CHEMICAL STABILIZATION OF DISPERSIVE CLAY SOILS

By

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Bachelor of Science in Civil Engineering

Tri-State College

Angola, Indiana

1974

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
July, 1975

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ACKNOWLEDGMENTS

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

To his major advisor, Professor T. A. Haliburton, for his encouragement, consultation and interest throughout this research.

To his committee members, Professor J. V. Parcher and Professor L. W. Reed, for their interest and encouragement.

To his fellow graduate student and assistant, A. El-Leboudy, for her assistance throughout this research.

To his fellow graduate student, M. Sabry, for his suggestions and fellowship.

To his wife, Judy, for her encouragement, interest, and assistance in this study.

To his parents for being outstanding and dedicated individuals from which to learn.

To Mrs. Robin Lee for typing the manuscript.

To Mr. Eldon Hardy for assistance in preparation of the graphical portions of this thesis.

To Mr. C. K. Sharp for his assistance in suggestions for maintaining and modifying equipment.

To the United States Department of the Interior, Bureau of Reclamation, for financial support during this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

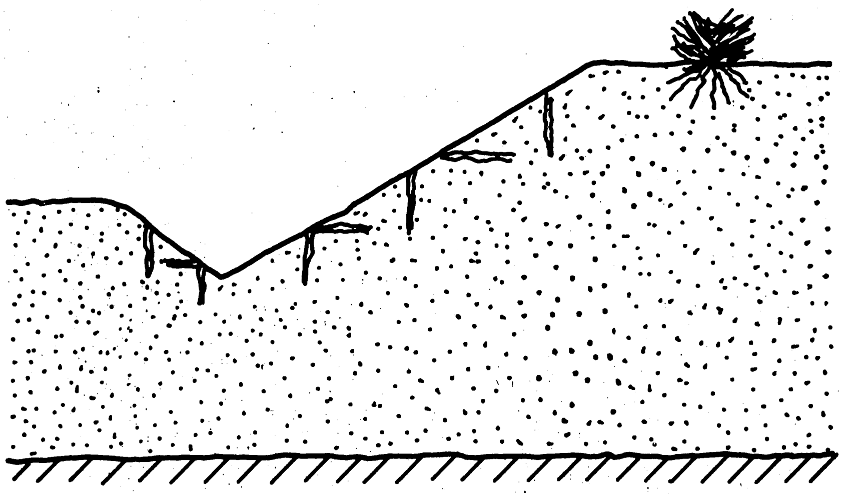
INTRODUCTION

Internal erosion of dispersive clay has created many problems in building compacted earth structures and natural cut slopes. In the past there was no adequate means for identification or treatment of dispersive clay. Information gained from this research study on identification and chemical treatment of dispersive clay could lengthen the life of both natural and artificial earth structures.

Statement of the Problem

Typical characteristics exemplified by slope failures resulting from internal erosion of dispersive clay are visible signs of piping and jugging. Piping of material, creating the failure of slopes cut into natural deposits, was found to be initiated by dispersion of clay particles in dessication cracks and propagated by seepage of water through the embankment formed by the construction of the slope. Figure 1.1 illustrates the failure of slopes cut in natural deposits from piping of dispersed clay. Photographs of dispersive clay erosion of a natural slope are included as Figure 1.2.

Another, and more serious kind of slope failure was determined to occur in embankments constructed with dispersive clay soil. Earth structures are more susceptible to failure initiated by piping of dispersive clay soil because embankment permeability is greater, dessication cracks



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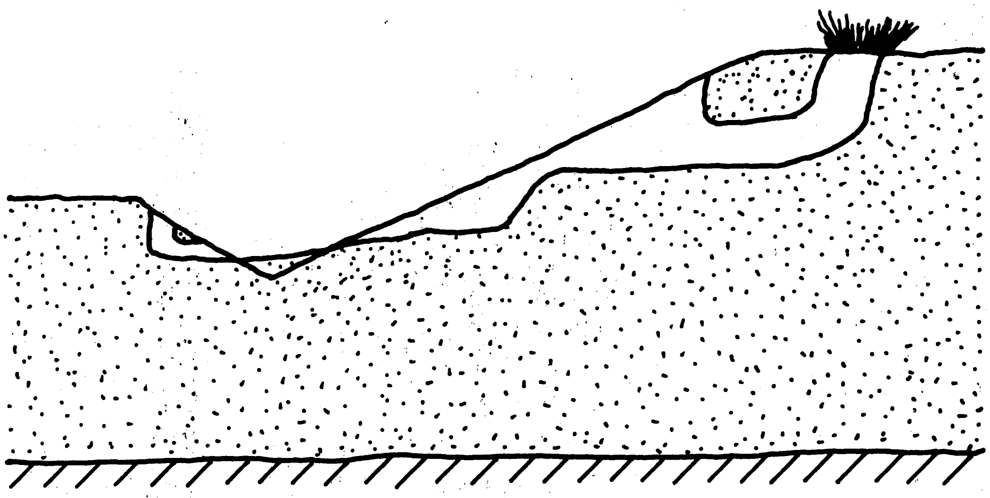


AFTER

Figure 1.1. Failure by Piping of Dispersed Clay in Slopes Cut Into Natural Deposits

FIGURE 1. TYPICAL DISPERSIVE SOIL EROSION

may be deeper and larger, and construction joints may provide planes of weakness where piping channels can start. An illustration of the type of damage found in slopes of earth structures constructed of these problem soils is shown in Figure 1.3.

In addition to development of means for identifying potentially dispersive clay, a need exists for an adequate solution to the problem besides avoidance of the material. The solution for this problem must encompass two factors: 1) it must be economical for field use and 2) its application must be understood by practicing engineers.

Scope of Investigation

The scope of this investigation was to use the Physical Erosion Test, as developed by Petry (1) to determine an adequate solution for prevention of internal erosion by utilizing chemical treatment. In addition, physical erosion test results were analyzed and correlated with those determined by Petry (1) and other proposed methods for identification of dispersive clay.

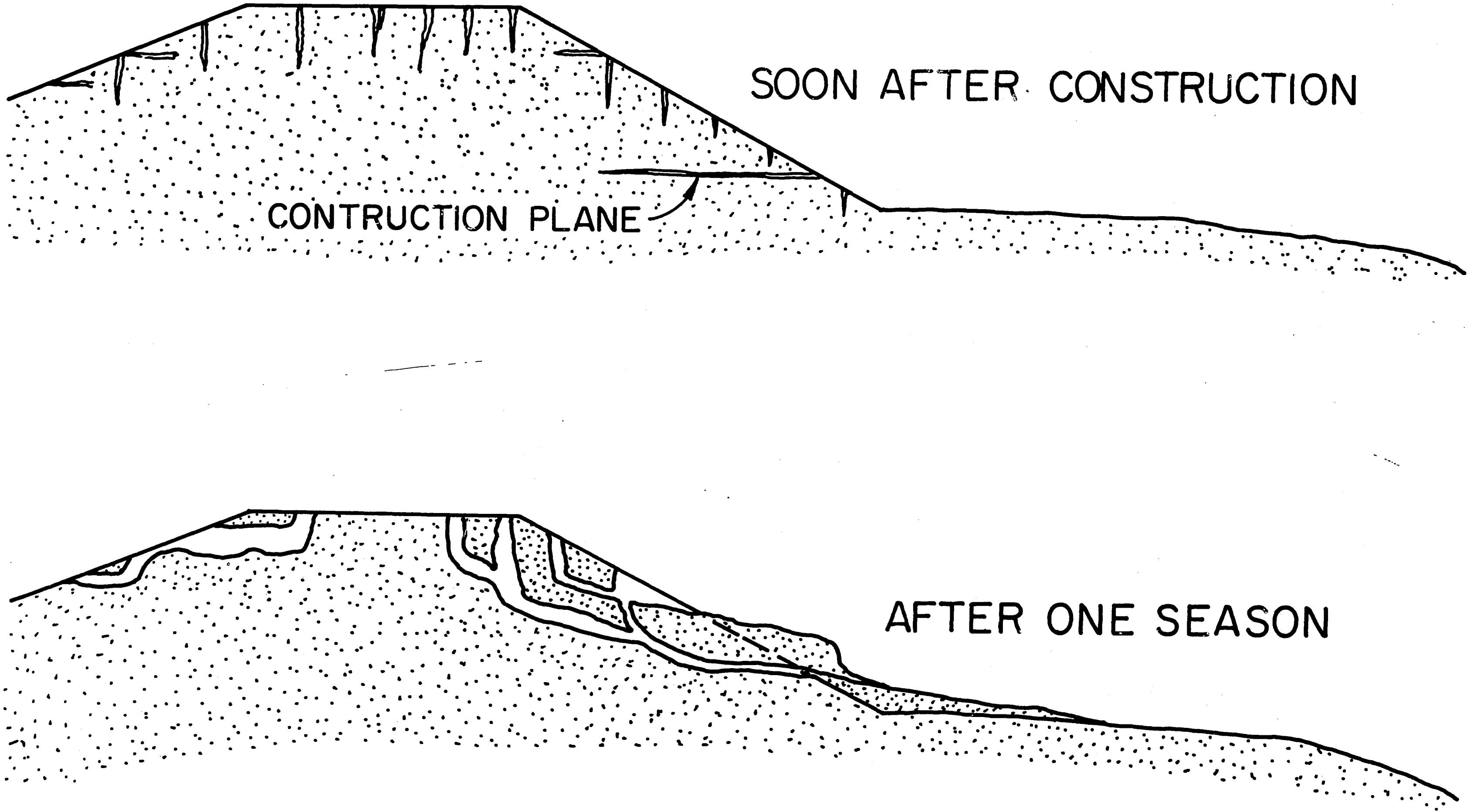


Figure 1.3. Slope Failures in Embankments Constructed of Dispersive Clay Soils

CHAPTER II

A LITERATURE CRITIQUE OF IDENTIFICATION AND CHEMICAL TREATMENT OF DISPERSIVE CLAY SOILS

Introduction

During the past 30 years erosion caused by dispersive clay soils has been of increasing interest to soil engineers. Current knowledge in the area of identification of potentially dispersive clay soils includes several methods used to find the dispersion potential of clay soils. Although the problem of identification of potentially dispersive clay soils has received considerable attention, correct chemical stabilization of these problem soils remains a mystery. Only through understanding and application of fundamental concepts of soil chemistry can chemical treatment be effectively utilized.

The purpose of this chapter is to review basic concepts and theories utilized in identification and treatment of potentially dispersive clay soils. Present theories and hypotheses concerning chemical treatment with several stabilizers are also presented.

Methods of Identification of Dispersive Clay Soils

The first widely accepted method of identification of a potentially dispersive clay soil was proposed by Volk (2). In 1937 he presented his procedure based on results of tests conducted on dispersive soils from Arizona. The procedure consisted of placing approximately 10g of soil, which had been crushed to pass through a two millimeter round hole sieve, in a flask to which was added about 250 cc of water. After allowing the soil to slake for approximately ten minutes, the flask was stoppered and evacuated of air. When the air was removed from the soil, the sample was washed into a regulation USDA pipette method cylinder and made into a one liter suspension by adding water. After slaking an additional half hour, the soil suspension was shaken by inverting the cylinder sixty times. The suspension was then allowed to sediment, the fraction which was equal to or less than 5μ size remained. A filtered aliquot of the solution was used as a salt blank.

The degree of dispersion of the clay fraction of the soil was determined in the following manner: the solids of the oven dried sample was subtracted from the weight of the pipetted aliquot, divided by the oven-dry weight of the soil, and then expressed as a percentage.

Fletcher and Carroll (3), in 1948, found two unique factors while conducting erosion tests on highly dispersive Arizona soils. The first factor was that the soils contained extremely high exchangeable sodium and secondly, the samples were high in calcium carbonate. They stated that for these factors to occur together appeared unique. It was interesting to note that the only cure for dispersive piping determined in their study was to either cut the water off at the inlet or the outlet. They felt this solution could be accomplished by cutoff walls, rodent control measures and care exercised in tillage operations.

In 1954, the USDA United States Salinity Laboratory staff (4) postulated that dispersion of the clay fractions of dispersive soils resulted from the high percentage of sodium ions surrounding clay particles, relative to other cations. To determine the percentage of sodium ions in the solution extract, the Sodium Absorption Ratio (SAR) was used. The SAR is defined as the concentration of sodium ions in the solution extract divided by the square root of the average of the concentrations of calcium and magnesium ions in the extract. In determining the concentration of sodium ions on the exchange complex of the soil, the Exchangeable Sodium Percentage (ESP) was used. The ESP is determined by dividing the concentration of sodium ions on the exchange complex by the Cation Exchange Capacity (CEC) of the soil.

Soil masses having ESP values from 7 to 10, through which relatively pure water percolated, were thought by soil scientists to be moderately dispersive. However soils with ESP values of 15 or greater were believed to posses serious piping potential when leached with water having less than 15 meq/l dissolved salts.

Quirk and Scholfield (5), in 1955, established a relationship between ESP and the total concentrations of cations in the ambient percolating solution which distinguished between the maintenance and the decline of the permeability in systems of soil aggregates. Similar relationships were obtained, with slight modification, by Collis-George and Smiles (6), Atchinson, Ingles and Wood (7) and Ingles and Atchinson (8). The relationship obtained by these researchers was a plot of the SAR versus total cation concentration for the percolating water. The relationship obtained indicated that a boundary exists between the flocculated and dispersed states for the clay soils. Since the relationships were developed for soils containing predominately one clay mineral, it was left to the user to interpret the results for the mixtures of clay minerals normally found under field conditions.

Emerson (9), in 1967, proposed a test to determine the dispersion of the clay fraction of soil aggregates in water. The test was based on immersion of dry soil aggregates in water, immersion of wet remolded aggregates in water and suspension of aggregates in water. During development of the test, Emerson tested both naturally occuring soils and prepared soils of predetermined clay minerology, chemical make-up and grain size. The behavioral characteristics of the soil sample on immersion placed it into one of eight classes. Emerson determined that, for all the samples in any one class, there was a range of ESP and particular mineralogical make-up. The disadvantage to this test is that since it was almost purely physical, it required the experimenter to determine whether or not dispersion had taken place.

In 1972, Sherard (10) introduced the Rapid Dispersion Test or Crumb Test, which was a refinement of the coherence test presented by Emerson. The test consisted of dropping an air dried crumb of soil into a small beaker of water and observing the tendency of the water adjacent to the crumb to become colored by a colloidal cloud of clay particles in suspension. A basic difference between the test Sherard proposed and the test proposed by Emerson was that Sherard used only four classifications of reactions, which he believed were based on expected field behavior. The reactions were classified by observing the reaction of the clay particles after immersion in the solution.

Sherard, Decker and Ryker (11) developed a relationship between selected soil chemistry properties and zones of soil behavior. They plotted percent sodium in solution extract arithmetically as the ordinate versus total soluble salts in the extract log arithmetically on the abscissa. On this plot they illustrated three zones of potential behavior. The plot is presented and discussed in Chapter IV.

The Laboratory Dispersion Test (LDT), which has been adopted by the SCS, is the most widely used method of dispersive clay identification. The LDT is a slight modification of the test proposed by Volk, described earlier. Based on the LDT, the degree of dispersion is classified by the following results: 30% or less the soil is non-dispersive, 30-50% the soil is moderately dispersive, 50-75% indicates a dispersive soil which is likely to exhibit internal erosion, and greater than 75% implies the soil is highly erosive, with critical field problems likely.

After examining the previous test, Petry (1), in 1974, developed a new test which he felt was more applicable to engineering. He developed a Physical Erosion Test which had quantitative rather than qualitative results, making the test particularly appealing to engineers. Another advantage to this test is its standardization, which limits differences in results based on observations of the person conducting the tests. This test was used exclusively in this research study and will be described in detail later.

Chemical Treatment

The most widely used and researched chemical treatment for engineering stabilization of cohesive soils is lime, in either the oxide or hydrated form. Although the use of lime for treatment of cohesive soils to produce more desirable engineering properties is common, the basic understanding of the reaction between lime and soil is one of the least understood.

Lime treatment is usually discussed in literature as lime stabilization, with no distinction being made between modification and stabilization. Marks and Haliburton (12) pointed out the difference between lime modification and lime stabilization. Lime modification of cohesive soils usually requires small percentages of lime. Physical properties or consistency limits of clays are affected by modification with very little strength gain attributable to the addition of lime. However, lime stabilization is the addition of lime to clay soils to obtain substantial strength gains. Thus, stabilization of cohesive soils requires greater percentages of lime than does modification.

The addition of lime usually results in the immediate reduction in plasticity. Jan and Walker (13) showed that the addition of lime to plastic soils resulted in a reduction of the plasticity index. Usually an immediate increase in the plastic limit is noted when lime is added. The amount of increase in the plastic limit varies directly with the amount of lime added up to some limiting lime content, after which further increases in lime results in little or no additional increase in the plastic limit. The point of inflection of the plot of lime versus plastic limit has been defined as the "lime fixation point" by Hilt and Davidson (14).

The effect of lime on the effective grain size distribution was studied by Lund and Ramsey (15). Their observations, utilizing standard sieve and hydrometer analysis, was that within the first hour there was a major decrease in the clay sized particles. After a period of approximately an hour only small additional changes in distribution were noted. The new "grains" produced as a result of the lime treatment were mostly sand sized.

Another physical property altered by lime treatment is the moisture density relationship. Herrin and Mitchell (16) summarized that up to a limited amount, on the order of 5 percent lime by weight of the soil, there was a decrease in maximum density and an increase in optimum moisture. Beyond this limited amount of lime, little or no change in optimum moisture requirement was observed. Lund and Ramsey (15) reported that with an increase in lime, a decrease in volume change and a corresponding increase in shrinkage limit was noted.

The previously mentioned change in physical properties of clays from lime treatment is generally agreed upon in literature as being valid. However, the soil chemistry properties responsible for these changes in physical properties are not agreed upon. There are usually at least four mechanisms which are found in literature to explain the phenomenon of lime treatment. These four mechanisms are: cation exchange, flocculation, carbonation and pozzolanic reaction. The major emphasis will be placed on the first two mechanisms as controlling dispersion, rather than the last two, which are felt to be long term effects controlling the gain in strength.

The cation exchange capacity has been found to depend on various factors, some of which are: particle size, temperature, exchangeable cations present, concentration of exchanging ion and pH. Of these factors, only the last two are altered during chemical treatment.

The cation exchange capacity has been found to increase with increasing lime content. Ho and Handy (17) support this fact by showing the amount of calcium retained by the clay particles of bentonite from lime-bentonite slurries, increased with increasing percentages of lime. The writer hypothesized that at a higher pH, more cations are absorbed because of increasing dissociation of weak acidic SiOH groups exposed on clay crystal edges. Below pH 5 the cation exchange capacity is fairly constant, due to isomorphous substitution in the clay mineral structure. The hypothesis is also supported by Scholfield (18).

The flocculation of clay which results from the addition of lime is generally explained by a colloid-chemical approach. According to colloid chemical concepts presented by Van Olphen (19), clays flocculate with the addition of electrolytes due to a modifying effect on the extension of the double layer. The modifying effect represses the double layer, thus reducing the electrostatic repulsive force produces a net attraction between the negatively charged faces and the positively charged edges of the clay floc which forms when the clay particles remain together after collision due to the Browian movement. Ho and Handy (17) suggest that the flocs increase in size with increase in pH until the "lime fixation point" is reached, at which time the maximum size of the flocs has also been reached.

Diamond and Kinter (20) suggest that the colloid chemistry explanation is correct during the initial stages of flocculation. But since flocculation is caused by the electrolyte, if the electrolyte was removed deflocculation would occur. They stated that in experiments which they conducted, deflocculation resulting from the removal of lime from the pore solution did not occur. Rather than deflocculate, the formed flocs persisted and became more pronounced and stable with time. They postulated that an immediate reaction takes place between the alumina-bearing edges of the clay particles and the lime absorbed on the clay surfaces. After curing, a calcium silicate hydrate is formed which stabilizes the flocs and knits the particles. Although the hypothesis of Diamond and

Kinter (20) has neither been confirmed nor disproved, there does exist evidence that a possible reaction does occur on the clay edges.

The two other mechanisms which are used to explain the gain in strength from addition of lime are carbonation and pozzolanic reactions. Carbonation is the reaction of lime with carbon dioxide from the atmosphere to form calcium carbonate. The calcium carbonate acts as a cementitious compound in the soil-lime mixture. The final mechanism involves pozzolanic reactions between the clay particles and lime to form new minerals. The new minerals are formed from the reaction of free calcium ions with amorphous silica and alumina.

The previously mentioned mechanisms, although used to describe the reaction between lime and clay particles, can partially be applied to other kinds of chemical treatment. Cation exchange and flocculation apply to sodium chloride and aluminum sulfate, whereas carbonation and pozzolanic reactions apply solely to lime.

In the United States, sodium chloride was first used in engineering for modification of soil shortly after 1900. When first used, sodium chloride was considered primarily as a dust palliative for open-surfaced aggregate roads. Since that time salt has become widely used for road construction, as pointed out by Sheeler (21) and Mainfort (22). Gow, Davidson and Wheeler (23) reported that there are several reasons sodium chloride has been used as a soil-aggregate stabilizer. One reason is that sodium chloride acts as a lubrication agent to increase compacted density. Another factor is moisture retention from reduced vapor pressure in the pore water. The lowering of the freezing point and thus reduction of frost action effects is another reason for the use of sodium chloride. Increased soil strength and stability has been attributed to recrystallization of sodium chloride. The recrystallization acts both to cement the particles together and fill the voids. Although some researchers believe this phenomenon to be true others indicate that further research is necessary.

Thornburn and Mura (24) present an excellent review of the ideas and test results obtained from the use of sodium chloride as a stabilizing agent. They report that, while the conclusions obtained about the change in physical properties of soil resulting from the use of sodium chloride are debatable, the following are generally accepted: 1) development of a hard coherent road surface, 2) reduction in volumetric shrinkage of clay, 3) reduction in expansion, 4) decrease in permeability, 5) lowering moisture film permeability, 6) increase in strength, and 7) increase in density with lower moisture content.

Kaufmann (25) and Sittig (26) point out that the exchange capacity for sodium ions is dependent on two factors: original ions associated with the clay mineral and concentration of the sodium ions in solution. These two factors control not only exchange capacity, but also flocculation and dispersion of a clay soil. Most literature agrees that the flocculation or dispersion of clay soil, from addition of sodium depends upon the initial chemical make-up of the clay mineral.

The use of aluminum sulfate as a chemical stabilizer has received very little attention. Aluminum sulfate has been used to some extent, as pointed out by Demirel, Benn, and Davidson (27), to provide metallic ions to be used with phosphoric acid in soil stabilization. It was concluded that aluminum sulfate was not an adequate chemical additive to provide the necessary sufficient gain in strength. The use of aluminum sulfate as a chemical additive will be investigated more fully in this research study.

The literature summarized in this chapter indicates that much remains to be learned about the chemical stabilization of soils. While many researchers agree on the property changes resulting from chemical treatment, contradiction exists concerning the causes. It appears that any study to clarify the physical-chemical relationships resulting from chemical stabilization of soils must involve carefully conducted research.

CHAPTER III

RESEARCH MATERIALS, EQUIPMENT AND PROCEDURES

Introduction

This chapter describes the soils, equipment and procedures used in this research study. The general physical properties, the soil series classification and geological units of the soil samples used in this study are presented. The specialized equipment developed for this research is described in the equipment section. Testing procedures initially developed by Petry (1) plus detailed descriptions of research-developed sample preparation procedures are also presented.

Materials

The research study was conducted on nine soils of varying physical properties, soil classifications and geologic histories, native to Oklahoma and Arkansas. Four of these soils were chosen for this study because of their tendencies of their related soil masses to exhibit dispersive clay erosion in the field. Three of the soils were provided by the U.S. Army Corp of Engineers, Foundations and Materials Branch, Tulsa District, because they were thought to exhibit dispersive clay erosion. The remaining two samples were added to provide a measure of control because they had been previously determined to be non-dispersive. To simplify laboratory testing, soils were numerically identified as Samples 201 through 209. Pertinent engineering properties of all samples are given in Table 3.1. Samples 201 through 203 were soils of similar color and properties taken from naturally occuring deposits located approximately eight miles southeast of Stillwater, Oklahoma. They were near-surface samples located adjacent to a two-lane country road. All the samples were taken from soil masses that were weakened by piping and jugging.

Figure 3.1 is a photo taken approximately 75 yards away from the location from which Sample 201 was obtained. It is not evident from the photo that any severe erosion exists on the slope to the rear of the small pond. A close-up of the slope, as shown in Figure 3.2, reveals the internal piping that has occurred.

Samples 202 and 203 were from areas that exhibited extensive slope erosion in addition to piping and jugging. The photos presented in Figure 3.3 and 3.4 show the eroded slopes at the locations from which Samples 202 and 203 respectively were obtained. Figures 3.5 and 3.6 depict the typical vertical piping which weakened the slopes at these locations.

All three soils were of low plasticity and fairly well-graded. The percentage of clay for Sample 201 was in the low twenties, whereas for Samples 202 and 203 the percentages were in the low thirties. Sample 201 possessed a moderate tendency to shrink and swell with changes in moisture. Samples 202 and 203 possess a moderately high shrink-swell potential. Their textures varied from silty clay to sandy silty clay.

These soils were of the Vernon series. The soils were from the A horizon, which was made up of calcareous, compact, massive, impervious marine clays. Fine modules of calcium carbonate were scattered throughout this soil series. The shales from which these weathered soils originated were part of the Wellington-Admire geologic unit which had its

TABLE 3.1

ENGINEERING PROPERTIES OF RESEARCH SAMPLES

							Grain Size Analysis (Percent Passing) U.S. Sieve								Std. Proctor		Mod. Proctor	
Sample Number	Specific Gravity	Liquid Limit	Plastic Limit	Plastic Index	Linear Shrinkage	Volumetric Shrinkage	0.002mm	0.05mm	0.02mm	0.05mm	#200	#140	#60	#40	γd pcf	ω	γd pcf	ω
201	2.76	43	18	25	11%	30%	23	33	47	61	80	86	98	100	113.8	12.6	128.3	8.6
202	2.73	46	21	25	17%	43%	33	51	79	89	92	95	99	100	107.6	13.5	121.4	10.0
203	2.75	48	20	28	15%	39%	33	54	81	90	93	95	99	100	107.2	13.7	120.5	10.3
204	2.75	60	19	41	17%	43%	30	73	83	86	87	100	---	---	95.8	20.5	110.2	16.9
205	2.85	107	30	77	21%	51%	55	75	93	97	99	100	---	---	84.9	28.0	99.4	19.0
206	2.70	34	18	16	9%	25%	19	30	47	64	74	83	95	100	106.3	17.5	117.9	13.5
207	2.65	61	27	34	15%	39%	7	65	93	96	99	100	---	---	90.5	25.0	105.6	19.0
208	2.72	47	16	31	17%	46%	36	51	69	82	86	87	100	---	106.5	16.9	115.6	15.0
209	2.70	45	18	27	14%	37%	31	41	70	90	97	98	100	---	103.7	19.0	114.9	15.4

Figure 3.1. Field Location of Sample 201

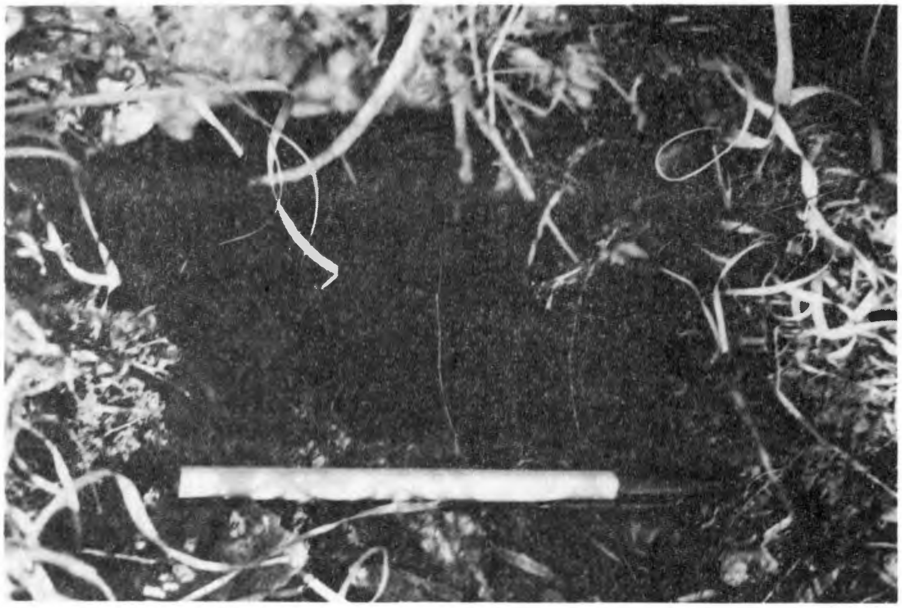


Figure 3.2. A Close-up Revealing the Internal Piping of the Slope Shown in the Above Figure

Figure 3.3. The Eroded Slope from Which Sample 202 was Obtained

Figure 3.4. The Eroded Slope from Which Sample 203 was Obtained

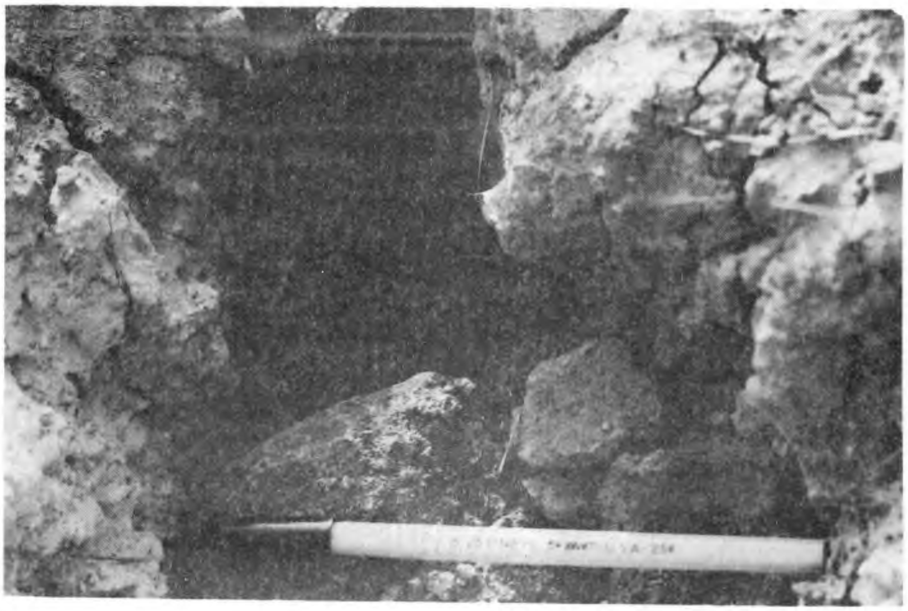


Figure 3.5. Typical Vertical Piping Observed at the Location of Sample 202

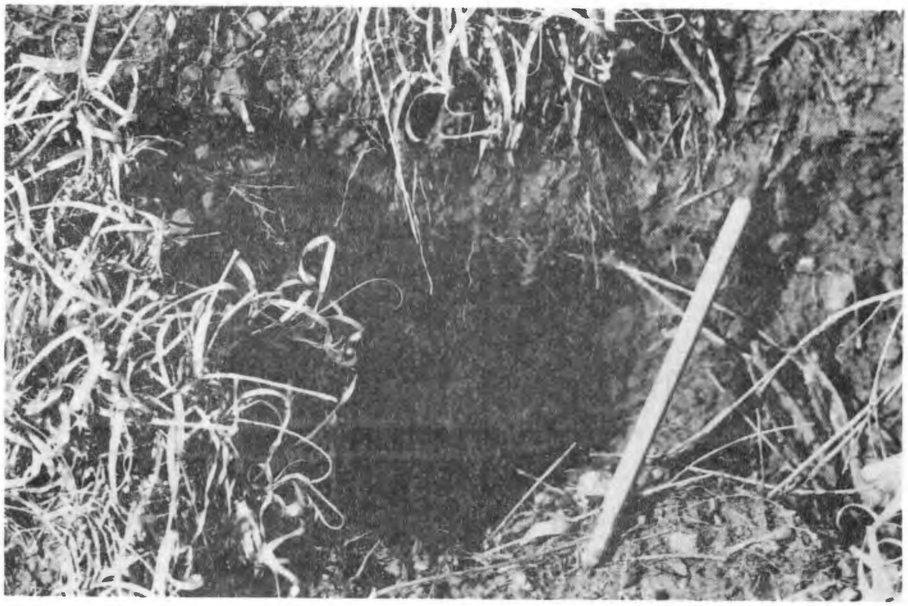


Figure 3.6. Typical Vertical Piping Observed at the Location of Sample 203

origin during the Permian Period. The parent material in this area is predominantly shale, which forms gently rolling hills.

Sample 204 was a gray clay of high plasticity from Roger Mills County in Western Oklahoma. This particular soil was chosen, not only for its relative availability, but more importantly because of its observed field resistance to internal and external erosion. The Roger Mills Gray Clay (RMGC) used in this study came from approximately three feet below the surface on private land seven miles west of Roll, Oklahoma (S11 T15N R25WIM). Adjacent to this location, there is a near vertical unprotected cut in the soil which has remained basicly unchanged since its construction. This sample, contained about 30% clay, exhibited a moderately high tendency to shrink and swell with changes in water content. The textural classification of this soil characterized it as a sandy silty clay of high plasticity.

This material was from the subsoil of Nobscot series. Subsoil of this series is a sandy soil with more clay than the surface layer and is lighter than the dark grayish-brown material found near the surface. It would be accurate to say that this sample came from the Brownfield series, that was mapped with the Nobscot series in this county. This would explain the larger amount of clay found since Brownfield soils have a higher clay content. Soils of this series, located at this depth, are moderately alkaline and calcareous. The description given also includes some soils that were formed from shale, since they can be coarse to medium blocky with a firm consistency when moist.

The geologic unit within which this weathered sandy shale lies was the Ogallala unit of the Tertiary Age. This unit covers the Permian red bed units of the Anadarko Basin. All of the beds in this part of the country are nearly horizontal. This unit of varied constituents is weathered into gently rolling terrain.

Samples 205, 206 and 207 were three samples provided by the Army Corps of Engineers, Tulsa District. Sample 205 was fairly well-graded, containing 55% clay-size particles. This sample exhibited high plasticity and relatively high shrink-swell potential during changes in moisture content. The sample had a light brown color and a texture of a silty clay. Sample 207 was a uniformly graded material which contained 7% clay-sized particles. The sample had a moderate shrink-swell potential with moisture content variation. The sample was light gray in color and possessed a silty texture. This sample contained 91% silt size particles.

The site location of these three samples, as well as the geologic and series data, were not available. These three samples were thought to exhibit internal dispersion characteristics in the field, but through physical erosion testing it was determined that they exhibited only surface sheet erosion.

Sample 208 is Permian Red Clay (PRC) which was chosen because of its lack of any tendency to erode internally and its relative availability. The sample used was taken from a depth of approximately 10 feet below the surface during construction of a building on the campus of Oklahoma State University at Stillwater. This red clay soil, abundant in the central portion of Oklahoma, has a low to medium plasticity and exhibits a moderately high tendency to shrink and swell with changes in moisture content. This material contained 36% clay and had a texture of silty clay with some sand. This soil had the same geologic history as

Samples 201, 202 and 203 but was not internally erodible. It was also chosen because it possessed a high tendency for surface sheet erosion.

Sample 209 was obtained from a relatively shallow highway cut about 7.6 miles east of Ponca City on the road that led to the Kaw Dam area. The distinct features of this natural deposit were visible signs of piping and jugging. This sample exhibited moderately high shrink-swell potential and was of medium plasticity. The color ranged from yellow-medium brown to medium brown.

The soil profile at this highway cut was most likely a combination of Newtonian silt loam overlying the Sogn-Summit complex. Small slick spots occurred in this series but were not mappable. The Sogn-Summit series varied in both depth and proportion of the constituent series, which were interbedded residual clays and limestone. Good management is necessary to preclude erosion in this complex series.

The geologic unit associated with this location is the Wellington unit of deposits, laid down during the Prairie Plains Homocline, which dips gently westward 40 to 50 feet per mile at this location. This unit consists predominantly of red, maroon and gray blocky shales with minor amounts of sandstone, gypsum and limestone. The gray colored deposits are located in Kay County. Topography varies from nearly level to slightly rolling. Figure 3.7 shows one of the horizontal piping tunnels found at this location.

Equipment

During the preliminary development of a physical identification method for dispersive clay erodibility, discussed by Petry (1), special equipment was designed and constructed to accomplish procedural tasks.

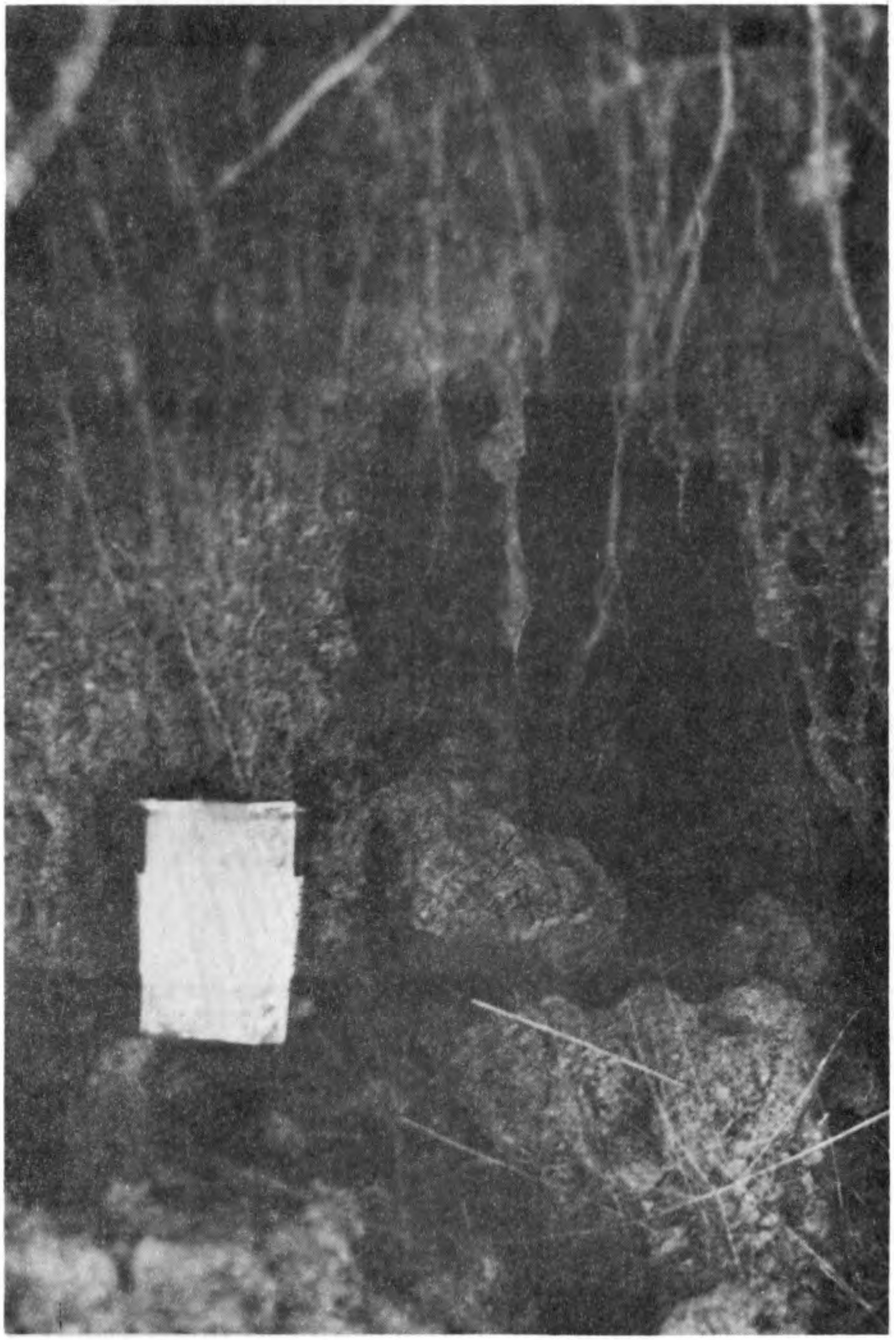


Figure 3.7. A Horizontal Piping Tunnel Found at the Location of Sample 207

An important part of Petry's overall research program was to develop an erosion device to simulate field situations, yet accelerate dispersive erosion so that it could be measured during a relatively short test period.

The erosion device simulated field conditions by the intermittent flow of pressurized water through the soil sample. Erosion testing was accelerated by drilling longitudinal holes in a compacted soil sample. Holding tanks, regulators, timers and valves were necessary to regulate and control the flow of water. Since the desired result was the weight of soil left at the completion of testing, the effluent water was collected and discarded. The relationship between the weight of dry soil at the start of the testing sequence and that remaining after testing was used to indicate the percent physical erosion. Special auxiliary equipment was built to assist in preparation of samples for testing. Prior to describing these special apparatuses, a brief discussion of standard equipment utilized is presented.

Gravity drying ovens (110°C), a soil grinding machine, U.S. Bureau of Standards No. 40 sieve, and balances (0.001g and 0.01g sensitivity) were utilized during initial sample preparation. Liquid and plastic limit determination and grain size distribution was achieved by using standard soil mechanics equipment. The Texas Highway Department Bar Shrinkage apparatus was utilized for the determination of linear and volumetric shrinkage. A Sargent-Welch Model NX pH meter was utilized for the determination of the pH of each soil sample before and after the addition of lime. Saturation extracts, ion content determinations and X-ray diffraction analyses were done by standard soil chemistry methods.

OSU Miniature Compaction Device

The OSU Miniature Compaction Device was built for prior research at Oklahoma State University. This device is a miniature mechanical impact compactor which used a freely falling hammer, lifted by a rack and pinion gear arrangement. Application of Standard Proctor compactive effort to a Harvard miniature size compaction sample is accomplished by the hammer falling 4 inches on each of 4 layers with 19 blows per layer (Figure 3.8). Modified Proctor effort was obtained when a weight was added to the top of the hammer (Figure 3.9) and 25 blows delivered through 4 inches for each of 5 layers. The mold and supporting base sit on a table which is rotated by an electric motor. The even distribution of hammer blows over the soil being compacted is accomplished by momentarily actuating the electric motor while the hammer is being lifted. This device is shown in Figure 3.10.

Erosion Testing Apparatus

The preliminary design and development of the erosion testing apparatus was described by Petry (1). The erosion testing apparatus is shown in Figure 3.11. A drawing of the erosion device is presented in Figure 3.12, showing the location of the equipment to be described below. A detailed description of the components of the erosion testing apparatus is as follows:

1. Cell. The cell was a lucite cylinder into which a Harvard miniature-sized cylinder of soil was placed after compaction, slightly compressed and perforated with longitudinal holes. Water entered the top of this enclosure through a 0.25 in. OD tube and was distributed over the top of the soil. Below the soil cylinder a disc of USBS No. 40 sieve

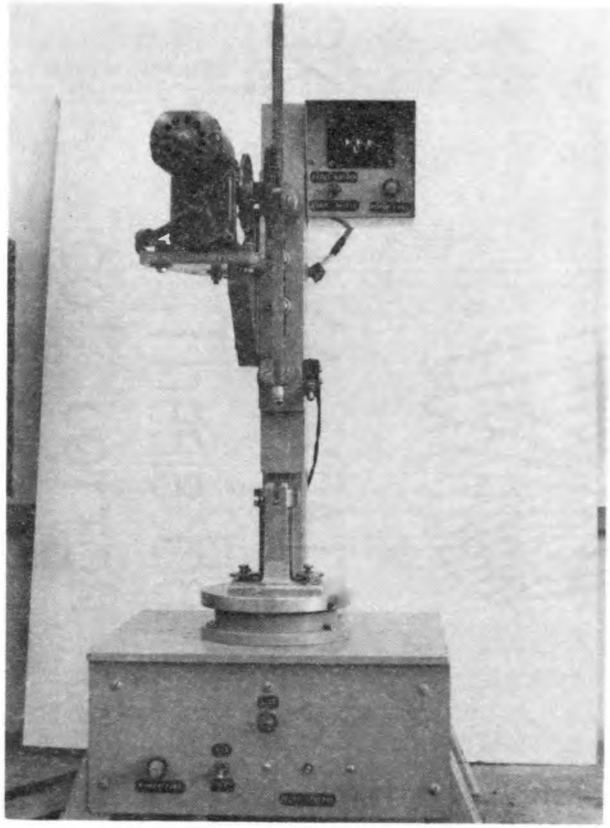


Figure 3.8. OSU Miniature Compaction Device Standard Proctor Operation

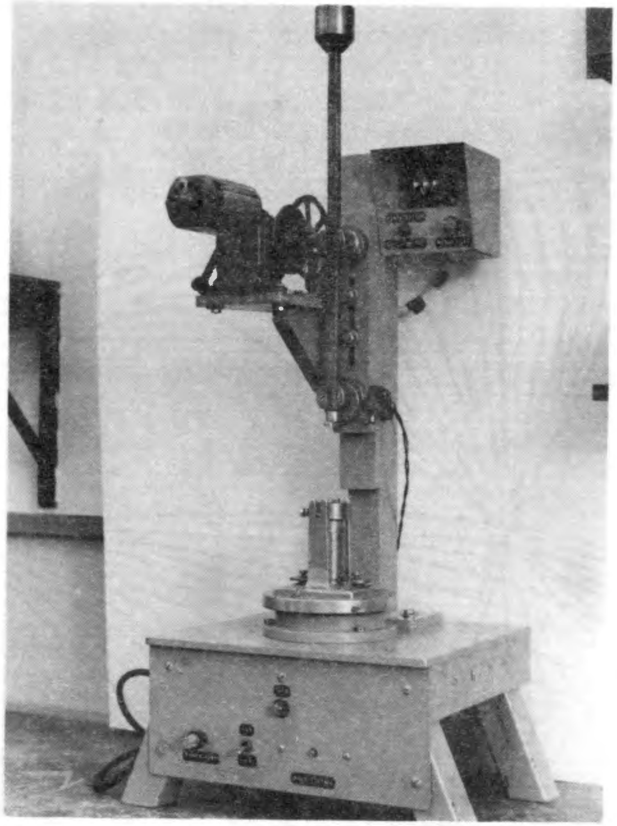


Figure 3.9. OSU Miniature Compaction Device-Modified Proctor Operation

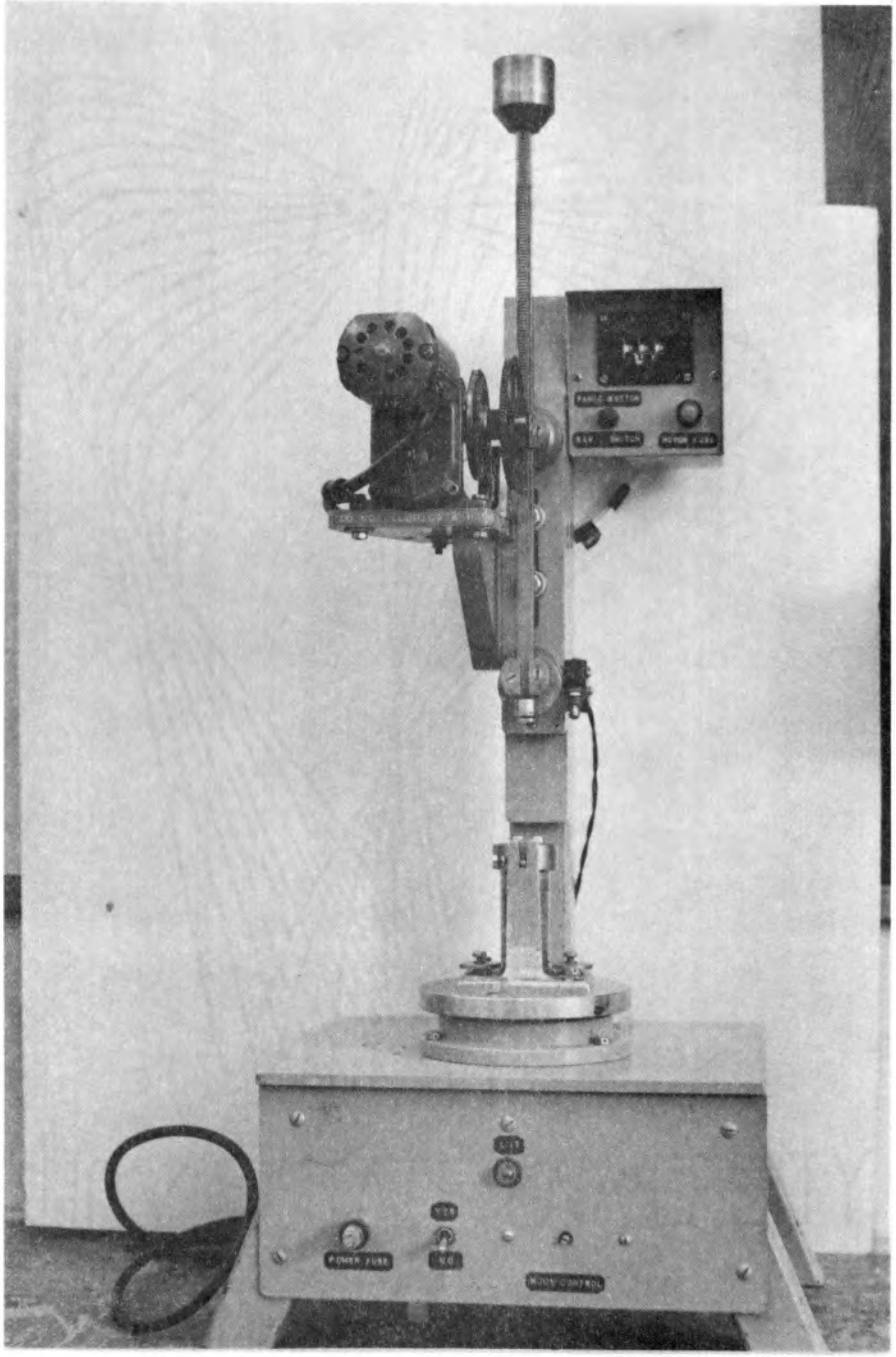


Figure 3.10. OSU Minaiture Compaction Device - Full View

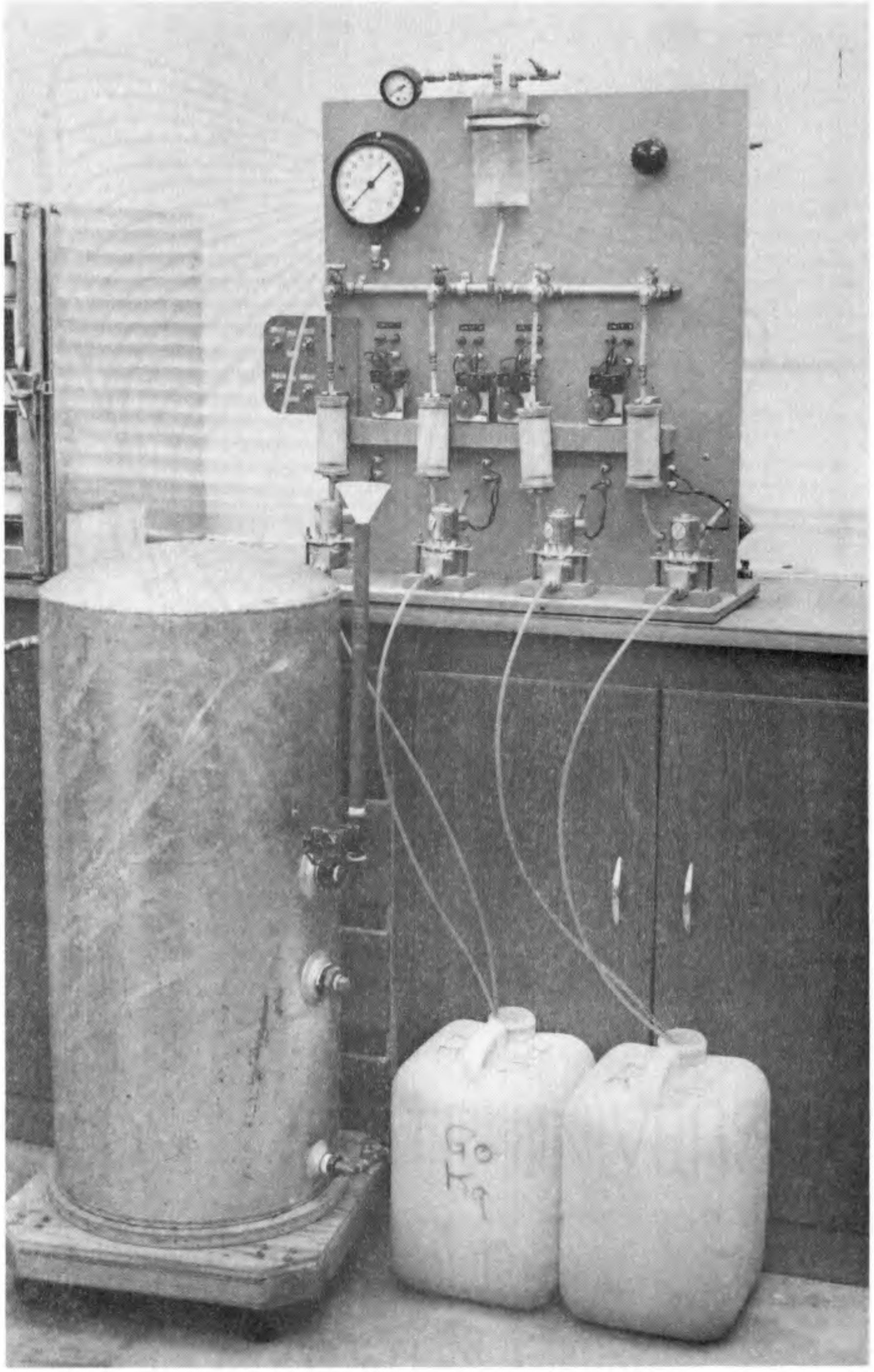


Figure 3.11. Erosion Device - Full View

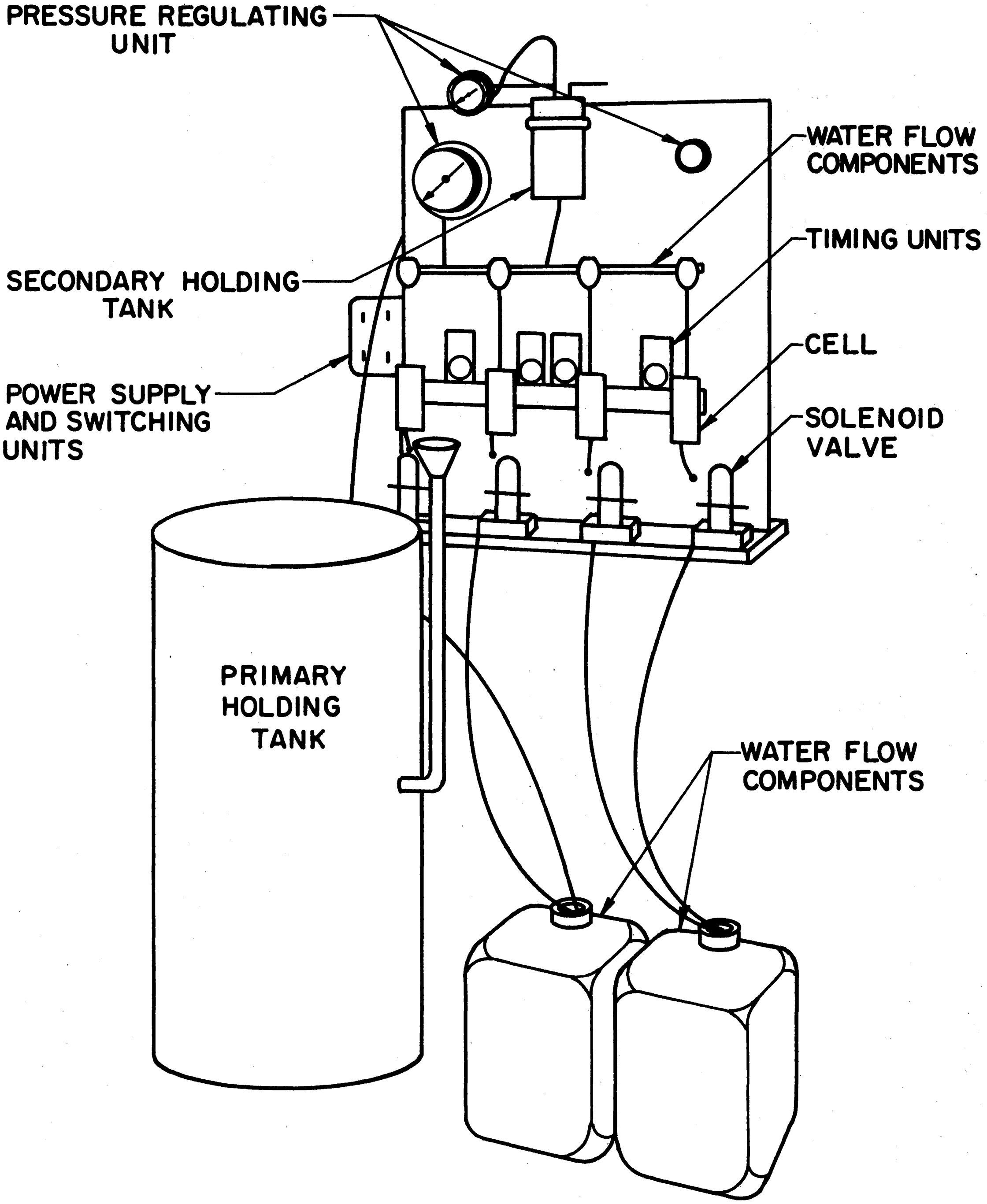


Figure 3.12. Drawing of the Erosion Device

wire was placed and was supported by a porous disc and support ring. Water collected under this porous disc and exited the cell through a 0.25 in. OD tube. The assembled cell, with soil cylinder, is shown in Figure 3.13.

2. Primary Holding Tank. The primary holding tank contained the water supply needed to operate the erosion device and was a galvanized steel container with an effective capacity of 25 gal. It was outfitted with valves and fittings for filling, pressurization and venting. A photograph of the primary holding tank is shown in Figure 3.14.

3. Secondary Holding Tank. The secondary holding tank, along with the air pressure regulating unit, water distribution manifold and fittings, which will be described below, are shown in Figure 3.15. The secondary holding tank, made of lucite, had a capacity of about 500 ml. and was positioned at the top of the erosion device. The output of the primary holding tank was routed to this tank, which contains fittings and valves for shutoff, monitoring of water pressure or input of prepared solutions, and venting. This reservoir, when filled and vented to the atmosphere, was used during initial filling of the lucite cells, and served as a water observation and pressure difference dampening chamber during testing.

4. Pressure Regulating Unit. This unit consisted of a regulator of 100 psi capacity, plus two pressure gages. One pressure gage was used to monitor the air pressure applied to the water surface in the primary holding tank while the other was equipped with a quick-connect fitting so that it could be placed into the auxiliary fitting at the top of the secondary holding tank, where it was utilized to monitor the back pressure

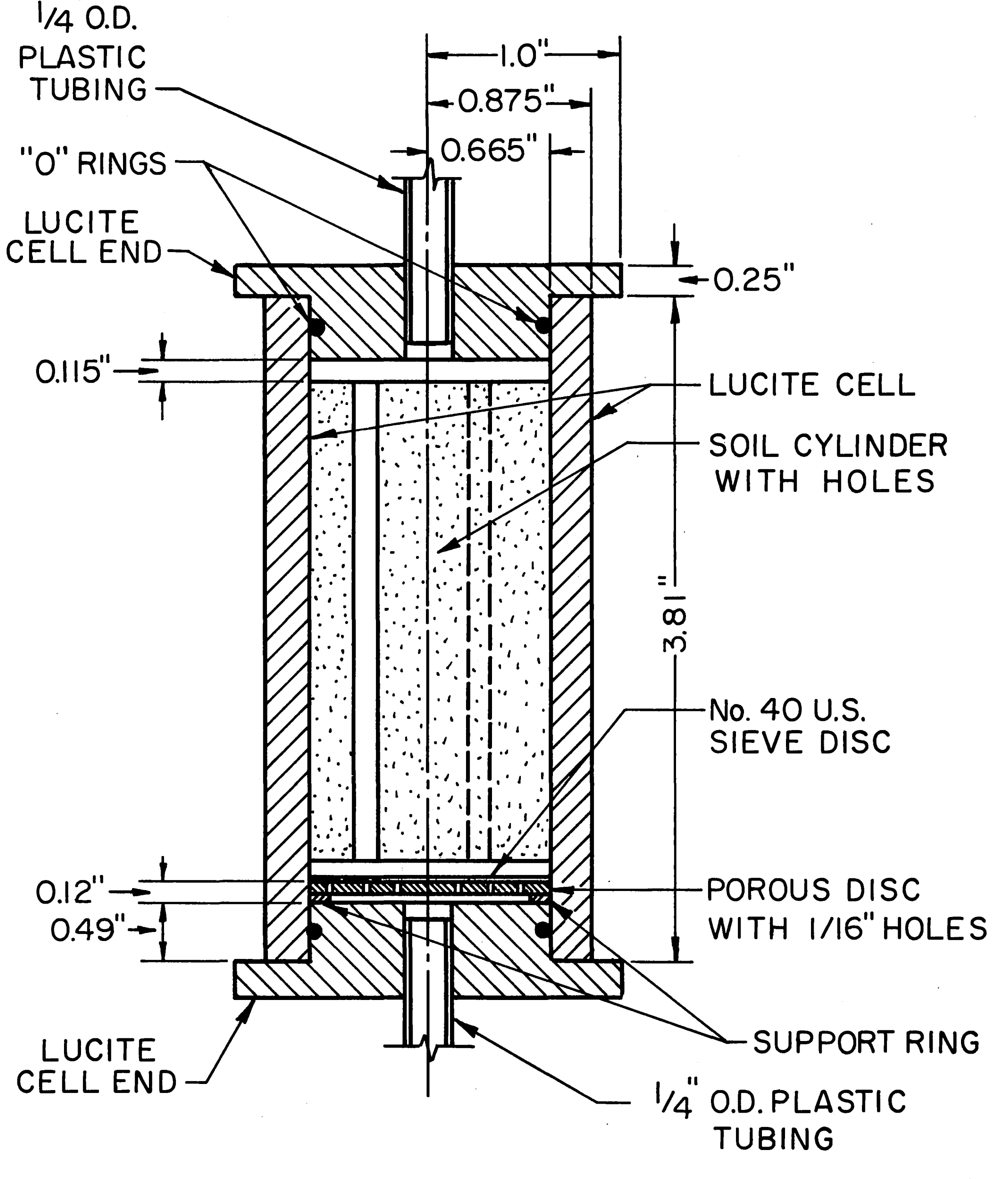


Figure 3.13. Assembled Erosion Device Cell with Soil Cylinder - Cross Section

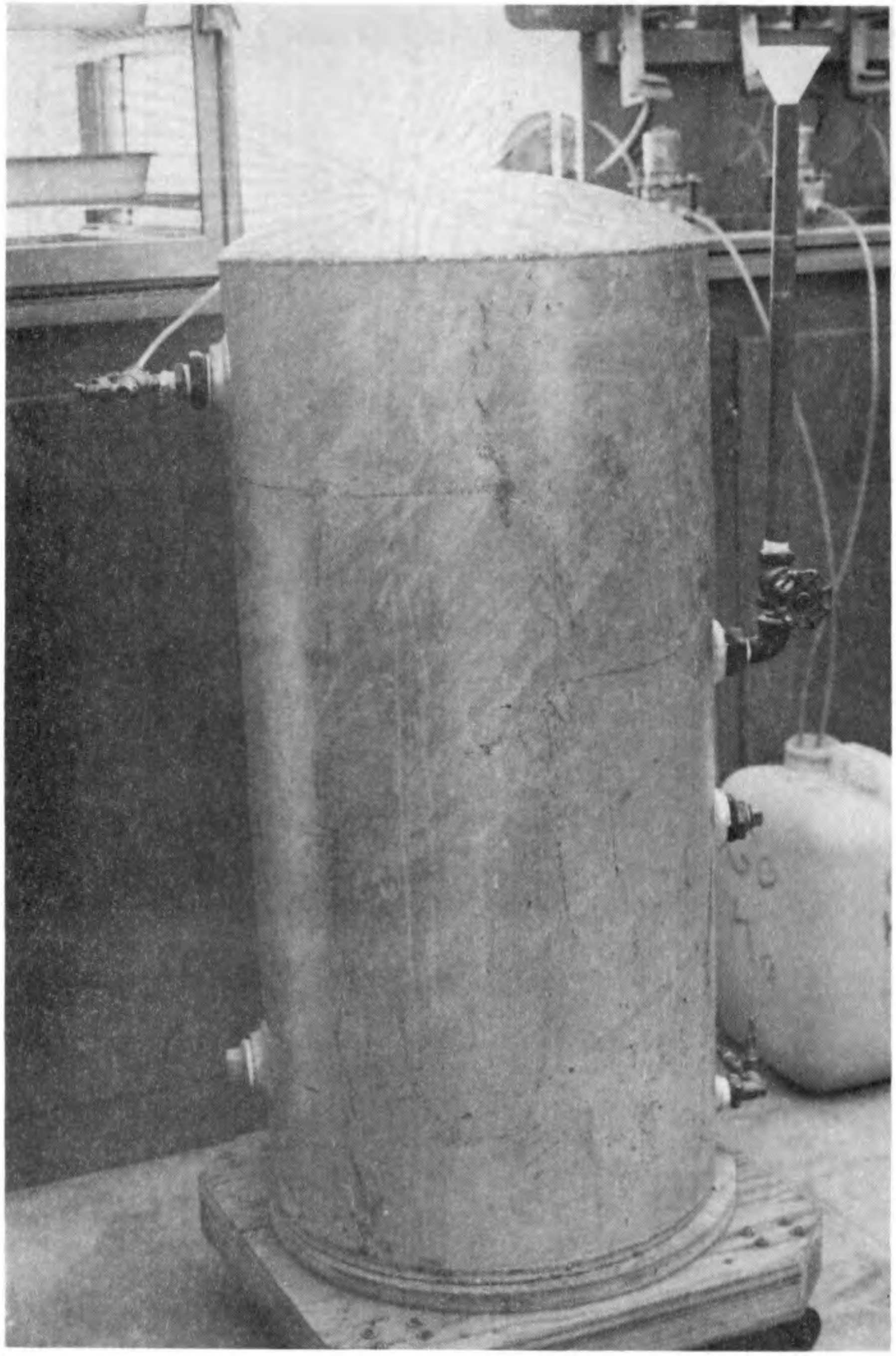


Figure 3.14. Primary Holding Tank - Full View

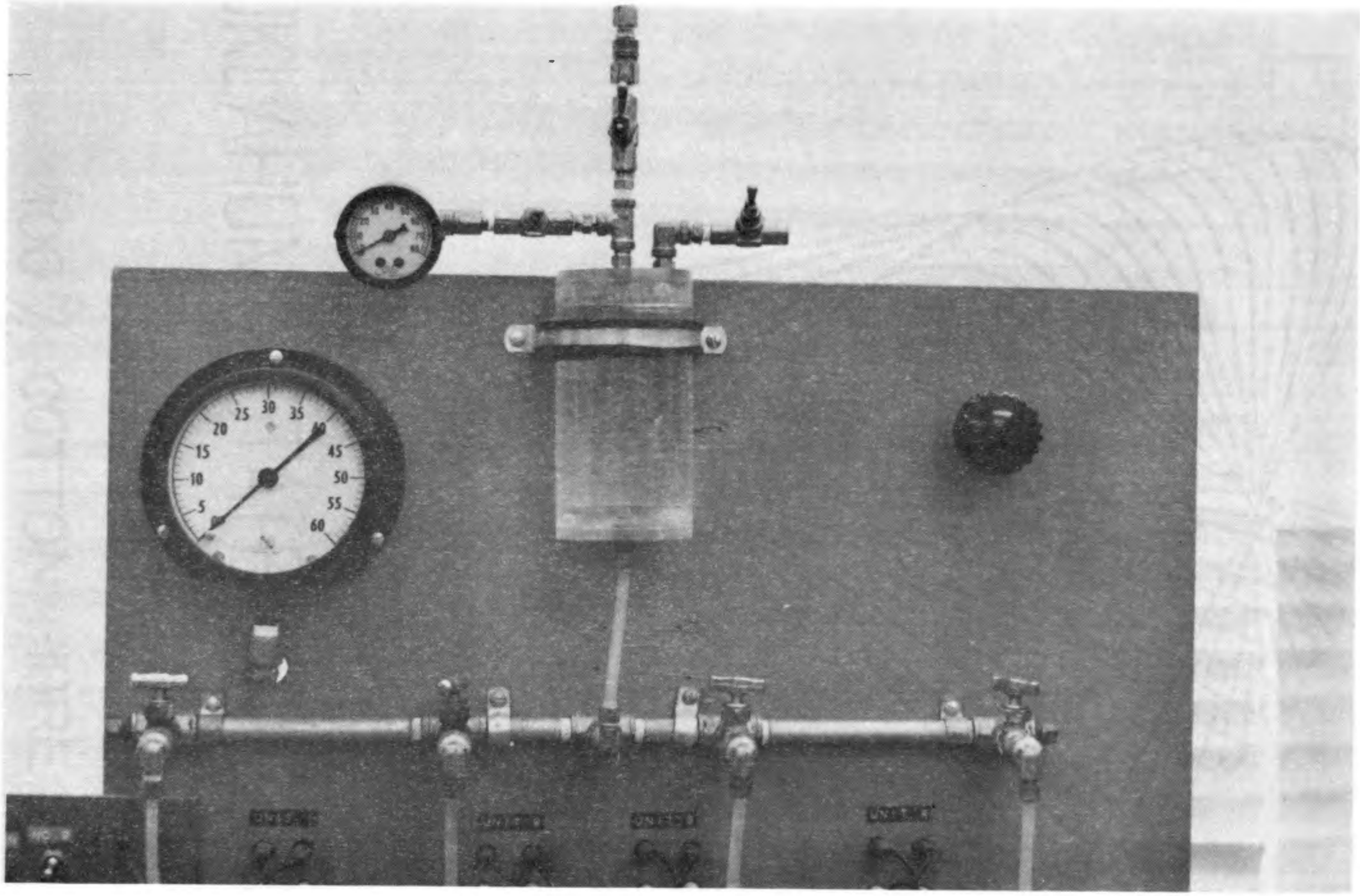


Figure 3.15. Secondary Holding Tank, Pressure Regulating Unit, Water Distribution Manifold and Fittings

applied to the cells. This unit maintained the near constant pressure regulation essential for testing.

5. Additional Water Flow Components. A water distribution manifold made of ½ in. steel pipe, equipped with brass fittings and a valve for each of the four cell units, was used to control and distribute water from the secondary holding tank to each of the cell units. All tubing used in the erosion device was 0.25 in. OD polyethylene tubing. Two 5 gal. PVC containers were used as waste water collection receptacles. The flow system is diagrammed in Figure 3.16.

6. Timing Units. The four timing units consisted of a constant speed motor with an adjustable cam mounted on its shaft, which either holds an intergal microswitch open or allows it to close. The total cycle time available with these devices was six minutes. The cams of all units were adjusted for a closed switch time of seven seconds, during which power was routed to four solenoid values (Item 8). A photo of the timing units is shown in Figure 3.17.

7. Power Supply and Switching Units. The power supply and switching unit consisted of four switches, one for each cell, through which 110 volt, 60 Hz power was routed. The output from these switches powered each corresponding timer motor and was routed through the microswitches of these timers to their respective solenoid values. When the switches were turned on, the timers of each cell were energized and power was available to operate the respective solenoid valves as each microswitch was closed.

8. Solenoid Valve. The solenoid valves operate on 110 volt, 60 Hz power and unless energized, remained in the closed position; when open they allowed water to exit from the cells. The main ball valve orifice

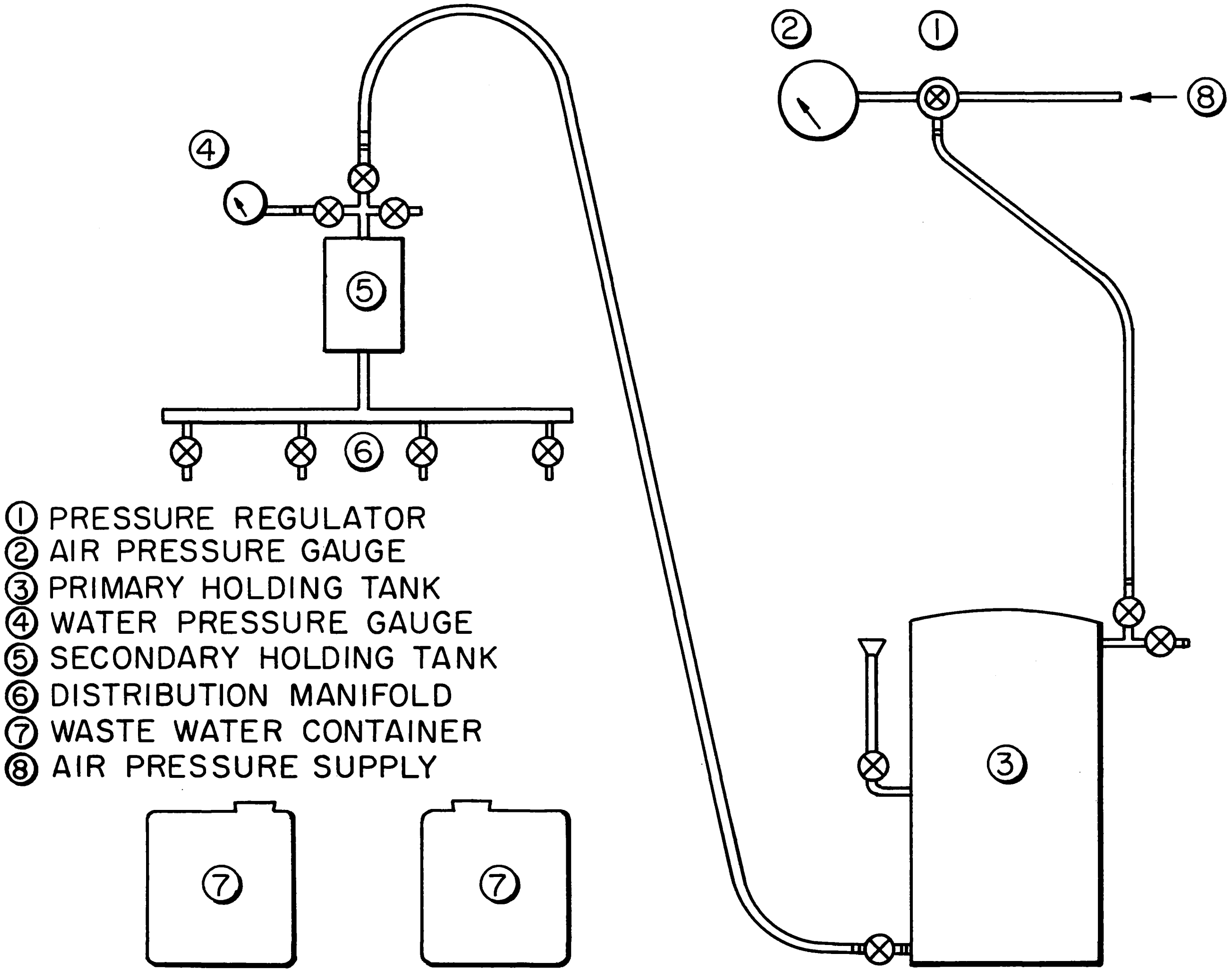


Figure 3.16. Erosion Device Water Flow System

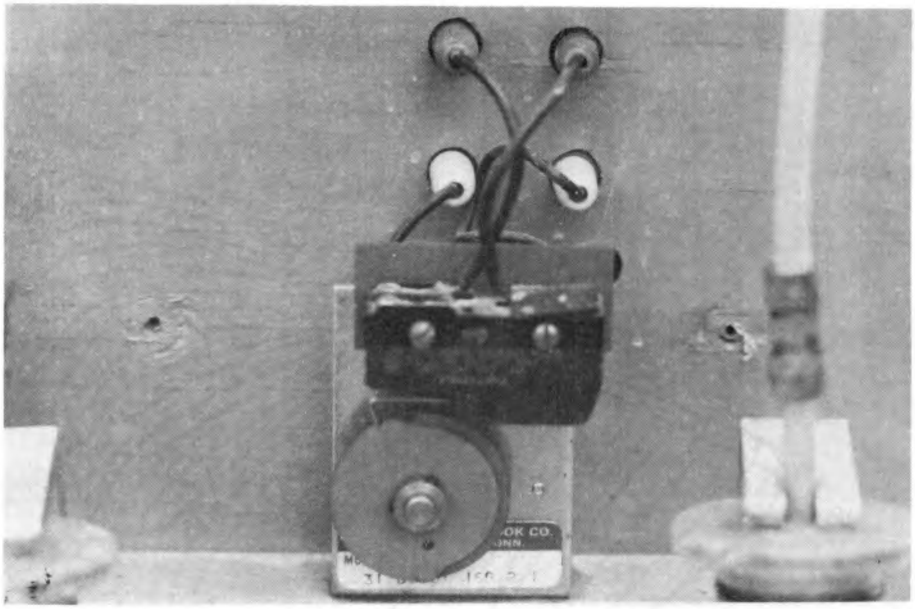


Figure 3.17. Timing Unit

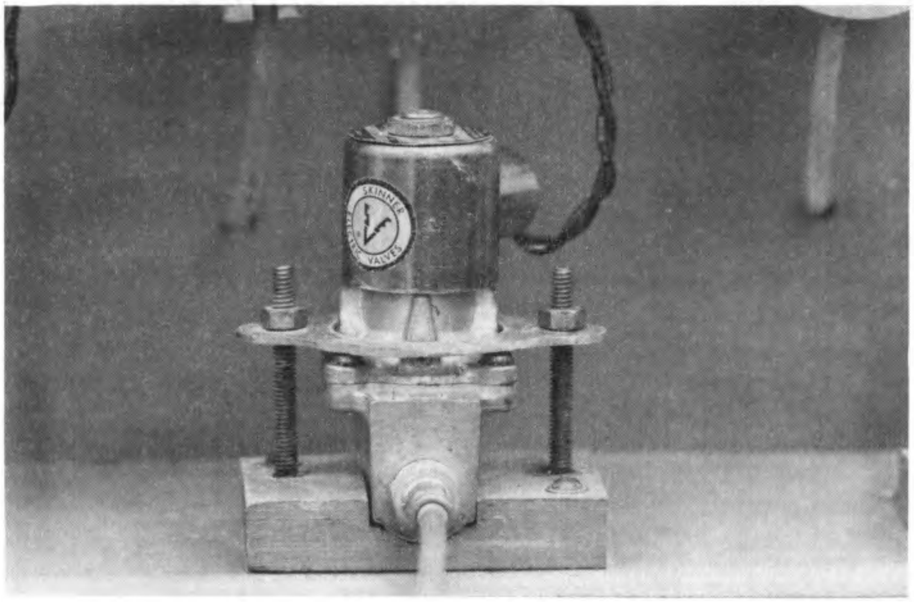


Figure 3.18. Solenoid Valve and Mounting

was 0.5 in. in diameter, with the control orifice 0.094 in. in diameter. A photograph of a solenoid valve and mounting is shown in Figure 3.18.

9. Settling Basin. The settling basin was located between each cell and its corresponding valve. These basins consisted of salvaged automotive cooling solution filter tanks, without filters. The input suspension entered horizontally at mid-depth and the output was taken from the top of the tank. The settling basins were used to prevent sand and silt particles from clogging the solenoid valves. Photographs of the settling basins are shown in Figures 3.19 and 3.20.

Auxiliary Equipment

The auxiliary equipment utilized in this research study was used in sample preparation for physical erosion testing. The use of the specially designed research equipment is outlined in the following descriptions.

1. Sample Extraction Spacer. After compaction, the Harvard miniature mold was placed in the extrusion press, top down. The sample extraction spacer was placed between the mold and extrusion rod as shown in Figure 3.21. The extraction spacer was forced into the mold until the top stop block was reached. The extruded length of the sample, 0.236 in. long, was cut off.

2. Compression Process. Two brass compression/spacing blocks were used to, simultaneously, vertically space and slightly compress the compacted soil cylinders. The slight compression was necessary to insure a space of 0.125 in. at each end of the completed cell and press the soil against the cell wall, to avoid water flow around the sample perimeter. A diagram of the spacing blocks used is given in Figure 3.22. The compression process is illustrated in Figure 3.23.

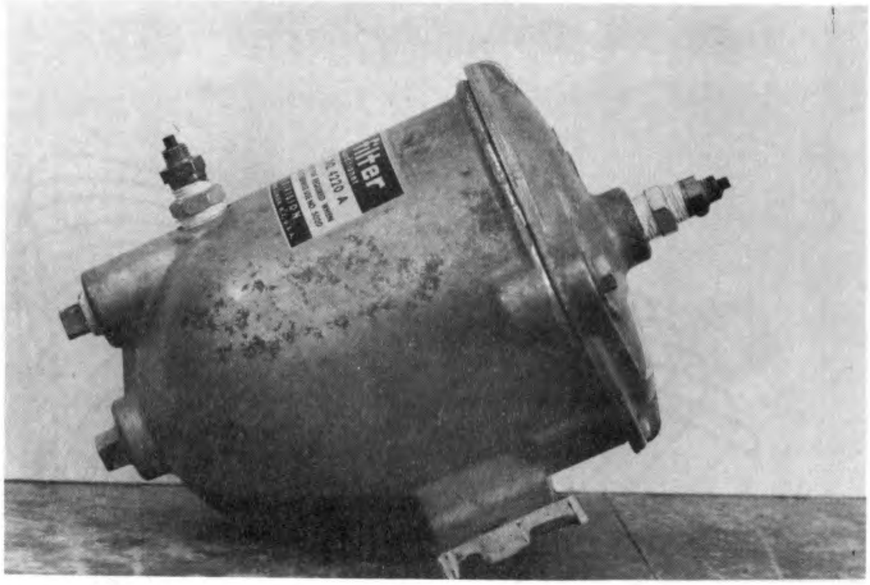


Figure 3.19. A Close-Up of the Settling Basin

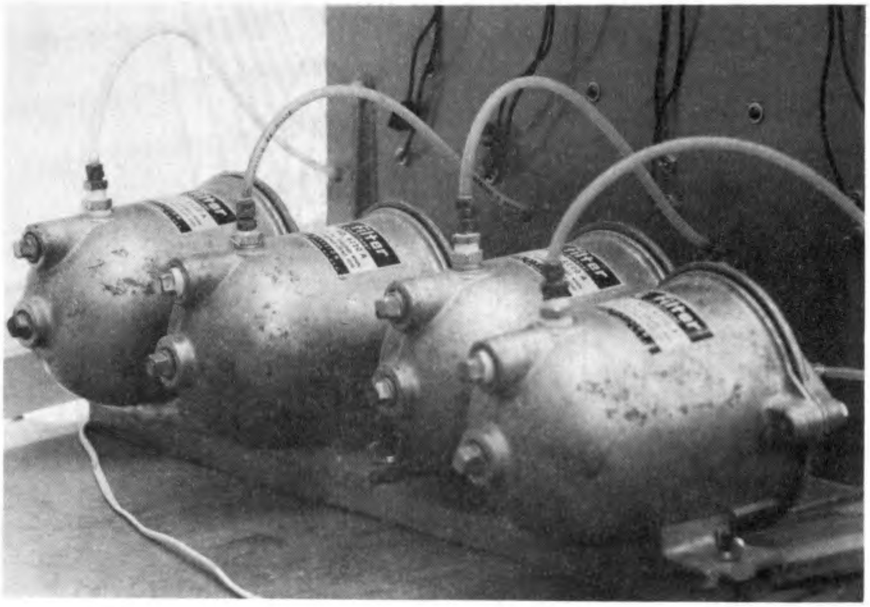


Figure 3.20. Arrangement of the Settling Basins

Figure 3.21. Use of Sample Extraction Spacer

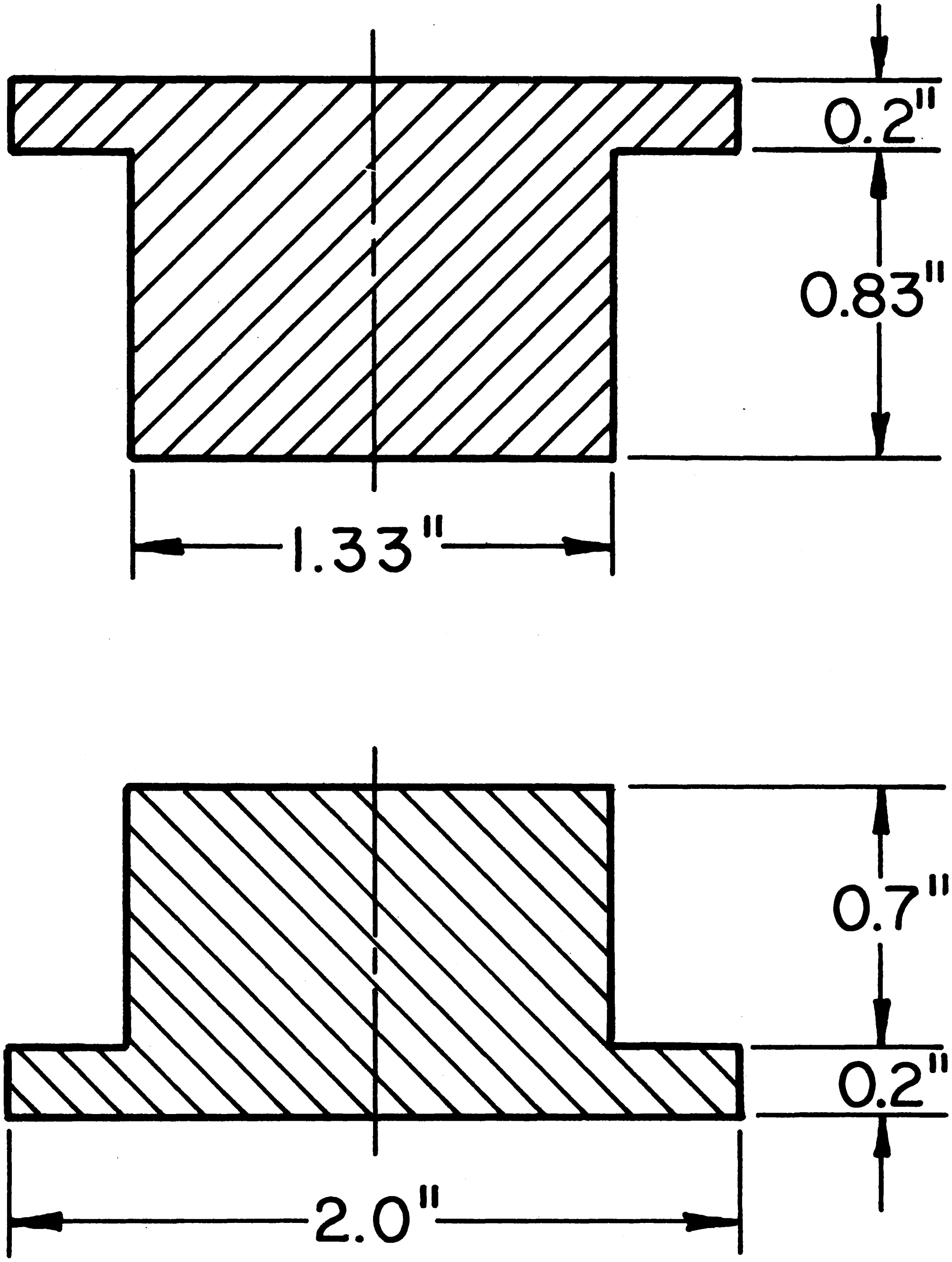


Figure 3.22. Cross Section of Spacing - Compression Blocks

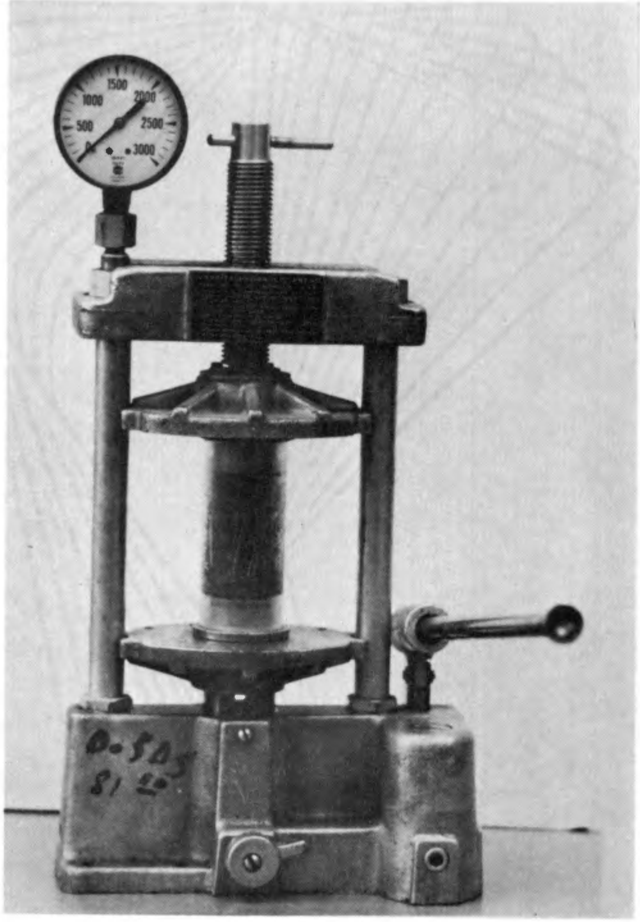


Figure 3.23. Compression Process

3. Location and Drilling of Holes. Holes for water flow were placed 120° apart, located at one-half the radius of the sample cross-section (Figure 3.24). Their location was marked on the top of each compressed soil cylinder using the device shown in Figure 3.25. Holes 0.125 in. in diameter were drilled through each soil cylinder, using a drill press and specially purchased long drill bits. A commercial 3/8 in. variable speed, table model drill press was utilized. The table of the drill press was modified by adding a cell securing jig, which prevented lateral movement of the soil cylinder and cell during the drilling process. The drilling process on hard soil cylinders was accomplished by use of a special carbide tip drill bit. Both drill bits utilized are included in Figure 3.26.

Controlled Temperature and Humidity Chamber

The controlled temperature and humidity chamber used for research was a Blue M, Vapor-temp. Floor Type, Model VP-400AT-1. Equipment controls consisted of:

1) Humidity: 34% to 98% (± 1%)
2) Dry Bulb: +4°C to +77°C (± 1/5°C)
3) Wet Bulb: +4°C to +77°C (± 1/2°C)
4) Wet and dry recorder which monitored wet and dry temperature and provided a permanent record.

The chamber was used to rapid cure the lime-treated samples. The complete controlled temperature and humidity chamber is shown in Figure 3.27.

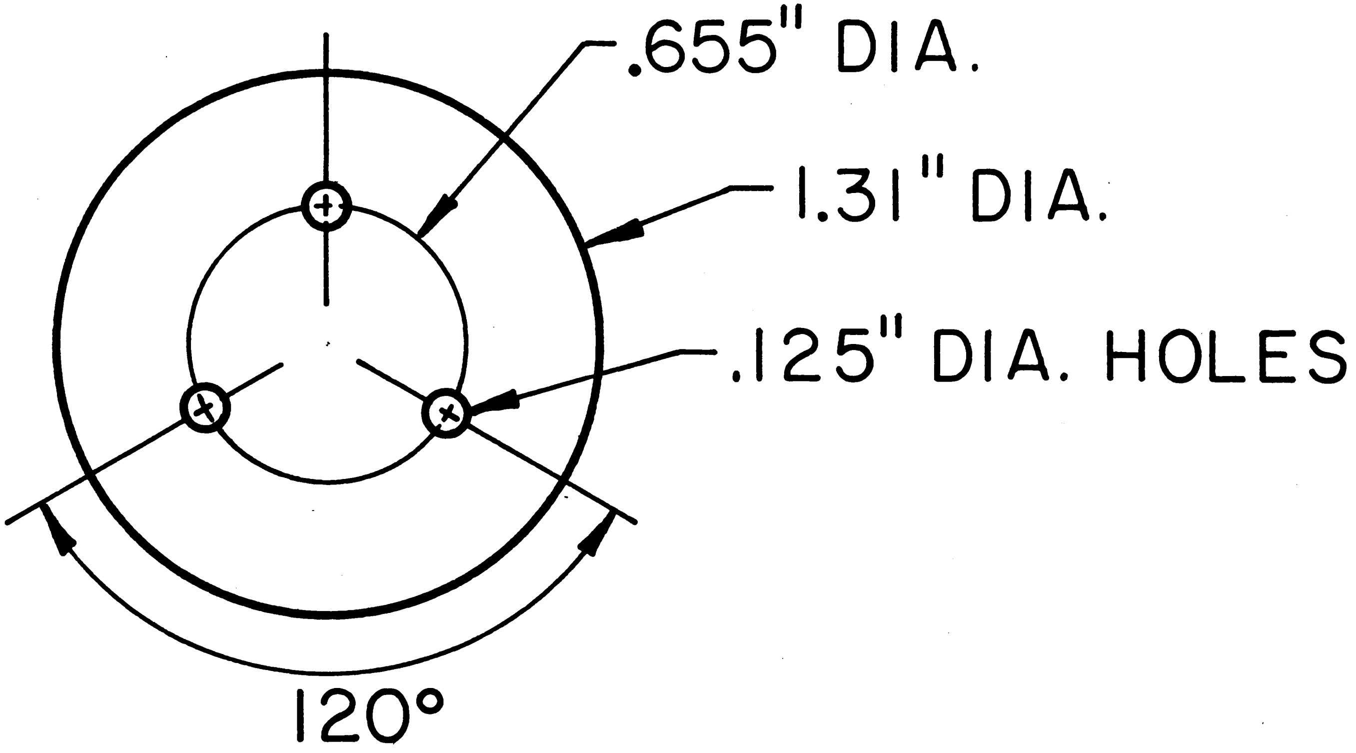


Figure 3.24. Longitudinal Hole Location

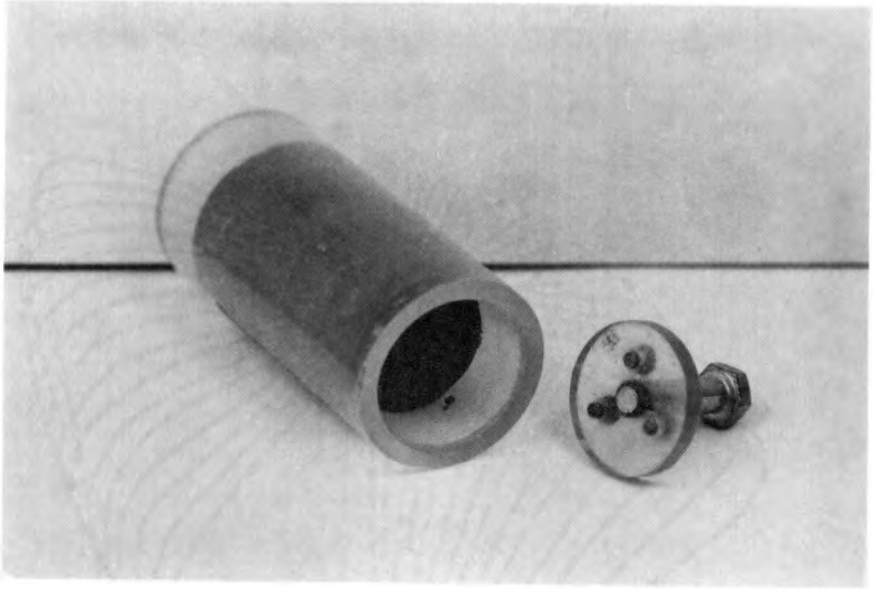


Figure 3.25. Hole Location Marking Device and Marked Cylinder

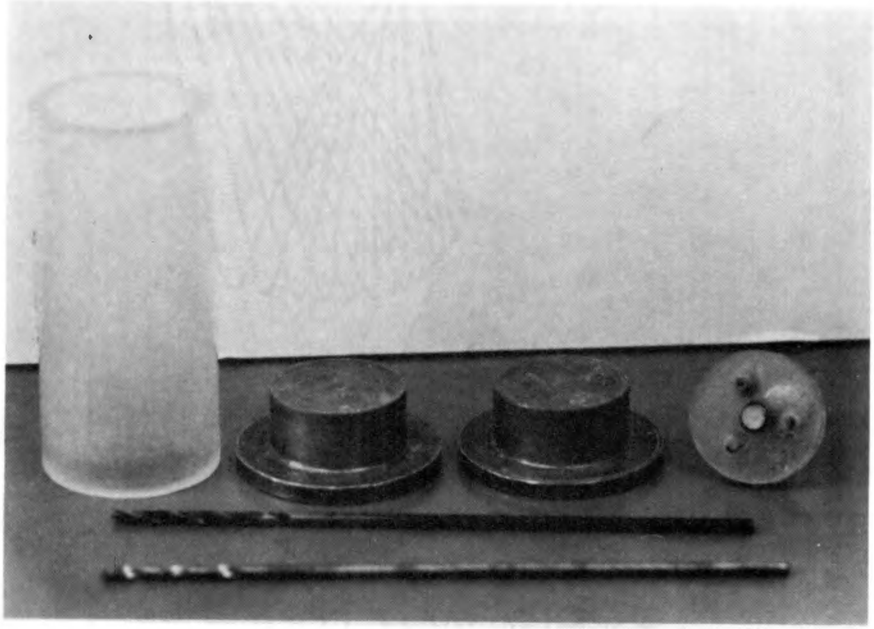


Figure 3.26. Auxiliary Equipment Used During Erosion Testing

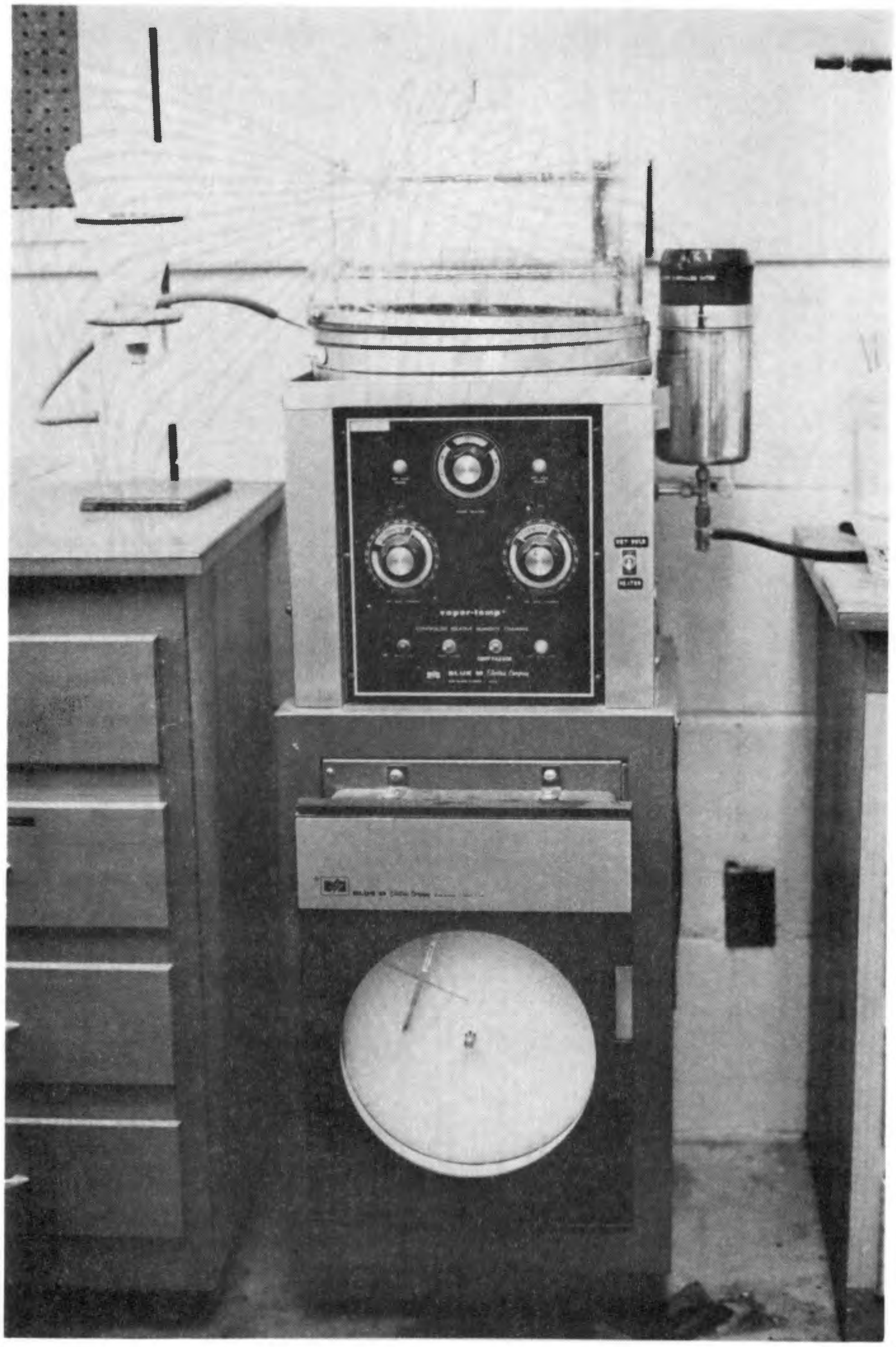


Figure 3.27. Controlled Temperature and Humidity Chamber

Procedure

The discussion of procedures utilized during this research study is presented in four parts: soil chemistry tests, engineering tests, chemical treatment, and erodibility testing. The engineering and soil chemistry procedures utilized were accepted standardized testing techniques, modified where necessary to use available equipment. All the samples were obtained in a disturbed state and upon arrival were oven dried at 110°C in a gravity oven. After drying, all were ground to pass a USBS No. 40 sieve before storage. The exceptions to this are Samples 208 and 209, in which the engineering properties applicable to this study were taken from data obtained by Petry (1).

Soil Chemistry Tests

The chemical properties desired were pH and percentage of soluble salts. The pH test was accomplished with a one to five suspension of soil in distilled deionized water. The pH of all the soils was determined prior to any chemical treatment. In the chemical treatment phase, the pH of all the soil samples was obtained after predetermined percentages of lime were added.

Analyses to determine the quantities of calcium, magnesium potassium and sodium in the pore water of each sample, plus their sodium absorption ratio (SAR) and exchangeable sodium percentage (ESP) were conducted by the Soil and Water Service Laboratory of the Agronomy Department at Oklahoma State University.

Engineering Tests

Engineering properties of all the samples used were obtained for two reasons: (1) to obtain background data on the samples and (2) to aid in correlation of the data obtained in this study to that obtained by previous research studies. Tests performed included Atterberg limits, grain size distribution, shrinkage properties, and Standard and Modified Proctor compaction.

Liquid and plastic limits were determined using ASTM D423-61T and D425-59 recommended procedures. The shrinkage properties were found utilizing the procedure and equipment of the Texas Bar Method for determining linear and volumetric shrinkage (Texas Highway Department Method Tex-107-E).

Grain size distribution was accomplished by the hydrometer method (ASTM D422-61T). An ASTM 151H hydrometer was used. A control cylinder was used to correct for temperature in the hydrometer calibration, change in specific gravity of the liquid by addition of dispersing agent, and the height of miniscus rise on the hydrometer stem.

Compaction tests utilizing both Standard and Modified Proctor efforts were run using Harvard miniature size molds, mold collars and bases. Compaction was accomplished with the OSU soil mechanics laboratory miniature sleeved hammers and the OSU soil mechanics laboratory miniature compaction device. Maximum dry densities and optimum water contents were established for all the samples.

Chemical Treatment

The procedure followed for chemically treating the soil during this research study is presented in detail in Appendix A. The procedure utilized in Appendix A was followed very closely, thereby insuring the same treatment for each of the samples tested. Three chemical treatments were evaluated: lime, sodium chloride, and aluminum sulfate.

Lime - The lime utilized in all phases of this research study was high-calcium Hydrated Marblite Lime Ca $(OH)_2$, provided by the St. Clair Lime Co., Sallisaw, Oklahoma. The amount of sample treated with each lime percentage was 500g, enough to compact four test cylinders. The assurance of sufficient moisture for complete chemical reaction was accomplished by mixing the sample at 2% wet of optimum moisture content. The rapid cure procedure of Drake and Haliburton (28) was used to simulate 28 day moist room cure, by curing the samples at 105°F at 98 to 100% humidity for 30 hours in the controlled temperature and humidity chamber shown in Figure 3.27.

Sodium Chloride - The treatment of soil samples with a sodium salt was confined to sample treatment with sodium chloride. The sodium chloride used was "Baker Analyzed" reagent grade, produced by the J. T. Baker Chemical Co., Phillipsburg, New Jersey. To insure a chance for complete chemical reaction, the salt was mixed with the sample at optimum water content and allowed to cure for 24 hr prior to compaction.

Two procedures for mixing the sodium chloride were used. In one procedure the sodium chloride was thoroughly mixed with the soil, while in the other procedure the sodium chloride was dissolved in the water and then mixed with the soil. The possible effect of these two procedures was determined from erodibility test results.

Aluminum Sulfate - The problems encountered with use of aluminum sulfate as a chemical treatment was the same as with lime and sodium chloride. The chemical reaction was facilitated by both the mixture of soil and water at optimum moisture content and the 24 hr delay before compaction. No additional curing was felt to be necessary; therefore, erodibility testing was accomplished immediately after compaction of the soil cylinders. The aluminum sulfate utilized in this research study was a laboratory grade aluminum sulfate, produced by the Fisher Scientific Co., Fair Lawn, New Jersey.

Erodibility Testing

The procedure followed during this research for erodibility testing is presented in detail in Appendix B. In order to measure erodibility by this procedure the dry weight of the soil in the cell was found before and after testing. The percent erosion was determined by comparing the loss of dry soil during testing to the original weight of dry soil.

$$\text{Percent Erosion} = \frac{\text{Initial Dry Weight} - \text{Ending Dry Weight}}{\text{Initial Dry Weight}} \times 100$$

CHAPTER IV

RESULTS AND DISCUSSION

This chapter discusses methods employed in correlation of data obtained in engineering and soil chemistry tests, relationships between physical erosion and chemical treatment, and correlation and evaluation of data collected in this study with data from previous research endeavors.

Engineering Properties

A general summary of the engineering properties determined for all samples is contained in Chapter III, Table 3.1. The following presentation was found useful for analysis of sample similarities and correlation of data from this research study with those obtained by Petry (1).

During initial preparation each sample was oven-dried, ground and sieved through a U.S. No. 40 sieve. In all cases the entire sample passed through this sieve. The results of the grain size analysis are shown in Table 4.1. The grain size properties of these samples indicate that all are fairly well-graded, with the exception of sample 207 which is uniformly graded. The percentages of sand were found to vary from 2% to 35% with an average of 13%.

Percentages of silt in the research samples were less variant than those of sand, varying from 42% to 66% with an average of 53%. The exception to this was Sample 207 which contained 91% silt. Variation in

TABLE 4.1

GRAIN SIZE PROPERTIES OF RESEARCH SAMPLES

	Percent Passing						Percent		
Sample	No. 40	No. 200	0.02mm	0.005mm	0.002mm	0.001mm	Sand	Silt	Clay
201	100	80	47	33	23	18	35	42	23
202	100	92	79	51	33	22	10	57	33
203	100	93	81	54	33	18	8	59	33
204	100	87	83	73	30	4	13	57	30
205	100	99	93	75	55	43	2	43	55
206	100	74	47	30	19	10	32	49	19
207	100	99	93	65	7	1	2	91	7
208	100	86	69	51	36	23	14	50	36
209	100	97	70	41	31	25	3	66	31

the percent of clay was found to be similar to those of the other fractions. After the data concerning Sample 207 were removed, the values ranged from 23% to 55% with an average value of 32% clay sized particles.

Among the most accepted indicators of the physical behavior of soils are the Atterberg Limits. Those determined for all research soils included the liquid limit and plastic limit, plus data on amount of linear shrinkage and extent of volumetric shrinkage. Pertinent data derived from this testing are shown in Table 4.2.

Most of the samples tested had properties representative of clay soils with low plasticity. The exceptions to this were Roger Mills Gray Clay, Sample 205 and Sample 207. Both Roger Mills Gray Clay and Sample 205 were clay soils with high plasticity. It should be noted that even though Sample 207 is classified as a clay soil of high plasticity, it contains 91% silt sized particles. The clay like behavior of the sample is believed to be caused by the relatively large silt fraction, 60%, between 0.005 mm and 0.002 mm sizes. The mineralogical make-up, although not determined in this research study, is also believed to be a factor.

The volumetric shrinkage results obtained indicate that all samples tested possess significant propensity to shrink when dried from near their liquid limit. In general, it was determined that the amount of volumetric shrinkage was directly related to the liquid limits of these samples. On the other hand, this property was not found to be directly related to the plasticity index, which is indicative of the moisture loss during shrinkage.

The remaining engineering property determined was the Standard and Modified Proctor compaction curves. The information gained from the compaction curves used in this research was the maximum dry densities and

TABLE 4.2

PROPERTIES OF SAMPLES DERIVED FROM ATTERBERG LIMITS DATA

Sample Number	201	202	203	204	205	206	207	208	209
Liquid Limit	43	46	48	60	107	34	61	47	45
Plastic Index	25	25	28	41	77	16	34	31	27
Volumetric Shrinkage	30	43	39	43	51	25	39	46	37
Classification	CL	CL	CL	CH	CH	CL	CH	CL	CL

the corresponding optimum moisture contents. The Standard Proctor or maximum dry densities ranged from 84.9 pounds per cubic feet and 28.0 percent water content to 113.8 pounds per cubic feet at 12.6 percent water content. The Modified Proctor maximum dry densities ranged from 99.4 pounds per cubic feet at 19.0 percent water content to 128.3 pounds per cubic feet at 8.6 percent water content. The reason for determination of the maximum proctor densities and corresponding water contents was twofold: 1) samples tested at these densities permitted correlation of this research data with that of Petry, and 2) these known densities and water contents made possible quality control of the samples being tested. The maximum dry densities from the Standard and Modified Compaction curves and the associated water content is shown in Table 4.3.

Soil Chemistry Properties

Soil chemistry characteristics determined for all tested samples were those needed during correlation of erosion testing results with other proposed methods of identification. The soil chemistry properties determined were the analysis for soluble salts. These properties are available for comparison and correlation in Table 4.4.

ESP (clay), which is the ESP divided by the percent clay, is believed by Petry (1) to be superior to the total ESP because it represents chemical environment surrounding clay particles in the soil mass. The SAR and thereby the ESP was determined by comparing the sodium concentration to the square root of the average of calcium and magnesium concentrations. These properties do not directly relate to the percent sodium in the solution-extract. Since the percent clay in each sample was utilized for finding the ESP clay, this property does not relate to the

TABLE 4.3

COMPACTION CHARACTERISTICS OF RESEARCH SAMPLES

Sample No.	201	202	203	204	205	206	207	208	209
STANDARD PROCTOR COMPACTION									
Max. Dry Density PCF	113.8	107.6	107.2	95.8	84.9	106.3	90.5	106.5	103.7
Optimum Water Content %	12.6	13.5	13.7	20.5	28.0	17.5	25.0	16.9	19.0
MODIFIED PROCTOR COMPACTION									
Max. Dry Density PCF	128.3	121.4	120.5	110.2	99.4	117.9	105.6	115.6	114.9
Optimum Water Content %	8.6	10.0	10.3	16.9	19.0	13.5	19.0	15.0	15.4

TABLE 4.4

SELECTED SOIL CHEMISTRY PROPERTIES OF RESEARCH SOILS

Sample No.	MEQ/L SODIUM	MEQ/L TOTAL CATIONS	% SODIUM	SAR	ESP	ESP (CLAY)
201	1.2	9.8	12.2	0.6	0.0	0.0
202	19.8	20.9	94.7	29.5	29.7	90.0
203	14.2	16.4	85.2	13.1	15.3	46.4
204	8.2	23.2	35.4	3.1	3.2	10.7
205	0.9	1.8	50.0	2.0	1.7	3.1
206	0.7	5.6	12.5	0.5	0.0	0.0
207	2.0	44.1	4.5	0.4	0.0	0.0
208	4.3	21.5	20.0	1.5	0.8	2.2
209	19.2	20.9	91.9	21.7	23.5	73.5

other chemical characteristics. The variation of soil chemistry properties of the test samples demonstrated a variety of dispersive clay erosion behavior expected during physical erosion testing.

Physical Erosion Test Results

The soil samples in this research study were tested by utilizing chemical treatment to determine the effect on erosion. The chemicals used were lime, sodium chloride and aluminum sulfate, in varying percentages of treatment. These chemicals were chosen to provide exchangable cations from the calcium, sodium and aluminum groups. It was believed that the dispersive clay could be flocculated and made non-erosive by addition of the chemicals.

Without Chemical Treatment

Each sample was tested for internal erodibility a total of 16 times; eight times at Standard Proctor density and eight times at Modified Proctor density. Table 4.5 represents the average results from this testing. The results obtained from samples compacted at Standard Proctor density and optimum water content were used as a control from which effectiveness of chemical treatment could be evaluated.

A comparison of test results obtained from samples compacted at both Standard and Modified Compaction efforts and corresponding water contents were approximately the same, which is in agreement with the results obtained by Petry (1). The explanation of this is based on a combination of two factors: 1) the increase in dry density as a result in increased compactive effort leads to a decrease in susceptibility to internal erosion, 2) lower water contents associated with optimum compaction under

TABLE 4.5

AVERAGE PHYSICAL EROSION TEST RESULTS ON CHEMICAL TREATMENT

Sample Number	201	202	203	204	205	206	207	208	209
Percent Erosion at SPC	73.0	57.5	51.4	4.9	6.8	9.3	0.9	22.4	59.2
Percent Erosion at MPC	68.0	48.0	55.9	7.3	6.5	2.0	2.2	14.4	28.3

increased compactive effort tend to increase erodibility. When both of these influences on the behavior of a soil mass occur simultaneously the result was no general change in average percent erosion.

Of the nine samples tested, Samples 204 and 208 were chosen to be used as control soils because they were known to be non-dispersive. The reason for use of control soils was twofold. The primary reason for their use was to determine the possible negative effect of the chemical treatment used, and secondly, to provide additional test data for correlation of results. Based upon results obtained from testing, Samples 205, 206 and 207 which were furnished by the Army Corps of Engineers, Tulsa Office, were found to be nonerosive. Therefore these samples were also used as control soils. The remaining four soil samples were selected because of their extensive field erosion.

The total loss or percent erosion was used as an indicator of field behavior because it could be measured quantitatively. During testing, the progress of sample breakup and internal erosion was visually monitored as a qualitative indicator of field behavior. Photographs shown in Figures 4.1 through 4.5 illustrate the visual monitoring utilized during testing. Sample 209 was chosen to be used in the above Figures because of its known dispersive erodibility in the field.

Although visual monitoring was necessary, the most precise indicator of the progress of internal erosion outside of the percent erosion was found to be the visual inspection of the soil cylinder mass after each cell was dismanteled. Figure 4.6 shows the necessity for additional inspection after dismanteling the cell in order to gain a more accurate knowledge of the true erosion.

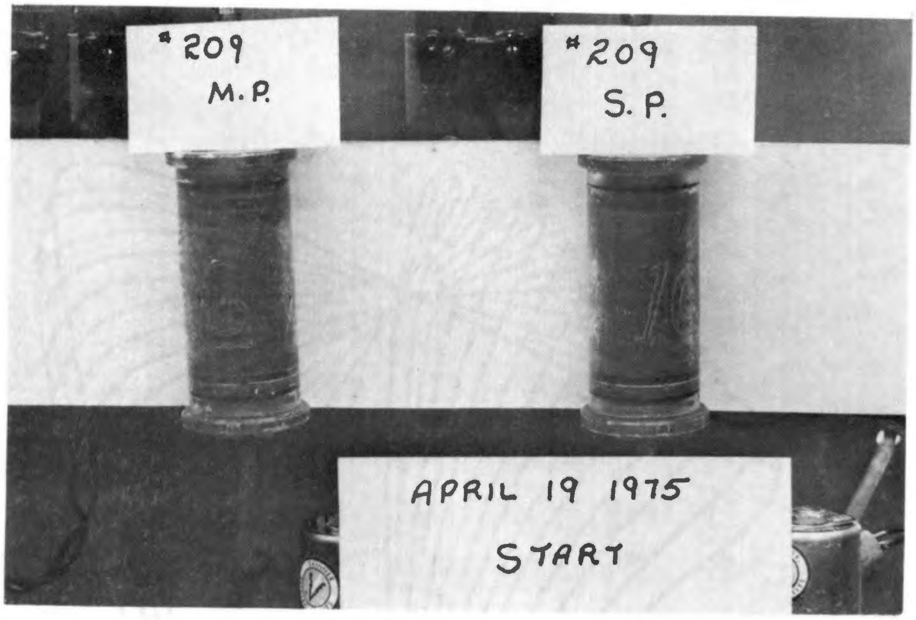


Figure 4.1. Typical Erosion Test Observations at Start of Testing for Sample 209

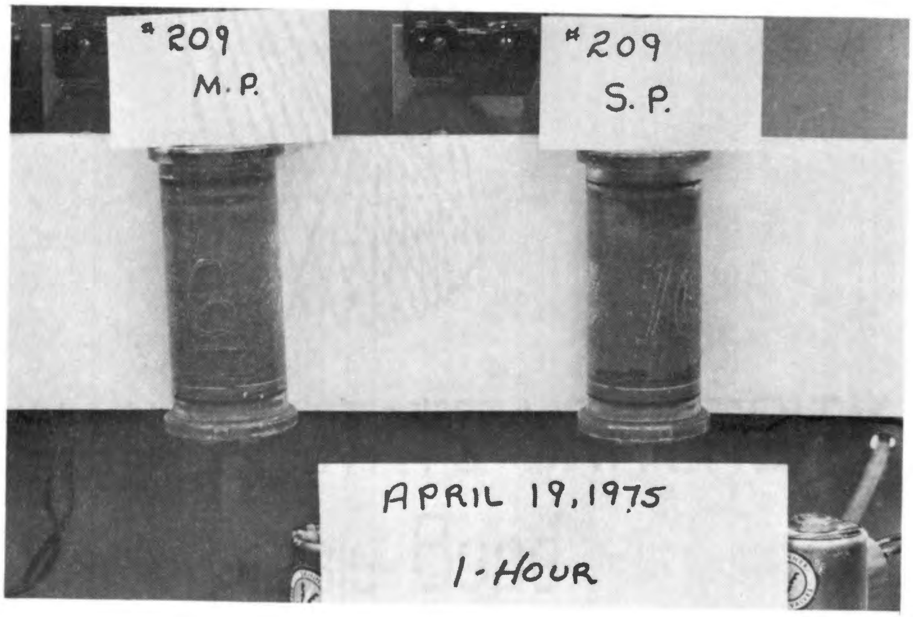


Figure 4.2. Typical Observed Erosion After 1 Hour of Testing for Sample 209

Figure 4.3. Typical Observed Erosion After 2 Hours of Testing for Sample 209

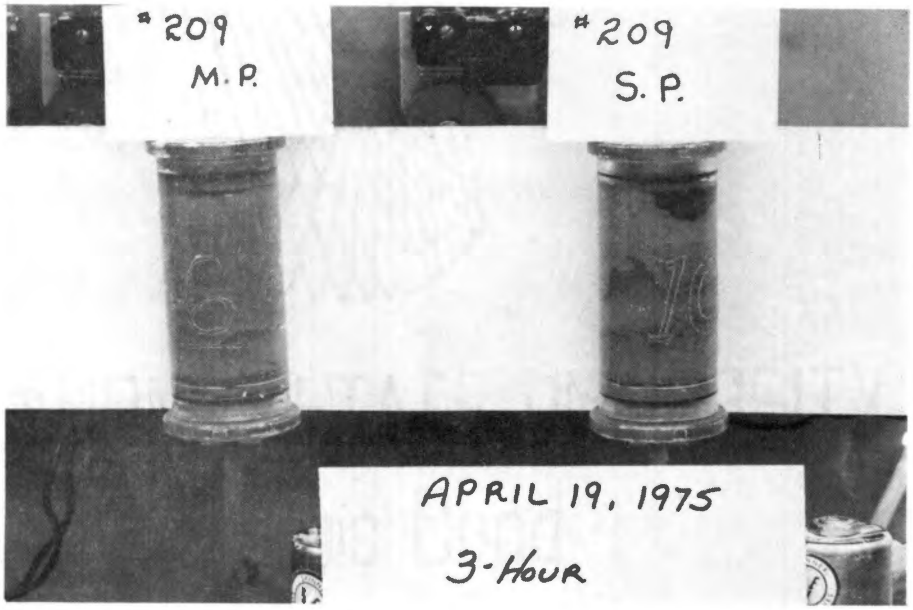


Figure 4.4. Typical Observed Erosion After 3 Hours of Testing for Sample 209

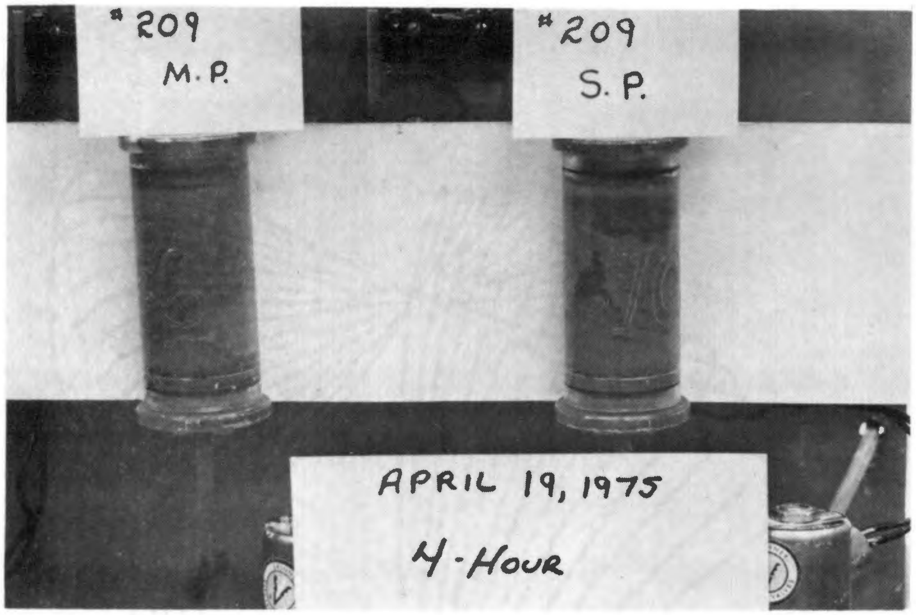


Figure 4.5. Typical Observed Erosion at Completion of Testing for Sample 209

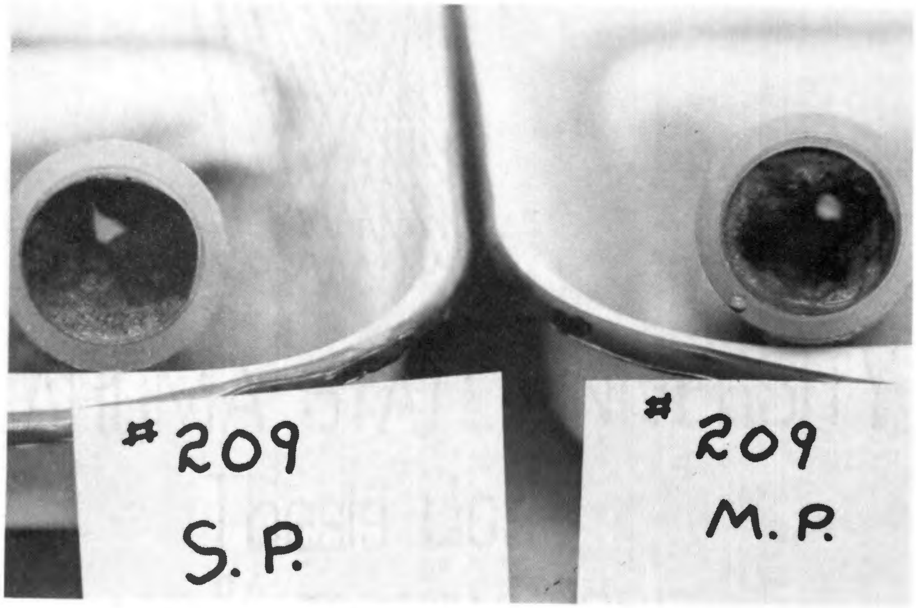


Figure 4.6. Examples of Internal Erosion Observed After Cell Dismantlement for Sample 209

The nonerosive soils tested exhibited only slight visual erosion during testing and after cell dismantlement. Soils which exhibited surface sheet erosion in the field, when tested appeared to erode in a different manner than those of dispersive clays. These soils could be visually detected by material slaking off the top of the cylinder rather than dispersing.

Lime Treatment

There are several reasons that lime was chosen as the representative from the calcium cation exchange group for a chemical treatment in this research study. The primary reason is that it has been used with limited success for the control of dispersive erosion. Another reason for its use was due to its availability and nominal cost. The final reason that lime was chosen was because of the familiarity of its use and application among engineers.

The percentages of lime chosen for chemical treatment were 0.5, 1.0 and 1.5% by dry weight. These percentages of lime were chosen for two reasons: 1) at 1.5% all samples reached an average pH of 12 with the exception of Sample 209 which required 2% lime, and 2) to measure the effect on erosion with varying degrees of available calcium. Complete chemical reaction was ensured by mixing at 2% above optimum water content for the untreated sample 24 hours prior to compaction. The samples were compacted at Standard Proctor Density, after which they were placed in the constant humidity chamber for 30 hours to simulate 28 days moist room curing, as recommended by Drake and Haliburton (28).

An explanation for the effectiveness of lime as a chemical treatment for dispersive clay soils is based on several factors. One factor is the increase in Ca^{++} cations exchange with the increase in soil pH. This idea is supported by Hilt and Davidson (14) who have determined that at a pH of 12.4 all the cation exchange reactions have taken place. It is this researchers opinion that this hypothesis is valid based on results of physical erosion testing. A relationship was observed between increase in the soil pH with the addition of lime and decrease in physical erosion due to flocculation of the dispersive clay.

Another factor believed to be the cause of decrease in physical erosion with increase in lime treatment is the compression of the ionic atmosphere around the clay particles. It was believed that with increased lime treatment, a less dispersive clay structure exists. It should be noted that there exists pozzolanic reactions between the lime and clay particles causing an increase in strength. Although this reaction existed, it was not directly measured.

The physical effects of lime chemical treatment on soil were also noted in this research study. It was observed that increase lime treatment resulted in a decrease in plasticity of the clay. This reduction in plasticity resulted from the increase in friability and silty texture upon curing. Based on this discussion and the physical erosion test results, lime treatment is an adequate solution to the dispersive clay problem.

The results obtained from physical erosion testing of lime treated samples showed a substantial decrease in the percent erosion with increase in the percentage of lime. This variation is presented in Table 4.6. Although a decrease in erosion was found with increase in lime percentages, Samples 204 through 208 were not studied extensively because they were nonerosive.

TABLE 4.6

AVERAGE PHYSICAL EROSION TEST RESULTS
LIME TREATMENT

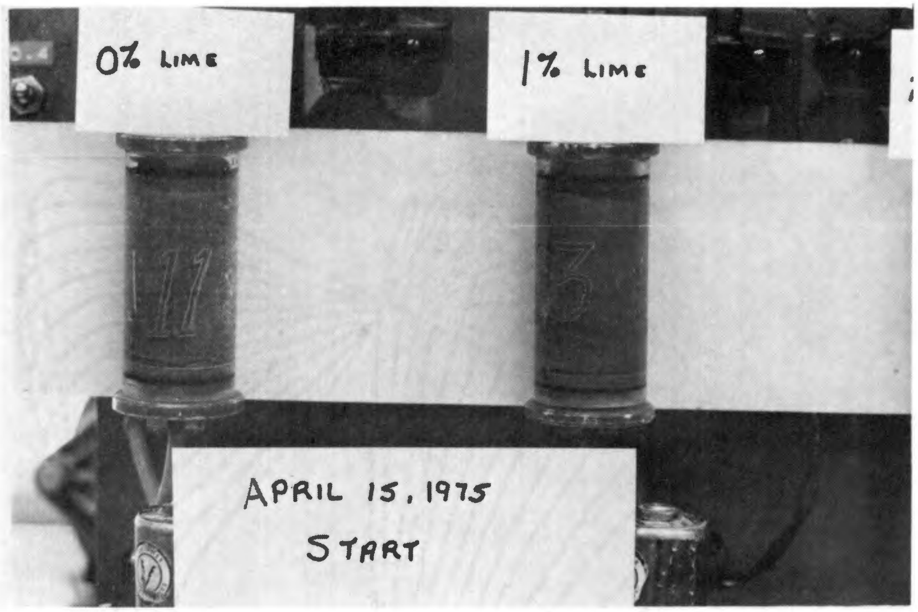
Sample Number	201	202	203	204	205	206	207	208	209
Percent Erosion at 0%	43.3	49.8	29.2	6.5	6.7	12.1	1.2	26.8	64.4
Percent Erosion at 0.5%	24.4	38.4	24.0	2.4	----	----	---	18.3	53.5
Percent Erosion at 1.0%	13.1	14.5	10.3	1.4	----	----	---	8.5	43.5
Percent Erosion at 1.5%	3.9	6.6	5.5	2.2	12.1	0.6	0.9	1.8	19.9

Figures 4.7 through 4.12 of Sample 202 are a typical illustration of the type of variation in erosion with the addition of lime. These photographs serve as a visual aid to illustrate the effect of lime on a dispersive soil. Figure 4.11 is an excellent illustration of the qualitative degree of erosion after physical erosion testing. It should be noted at this point that in comparing the photos in Figure 4.11 very little visual erosion took place at the higher percentages of lime. In order to further study the effects of lime treatment on the erodibility of soils, a plot of percent erosion versus chemical treatment for each soil tested is presented in Figures 4.13 through 4.21. It can be seen from these graphs that there exists a relationship between the percent lime treatment and percent physical erosion. Although this relationship is not linear there is a definite decrease in percent erosion with increase in percent lime treatment.

Sodium Chloride

Relative availability and economy was the primary reason sodium chloride was selected to represent the Na^{++} cation exchange group. Another factor involved in the decision to use sodium chloride was that it has had prior use as a soil stabilizer.

To determine the effectiveness of sodium chloride as a chemical treatment for potentially erosive soils, the amount of exchangeable cations in solution was varied. Percentages of sodium chloride chosen were 1, 2 and 3% by dry weight. Two methods were utilized in adding the sodium chloride to the soil sample. One method involved mixing the sodium chloride and the soil prior to the addition of water, whereas the other method involved dissolving the sodium chloride in water prior to mixing



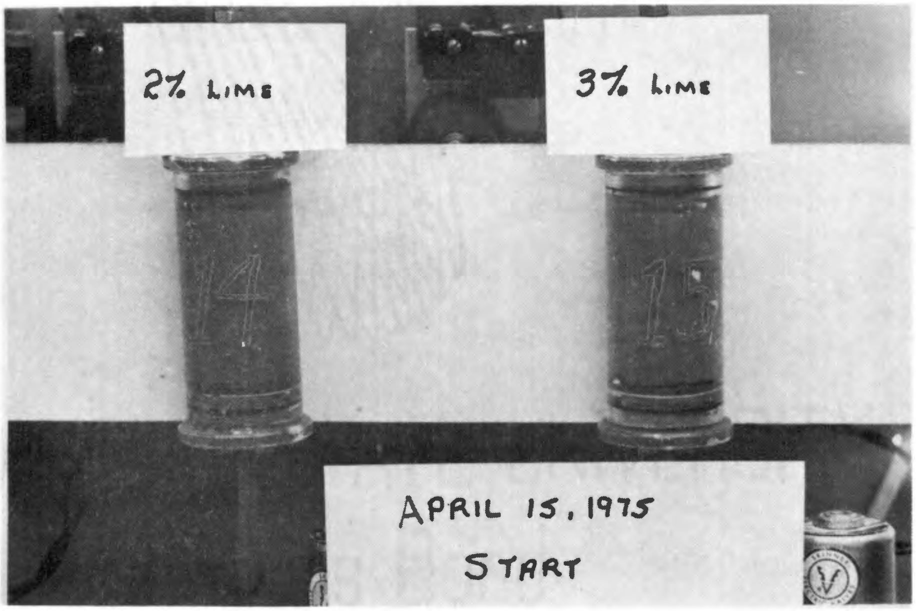
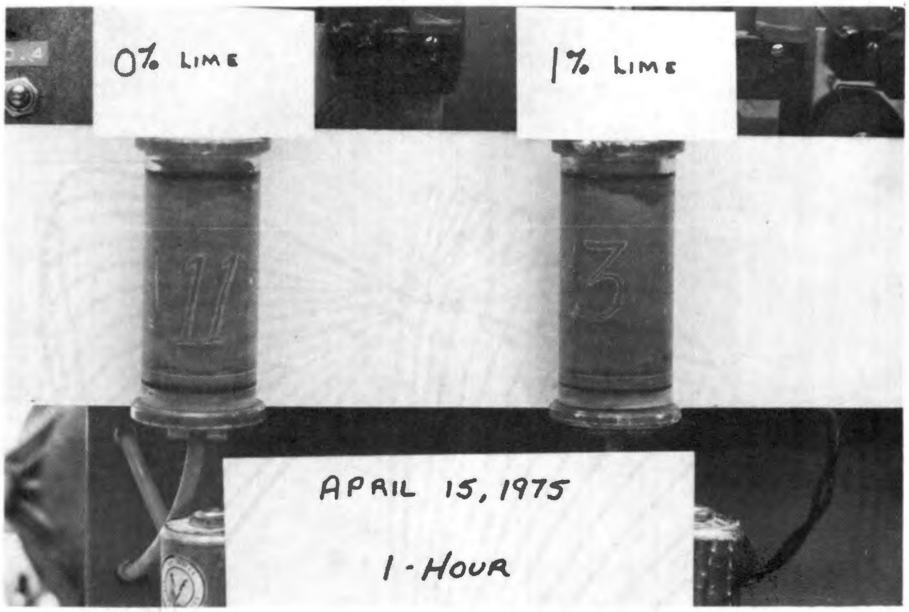


Figure 4.7. Typical Erosion Test Observations at Start of Testing for Sample 202 with Lime Treatment



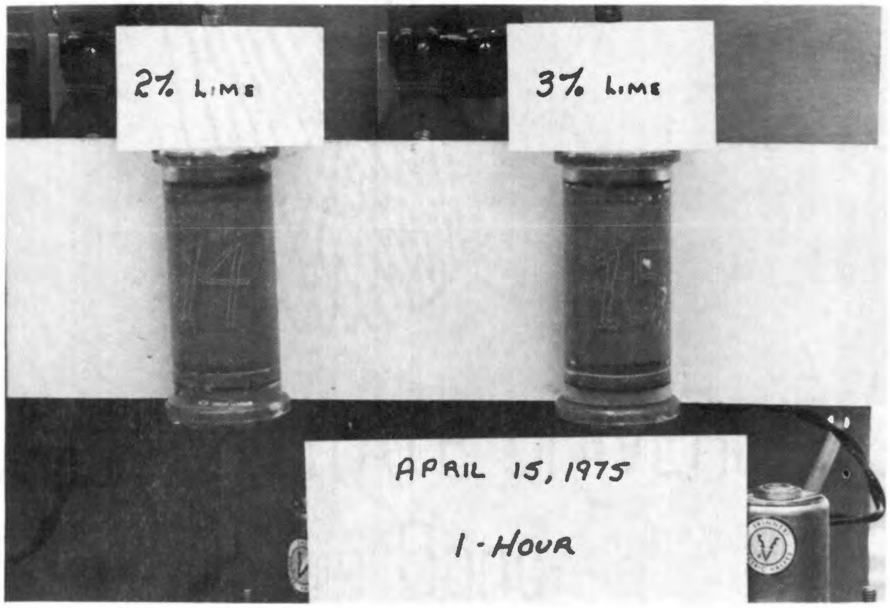
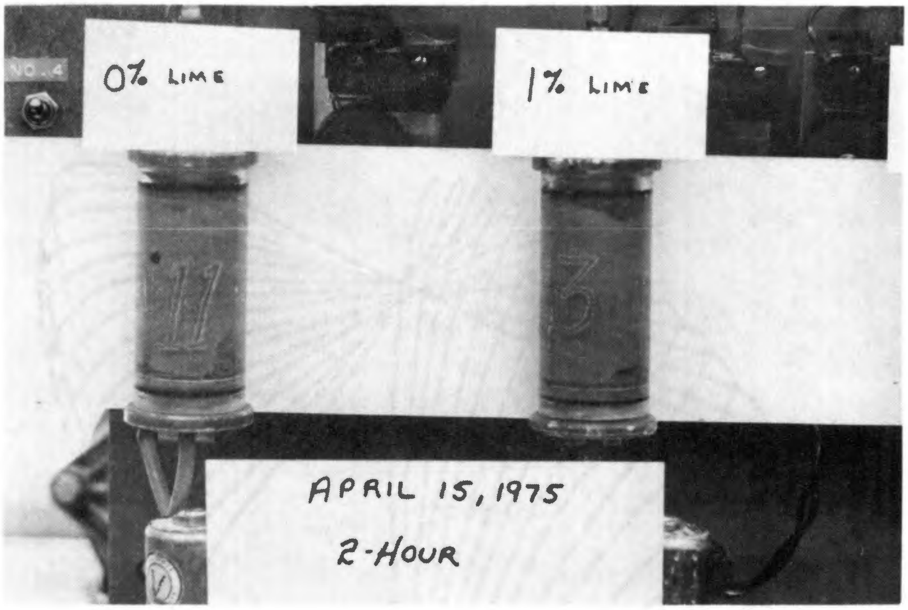


Figure 4.8. Typical Observed Erosion After 1 Hour of Testing for Sample 202 With Lime Treatment



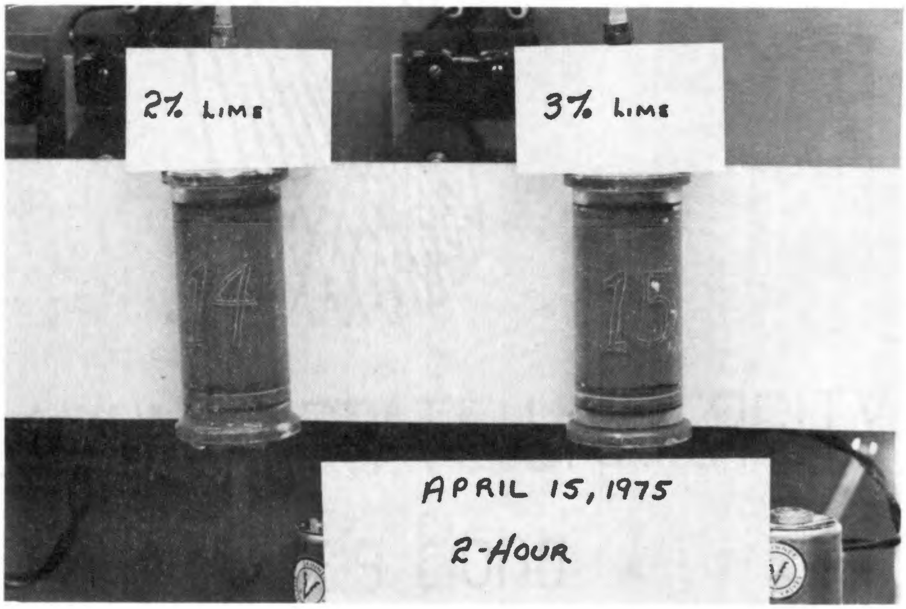


Figure 4.9. Typical Observed Erosion After 2 Hours of Testing for Sample 202 With Lime Treatment

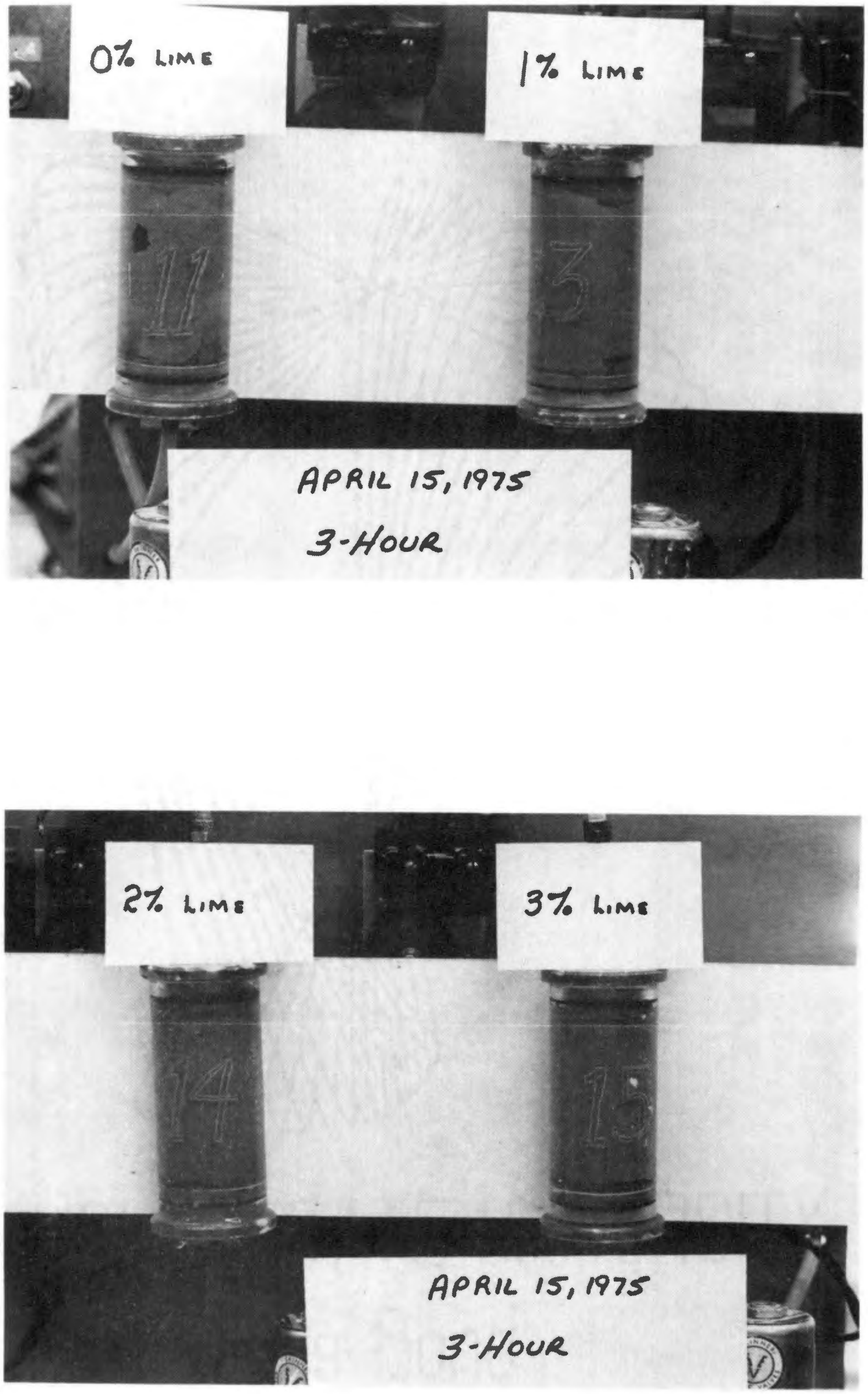


Figure 4.10. Typical Observed Erosion After 3 Hours of Testing for Sample 202 With Lime Treatment

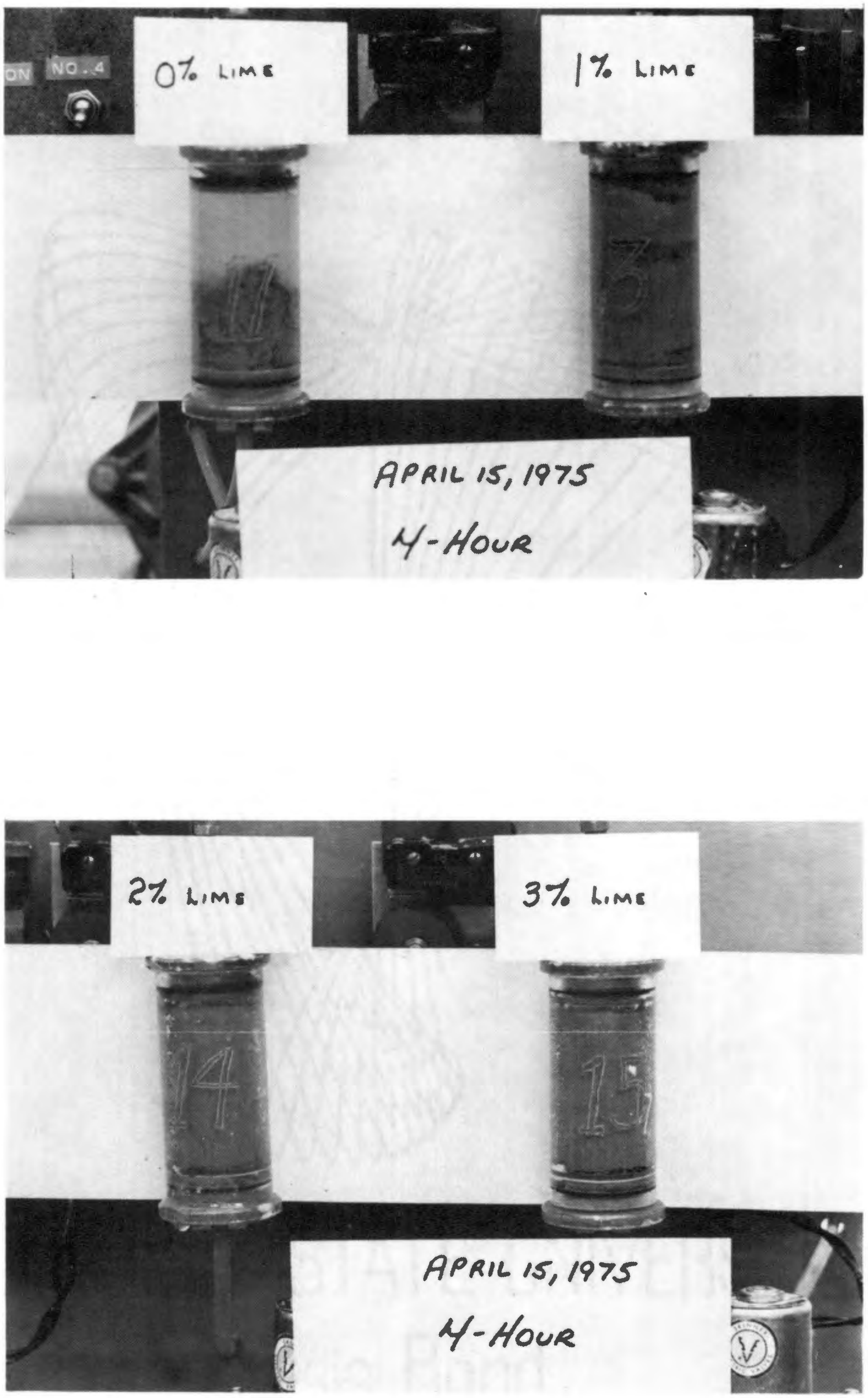


Figure 4.11. Typical Observed Erosion at Completion of Testing for Sample 202 With Lime Treatment

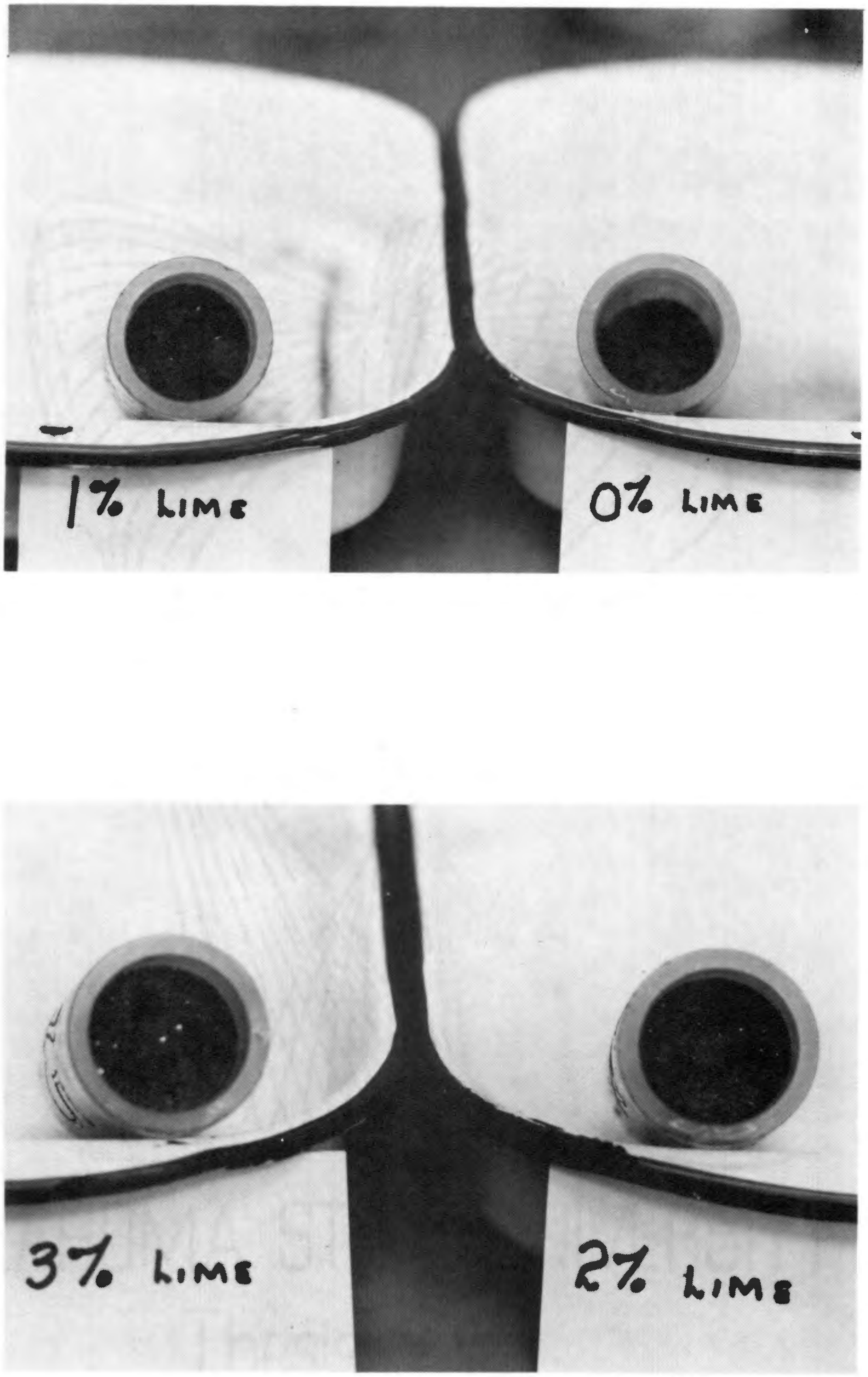


Figure 4.12. Examples of Internal Erosion Observed After Cell Dismantlement for Sample 202 with Lime Treatment

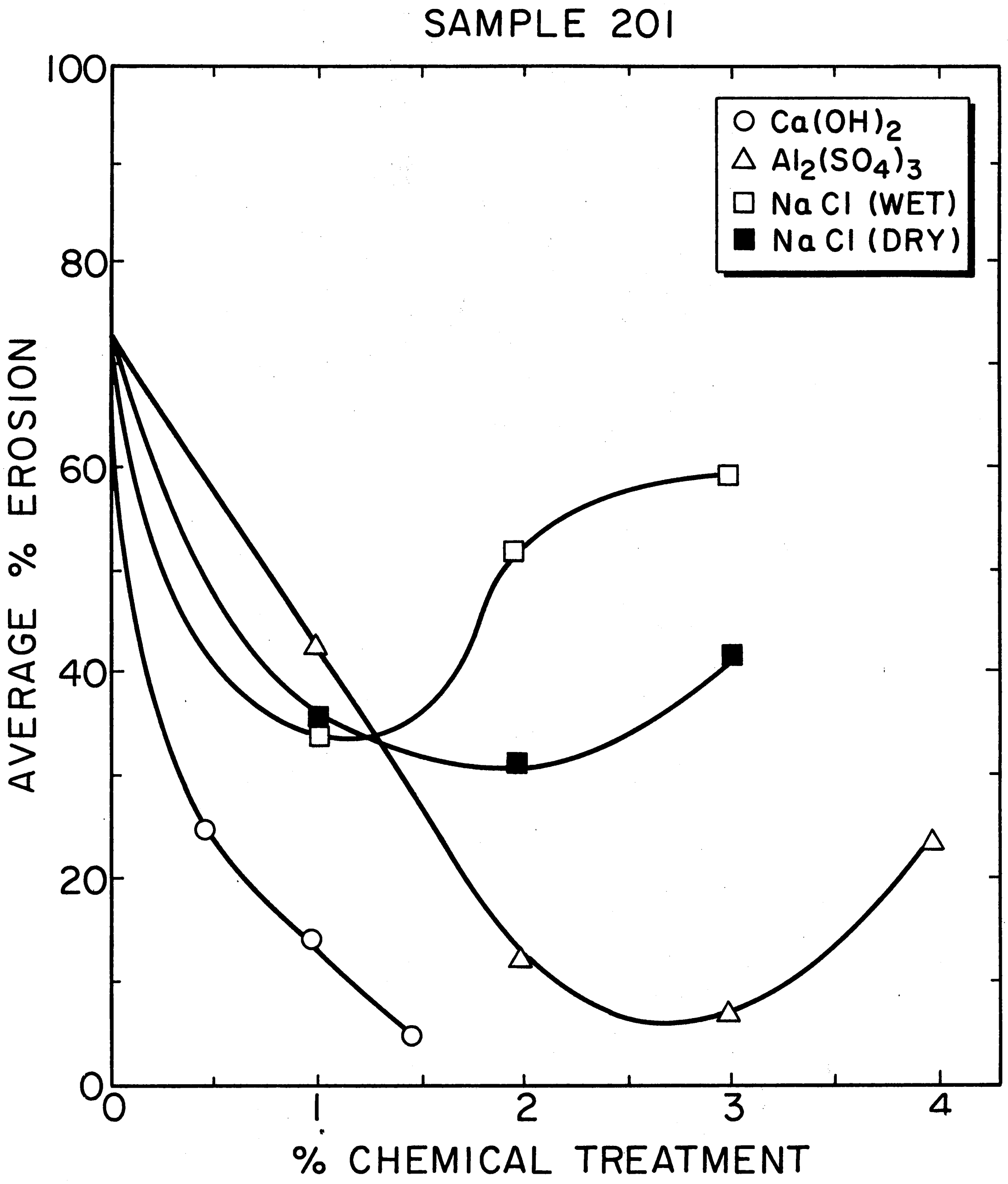


Figure 4.13. Percent Erosion Versus Percent Chemical Treatment for Sample 201

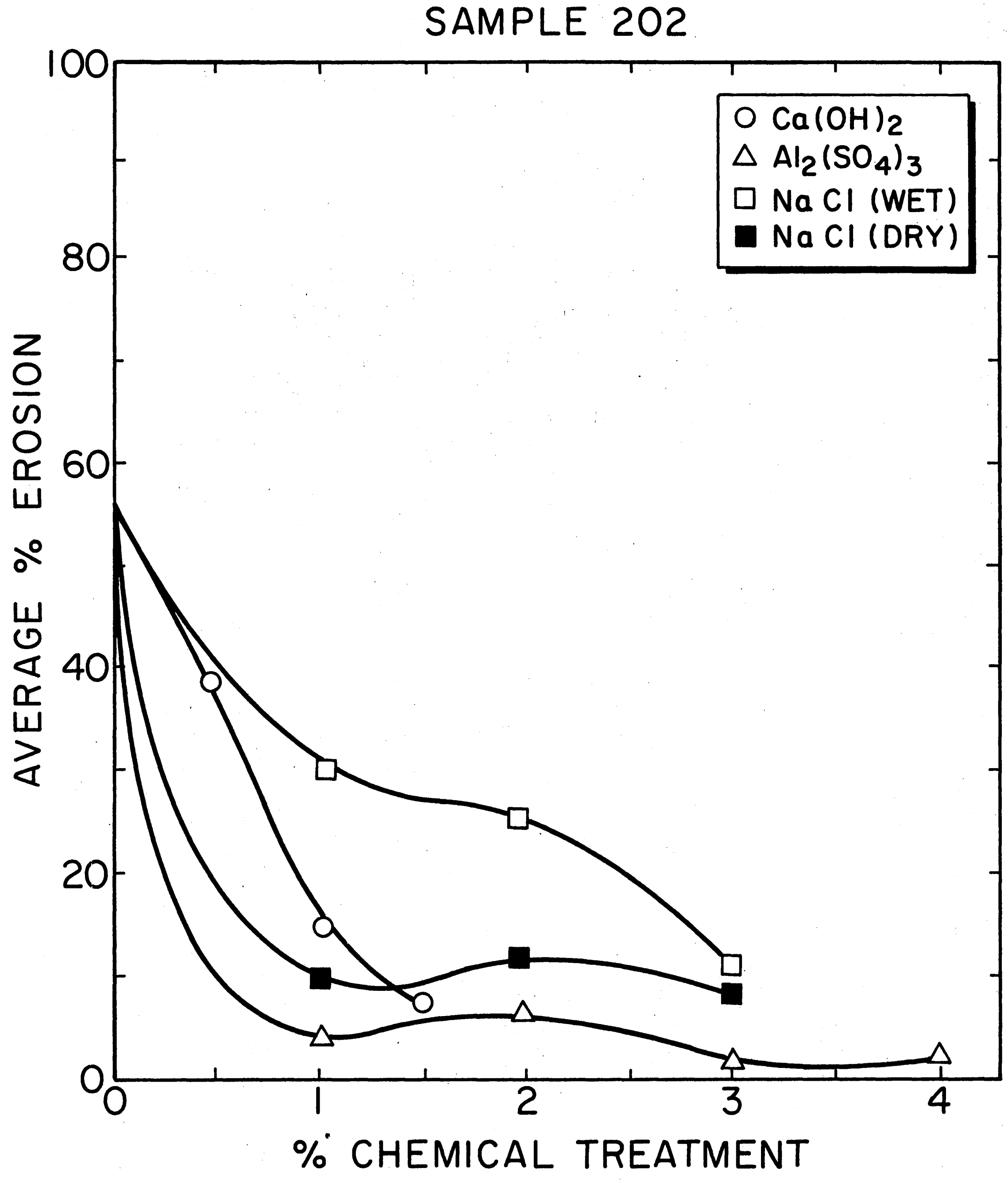


Figure 4.14. Percent Erosion Versus Percent Chemical Treatment for Sample 202

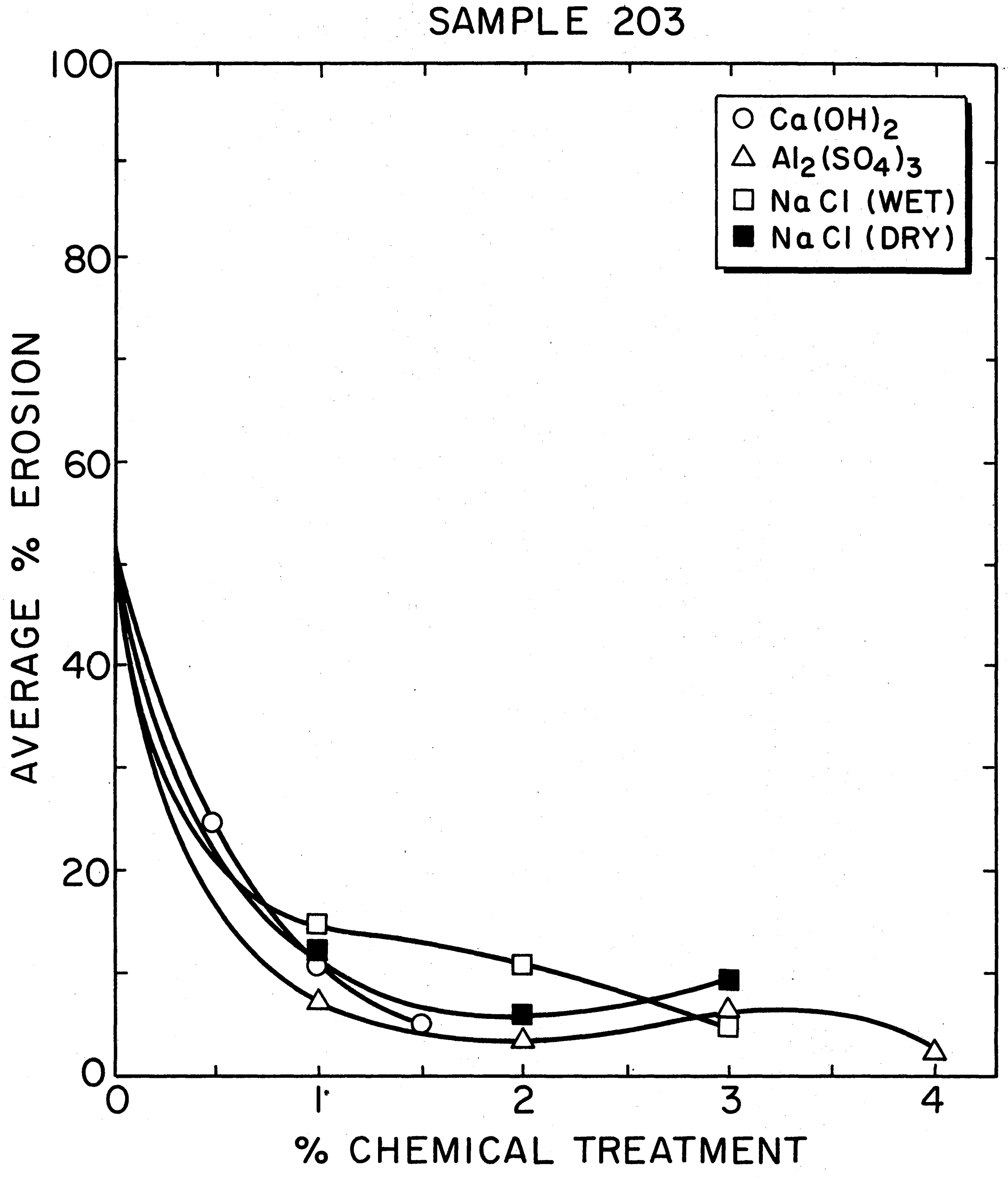


Figure 4.15. Percent Erosion Versus Percent Chemical Treatment for Sample 203

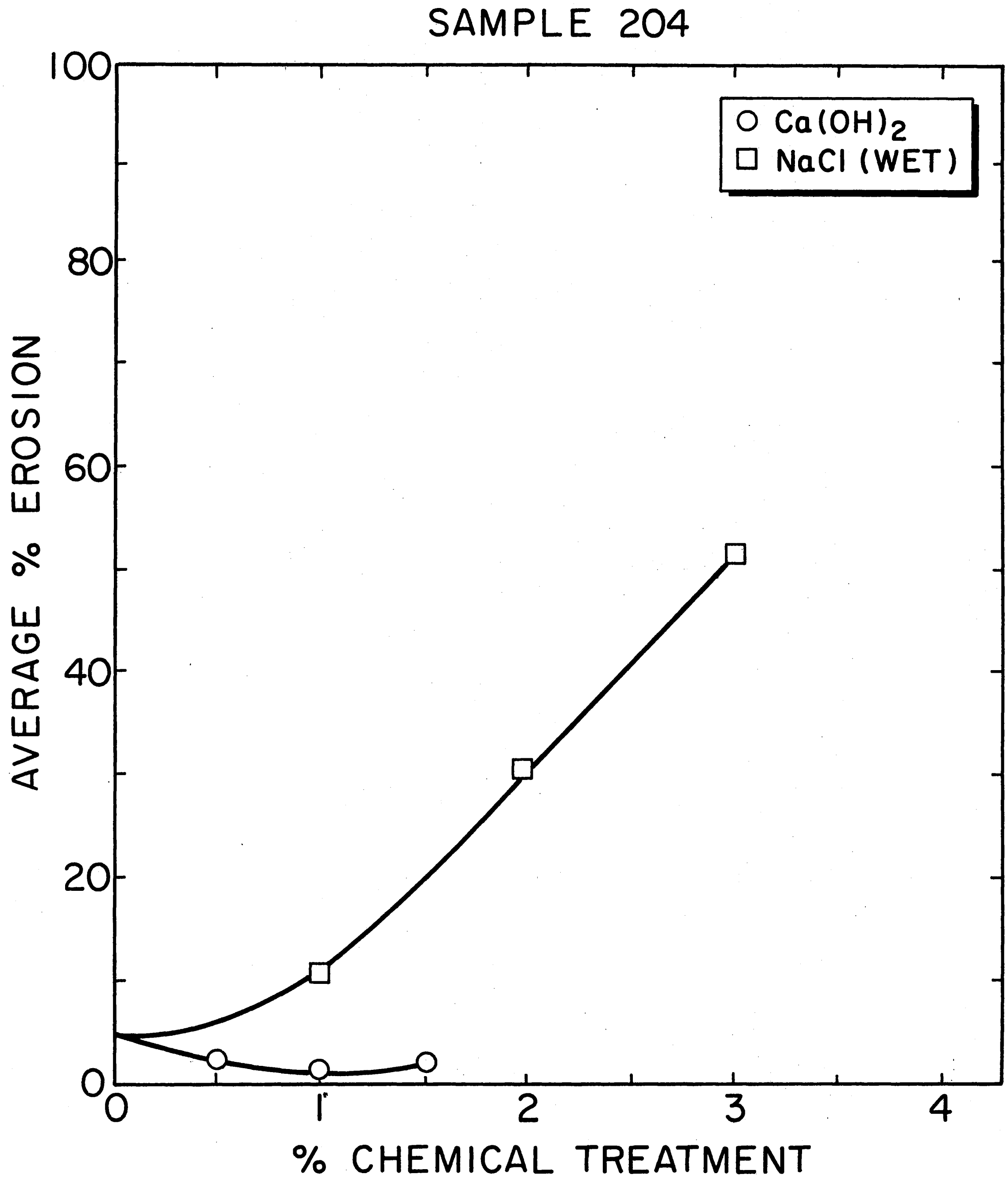


Figure 4.16. Percent Erosion Versus Percent Chemical Treatment for Sample 204

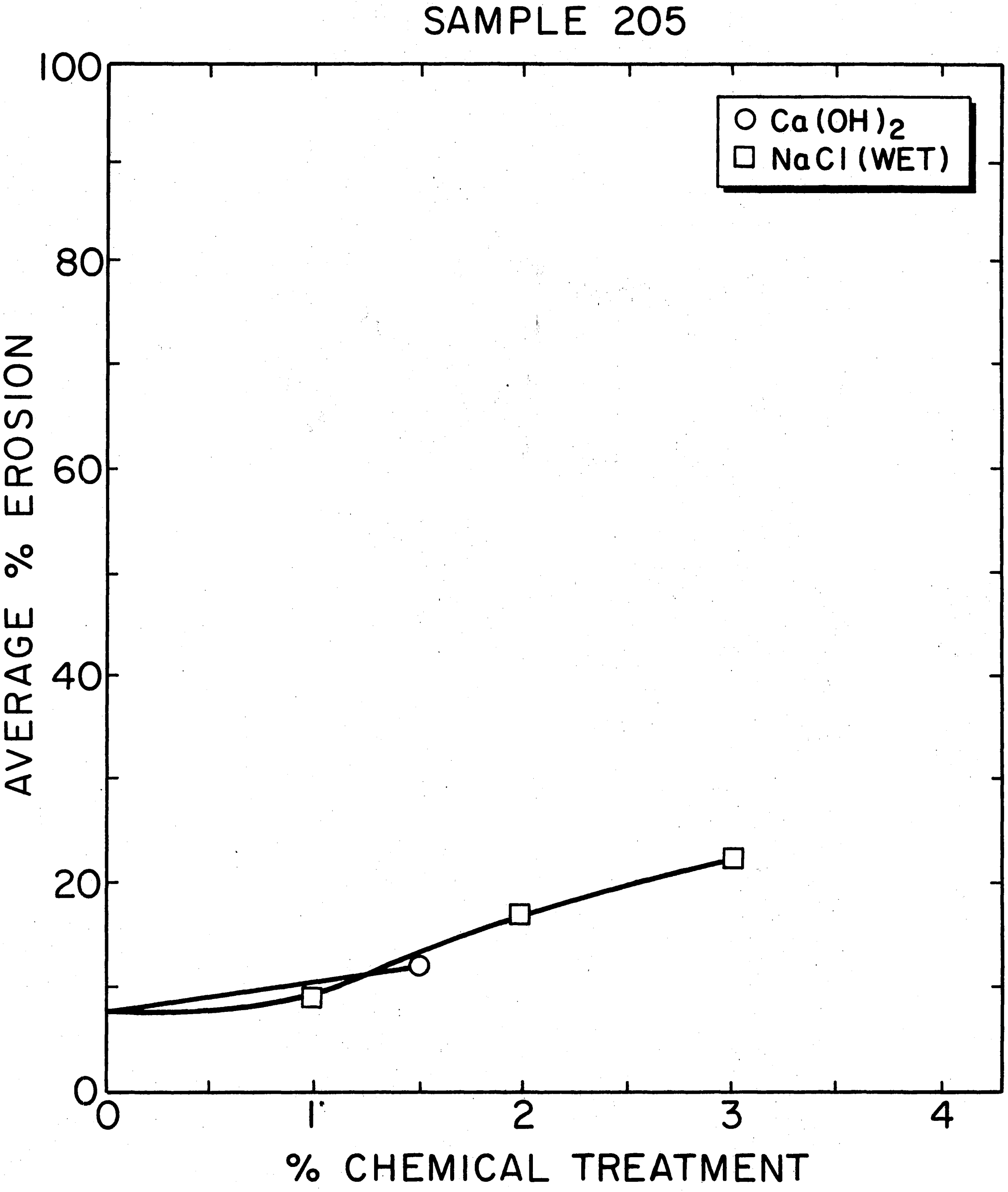


Figure 4.17. Percent Erosion Versus Percent Chemical Treatment for Sample 205

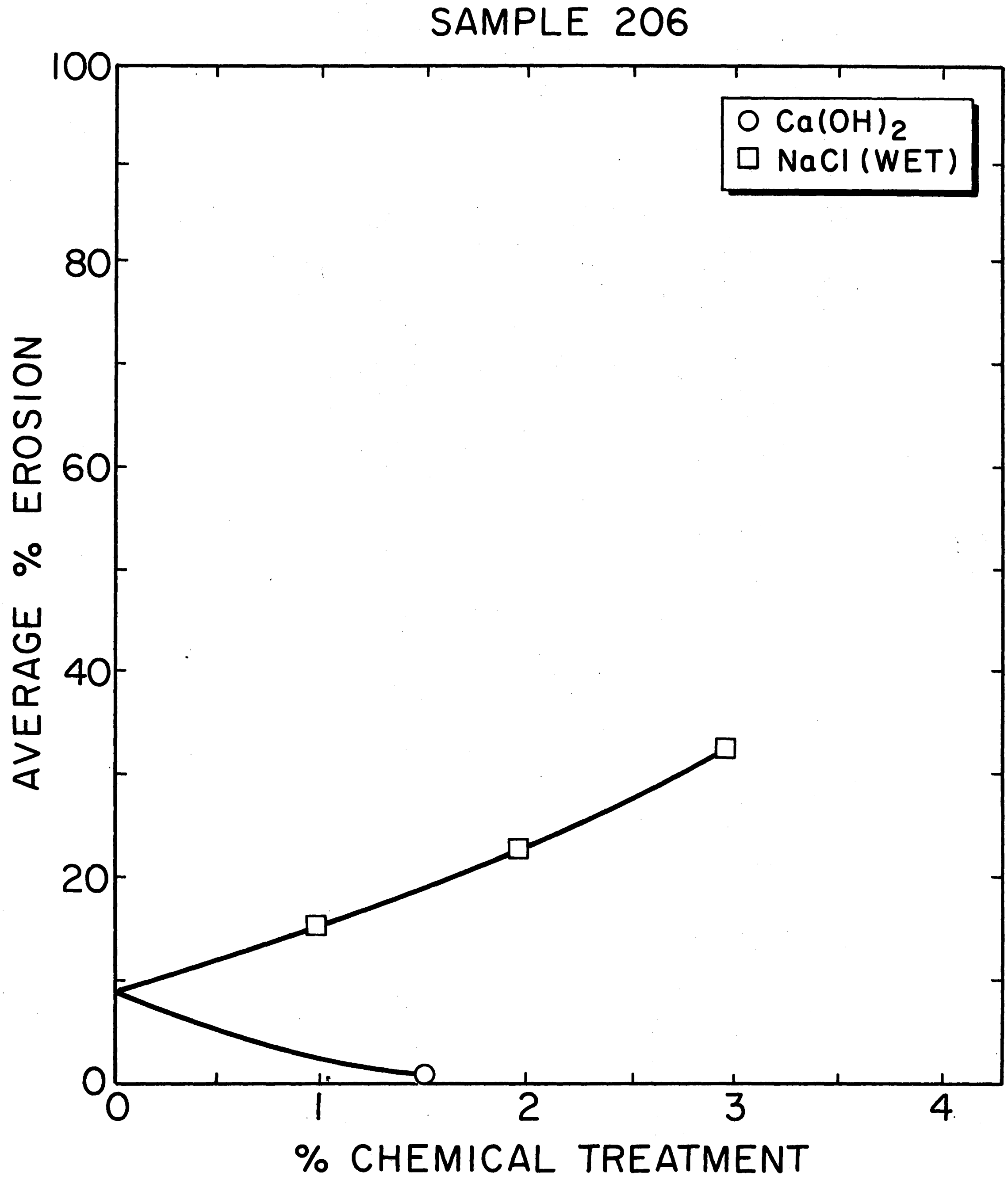


Figure 4.18. Percent Erosion Versus Percent Chemical Treatment for Sample 206

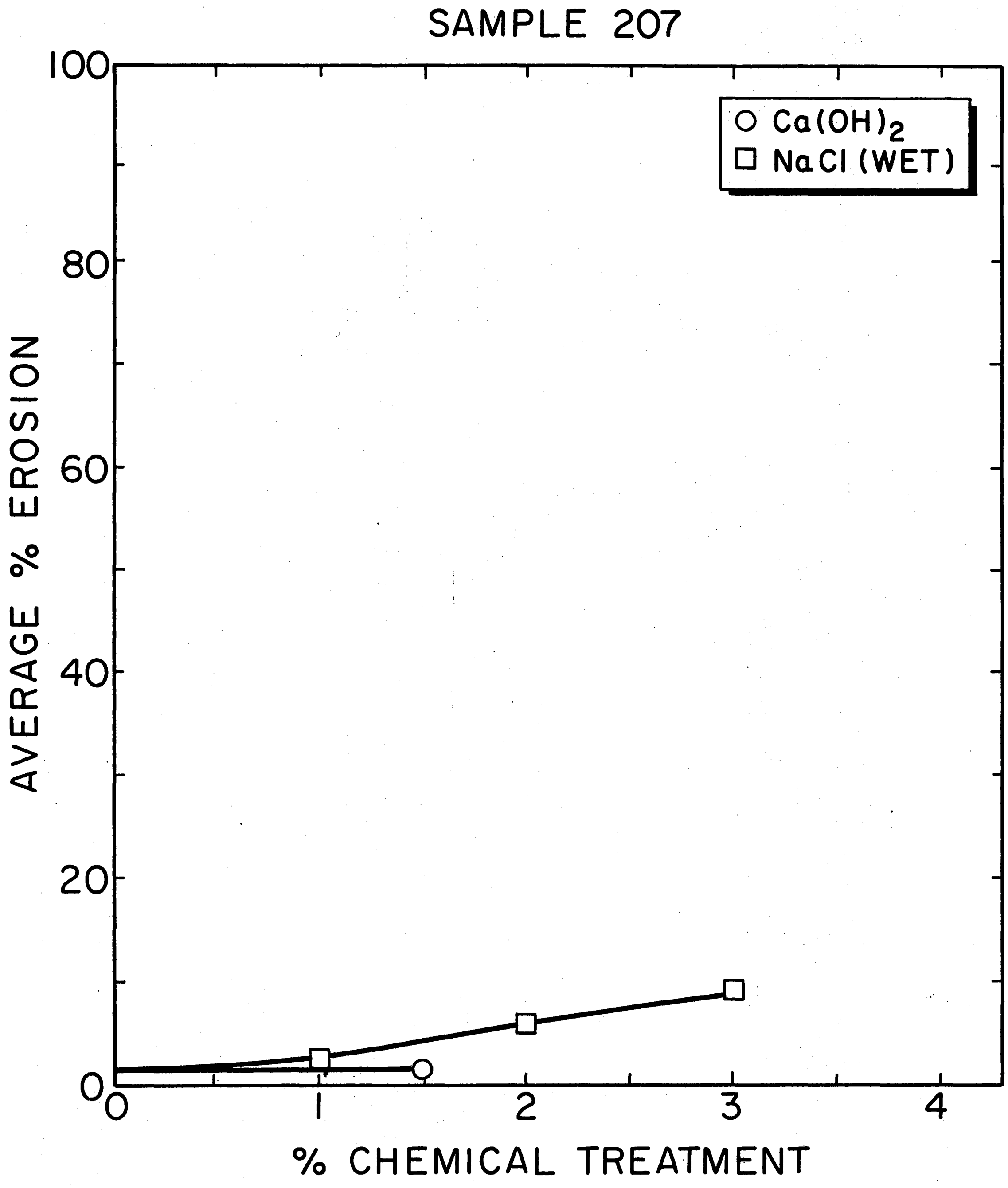


Figure 4.19. Percent Erosion Versus Percent Chemical Treatment for Sample 207

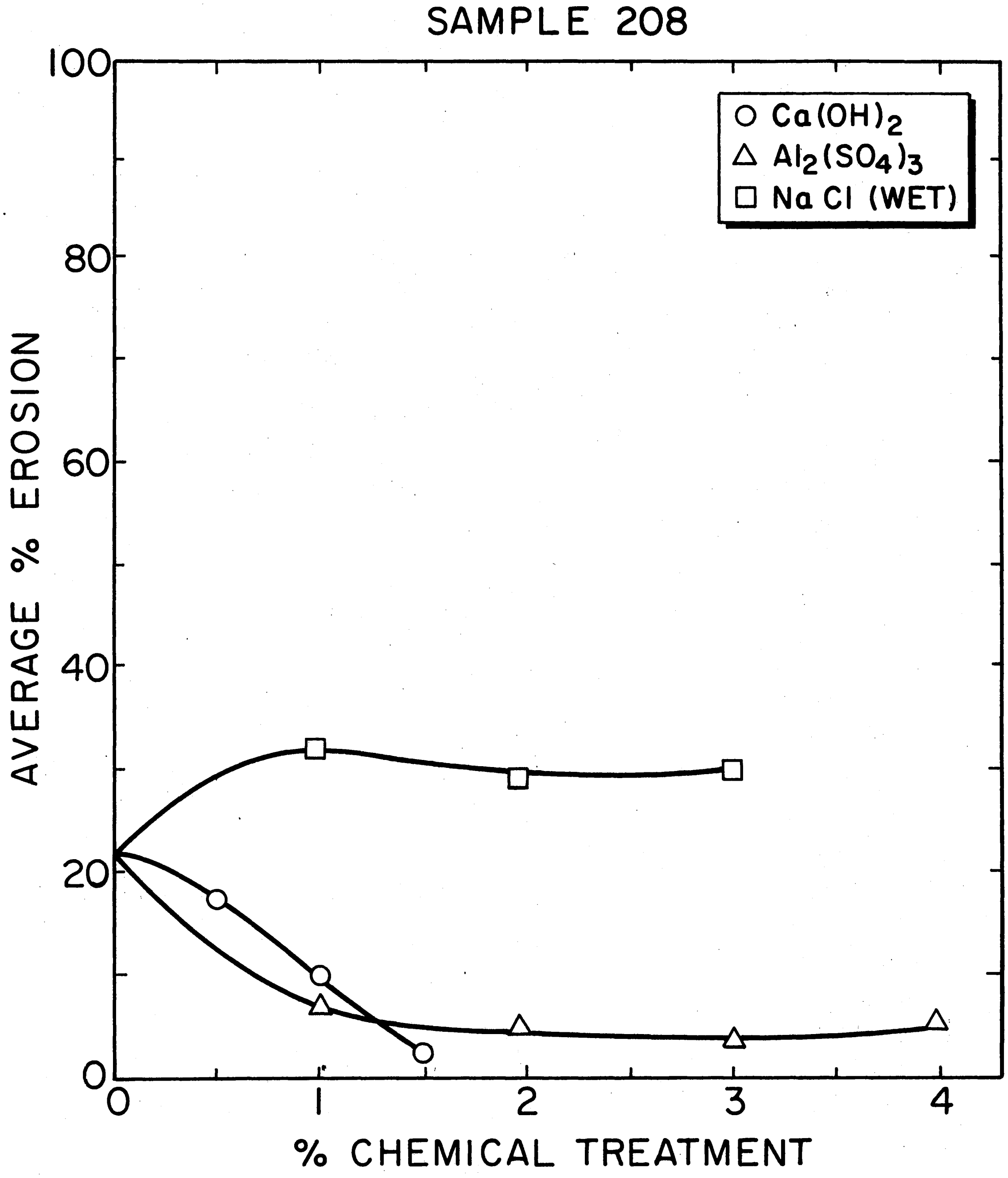


Figure 4.20. Percent Erosion Versus Percent Chemical Treatment for Sample 208

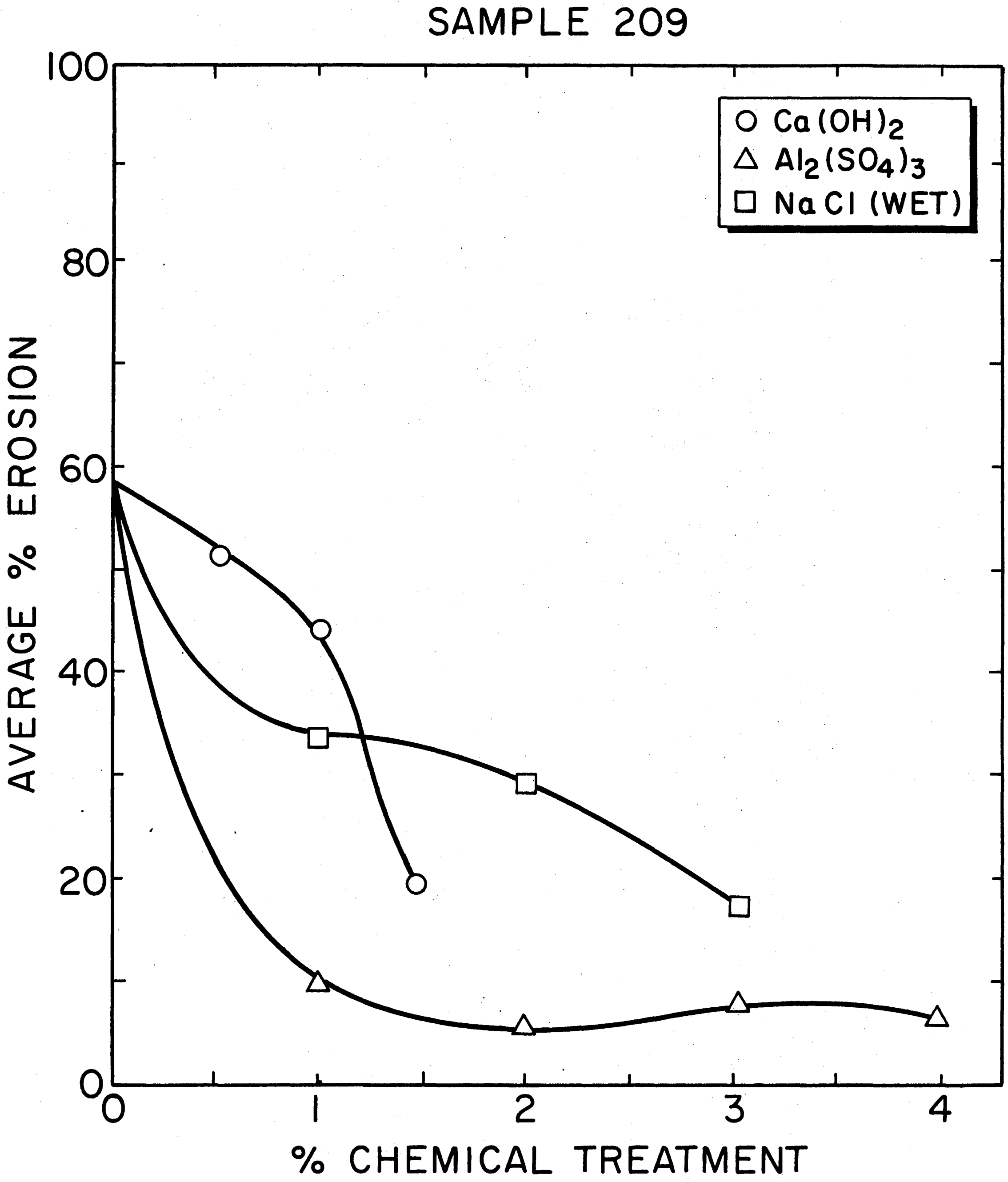


Figure 4.21. Percent Erosion Versus Percent Chemical Treatment for Sample 209

with dry soil. The reaction between the free sodium cations and the clay sized particles was further enhanced by mixing the soil and sodium salt at 2% wet of optimum water content, 24 hours prior to compaction.

The results obtained from physical erosion testing utilizing sodium chloride as a chemical treatment are presented in Tables 4.7 and 4.8. Because the similarities of the results obtained from the two mixing procedures, an extensive study was not conducted on the sodium chloride when mixed in its dry state. The relationships between the percent sodium chloride, both wet and dry mixed, and the average percent physical erosion are visually illustrated in the graphs presented in Figures 4.12 through 4.21.

In analyzing these results, three different patterns of erosion were noted with the addition of sodium chloride. The first erosion pattern was exemplified by Sample 201. This pattern consisted of an initial decrease then increase in percent erosion with increase in percent sodium chloride. The second pattern, illustrated by Samples 202, 203 and 209, consisted of a continual decrease in average percent erosion with increase in the percentages of salt. The final pattern was exemplified by Samples 204 through 208 which was a continual increase in the average percent erosion with increase in percent sodium chloride. This final pattern is visually represented by the photos in Figures 4.22 through 4.27. Sample 206, a nonerosive soil, was utilized in these Figures to illustrate the final pattern of erosion.

The different patterns of erosion can be explained when considering that sodium chloride acts as a peptizing agent. Van Olphen (14) points out that as the concentration of ions increases from addition of sodium chloride an edge-charge reversal is likely to result because of the anion

TABLE 4.7

AVERAGE PHYSICAL EROSION TEST RESULTS
SODIUM CHLORIDE TREATMENT (WET MIXED)

Sample Number	201	202	203	204	205	206	207	208	209
Percent Erosion at 1%	33.3	8.9	13.2	10.3	8.5	16.3	2.4	31.2	33.1
Percent Erosion at 2%	51.7	10.8	11.7	30.6	16.5	22.7	4.8	28.7	28.5
Percent Erosion at 3%	59.7	7.1	5.8	51.8	21.5	32.8	7.0	29.4	18.9

TABLE 4.8

AVERAGE PHYSICAL EROSION TEST RESULTS
SODIUM CHLORIDE TREATMENT (DRY MIXED)

Sample Number	201	202	203
Percent Erosion at 0%	40.0	38.6	12.8
Percent Erosion at 1%	34.7	30.1	10.7
Percent Erosion at 2%	30.7	24.9	5.9
Percent Erosion at 3%	41.2	8.4	9.8

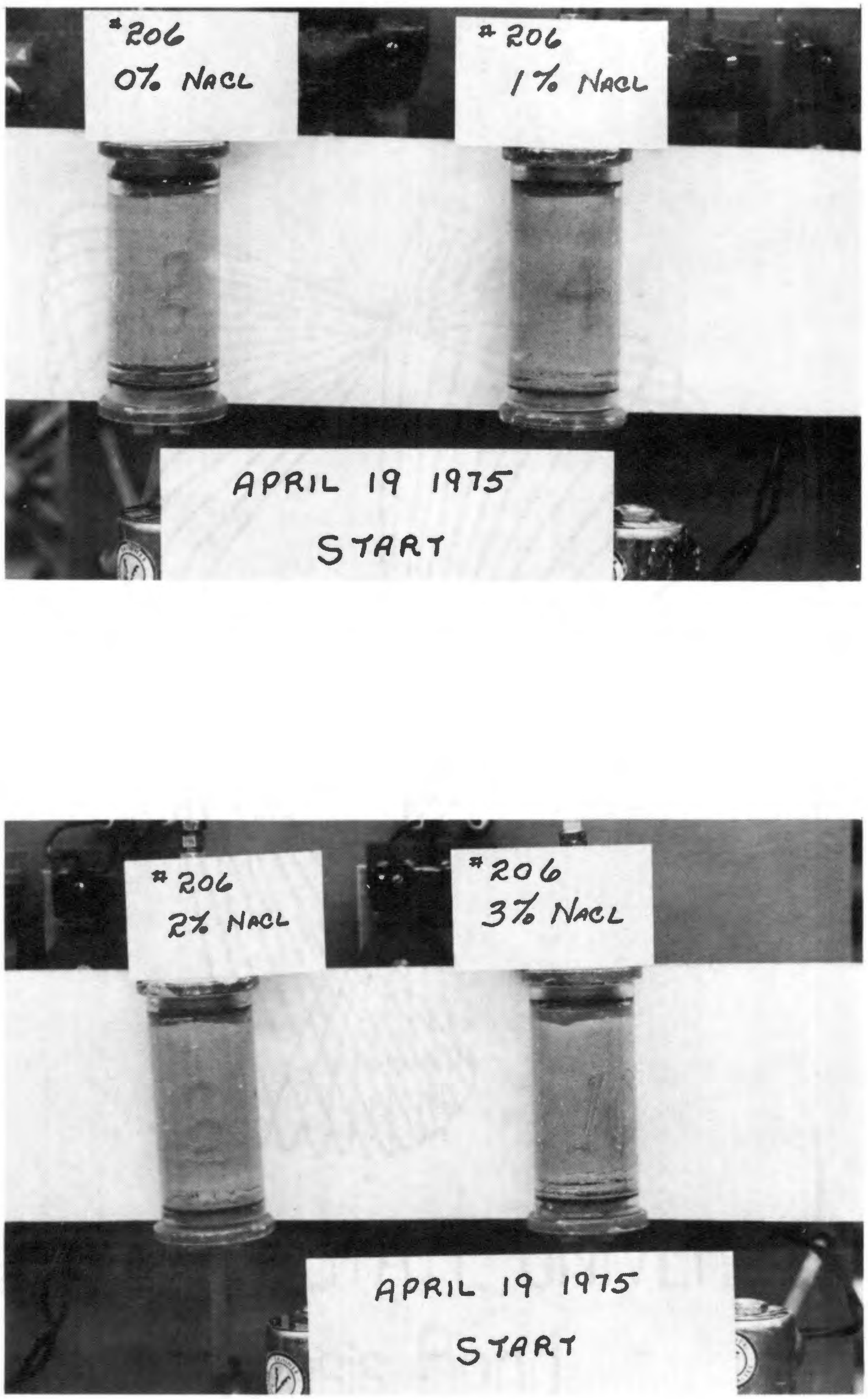


Figure 4.22. Typical Erosion Test Observations at Start of Test for Sample 206 with Sodium Chloride Treatment

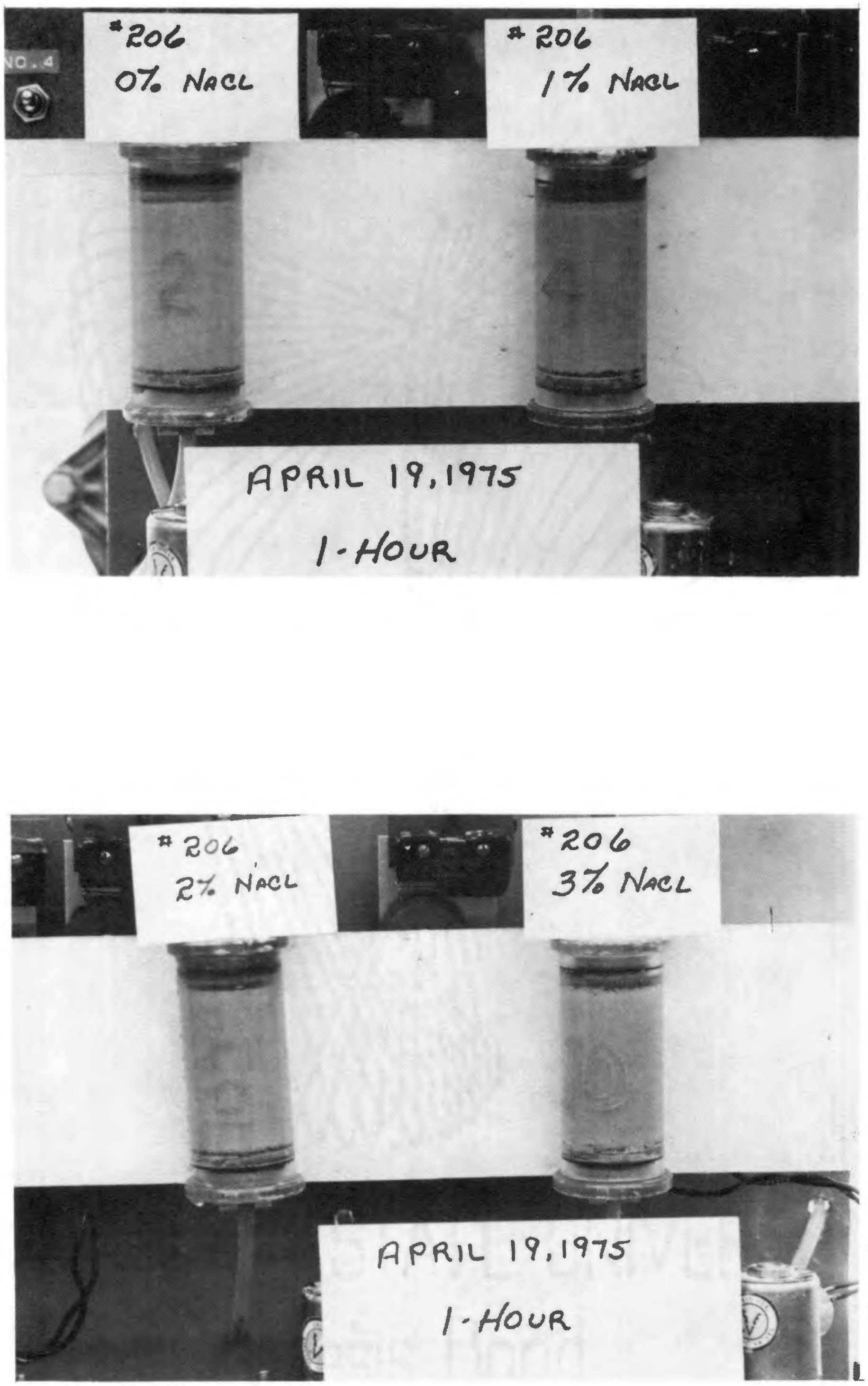


Figure 4.23. Typical Observed Erosion After 1 Hour of Testing for Sample 206 with Sodium Chloride Treatment

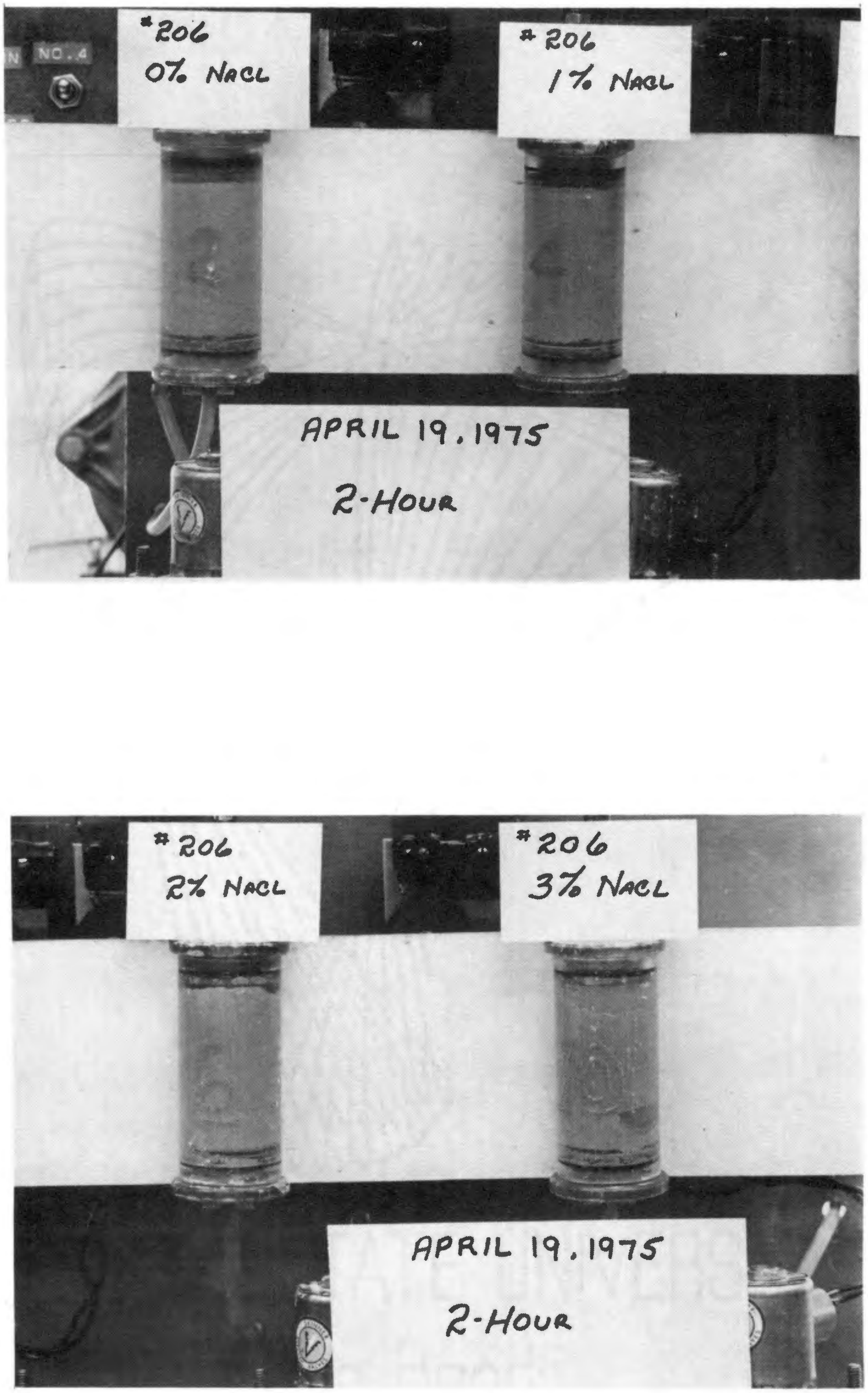


Figure 4.24. Typical Observed Erosion After 2 Hours of Testing for Sample 206 With Sodium Chloride Treatment

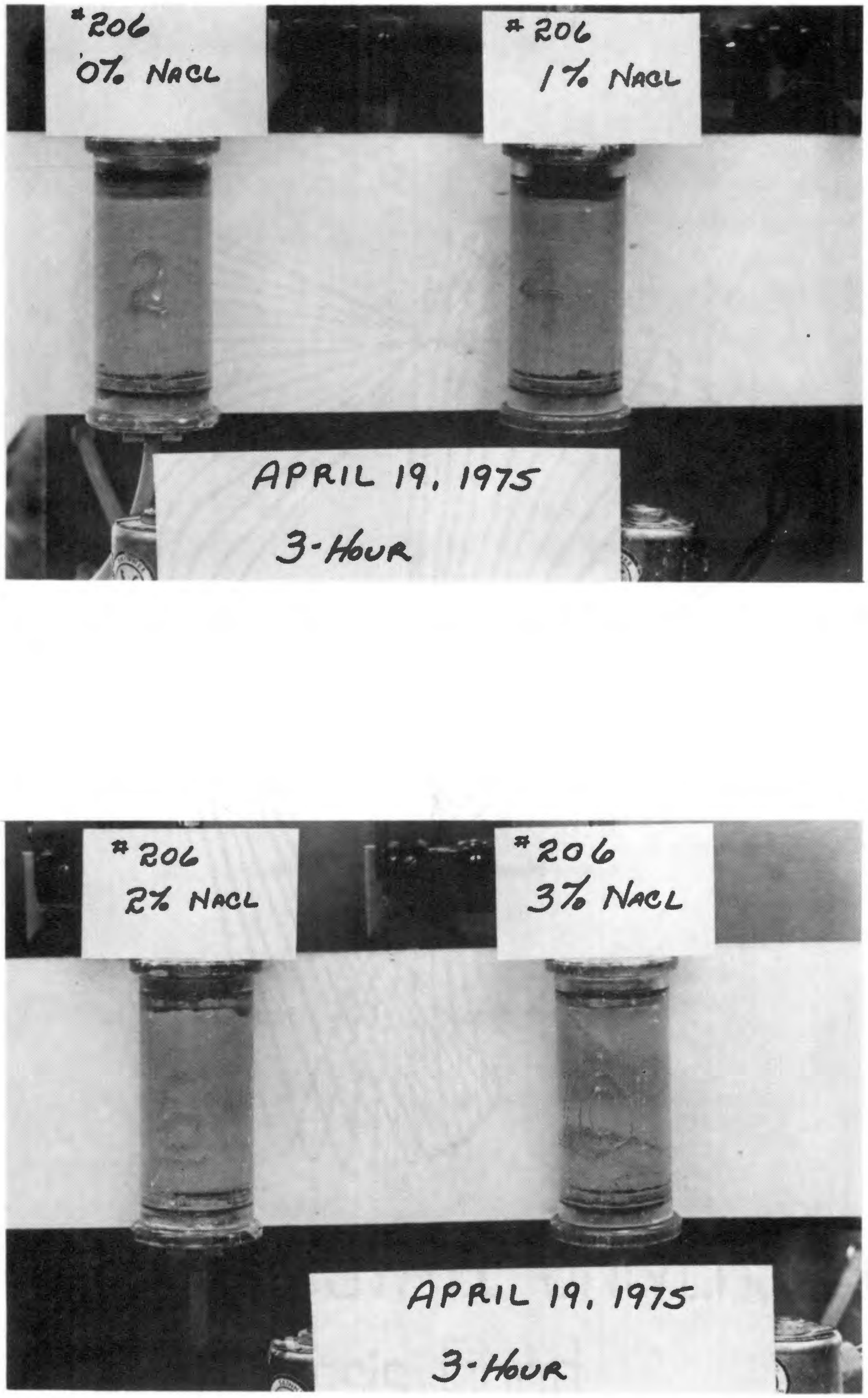
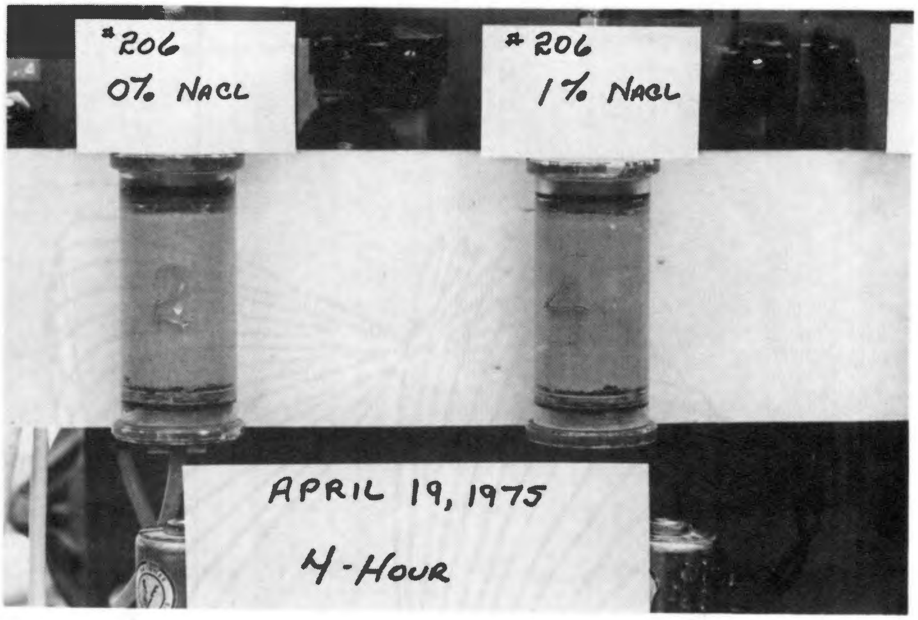


Figure 4.25. Typical Observed Erosion After 3 Hours of Testing for Sample 206 With Sodium Chloride Treatment



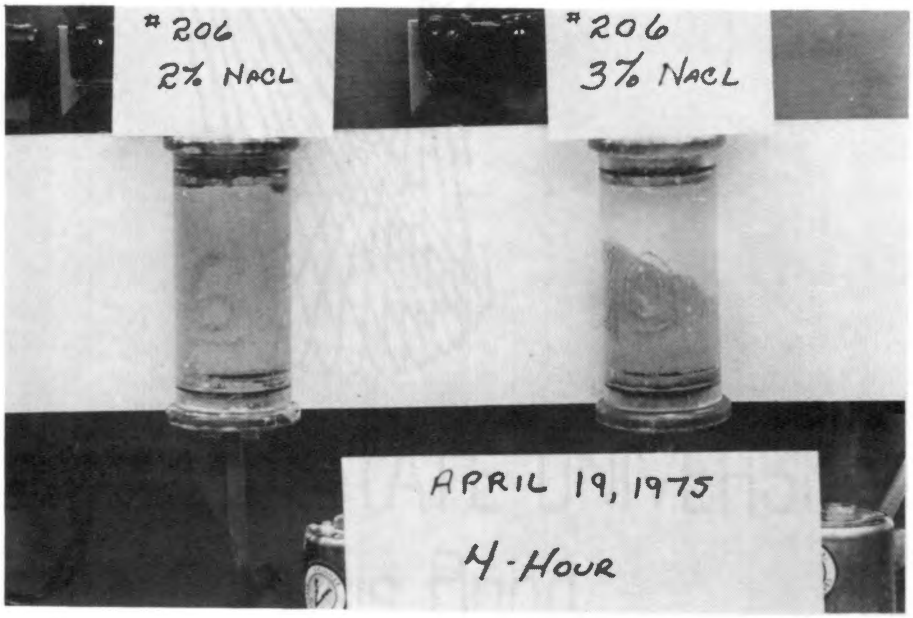


Figure 4.26. Typical Observed Erosion at Completion of Testing for Sample 206 With Sodium Chloride Treatment

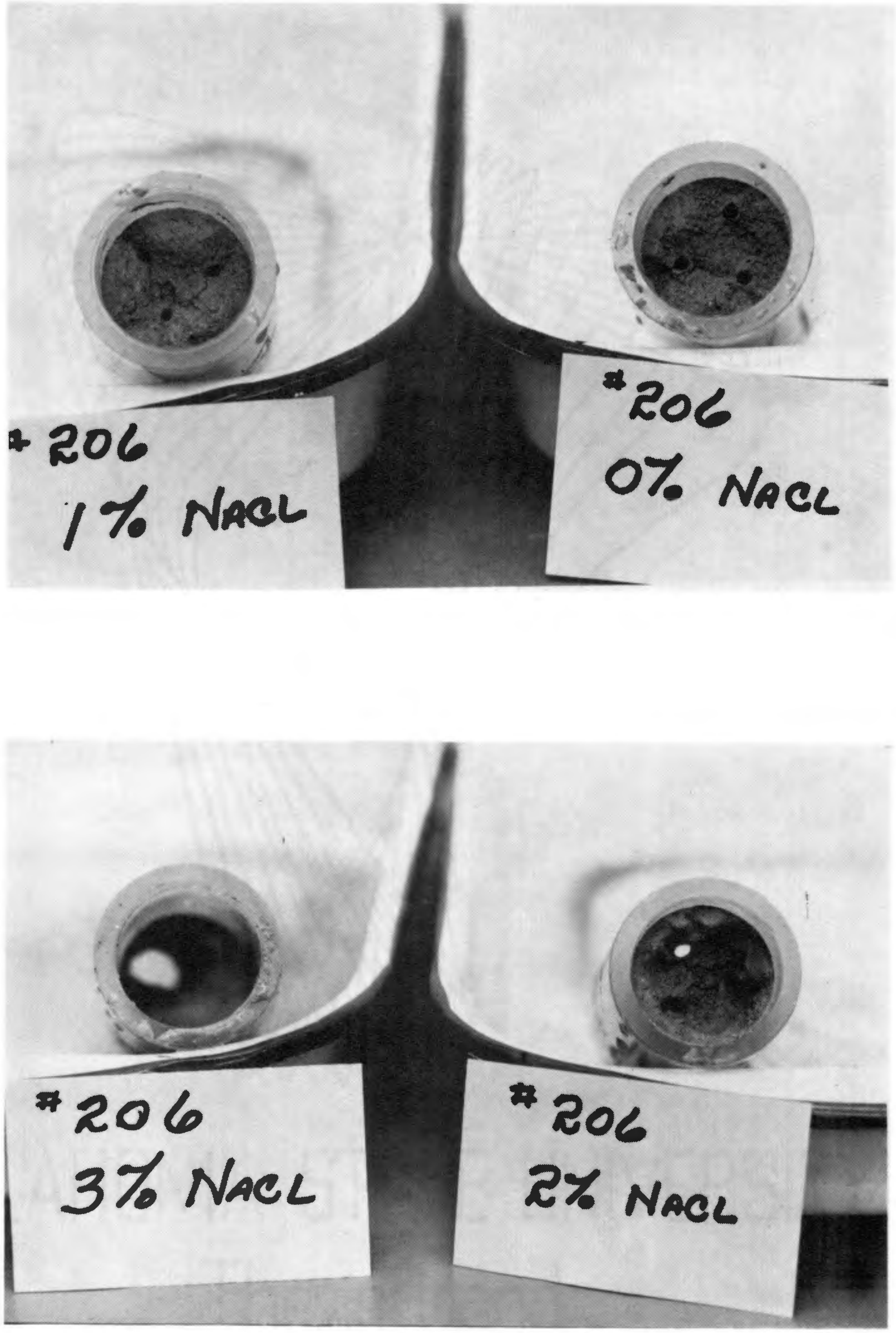


Figure 4.27. Examples of Internal Erosion Observed After Cell Dismantlement for Sample 206 With Sodium Chloride Treatment

absorption on the clay edges. Because of this charge with low concentrations of absorbed sodium ions, the clay disperses. Then, according to Myseles (29), as the concentration of sodium cations increase on the clay surface due to the replacement of the absorbed anions a flocculated structure results.

It is believed Samples 201 and 204 through 208 demonstrate that with increase in sodium chloride an increase in dispersion occurs. These samples possessed an initially low ESP (clay), which indicates a small amount of absorbed sodium ions when compared to the total cation exchange capacity of the clay fraction. It is further believed that there exists a point after which the addition of more sodium chloride will result in flocculation rather than dispersion.

Samples 202, 203 and 209, which possessed an initially high ESP (clay), demonstrated no dispersion with the addition of sodium chloride. The high initial sodium concentration prevented a charge reversal on the clay edges, thus making sodium chloride a flocculating agent rather than a peptizing agent.

It was demonstrated that sodium chloride, when used prior to soil chemistry considerations, was not an adequate chemical additive for prevention of dispersive clay erosion. In some instances the addition of sodium chloride will increase or create a potentially dispersive clay soil. It is felt that ESP (clay) is an adequate test to determine the usefullness of sodium chloride as a chemical treatment for prevention of dispersive clay erosion.

Aluminum Sulfate

Aluminum sulfate has been used by agronomists to flocculate soil. It also has limited use for slope erosion on the west coast of the United States. Because of these reasons, aluminum sulfate was chosen as a representative of the Al^{+++} cation group for this research study.

Saturation of the soils with the trivalent aluminum cation was accomplished by the addition of 1, 2, 3 and 4 percent by dry weight of aluminum sulfate on potentially erosive soil are presented in Table 4.9. An extensive study was not carried out on Samples 204 through 207 which were known to be nonerosive. The graphs presented in Figures 4.13 through 4.21, which are plots of percent erosion versus percent chemical treatment, visually illustrates the effectiveness of aluminum sulfate as a chemical treatment. The decrease in erosion as seen in Table 4.9 and Figures 4.13 through 4.21 was thought to be due to the flocculation of the soil as a result of increased amounts of chemical addition.

Although aluminum sulfate appears to be an adequate chemical treatment for dispersive soil, there is a negative effect which must be considered. The increase in exchangeable aluminum results in an increase in soil acidity. The exchangeable aluminum hydrolizes, liberating free hydrogen ions which decrease soil pH as shown by Buckman and Brady (30) and Foth and Turk (31). Associated with the increase in soil acidity is increase in corrosion potential for metal pipes, anchors, etc. In light of these considerations, aluminum sulfate as a chemical treatment for dispersive clay may not be the optimum choice when compared to lime.

TABLE 4.9

AVERAGE PHYSICAL EROSION TEST RESULTS ALUMINUM SULFATE TREATMENT

Sample Number	201	202	203	208	209
Percent Erosion at 1%	41.7	3.6	6.8	6.8	11.2
Percent Erosion at 2%	11.1	5.2	3.5	4.2	6.2
Percent Erosion at 3%	6.7	1.4	6.7	3.8	8.5
Percent Erosion at 4%	23.7	1.6	2.0	4.9	6.7

Correlation of Results

The main emphasis of this section is the correlation of results obtained from this research study to those obtained by Petry (1) and Gibbs and Holtz (32). The graphs obtained by Petry utilized in this section are relationships involving physical erosion test results and soil chemistry properties of chemically untreated soil samples. The results were also used as a comparison between the physical erosion test and a method proposed by Gibbs and Holtz of the U.S. Bureau of Reclamation for determining cohesive soil erosion characteristics.

The first correlation obtained by Petry was the relationship between the physical erosion test results and the exchangeable sodium percentage of the samples. The average percents of erosion determined by testing the soil samples at both Standard and Modified Proctor compactive efforts were plotted against the ESP determined for each corresponding sample. The graph shown in Figure 4.28 illustrates the absence of a significant relationship between the results found by these two methods. There was complete agreement in this negative correlation between the results obtained by this research study and those obtained by Petry.

The second relationship correlated was the average percent erosion found for each compactive effort to the ESP (clay) of all the samples tested. This relationship is shown in Figure 4.29. The linear relationship noted in Figure 4.29 was further supported by plotting data obtained in this research study. The ESP (clay) did provide a more adequate description of the effect of chemical properties on their clay fraction and definitely improved the relationship between chemical properties and observed internal erodibility.

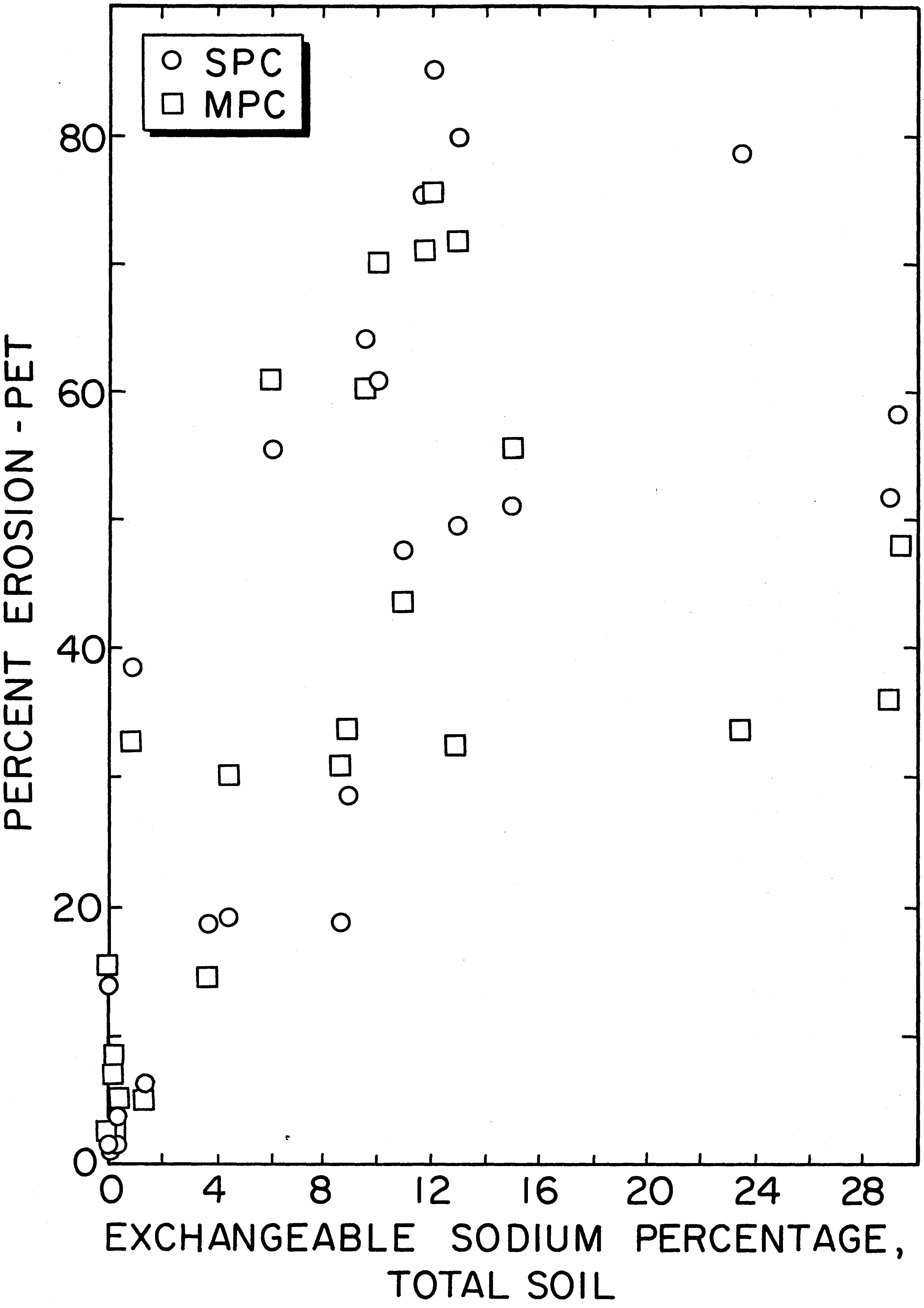


Figure 4.28. Correlation of Results from Physical Erosion Tests to Total Soil ESP's

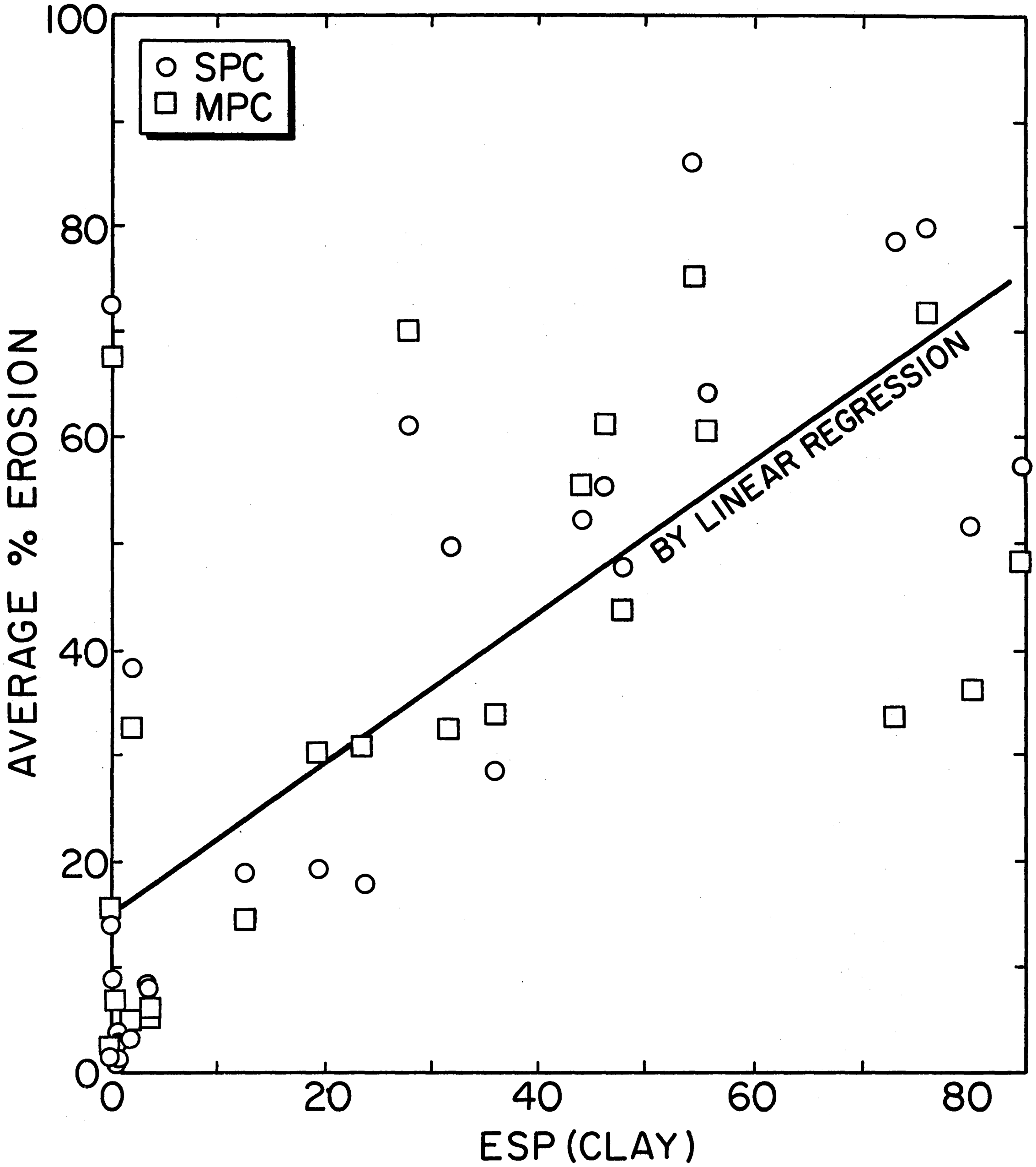


Figure 4.29. Correlation of Results from Physical Erosion Tests to ESP (Clay)'s

The final correlation of results to those of Petry was the chemical properties of the samples tested plotted on a reference graph which had been divided into behavior zones. The plotted results are shown in Figure 4.30 utilizing symbols to indicate percent erosion groups. With one exception, the results obtained from this research study and those obtained by Petry are in agreement. The results shown in Figure 4.30 supplied a quantitative result which could be utilized to assess the combined effects of physical and chemical properties on dispersive clay erosion potential and predict field behavior.

A comparison was also made between physical erosion testing (PET) and a method proposed by Gibbs and Holtz for determining the erosive characteristics of soils. In the comparison of the two procedures for determining erosive characteristics of a cohesive soil the results obtained from the physical erosion testing involved only dispersive clay erosion.

The first analyses made was a relationship involving natural density versus liquid limit using symbols to indicate percent erosion groups. This relationship is shown in Figure 4.31. Because the research samples were received in a disturbed state, Standard Proctor maximum dry density was used rather than natural dry density in the graph. When examining the relationship presented in Figure 4.31, no discernable pattern of erosion is evident, but both the non dispersive and dispersive clay soils fall in and along the zone of highest erosion resistance.

The other analyses made was erosive characteristics of cohesive soils with respect to plasticity utilizing an A-line chart of the unified classification system. The shaded area in Figure 4.32 was believed by Gibbs and Holtz to represent the erosion potential of fine grained

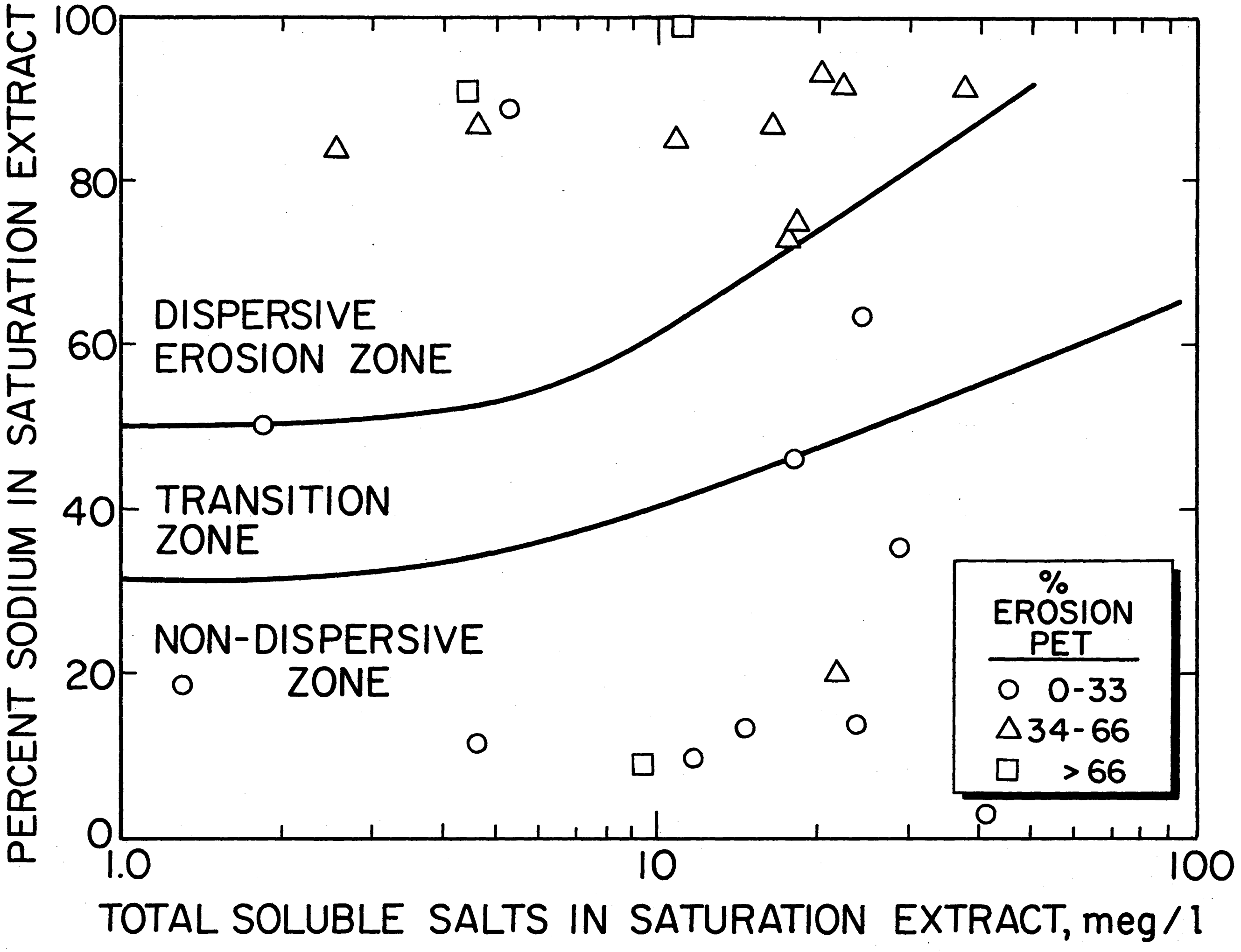


Figure 4.30. Correlation of Physical Erosion Test Results to Field Behavior as Determined By Solution Extract Chemical Properties

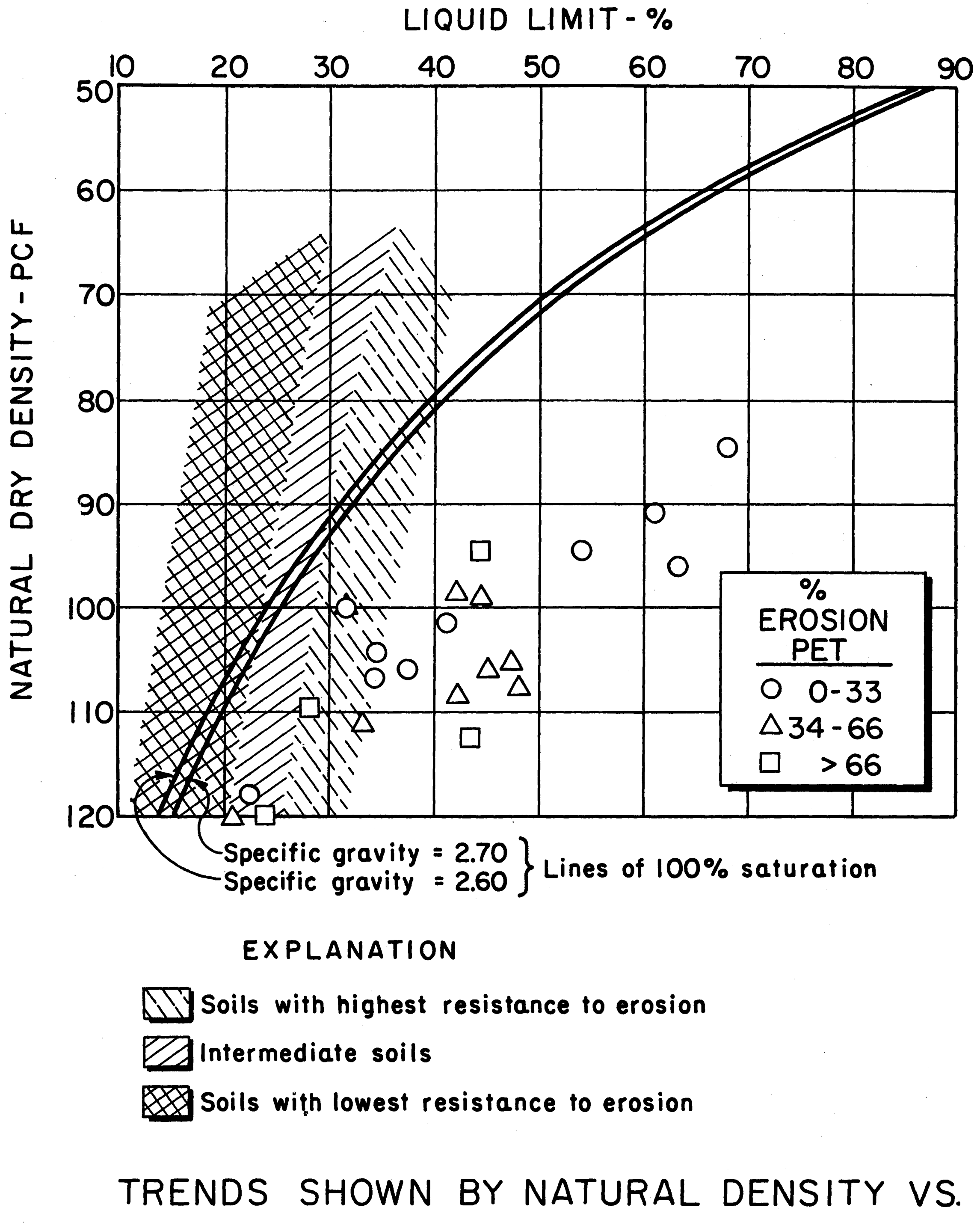
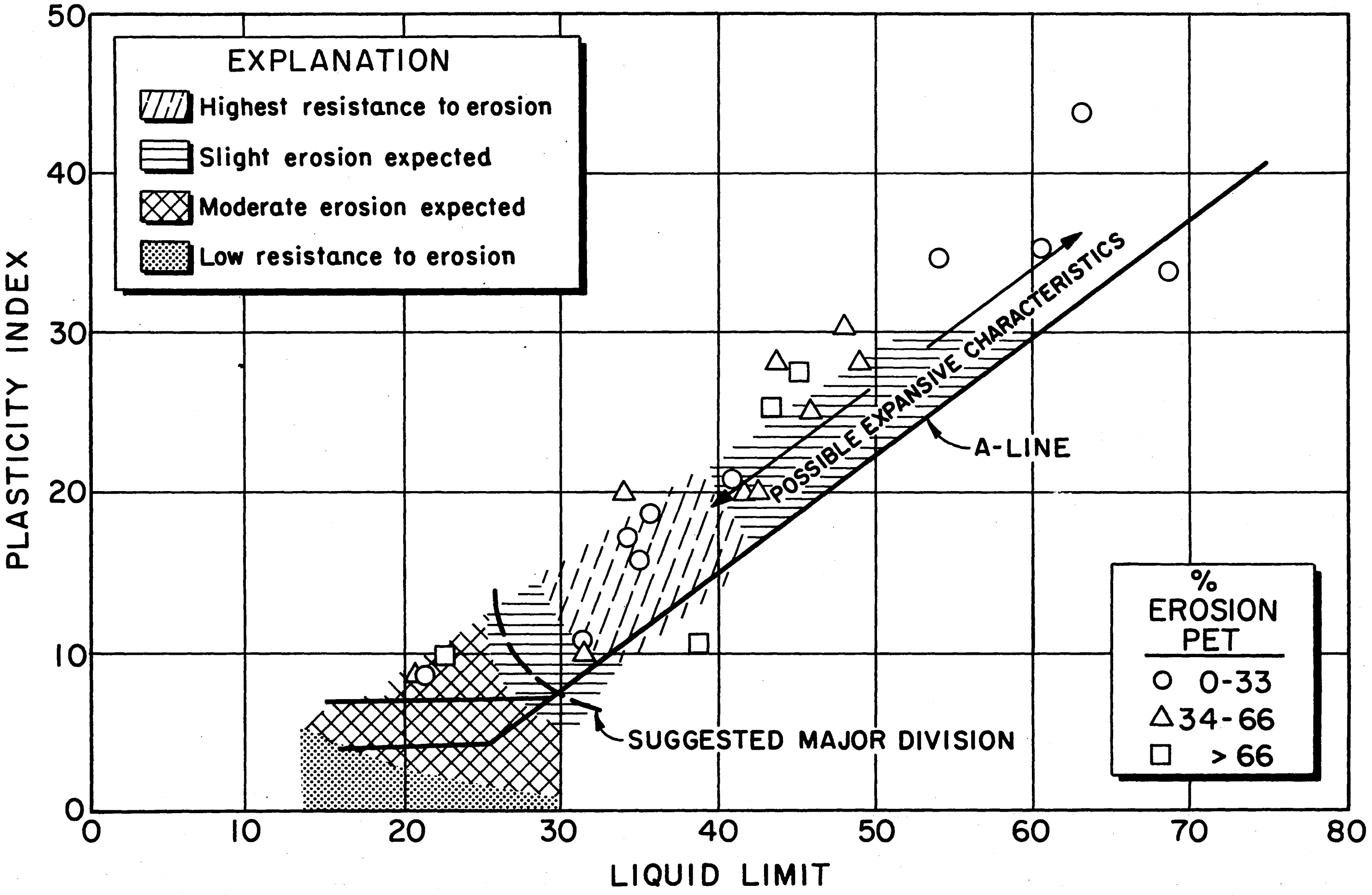


Figure 4.31. Physical Erosion Test Results as Related to Natural Density Versus Liquid Limit (After Gibbs and Holtz, 1962)



SUGGESTED TREND OF EROSION CHARACTERISTICS FOR FINE-GRAINED COHESIVE SOILS WITH RESPECT TO PLASTICITY

Figure 4.32. Physical Erosion Test Results as Related to Plasticity (After Gibbs and Holtz, 1962)

cohesive soils based on plasticity characteristics. When the results obtained from physical erosion testing were plotted according to major groups on the graph presented in Figure 4.32, a descrepency was noted. There was found to be no definite relationship between the results obtained from physical erosion testing and those based on plasticity of the soils used.

There was no definite relationship found between the physical erosion test results and the methods proposed by Gibbs and Holtz. The relationships proposed by Gibbs and Holtz were based on soil erosion whereas the results obtained from physical erosion testing were based on dispersive clay erosion. It is not believed that either plasticity or dry density are an adequate indication of potentially erosive dispersive clay soils.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this research study was to determine if chemical treatment could be used to adequately prevent erosion caused by dispersive clay. This objective was accomplished by evaluating the effectiveness of various chemical treatments on the erosion pattern determined by physical erosion testing. From the analysis of the data obtained during this research investigation the following may be concluded:

1. The results obtained in this research study further verified that physical erosion testing was an adequate indicator of potentially dispersive clay.

2. Dispersive clay soil erosion was dependent on the chemical dispersion potential of the clay particles as well as the surface erosion of the soil mass.

3. Chemical treatment can be used successfully to control the erosion of potentially dispersive clay.

4. Hydrated lime was found to be the optimum chemical treatment for controlling dispersive clays.

5. The initial sodium ion content of the soil has an appreciable influence on the effectiveness of sodium chloride as a chemical treatment. The initial ESP (clay) should be used as an indicator of the effect of sodium chloride on a potentially dispersive clay.

6. Aluminum sulfate was an adequate prevention of clay dispersion, however, the associated rise in soil acidity may limit the use of this chemical.

With respect to future research of chemical treatment on dispersive clays the following recommendations were made:

1. Further investigate the effect of curing chemically treated samples prior to erodibility testing.

2. A study should be conducted to determine the effect of both magnesium and potassium as chemical stabilizers.

3. Investigate the use of certain industrial wastes as a means of controlling dispersive erosion.

4. A research study should be undertaken to determine the relationship between the results obtained from this research study and those obtained utilizing undisturbed samples.

5. Investigate application of the results obtained in this study to field conditions.

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APPENDIX A

PROCEDURE UTILIZED IN CHEMICAL TREATMENT FOR PHYSICAL EROSION TESTING

There are two procedures listed within the chemical treatment procedure. One procedure is for lime, while the other is for sodium chloride and aluminum sulfate.

LIME

1. 500g of soil were placed in a mixing dish. The desired amount of lime was weighed to the nearest 0.01g and thoroughly mixed with the soil.
2. Enough distilled deionized water was thoroughly mixed with the soil to bring it 2% wet of optimum water content.
3. The mixture was then sealed in a plastic bag and allowed to cure for 24 hr.
4. After the 24 hr the sample was compacted by the procedure described in Appendix B. Immediately After compaction the cylinders were wrapped in plastic wrap to prevent loss of moisture. The wrapped cylinders were then sealed and waxed.
5. The samples were placed in the constant temperature and humidity chamber for 30 hr at 105°F and 98-100% humidity.
6. The samples, after curing, were then unwrapped and drilled, four cylinders at a time.
7. The remaining procedure is the same as listed in Appendix B from Step 7 on. The cylinders were tested as soon as possible after being rapid-cured.

SODIUM CHLORIDE AND ALUMINUM SULFATE

1. 500g of soil were placed in mixing dish, to which was added the desired percentage of either sodium chloride or aluminum sulfate.

2. Enough distilled deionized water was thoroughly mixed with the soil to bring it 2% wet of optimum water content.
3. The mixture was sealed in a plastic bag and allowed to cure for 24 hr.
4. After 24 hr the sample was compacted and tested according to the procedure listed in Appendix B.

APPENDIX B

PROCEDURE UTILIZED DURING PHYSICAL EROSION TESTING

1. If chemical treatment was carried out before erosion testing, samples were chemically treated according to procedures in Appendix A.

2. Sufficient distilled deionized water was added to obtain optimum water content and thoroughly mixed to obtain homogenity of each sample. After mixing, moist samples were broken down such that all particles were smaller than the U.S. No. 10 sieve size.

3. An Erodibility Test Data Sheet (Figure B.1) was prepared to include all pertinent data.

4. Each sample was then compacted with the desired compactive effort, using the OSU Miniature Compaction device.

5. After compaction, the sample was trimmed level with the top of a Harvard miniature mold. The soil cylinder and mold were weighed to the nearest 0.01g.

6. To prevent later overcompression of cylinders, each cylinder was partially extracted from the mold using a small spacing block. The cylinder was trimmed level with the top of the mold and the sample trimmings were placed in a tare can for water content determination.

7. The cylinders were then placed into assigned cells of the Erosion Device. Cylinders were oriented so that the top of the cylinder was at the top of the cell.

8. Compression and spacing blocks were placed into the ends of each cell. The assemblage (cell, cylinder and blocks) was placed in a hydraulic press so that the top of the cell was up. The soil cylinders were then compressed into the cells.

9. After compression the positions for longitudinal holes were marked in the tops of the cylinders. Three 0.125 in diameter holes were then drilled through each cylinder, using a drill press to insure

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ERODIBILITY TEST DATA SHEET

Tested by **Test No.**

Date **Sheet No.** **of**

Type of Compaction **Sample Water Content**

Description of Samples: **Test Water Pressure** **psi**

Unit #1

Unit #2

Unit #3

Unit #4

Start of Test: Day **Time** **End of Test: Day** **Time**

UNIT NO.				
Wt. Cell and Sample w/holes				
Wt. Cell				
Wt. Sample w/holes (wet)				
Wet Density, γ_w				
TARE CAN NO.				
Wt. Sample Wet + TC				
Wt. Sample Dry + TC				
Wt. Tare Can				
Wt. Water				
Wt. Dry Soil				
Water Content, w%				
Dry Density, γ_d				
Wt. Dish + Dry Soil, End				
Wt. Dish				
Wt. Dry Soil, End				
Wt. Dry Soil, Start				
Percent Erosion				

Figure B.1. Erodibility Test Data Sheet

alignment. Drilling proceeded at such a speed as to minimize disturbance of the soil cylinder.

10. Each hole was then cleaned and the drill "polishing" removed by a pipe cleaner. Each cell and sample cylinder was weighed to the nearest 0.01g.

11. The Erosion Device was then prepared for testing by the following process:

a. Each settling chamber and solenoid operated valve were cleaned and filled with water.

b. The air pressure supply line was connected to a source capable of 20 psi pressure.

c. The primary water tank was filled with enough distilled water for the complete test (12 gallons).

d. The air pressure input line was connected from the pressure regulator to the primary water tank and the pressurized water line from the primary water tank to the secondary water tank was installed.

e. The tank was then pressurized so that 15 psi water pressure was available to the secondary water tank.

f. The output end of each waste waterline was placed in a collection container.

12. The sieve disk, porous disc, and support ring were placed in the bottom of each cell.

13. Each cell was then placed into the device by pushing the cell end pieces into the cell and rotating them relative to the cell ends in order to properly seat their "O" rings. The completed cells were then placed in their "C" brackets and secured to prevent cell movement during testing.

14. The secondary holding tank was then filled and pressure vented. Five minutes prior to the beginning of testing, the manifold-cell valves were progressively opened. The secondary holding tank was kept one-half full of water during this time and was filled and put under test pressure of 15 psi, at the beginning of the test.

15. The test was begun by turning on each unit timer at intervals of 15 seconds. The timers were set to open each solenoid valve at six minute intervals for approximately seven seconds, providing a system to flush out any soil suspension in the soil cylinder holes and cell, and replace it with fresh distilled water.

16. After four hours of elapsed testing time each unit timer was turned off. Prior to the last time each solenoid valve opened, its corresponding manifold valve was closed. Power switches were shut off as soon as each solenoid valve closed.

17. The water pressure input valve on the secondary holding tank was then closed and the tank was vented.

18. The water supply lines for each cell were disconnected from the manifold valves. The cell ends were removed and the remaining soil was pushed, scraped and washed into a preweighed dish. The dish and sample was then dried in a 110°C oven. When dry, it was placed in a desicator to cool, then weighed to the nearest 0.01g. The dry weight of the soil was used to determine erodibility, expressed as percentage loss.

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