STABILIZATION OF MONTMORILLONITE CLAY BY ELECTRO-OSMOSIS AND BASE EXCHANGE OF IONS

By

CHARLES EDWARD O'BANNON

Bachelor of Science
University of New Mexico
Albuquerque, New Mexico
1956

Master of Science
Harvard University
Cambridge, Massachusetts
1964

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
July, 1971

STABILIZATION OF MONTMORILLONITE CLAY BY ELECTRO-OSMOSIS AND BASE EXCHANGE OF IONS

Thesis Approved:

J. V. Parcher
Thesis Adviser

T. A. Haliburton

M. Abdel-Hady

D. Durham
Dean of the Graduate College

To my wife, Nancy, for her
understanding, encouragement
and patience throughout this
entire program of study and
research.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation and gratitude to the following individuals and organization:

To his adviser, Dr. James V. Parcher, for his encouragement, valuable suggestions and counsel during this entire program.

To Dr. T. Allan Haliburton for his interest, understanding and assistance on many facets of the research program.

To Dr. M. A. Hady for his invaluable instruction in the course work and also for his interest in the research phase of the program.

To Dr. John F. Stone for his guidance and suggestions involving the Soil Physics aspects of this study.

To Dr. Lester W. Reed for his interest and assistance with the Soil Chemistry portion of the research.

To Dr. Ronald McNew for his invaluable counsel with the statistical design of the experiment.

To his fellow graduate student, Richard Stephenson, for his sharing of knowledge, his undying humor when things looked the darkest, and his physical aid when needed.

To Dr. E. R. Harrington for the example he set during the author's formative years in high school.

To Dr. Eugene Zwoyer for his outstanding teaching during the author's undergraduate civil engineering curriculum, and for the standards and values which he instilled.

To Dr. Leo Casagrande for his early guidance in electro-osmosis.

To the author's children, Douglas, D'Ann, and Carey, for their understanding, behavior, and maturity far above their chronological age.

To the author's grandmother, Mrs. Dan O'Bannon, for her encouragement from the commencement of the study.

To the National Science Foundation for the financial support.

To Dr. Collin S. MacCarty for having the greatest right hand in America.

To John A. Drake and David R. Friels for their assistance in the laboratory testing.

To Cecil Sharp, Civil Engineering Shop Technician, for his assistance in construction of special laboratory equipment.

To Eldon Hardy for his assistance in preparing the graphic portions of this dissertation.

To the author's wife, Nancy, for typing the rough draft and Mrs. Carl Estes for preparing the final manuscript of this dissertation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

The term "soil stabilization" has been a source of a great deal of misunderstanding. This confusion has probably slowed development in this area. In its broadest sense, soil stabilization is the altering of any of the properties of soil in such a way as to improve its engineering performance. The objective of soil stabilization most frequently sought is an increase in loadbearing capacity. However, methods of soil treatment have evolved in such a way as to make possible the alteration of almost every engineering property.

Engineers are using several methods to stabilize areas of unstable soils to provide reliable support for structures. Some of the methods are: (a) surcharging, pre-consolidation, or vertical sand drains, (b) excavation and replacement, (c) displacement, (d) addition of lime, Portland cement and similar physical/chemical agents, and (e) electro-osmosis. For each different site there will be different governing conditions such as cost, time available, and soil conditions that may make any one or a combination of the above methods the most advantageous to use.

Electro-osmotic stabilization of soils is a relatively unexplored area of soil mechanics even though the principles on which it is based have been known for more than 150 years. Because of the small amount of published information concerning theoretical and practical electro-osmosis, most engineers have only a vague knowledge of how effective the process may be in solving their particular soils problem.

Since 1930, a number of investigators have experimented with electro-chemical methods to improve the structural properties of clays. The name for the process is usually shortened to electro-osmosis. It may be defined as the movement of a liquid through a porous medium (soil) under the influence of an electric field. Potential for future utilization of electro-osmosis seems promising, but its actual use will depend greatly upon the interest and information generated by research.

The Scope of This Study

This investigation was primarily concerned with the measurement of the effect of electro-osmotic treatment on the expansive characteristics of a clay mineral. The most important factors governing expansive pressure of a clay were investigated; they are as follows:

(1) per cent clay mineral,
(2) density,
(3) degree of saturation,
(4) time of treatment,
(5) voltage gradient, and
(6) chemical solution.

The investigation was limited to only one expansive clay mineral, montmorillonite, although there are other clay minerals that have expansive characteristics. For each of the first four parameters listed above, four levels of existing conditions were tested. Only one level of factors (5) and (6) were used since the effects of varying these parameters was investigated by the author at Arizona State University during the time period 1965 through 1969.

Object of Research

The object of this research was to develop a method of reducing the swelling characteristics of an expansive clay, using electro-osmosis to facilitate cation exchange within the clay.

CHAPTER II

THE STRUCTURE OF CLAY AND THE INTERACTING BONDING FORCES

General

Fundamental to the understanding of the behavior of clay soils is a basic knowledge of the structure of the elements of the individual clay particle. Although the discussion that follows is generally applicable to all clay soils, attention will be centered on the characteristics of the clay mineral montmorillonite. Such a restriction is justified since this particular clay mineral is one of the most difficult to stabilize and it is the principle constituent of the expansive fines in the clayey soil used in the research work of this report. Of necessity, this examination must be limited. The reader is referred to authors in the field of clay mineralogy such as Grim, Ross and Pauling [12, 30, 25] for a more extensive discussion.

Bonding Forces in Clay Particles

Before reviewing the structure of clays, it is appropriate to examine first the forces working to bond individual as well as aggregate particles together. The discussion will be limited to those of particular interest in clays.

Primary (High-Energy) Bonds

Although numerous types of primary bonds can be discussed in connection with chemical bonds in general, three are of principal interest to the student of clay mineralogy.

Ionic Bonds

Elements in the periodic table capable of combining chemically do so by a stabilizing process of either gaining or losing electrons. Typically, this reaction can be demonstrated using sodium and chlorine, as examples:

$$\mathrm{Na} - e \rightarrow \mathrm{Na}^+$$

$$\mathrm{Cl} + e \rightarrow \mathrm{Cl}^- \quad .$$

Thus, the gain or loss of an electron does not produce an electrically neutral particle but rather one with a positive or negative charge. Combining the two equations gives

$$(\mathrm{Na} - e) + (\mathrm{Cl} + e) \rightarrow \mathrm{Na}^+\mathrm{Cl}^- \quad . \tag{2.1}$$

The forces holding the sodium and chlorine atoms together are called ionic bonds. The positive ion (Na^+) is termed a cation while the negative (Cl^-) is called an anion.

Covalent Bonds

Covalent bonds involve a combining of atoms lacking electrons through sharing those available to both. Such bonds are typified by the bonding of numerous gases such as oxygen and hydrogen and the carbon bonding in organic compounds.

Heterpolar Bonds

Heterpolar bonds are those bonds formed by either ionic or covalent electron sharing that leaves the completed molecule in a state of electrical dissymmetry. The most common example is that of water where the two hydrogen ions and the single oxygen ion are bonded together with the hydrogen ions, being separated by an angle of 105°. This lack of symmetry provides an electrical moment, giving rise to secondary forces.

In general, high-energy bonds are considered to be those binding atoms together to form molecules. Because their high strength precludes breaking by ordinary methods, these bonds, of themselves, are of limited interest to the soils engineer. Of more value are the effects of these bonds, particularly those producing dissymmetry (heterpolar) and residual electro-static charges (ionic).

Secondary (Low-Energy) Bonds

Low-energy bonds, often referred to as residual forces, are principally concerned with attractive or repulsive forces between molecules.

Van der Waals - London Bonds

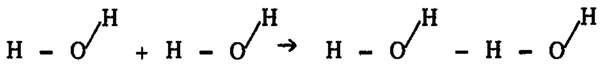
The orbital movement of electrons around atoms gives rise to an electrical field capable of interacting, in an attractive manner, with nearby molecules. This attractive force is termed the Van der Waals - London force. While heavily dependent on the distance between particles and the atomic number of the element, the extent of these forces is also a function of the dielectric fluid and the orientation of the particles with respect to each other. In water with low electrolytic concentration, variations are considered to be negligible. In a clay-water system, the Van der Waals - London forces are essentially dependent on the structure of the clay particle. Provided that a parallel orientation is assumed, the force varies as the inverse of a power of the distance between particles. In random, or non-parallel orientations, such proportionality is disrupted by the varying particle orientation.

Electrical Bonds

Electrical bonds arise from the unsymmetrical centers of positive and negative polarity in a molecule. This lack of symmetry causes the molecule to behave as a small dipole, attracted, therefore, to another molecule or particle of the opposite charge.

Hydrogen Bonds

The hydrogen bond is, in terms of bond strength, a hybrid. While stronger than the secondary bonds previously described, its strength is less than that of any of the primary bonds. This bond occurs when a hydrogen ion is attracted to two separate anions and has difficulty in permanently bonding to either. In this case, the hydrogen ion simply oscillates between the two molecules, sharing its electrons with both.



$$\mathrm{H} - \overset{\mathrm{H}}{\mathrm{O}} + \mathrm{H} - \overset{\mathrm{H}}{\mathrm{O}} \rightarrow \mathrm{H} - \overset{\mathrm{H}}{\mathrm{O}} - \mathrm{H} - \overset{\mathrm{H}}{\mathrm{O}}$$

A discussion of the applicability of these various forces to clay particles is more appropriately continued as a part of the discussion of the structure of clay particles themselves [15].

The Structure of Clays

As noted by Grim [12], the term clay can present totally different meanings to different people. For the purposes of this report, the term clay will refer to that fraction of soil particles in a soil mass having a diameter smaller than two microns (0.002 mm) that exhibit properties of cohesion and plasticity.

Extensive mineralogical investigations have shown that most clay particles have a number of characteristics not commonly found in other soil fractions. First, clay particles are generally plate or rod-shaped and exhibit a high specific surface when compared, for example, to a cube of equal volume. Secondly, behavioral characteristics of clay fractions are governed by the colloidal forces of surface energy rather than the aspects of mass and gravitation. Typical dimensions of the most common clay minerals of the major groups are shown in Table I.

In discussing the constituents of a clay particle, a system of easily understood and logically sequenced terms should be established. However, there exists a considerable difference of opinion. Therefore, a combination of the work of both of the Nomenclature Committee of the Clay Minerals Society and that of Lambe will be used to define the following terms:

Crystal: The crystal is the largest non-repeating structural unit.

Plane, Sheet, and Layer: It is recommended that these terms be used in the following manner: A plane of atoms, a tetrahedral or octahedral sheet, a 1:1 or 2:1 layer. Thus, plane, sheet, and layer refer to increasingly thicker arrangements; a sheet is a combination of planes, and a layer is a combination of sheets. In addition,

TABLE I

DIMENSIONS OF TYPICAL CLAY PARTICLES [12]

Clay Mineral	Characteristic Ratios of Dimensions	Approximate Range of Actual Dimensions (A)		Specific Surface (m^2/gram)
		Length and Breadth	Thickness	
Montmorillonite	100 X 100 X 1	1000 to 5000	10 to 50	800
Kaolinite	10 X 10 X 1	1000 to 20000	100 to 1000	10

layers may be separated from one another by various interlayer materials, including cations, hydrated cations, organic molecules, and hydroxide octahedral groups and sheets [28].

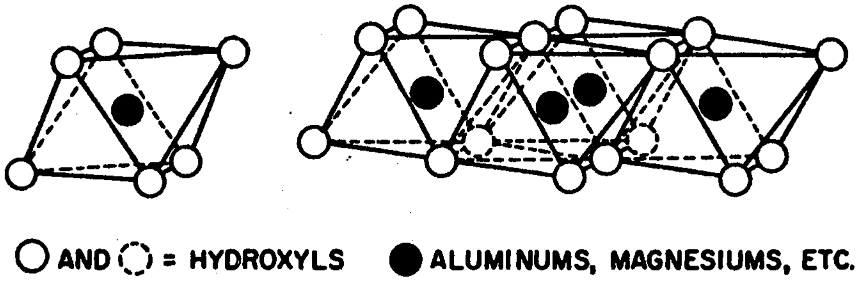
Aggregate: Aggregates are random agglomerates of crystals.

Particle: The particle is the smallest apparent unit of the soil and can be either a sheet, a crystal, or an aggregate [15].

Basically, different clay minerals are formed by the varied structural lamination of two or three common minerals. The first, commonly constituting the octahedral sheet, is composed of hydrated oxides of aluminum (Gibbsite) or magnesium (Brucite) as shown in Figure 1. In an abbreviated symbology, this sheet can also be expressed as shown in Figure 1c. The second mineral sheet is composed of tetrahedrons of silicon and oxygen as shown in Figure 2. The symbol for this sheet is shown in Figure 2c.

The structure of montmorillonite, from a theoretical standpoint, is shown in Figure 3. Expressed in chemical terminology, this structure has the formula $(OH)_4Si_8Al_4O_{20}\cdot nH_2O$. More commonly, however, some isomorphic substitution has occurred within the atomic lattice during the life of the clay. This substitution usually involves the partial replacement of aluminum within the Gibbsite sheet by other cations such as magnesium or iron, and, to a lesser extent, replacement of the silicon atom by aluminum.

The stacking of crystals of montmorillonite to form particles results in adjacent crystals having oxygen molecules opposite oxygen molecules, eliminating the possibility of hydrogen bonding. The only forces holding the crystal forms together, then, are weak Van der Waals

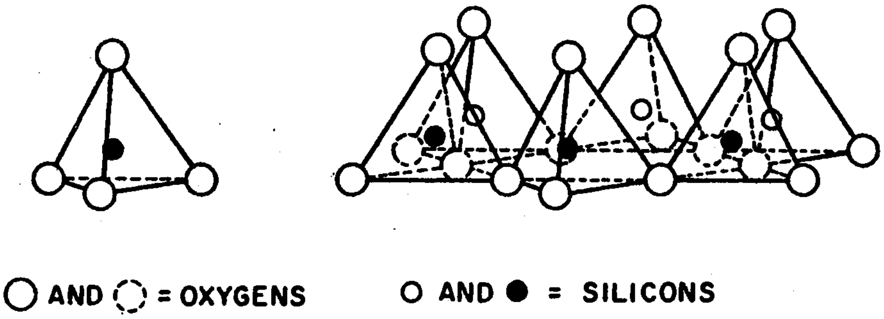


(a) SINGLE OCTAHEDRAL UNIT

(b) SHEET STRUCTURE OF THE OCTAHEDRAL UNITS

(c) BUILDING BLOCK SYMBOL FOR THE OCTAHEDRAL SHEET

Figure 1. Structure of the Octahedral Sheet [12]

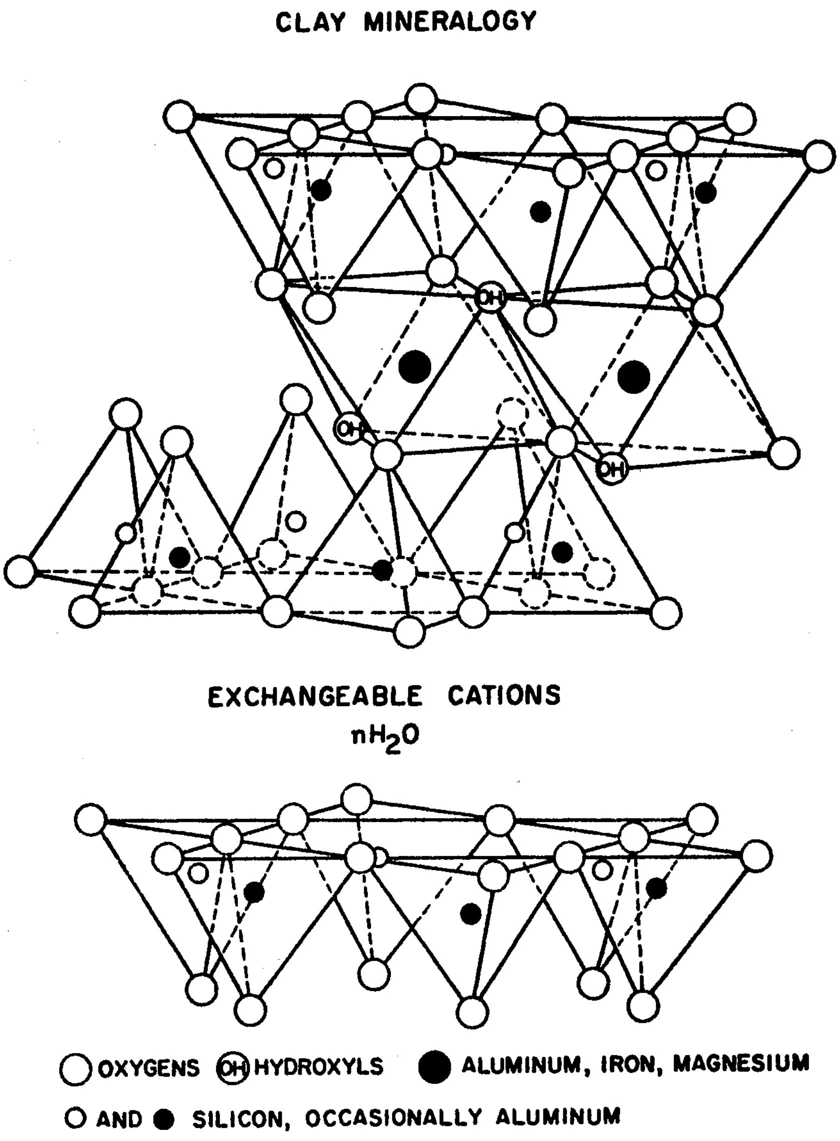


(a) SINGLE SILICA TETRAHEDRONS

(b) SHEET STRUCTURE OF SILICA TETRAHEDRONS ARRANGED IN A HEXAGONAL NETWORK

(c) BUILDING BLOCK SYMBOL FOR THE TETRAHEDRAL SHEET

Figure 2. Structure of the Tetrahedral Sheet [12]



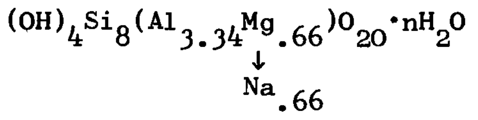
NOTE:

DIAGRAMMATIC SKETCH OF THE STRUCTURE OF MONTMORILLONITE ACCORDING TO HOFMANN, ENDELL, AND WILM,[27] MARSHALL,[29] AND HENDRICKS.[18]

Figure 3. The Structure of Montmorillonite [12]

forces and various forms of cation-dipole linkages. This feature of montmorillonite allows easy access of various polar fluids, such as water, between adjacent crystal units, accounting for the relatively high expansive characteristics of montmorillonite [12].

The net result of isomorphic substitution is to leave the crystal lattice with a charge deficiency so that the particle is negatively charged. However, it is understood that even without isomorphic substitution, there exists to some degree a negative charge deficiency in the clay lattice system. In an attempt to maintain electrostatic equilibrium, the negative charge on the particle is countered by adsorbing various positive cations. This process is known as base exchange. Grim demonstrates the changes in the chemical formula after a partial magnesium substitution as:



$$(OH)_4Si_8(Al_{3.34}\underset{\underset{Na_{.66}}{\downarrow}}{Mg_{.66}})O_{20}\cdot nH_2O \tag{2.2}$$

where the sodium (Na) represents the exchangeable ions. In the hydrated state, these cations are tightly bonded to the soil particles [12].

Providing water to the pores of a soil containing a montmorillonite, as just described, permits the exchangeable ions to shift from a total concentration at the surface of the soil particle to a concentration varying from relatively high near the surface to close to zero at a distance away. This state typifies the double-layer theory presented in the following chapter.

CHAPTER III

REVIEW OF THEORIES AND EQUATIONS GOVERNING ELECTRO-OSMOTIC FLOW

The discovery and present development of electro-osmosis can be attributed largely to the cumulative efforts of Russian, German, and American scientists.

The first recorded observation was made by Reuss in 1807. He noted that when a potential was applied across two electrodes driven into the moist earth of his Moscow garden, electricity moved easily through the soil. Further investigation lead him to discover that when a potential was applied across a porous water-saturated medium (quartz powder) water moved from the anode to the cathode [29].

Quincke was the first to explain this flow process on the basis of an electrical double layer. Postulating the existence of single capillaries within the soil, he assumed that the double layer was composed of an inner, negatively charged immobile or solid layer and an adjoining liquid layer with a positive charge. Thus, when a potential was applied across electrodes in the soil, the positively charged ions would be moved toward the cathode through the soil capillaries, carrying with them attached dipolar water molecules [4].

Theory of Helmholtz

In 1879, Helmholtz presented the first mathematical theory governing the rate of electro-osmotic flow. In developing his theory, Helmholtz assumed (1) a cylindrical, straight, uniform capillary tube filled with water, and (2) a double layer composed of a thin, negatively charged, rigidly attached inner layer and a much thicker, positively charged, movable outer layer. In the interior of the tube, free water, unaffected by electrical potentials, is assumed to exist. That is, no interaction between double layers is present. Thus, the Helmholtz theory is generally derived for wide capillaries and thin double layers.

According to the Helmholtz equation, the quantity of liquid moved per unit time through a single rigid capillary is as follows [14]:

$$q_e = \frac{EDr^2Z}{4nL} \tag{3.1}$$

where all dimensions are in cm-g-sec system and electro-static units, and

q_e = quantity of water,

E = electric potential,

D = dielectric constant of the liquid,

r = radius of the capillary tube,

Z = zeta potential,

n = viscosity of the liquid, and

L = length of the capillary.

In the Helmholtz equation, the dielectric constant D is a measure of the polarity of the liquid. Since the soil-liquid bonds are polar type forces, polar type forces are a factor in electro-osmosis. The dielectric constant for water is 81 [13].

The concept of double-layer stems from the difference noted between thermodynamic and electrokinetic potentials. This difference is assumed to be due to the fact that a portion of the cation cloud nearest the particle is immobile, thereby reducing the zeta potential below the theoretical. The most generally accepted diagram of a clay particle with the surrounding ion cloud is shown in Figure 4.

The zeta potential is the potential used in electro-osmosis computations. The variation of this potential with distance from a clay particle is an expotential curve as shown in Figure 5.

The zeta potential as shown is the potential at the boundary between the "inner" and "outer" halves of the double layer. Noting the shape of the curve, it seems unreasonable to assume that this boundary would be at a fixed location since the transition is gradual. Rather, it is probably best visualized as an approximate location which, when used in computations, fits experimental results. However, a distinct boundary is shown for graphical purposes in most cases.

The potential E_o at the particle surface is called the Nernst potential and may be calculated thermodynamically. If the Nerst potential were used in the Helmholtz equation, the velocity determined would be greater than the actual value, since the ions at the particle surface are immobile. The fact that this occurs is considered proof of the existence of a double layer.

The diffuse double layer theory varies slightly from the original double layer theory of Helmholtz. The work of Lambe and others has shown that the concept of two positively charged layers - one immobile and the other mobile and diffuse - is more nearly correct. However, the Helmholtz equation also holds for the diffuse double layer theory.

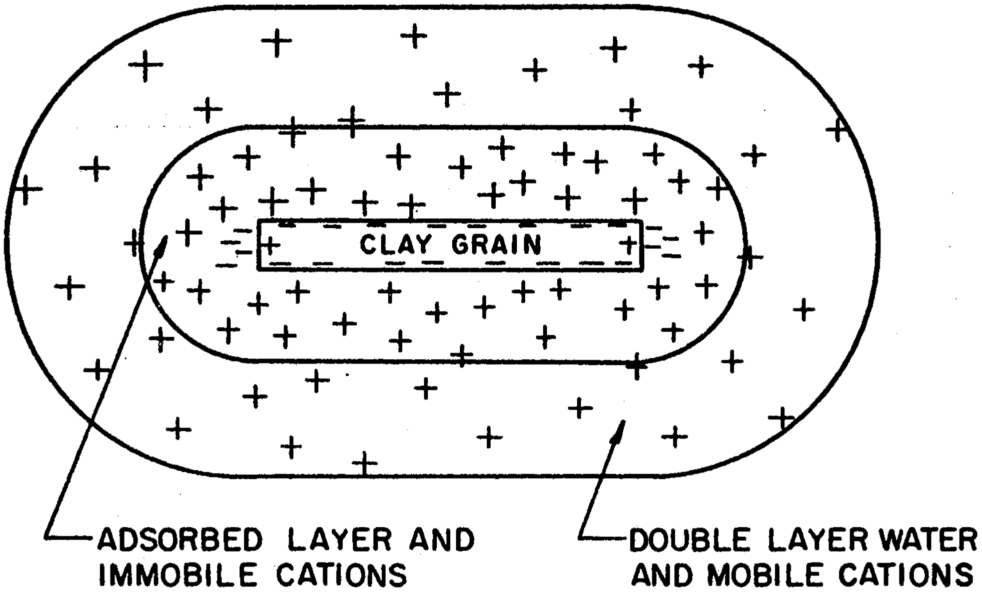


Figure 4. Water Layers and Cation Distribution About a Clay Grain [18]

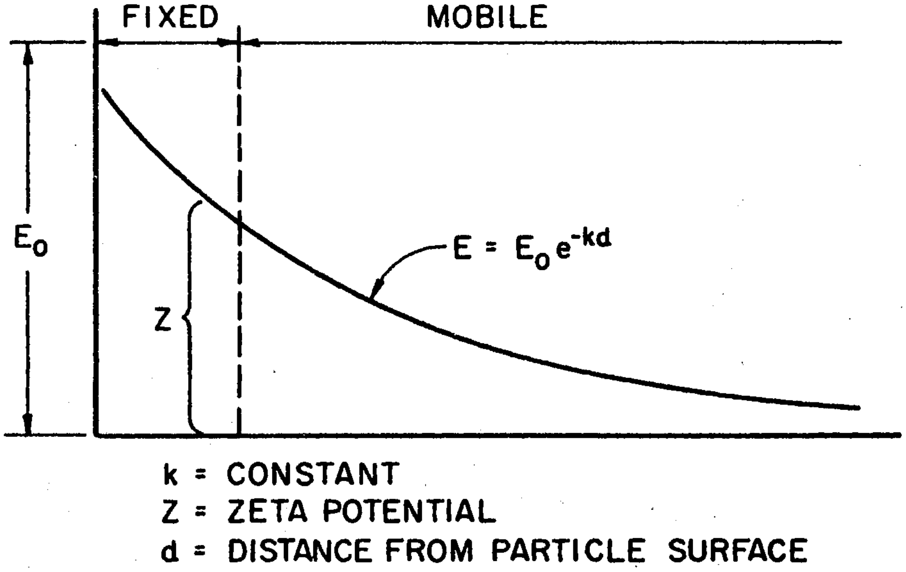


Figure 5. Zeta Potential of a Particle [18]

In revised notation, the Helmholtz equation can be re-written:

$$q_e = C_1 \cdot i_e \cdot a \tag{3.2}$$

where C_1 is $DZ/4\pi\eta$ and assumed constant, i_e is E/L and a is the cross-sectional area of the capillary, πr^2. For a bundle of N capillary tubes with a total cross-sectional area of A perpendicular to the direction of flow and a void ratio of e and where $e/(1+e)$ is the fraction of cross-sectional area taken up by pores

$$\begin{aligned} Q_e &= N \cdot q_e = \frac{A}{a} \cdot \frac{e}{1+e} \cdot C_1 \cdot i_e \cdot a \\ &= \left(\frac{e}{1+e} \cdot C_1\right) \cdot i_e \cdot A \\ &= k_e \cdot i_e \cdot A \end{aligned} \tag{3.3}$$

where k_e is called the electro-osmotic coefficient of permeability. Thus, according to the Helmholtz equation, the rate of flow is independent of the size of the capillary tubes.

Figure 6 shows the distribution of ions in the double layer on both sides of a wide capillary. If a potential gradient is applied, the mobile layer is pulled to the negative electrode (cathode), and the negatively charged capillary walls are attracted toward the anode. As the positive ions migrate to the cathode, they drag with them the pore water in the center of the tube. After a short time, the velocity distribution across the capillary will be as shown, according to the Helmholtz theory [14].

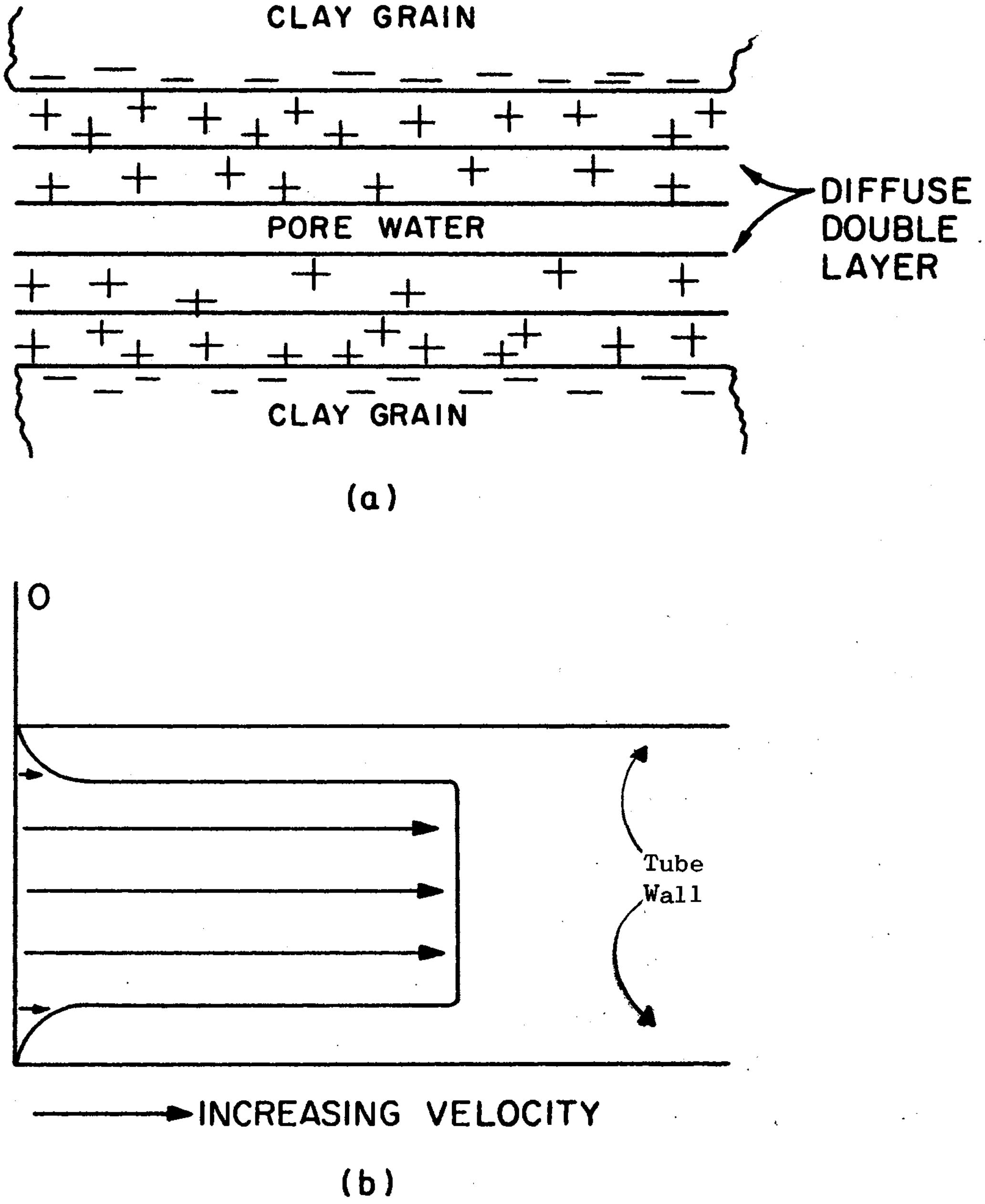


Figure 6. Helmholtz-Smoluchowski Theory of Cation Distribution in a Capillary Tube and Velocity Distribution Across Capillary Tube During Electro-Osmosis for Helmholtz-Smoluchowski Theory [14]

Theory of Schmid

A second important theory available to explain the mechanism of water transport is the Schmid theory. It was developed for microporous systems where the cations balancing the colloid charge can be considered to be uniformly distributed throughout the liquid in the capillary tube. This should approximate the condition when the thickness of the double layer is large in comparison to the radius of the capillary tube. When a potential is applied to the tube, all the cations are attracted to the cathode. The resulting velocity distribution is parabolic - the same shape as that resulting from hydraulic flow. Figure 7 depicts Schmid's concept. His formula may be written as [9]

$$V = \frac{r^2 \bar{\sigma} E}{8u} \tag{3.4}$$

where

r = capillary radius,

$\bar{\sigma}$ = average mobile electron charge density,

E = potential gradient, and

u = fluid viscosity.

There has been considerable discussion among authorities of the differences between the two theories and the types of material in which each is expected to be valid [9].

Developments by Esrig

In 1964, Esrig reported theoretical considerations that suggest that the Schmid and Helmholtz theories are identical. His stated aim was "to develop a new relationship among the variables affecting

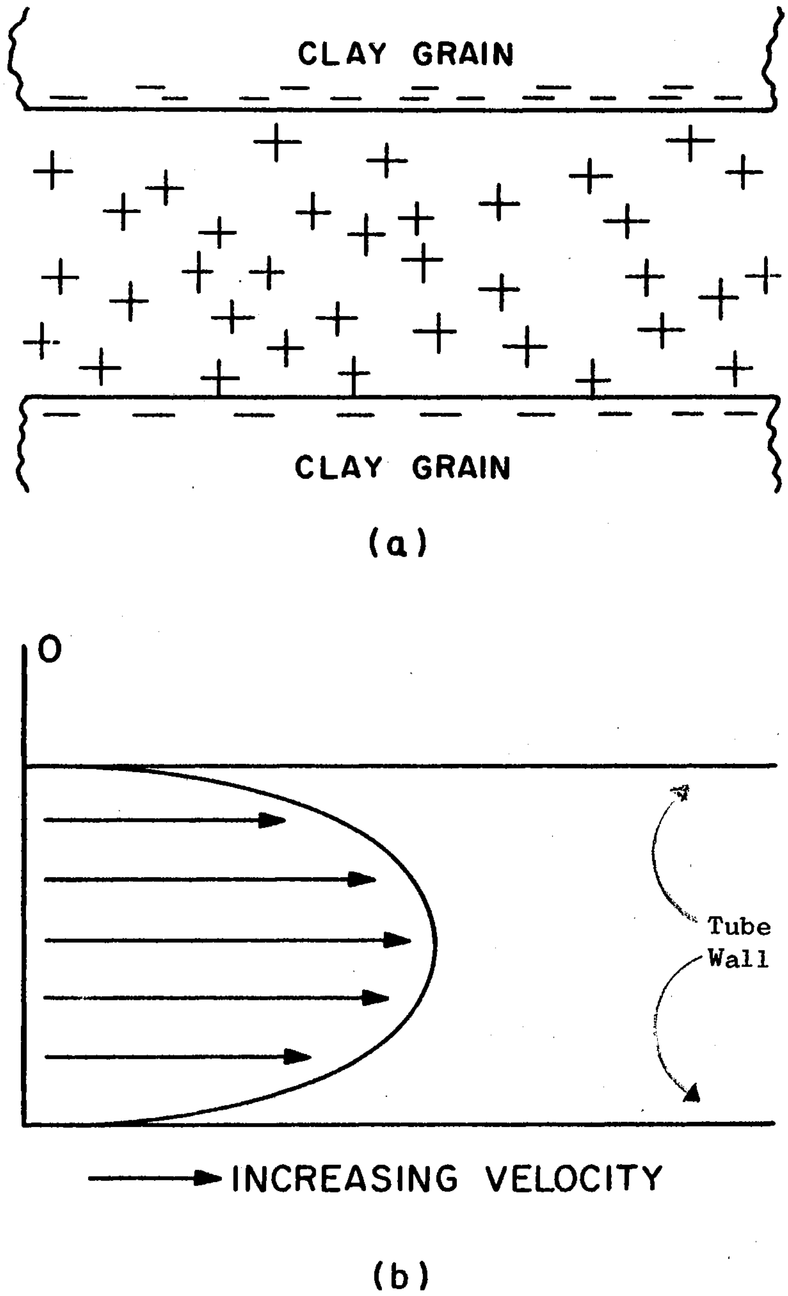


Figure 7. Schmid Theory of Cation Distribution in a Capillary Tube and Velocity Distribution Across a Capillary Tube During Electro-Osmosis for the Schmid Theory [9]

electro-osmotic flow, to transform the well-known Helmholtz-Smoluchowski equation and to re-derive the Schmid equation" [9]. Using this approach, Esrig derived a new, unifying equation for electro-osmotic flow. His theoretical work indicates that the Schmid and Helmholtz equations are the same. The Esrig equation is given as [9]:

$$V = \frac{1}{2} \log_e \left(1 + \frac{d}{r}\right) \frac{r^2 F}{u} \tag{3.5}$$

where

d = an effective distance from the center of electric charge of the electric double layer to the capillary wall (a parameter to characterize the electric double layer),

r = capillary radius,

F = $\bar{\sigma}$ E, average electric driving force per unit volume of electrolyte in the capillary,

$\bar{\sigma}$ = average mobile electric charge density,

E = potential gradient,

u = fluid viscosity, and

v = velocity of water migration in a steady-state condition.

Esrig believes this to be a significant improvement over the popular equations of electro-osmotic flow because it does not require the evaluation of the zeta potential and can be used for electrolytes of all concentrations, since the characteristics of the double layer are taken into account.

Further, by considering the quantity of flow per unit time through a unit area containing m capillaries all of radius r, and remembering that

$$Q = k_e \cdot i_e \cdot A \quad , \tag{3.6}$$

Esrig has shown that his equation leads to the expression

$$k_e = \frac{1}{2} \log_e\left(1 + \frac{d}{r}\right) \frac{m \pi r^4 \bar{\sigma}}{u} \quad . \qquad \text{(Esrig's Eq. 23)}$$

This equation can also be written as:

$$k_e = m\bar{k}_e \quad , \tag{3.7}$$

where

$$\bar{k}_e = \frac{1}{2} \log_e\left(1 + \frac{d}{r}\right) \frac{\pi r^4 \bar{\sigma}}{u} \quad .$$

Since the radii of the capillaries in a soil mass are not all equal, the flow rate from a uniform potential gradient should be written as:

$$Q = E(m_1 \bar{k}_{e_1} A_1 + m_2 \bar{k}_{e_2} A_2 + \ldots m_n \bar{k}_{e_n} A_n) \quad . \tag{3.8}$$

This equation cannot be factored so that it can be written in the form of Equation (3.6). Thus, it is impossible to eliminate the dependence of k_e on the radius of the individual soil capillaries.

Previous to Esrig's assertion, Schaad suggested about the same thing. He discussed the fact that Helmholtz's theory seems inconsistent with certain mathematical and practical considerations. While the Helmholtz theory held that for a soil with a given void ratio and zeta potential the quantity of flow is independent of size of capillary, Schaad noted that practical experience indicates a variation of electro-osmotic flow with capillary diameter [35].

In developing and discussing his new unified equation for electro-osmotic flow, Esrig was able to cast light on some of these puzzling observations.

It can be seen from Esrig's Equation (23) that k_e is dependent upon the thickness of the double layer represented by the parameter d. If the function $\log_e\left(1 + \frac{d}{r}\right)$ is expanded, we find

$$\log_e\left(1 + \frac{d}{r}\right) = \frac{d}{r} - \frac{d^2}{2r^2} + \frac{d^3}{3r^3} \ldots \qquad \text{Esrig (26)}$$

When d is small in comparison to r, an assumption which is valid for the Helmholtz - Smoluchowski conditions, all terms in the expansion following the first can be neglected without introducing significant error. We therefore find that k_e is approximately a linear function of double layer thickness which, in turn, is a function of the ion concentration in the pore fluid.

Prediction of the relationship between d and ion concentration for a wide range of concentrations is a complex physical-chemical problem which is not readily soluble. However, it is known that d decreases sharply as the ion concentration is increased.

From Equation (23) it can also be seen that k_e is a function of the viscosity of the pore fluid u and of the average mobile electric charge, density $\bar{\sigma}$. The former, which is primarily temperature dependent, tentatively can be assumed to be constant for a given soil in the ground although it is possible that it varies somewhat within the capillary as a result of the charge on the walls. The latter is a function of the surface activity of the soil. As the surface activity increases, the quantity of water discharged should also increase. Thus, treatment of a montmorillonitic soil should be more efficient than treatment of a kaolinitic soil.

...

The information provided in the preceding discussion can be used to predict, in a qualitative way, the effect of the moisture content of a soil on the volume of water flowing during treatment and the efficiency of the treatment. For example, Equation (23) suggests that if d is maintained constant, as the water content (hence the radii of the capillaries) of a soil increases the volume of outflow will increase until a fluid state is reached. At this stage, we can expect the $\log_e(1 + d/r)$ to begin to approach zero and the outflow to stop. Because the fluid state is approached rapidly as the moisture content of a soil exceeds about its liquid limit, it might be expected that the maximum volume of

> outflow will occur when the soil under treatment has a moisture content in the vicinity of its liquid limit ... [9].

Theory of Winterkorn

Winterkorn has attempted to show a relation between the Schmid and the Helmholtz-Smoluchowski theories by postulating that both are valid, and that the theory which is applicable at a given time in any electro-osmosis system is a function of the cube of the capillary radius. He believes there is a transition point which can be expressed as

$$d = \frac{\pi r^3}{4} \qquad (3.9)$$

where

d = the distance between the loci of the wall and of the cations, or the thickness of the double layer, and

r = capillary radius.

From this he concludes that Schmid behavior can be expected in soils whose capillary pores have effective radii smaller than 0.1 mm [44].

Casagrande, however, believes that Winterkorn's experimental results have been distorted by gas bubbles, sample shrinkage, and electro-phoresis. A simple description of electro-phoresis is given in Figure 8. It is the movement of solid particles, floating in a liquid, toward the anode when an electrical potential is placed across electrodes immersed in the liquid. In a saturated clay soil there may be pores containing free water which are large enough to permit a quantity of the extremely fine clay particles to be carried in the water. When an electrical potential is placed across the clay these extremely fine particles will move in the pores by electro-phoresis action. At the

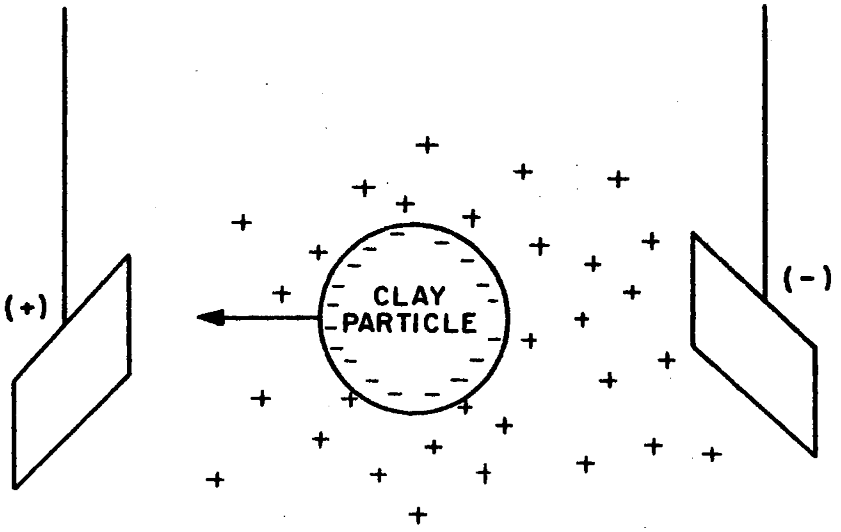


Figure 8. Electro-Phoresis; Movement of a Clay Particle in a Solution Under the Influence of Electrical Current

cathode, particles may be removed completely from the soil mass by this action.

A comparison can be made between an electro-osmotic process and an electrolytic cell process. Both have a cathode and an anode connected through a source of electro-motive force. Both require an electrolyte, i.e., a substance which (partially) dissociates into ions, and thus is made capable of conducting an electric current. And both processes generate gas bubbles at one of the electrodes and/or cause a deposition of solids derived from the electrolyte and electrodes. When the electro-motive force (emf) is applied, the quantity of electrons at the negative pole and hence on the cathode in the electrolytic cell, is increased. Simultaneously this emf increases the positive charge at the anode by removing electrons and thus there is a difference of electrical potential created between the two electrodes. In order to restore equilibrium in the system the anode will tend to take on electrons and give up cations while the cathode will tend to give up electrons and take on cations. Any cations in the electrolyte will be attracted toward the cathode at the same time any anions in the electrolyte will be drawn toward the anode.

The laws which Michael Faraday formulated on the subject of electrolysis can be summarized in the general statement: "The quantity of any ion liberated during the electrolysis of any electrolyte depends upon the quantity of electricity that passes through the solution; the same quantity of electricity liberates equivalent quantities of different ions" [2]. This holds true regardless of conditions such as concentration, temperature and length of time that the electric current passes through the electrolyte. While quantity of liberated ions is dependent only on the amount of current, the intensity or speed with which the liberation takes place is dependent on voltage.

It should be understood that there is a minimum emf called the decomposition voltage which is necessary to free the ions of an electrolyte at the electrodes of an electrolytic cell. The decomposition voltage is dependent upon the ability of an element to form positive ions by giving up electrons. This ability is measured by the element's ionization potential, which is discussed below. Decomposition voltage must also overcome the tendency of some elements produced by electrolysis to return to their ionized state, which creates an internal emf counter to the outer supplied decomposition voltage. In electrolytic cells containing electrodes of certain elements, such as copper, it is found that the minimum decomposition emf is negligible. For these particular elements electrolysis proceeds continuously even with faint currents and very low voltages.

In a saturated clay two processes probably occur when electro-osmosis is applied. First, the mobile cations, dragging along water molecules, are drawn toward the cathode where the cations have their electron deficiency satisfied and where the water is dumped. Secondly, a reaction occurs which can be expressed in the general form

$$\Omega^{+} + HOH \rightarrow \Omega(OH) + H^{+}$$

in which Ω^{+} is a cation produced from anode corrosion, $(OH)^{-}$ is a hydroxl anion produced from hydrolysis of the water, and H^{+} is a hydrogen ion also produced from hydrolysis. The compound $\Omega(OH)$ is deposited in the clay structure before it reaches the cathode. The H^{+}, because of its small size, easily travels to the cathode where it picks up an electron and forms a molecule of hydrogen gas.

Casagrande has shown that by using aluminum anodes in electro-osmosis, clay soils can be stabilized and hardened irreversibly. Casagrande attributed this ability to the replacement of Na^+ in the diffuse double layer by Al^{+++}, to the reduction in water content by electro-osmosis, and to aluminates formed in the soil pores. In the base exchange of Na^+ by Al^{+++}, Kumutat believes that the Na^+ is attracted toward the cathode and is deposited as aluminates, leaving a "cation void" to be filled by Al^{+++} boiling off the anode, and H^+ produced at the anode by the following reaction:

$$Al^{+++} + 2HOH \rightarrow Al(OH)_3 + 3H^+ \quad .$$

The aluminum cations tend to be deposited as aluminates instead of traveling very far through the clay pores. The base exchange with aluminum electrodes then tends to be H^+ for Na^+ rather than Al^{+++} for Na^+. The deposition of the Al^{+++} and Na^+ aluminates causes the irreversibility of the electro-osmosis [6].

The above discussion prompts the question of why aluminum and hydrogen would displace sodium in a base exchange when both Al and H are lower than Na on the chemical activity series. The answer is that the ionization potential of the sodium is less than that of aluminum or hydrogen (see Table II). The ionization potential is the strength of electric field in volts per centimeter necessary to transfer an electron from its normal atomic energy level to infinity. The ionization potential is dependent on the size or radius of the atom which in turn is dependent on the charge of the nucleus. As the charge of the nucleus

TABLE II

RADII AND IONIZATION POTENTIALS OF SELECTED ELEMENTS [13]

Element	Atomic No.	Atomic Radius Å	Ionic Radius Å	Ionization Potential Volts
Hydrogen	1	0.37	1.36	13.595
Sodium	11	1.86	0.98	5.12
Magnesium	12	1.595	0.71	7.61
Aluminum	13	1.48	0.55	5.96
Silicon	14	1.17	0.44	8.12
Potassium	19	2.27	1.33	4.32
Calcium	20	1.97	0.98	6.09
Manganese	25	1.24	0.91	7.41
Iron	26	1.238	0.83	7.83

gets larger it more strongly pulls in the surrounding electrons and removing them becomes more difficult. Conversely, the more electrons there are, the greater the atomic radius is, and the easier it is to remove one of the outer electrons.

Because of its low ionization potential, the sodium ion tends to remain ionized instead of combining with other salts, and, hence, is susceptible to the electro-osmotic force. On the other hand the aluminum, because of its relatively higher ionization potential and small atomic radius, will tend to share its outer electrons instead of giving them up. The resultant compounds, such as $Al(OH)_3$, are not susceptible to the electro-osmotic force because of their electrical neutrality.

To the knowledge of the writer, the chemical reactions and products from metallic electrodes other than aluminum have not been determined for electro-osmosis in a clay soil. However, based on this information, a research project was conducted in which soluble metallic salts were introduced at the anode of an electro-osmotic system and the resulting change in the expansive pressure of a swelling clay was measured. The results of this work will be discussed in the next chapter.

CHAPTER IV

PRIOR ELECTRO-OSMOTIC RESEARCH AT ARIZONA STATE UNIVERSITY

General

This chapter is based on work performed by the author at the Engineering Research Center, Arizona State University, Tempe, Arizona, during the time period May 1, 1965, through August 31, 1969. The research contract was with the Arizona State Highway Department to investigate "Stabilization of Chinle Clay by Electro-Osmotic Treatment." Funds for the project were provided by the Bureau of Public Roads, Department of Commerce, and the Arizona State Highway Department [20, 21, 23, 24].

Nature of Problem

A vast extent of Northern Arizona is covered by an expansive montmorillonite clay. This formation is called the Chinle clay and has approximately 6,000 square miles of surface exposure as shown in Figure 9. Throughout this area the clay has many colors ranging from light gray to dark purple. Although one will find this material in a wide range of colors, the swelling characteristics are quite similar. The natural expansive characteristics of the Chinle clay are large, and in the past they have caused excessive swelling and heaving in the

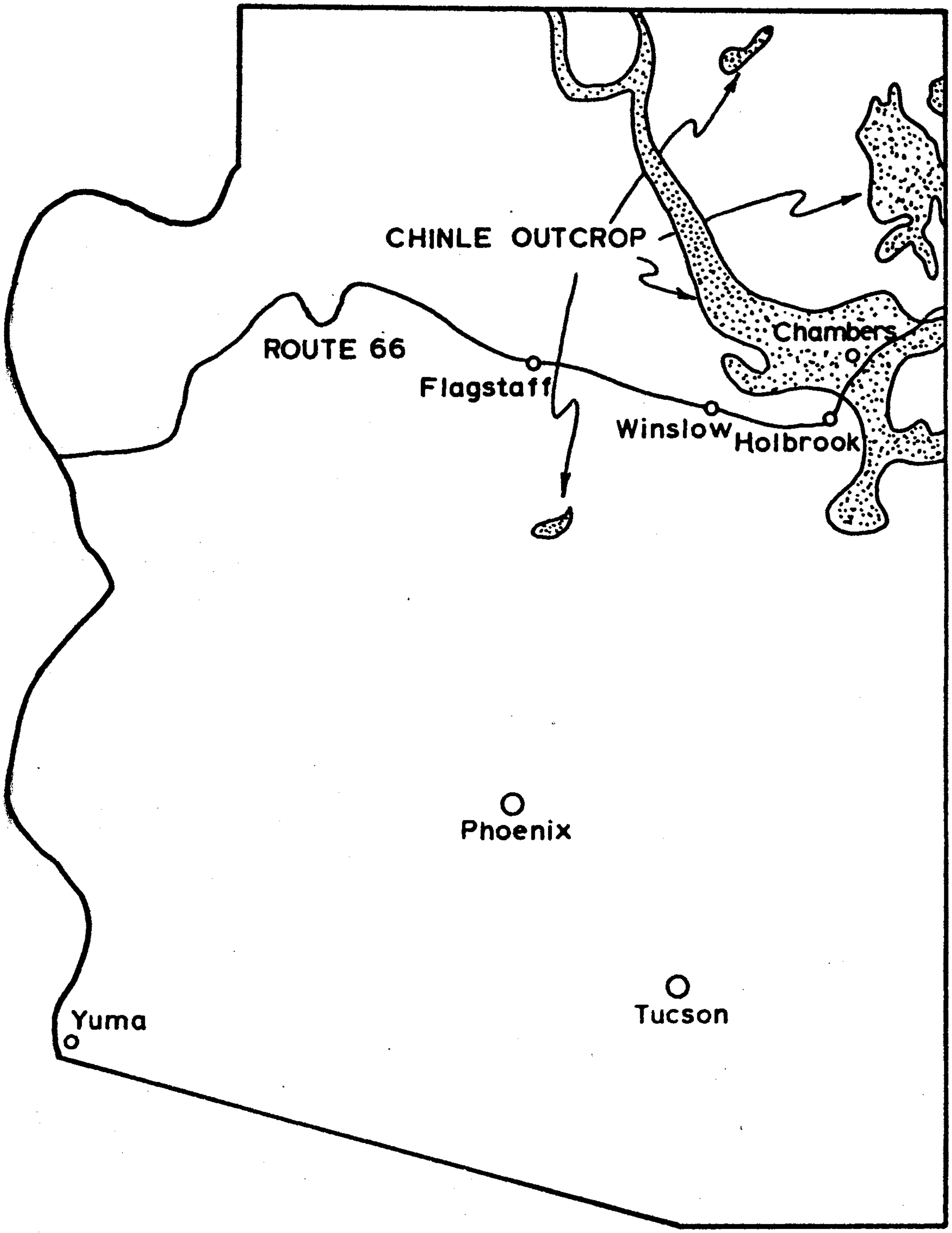


Figure 9. Map of Arizona Showing Major Chinle Outcrops

highway subgrade. This volumetric change has caused damage or failure to the wearing surface on existing highways.

Recognizing this condition, the Arizona Highway Department has made every attempt to control the swelling by preventing the drying of the material during the construction program. This requires additional work and material, and to date, the method has not been completely adequate.

Geology of the Area and Site

The highway test section chosen for study is located in Northeastern Arizona on the Colorado Plateau geological province. The nearly horizontal sandstones and shales of Triassic and Jurassic age in this area are intermittently covered by thin-bedded Tertiary sandstones and shales. This region is characterized by low, broad mesas over-looking wide, flat, stream valleys containing Quaternary to Recent sands and silt alluvium with low terraces containing a very limited quantity of gravel.

U. S. Interstate 40 traverses primarily the Triassic Chinle formation as it crosses this area. The Chinle formation is composed of shale, clay, sandstone, and minor amounts of limestone [41].

Characteristics of the Chinle formation vary greatly in both the physical and chemical aspects. Chinle formation colors include red, pink, brown, green, purple, and grey tints. It has been previously mentioned that shale, clay, sandstone, and minor amounts of limestone are present. Physical and chemical characteristics of sedimentary deposits are dependent for the most part on three factors: (1) petrographic features and parent material, (2) method of transportation of sediments, and (3) changes after deposition. Several depositional environments are responsible for the characteristics of the Chinle formation. It is held that the conditions under which the Chinle was deposited were wholly continental--probably those of a well-graded but rather arid plain across which streams meandered and on which there were perhaps scattered lakes. Conglomerates of resistant materials transported from a great distance are scarce; hence, it is evident that stream gradients were low. Continental origin is evidenced by the presence of fresh-water fossils, land vertebrates and the trees of the petrified forest. Evidence is present for the existence of a warm marine environment in portions of the area in which the Chinle outcrops. Montmorillonoid and bentonitic clay minerals are suggestive of volcanic activity at the time of the warm marine climate. The alteration of volcanic ash in such an environment is favorable to the formation of the aforementioned clays [41].

In the general area of the test site, the Chinle varies in thickness and has a maximum depth of 1,500 feet. At the test site on Interstate 40, the highway is in a 15-foot shale cut. The weathered material on the slopes of the cut extends to a depth of about one foot. This material has the typical reticulated appearance of an expansive clay, weathered in place from the parent material. The underlying material is very hard and brittle. The outcrop is fractured, slickensided, and shows no visible bedding planes [41].

Field Work - Phase I

The field work commenced on May 6, 1965, with a visual survey of the completed portion of Interstate 40 alignment east of Holbrook to find the most distressed sections of roadway.

Three sites were chosen from which samples of expansive clay were obtained. The locations of these areas are mile posts 325, 345.50, and 353, respectively. At each of these locations, about two cubic yards of disturbed material were obtained from the median with a small back hoe shovel. At the same time, the natural moisture content (18.0%) and the inplace dry density (104 lbs./ft.^{3}) were determined for future work to be performed in the laboratory. Of the three sites sampled, it was decided to use mile post 345.50 as the test section [20].

Laboratory Work - Phase I

General

The purpose and scope of the laboratory section of the electro-osmotic stabilization study of Chinle clay has been: (1) to prepare a representative sample of Chinle clay for the testing program, (2) to perform physical tests to determine the index properties of the material, and (3) to determine an electro-osmotic treatment, consisting of charged metal electrodes and a water soluble chemical, which when applied to the soil will effectively reduce its expansion characteristics.

Sample Preparation. Starting with the original subgrade soil sample obtained from the median, the material was spread in a four-inch layer on a concrete surface and allowed to air dry for several days. When the soil was dry, it was crushed in a ball mill, passed through a #10 sieve and stored in a 64-cubic foot steel bin. At all times, care was taken to insure that the total sample was well mixed and uniform when placed in the bin. This enabled a homogenous sample to be obtained throughout the testing program [20].

Physical Testing. Index properties and grain size distribution of the clay were determined first. The material classifies as a CL on the Unified Classification Chart and as a A-7-6(16) according to the AASHO System. The sample has a LL = 49; PL = 24; PI = 25, and specific gravity = 2.81. One hundred per cent of the sample passed the #200 sieve; the grain size distribution curve is shown in Figure 10 [20].

Electro-Osmotic Tube Testing

4.5 Inch Tube. A procedure was developed to measure the expansive pressure of treated samples when allowed access to water. This method consisted of mixing 18% distilled water with the untreated soil, and statically compacting it into a 4.5 inch diameter by six inch long Plexiglas tube to a density of 100 lbs./ft.^{3}. The tubes were then fitted fitted with stoppers and electrodes, and the samples were treated electro-osmotically with various chemical solutions as shown in Figure 11.

Following electro-osmotic treatment, the electrodes and material within one-half inch of the electrodes was removed and discarded. Both ends of the tube containing the remaining treated sample were then sealed with a wax and the sample was allowed to cure for one week in a moist room. At the end of seven days, the wax was removed and the treated sample removed from the Plexiglas tube. The sample was divided into two parts representing, respectively, the ends nearest the positive and negative electrodes, and a moisture content sample was taken from

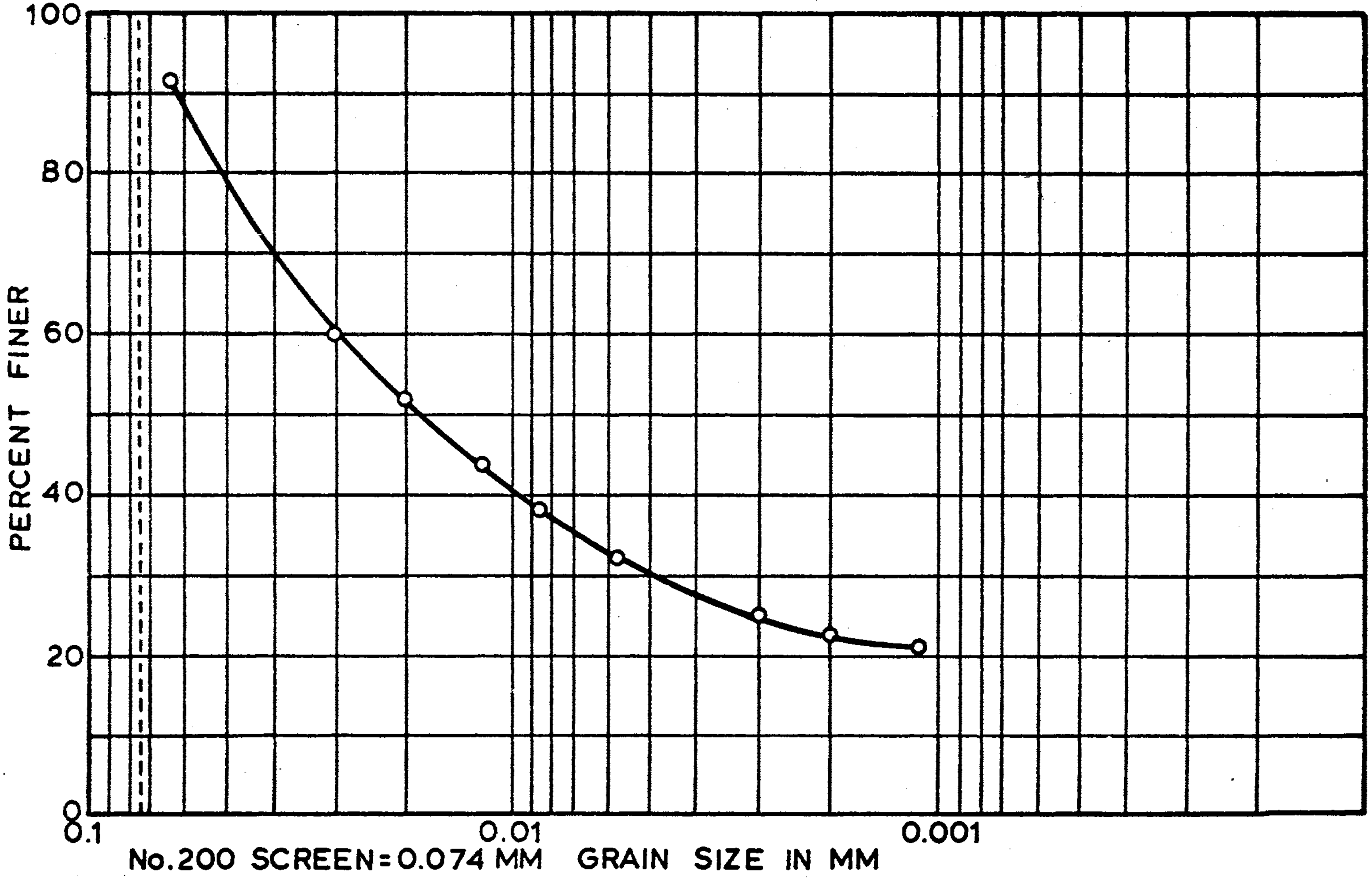


Figure 10. Grain Size Distribution

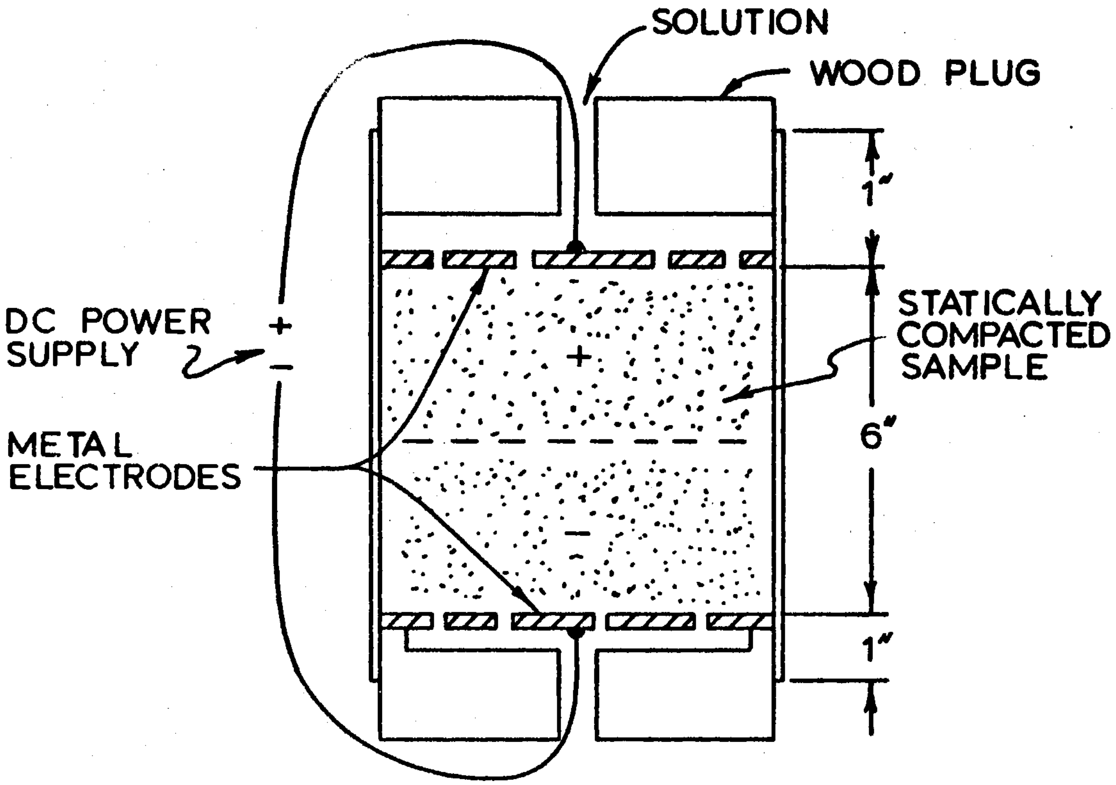


Figure 11. 4.5 Inch Plexiglas Tube Apparatus

each end. The remaining material was air dried and pulverized to pass a #20 sieve. A portion of the minus #20 material was now prepared for the standard one cycle expansion test using the California R-Value test procedure. The remaining material was retained and stored for future testing. That part of the sample to be tested was mixed with enough distilled water to increase the moisture content to 24% and then allowed to cure 24 hours. The choice of 24% moisture to be used in testing all electro-osmotically treated samples was determined by the Arizona Highway Department's one cycle expansive tests on the untreated material. Tests on untreated material at various moisture contents indicated that 24% moisture was the minimum that could be used in the tests. In tests using less than 24% moisture, the expansive pressures were so large that they exceeded the capacity of the test apparatus before the final expansive pressure could be determined. Therefore, in order to compare the results of treated samples to the untreated, it was necessary to utilize a constant moisture content at which the expansive pressure of the untreated material was known. After curing, the treated material was compacted to a height of one inch and a density of 100#/ft.^{3} in the California four-inch diameter R-Value mold with the standard kneading compactor. The mold was placed in the standard California expansion pressure device and the standard one cycle expansion pressure was obtained as shown in Figure 12.

The expansion pressure tests were conducted at the Arizona Highway Department's central laboratory in Phoenix. The results of these tests are shown in Appendix A.

A summary of these tests indicated that using a voltage gradient of 0.5 to 1.0 volts/inch and a saturated solution of KCl was the most

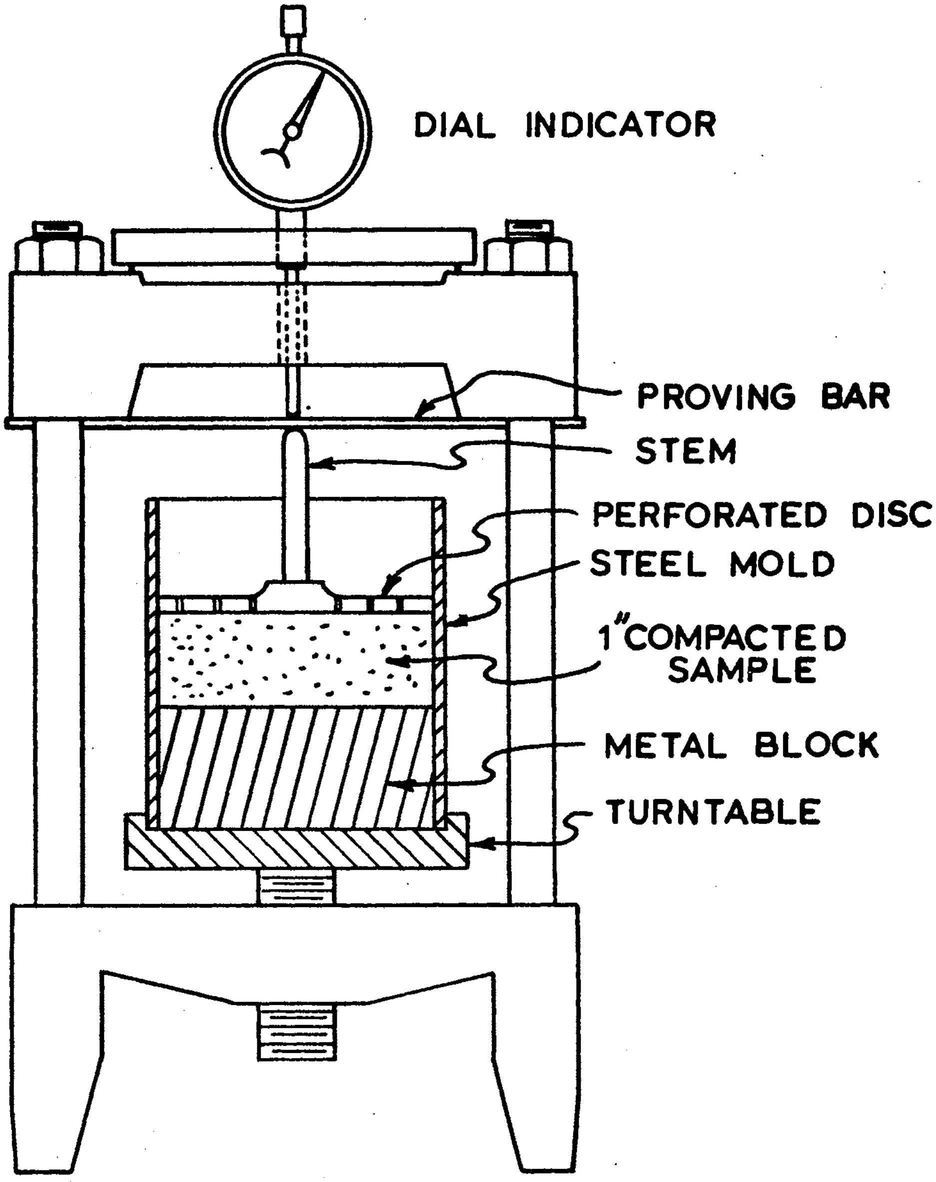


Figure 12. R-Value Mold--For California Expansive Pressure Test

effective treatment to reduce the expansive pressure of the Chinle clay [20].

Laboratory Work - Phase II

General

The purpose of laboratory work during Phase II was to determine the expansive characteristics of the untreated soil obtained from a new test site and to determine the chemical and electrode configuration best-suited for the attempted field stabilization of this soil.

Site Selection and Sampling

The field work for this study began in July, 1968, with the selection of a new test site about one mile east of Holbrook, Arizona. The site was located on a section of I-40 which was still in the construction stage. About two cubic yards of disturbed soil were obtained from the roadway. The Highway Department transported the sample to Arizona State University where it was prepared as before for use in laboratory studies [24].

Properties of Untreated Material

Tests were conducted on the clay to determine the index properties and the grain size distribution of the material. The sample had a LL = 48.5, PL = 24.5, PI = 24, and a specific gravity of 2.74. The material classifies as a CL based on the unified classification system, and as an A-7-5 according to the AASHO System. The grain size distribution is shown in Figure 13. The expansive pressure at various moisture contents was determined and is shown in Figure 14. The

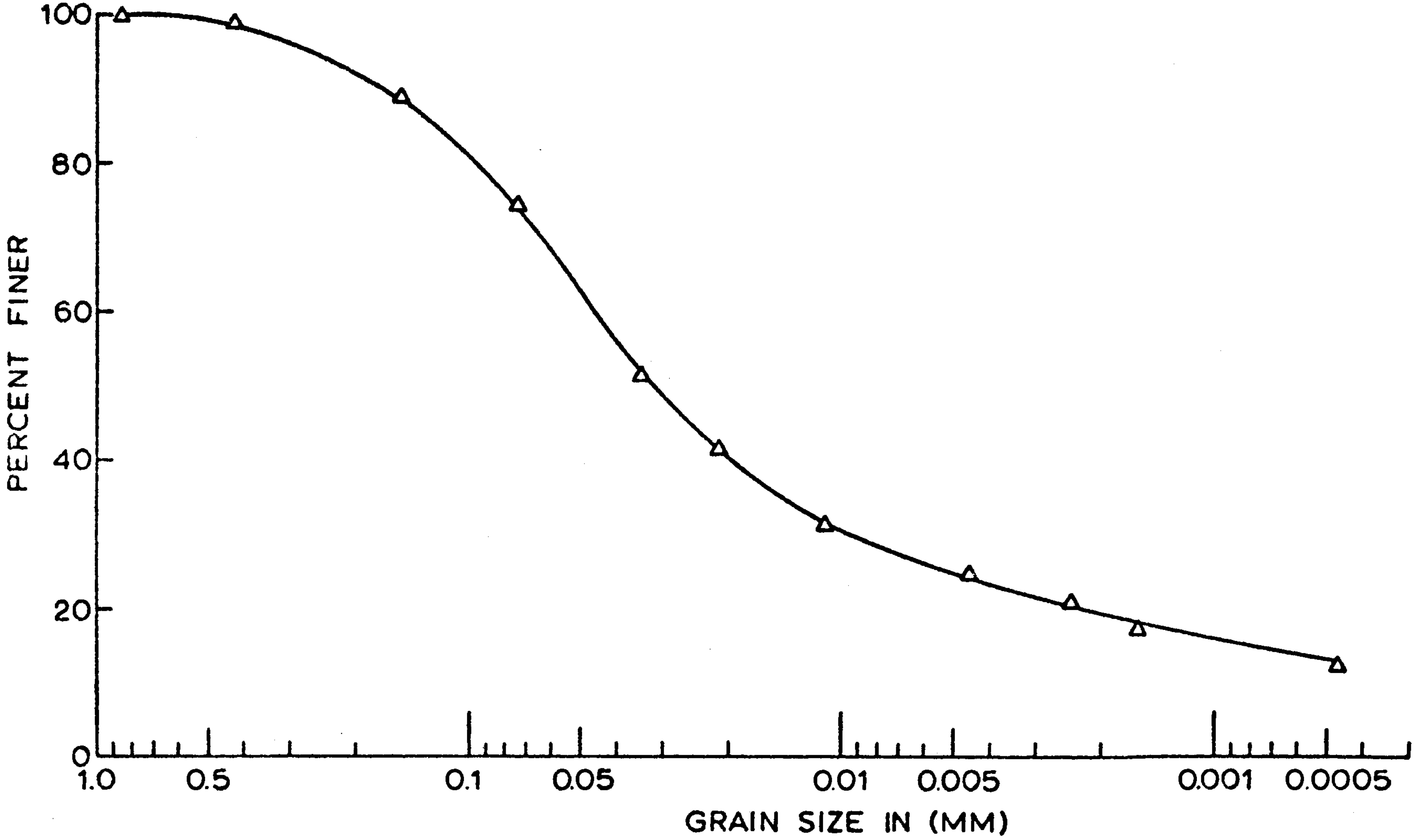


Figure 13. I-40 New Construction Grain Size Distribution

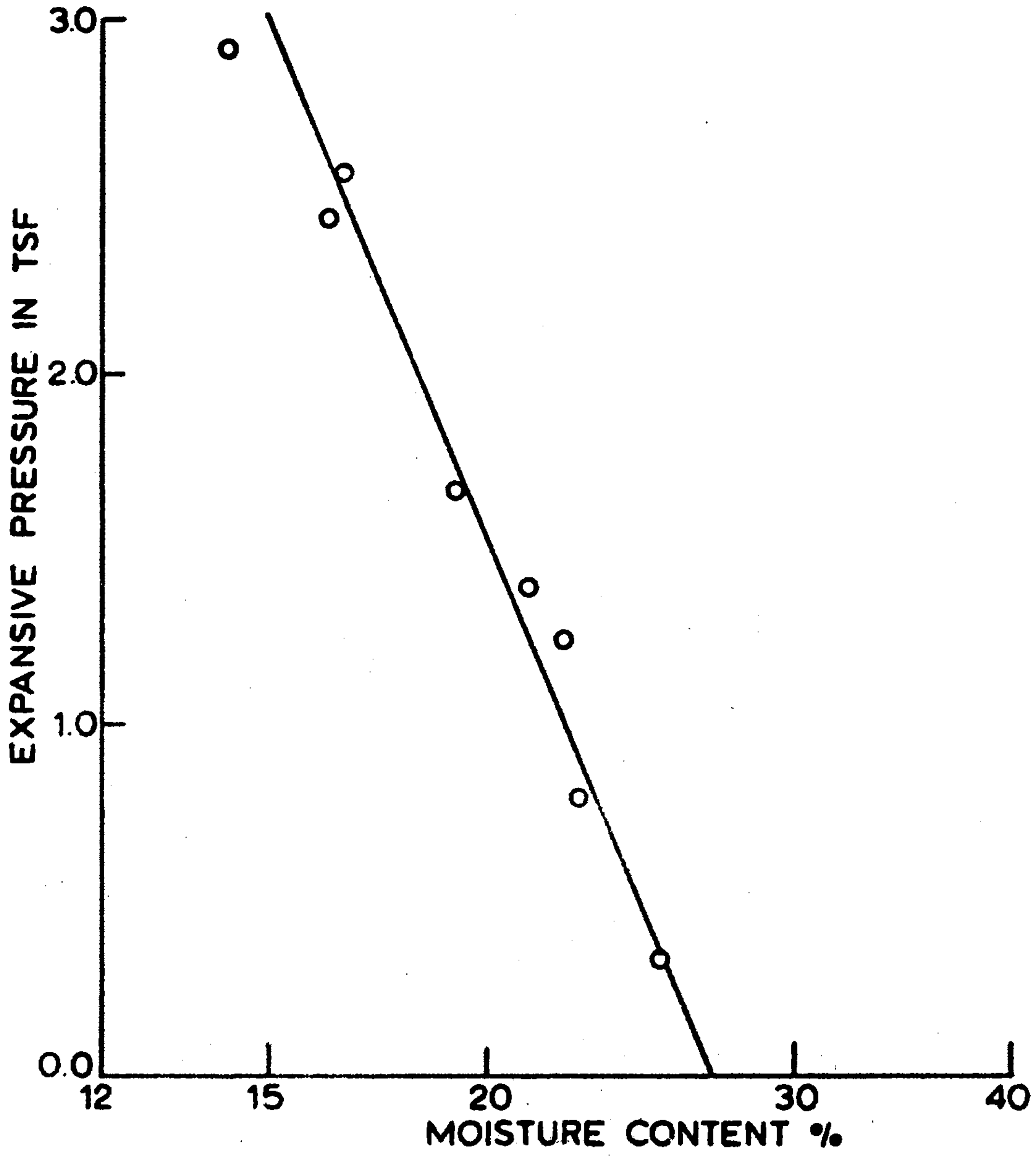


Figure 14. Expansive Pressure Versus Moisture Content for Untreated Clay

equation for this curve was determined to be

$$EP_{(TSF)} = 17.14 - 5.21\ Ln_{(MC)} \tag{4.1}$$

where

$EP_{(TSF)}$ = expansive pressure in tons per square foot, and

$Ln_{(MC)}$ = natural logarithm of the per cent moisture content of the sample.

Tube Model Testing of Untreated Material

To determine the most successful chemical for stabilization of the new soil, 25 electro-osmotic tests on 3.75-inch diameter tube samples were performed. The results of these tests showed that the soil was similar to the Chinle clay treated in the past. Therefore, it was decided for the field test to use the chemicals that had previously shown favorable results [20, 21, 23].

In addition to potassium chloride and calcium chloride, a waterproofing agent, Terebec C7, was also used in the small tube studies [24].

Various voltage gradients and treatment times were used in these tests. The results are listed in Table III.

Large Model Studies

In an attempt to simulate field conditions, an analysis of various electrode configurations was studied in the laboratory. Based on this, it was decided to perform three box model studies on the untreated material, and if these proved to be successful, to use the same configurations for the field test. A 15" X 30" X 24" steel mold was used to contain the compacted sample of soil (see Figure 15). Rather than use

TABLE III

3.75" DIAMETER TUBE MODEL TEST RESULTS

Sample No.	Chemical Solution	Voltage Gradient (V/in)	Treatment Time (hrs)	Solution Consumption (gal/ft^3)	Expansive Pressure TSF @ 20% MC	Reduction Factor
Untreated					1.600	1.00
106802A	KCl	0.5	100	1.98	.385	4.16
106802B		0.5	200	3.63	.192	8.33
106802C		0.5	300	3.52	.095	16.84
106802D		1.0	100	2.02	.160	10.00
106802E		1.0	200	2.90	.124	12.90
106802F		1.0	300	3.91	.120	13.30
106802G		1.5	100	2.11	.108	14.81
106802H		1.5	200	2.34	.105	15.23
106802I		1.5	300	4.36	.092	17.40
116808A		1.0	200	1.00	.582	2.75
116808B		1.5	200	1.00	.777	2.06
106815A	10% $CaCl_2$	0.5	100	1.57	.891	1.79
106809A		0.5	200	3.49	1.167	1.37
106811A		0.5	300	3.84	.696	2.30
106815B		1.0	100	1.68	1.075	1.49
106809B		1.0	200	2.02	1.377	1.16
106811B		1.0	300	3.04	.842	1.90
106815C		1.5	100	2.21	.891	1.79
106809C		1.5	200	3.08	1.073	1.49
106811C		1.5	300	2.48	1.330	1.20
106823A	Terebec C7	1.0	100	0.69	1.557	1.03
106823B		1.0	200	0.69	1.451	1.10

$$\text{Reduction Factor} = \frac{\text{Expansive Pressure of Untreated Material @ } 100\#/ft^3 \text{ \& } 20\%\ H_2O}{\text{Expansive Pressure of Treated Material @ } 100\#/ft^3 \text{ \& } 20\%\ H_2O}$$

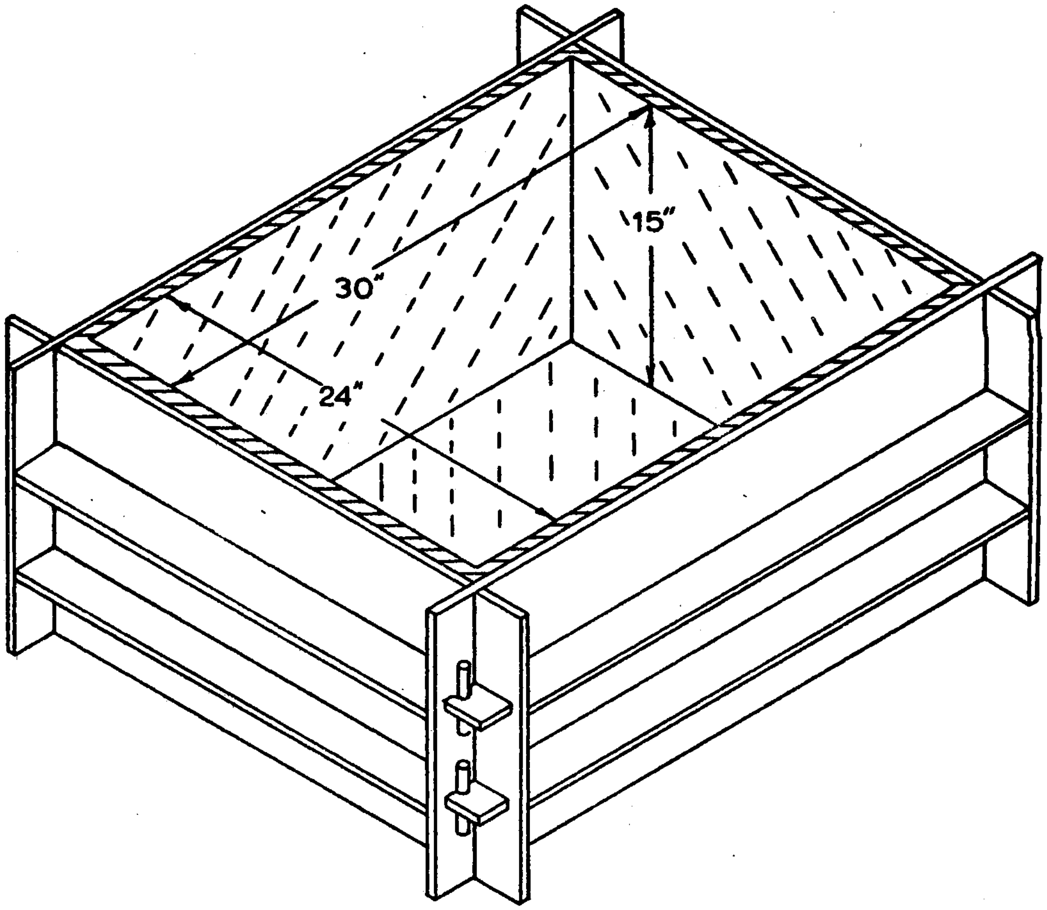


Figure 15. Steel Mold and Plexiglas Box

the Plexiglas box inside of the steel mold, as was done in previous models, a heavy plastic sheet lining was used to cover the steel mold. This eliminated the problem of the Plexiglas separating at the corners and allowing the solution to leak out of the model. Since the steel mold was used in conjunction with the plastic sheet, little or no lateral strain occurred during treatment.

The preparation of soil for treatment in the model began by obtaining a 500-pound representative sample of the previously prepared untreated material obtained from the new Interstate 40 road section. This material was divided into 50-pound batches and combined with sufficient distilled water to obtain 20 per cent moisture content. The moist soil was thoroughly mixed in a paddle mixer and allowed to cure for 72 hours in a moist room [20, 21, 23, 24].

The sample was then compacted in the plastic-lined steel mold in three equal lifts to obtain a depth of ten inches. The lower layers were well scarified after compaction to insure that a good bond would be obtained with the next higher layer. Compaction was accomplished by using a 24" X 30" X 3/4" steel loading plate and the 300,000-pound Universal testing machine at the Arizona Highway Department Central Laboratory. Sufficient load was applied to compact the soil to a density of 100 pcf.

Discussion of Model #10

Model #10 was constructed so that an electrode configuration in which positive and negative electrodes were placed vertically could be studied. The compacted soil was prepared for treatment by driving 9-1/2" X 1/4" solid steel rods which were used as negative electrodes.

The first negative electrode was located two inches from the short side and five inches from the long side of the model. All other negative electrodes were spaced ten inches on center. A single positive electrode was used in this model, and located in the center of the box. To install the positive electrode, a two-inch diameter hole was augered to a depth of 8-1/2 inches. A 9-1/2-inch long by 1-1/4-inch diameter slotted metal pipe was used for the positive electrode. This pipe was driven the last one-half inch to insure that it was held firmly in place. A sand blanket was poured in the void between the casing and the compacted soil to provide a uniform medium for flow from the pipe casing to the soil. Steel rods identical to the negative electrodes were used for resistance measurements (see Figure 16). Finally, the entire surface of the model was covered with a thin layer of wax to prevent escape of moisture during treatment [24].

Testing was started at 12:00 noon on December 13, 1968. An average voltage gradient of one volt per inch was established by placing a potential of 14 volts across the model. The solution well was filled and, thereafter, the saturated potassium chloride solution was added periodically to keep the well filled. On December 27, 1968, the test on Model #10 was completed.

Table IV shows the moisture contents of the samples when removed from the model, and the expansive pressures of these treated specimens.

Discussion of Model #11

Due to technical difficulties, Model #11 was assembled but not tested or sampled.

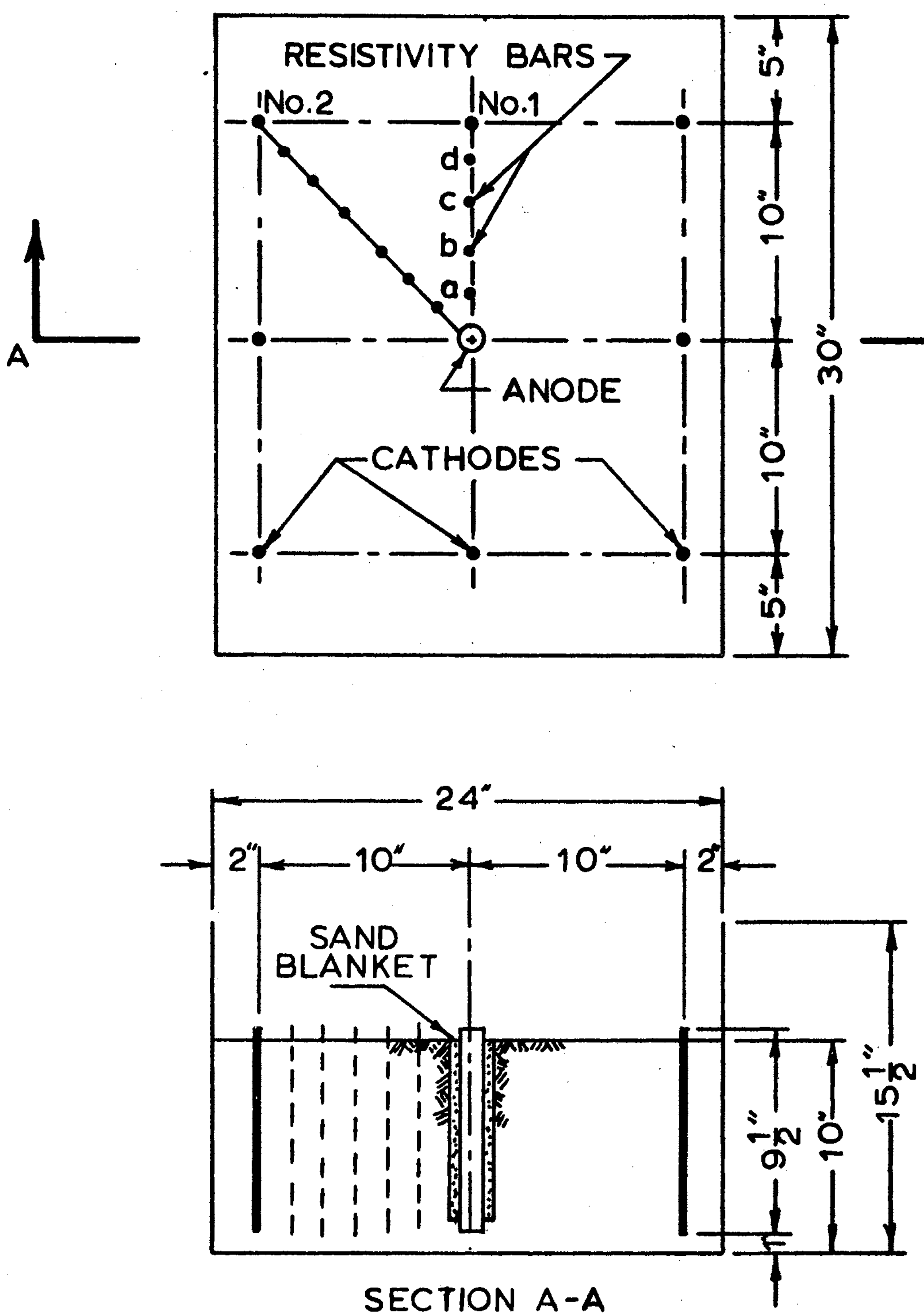


Figure 16. Box Model #10

TABLE IV

FINAL MOISTURE CONTENT, EXPANSIVE PRESSURE, AND REDUCTION FACTOR OF SAMPLES (Model #10)

Sample No.	Final MC in Model %	Expansive Pressure TSF@ 20% MC	Reduction Factor
1001	19.3	.173	9.25
1002	----	.158	10.01
1003	22.0	.142	11.25
1004	23.9	.386	4.15
1005	24.6	.047	34.10
1006	21.6	.082	19.50
1007	23.0	.199	8.04
1008	24.8	.565	2.84
1009	28.0	.788	2.04
1010	27.4	.750	2.14
1011	20.6	.484	3.31
1012	21.4	.445	3.60
1013	22.1	.208	7.70
1014	24.8	.521	3.07
1015	32.4	.665	2.41
1016	27.5	.774	2.07
1017	23.8	.129	12.40
1018	28.4	.654	2.45
1019	26.1	.524	3.06
1020	23.0	.145	11.00
1021	28.8	.790	2.03
1022	22.5	.115	13.90
1023	26.4	.137	11.66
1024	24.2	.080	20.00
1025	21.1	.099	16.16
1026	20.6	.074	21.60
1027	22.3	.049	32.70
1028	23.8	.538	2.97
1029	22.7	.134	11.90
1030	22.0	.082	19.50
1031	22.2	.134	11.90
1032	22.8	.376	4.26
1033	23.4	.041	39.00
1034	24.4	.076	21.10
1035	21.4	.027	59.30
1036	24.4	.539	2.97
1037	23.6	.457	3.51
Untreated		1.600	1.00

$$\text{Reduction Factor} = \frac{\text{Expansive Pressure of Untreated Material*}}{\text{Expansive Pressure of Treated Material*}}$$

*@100#/ft^3 and 20% H_2O

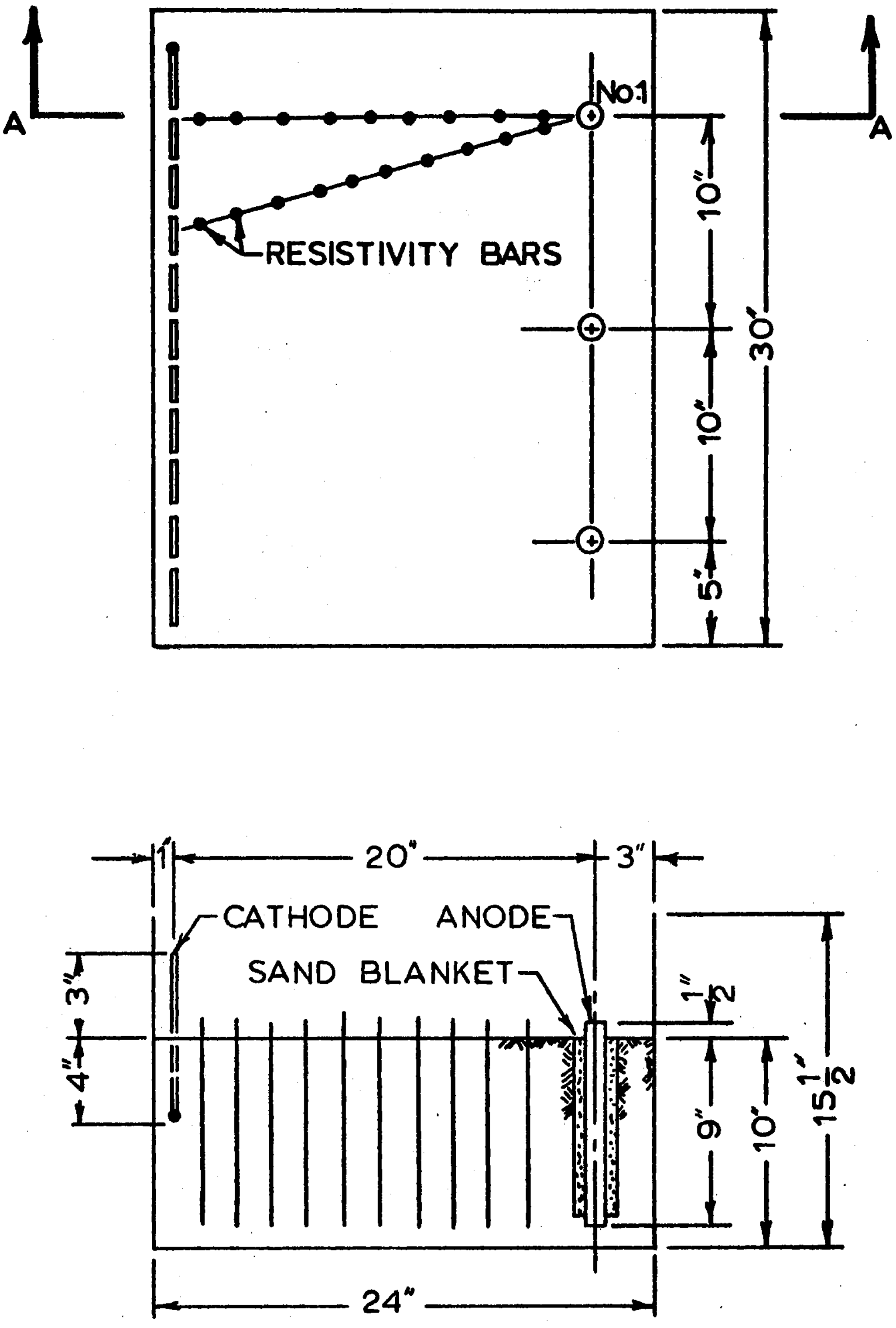
Discussion of Model #12

Model #12 was constructed to study treatment effects due to an electrode configuration of vertical anodes and a horizontal cathode. The model was prepared in the same way as Model #10.

The compacted soil was prepared for treatment by installing the electrodes according to Figure 17. The cathode was installed by cutting a groove four inches deep parallel to the long side of the model. The cathode was a 28" X 1/4" steel bar that had a riser on one end to make the electrical connection. The cathode was placed, covered, and the soil above it was recompacted. Three positive electrodes were used in this model and located along the 30" side of the box. To install the positive electrodes, two-inch diameter holes were augered to a depth of 8-1/2 inches. Slotted metal pipes, 9-1/2-inch long by 1-1/4-inch diameter, were used for positive electrodes. These pipes were driven the last one-half inch to insure that they were held firmly in place. A sand blanket was poured in the void between the casing and the compacted soil to provide a uniform medium for flow from the pipe casing to the soil.

Testing was started at 9:30 a.m., January 24, 1969. A voltage gradient of one volt per inch (20 volts total) was applied to the model and the solution wells were then filled with saturated potassium chloride solution. Potassium chloride solution was added periodically to keep the wells filled. The test on Model #12 was completed on February 7, 1969 [24].

A listing of the moisture contents of the samples when removed from the model and the results of expansive pressure tests are found in Table V.



SECTION A-A

Figure 17. Box Model #12

TABLE V

FINAL MOISTURE CONTENT, EXPANSIVE PRESSURE, AND REDUCTION FACTOR OF SAMPLES (Model #12)

Sample No.	Final MC in Model %	Expansive Pressure TSF @ 20% MC	Reduction Factor
1201	20.6	.421	3.80
1202	22.6	.329	4.86
1203	23.3	.647	2.47
1204A	26.1	.196	8.17
1204B	23.1	.940	1.70
1205A	31.0	.381	4.20
1205B	21.3	1.363	1.17
1206A	32.6	1.187	1.35
1206B	24.1	.895	1.79
1207A	23.9	.080	20.00
1207B	21.5	.830	1.93
1208A	24.4	.143	11.19
1208B	21.3	.927	1.72
1209A	28.1	.387	4.14
1209B	23.2	.973	1.65
1210A	32.9	1.460	1.09
1210B	23.9	1.541	1.04
1211A	33.9	1.395	1.15
1211B	23.8	.891	1.80
1212	25.5	.940	1.71
1213A	25.5	.206	7.77
1213B	----	1.164	1.37
1217A	24.1	.115	13.90
1217B	23.1	.336	4.76
1218A	24.1	.141	11.40
1218B	23.2	.654	2.45
1219A	24.8	.258	6.20
1219B	23.9	.859	1.86
1220A	22.5	.141	11.34
1220B	23.1	.696	2.30
1221A	23.3	.209	7.66
1221B	22.2	.745	2.14
1222A	26.8	.778	2.06
1222B	25.2	1.200	1.33
1223A	30.1	.485	3.30
1223B	25.3	1.610	1.00
1224A	29.3	.591	2.70
1224B	27.3	1.168	1.37
1225A	21.8	.059	27.20
1225B	21.6	.179	8.94

TABLE V (Continued)

Sample No.	Final MC in Model %	Expansive Pressure TSF @ 20% MC	Reduction Factor
1226A	22.4	.105	15.20
1226B	24.4	.895	1.79
1227A	22.8	.046	34.85
1227B	25.5	.451	3.55
1228A	29.2	.368	4.36
1228B	26.3	.352	4.56
1229A	30.2	.462	3.47
1229B	19.2	.761	2.11
Untreated		1.600	1.00

$$\text{Reduction Factor} = \frac{\text{Expansive Pressure of Untreated Material*}}{\text{Expansive Pressure of Treated Material*}}$$

*@100#/ft^3 and 20% H_2O

Discussion of Model #13

Model #13 was constructed to study the effectiveness of treatment using an electrode configuration consisting of a horizontal positive electrode and horizontal negative electrode.

The compacted soil was prepared for treatment by installing the electrodes according to Figure 18. The negative electrodes were installed by cutting a groove four inches deep parallel to the long side of the model. These three electrodes were 9" X 1/4" steel bars with a riser on one end to make the electrical connections. The negative electrodes were placed, covered, and the soil was replaced and recompacted. The positive electrode was installed in a manner similar to that of the negative electrodes. A groove four inches deep and parallel to the negative electrodes was cut. This groove was cut 20 inches away from the negative electrodes. The positive electrode was a 29" X 1-1/4" steel pipe with risers on each end. One riser would serve as the electrical connection and the other was for addition of solution. Eighteen 9-1/2" X 1/4" steel bars were placed on two inch centers across the model in order to obtain resistivity measurements at these points.

The test began at 10:30 a.m., April 3, 1969. A voltage gradient of one volt per inch (20 volts total) was applied to the model and the solution well was then filled with saturated potassium chloride solution. Potassium chloride solution was added periodically to keep the well filled. Testing on Model #13 was completed on April 21, 1969 [24].

Thirty samples were obtained for moisture content determination and expansive pressure testing. Table VI contains the results of the expansive pressure tests as well as the initial moisture contents of the treated material when it was removed from the model.

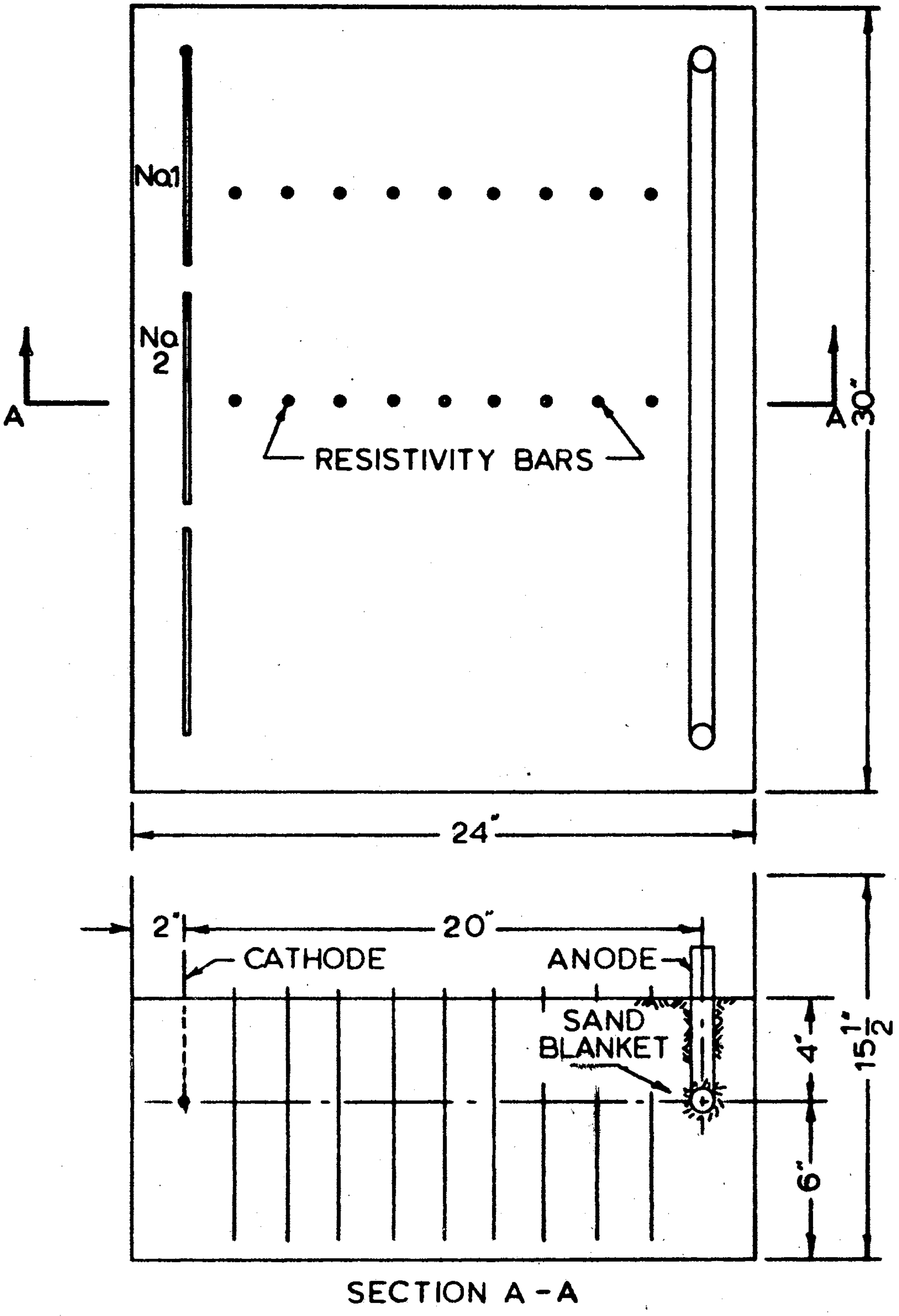


Figure 18. Box Model #13

TABLE VI

FINAL MOISTURE CONTENT, EXPANSIVE PRESSURE, AND REDUCTION FACTOR OF SAMPLES (Model #13)

Sample No.	Final MC in Model %	Expansive Pressure TSF @ 20% MC	Reduction Factor
1301	24.0	.052	30.80
1302	26.8	.220	7.28
1303	28.8	.562	2.85
1304	30.5	.595	2.69
1305	30.1	.400	4.00
1306	24.0	.069	23.20
1307	29.2	.280	5.71
1308	28.0	.268	5.96
1309	30.1	.584	2.74
1310	28.2	.374	4.28
1311	23.8	.048	33.40
1312	25.9	.298	5.36
1313	29.0	.580	2.76
1314	29.8	.550	2.91
1315	26.6	.376	4.26
1316	24.6	.102	15.65
1317	25.8	.151	10.60
1318	29.0	.600	2.66
1319	30.5	.520	3.08
1320	28.4	.409	3.92
1321	23.2	.089	18.00
1322	24.9	.087	18.40
1323	28.6	.415	3.86
1324	30.3	.590	2.72
1325	31.1	.560	2.86
1326	23.0	.071	22.50
1327	24.9	.061	26.25
1328	25.0	.067	23.85
1329	29.7	.390	4.10
1330	31.3	.486	3.29
Untreated		1.600	1.00

$$\text{Reduction Factor} = \frac{\text{Expansive Pressure of Untreated Material*}}{\text{Expansive Pressure of Treated Material*}}$$

---

*@100#/ft^3 and 20% H_2O

Summary

Table VII is a summary of the general treatment data for the large model tests. The average reduction factors obtained from the expansive pressure tests indicate that Model #10 and Model #13 had quite good overall treatment while Model #12 had less favorable results.

Field Work - Phase II

General

The scope of the field portion of the electro-osmotic stabilization of Chinle clay, for this phase, was as follows:

(1) To choose a new test site on an unpaved section of I-40 near Holbrook, Arizona, and obtain a representative sample of the expansive soil.

(2) To design, install, and operate a full-scale field test on the test section.

(3) To sample the electro-osmotically treated section.

Site Selection and Sampling

The field work for this study began in July, 1968, with the selection of a new test site east of Holbrook. The site is located on a section of I-40 which was still in the construction stage. About two cubic yards of disturbed soil were obtained from the roadway. The Highway Department transported the sample to Arizona State University where it was prepared and used in laboratory studies.

TABLE VII

SUMMARY OF GENERAL DATA FOR BOX MODEL TESTS

Item	Model #10	Model #12	Model #13
Dry Density	100 pcf	100 pcf	100 pcf
Initial Moisture Content	19.8%	20.1%	19.7%
Chemical Solution	Saturated KCl	Saturated KCl	Saturated KCl
Electrode Configuration	Vertical Positive and Negative Steel Electrodes	Vertical Positive Steel Electrodes, Horizontal Negative Steel Electrode	Horizontal Positive and Negative Steel Electrodes
Voltage Gradient	1.0 V/in	1.0 V/in	1.0 V/in
Quantity of Solution Used	1.53 gal/ft^3	0.836 gal/ft^3	1.34 gal/ft^3
Treatment Time	14 days	14 days	18 days
Reduction Factor	5.11 average of 37 samples	Part A 3.89 average of 26 samples Part B 1.99 average of 26 samples Total model 2.55 average of 48 samples	4.87 average of 30 samples

Field Test

Design. The highway field installation was designed to reproduce the electrode configurations of large model studies 10, 12, and 13. To this end, a design was chosen that incorporated the desirable characteristics of a model study with the realities of conducting the work in the field on a much larger scale.

It was decided not to treat the soil to a depth greater than three feet below top of subgrade. This decision resulted from the Arizona Highway Department's lime ponding study in the same general area. The Highway Department found that there was no significant change in water content of the Chinle clay three feet below a lime water pond treatment of subgrade thirty days after the pond had been constructed.

The electrode configuration of laboratory model 10 was used on two 19-foot square sections of the highway. The injection well for each section was designed as a 10-inch diameter, 3-1/2-foot deep bored hole with a 6-inch diameter, one-fourth inch wall, steel pipe placed in the center of the hole. The area between the pipe and the hole was filled with a sand filter. The bottom three feet of the pipe was slotted to allow the solution to move uniformly into the sand filter and ultimately into the Chinle clay. A number six rebar was chosen for negative electrodes and resistivity measurement bars. For a plan view of the field test see Figure 19, Section "A."

The electrode configuration of laboratory model 12 was used on a 19 X 20-foot section of the highway. Three injection wells similar to those in Section "A" were used. Three 10-foot long number six rebars bent four feet from one end were used as negative electrodes. A trench two feet deep was cut and the three electrodes were then spaced evenly

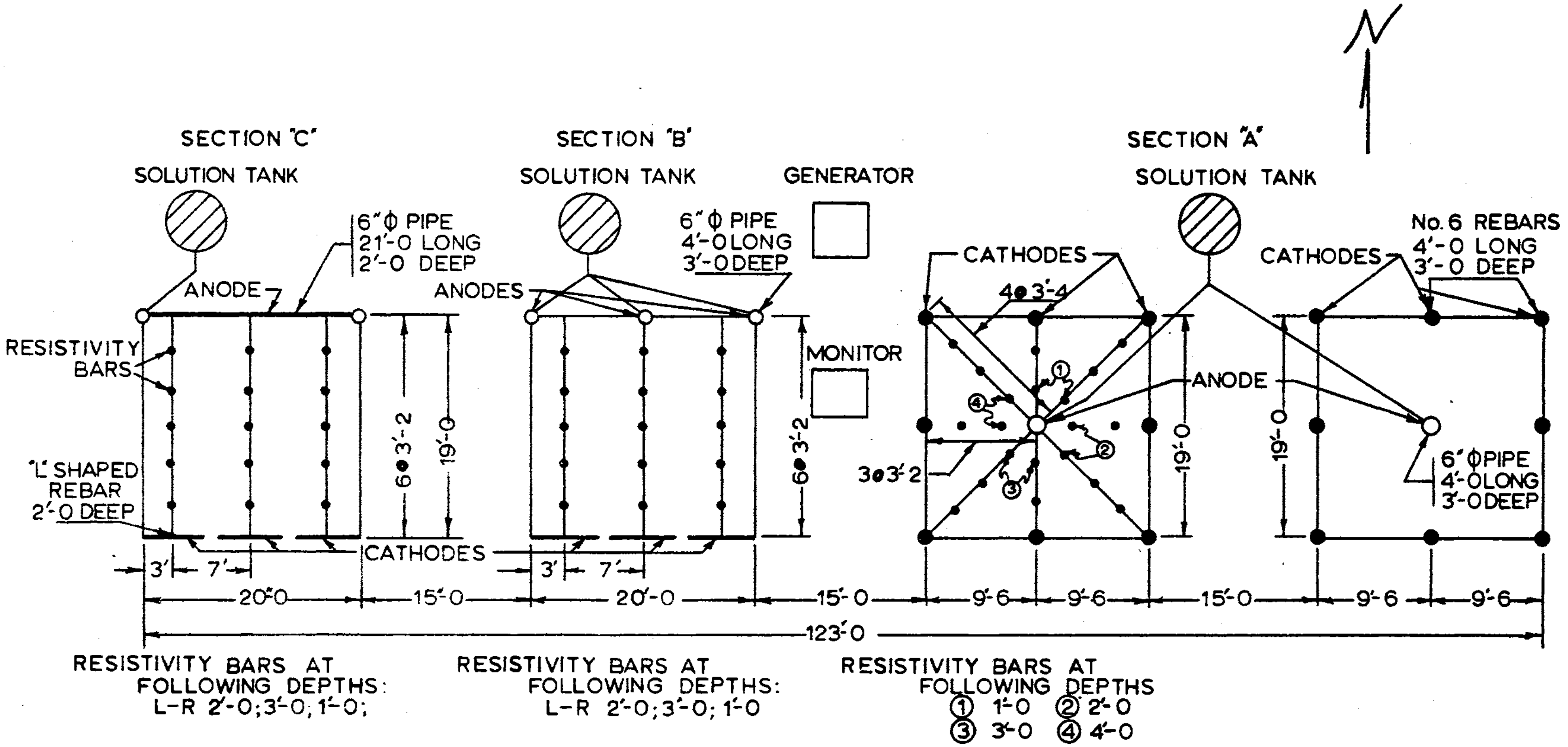


Figure 19. Electro-Osmotic Test Section

in the trench with the four-foot riser protruding above ground for the electrical connection. After the negative cathode had been placed, the trench was backfilled with clay and recompacted to approximately the inplace density of the surrounding material. Resistivity bars similar to those of Section "A" were placed as shown in Figure 19, Section "B" [24].

The electrode configuration of laboratory model 13 was used on a 19 X 20-foot section of the highway. A single 20-foot-long, 6-inch diameter, 1/4-inch steel-wall pipe, slotted the entire length, with risers on each end, was used as the positive electrode. This electrode was placed in a two-foot-deep trench and covered with a sand blanket. Then the trench was backfilled with clay and recompacted to approximately the same inplace density as the surrounding material. The negative electrodes and resistivity bars were identical to those of Section "B," see Figure 19, Section "C."

With the structural components of the installation fixed, the chemical and electrical aspects of the problem were studied.

The quantity of solution necessary to complete the field test was estimated from performance of the models. The models indicated that 8,000, 4,000, and 4,000 pounds of potassium chloride would be needed for Sections A, B, and C, respectively. The 16,000 pounds of chemical was mixed at the ratio of 100 pounds of potassium chloride to 60 gallons of water, or approximately two gallons of solution per cubic foot of soil to be treated [24].

Since it was not possible to apply a different voltage to each of the three sections, it was decided to use a potential difference of 100 volts, or approximately one volt per inch in Section "A" and four-tenths of a volt per inch in Sections B and C. The current necessary necessary to maintain this potential was known from previous tests to be well within the capacity of the 120 volt/500 amp direct current diesel-driven generator which was used in the May, 1967, field test [21].

Solution Consumption

A total of 3150 gallons of potassium chloride solution was used in the three treated sections. The distribution of solution was as follows:

Section A	600 gallons
Section B	550 gallons
Section C	2,000 gallons

Field Sampling

A total of 185 six-inch auger samples were obtained from the three electro-osmotically treated sections. The distribution was as follows:

Section A	83 samples
Section B	48 samples
Section C	54 samples

The location of the samples is shown in Figure 20. At each location two representative samples, one from 0'6" to 2'0" and the second 2'0" to 3'6" were obtained. In addition, at several selected points, samples representative of 3'6" to 9'0" were obtained [24].

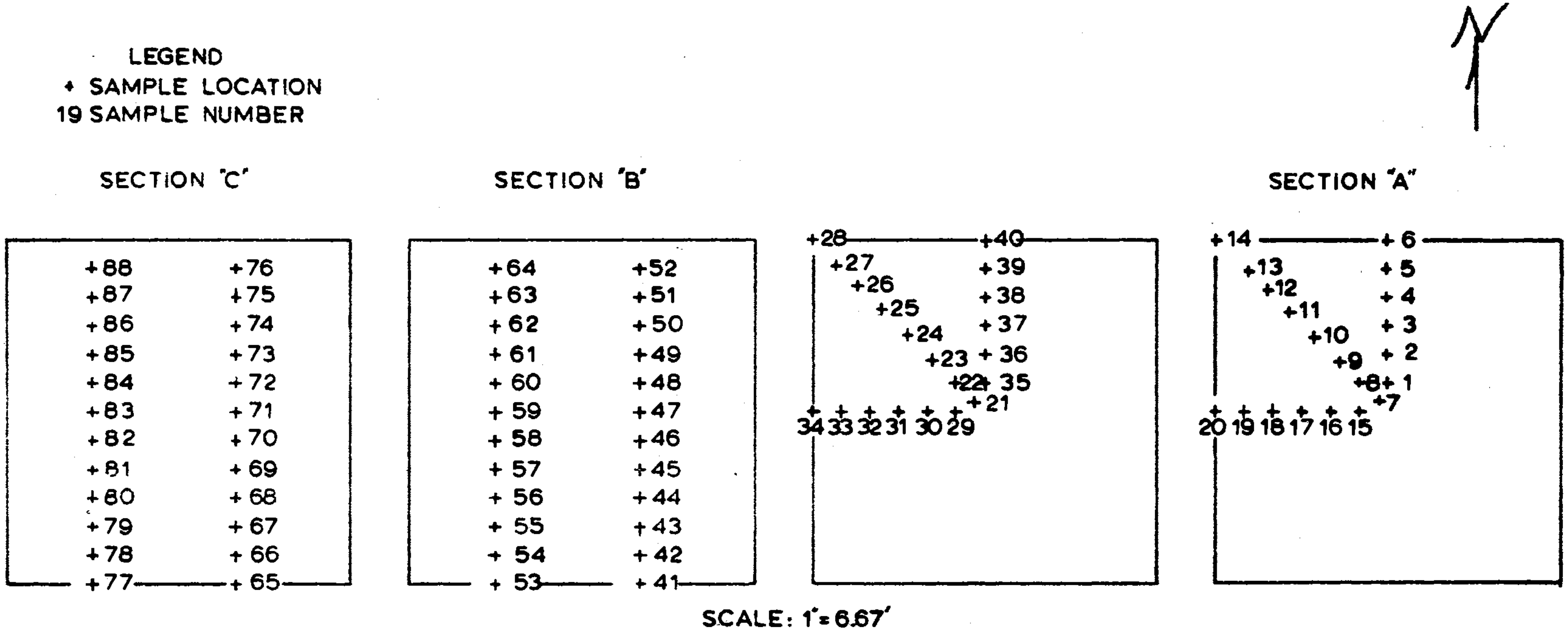


Figure 20. Electro-Osmotic Treated Section Test Section Sampling Plan

Field Test Results, Summary, and Conclusions

- Phase II

General

This section is divided into the following three parts:

(1) A presentation of expansive pressure results on samples taken from the field test area of May, 1969.

(2) A summary of important results for laboratory and field work during Phase II.

(3) Conclusions that became apparent from laboratory and field work during Phase II.

Field Test Results

Preparation of Field Test Samples. Samples obtained from the field test site were delivered to Arizona State University Soils Laboratory where they were prepared in the following manner.

Soil samples were removed from their sacks and spread in a thin layer on a concrete surface and allowed to air dry for several days. Each sample was then split twice to obtain a representative sample of approximately 1000 grams. The remaining portion was replaced in the sack for storage. The sample of approximately 1000 grams was ground in a mortar with a rotating rubber pestle attached to a drill press. This material was broken down to pass a number 10 sieve and stored for future testing [24].

Expansive Pressure Testing of Field Test Samples. The procedure followed for this test was to obtain a representative 500-gram sample from the previously dried and prepared soil. The material was mixed to

20% moisture and allowed to cure in a moist room overnight. Sufficient soil was compacted into a one-inch-thick sample in the R-value mold at 100 pounds per cubic foot dry density and then placed in the expansive pressure device (see Figure 12). The water content of the sample was checked by oven drying a portion of the 500-gram soil not used in the expansive pressure device. The expansive pressure test was run according to Test Method No. Calif. 301-F, Part IV, "Method of Determining the Expansive Pressure of R-value Test Specimens."

Results of expansive pressure tests from each of the three treatment sections are listed in Tables VIII through X.

The deep samples denoted as "b" had no expansive pressure because these samples contained large amounts of sand.

In Tables VIII through X, the variation in expansive pressures of samples from each section may be seen. Samples from Section "A" had expansive pressures varying from 0.032 TSF to above 0.7 TSF with an average of 0.450 TSF. Samples from Section "B" had expansive pressures varying from 0.106 TSF to above 0.65 TSF with an average of 0.426 TSF. Samples from Section "C" had expansive pressures varying from 0.135 TSF to less than 0.6 TSF with an average of 0.385 TSF. These variations in expansive pressure for each test section may be seen graphically in Figures 21 through 27. The expansive pressure as a function of position between anode and cathode is plotted for the two different depths of samples. Note that samples from Test Section "A," Figures 21 through 23 have rather low expansive pressure near the anode; however, the expansive pressure of samples increases as distance from the anode increases. This is an indication that the chemical solution had not migrated completely through the soil. Figures 24 and 25 show that

TABLE VIII

FIELD TEST -- SECTION A
EXPANSIVE PRESSURE

Sample	Expansive Pressure TSF	Reduction Factor
1	.032	50.20
1A	.279	5.75
1B	----	-----
2	.542	2.96
2A	.359	4.46
3	.504	3.18
3A	.538	3.01
4	.530	3.02
4A	.708	2.27
5	.248	6.46
5A	.473	3.39
6	.627	2.56
6A	.656	2.44
7	.108	14.20
7A	.188	8.50
8	.285	5.62
8A	.355	4.52
9	.524	3.06
9A	.418	3.83
9B	----	-----
10	.372	4.30
10A	.644	2.49
11	.564	2.84
11A	.624	2.56
12	.493	3.25
12A	.580	2.76
13	.469	3.42
13A	.650	2.46
14	.525	3.05
14A	.614	2.61
15	.127	12.60
15A	.302	5.30
16	.385	4.16
16A	.566	2.82
17	.505	3.17
17A	.515	3.11
18	.380	4.21
18A	.596	2.68
19	.534	3.00
19A	.475	3.37
20	.441	3.63
20A	.579	2.77

TABLE VIII (Continued)

Sample	Expansive Pressure TSF	Reduction Factor
21	.112	14.30
21A	.238	6.73
22	.445	3.60
22A	.471	3.40
23	.318	5.04
23A	.419	3.82
24	.253	6.34
24A	.581	2.76
25	.335	4.78
25A	.689	2.33
26	.711	2.25
26A	.646	2.48
27	.592	2.71
27A	.676	2.37
28	.468	3.42
28A	.622	2.57
29	.097	16.50
29A	.209	7.66
30	.426	3.76
30A	.486	3.29
31	.531	3.02
31A	.473	3.39
32	.620	2.58
32A	.607	2.64
33	.598	2.68
33A	.426	3.75
34	.412	3.88
34A	.598	2.68
35	.110	14.50
35A	.227	7.06
36	.300	5.34
36A	.352	4.55
37	.452	3.52
37A	.417	3.84
38	.335	4.76
38A	.525	3.05
38B	----	-----
39	.436	3.67
39A	.378	4.23
40	.507	3.16
40A	.532	3.01

$$\text{Reduction Factor} = \frac{\text{Expansive Pressure of Untreated Material*}}{\text{Expansive Pressure of Treated Material}}$$

---

*@100 pcf and 20% H_2O

TABLE IX

FIELD TEST -- SECTION B
EXPANSIVE PRESSURE

Sample	Expansive Pressure TSF	Reduction Factor
41	.216	7.41
41A	.526	3.04
42	.199	8.05
42A	.562	2.84
43	.441	3.63
43A	.584	2.74
44	.476	3.36
44A	.499	3.21
45	.370	4.33
45A	.498	2.68
46	.244	6.55
46A	.677	2.36
47	.493	3.24
47A	.430	3.72
48	.372	4.30
48A	.572	2.79
49	.292	5.47
49A	.408	3.92
50	.558	2.86
50A	.506	3.16
51	.471	3.39
51A	.502	3.19
52	.240	6.67
52A	.560	2.86
53	.222	7.21
53A	.464	3.45
54	.318	5.04
54A	.553	2.89
55	.313	5.11
55A	.491	3.25
56	.298	5.36
56A	.538	3.97
57	.238	6.72
57A	.460	3.48
58	.223	6.18
58A	.331	4.84
59	.106	15.10
59A	.376	4.26
60	.316	5.06
60A	.601	2.66
61	.276	5.80
61A	.484	3.31

TABLE IX (Continued)

Sample	Expansive Pressure TSF	Reduction Factor
62	.501	3.19
62A	.577	2.77
63	.397	4.04
63A	.544	2.94
64	.523	3.06
64A	.493	3.24

$$\text{Reduction Factor} = \frac{\text{Expansive Pressure of Untreated Material}^*}{\text{Expansive Pressure Treated Material}^*}$$

---

*@100 pcf and 20% H_2O

TABLE X

FIELD TEST -- SECTION C
EXPANSIVE PRESSURE

Sample	Expansive Pressure TSF	Reduction Factor
65	.255	6.27
65A	.440	3.64
66	.489	3.28
66A	.400	4.00
67	.411	3.89
67A	.590	2.72
68	.380	4.21
68A	.488	3.27
68B	----	----
69	.422	3.80
69A	.229	7.00
70	.406	3.94
70A	.497	3.22
70B	----	----
71	.385	4.16
71A	.392	4.08
72	.300	5.33
72A	.448	3.57
73	.389	4.12
73A	.503	3.18
73B	----	----
74	.123	13.00
74A	.472	3.40
75	.232	6.90
75A	.342	4.68
76	.223	7.18
76A	.350	4.57
77	.518	3.10
77A	.410	3.91
78	.421	3.80
78A	.450	3.56
79	.490	3.27
79A	.430	3.72
79B	----	----
80	.444	3.61
80A	.444	3.61
81	.458	3.50
81A	.411	3.90
82	.404	3.96
82A	.432	3.72
82B	----	----

TABLE X (Continued)

Sample	Expansive Pressure TSF	Reduction Factor
83	.350	4.56
83A	.472	3.39
84	.281	5.70
84A	.455	3.52
85	.246	6.51
85A	.385	4.16
85B	----	----
86	.227	7.06
86A	.454	3.54
87	.312	5.13
87A	.357	4.48
88	.135	11.80
88A	.322	4.97

$$\text{Reduction Factor} = \frac{\text{Expansive Pressure of Untreated Material*}}{\text{Expansive Pressure of Treated Material*}}$$

---

*@100 pcf and 20% H_2O

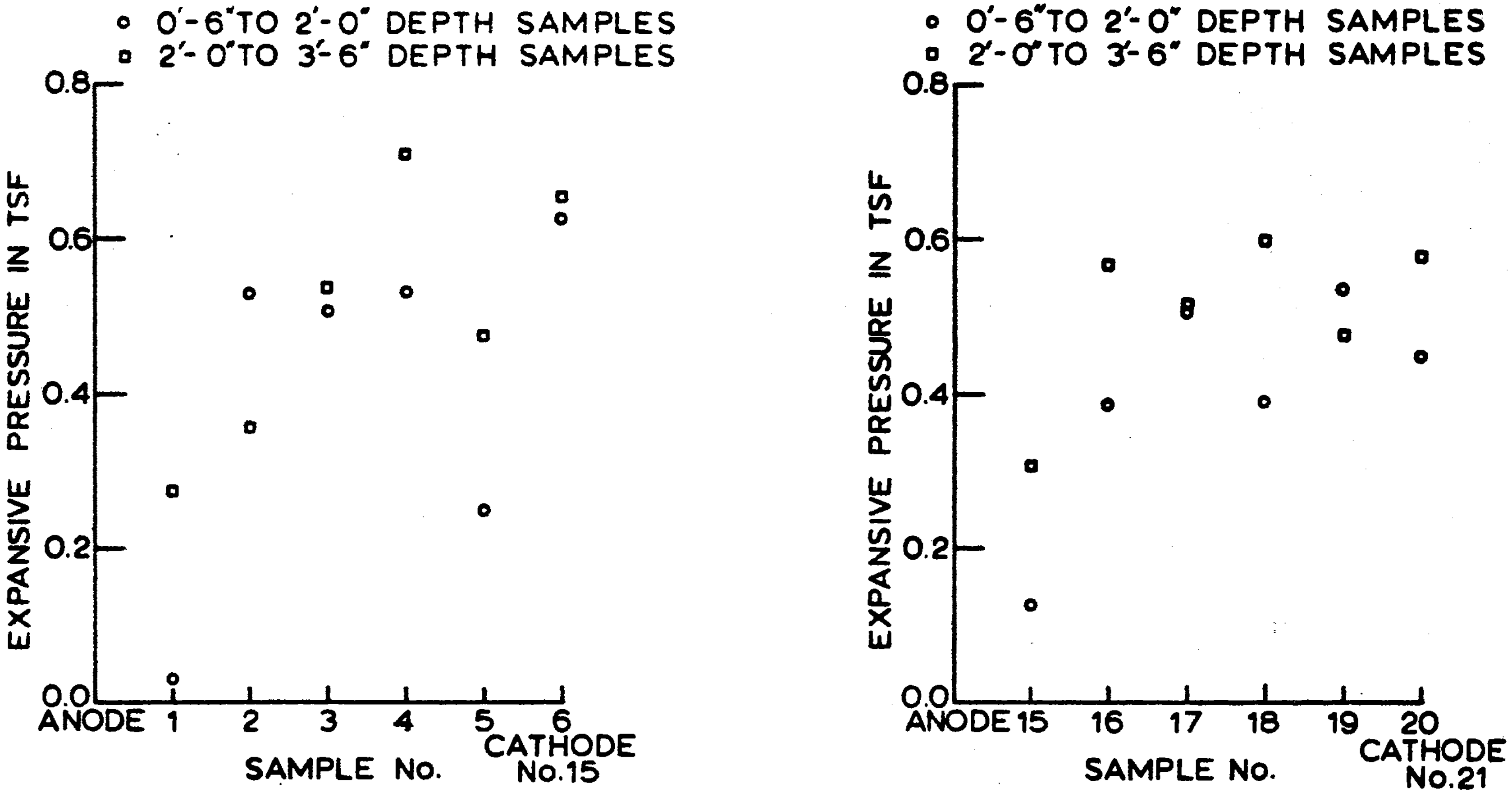


Figure 21. Expansive Pressure of Samples Between Anode and Cathode Numbers 15 and 21 --Test Section A

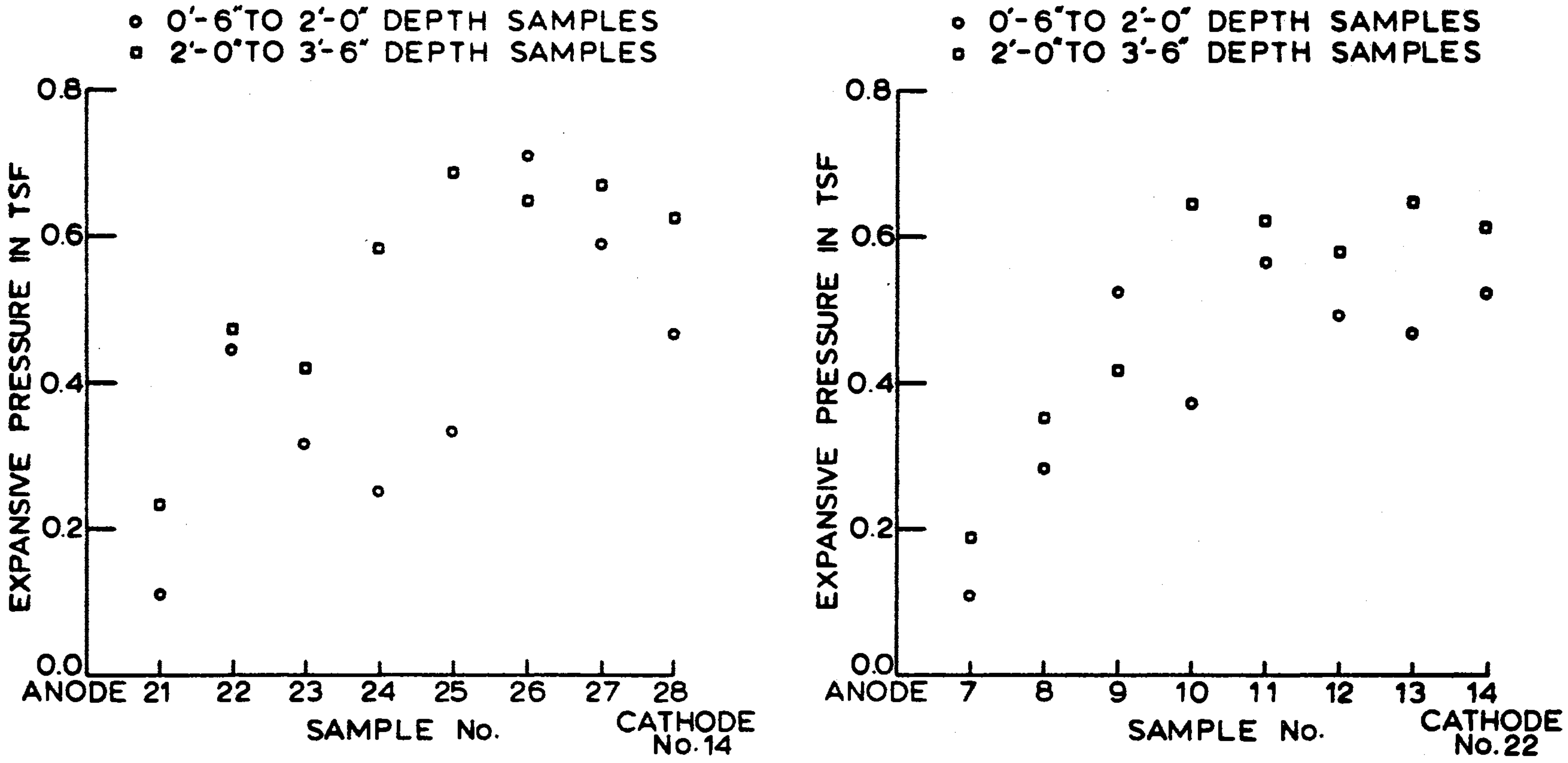


Figure 22. Expansive Pressure of Samples Between Anode and Cathode Numbers 14 and 22 --Test Section A

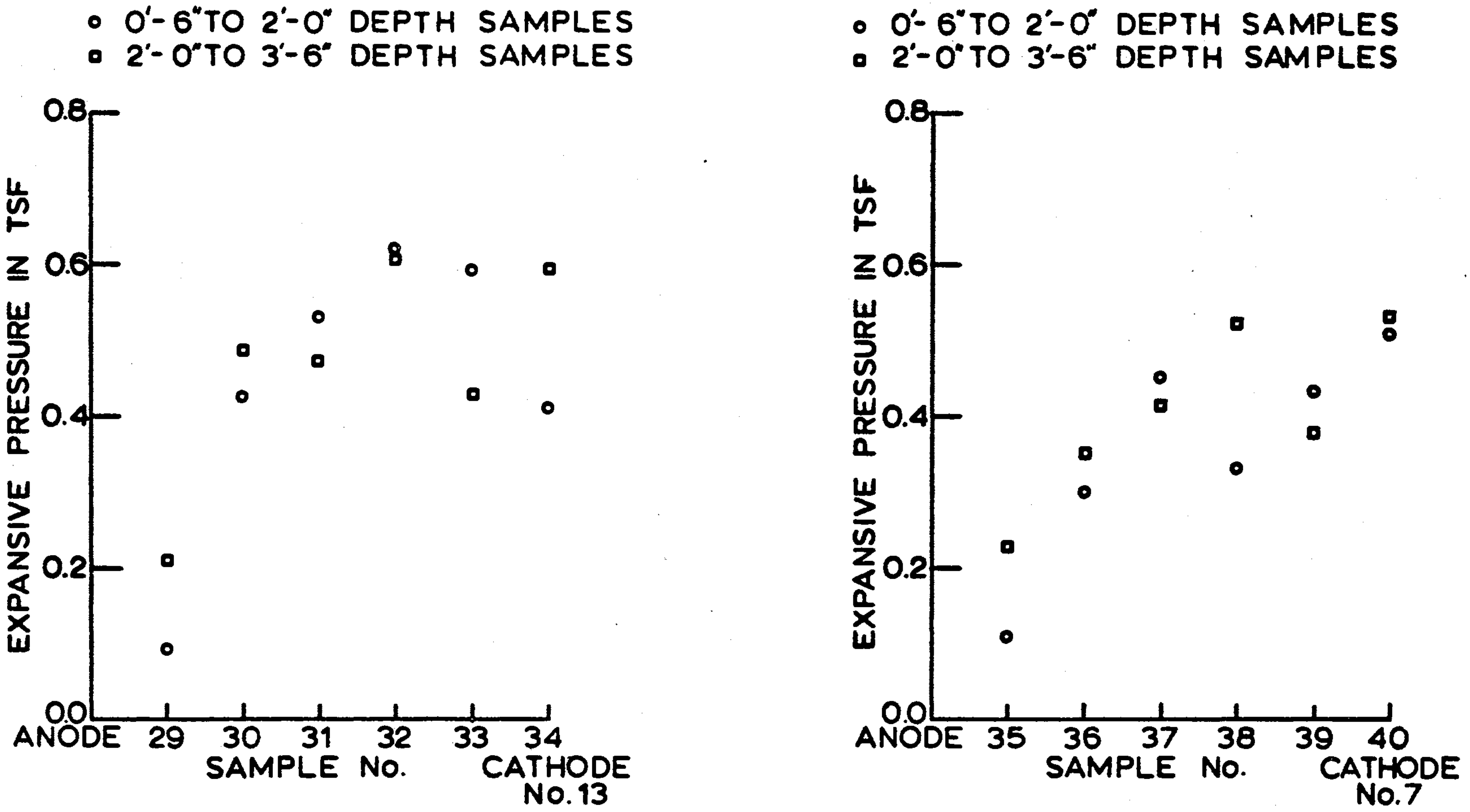


Figure 23. Expansive Pressure of Samples Between Anode and Cathode Numbers 13 and 7 --Test Section A

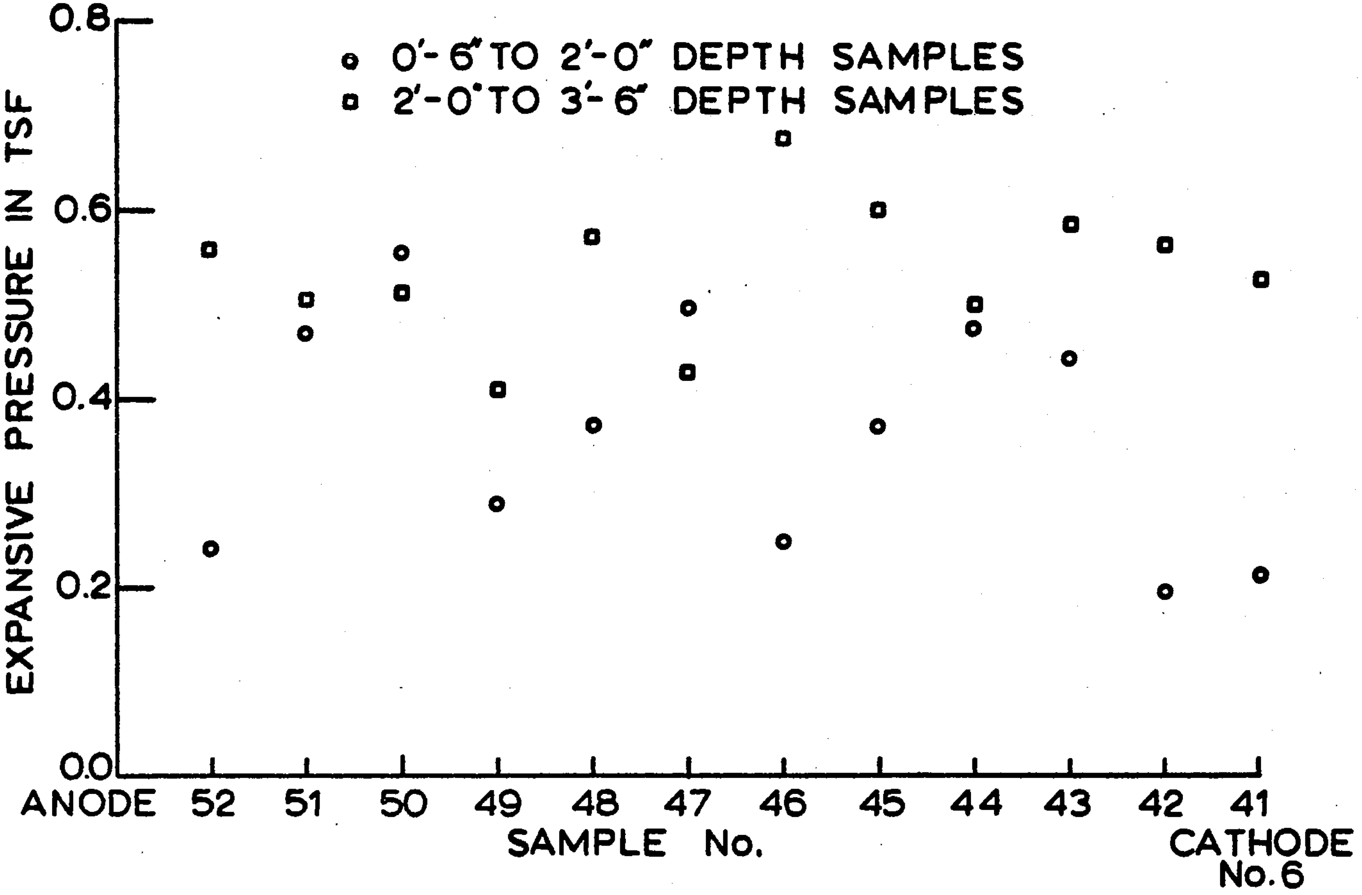


Figure 24. Expansive Pressure of Samples Between Anode and Cathode Number 6 --Test Section B

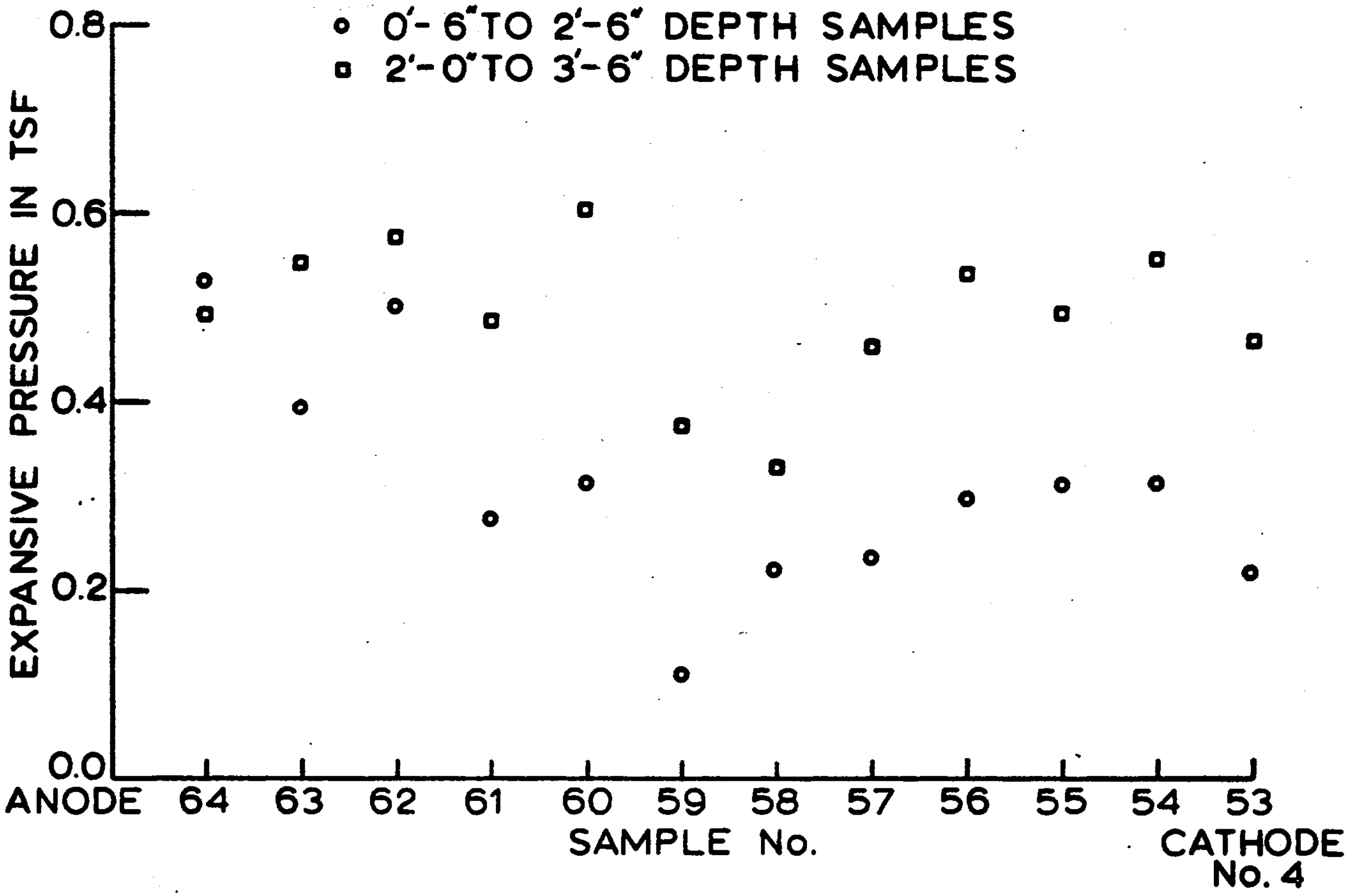


Figure 25. Expansive Pressure of Samples Between Anode and Cathode Number 4 --Test Section B

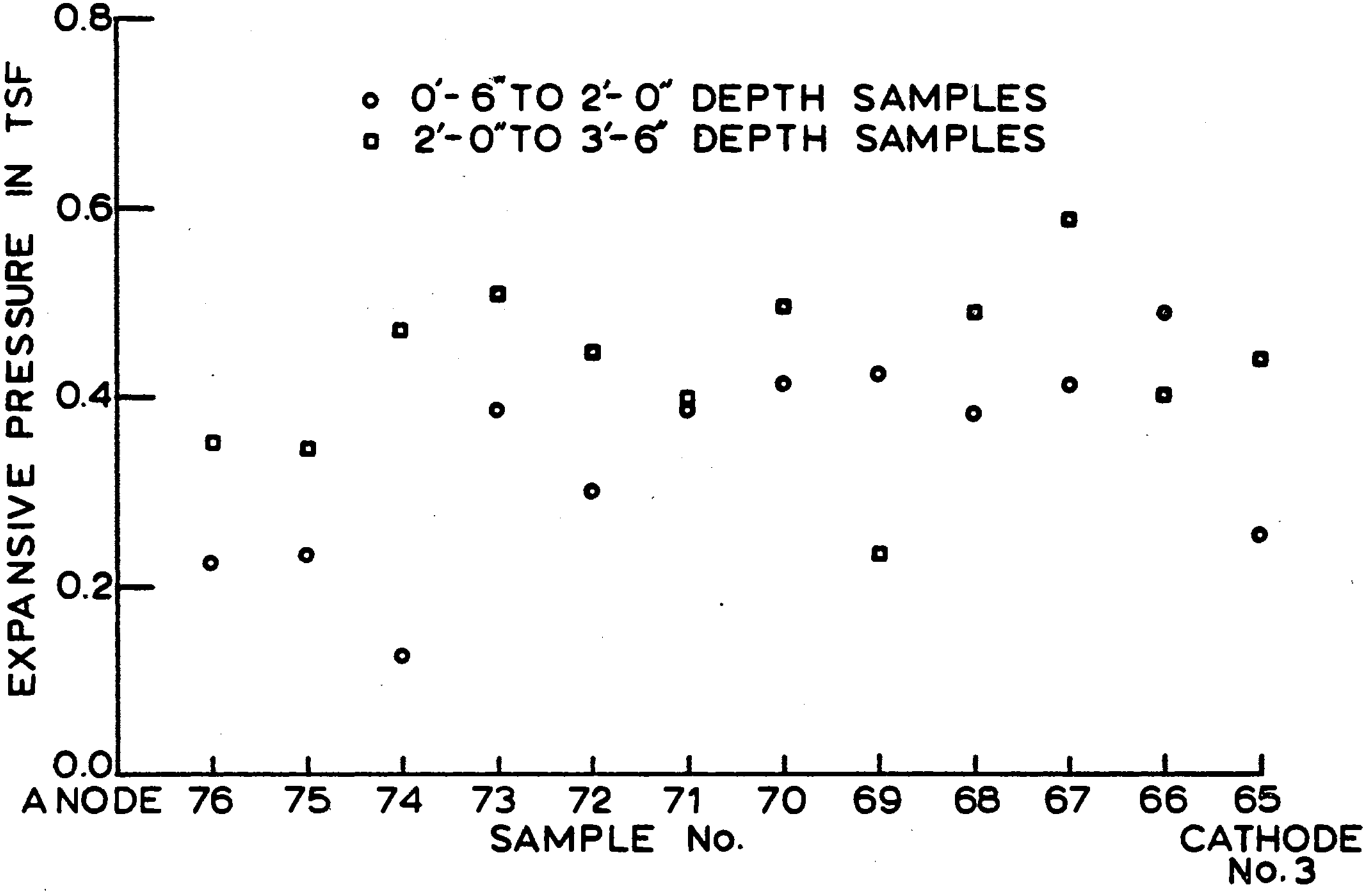


Figure 26. Expansive Pressure of Samples Between Anode and Cathode Number 3 --Test Section C

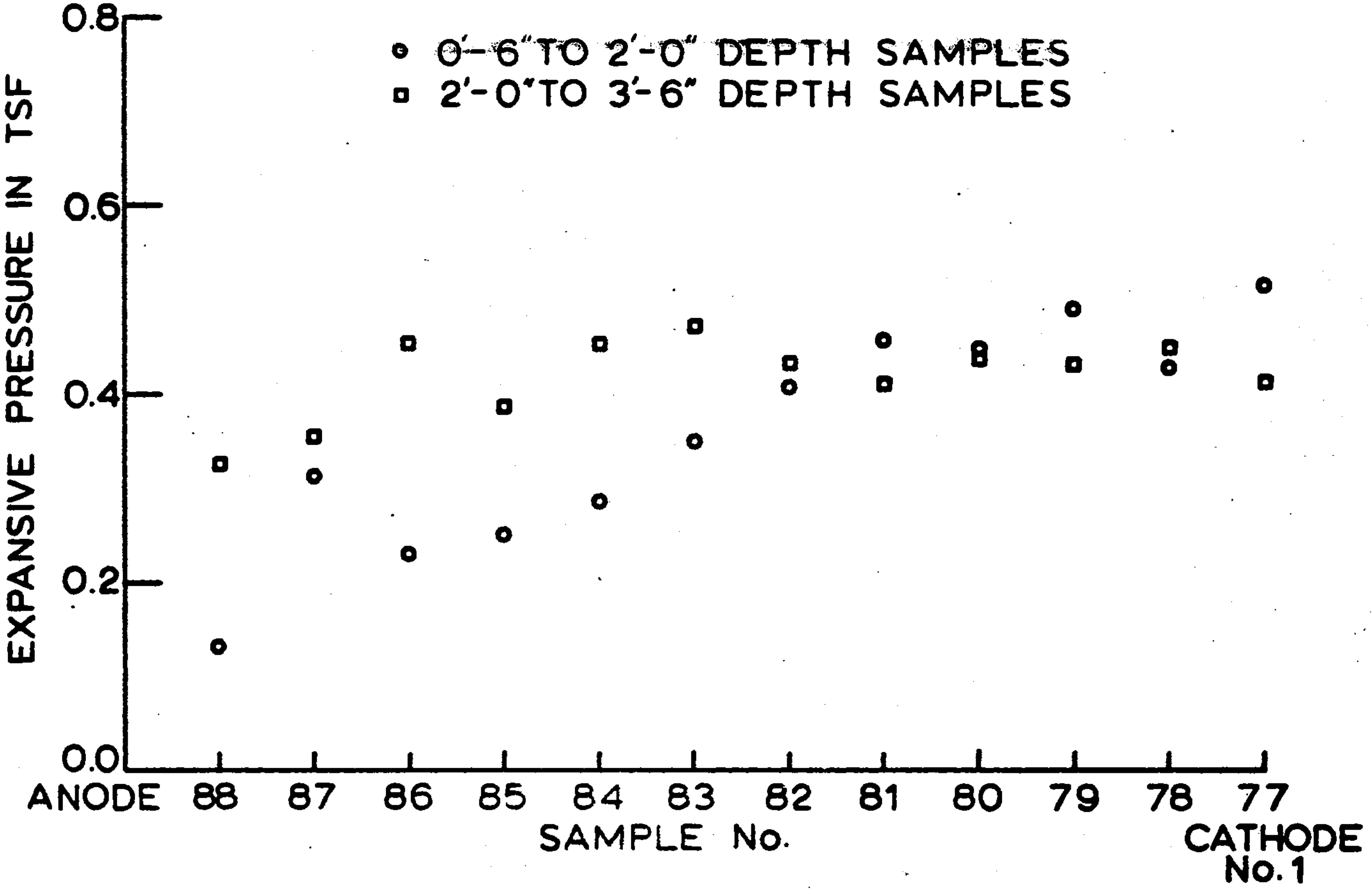


Figure 27. Expansive Pressure of Samples Between Anode and Cathode Number 1 --Test Section C

expansive pressures in Test Section "B" were more uniform throughout the distance between the anode and cathode. Expansive pressures varied widely, but they do not go from low values at the anode to high values at the cathode. Figures 26 and 27 show that expansive pressure results from Test Section "C" were considerably more uniform than those from Test Sections "A" or "B." Expansive pressures for Test Section "C" samples are grouped very closely. This is an indication that the horizontal anode and cathode configuration produces a more uniform distribution of solution.

Table XI contains a summary of expansive pressures and reduction factors for the three test sections. Note that the samples for Test Section "B,", 0'-6" to 2'-0", had an average expansive pressure of 0.338 TSF while samples for 2'-0" to 3'-6" had an average expansive pressure of 0.514. The deeper samples had an average expansive pressure considerably higher than the shallow samples. From Table IX, it may be seen that only two samples from the 2'-0" to 3'-6" depth had lesser expansive pressures than those of the 0'-6" to 2'-0" depth samples directly above. A similar effect took place with the vertical anodes and horizontal cathode model study. (See discussion of Box Model #12.) Test Section "C" samples had average expansive pressures of 0.346 and 0.424 TSF for the 0'-6" to 2'-0" and 2'-0" to 3'-6" depth samples, respectively. This is considerably more uniform than was the case for Test Section "B." Note that the average reduction factor for Test Section "C" is much better than those of Sections "A" and "B." Average reduction factor for Section "C" is 4.16 while Test Sections "A" and "B" yielded reduction factors of 3.55 and 3.75. These results also show

TABLE XI

AVERAGE EXPANSIVE PRESSURES AND REDUCTION FACTORS FOR FIELD TEST SAMPLES

Test Section	Number of Samples	Depth (ft)	Average Expansive Pressure (TSF)	Average Section Expansive Pressure (TSF)	Average Section Reduction Factor
A	40	0'-6"--2'-0"	.406	.450	3.55
A	40	2'-0"--3'-6"	.492		
B	24	0'-6"--2'-0"	.338	.426	3.75
B	24	2'-0"--3'-6"	.514		
C	24	0'-6"--2'-0"	.346	.385	4.16
C	24	2'-0"--3'-6"	.424		
Untreated			1.600		

$$\text{Average Reduction Factor} = \frac{\text{Average Expansive Pressure of Untreated Material}^{*}}{\text{Average Expansive Pressure of Treated Material}^{*}}$$

---

*@100 pcf and 20% H_2O.

that Section "C," which utilized the horizontal anode and cathode, was superior to the other configurations.

Summary

From expansive pressure tests performed on the soil treated in the 3.75-inch diameter tube models, it was determined that potassium chloride (KCl) was far superior to calcium chloride as a stabilizing agent. This result agreed with that of past work done on the Chinley clay by the author. It was decided to use KCl on the proposed large models and the subsequent field test.

Three electrode configurations were proposed and tested in Box Models #10, #12, and #13. Expansive pressure results indicated that Model #10 (vertical anode and cathode) and Model #13 (horizontal anode and cathode) had quite good overall treatment while Model #12 gave less favorable results.

A field test was designed to reproduce the electrode configurations of Box Models #10, #12, and #13. Expansive pressure results of the samples taken from the field test area and visual observation of salt crystals at the cathode indicate that Test Section "C" (horizontal anode and cathodes) was the most effective [24].

Conclusions

Several conclusions appeared to be justified by the laboratory and field work.

(1) Electro-osmotic treatment and the base exchange of ions can be successfully applied to highway projects.

(2) Potassium chloride is the most effective chemical for treating Chinle clay.

(3) The horizontal anode and cathode arrangement is, by far, superior to other anode-cathode arrangements based on the rate at which solution was consumed in the May, 1969, field test and the overall reduction in expansive pressure of the treated material.

(4) Approximately 1.5 gallons of potassium chloride solution are necessary to stabilize a cubic foot of Chinle clay. This is based on the 2000 gallons of solution consumed by Test Section "C" during the May, 1969, field test.

(5) A treatment time of approximately one week for a horizontal spacing of 20 feet between anode and cathode may be used as a general guideline [24].

CHAPTER V

LABORATORY TESTING

General

The testing program conducted during this study was a continuation of the electro-osmotic testing developed at Arizona State University. The primary purpose of this research was to develop an equation that would describe the expansive pressure of a montmorillonite clay when the factors which affect its expansive characteristics were allowed to vary. The factors deemed to be of primary importance were density, per cent montmorillonite, degree of saturation and time of electro-osmotic treatment. An experiment was designed in which four levels of each of the variables were included; this would have required 256 tests. However, by a statistical technique of confounding the variables, it was necessary to only perform 64 tests in order to obtain the information desired. The determination of the four levels of each variable was a matter of extensive consideration and discussion. It was concluded that site foundation problems arising from expansive montmorillonic clays exist when the percentage of montmorillonite lies somewhere between 10 and 40 per cent. It is this range of montmorillionite that would give the most problems to a practicing engineer. Therefore, 10, 20, 30, and 40 per cent montmorillonite were used in this study. The montmorillonite used was a commercial product which was sold under the trade name of

Magcogel. The remainder of the sample was made up of kaolin. This clay was also a commercially produced material and sold under the trade name of National Lead, Edgar Plastic Kaolin. Kaolin was chosen as the filler material because: (1) it is a non-expansive clay mineral and, therefore, would not influence the effect of the electro-osmotic treatment, and (2) it was fine-grained and plastic, making it easy to compact and trim samples for both the electro-osmotic tests and the expansive pressure tests. The Standard Proctor Compaction Test showed the maximum density to be about 77#/ft.^{3} for the four combinations of montmorillonite and kaolin. Therefore, it was decided to select 70, 75, 80, and 85#/ft.^{3} as the levels of density. The degree of saturation was the next variable to be studied and the limitation of equipment was the determining factor for this parameter. It was found that below 60 per cent saturation, the static load required to compact the sample was so large that the Plexiglas tube would fail. Above 90 per cent saturation, there was squeezing of the sample around the plunger. Therefore, it was decided to vary the degree of saturation from 60 to 90 per cent in even 10 per cent increments. Treatment times of one, two, three, and four days were adopted in the belief that differences in the results obtained would be significant and of sufficient range to be of value in determining the minimum time requirement.

Sample Preparation

On Friday morning of each week, twelve samples were prepared for the following week's testing. This consisted of weighing out the correct percentage of montmorillonite and kaolin, placing the well-mixed samples in a flat pan and sprinkling the required amount of water on top of the sample. A plastic bag was then placed over the sample and the weight was recorded. The samples were then allowed to cure for 72 hours until Monday morning. The sample was re-weighed and any moisture loss was added to bring the sample up to the desired moisture content. The sample was then thoroughly mixed and the required amount of wet material was weighed into the 8-inch by 3.75-inch round Plexiglas tube. The material was then statically compacted to a height of 4.0 inches to obtain the desired density and degree of saturation. When all 12 samples had been compacted in this manner, the steel electrodes were attached to both ends of the sample and an average voltage gradient of one volt/inch was applied using a constant voltage D. C. power source. A saturated solution of potassium chloride was maintained at the anode throughout the testing program.

Sample Testing

At the end of electro-osmotic testing, the sample was extruded from the Plexiglas tube using a hydraulic jack. The plunger was always placed on the cathode side of the sample and the sample was removed in this manner. This procedure caused as little disturbance as possible near the anode. Once the sample had been removed from the tube, the top one-half inch near the anode was removed and discarded. From the remaining material, a sample was trimmed into a standard 1-inch by 2.5-inch diameter consolidation ring. The sample was weighed and a moisture content of the trimmings was obtained. The sample was then placed into an Anteus Model A Air Pressure Consolidometer. The initial height was recorded and the head seated onto the sample. The chamber was then flooded and, as the sample attempted to swell, an additional load was applied to maintain zero vertical strain within ± 0.001 of an inch. Generally, no pressure adjustment was required after approximately four hours; however, the test was continued for 24 hours before the final reading was recorded.

In this manner, 64 original and 16 randomly selected repeat samples were tested. The results of these tests are found in Table XII.

In addition to the electro-osmotic treated samples, the expansive pressures of 16 untreated samples were determined in a similar manner. The results of these tests are shown in Table XIII and Figure 28. From Figure 28 it can be seen that as the degree of saturation is increased, the expansive pressure of the montmorillonite decreases. Also, for a constant degree of saturation, the higher the percentage of montmorillonite, the higher the expansive pressure. These results appear reasonable and one would expect to determine similar results at various densities for this combination of clays.

X-Ray Diffraction

To provide information concerning the effects of the treatment on the mineralogical characteristics, eight X-Ray Diffraction Tests were performed on selected treated and untreated samples. The samples chosen were four untreated samples--one for each level of per cent montmorillonite; also, four treated samples at the same level of montmorillonite. The results of these tests are shown in Figures 29 through 32. It can be clearly seen from these figures that the primary montmorillonite peak has been greatly reduced or completely destroyed in the treated sample. This confirms that the method of treatment is very effective in changing the basic clay material which will have the desired effect of reducing the expansive pressure of montmorillonite clay. The reason that the potassium ion is so effective is that this ion has almost the correct size and coordination properties to fit on the basal oxygen sheet of the montmorillonite clay mineral. As a consequence, the potassium ion will relatively easily enter the basal sheet, thereby changing the highly expansive characteristics of the montmorillonite mineral to some other clay mineral that has less pronounced expansive properties.

TABLE XII

EXPANSIVE PRESSURE OF ELECTRO-OSMOTIC TREATED SAMPLES

Sample No.	Treatment Time Hrs.	Montmorillonite %	Kaolin %	Initial Degree Saturation %	Initial Density #/ft.^{3}	Initial Moisture Content %	Final Density #/ft.^{3}	Final Moisture Content %	Expansive Pressure TSF
1	24	10	90	60	70	32.98	73.4	34.90	0.558
2	24	10	90	70	80	28.95	83.7	30.26	1.174
3	24	10	90	90	75	41.91	79.3	35.59	1.348
4	48	10	90	60	80	24.80	84.3	29.11	1.609
5	48	10	90	70	70	38.48	79.1	33.47	0.189
6	48	10	90	80	75	37.25	81.6	30.80	0.805
7	72	10	90	60	75	27.97	75.5	39.40	0.761
8	72	10	90	70	85	25.73	84.9	30.32	0.732
9	72	10	90	80	80	33.08	84.3	30.60	1.062
10	96	10	90	60	85	22.05	76.6	38.66	0.125
11	96	10	90	70	75	32.59	78.3	36.13	0.000
12	96	10	90	80	70	43.97	74.6	39.88	0.000
13	24	10	90	80	85	29.41	84.9	31.06	1.667
14	48	10	90	90	85	33.08	91.4	27.78	1.377
15	72	10	90	90	70	49.47	78.4	38.52	0.732
16	96	10	90	90	80	37.22	87.4	29.58	2.000

TABLE XII (Continued)

Sample No.	Treatment Time Hrs.	Montmor-illonite %	Kaolin %	Initial Degree Saturation %	Initial Density #/ft.^{3}	Initial Moisture Content %	Final Density #/ft.^{3}	Final Moisture Content %	Expansive Pressure TSF
17	24	20	80	60	80	24.80	79.7	34.29	0.790
18	24	20	80	70	70	38.48	71.2	38.78	0.834
19	48	20	80	60	70	32.98	73.4	39.43	0.000
20	48	20	80	70	80	28.95	75.2	37.83	0.471
21	72	20	80	60	85	22.05	84.8	32.59	0.645
22	72	20	80	70	75	32.59	78.9	32.79	0.726
23	96	20	80	60	75	27.97	76.7	39.63	0.000
24	96	20	80	70	85	25.73	87.4	30.21	0.877
25	24	20	80	80	75	37.25	67.7	40.97	0.848
26	24	20	80	90	85	33.08	86.0	31.76	2.725
27	48	20	80	80	85	29.41	84.9	30.23	3.411
28	48	20	80	90	75	41.91	73.5	39.40	0.761
29	72	20	80	80	70	43.97	78.1	34.92	0.375
30	72	20	80	90	80	37.22	87.3	29.52	2.580
31	96	20	80	80	80	33.08	84.7	29.63	1.276
32	96	20	80	90	70	49.47	77.5	38.88	0.979
33	24	30	70	60	75	27.97	73.4	38.16	0.940
34	48	30	70	60	85	22.05	84.1	32.86	0.935

TABLE XII (Continued)

Sample No.	Treatment Time Hrs.	Montmor-illonite %	Kaolin %	Initial Degree Saturation %	Initial Density #/ft.^{3}	Initial Moisture Content %	Final Density #/ft.^{3}	Final Moisture Content %	Expansive Pressure TSF
35	72	30	70	60	70	32.98	73.1	38.93	0.140
36	96	30	70	60	80	24.80	83.0	32.36	0.935
37	24	30	70	70	85	25.73	82.0	34.53	1.319
38	48	30	70	70	75	32.59	79.3	31.87	0.375
39	24	30	70	80	80	33.08	79.0	33.10	1.551
40	24	30	70	90	70	49.47	73.3	41.33	1.216
41	48	30	70	80	70	43.97	77.7	33.55	1.426
42	48	30	70	90	80	37.22	86.4	29.05	3.015
43	72	30	70	70	80	28.95	84.2	29.01	1.624
44	96	30	70	70	70	38.48	77.7	32.30	0.699
45	72	30	70	80	85	29.41	87.7	27.85	2.609
46	72	30	70	90	75	41.91	86.1	30.28	3.545
47	96	30	70	80	75	37.25	80.0	34.83	1.189
48	96	30	70	90	85	33.08	91.0	26.61	3.855
49	24	40	60	60	85	22.05	80.0	37.28	0.747
50	24	40	60	70	75	32.59	68.4	36.67	1.116
51	24	40	60	80	70	43.97	72.3	39.13	1.131
52	48	40	60	60	75	27.97	77.6	34.71	0.558

TABLE XII (Continued)

Sample No.	Treatment Time Hrs.	Montmor-illonite %	Kaolin %	Initial Degree Saturation %	Initial Density #/ft.^{3}	Initial Moisture Content %	Final Density #/ft.^{3}	Final Moisture Content %	Expansive Pressure TSF
53	48	40	60	70	85	25.73	82.1	36.25	1.434
54	48	40	60	80	80	33.08	82.6	30.33	3.594
55	72	40	60	60	80	24.80	83.9	30.47	1.682
56	72	40	60	70	70	38.48	75.5	34.40	0.906
57	72	40	60	80	75	37.25	79.4	29.92	2.435
58	96	40	60	60	70	32.98	75.9	34.66	0.674
59	96	40	60	70	80	28.95	81.3	34.81	1.609
60	96	40	60	80	85	29.41	86.0	32.62	0.935
61	24	40	60	90	80	37.22	81.3	34.67	4.102
62	48	40	60	90	70	49.47	73.8	40.27	1.319
63	72	40	60	90	85	33.08	89.9	27.39	3.681
64	96	40	60	90	75	41.91	84.8	31.51	1.942
18R	24	20	80	70	70	38.48	69.6	38.18	0.848
13R	24	10	90	80	85	29.41	84.4	30.02	1.696
14R	48	10	90	90	85	33.08	87.2	30.14	1.319
58R	96	40	60	60	70	32.98	76.1	35.23	0.616
28R	48	20	80	90	75	41.91	84.1	31.71	2.189

TABLE XII (Continued)

Sample No.	Treatment Time Hrs.	Montmorillonite %	Kaolin %	Initial Degree Saturation %	Initial Density #/ft.^{3}	Initial Moisture Content %	Final Density #/ft.^{3}	Final Moisture Content %	Expansive Pressure TSF
45R	72	30	70	80	85	29.41	84.1	32.59	1.435
10R	96	10	90	60	85	22.05	84.4	33.09	0.058
21R	72	20	80	60	85	22.05	85.3	32.94	0.631
46R	48	30	70	90	75	41.91	84.6	30.15	3.594
42R	48	30	70	90	80	37.22	83.6	29.71	3.044
56R	72	40	60	70	70	38.48	77.6	34.25	0.783
35R	72	30	70	60	70	32.98	78.9	34.45	0.174
26R	24	20	80	90	85	33.08	84.6	30.98	2.798
51R	24	40	60	80	70	43.97	72.2	39.98	1.928
54R	48	40	60	80	80	33.08	82.7	31.45	1.863
38R	48	30	70	70	75	32.59	79.7	31.87	1.087

TABLE XIII

EXPANSIVE PRESSURE OF UNTREATED SAMPLES

Sample No.	Montmorillonite %	Kaolin %	Initial Degree Saturation %	Initial Density $\#/ft.^3$	Initial Moisture Content %	Final Density $\#/ft.^3$	Final Moisture Content %	Expansive Pressure TSF
B-1	10	90	60	80	24.80	79.4	23.38	3.465
B-2	10	90	70	80	28.95	82.1	26.85	3.001
B-3	10	90	80	80	33.08	80.4	31.16	2.392
B-4	10	90	90	80	37.22	74.5	35.77	1.377
B-5	20	80	60	80	24.80	80.7	23.17	4.725
B-6	20	80	70	80	28.95	73.4	27.95	3.798
B-7	20	80	80	80	33.08	80.9	31.47	3.565
B-8	20	80	90	80	37.22	81.2	35.13	2.566
B-9	30	70	60	80	24.80	81.8	22.85	6.857
B-10	30	70	70	80	28.95	79.5	27.52	6.175
B-11	30	70	80	80	33.08	79.0	32.10	5.827
B-12	30	70	90	80	37.22	79.7	35.75	5.291
B-13	40	60	60	80	24.80	79.7	22.82	8.435
B-14	40	60	70	80	28.95	80.4	26.94	7.277
B-15	40	60	80	80	33.08	79.3	31.73	7.074
B-16	40	60	90	80	37.22	78.9	36.28	6.349

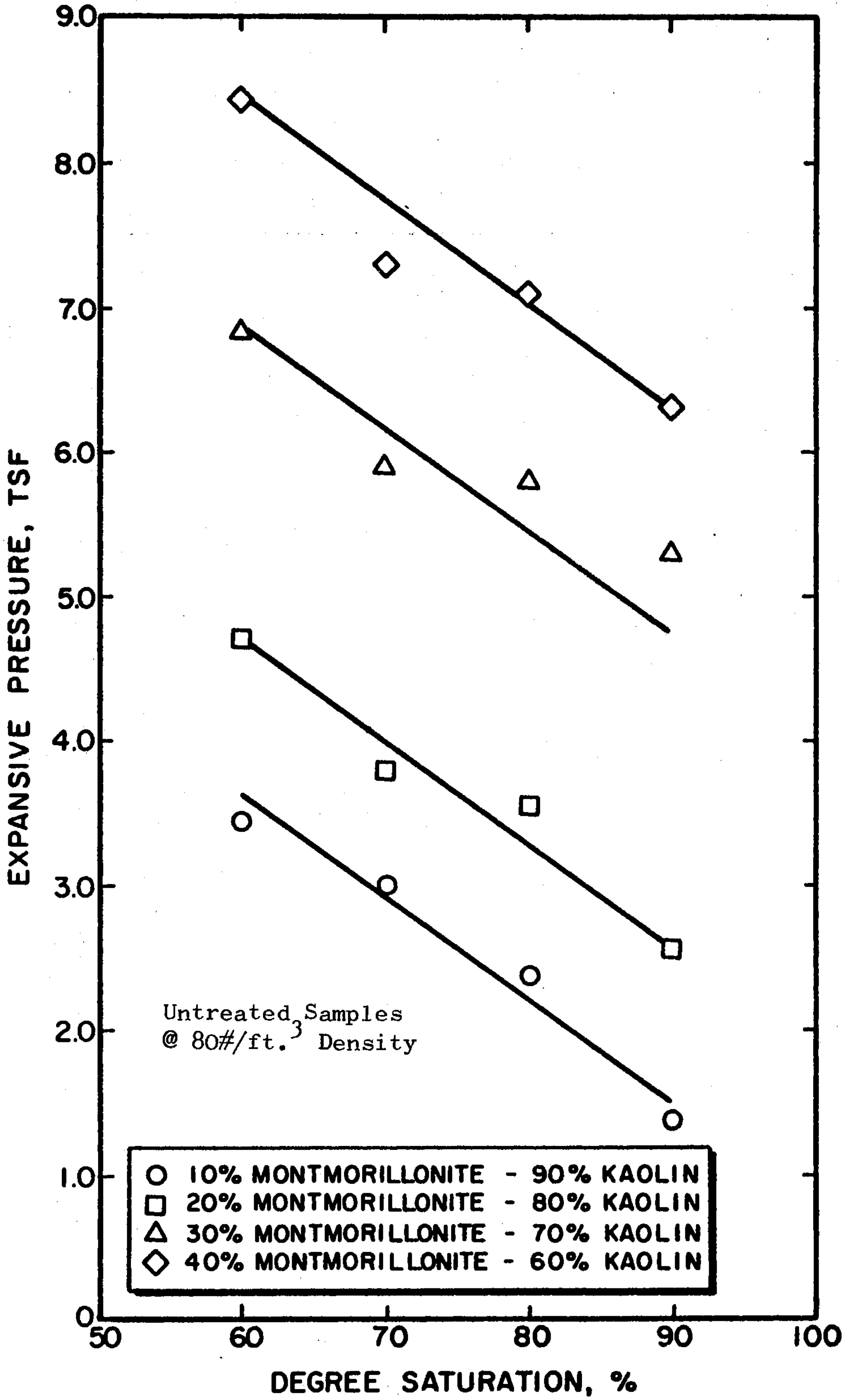


Figure 28. Expansive Pressure Versus Degree of Saturation

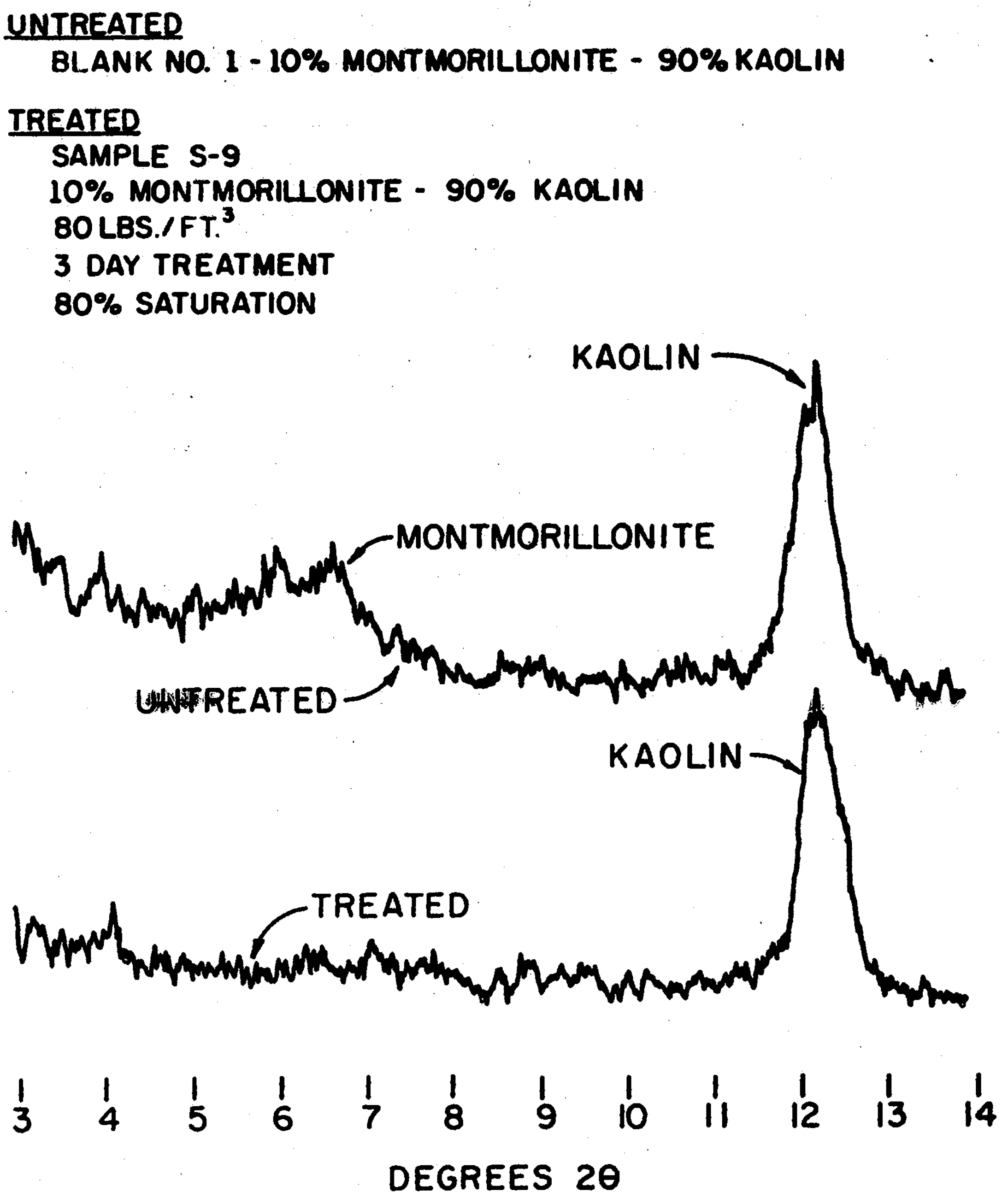


Figure 29. X-Ray Diffraction on Treated and Untreated Samples

<u>UNTREATED</u>
BLANK NO. 2 - 20% MONTMORILLONITE - 80% KAOLIN

<u>TREATED</u>
SAMPLE S-31
20% MONTMORILLONITE - 80% KAOLIN
80 LBS./FT^3
4 DAY TREATMENT
80% SATURATION

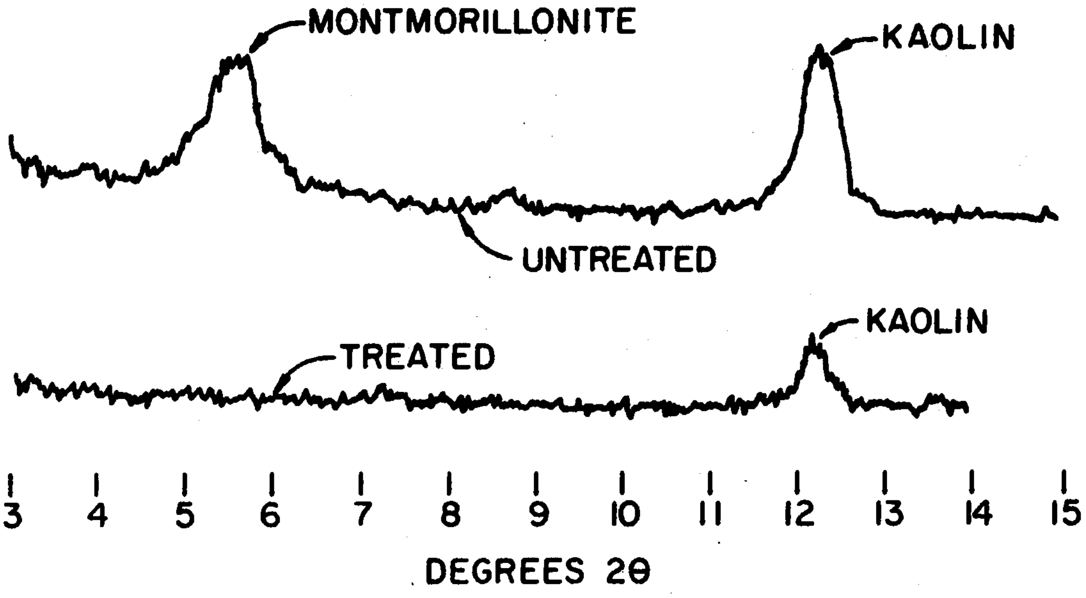


Figure 30. X-Ray Diffraction on Treated and Untreated Samples

UNTREATED

BLANK NO. 3 - 30% MONTMORILLONITE - 70% KAOLIN

TREATED

SAMPLE S-39
30% MONTMORILLONITE - 70% KAOLIN
80 LBS./FT^3
1 DAY TREATMENT
80% SATURATION

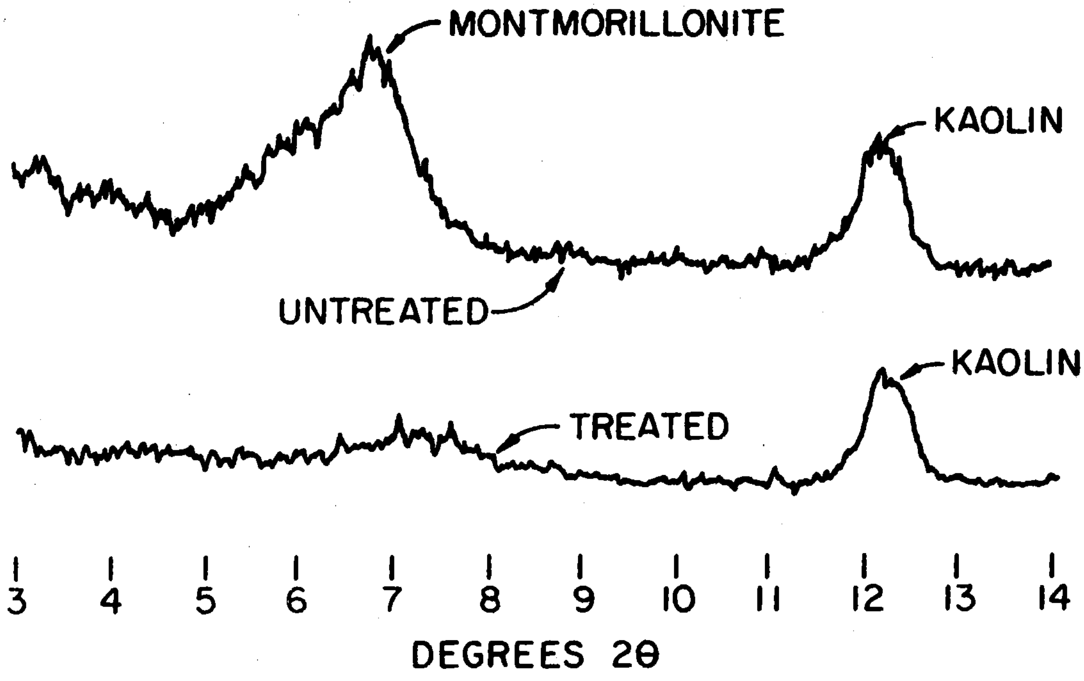


Figure 31. X-Ray Diffraction on Treated and Untreated Samples

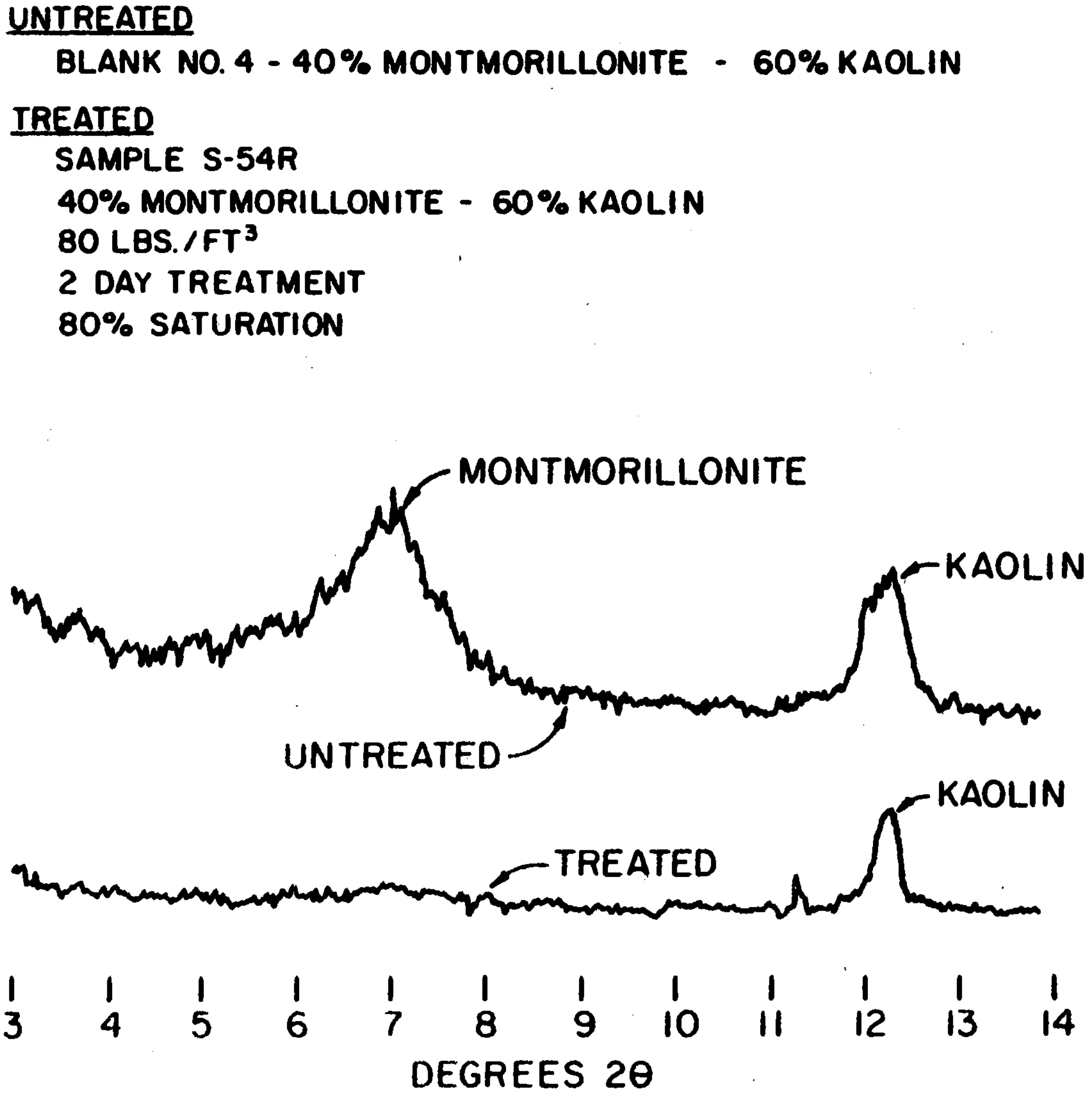


Figure 32. X-Ray Diffraction on Treated and Untreated Samples

CHAPTER VI

ANALYSIS OF RESULTS

A statistical analysis of the data obtained from the expansive pressure tests of treated samples was performed, assuming the following regression model:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 D + \beta_2 S + \beta_3 T + \beta_4 C + \beta_5 D^2 + \beta_6 S^2 \\ & + \beta_7 T^2 + \beta_8 C^2 + \beta_9 DS + \beta_{10} DT + \beta_{11} DC \\ & + \beta_{12} ST + \beta_{13} SC + \beta_{14} TC \end{aligned} \tag{6.1}$$

where

Y = expansive pressure of clay TSF,

$\beta_0 \ldots \beta_{14}$ = the beta coefficient for the given variables,

D = density #/ft.^{3}, $70 \leq D \leq 85$,

C = montmorillonite per cent, $10 \leq C \leq 40$,

S = degree saturation per cent, $60 \leq S \leq 90$, and

T = time in hours.

The data were programmed for the SAS Program, a statistical analysis system developed at North Carolina State University, and a multiple regression analysis was performed. Based on the computer output, it was determined that several of the variables were not significant. These were: T, T^2, C^2, DT, DC, ST, and TC.

When these variables were excluded, the revised model became:

$$Y = \beta_0 + \beta_1 D + \beta_2 S + \beta_3 C + \beta_4 D^2 + \beta_5 S^2 + \beta_6 DS + \beta_7 SC \quad . \tag{6.2}$$

The data were again analyzed with the same program, and the equation for the expansive pressure was found to be

$$Y = -9.0687 + 0.5949D - 0.4497S - 0.0790C - 0.0051D^2 + 0.0012S^2 + 0.0036DS + 0.0015SC \quad . \tag{6.3}$$

The complete analysis showing the observed, predicted, and 95% Confidence Interval is shown in Appendix B. Employing the above equation, an engineer can predict the expansive pressure that will exist in the field if electro-osmotic treatment is used. In addition to this calculation, if one has determined the expansive pressure of the untreated material, a direct prediction of the effectiveness of the treatment can be evaluated.

In addition, Figures 33 through 36 are graphs comparing the swelling pressures of untreated material to those of treated material at the same per cent clay, density, and degree of saturation. It may be seen that the treatment is much more effective at the lower moisture contents. Also, the reduction in expansive pressure of the treated material increases as the percentage of montmorillonite increases. It should also be noted that all of the treated samples were within the 95% Confidence Interval that was predicted by the regression formula.

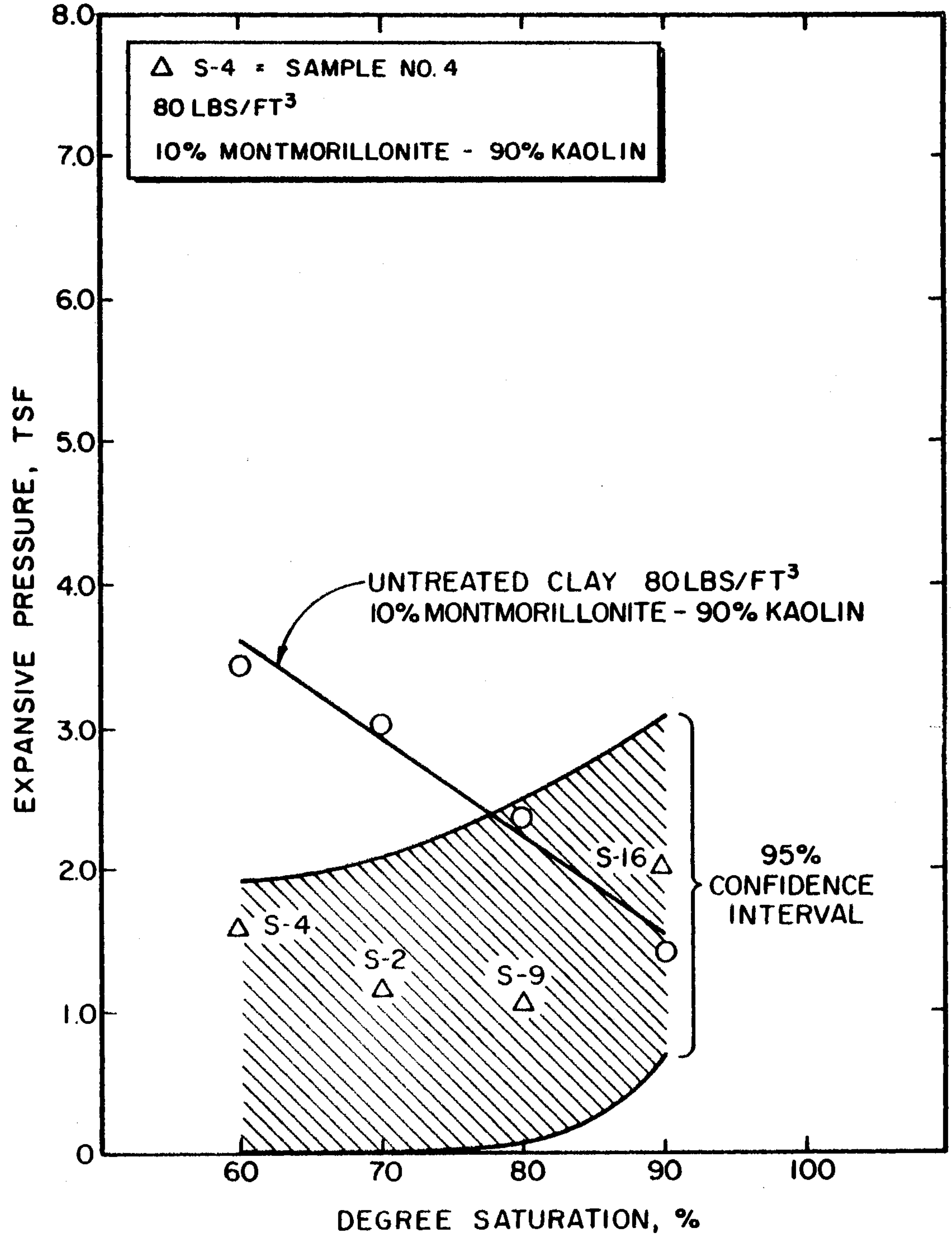


Figure 33. Expansive Pressure Versus Degree of Saturation Treated and Untreated Samples

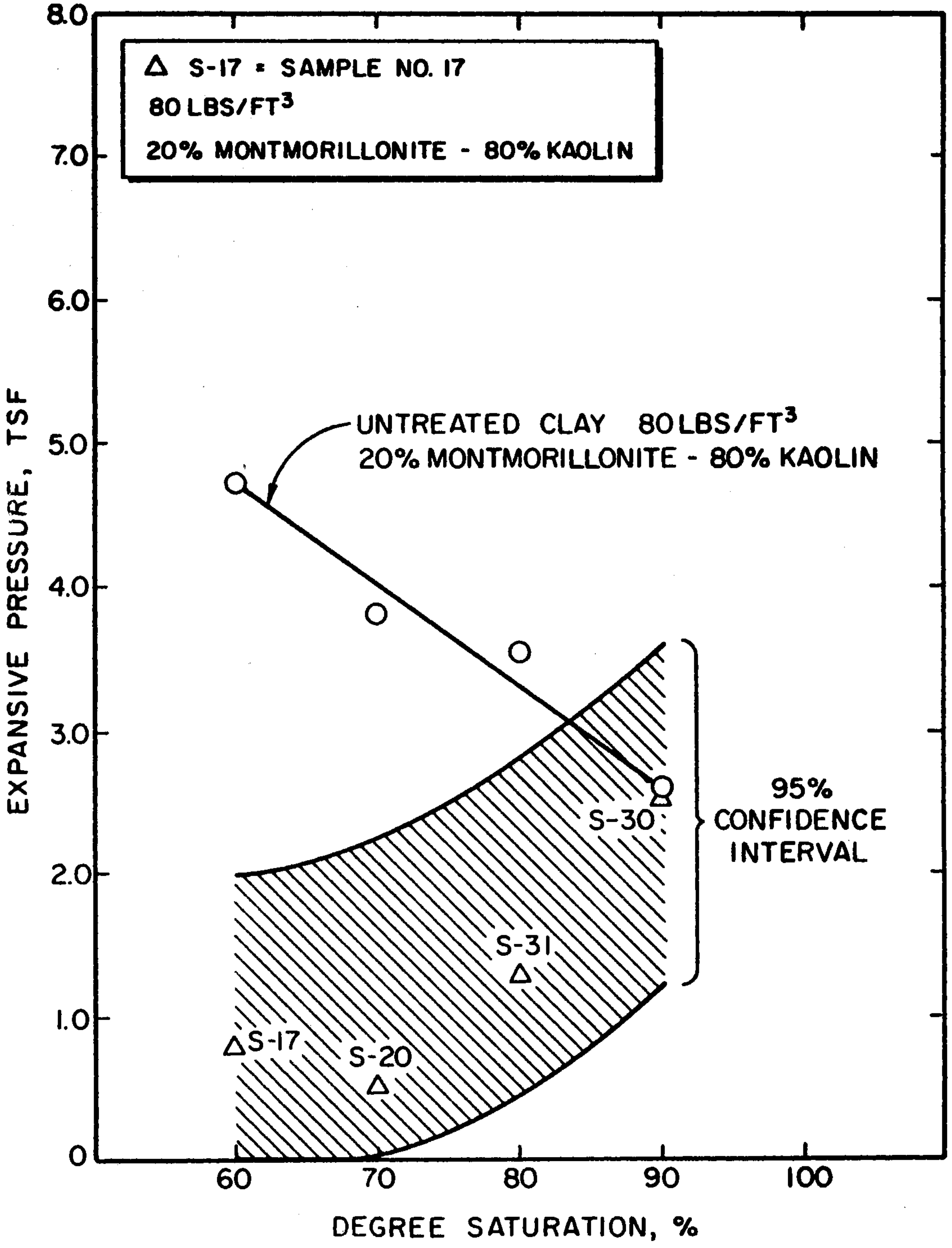


Figure 34. Expansive Pressure Versus Degree of Saturation Treated and Untreated Samples

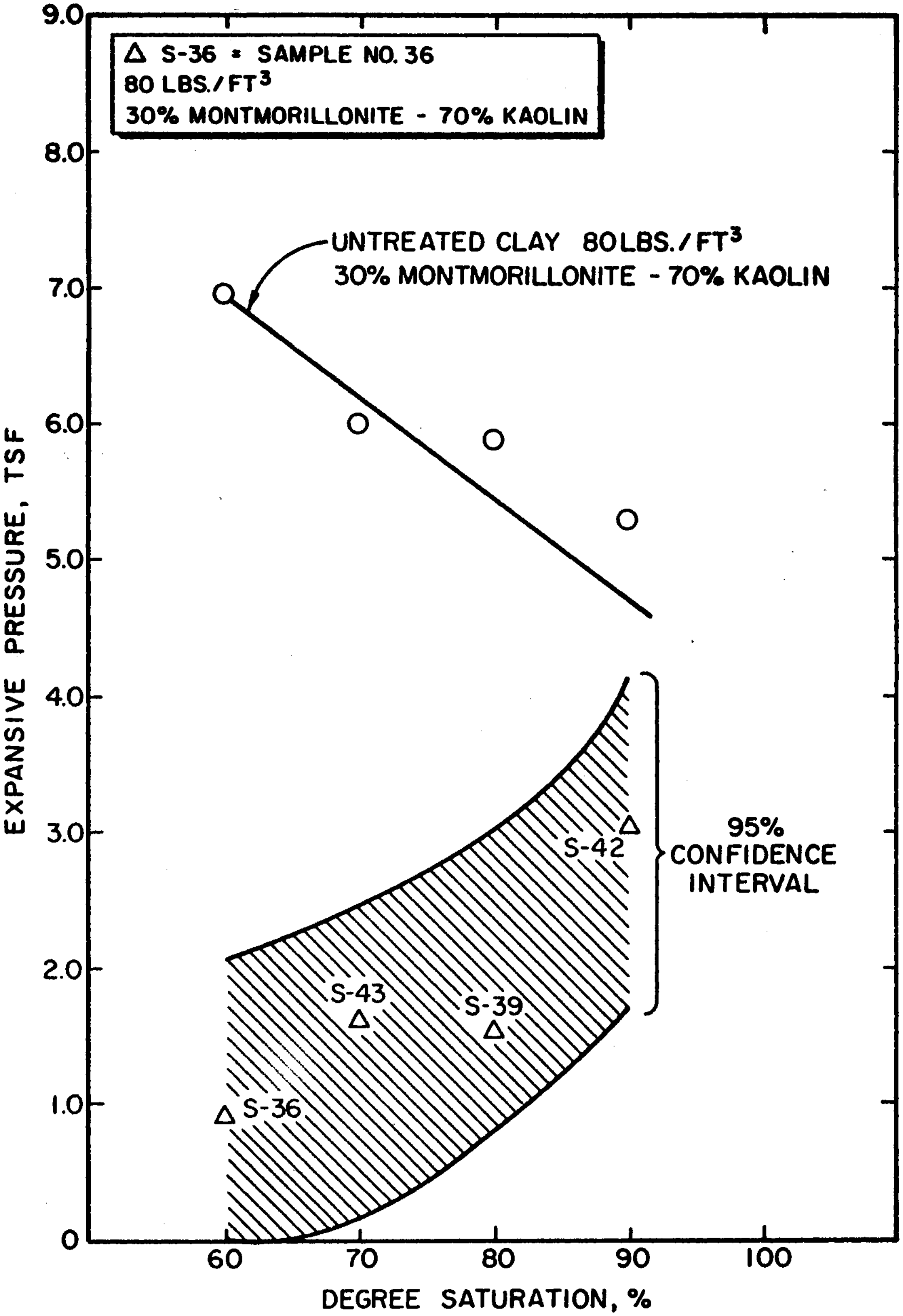


Figure 35. Expansive Pressure Versus Degree of Saturation
Treated and Untreated Samples

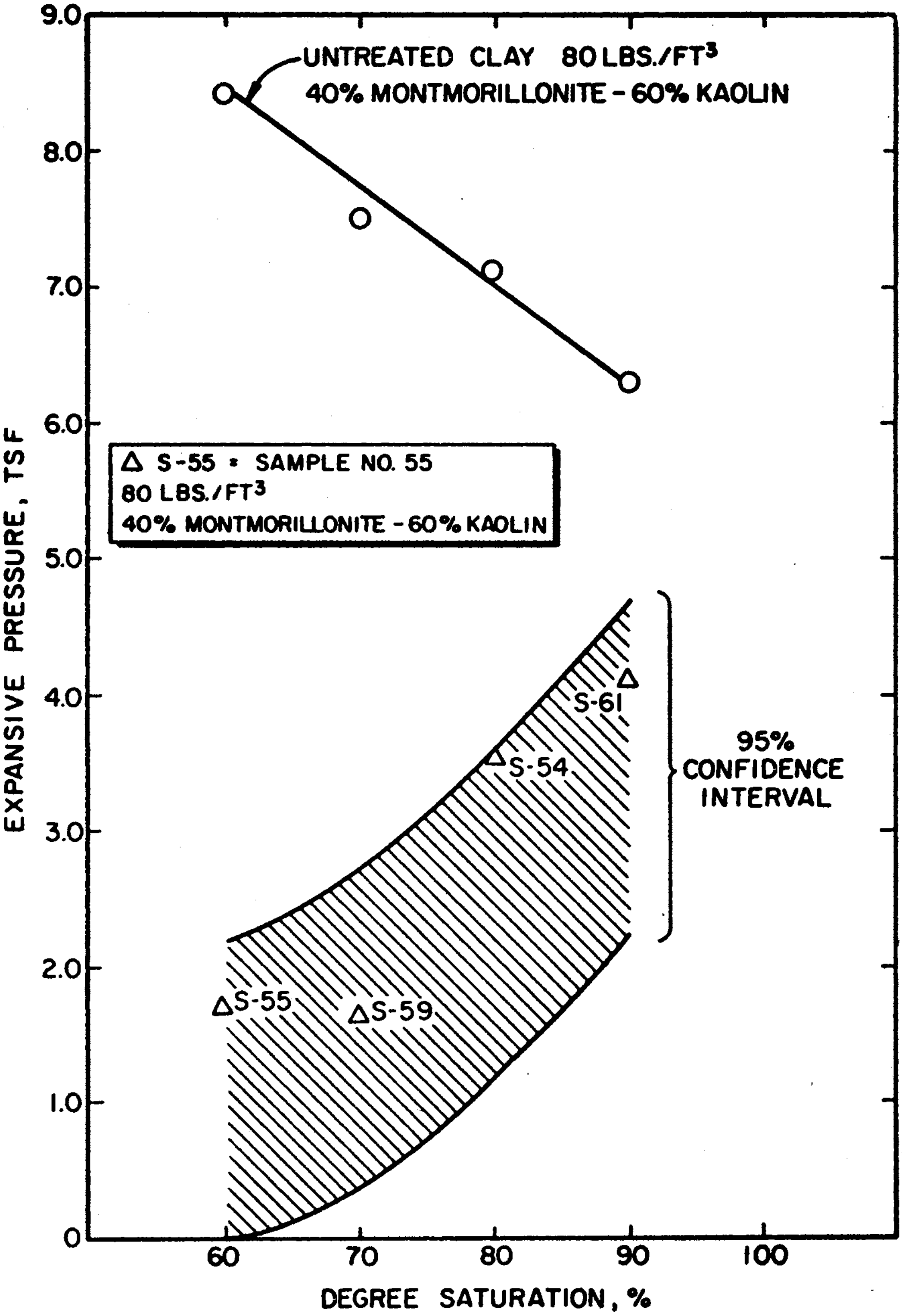


Figure 36. Expansive Pressure Versus Degree of Saturation Treated and Untreated Samples

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The breadth of this study was so large that it encompassed a wide range of significant developments. Initially, over 200 tube samples were electro-osmotically tested in order to determine the effects on the expansive pressure of the Chinle clay. In these tests, the variables studied were:

(1) more than ten different chemical solutions and concentrations,
(2) four types of metal electrodes,
(3) time of treatment ranging from 24 to 300 hours, and
(4) voltage gradient ranging from 0.25 volts/inch to 2.5 volts/inch.

Based on the information gained from the tube testing, 12 small model tests were performed in which the most promising combination of the factors described above were further studied. Upon completion of this phase of the study, it was decided to perform a full scale field test along lines that appeared, from the model studies, to be most promising. This was accomplished in the spring of 1969 and one should refer to Table XI for the results and findings of this project.

Based on the results of the field test, it can be stated that the use of electro-osmosis in conjunction with a water soluble metallic salt will reduce the expansive pressure of the Chinle clay by a factor of four or more.

It is the opinion of the author that this process offers a method which will reduce or eliminate excessive swelling pressures if they are encountered in an existing structure.

Conclusions

This study has produced several important findings that will facilitate the field treatment of expansive clays to reduce their swelling potential.

(1) Electro-osmosis with a water soluble metallic salt will reduce the expansive pressure of montmorillonite clays by factors generally ranging from two to eight.

(2) The equation for the expansive pressure of a montmorillonite clay was determined for practical ranges of certain of its variable properties. Within the ranges of 10 to 40 per cent montmorillonite, 60 to 90 per cent saturation and 70 to 85#/ft.^{3} density, the governing equation is:

$$\begin{aligned} Y = & -9.0687 + 0.5949D - 0.4497S \\ & - 0.0790C - 0.0051D^2 + 0.0012S^2 \\ & + 0.0036DS + 0.0015SC \end{aligned} \qquad (6.3)$$

in which

Y = expansive pressure of clay TSF,

D = density #/ft.^{3},

C = montmorillonite per cent, and

S = degree saturation per cent.

(3) The lower the moisture content at the beginning of treatment, the more effective the treatment.

(4) The higher the percentage of montmorillonite, the more effective the treatment.

(5) No data for the minimum time requirement was developed in this research; however, there must be sufficient time to allow the ions to move through the soil zone that is to be treated. This will vary, depending on the electrode spacing. However, treatment progresses rapidly enough to be practicable in field applications.

(6) Potassium chloride is a water soluble metallic salt that will effectively reduce the expansive pressure of a montmorillonite clay.

(7) It is recommended that the average voltage gradient (potential/distance between electrodes) for field projects lie between 0.5 to 1.0 volts/inch. Below 0.5 volts/inch, the time requirement is too long. Above 1.0 volts/inch, there is a noticeable heating of the soil which is an indication of an energy loss and the waste associated with this loss. Evidence from field tests indicate that the voltage gradient within the soil mass is not a constant but changes as treatment progresses. The average gradient behind the leading edge of the ion front steadily decreases whereas that between the leading edge and cathode steadily increases.

(8) From the x-ray diffraction pattern, Figures 29 through 32, it is evident that the electro-osmotic treatment with KCl solution is very effective in permanently altering the mineralogical

characteristics of montmorillonite. The observed collapse of the crystalline lattice would lead one to expect a significant reduction in expansive pressure of the treated clay. Expansive pressure tests on treated samples confirmed these findings.

(9) Based on the field test of 1969, it would appear that the most effective configuration of electrodes for field installations is one in which both the anode and cathodes are placed in a horizontal position.

Recommendations for Future Study

The areas for continued research in electro-osmosis are manifold and it would be impossible to mention all of them. However, in the opinion of the author, there are several of primary importance that should be discussed. It has been shown by other researchers that the coefficient of electro-osmotic permeability is a constant for a saturated soil; however, this parameter has not been established for a partially saturated soil. Until this has been accomplished, any accurate prediction for the time required for various field stabilization projects is impossible.

In addition to the work performed in this study, it would be of immense value to determine the effectiveness of the electro-osmotic treatment at water contents below 60 per cent saturation.

Finally, a large area for additional research would be the extension of the technique developed in this study to determine the effectiveness of electro-osmotic treatment on other expansive clay minerals, either separately or in various combinations.

BIBLIOGRAPHY

(1) Barber, E. S. "Electrical Stabilization of Soil." Roads and Streets, Vol. 91, No. 6 (June, 1948), pp. 64-65.

(2) Briscoe, Herman T. General Chemistry for Colleges. Boston: Houghton Mifflin Co., 1943.

(3) Casagrande, Leo. "Electro-Osmotic Stabilization of Soils." Contributions to Soil Mechanics 1941-1953. Boston: Boston Society of Civil Engineers, 1953.

(4) Casagrande, Leo. "Electro-Osmosis in Soils." Geotechnique, Vol. 1, No. 3 (June, 1949), pp. 159-177.

(5) Casagrande, Leo. "Electro-Osmotic Soil Stabilization." Electrical Journal, 157 (July 20, 1956), pp. 200-201.

(6) Casagrande, Leo. "Review of Past and Current Work on Electro-Osmotic Stabilization of Soils." Harvard Soil Mechanics Series No. 45, Harvard University, Cambridge, Mass. (December, 1953), (containing supplement, June, 1957).

(7) Casagrande, Leo. "Practical Aspects of Electro-Osmosis in Foundation Engineering." Primer Congresso Panamericano De Mecanica De Suelos Y Cimentaciones Memoria-Proceedings, Vol. I, Mexico, D. F. (1960), pp. 217-234.

(8) Endell, K., and U. Hoffman. "Electrochemical Hardening of Clay Soils." Proc. 1st Int. Conf. on Soil Mech. and Found. Engr., Vol. 1, Cambridge, Mass. (1936), pp. 273-275.

(9) Esrig, Melvin I. "A Feasibility Study of Electrokinetic Processes for Stabilization of Soils for Military Waterways Experiment Station, Vicksburg, Mississippi, May, 1964." (Unpublished).

(10) Esrig, Melvin I., and John P. Gemeinhardt, Jr. "Electrokinetic Stabilization of an Illitic Clay." Journal of the Soil Mechanics and Foundations Division, A.S.C.E., Vol. 93, No. SM3, Proc. Paper 5235 (May, 1967), pp. 109-128.

(11) Freundlich, H. Colloid and Capillary Chemistry. (Trans. from the third German edition by H. S. Hatfield.) New York: E. P. Dutton & Co., 1922.

(12) Grim, Ralph E. Clay Mineralogy. New York: McGraw-Hill, 1953.

(13) Handbook of Chemistry and Physics, 51st Edition. Cleveland, Ohio: Chemical Rubber Company, 1970.

(14) Helmholtz, Wiedemanns. Annalen d. Physik. 1879, p. 337.

(15) Lambe, T. William. "The Structure of Inorganic Soil." Proc. Am. Soc. of Civil Engrs., Vol. 79, Separate No. 315, New York (October, 1953).

(16) Matsuo, S. "A Study of the Effect of Cation Exchange on the Stability of Slopes." Proc. 4th Int. Conf. on Soil Mech. and Found. Engr., Vol. 2, Butterworth's Scientific Publications, London (1957), pp. 330-333.

(17) Miller, R. D. "Neglected Aspects of Electro-Osmosis in Porous Bodies." Science, Vol. 122, No. 3165 (August 26, 1955), pp. 373-374.

(18) Newlin, C. W. "Electro-Osmosis." Tempe, Arizona: Arizona State University, August, 1965 (unpublished classnotes).

(19) O'Bannon, C. E. "Research on Stabilization of Expansive Clays Using Electro-Osmotic Treatment." Proc. 15th Arizona Conf. on Roads and Streets (April, 1966), pp. 76-86.

(20) O'Bannon, C. E. "Stabilization of Chinle Clay by Electro-Osmotic Treatment, Phase One." (Unpublished Soils Research Report, Arizona State University, July, 1966).

(21) O'Bannon, C. E. "Stabilization of Chinle Clay by Electro-Osmotic Treatment, Phase Two." (Unpublished Soils Research Report, Arizona State University, July, 1967).

(22) O'Bannon, C. E. "Stabilization of Expansive Clays Using Electro-Osmotic Treatment and Base Exchange of Ions." Fifth Paving Conference, Albuquerque, New Mexico (December, 1967), pp. 60-82.

(23) O'Bannon, C. E. "Stabilization of Chinle Clay by Electro-Osmotic Treatment, Phase Three." (Unpublished Soils Research Report, Arizona State University, July, 1968).

(24) O'Bannon, C. E. "Stabilization of Chinle Clay by Electro-Osmotic Treatment, Phase Four." (Unpublished Soils Research Report, Arizona State University, August, 1969).

(25) Pauling, Linus. "The Structure of Micas and Related Minerals." Proceedings of the National Academy of Scientists, 16 (1930), pp. 123-127.

(26) Peck, R. B. "Stabilization by Electro-Osmosis." Report of Committee 1 - Roadway and Ballast, Report on Assignment 6 (a), Part 2; Proc. American Railway Engineering Association, Vol. 57 (1956), pp. 658-660.

(27) Piaskowski, A. "Investigations on Electro-Osmotic Flow in Soils in Relation to Different Characteristics." Proc. 4th Int. Conf. on Soil Mech. and Found. Engr., Vol. 1, Butterworth's Scientific Publications, London (1957), pp. 89-92.

(28) Report of the Nomenclature Committee. Clay and Clay Minerals Journal of the Clay Minerals Society, Vol. 16 (1968), pp. 322-324.

(29) Reuss, Mem. de la Soc. Imper. des Naturalistes de Moscou, 1809, p. 327.

(30) Ross, C. S., and S. B. Hendricks. "Minerals of the Montmorillonite Group." USGS Professional Paper 2053 (1948), pp. 27-79.

(31) Ross, C. S., and P. R. Kerr. "The Clay Minerals and Their Identification." Journal of Sedimentary Petrology, 1 (1931), pp. 55-65.

(32) Ruiz, C. L. "Osmotic Interpretation of the Swelling of Expansive Soils." Highway Research Board Bulletin 313, pub. 958 (January, 1961), pp. 47-77.

(33) Rzhanitzin, B. A. Elektrokimischeskoe Zakreplenie Glinistyh Gruntov (Electro-Chemical Stabilization of Railroad Foundations), I Doklady, Akademiia Nauk SSSR, pp. 55-66, Moscow, 1941; English Translation by U. S. Geol. Survey, Washington, 1947.

(34) Schaad, W. "Electrical Treatment of Soils." Proc. 3rd Int. Conf. on Soil Mech. and Found. Engr., Vol. 6, Zurich (1953), p. 85.

(35) Schaad, W. "Discussion" (on electro-osmosis). Proc. 4th Int. Conf. on Soil Mech. and Found. Engr., Vol. III, London: Butterworth's Scientific Publications (1958), pp. 99-101.

(36) Seed, H. B., J. K. Mitchell, and C. K. Chan. "Studies of Swell and Swell Pressure Characteristics of Compacted Clays." Highway Research Board Bulletin 313, pub. 958 (January, 1961), pp. 12-39.

(37) Snedecor, George W., and William G. Cochran. Statistical Methods. Ames, Iowa: Iowa State University Press, 1967.

(38) Solntzev, D. I., and V. S. Sorkov. Elektrokimischeskoe Zakreplenie Gruntov dlia Borby S Puchinami na Zhelesnodorozhnom Transporte (Electro-Chemical Stabilization of Railroads on Frost-Susceptible Ground), I Doklady, Soveschanie po Zakrepleniiu Gruntov i Gornyh Porod, Akademiia Nauk SSSR, pp. 67 to 79, Moscow, 1941; English Translation by U. S. Geological Survey, Washington, 1947.

(39) Spangler, M. G., and Harry L. King. "Electrical Hardening of Clays Adjacent to Aluminum Friction Piles." Proc. Highway Res. Board 29, Washington, D. C. (1949), pp. 589-599.

(40) Wang, W. S., and E. Vey. "Stresses in a Saturated Soil Mass During Electro-Osmosis." Proc. 3rd Int. Conf. on Soil Mech. and Found. Engr., Vol. I, Zurich (1953), pp. 76-80.

(41) Wilson, Eldred D. "A Resume of the Geology of Arizona." Arizona Bureau of Mines No. 171, Tucson, Arizona (1962).

(42) Winterkorn, Hans F. "Fundamental Similarities Between Electro-Osmotic and Thermo-Osmotic Phenomena." Proc. Highway Res. Board 27, Washington, D. C. (1947), pp. 443-445.

(43) Winterkorn, Hans F. "Physiochemical Properties of Soils." Proc. 2nd Int. Conf. on Soil Mech. and Found. Engr., 1, Rotterdam (1948), p. 23.

(44) Winterkorn, Hans F. "Surface Chemical Properties of Clay Minerals and Soils from Theoretical and Experimental Developments in Electro-Osmosis." ASTM Symposium on Exchange Phenomena in Soils, Special Technical Publication #142, Baltimore (1953), pp. 44-52.

APPENDIX A

EXPANSIVE PRESSURE TESTS ON ELECTRO-OSMOTIC TREATED 4.5 INCH TUBE SAMPLES

TABLE XIV

EXPANSIVE PRESSURE TESTS ON ELECTRO-OSMOTIC TREATED 4.5 INCH TUBE SAMPLES

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	*Average Reduction Factor
1		UNTREATED MATERIAL	None	None	-	6.84	1.0
36608C	+ half	10% $CaCl_2$	Aluminum	0.50	305	1.33	3.6
"	- half	"	"	"	"	2.47	
36607A	+ half	2.5% $CaCl_2$, 2.5% $MgCl_2$	Aluminum	0.50	313	1.06	3.4
"	- half	" "	"	"	"	2.93	
46627A	+ half	10% $CaCl_2$	Aluminum	1.50	112	3.00	2.5
"	- half	"	"	"	"	2.43	
86526B	+ half	2.5% $CaCl_2$, 2.5% $MgCl_2$	Aluminum	1.50	115	1.56	3.0
"	- half	" "	"	"	"	2.93	
86510A	+ half	10% $CaCl_2$	Aluminum	1.50	144	3.00	2.1
"	- half		"	"	"	3.50	
86510B	+ half	19% $AlCl_3$	Aluminum	1.50	144	2.20	1.9
"	- half	"	"	"	"	4.86	
96515A	+ half	6% H_3PO_4	Aluminum	1.50	166	4.83	1.3
"	- half	"	"	"	"	5.89	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
106515A	+ half	12% H_3PO_4	Aluminum	1.50	173	2.62	1.6
"	- half	"	"	"	"	6.08	
106519A	+ half	24% Ethyl	Aluminum	1.50	190	1.78	2.7
"	- half	"	"	"	"	3.27	
96529A	+ half	6% Ethyl	Aluminum	1.50	192	4.14	1.8
"	- half	"	"	"	"	3.65	
46627B	+ half	10% $CaCl_2$	Aluminum	1.50	200	1.60	3.5
"	- half	"	"	"	"	2.28	
46626C	+ half	10% $CaCl_2$	Aluminum	1.50	208	2.09	5.9
"	- half	"	"	"	"	0.23	
46626D	+ half	10% $CaCl_2$	Aluminum	2.0	100	2.24	4.2
"	- half	"	"	"	"	1.10	
36623E	+ half	2.5% $CaCl_2$, 2.5% $MgCl_2$	Aluminum	2.0	114	0.57	4.7
"	- half	" "	"	"	"	2.32	
36623F	+ half	10% $CaCl_2$	Aluminum	2.0	158	3.88	3.5
"	- half	"	"	"	"	0.08	
86517A	+ half	Silica Gel	+ Aluminum	1.50	52	4.60	1.4
"	- half	Lime Water	- Steel	"	"	5.40	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
26616A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	0.50	100	2.47	1.4
"	- half	" " "	"	"	"	6.16	
26617A	+ half	25% $CaCl_2$, 2.5% $MgCl_2$	Steel	0.50	124	1.67	2.4
"	- half	" "	"	"	"	3.95	
36602A	+ half	25% $CaCl_2$, 2.5% $MgCl_2$	Steel	0.50	200	1.03	4.2
"	- half	" "	"	"	"	2.36	
26616B	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	0.50	210	0.99	2.8
"	- half	" " "	"	"	"	3.95	
26624A	+ half	10% $CaCl_2$	Steel	0.50	244	2.39	2.0
"	- half	"	"	"	"	3.31	
36607B	+ half	10% $CaCl_2$, 10% $MgCl_2$	Steel	0.50	293	0.99	6.3
"	- half		"	"	"	1.18	
36608A	+ half	10% $MgCl_2$	Steel	0.50	299	0.84	5.8
"	- half	"	"	"	"	1.52	
26608A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	0.50	300	0.95	2.9
"	- half	" " "	"	"	"	3.72	
36608B	+ half	3.5% $CaCi_2$, 1.5% $MgCl_2$	Steel	0.50	306	2.74	2.6
"	- half	"	"	"	"	2.58	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
26624B	+ half	10% $CaCl_2$	Steel	0.50	350	3.34	1.8
"	- half	"	"	"	"	4.41	
26616C	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	0.50	401	0.53	4.9
"	- half	" " "	"	"	"	2.28	
36601A	+ half	10% Cement, 20% H_3PO_4, 2% $AlCl_3$	Steel	0.75	298	6.35	1.4
"	- half	" " "	"	"	"	3.23	
26628A	+ half	10% Ethyl, 6% Cement, 10% H_3PO_4 and 1% $AlCl_3$	Steel	0.75	158	3.61	1.6
"	- half	" " "	"	"	"	4.94	
56611A	+ half	Saturated KCl	Steel	1.0	110	0.34	10.7
"	- half	"	"	"	"	0.95	
56617A	+ half	Saturated KCl	Steel	1.0	211	0.53	8.4
"	- half	"	"	"	"	1.10	
56617B	+ half	Saturated KCl	Steel	1.0	308	0.68	13.4
"	- half	"	"	"	"	0.34	
116519A	+ half	12% $AlCl_3$	Steel	1.50	2	1.37	2.2
"	- half	"	"	"	"	4.86	
126506B	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	24	1.33	2.1
"	- half	" " "	"	"	"	5.09	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
126507A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	24	5.93	1.1
"	- half	" " "	"	"	"	6.92	
116524B	+ half	25% $CaCl_2$, 2.5% $MgCl_2$	Steel	1.50	24	1.94	2.0
"	- half	" "	"	"	"	4.75	
16627A	+ half	None	Steel	1.50	25	5.28	1.3
"	- half	"	"	"	"	5.28	
116524C	+ half	19% $AlCl_3$	Steel	1.50	48	4.18	1.2
"	- half	"	"	"	"	7.68	
126510A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	48	3.08	1.5
"	- half	" " "	"	"	"	6.31	
126510B	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	48	2.47	2.1
"	- half	" " "	"	"	"	4.07	
126527A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	48	0.65	2.4
"	- half	" " "	"	"	"	5.02	
116524A	+ half	22% $CaCl_2$, 4% $MgCl_2$	Steel	1.50	48	1.90	2.2
"	- half	" "	"	"	"	4.25	
16627B	+ half	None	Steel	1.50	50	4.86	1.3
"	- half	"	"	"	"	5.47	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
116530A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	72	2.55	1.5
"	- half	" " "	"	"	"	6.84	
86523A	+ half	2.5% $CaCl_2$, 2.5% $MgCl_2$	Steel	1.50	94	5.89	1.5
"	- half	" "	"	"	"	2.93	
86523B	+ half	3.75% $CaCl_2$, 1.25% $MgCl_2$	Steel	1.50	99	3.61	2.7
"	- half	" "	"	"	"	1.37	
126513A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	96	0.99	2.3
"	- half	" " "	"	"	"	5.05	
126531A	+ half	20% $CaCl_2$, 10% $MgCl_2$, 10% $AlCl_3$	Steel	1.50	96	1.74	2.1
"	- half	" " "	"	"	"	4.90	
116518A	+ half	10% $CaCl_2$, 10% $MgCl_2$	Steel	1.50	96	2.96	2.1
"	- half	" "	"	"	"	3.42	
16621B	+ half	None	Steel	1.50	100	5.78	1.4
"	- half	"	"	"	"	3.91	
16628A	+ half	Saturated KCl	Steel	1.50	100	3.12	1.6
"	- half	"	"	"	"	5.59	
16621A	+ half	None	None	-	100	5.66	1.3
"	- half	"	"	-	"	5.13	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
86526A	+ half	10% $MgCl_2$	Steel	1.50	115	2.36	2.7
"	- half	"	"	"	"	2.62	
116517A	+ half	6% $AlCl_3$	Steel	1.50	119	1.94	2.8
"	- half	"	"	"	"	3.00	
126513B	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	120	1.67	5.1
"	- half	" " "	"	"	"	0.99	
56603A	+ half	Saturated KCl	Steel	1.50	139	0.72	3.2
"	- half	"	"	"	"	3.53	
86503C	+ half	Cement	Steel	1.50	139	2.58	1.2
"	- half	"	"	"	"	8.55	
126528A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	144	0.61	2.2
"	- half	" " "	"	"	"	5.74	
126529A	+ half	20% $CaCl_2$, 10% $MgCl_2$, 10% $AlCl_3$	Steel	1.50	144	0.46	3.9
"	- half	" " "	"	"	"	3.04	
86503A	+ half	50% $CaCl_2$	Steel	1.50	146	2.62	4.0
"	- half	"	"	"	"	0.76	
16627C	+ half	None	Steel	1.50	150	6.38	1.0
"	- half	"	"	"	"	7.37	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
96522A	+ half	6% H_3PO_4	Steel	1.50	167	9.20	0.94
"	- half	"	"	"	"	5.36	
96522B	+ half	25% $CaCl_2$, 2.5% $MgCl_2$	Steel	1.50	167	2.51	4.3
"	- half	" "	"	"	"	0.65	
106520A	+ half	22% $CaCl_2$, 4% $MgCl_2$	Steel	1.50	167	1.52	4.8
"	- half	" "	"	"	"	1.33	
96529B	+ half	19% $AlCl_3$	Steel	1.50	192	1.67	5.6
"	- half	"	"	"	"	0.80	
126527B	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	192	0.00	5.6
"	- half	" " "	"	"	"	2.58	
16609A	+ half	20% $CaCl_2$, 10% $MgCl_2$, 10% $AlCl_3$	Steel	1.50	200	1.22	1.4
"	- half	" " "	"	"	"	8.36	
16627D	+ half	None	Steel	1.50	214	5.70	1.1
"	- half	"	"	"	"	6.35	
56603B	+ half	Saturated KCl	Steel	1.50	214	1.52	5.1
"	- half	"	"	"	"	1.14	
56620A	+ half	Saturated KCl	Steel	1.50	214	0.27	21.4
"	- half	"	"	"	"	0.38	

TABLE XIV (Continued

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
106505A	+ half	4.9% Cement, 13% H_3PO_4	Steel	1.50	216	10.60	1.2
"	- half	" "	"	"	"	0.72	
116509A	+ half	12% $AlCl_3$	Steel	1.50	216	1.94	2.8
"	- half	"	"	"	"	3.00	
16628B	+ half	Saturated KCl	Steel	1.50	222	1.37	2.9
"	- half	"	"	"	"	3.31	
126520B	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	240	1.29	6.7
"	- half	" " "	"	"	"	0.76	
126527C	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	240	0.15	12.4
"	- half	" " "	"	"	"	0.95	
126524A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	240	1.25	1.8
"	- half	" " "	"	"	"	6.19	
16627E	+ half	None	Steel	1.50	240	4.48	1.2
"	- half	"	"	"	"	7.07	
106522A	+ half	4.9% Cement, 13% H_3PO_4	Steel	1.50	264	8.63	1.0
"	- half	" "	"	"	"	5.02	
16606A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	300	0.49	11.4
"	- half	" " "	"	"	"	0.72	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
26601A	+ half	Saturated KCl	Steel	1.50	304	0.95	3.9
"	- half	"	"	"	"	2.55	
56603C	+ half	Saturated KCl	Steel	1.50	305	1.90	3.8
"	- half	"	"	"	"	1.71	
16630A	+ half	19% $AlCl_3$	Steel	1.50	309	3.57	1.4
"	- half	"	"	"	"	6.35	
16630B	+ half	22% $CaCl_2$, 4% $MgCl_2$	Steel	1.50	309	3.88	1.5
"	- half	" "	"	"	"	5.17	
26603A	+ half	25% $CaCl_2$, 2.5% $MgCl_2$	Steel	1.50	312	2.05	2.2
"	- half	" "	"	"	"	4.29	
116502A	+ half	10% $MgCl_2$, 5% $AlCl_3$	Steel	1.50	312	0.68	10.4
"	- half	" "	"	"	"	0.65	
36623C	+ half	6% $AlCl_3$	Steel	2.0	120	1.70	4.0
"	- half	"	"	"	"	1.71	
46601A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	2.0	144	0.87	10.7
"	- half	" " "	"	"	"	0.41	
36622A	+ half	50% $CaCl_2$, 1% $MgCl_2$	Steel	2.0	146	0.34	26.4
"	- half	" "	"	"	"	0.19	

TABLE XIV (Continued)

Sample No.	Location	Solution	Electrode	Voltage Gradient v/in.	Time Hours	Expansion Pressure psi	Average Reduction Factor
36622B	+ half	3.75% $CaCl_2$, 1.25% $MgCl_2$	Steel	2.0	149	1.48	7.2
"	- half	" "	"	"	"	0.42	
36623B	+ half	19% $AlCl_3$	Steel	2.0	167	3.72	3.4
"	- half	"	"	"	"	0.27	
36623A	+ half	19% $AlCl_3$	Steel	2.0	192	2.28	4.7
"	- half	"	"	"	"	0.65	
46626A	+ half	Saturated KCl	Steel	2.0	200	0.38	9.8
"	- half	"	"	"	"	1.03	
46626B	+ half	Saturated KCl	Steel	2.0	222	0.72	12.5
"	- half	"	"	"	"	0.38	
36623D	+ half	Saturated KCl	Steel	2.0	222	0.68	20.2
"	- half	"	"	"	"	0.00	
36615A	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	3.0	100	0.87	7.2
"	- half	" " "	"	"	"	1.03	
36616B	+ half	25% $CaCl_2$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	4.5	50	0.65	4.3
"	- half	" " "	"	"	"	2.51	
36616A	+ half	25% $CaCl_3$, 10% $MgCl_2$, 5% $AlCl_3$	Steel	4.5	111	0.87	9.8
"	- half	" " "	"	"	"	0.53	

*Average Reduction Factor = $\frac{\text{Expansive Pressure of Untreated Material}}{\text{Average Expansive Pressure of Treated Material}}$

APPENDIX B

STATISTICAL ANALYSIS

STATISTICAL ANALYSIS SYSTEM

ANTHONY J. BARR
JAMES HOWARD GOODNIGHT

DEPARTMENT OF STATISTICS
NORTH CAROLINA STATE UNIVERSITY

AUGUST 1970
RALEIGH, N.C.

THE DEVELOPEMENT OF THIS SYSTEM WAS MADE POSSIBLE BY
FUNDS FROM THE NATIONAL INSTITUTE OF HEALTH
PROJECT NO. FR-00011.

```
****************************************************************************************
*                                                                                      *
*  MODEL         :  OBANNON.  ELECTRO-OSMOTIC TREAT OF EXP CLAYS.  1971.               *
*                                                                                      *
*  DEPENDENTS    :  EP                                                                 *
*                                                                                      *
*  INDEPENDENTS  :  D S C D2 S2 DS SC                                                  *
*                                                                                      *
****************************************************************************************



                    OBANNON.  ELECTRO-OSMOTIC TREAT OF EXP CLAYS.  1971.

ANALYSIS OF VARIANCE TABLE , REGRESSION COEFFICIENTS , AND STATISTICS OF FIT FOR DEPENDENT VARIABLE EP


SOURCE              DF       SUM OF SQUARES        MEAN SQUARE         F VALUE     PROB > F      R-SQUARE            C.V.

REGRESSION           7          47.28050238         6.75435748        21.01247       0.0001    0.72425648       42.85271 %

ERROR               56          18.00093248         0.32144522

CORRECTED TOTAL     63          65.28143486



SOURCE              DF        SEQUENTIAL SS          F VALUE      PROB > F          PARTIAL SS          F VALUE      PROB > F

D                    1          11.03095178         34.31674        0.0001          0.56746592          1.76536        0.1863
S                    1          21.25045740         66.10911        0.0001          3.37367485         10.49533        0.0024
C                    1           7.58080628         23.58351        0.0001          1.08549435          3.37692        0.0680
D2                   1           1.04320689          3.24536        0.0735          1.04320689          3.24536        0.0735
S2                   1           0.96948639          3.01602        0.0842          0.96948639          3.01602        0.0842
DS                   1           3.26281001         10.15044        0.0027          3.26281001         10.15044        0.0027
SC                   1           2.14278363          6.66609        0.0120          2.14278363          6.66609        0.0120



SOURCE             B VALUES         T FOR H0:B=0           PROB > |T|          STD ERR B        STD B VALUES

MEAN            -9.06870000             -0.48622               0.6342        18.65154349        0.0
D                0.59488313              1.32867               0.1863         0.44772902          3.29269725
S               -0.44965381             -3.23965               0.0024         0.13879702         -4.97769667
C               -0.07900375             -1.83764               0.0680         0.04299198         -0.87457660
D2              -0.00510688             -1.80149               0.0735         0.00283481         -4.38316451
S2               0.00123078              1.73667               0.0842         0.00070870          2.04735422
DS               0.00361265              3.18598               0.0027         0.00113392          3.45041971
SC               0.00146383              2.58188               0.0120         0.00056696          1.29383651
```

```
  OBS        ORSERVED        PRECICTED         RESIDUAL      LOWER 95% CL     UPPER 95% CL
NUMBER         VALUE            VALUE                       FOR INDIVIDUAL   FOR INCIVIDUAL

    1       C.558C0000       0.26240250       0.29559750      -0.99849458       1.52329958
    2       1.17400000       0.85849125       0.31550875      -0.32591532       2.04289782
    3       1.34800000       1.23464000       0.11336000       0.01007271       2.45920729
    4       1.60900000       C.71851125       0.89048875      -0.50605604       1.94307854
    5       0.18900000       0.04111750       0.14788250      -1.15951457       1.24174957
    6       C.805C000C       0.78298000       0.02202000      -0.40142657       1.96738657
    7       0.76100000       0.61812875       0.14287125      -0.60643854       1.84269604
    8       0.73200000       0.8841625C      -0.15216250      -0.31646957       2.08479457
    9       1.06200000       1.24462750      -0.18262750       0.06022093       2.42903407
   1C       0.125000CC       C.5635500C      -0.43855000      -0.69734708       1.82444708
   11       0.0              0.57747625      -0.57747625      -0.60693032       1.76188282
   12       0.0              0.06598875      -0.06598875      -1.13464332       1.26662082
   13       1.66700000       1.45093125       0.21606875       0.25029918       2.65156332
   14       1.37700000       2.26385625      -0.88685625       1.00295917       3.52475333
   15       C.73200000       0.33701625       0.39498375      -0.92388083       1.59791333
   16       2.00000000       1.87692000       0.12308000       0.65235271       3.10148729
   17       C.79000000       0.80676875      -0.01676875      -0.38035747       1.99389497
   18       0.83400000       0.27575750       0.55824250      -0.90864907       1.46016407
   19       0.0              C.35066000      -0.35066CC0      -0.87390729       1.57522729
   20       0.47100000       1.09313125      -0.62213125      -0.07482443       2.26108693
   21       0.64500000       C.65180750      -0.00680750      -0.57275979       1.87637479
   22       0.72600000       0.81211625      -0.08611625      -0.35583943       1.98007193
   23       C.0              0.70638625      -0.70638625      -0.48073997       1.89351247
   24       0.87700000       1.1188025C      -0.24180250      -0.06560407       2.30320907
   25       C.84800000       1.16400250      -0.31600250      -0.00395318       2.33195818
   26       2.725000C0       2.79126125      -0.06626125       1.56669396       4.01582854
   27       3.41100000       1.83195375       1.57904625       0.64754718       3.01636032
   28       C.76100000       1.76204500      -1.00104500       0.57491878       2.94917122
   29       0.37500000       0.44701125      -C.07201125      -0.73739532       1.63141782
   3C       2.58000000       2.40432500       0.175675C0       1.21719878       3.59145122
   31       1.27600000       1.62565000      -0.34965000       0.45769432       2.79360568
   32       0.97900000       C.86442125       0.11457875      -0.36014604       2.08898854
   33       0.94000000       0.79464375       0.14535625      -0.39248247       1.98176997
   34       0.93500000       C.74006500       0.19493500      -0.48450229       1.96463229
   35       0.14000000       0.4389175C      -C.2989175C      -0.78564979       1.66348479
   36       C.935000C0       0.89502625       0.03997375      -0.29209997       2.08215247
   37       1.31900000       1.35344250      -0.03444250       0.16903593       2.53784907
   38       0.37500000       1.04675625      -0.67175625      -0.12119943       2.21471193
   39       1.55100000       2.00667250      -0.45567250       0.83871682       3.17462818
   40       1.21600000       1.39182625      -0.17582625       0.16725896       2.61639354
   41       1.426C0000       0.82803375       0.59796625      -0.35637282       2.01244032
   42       3.015C0000       2.93173000       0.08327000       1.74460378       4.11885622
   43       1.62400000       1.32777125       0.29622875       0.15981557       2.49572693
   44       0.659C0000       0.51039750       0.18860250      -0.67400907       1.69480407
   45       2.60900000       2.21297625       0.39602375       1.02856968       3.39738282
   46       3.545C0000       2.28945000       1.25555000       1.10232378       3.47657622
   47       1.18900000       1.54502500      -0.35602500       0.37706932       2.71298068
   48       3.85500000       3.31866625       0.53633375       2.09409896       4.54323354
   49       C.747C0000       0.82832250      -0.08132250      -0.43257458       2.08921958
   50       1.116C0000       1.28139625      -0.16539625       0.09698968       2.46580282
   51       1.13100000       1.20905625      -0.07805625       0.0C842418       2.40968832
   52       C.5580CCC0       C.88290125      -0.32490125      -0.34166604       2.10746854
   53       1.43400000       1.5880825C      -0.15408250       0.38745043       2.78871457
   54       3.59400000       2.38769500       1.20630500       1.20328843       3.57210157
   55       1.68200000       C.98328375       0.69871625      -0.24128354       2.20785104
   56       0.90600000       0.74503750       0.16C96250      -0.45559457       1.94566957
   57       2.43500C00       1.92604750       0.50895250       0.74164093       3.11045407
   58       0.67400000       0.5271750C       0.14682500      -0.73372208       1.78807208
   59       1.60900000       1.56241125       0.04658875       0.378C0468       2.74681782
   6C       C.935C0C00       2.59399875      -1.65899875       1.39336668       3.79463082
   61       4.10200000       3.4591350C       0.642865C0       2.23456771       4.68370229
   62       1.319000CC       1.91923125      -0.60023125       0.65833417       3.18012833
   63       3.68100000       3.84607125      -0.16507125       2.58517417       5.10696833
   64       1.94200000       2.8168550C      -0.874855C0       1.59228771       4.04142229

            SUM CF RESIDUALS                     =           -0.00000000

            SUM OF SQUAREC RESIDUALS             =           18.00093248

            SUM CF SQUAREC RESICUALS - ERROR SS  =            0.CCC00C00
```

VITA

Charles Edward O'Bannon

Candidate for the Degree of

Doctor of Philosophy

Thesis: STABILIZATION OF MONTMORILLONITE CLAY BY ELECTRO-OSMOSIS AND BASE EXCHANGE OF IONS

Major Field: Civil Engineering

Biographical:

Personal Data: Born March 22, 1933, in Albuquerque, New Mexico, the son of Charles P. and Della M. O'Bannon.

Education: Attended elementary school in Albuquerque and graduated from Albuquerque High School in 1952; received a Bachelor of Science Degree in Civil Engineering from The University of New Mexico, Albuquerque, New Mexico, in June, 1956; received a Master of Science Degree in Engineering from Harvard University, Cambridge, Massachusetts, in June, 1964; completed requirements for the Doctor of Philosophy Degree in Civil Engineering in July, 1971.

Professional Experience: Employed by The New Mexico State Highway Department as Materials Engineer II, 1956-57; U. S. Corps of Engineers, Civil Engineer (Soil Mechanics), Foundation and Materials Branch, 1957-63; Arizona State University, Assistant Professor of Civil Engineering, 1964-69; Special Consultant to Arizona Highway Department on Electro-Osmotic Research Project, 1965-69; Special Consultant to U. S. State Department, Agency for International Development on Research Project, "Transportation Systems in an Underdeveloped Nation," 1966-67; Independent Consultant for various individuals and firms, 1964-69.

Professional Societies: Member of The American Society of Civil Engineers, Boston Society of Civil Engineers, New Mexico Society of Professional Engineers, Arizona Society of Professional Engineers, and American Society for Engineering Education.