Interface Modeling for Electro-Osmosis In Subgrade Structures

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ABSTRACT

Conventional waterproofing techniques for below grade structures are ineffective, expensive and short lived. Electro-Osmotic Pulse technology is an alternative technique to controlling moisture movement in porous medium. A research study was undertaken to model the complex osmotic behavior of a system consisting of portland cement with aggregate and different clays (kaolinite, montmorillonite, limestone and quartz sands) created to simulate below grade structures. A direct current 30- to 45-Volt source was applied across the 8-inch cell of concrete and backfill. The electrolytes used were sodium chloride and calcium chloride. The results showed the electromigration of a low pH front interacted with the high pH present in the concrete matrix to form complex calcium precipitates ($CaCO_3$) that fill the pore space and microcracks along the path of osmotic flow. As the experiment continued, the osmotic flow reduced as the pore voids continued to fill with water insoluble precipitate.

1. INTRODUCTION

In below-grade buildings and buried structures, such as those constructed as hardened secure facilities and used for munitions storage on U.S. Army installations, water intrusion can cause serious damage and reduce penetration resistance. Inside the building active water and high humidity can ruin expensive HVAC, electronic equipment, as well as damage or disrupt mission critical electronic equipment. In the adjacent backfill and the structure itself, excessive water can seriously compromise the structural hardening of the facility. Thus, it is vital to Army sustainability to control moisture in and around below-grade structures.

Control of water movement involves both actively removing water in and around a building, and the use of barriers to prevent water from penetrating to interior spaces. A pumping system is typically required with the use of a barrier system to assist in controlling the movement of moisture into the structure. Conventional waterproofing technologies are expensive and often have short service life. A new approach is needed—a cost effective and robust solution—to the pervasive problem of water intrusion. Electro-Osmotic Pulse is a promising alternative solution presented here.

Electro-Osmotic Pulse (EOP) technology uses pulses of electricity to reverse the flow of water seepage. The applied voltage causes moisture to flow out of the basement walls and away from the building. The technology works by alternately pulsating a direct electric field with an off period. The first part of the sequence consists of a pulse of positive voltage (as seen from the dry side of the concrete wall), followed by a pulse of negative voltage. This is followed by a period of rest (the "off period") when no voltage is applied. Of the three parts, the positive voltage pulse has the greatest time duration. The amplitude of the positive signal is typically on the order of 30 to 40 Volts DC. This electrical pulse causes cations (e.g., Ca^{2+}) and associated water molecules to move from the dry side (anode) towards the wet side (cathode) against the direction of flow induced by the hydraulic gradient, thus preventing water penetration through buried concrete structures.

Electro-Osmotic Pulse (EOP) technology has been successfully installed in military structures and has been shown to prevent moisture seepage into below-grade structures. It is effective at keeping concrete surfaces at or below 50 percent humidity content, meaning the treated space stays dry, indoor relative humidity stays low, and no mold or mildew can grow.

A laboratory study was undertaken to model the complex osmotic behavior of a system consisting of portland cement with aggregate and different clays and sands created to simulate below grade structures. The objective was to investigate the physical and electrochemical processes that occur at material interfaces and their effect on capillary water transport in order to develop a fundamental understanding of these processes. The end result was an electrokinetic transport model for the system.

In 1809, F.F. Reuss (Reuss, 1809) originally described electro-osmosis in an experiment that showed that water could be forced to flow through a clay-water system when an external electric field was applied to the

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soil. Research has since shown that flow is initiated by the movement of cations (positively charged ions) present in the pore fluid of clay or similar porous medium such as concrete; the water surrounding the cations moves with them. Electro-osmosis can be used to arrest or cause flow of water as well as the ions in it. Electro-osmosis has been used in civil engineering to dewater dredgings and other high-water content waste solids, consolidate clays, strengthen soft sensitive clays, and increase the capacity of pile foundations. It has also received significant attention in the past 5 years as a method to remove hazardous contaminants from groundwater or to arrest water flow.

The basic physics and chemistry of electro-osmosis can be found in several textbooks and treatises (Glasstone 1946, Tikhomolova 1993). For electro-osmosis to be effective, capillary pores must be present in the medium, the medium must have fixed surface charges (clays, concrete, and related materials are common media), the medium should be saturated, and the fluid (pore solution) must be a dilute electrolyte. There are several forces operating on the pore solution within the medium; forces due to gravity, hydraulic pressure, viscosity, electro-osmosis, and temperature. The dominant force components are generally those due to pressure and electro-osmosis. In applications for preventing water seepage, where the seepage is caused by hydrostatic pressure, the electro-osmotic force must balance or exceed the hydraulic pressure force.

The velocity equation of the pore solution in the medium is expressed as:

$$(1) \quad \mathrm{v}_e = \frac{\varepsilon \xi E}{4 \pi \mu l}$$

Where:

v_e = flow velocity of solution (meters/second)
ε = dielectric constant of water (Farads/meter)
ξ = zeta potential[1] (Volts)
E = potential applied across material (Volts)
μ = viscosity of liquid (Pascal-seconds)
l = distance between electrodes (meters).

The water and ions form an electrolyte where the positive ions tend to be solvated and the negative ones unsolvated. Thus, as the positive ions move through the pores, the water molecules move as well. So the water movement in practice is heavily dependent on ion concentration, type of material, and magnitude of applied electric field. Of the independent variables, E and j can be controlled to redirect the movement of the solution.

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[1] The difference of potential between the plates of a hypothetical capacitor used to model the diffuse layer in the capillary structure.

2. EXPERIMENTAL PROCEDURE

The primary controlled variables for this experiment were soil type, electrolyte, and applied voltage. The types of backfill investigated are given in table 1. Multiple 6-inch diameter concrete cylinders with dense, low-reactivity quartz gravel used as coarse and fine aggregates as concrete specimens. Granular materials (clay and sand) used in the cell are well-characterized samples, and were contained using a geotextile mesh. The system tank (figure 1) was designed to maintain an equal fluid head on both sides of concrete-soil interface. Over the course of the experiment, current flow, voltage potentials, pH and rate of water transfer were measured.

Table 1: Particulate Backfills Investigated
Limestone Sand 100 Sieve
Quartz Sand 100 Sieve
Ca Montmorillonite
Na Montmorillonite
Kaolinite

The test setup used a 0.45 water to cement ratio concrete cylinder section 4-inches long and 6-inches in diameter sealed in the center of the setup (Figure 2). Immediately adjacent to the concrete was a 4-inch long section filled with either a type of clay or sand supported by geotextile. The balance of space in the tank was filled with electrolyte. Electrodes consisting of a 1-foot long, $1/16^{th}$-inch diameter titanium wire coated with conductive ceramic were used at both the anode and cathode. The electrodes were maintained parallel and 2-inches from the face of each exposed end. All connections were sealed to prevent shorting and corrosion problems.

A driving voltage of 30 to 45V was applied across the 8-inch cell of concrete and backfill. The electrolytes used were 0.1M Sodium Chloride and Calcium Chloride in distilled water to minimize the total cell electrical resistance. This voltage supplied the necessary osmotic driving pressure to migrate water through the concrete and clay cell under test. The net migration of electrolyte was from anode (+) to cathode (-), and the cumulative transport was measured by weighing the overflow flask.

Experimental data was collected every two to six hours over the course of each run. The experiments ran over the course of one week. The anode pH was measured using a hand held instrument inserted into the anode well with the applied voltage momentarily shut off to avoid interference from the applied electric field and the pH reference cell. The cathode pH was estimated by measuring the pH of the displaced electrolyte in the

overflow flask. This measurement was taken indirectly to avoid displacing electrolyte in the cathode well into the overflow flask. The mass of water in the overflow flask was weighed and added to a cumulative total. The cell current was measured as a voltage drop across a resistive series shunt.

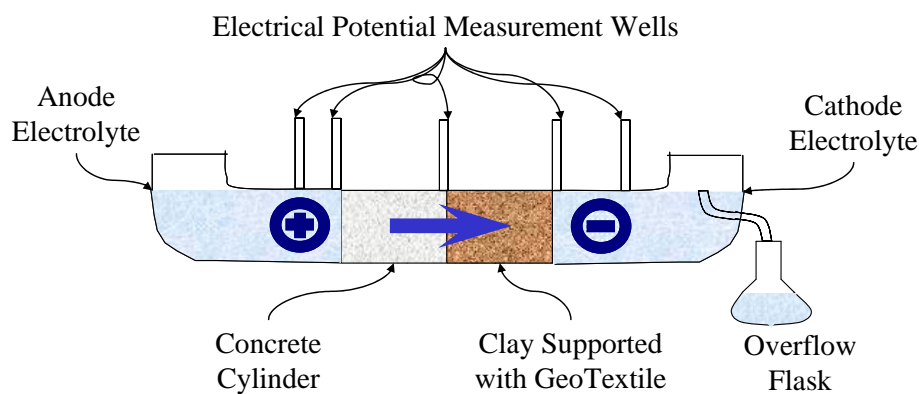Figure 1. Picture of bench scale test cell

Figure 2. Cutaway view of experimental apparatus

3. RESULTS

A plot of the cumulative electrolyte transported with respect to time is plotted simultaneously with the current in figure 3 for a concrete and kaolinite cell with 30-VDC applied. When the experiment was initiated, there was a high transport rate that quickly lowered after the first half day. For the first two days the transport behavior resembled a sigmoidal or logarithmic behavior. For the third day to the end of the experiment the transport modeled reasonably well to a linear fit of much lower positive slope.

The electrolyte transport behavior was similar in nature across all backfill materials tested, including the non-reactive quartz sand. Thus, it is likely that the

concrete plays a dominant and limiting role in the net system transport. The change in transport as the experiment progressed is likely due to shifts in the concrete chemistry and pore structure.

It is well known that the pH of the solution can change dramatically near the electrodes during electro-osmosis (Nemec 1988). This is due to the oxidation and reduction reactions that occur at the anode and cathode. For each experimental run, the pH change of the solution in both the anode and cathode wells was measured. A representative plot of pH evolution for concrete and Na montmorillonite cell are plotted in Figure 4. The anode well becomes very acidic while the cathode well becomes basic. The observed pH changes are moderated compared to the calculated changes due to carbon dioxide (CO_2) reaction with water (H_2O) to form carbonic acid (H_2CO_3), which reacts with the acidic and alkaline pH changes in the anode and cathode wells.
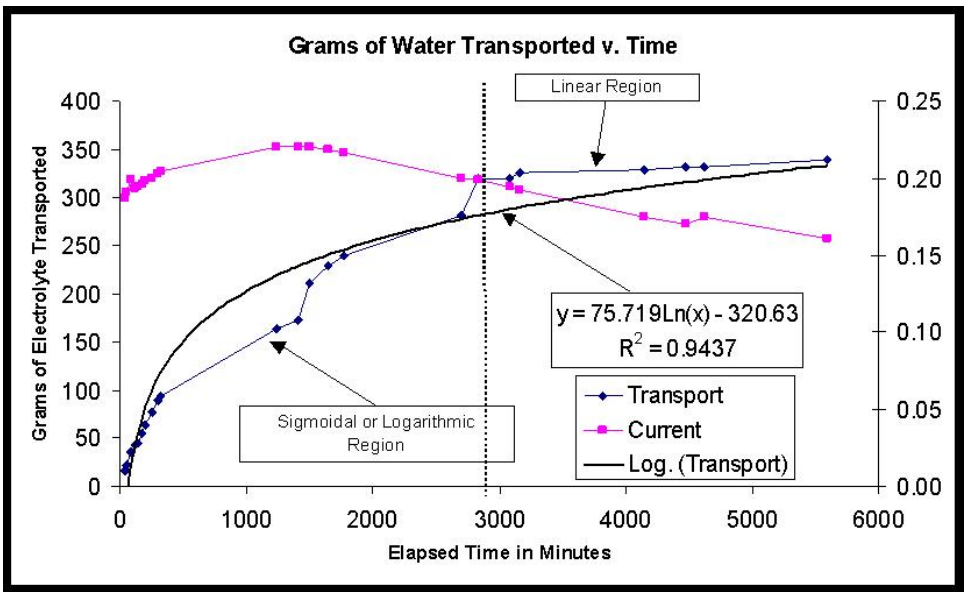

Figure 3. Cumulative electrolyte transported and cell current for concrete and Kaolinite cell
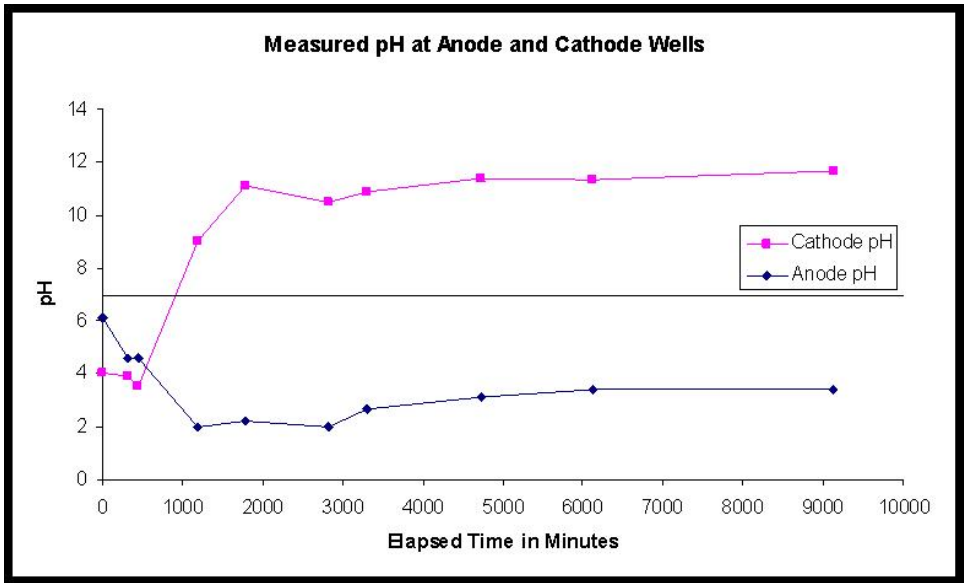

Figure 4. Measured pH for Concrete and Na Montmorillonite cell

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Scaling occurred at the interface between the anode electrolyte and the concrete. Energy-dispersive X-ray Analyses analysis determined the scale was composed of Calcite (figure 5). Some etching also occurred. Electro-osmosis results in the migration of calcium and silicate ions in the concrete along with the capillary water.

The combination of etching and electromigration creates deposits of calcium-rich compounds at the cathode and silicate rich-phases at the anode. Ion migration and scaling significantly change the electrical resistance and the permeability of the concrete, altering the water transport properties.
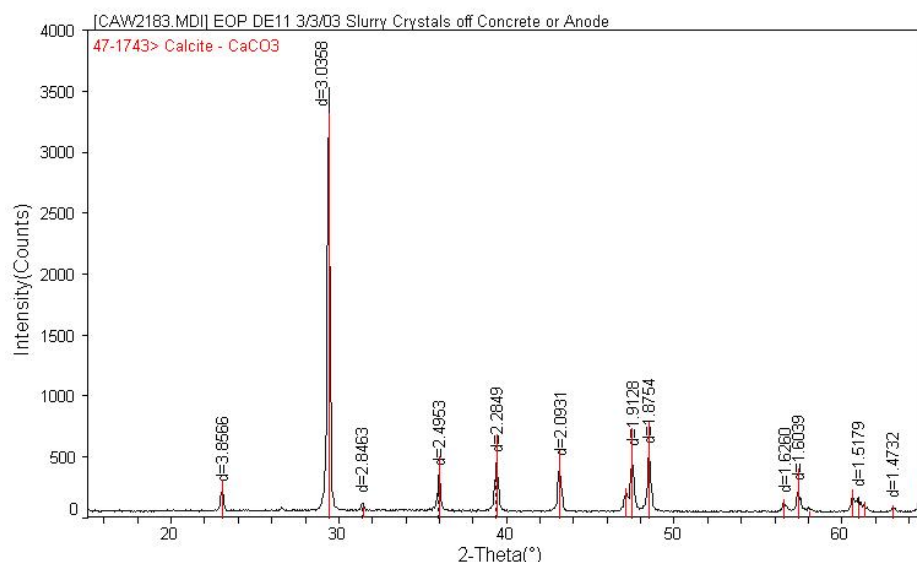

Figure 5 X-ray diffraction pattern of scale deposits on concrete face, on anode side
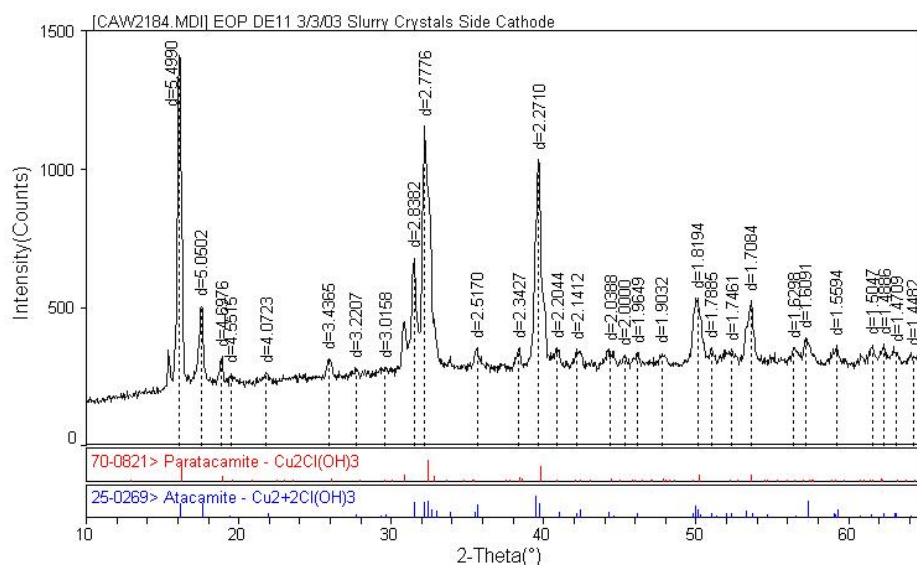

Figure 6. X-ray diffraction pattern showing hydroxide corrosion of concrete on the cathode face

The results showed the electromigration of a low pH front (from the anode side) interacted with the high pH present in the concrete matrix to form complex calcium precipitates ($CaCO_3$) that fill the air voids and microcracks along the path of osmotic flow. As the experiment continued, the osmotic flow greatly reduced as the pore voids continued to fill with water insoluble precipitate.

Figure 5 shows how the electro-osmotic flow generates and migrates an alkali front. This front produces a permanent precipitation zone or cemented zone in the concrete. The alkali production rate depends

on the spacing of the electrodes and relative rates of transport from the anode and cathode (diffusion) and electromigration. Precipitation can occur in both capillary pores and fractures. The net effect is to make the concrete denser and less hydraulically permeable.
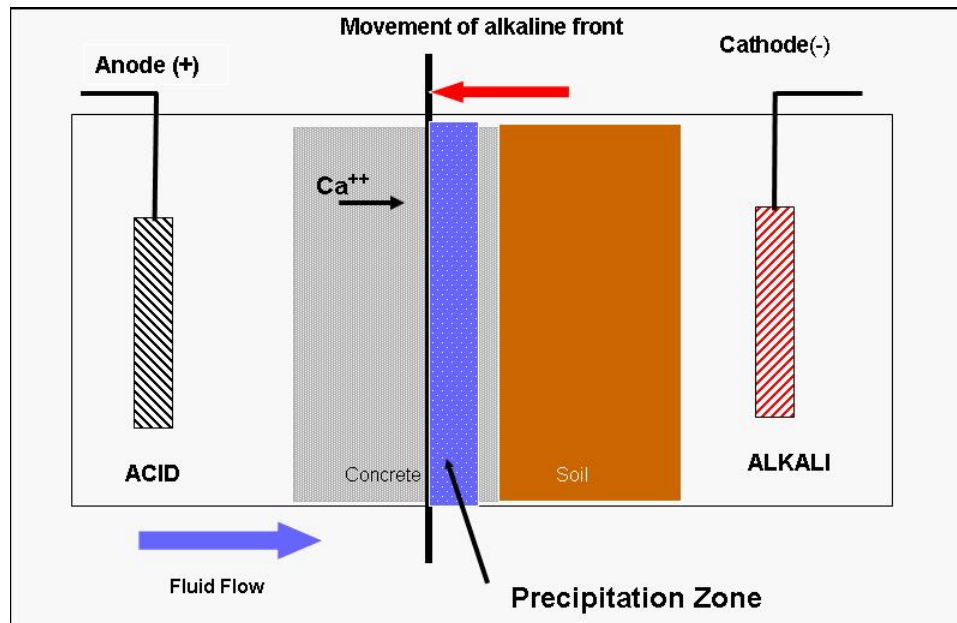

Figure 5. Diagram for Migrating Alkaline front theory

CONCLUSIONS

The major conclusions drawn from this investigation are:

a. The interaction of electro-osmotic flow and alkali front can produce a permanent precipitation zone or cemented zone in the concrete.

b. Precipitation of water insoluble Ca compounds in the capillary pores and microcracks is the likely mechanism for shutdown of osmotic flow.

c. The precipitate production rate depends on the spacing of the electrodes and relative rates of transport from the anode (electro-osmosis) and cathode (diffusion).

d. The net effect of the migrating ionic fronts is to make the concrete denser and less pervious.

REFERENCES

Reuss, F.F., 1809: "Memoires de la Societe Imperiale des Naturalistes de Moscou." 2, 327.

Glasstone, S., 1946: Textbook of Physical Chemistry, 2d ed., D. Van Nostrand Company, Inc., Princeton, NJ.

Nemec, H. T., 1988: "Environmental pH Changes in Electrochemical Cell During Electro-osmotic Stabilization of Soils." Studia Geotechnica et Mechanica, vol V, No. 1 (1983), pp 13-38.

Tikhomolova, K.P., 1993: Electro-Osmosis., Ellis Horwood Ltd. Chichester, West Sussex, England.