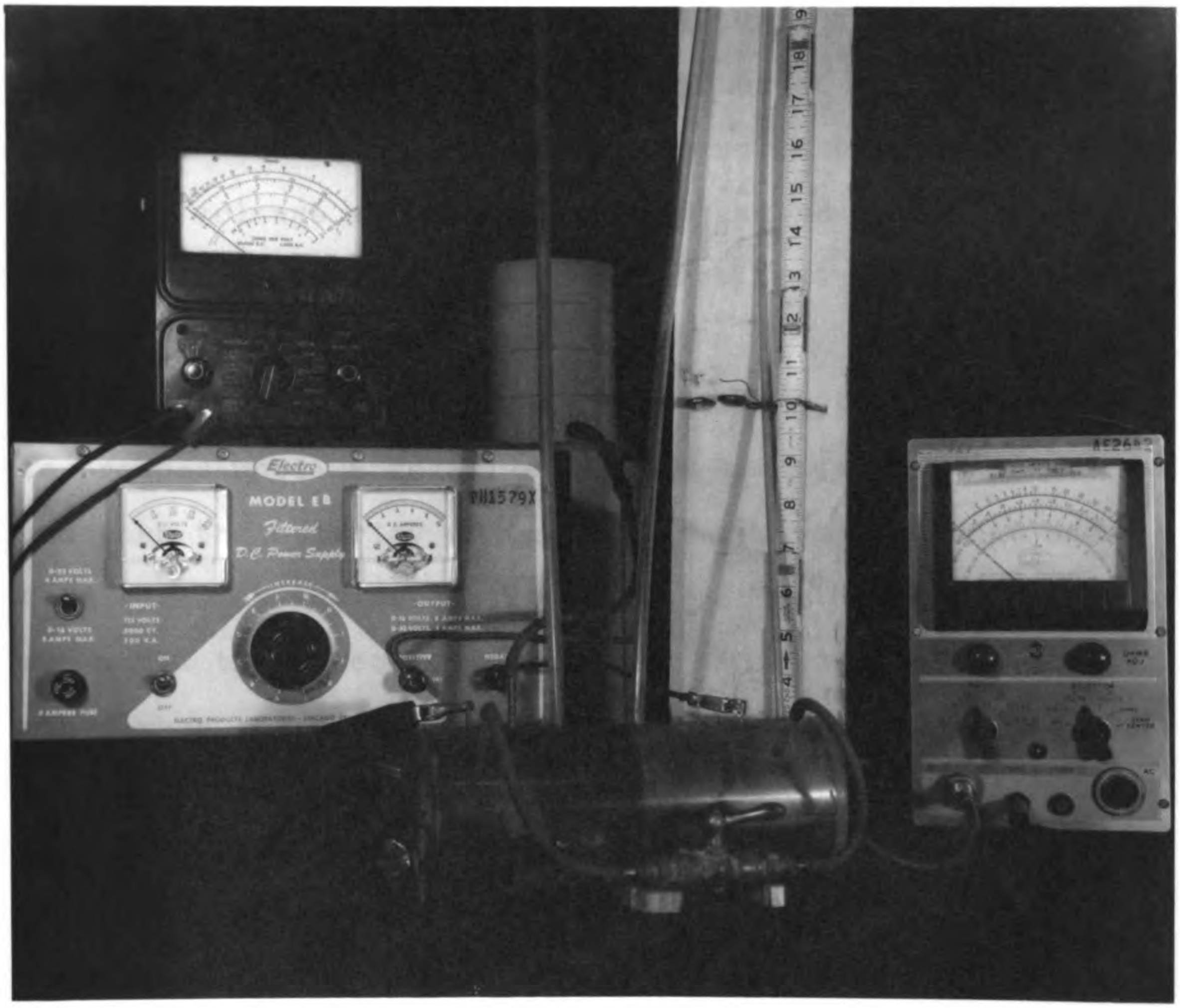


Figure 11. Assembled test apparatus.

The electrical connections outside the tube were made as shown in Figure 12. The D.C. power supply was set at the desired voltage and the initial current and head for each chamber were recorded. Thereafter at appropriate time intervals the electro-osmotic head, current through each chamber, voltage and time were read and recorded. The voltage was held constant during each test by a slight adjustment each time a reading was taken.

In the case of the clay samples the test was allowed to proceed until a negative electro-osmotic head was observed and then the polarity of the electrodes was reversed and data taken as indicated above. These tests were allowed to run until the direction of flow of water could be determined when the electrode polarity was reversed. Other soil types were run until a steady state was established or until they developed a negative head.

The only change made in this procedure occurred when sand soil plugs were used. In this case the electrodes were covered with a paper towel in order to keep the sand from washing through the holes in the electrode. For the other soil types used this was not necessary because the soil did not flow through the holes in the electrodes.

Fifteen and twenty volts were selected as the voltage to be used in this experiment. These voltages were selected since preliminary tests showed that they gave a head rise which was convenient to work with. They also were the highest voltages which did not cause noticeable joule heating in the sample.

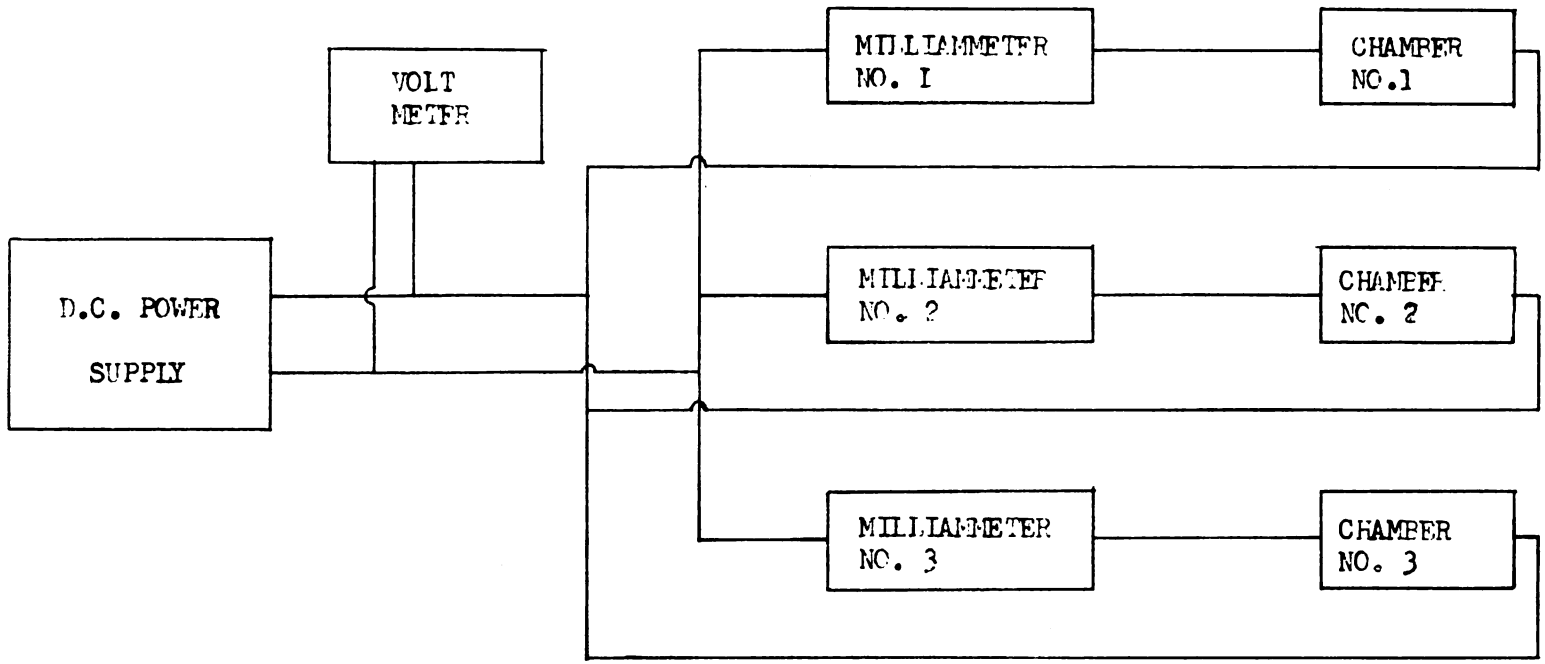


Figure 12. Electro-osmotic electricial circuit diagram.

DISCUSSION OF RESULTS

Electrodes

The first electrodes used were made of copper window screen soldered to a steel ring. However, corrosion was so severe that the anode had to be replaced after 50 to 60 hours and the cathode after every 150 hours of use. Coating the copper electrodes with solder improved their useful life to about 90 hours for the anode and 250 to 300 hours for the cathode. This also was unsatisfactory since a test usually ran over 100 hours.

Twenty-four gauge stainless steel sheet metal perforated with 5/64 inch diameter drilled holes was tested. The holes allowed water to pass through the electrodes. This material was satisfactory since over 1000 hours of use did not cause destructive damage to the electrodes. However, some corrosion on the anode and very slight corrosion on the cathode was observed.

Soil Modification

Material eroded from the electrodes entered the soil and caused changes to occur in the soil. When copper electrodes were used an area of green coloration of approximately 1/4 inch in thickness and extending entirely across the soil plug was observed to form at the anode. After formation the colored area was observed to slowly move towards the cathode.

When solder-coated copper electrodes were used the same phenomenon was observed except the colored area was grey. Stainless steel electrodes also produced a grey coloration (Figure 13). This colored area was due to a concentration of metallic particles eroded from the anode and the different colors were due to different anode materials.

When removing the soil from the chamber after a test was completed, it was noticed that the soil between the anode and the colored area was soft, wet and quite easily removed, but the soil between the colored area and the cathode appeared to be dryer than the soil on the anode side, very hard and difficult to remove.

The chemical equations for the reactions at the anode and cathode are given by Murayama (1953) as follows:

at the cathode

$$2\ A^{+} + 2\ e^{-} + 2\ H_2O \longrightarrow 2\ AOH + H_2 \uparrow \qquad (2.5)$$

at the anode

$$2\ B^{-} + 2\ e^{+} \longrightarrow B_2 \uparrow \qquad (2.6)$$

or

$$2\ B^{-} + 2\ e^{+} + 2\ H_2O \longrightarrow 2\ H_2B + O_2 \uparrow \qquad (2.7)$$

where

A = anion (na^{+}, K^{+}, Ca^{++}, Al^{+++} . . .)

B = cation (SO_4^{--}, Cl^{-}, CO_3^{--} . . .)

e = charged particle

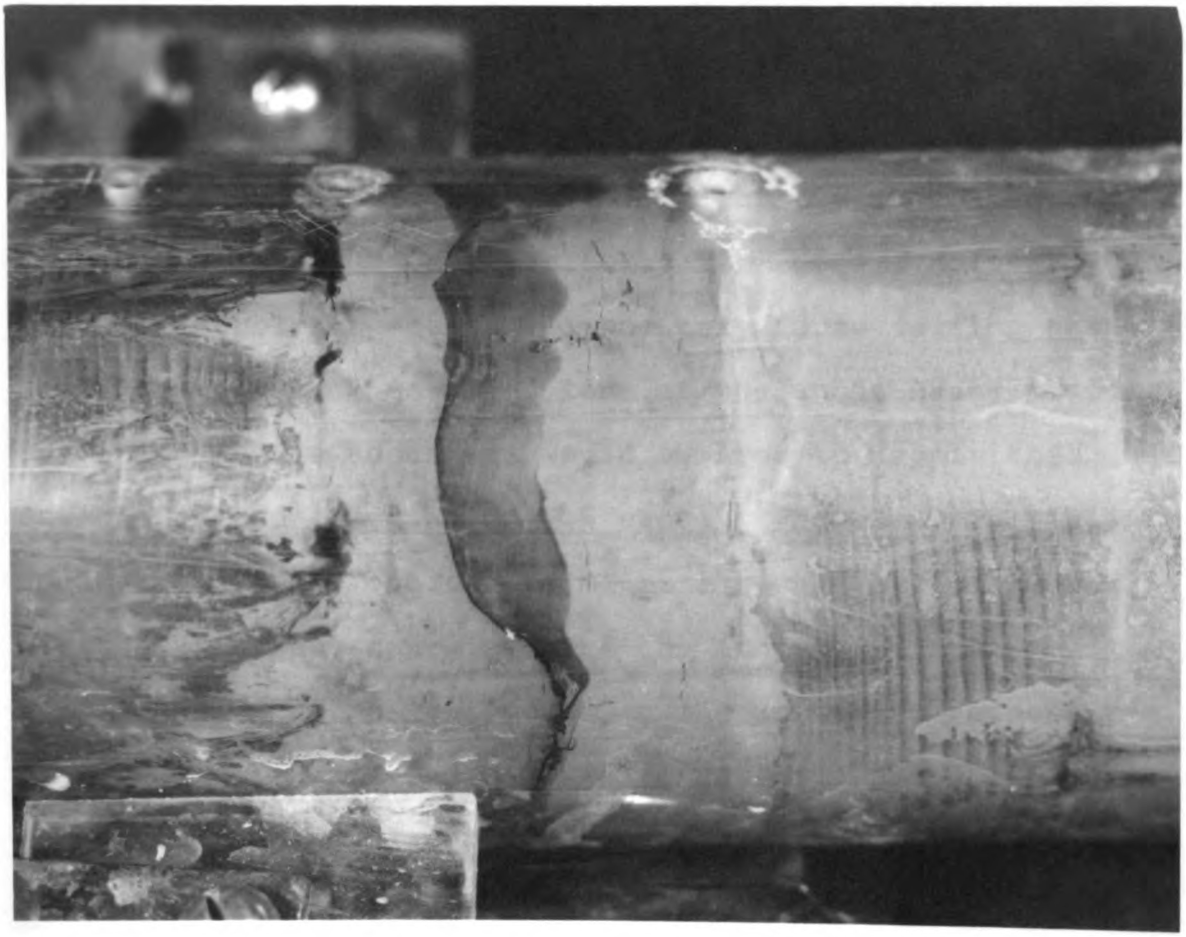


Figure 13. Main tube assembly showing grey area.

A litmus paper test gave a basic reaction on the cathode side of the soil plug which the above equations predict. However, the acid reaction which would be expected on the anode side was not observable with litmus paper. Therefore, if an acid is formed at the anode, it is formed very slowly.

Murayama (1953) states that electrolytic action caused aluminum electrodes to dissolve to form metallic ions. Since electrolytic action was the only force causing the anode to dissolve, metallic ions of the anode metal would be formed at the anode and would be free to supply the cations needed in equation 2.5 above. The electric field would cause these cations to migrate toward the cathode. Electrolytic action would cause the anode to dissolve rapidly until corrosion formed on the anode and reduced the current flow. This rapid dissolving of the anode initially would explain the "layer like" characteristic of the colored area in the soil mass. Later migration toward the cathode of the concentrated ions would account for the slow movement of the colored area toward the cathode.

The changes observed in the soil hardness and moisture content are due to the changes in chemical characteristics of the soil particles which are caused by exposure of the soil particles to the high concentration of one type of metallic ion--the type of ion depending on the anode material. The exposure of the soil would cause an alteration in the exchange complex of the soil particles. This would change the amount of water bound to the particles.

Baver (1929) and Lutz (1934) showed that the type of ions on the exchange complex of the clay influences the permeability of the soil. Therefore, since electro-osmosis can change the ions on the exchange complex, care must be taken that the permeability of the soil would not be reduced if electro-osmosis were used for irrigation or drainage.

Flow Reversal

The clay samples were allowed to run until a negative electro-osmotic head (hydraulic head on the anode side was greater than the electro-osmotic head on the cathode side) developed. The polarity of the electrodes was then reversed and the direction of flow of water could be determined by observing the change in head. Figures 15 through 19 show the water moved from the original cathode toward the original anode when the polarity of the electrodes was reversed. Figures 20 through 21 show that the same occurs in loam soils. This would be expected unless the charge on the water had been changed from positive to negative. Therefore, the soil and the water do not reverse electrical charges by being subjected to electro-osmosis. This means that the alterations in the exchange complex of the clay which took place in these tests did not change the sign of the effective charge on the clay. However, this does not mean that different materials used for the anode would not change this effective charge.

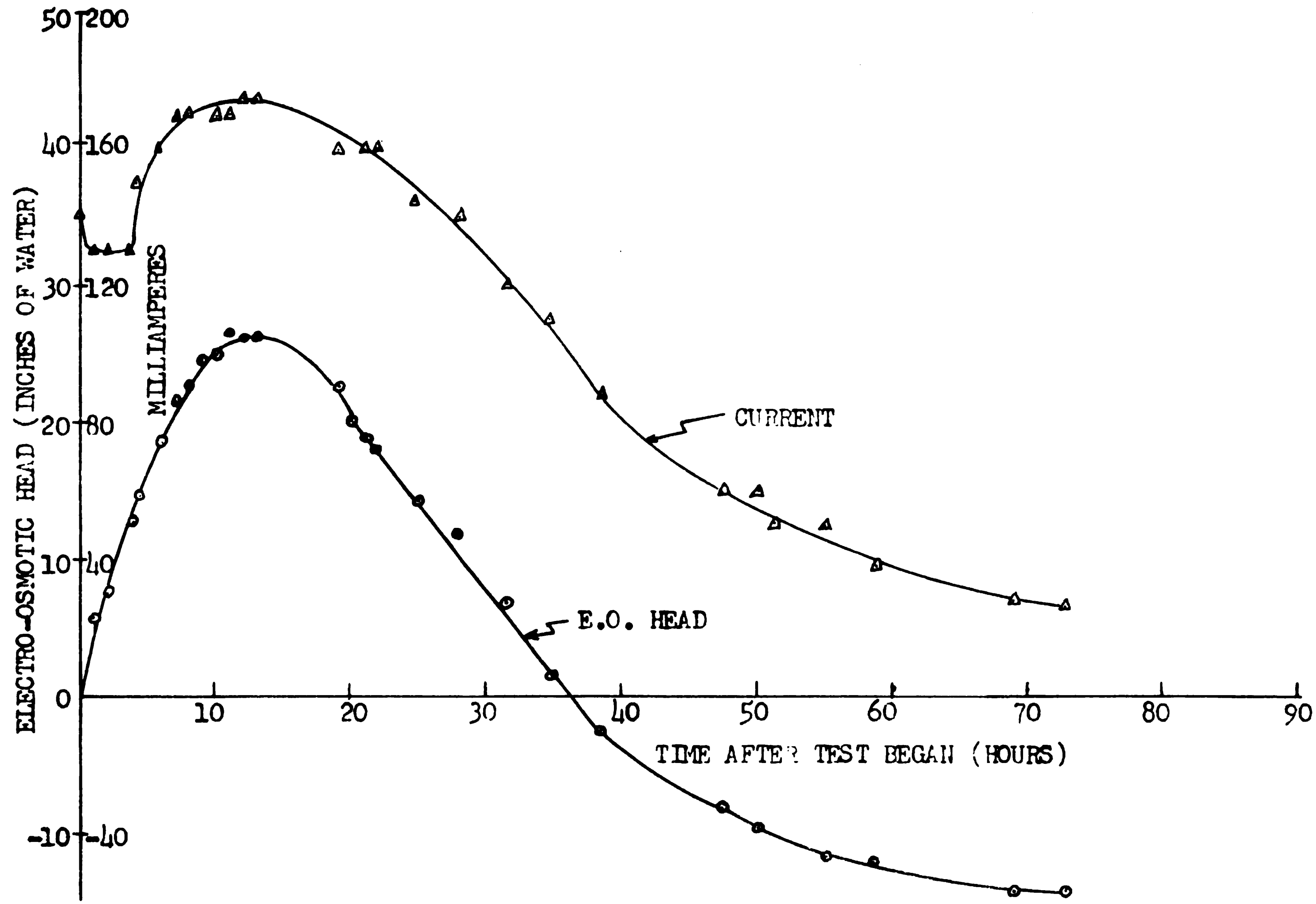


Figure 14. Electro-osmotic head and current versus time for clay soil under a potential of 20 volts.

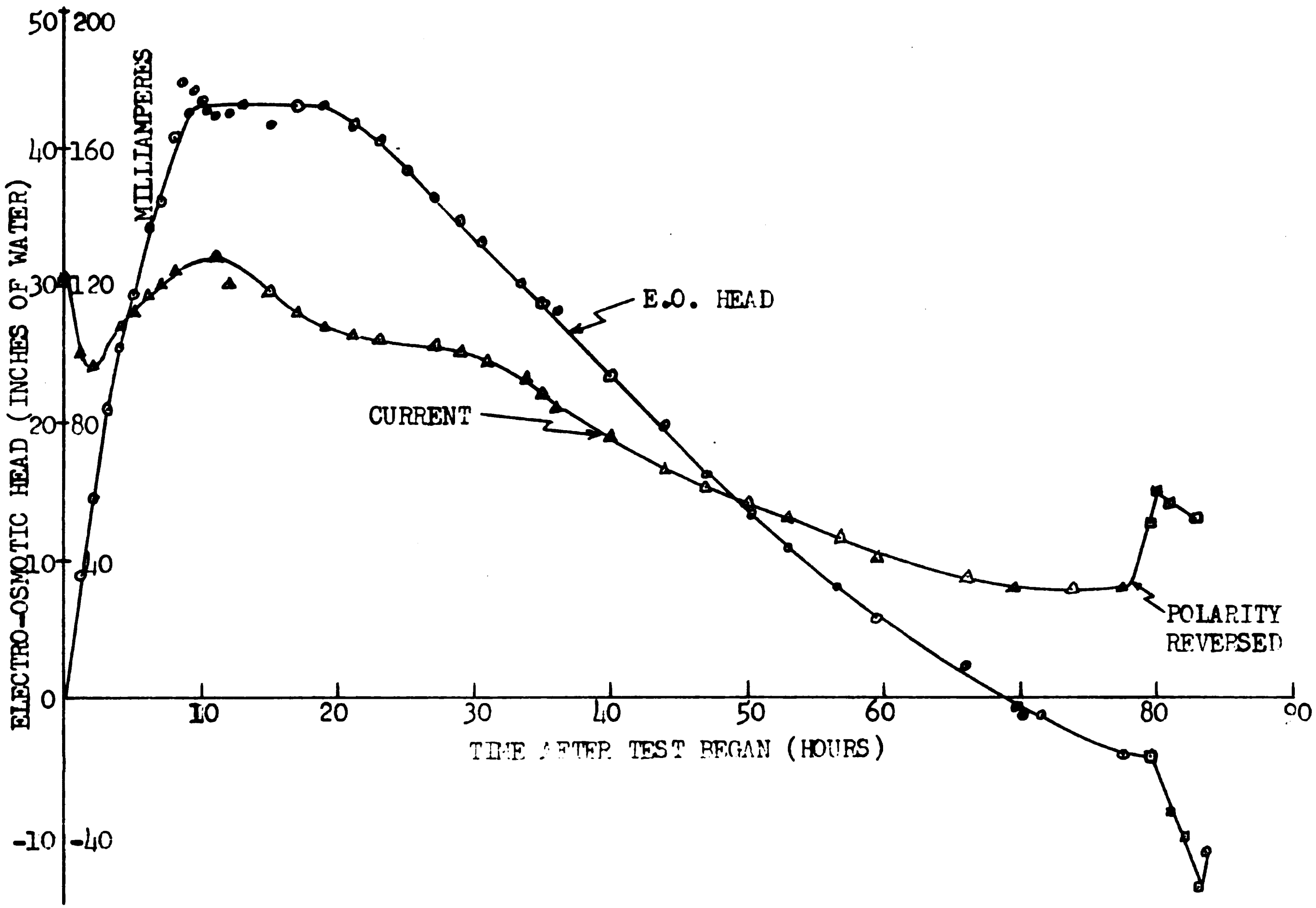


Figure 15. Electro-osmotic head and current versus time for clay soil under a potential of 20 volts.

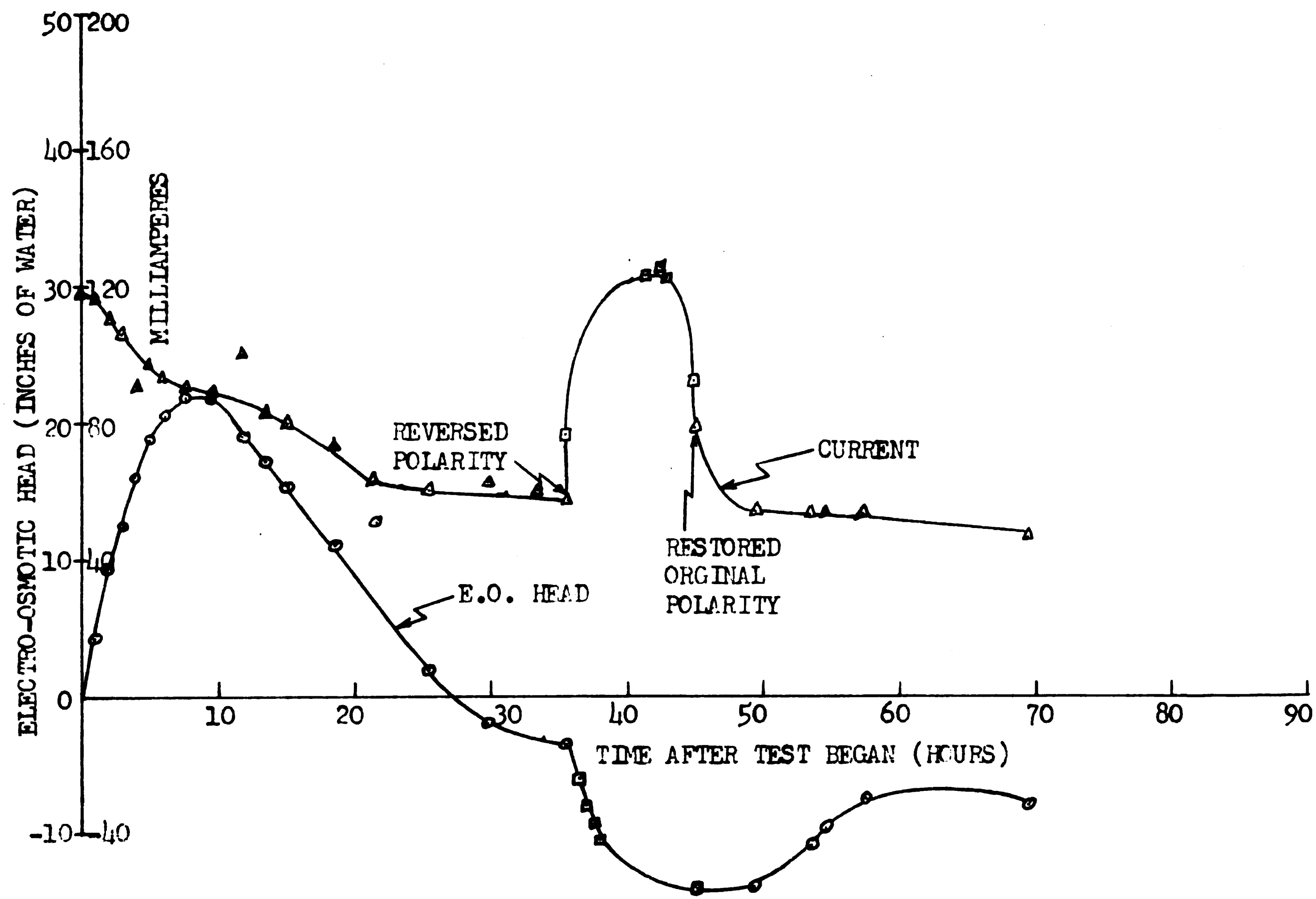


Figure 16. Electro-osmotic head and current versus time for clay soil under a potential of 20 volts.

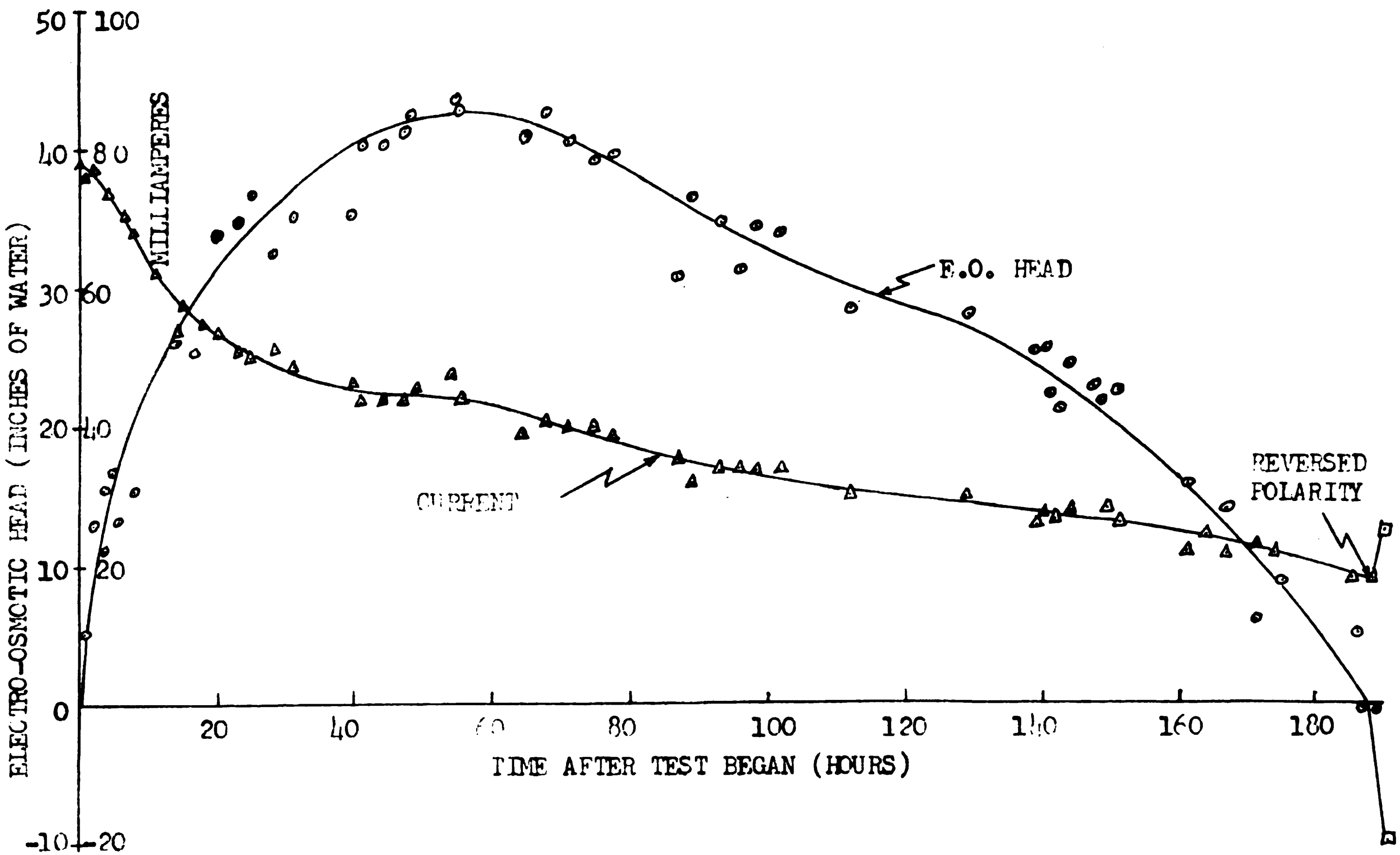


Figure 17. Electro-osmotic head and current versus time for clay soil under a potential of 15 volts.

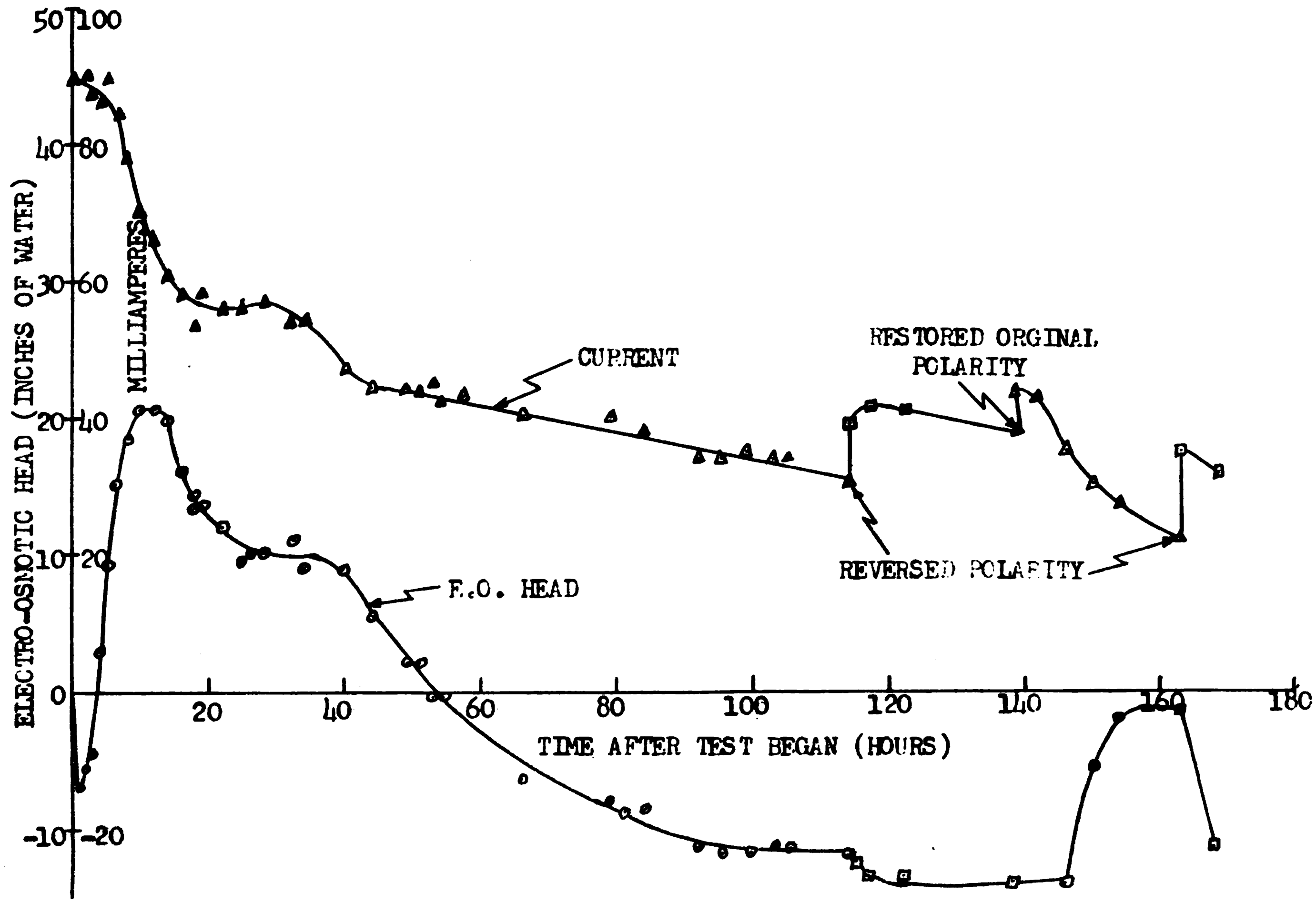


Figure 18. Electro-osmotic head and current versus time for clay soil under a potential of 15 volts.

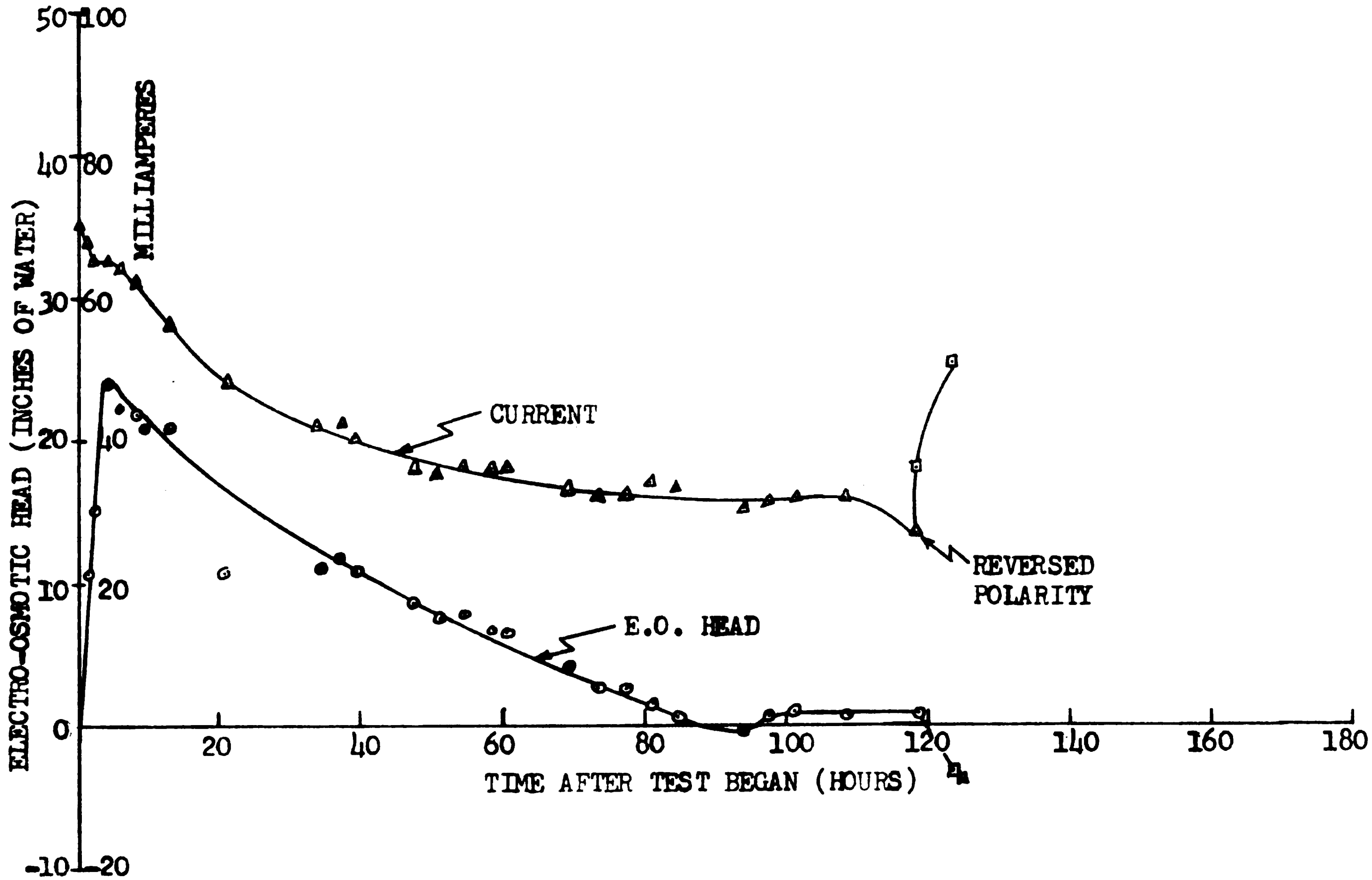


Figure 19. Electro-osmotic head and current versus time for clay soil under a potential of 15 volts.

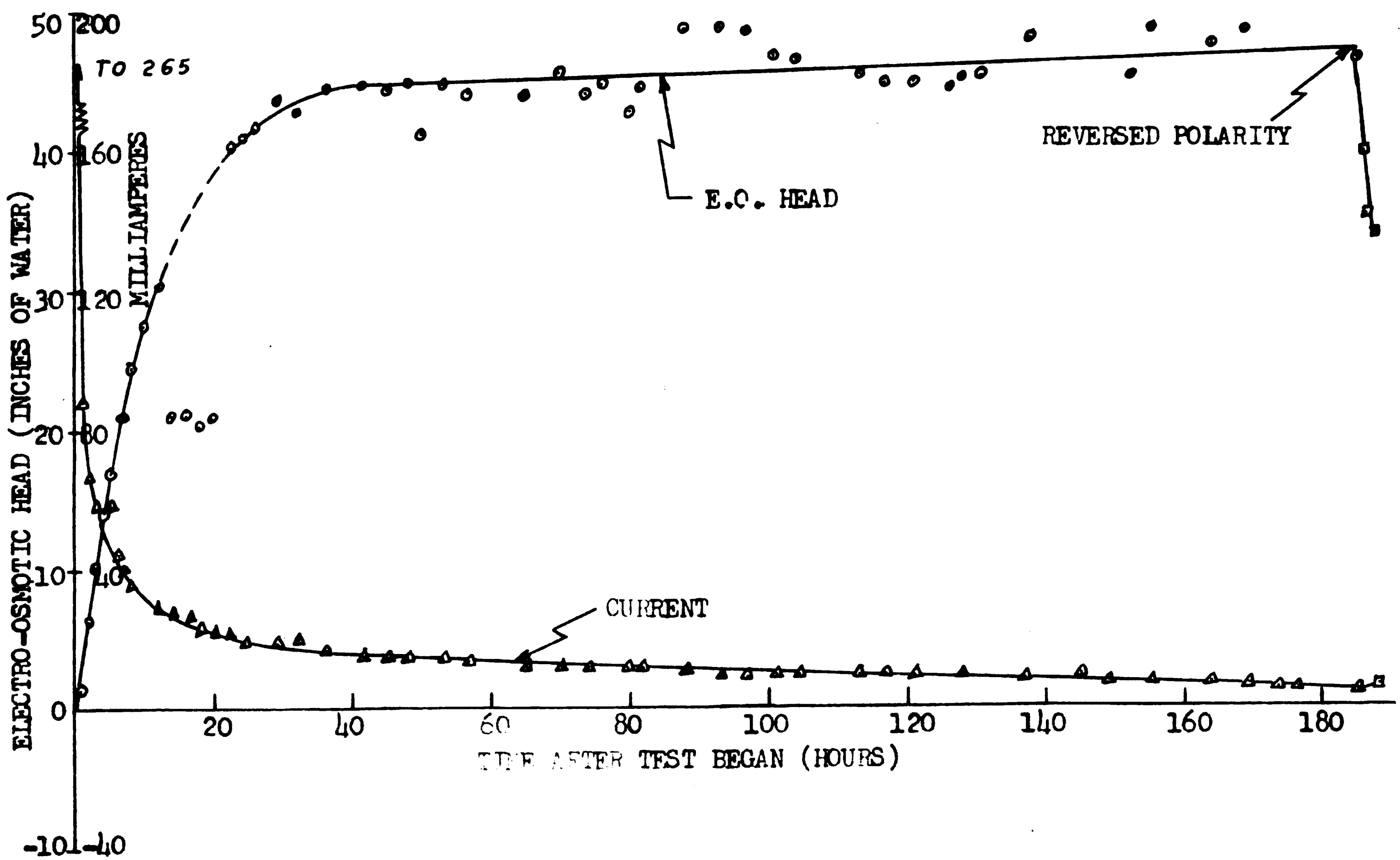


Figure 20. Electro-osmotic head and current versus time for loam soil under a potential of 20 volts.

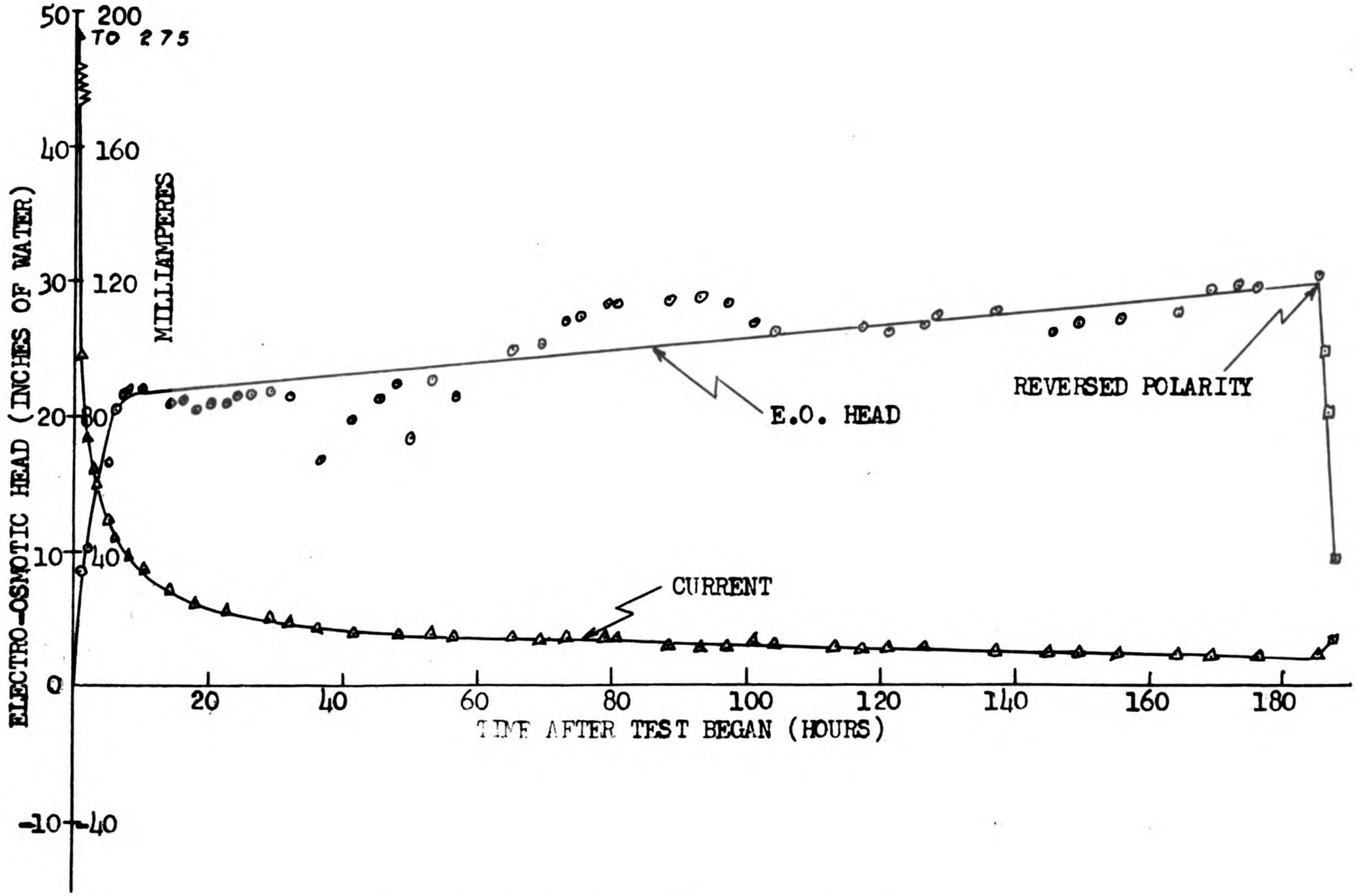


Figure 21. Electro-osmotic head and current versus time for loam soil under a potential of 20 volts.

Electro-Osmotic Head

Figures 14 through 16 show the results obtained when a clay soil plug 1-1/2 inches in length has 20 volts impressed across it. Figure 14 shows a maximum head rise of 26.5 inches of water while Figure 15 shows a maximum of 43.0 inches of water and Figure 16 shows a maximum of 22.0 inches of water. Writing equation 2.4 as:

$$\frac{h\ max}{E} = \frac{K_e}{K_h}$$

it was found that for E = 20 volts the ratio $\frac{K_e}{K_h}$ varies from 2.15 to 1.1. From the equation developed by Vey (1949) (equation 1.6) it can be seen that this variation in head may be explained in two ways. If the zeta potential was different the pressure would be different. However, all the soil used in these tests came from the same sample of soil, hence, any difference in zeta potential between samples would be small. Therefore, if Vey's work is excepted, the voids ratio must be different for different samples. This was due to the difference in packing of the samples in the tube.

The same reason would explain the variation in maximum head observed for clay soil with E = 15 volts as shown in Figures 17 through 19.

Another interesting phenomenon which Figures 14 through 19 illustrate was the loss of the electro-osmotic head with increased time. Geuze (1948) observed this also and postulated that the metallic ions from the anode which went into solution had a strong flocculating power on the negatively charged colloidal soil particles or that these metallic ions caused a formation of insoluable compounds which would depend on the acidity and composition of the soil solution.

Baver (1929) and Lutz (1934) proved that the hydraulic permeability depended on the type of ion which dominated the exchange capacity of the soil.

It was also noted that the electro-osmotic head dropped off while the colored area referred to above moves through the soil. This concentration of metallic ions changes the type of ions on the exchange complex of the clay and must therefore change the hydraulic permeability of the soil. Since the electro-osmotic head decreases the ratio of $\frac{K_e}{K_h}$ must decrease.

Casagrande (1948b) stated that cracking which occurs in clay soils due to electro-osmosis caused the hydraulic permeability (K_h) to increase due to the increased size of some of the water passageways. Cracking was observed to occur in the clay samples tested, hence, K_h would increase. This would cause the $\frac{K_e}{K_h}$ fraction to decrease and the electro-osmotic head to decrease as was observed.

The consolidation observed to occur in these tests would tend to decrease K_h and would cause the electro-osmotic head to increase. These two factors would tend to counteract each other. Which factor was governing for a given soil must be determined for each soil. For the clay soil used in these tests the effect of cracking was the most important.

When a loam soil was used different head curves were obtained (Figures 20 through 21). In this case there was no evidence of a decrease in the ratio of $\frac{K_e}{K_h}$ since the electro-osmotic head slowly increases with time. Since the voltage was constant the rise in head was caused by an increase in K_e or a decrease in K_h. Other date indicates K_h decreases from 0.10 to 0.02 inches per hour after being subjected to electro-osmosis for 180 hours. Therefore, the decrease in K_h accounts for the slow increase in head with time.

The decrease in K_h (hydraulic permeability) was due to changes in the principal ion on the exchange complex of the clay particles and to the consolidation of the soil which was observed during each test. If this process was employed for drainage and irrigation of soils the above mentioned factors must be carefully considered.

The dotted portion of the head curve in Figure 20 was due to the development of a leak in the system which allowed the head to drop. This explains the large variation observed in the readings in the dotted portion of the curves.

The data obtained for sand supports Casagrande's (1948b) work. He states that electro-osmosis was practical for drainage only on tight soils since the hydraulic permeability was much greater than the electro-osmotic permeability in sands. The electro-osmotic head developed in sand was found to be zero. Therefore, electro-osmosis could not be used for irrigation or drainage of sandy soils since the downward hydraulic flow would greatly exceed the upward electro-osmotic flow.

Current

Figures 14 and 15 show an unusual feature in that the current drops rapidly during the first two hours and then begins to rise again. This tendency was also slightly evident in Figure 16. However, Figures 17 through 19 reveal a relatively slow decrease in current with time. The voltage used was the only difference in these two sets of curves. Figures 20 through 21 reveal a very rapid drop in current during the first 2 to 3 hours with a gradual decrease in the rate of decline after this period. These observations show that the amount of current passed through the soil depends on the soil type and the voltage impressed across it.

Clay soil will carry more current over a longer period of time (Figures 14 through 19) but loam soil has a very high initial current carrying capacity which rapidly decreases with time (Figure 20 through 21). Sand (Tables 1 and 2 in appendix) initially will carry only low currents and this decreases rapidly with time. Since Casagrande (1948b) found that the amount of water and the head sustained due to electro-osmosis was a direct function of the amount of current passing through the soil, the low current carrying capacity and high hydraulic conductivity of sand would explain why it can not be drained or irrigated by electro-osmosis. The relatively high current carrying capacity (low resistance) and the low hydraulic permeability of clay would make clay an ideal soil for the application of electro-osmosis. A loam would not be the best soil on which to use electro-osmosis since large current carrying equipment would have to be employed to allow for the high initial current consumption. The large electrical equipment would be expensive. However, the use of appropriate current limiting devices should provide a solution to this problem.

On clay and loam soils reversal of the electrode polarity after the soil has been subjected to electro-osmosis for a period of time causes the current to rise rapidly (Figures 15 through 21). This phenomenon was more pronounced on clay than on loam soils.

CONCLUSIONS

1. A reversal of electric charge on the clay particles does not occur due to the application of an electric potential alone.
2. Electrolytic action caused serious corrosion of the electrodes, particularly the anode. Copper and solder-coated copper electrodes were unsatisfactory. Perforated stainless steel electrodes were acceptable but some corrosion was evident.
3. The electro-osmotic head developed depended on the hydraulic permeability, electro-osmotic permeability, and voltage applied.
4. Sand having a high hydraulic conductivity can not be drained or irrigated by electro-osmosis.
5. Both drainage and irrigation of clay and loam soils by electro-osmosis appears to be feasible.
6. The ion theory and the double layer theory are the same theoretical explanation of electro-osmosis.
7. Corrosion of the electrodes caused changes to take place in the exchange complex of the clay particles.
8. The hydraulic permeability was decreased on loam soil by the application of electro-osmosis.
9. Soil type affects the amount of current passed through a soil.

SUMMARY

This investigation explored the possibility of a charge reversal on the clay particles due to the extended application of an electric potential. The results indicated that a charge reversal does not occur on clay or loam soil after subjection to electro-osmosis for 80 hours under a potential of 20 volts. A charge reversed did not occur after 180 hours on clay soil with a potential of 15 volts.

The electro-osmotic head developed in a clay, a sand, and a loam soil due to an electric potential of 20 volts impressed across a soil plug 1-1/2 inches in length was determined. Clay soil was found to develop a maximum head ranging from 20 to 43 inches of water. A maximum head of from 31 to 48 inches of water was observed on a loam soil after 185 hours. If Vey's (1949) work is accepted the variations in head observed for the same type of soil were due to differences in the void ratios of the soil samples. In sand no electro-osmotic head was developed because of the high hydraulic conductivity of sand. These investigations indicate that the head developed under saturated conditions depends on the hydraulic conductivity, the electro-osmotic conductivity and the voltage applied.

The fact that a flow reversal did not occur and an electro-osmotic head was developed in the clay and loam soil indicates that these soils might be irrigated and drained by electro-osmosis.

Several types of electrode material were used. Copper and solder-coated copper electrodes eroded rapidly and were rejected. Perforated stainless steel was found to be the most satisfactory.

Theoretical evidence presented indicates that the ion theory and the double layer theory are not two theoretical explanations for electro-osmosis but are the same theory stated in two forms.

SUGGESTIONS FOR FURTHER STUDY

1. Determine the amount and height of rise of moisture under unsaturated conditions for natural and pure soils.
2. Determiné the effect of different types of electrode material on soil characteristics (i.e. permeability, consolidation, plant reaction, etc.).
3. Determine the reaction of plants to the passage of electricity through the soil.
4. Determine if soil aeration will become restricted due to gas generated by electro-osmosis under field conditions.
5. Study the possibility of using electro-osmosis for the desalinazation of alkaline soils.
6. Determine if electro-osmosis can be used to remove salt from sea water.
7. Explore the possibility of using electro-osmosis to dry grain, forage crops and manures.
8. Determine if electro-osmosis could be used as a process for the drying of food products such as cherries, apples. potatoes, etc.
9. Determine the energy requirements and the cost of using electro-osmosis for drainage of clay and loam soils.
10. Study the possibility of using thermo-osmosis and a nuclear reactor for conversion of energy directly from heat to electricity.

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TABLE 1.--Date for sand soil under a potential of 20 volts.

Hydraulic head (H_h) (in. of water)	Electro-osmotic head (H_e) (in. of water)	H_e-H_h	Milliamperes	Time after test began (hours)
16.50	16.50	0.00	22	0
16.50	16.50	0.00	7	1
16.50	16.50	0.00	6	2
16.50	16.50	0.00	4	4
16.50	16.50	0.00	4	6
16.50	16.50	0.00	4	8
16.50	16.50	0.00	2	18
16.50	16.50	0.00	2	21

TABLE 2.--Data for sandy soil under a potential of 20 volts.

Hydraulic head (H_h) (in. of water)	Electro-osmotic head (H_e) (in. of water)	H_e-H_h	Milliamperes	Time after test began (hours)
16.50	16.50	0.00	35	0
16.50	16.50	0.00	7	1
16.50	16.50	0.00	4	3
16.50	16.50	0.00	5	5
16.50	16.50	0.00	4	7
16.50	16.50	0.00	2	17
16.50	16.50	0.00	2	20

TABLE 3.--Typical data for loam soil under a potential of 20 volts.

Hydraulic head (H_h) (in. of water)	Electro-osmotic head (H_e) (in. of water)	H_e-H_h	Milliamperes	Time after test began (hours)
16.50	16.50	0.00	265	0
16.50	19.00	2.50	88	1
16.50	23.00	6.50	67	2
16.50	26.75	10.25	59	3
16.50	30.50	14.00	53	4
16.50	33.50	17.00	58	5
16.50	36.00	19.50	44	6
16.50	38.50	22.00	41	7
16.50	41.00	24.50	36	8
16.50	44.00	27.50	32	10
16.50	46.75	30.25	29	12
16.50	37.50	21.00	28	14
16.50	37.75	21.25	26	16
16.50	37.00	20.50	25	18
16.50	57.00	40.50	21	22½
16.50	57.50	41.00	20	24
16.50	58.25	41.75	20	26
16.50	60.25	43.75	20	29
16.50	59.25	42.75	20	32
16.50	61.00	44.50	17	36½
16.50	61.25	44.75	16	41½
16.50	60.75	44.25	15	45
16.50	61.50	45.00	15	48
16.50	57.50	41.00	15	50
16.50	61.25	44.75	15	53
16.50	60.50	44.00	14	56½
16.50	60.50	44.00	12	65
16.50	62.25	45.75	12	70
16.50	60.75	44.25	12	74

TABLE 3.--(Continued)

Hydraulic head (H_h) (in. of water)	Electro-osmotic head (H_e) (in. of water)	H_e-H_h	Milliamperes	Time after test began (hours)
16.50	61.50	45.00	12	76
16.50	59.25	42.75	12	80
16.50	61.00	44.50	12	81½
16.50	65.50	49.00	11	88
16.50	65.50	49.00	10	93
16.50	65.25	48.75	10	97
16.50	63.50	47.00	10	101
16.50	63.25	46.75	10	104
16.50	64.50	48.00	10	113
16.50	64.00	47.50	10	117
16.50	64.00	47.50	10	121
16.50	63.50	47.00	10	126
16.50	64.50	48.00	10	128
16.50	65.00	48.50	9	137
16.50	57.50	41.00	8	149
16.50	65.50	49.00	8	155½
16.50	64.50	48.00	8	164
16.50	65.50	49.00	7	169
16.50	63.75	47.25	6	173
16.50	63.75	47.25	6	176
16.50	63.25	46.75	5	185
		Reversed Electrode Polarity		
16.50	63.25	46.75	6	185
16.50	56.50	40.00	7	186
16.50	52.00	35.50	6	186½
16.50	50.75	34.25	7	187½
16.50	33.75	17.25	6	189
16.50	19.50	3.00	8	193

TABLE 4.--Typical data for clay soil under a potential of 20 volts.

Hydraulic head (H_h) (in. of water)	Electro-osmotic head (H_e) (in. of water)	H_e-H_h	Milliamperes	Time after test began (hours)
17.00	17.00	0.00	121	0
17.00	21.00	4.00	110	1/4
17.00	22.75	5.75	106	1/2
17.00	24.00	7.00	102	3/4
17.00	26.00	9.00	100	1
17.00	29.25	12.25	96	2
17.00	34.25	17.25	100	2½
17.00	37.75	20.75	102	3
17.00	39.50	22.50	105	3½
17.00	42.50	25.50	108	4
17.00	44.25	27.25	110	4½
17.00	46.25	29.25	112	5
17.00	50.75	33.75	118	6½
17.00	53.00	36.00	120	7
17.00	53.00	38.00	120	7½
17.00	57.75	40.75	121	8
17.00	61.50	44.50	120	8½
17.00	59.50	42.50	121	9
17.00	61.25	44.25	122	9½
17.00	60.50	43.50	122	10
17.00	59.50	42.50	122	10½
17.00	59.25	42.25	122	11
17.00	60.50	43.50	120	11½
17.00	59.50	42.50	120	12
17.00	60.00	43.00	120	13
17.00	58.50	41.50	118	15
17.00	60.00	43.00	112	17
17.00	60.00	43.00	108	19
17.00	58.50	41.50	105	21

TABLE 4.--(Continued)

Hydraulic head (H_h) (in. of water)	Electro-osmotic head (H_e) (in. of water)	H_e-H_h	Milliamperes	Time after test began (hours)
17.00	57.25	40.25	104	23
17.00	55.25	38.25	104	25
17.00	53.25	36.25	102	27
17.00	51.50	34.50	100	29
17.00	50.00	33.00	97	31
17.00	47.00	30.00	92	34
17.00	45.50	28.50	88	35
17.00	45.00	28.00	84	36
17.00	40.25	23.25	76	40
17.00	36.75	19.75	66	44
17.00	33.00	16.00	62	47
17.00	30.25	13.25	56	50½
17.00	27.75	10.75	52	53
17.00	25.00	8.00	46	57
17.00	22.75	5.75	40	59½
17.00	19.25	2.25	34	66
17.00	16.25	-0.75	31	69½
17.00	15.75	-1.25	31	71½
17.00	15.00	-2.00	31	74
17.00	12.75	-4.25	31	77½
Reversed Electrode Polarity				
17.00	12.75	-4.25	50	79½
17.00	11.50	-5.50	60	80
17.00	8.50	-8.50	56	81
17.00	6.75	-10.25	53	82
17.00	3.00	-14.00	52	83

TABLE 5.--Mechanical analysis of soils used.

Soil	Fraction	Per Cent
	sand	4.4
clay	silt	61.2
	clay	34.4
	sand	45.9
loam	silt	29.7
	clay	24.4
sand	sand	82.3
	silt and clay	17.7