IDENTIFICATION OF DISPERSIVE CLAY SOILS
BY A PHYSICAL TEST

By

THOMAS MERTON PETRY

Bachelor of Science
University of Missouri at Rolla
Rolla, Missouri
1967

Master of Science
University of Missouri
Columbia, Missouri
1968

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Thesis Approved:

L. Allen Haliburton
Thesis Adviser

Phillip L. Manke

James V. Parcher

Lester W. Reed

N. N. Durham
Dean of Graduate College

To my wife, Susan and daughters, Karol and Kim, for their understanding, devotion and support during these efforts.

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CHAPTER I

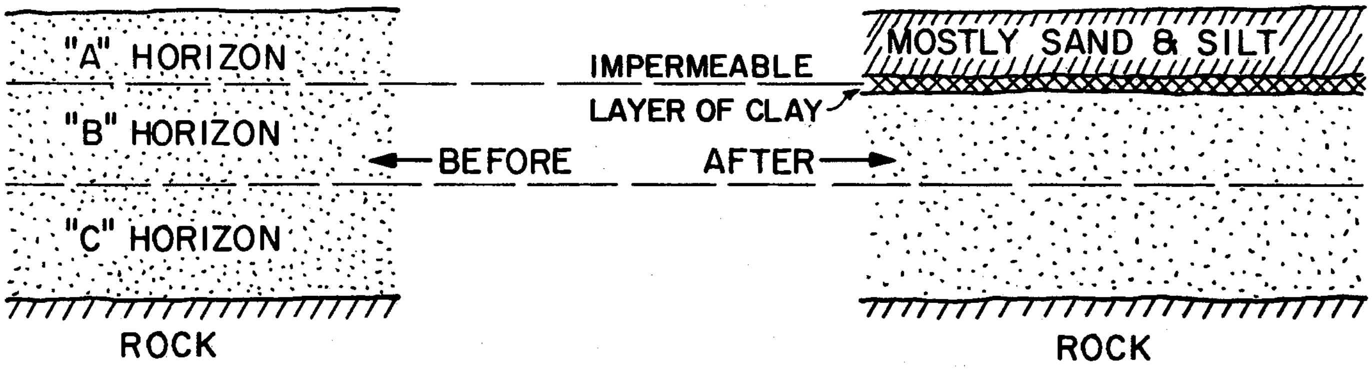
INTRODUCTION

Statement of Problem

Agronomists first noted the problems associated with dispersive clay soils over 100 years ago. They recognized the significance of the detrimental affects that these soils have on cultivation, irrigation and growth of crops. Soil scientists were able to identify the cause of the difficulties confronting agronomists as the self dispersion of clay particles into water seeping through the soil mass and subsequent removal of these suspended clay particles from the soil mass by normal ground water movement.

Two types of difficulties were found to occur in natural deposits of dispersive clay soils used for agricultural purposes. Illustrations of these may be found in Figure 1.1. The first was encountered where no underground aquifer was found near the surface. Dispersion and loss of clay particles was determined to occur in the surface layer of soil. This happened when rain or irrigation water was introduced into this layer of soil and seeped downward into lower layers. Because of the filtering action of the soil mass and reduction in velocity of seepage water, the dispersed clay particles were deposited as a layer of relatively impermeable clay adjacent to the surface layer of soil. The resultant soil profile has a surface layer consisting of mostly sand and

A. NO UNDERGROUND AQUIFER



B. WITH UNDERGROUND AQUIFER

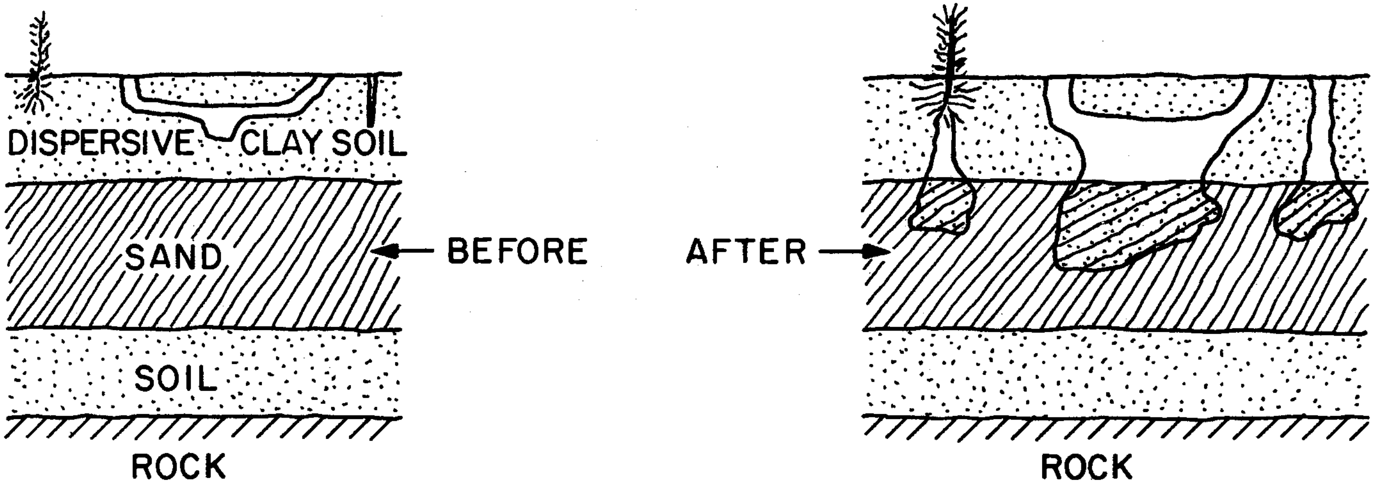


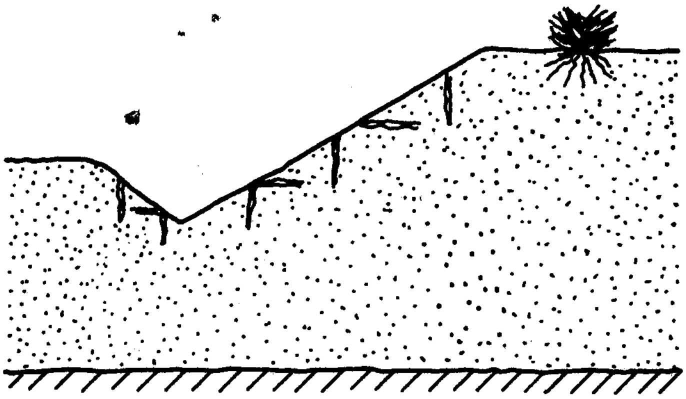
Figure 1.1. Agricultural Problems in Natural Deposits of Dispersive Clay Soil

silt over a relatively thin impermeable layer which covers lower soil layers unaffected by the action of dispersive clay. Use of this resultant soil profile for agricultural pursuits was found impossible because the surface layer of soil could not hold nutrients for crops, and water introduced would flood the surface layer.

The second difficulty illustrated in Figure 1.1 occurred when an aquifer was present adjacent to the surface layer of soil. If surface cracks, root holes or animal burrows were located in the surface layer of soil, these provided places for collection of water into which clay particles dispersed and channels for piping of soil into the aquifer. The result of this internal erosion was found to be relatively large vertical pipes and underground caverns. Agricultural use of soil masses damaged by this process was obviously impossible.

Soils engineers have become acquainted with serious damage occurring in earth structures of dispersive clay soils in the last two decades. Failures of slopes cut into natural deposits have occurred by piping of dispersed clay as illustrated by Figure 1.2. The piping of material out of these slopes was found to be initiated by dispersion of clay particles in dessication cracks and propagated by seepage of water through the embankment formed by construction of these slopes. Pictures of dispersive clay erosion in a slope cut into natural deposits of these problem soils are included as Figure 1.3.

A second, and more serious, kind of slope failure was determined to occur in embankments constructed of dispersive clay soils. Because dessication cracks may be deeper and larger in these embankments, permeability of these embankments are greater, and construction joints may provide planes of weakness and channels where piping may start in these



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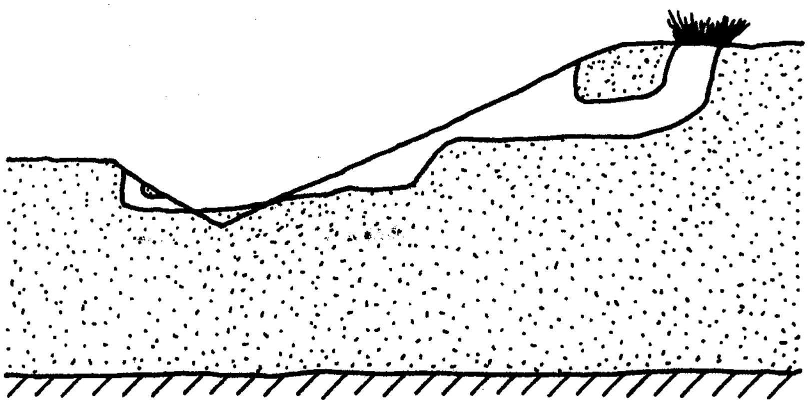

AFTER

Figure 1.2. Failure by Piping of Dispersed Clay in Slopes Cut Into Natural Deposits

Figure 1.3. Typical Dispersive Soil Erosion

structures, these earth structures are more susceptible to failure initiated by piping of dispersive clay soil. Circular arc failures involving significant portions of the slopes of these embankments have been known to occur because of dispersive clay erosion. Examples of the kinds of damage noted in slopes of earth structures constructed of these problem soils are shown in Figure 1.4.

The most serious problem associated with dispersive clay soils has been noted by soils engineers as the failure of small homogeneous earth dams constructed of these problem soils. The cross section of such a structure at the location of this overflow/outlet conduit is shown before and after failure by piping and breaching of the embankment in Figure 1.5. The effects of dispersion of the clay particles in this soil mass and action of seepage water piping material out of the embankment were found to be similar to those encountered during piping in other dispersive clay soil masses.

These dam failures were considered much more significant than those previously discussed because of their related potential for destruction of lives and property. Many cases where small homogeneous earth dams of dispersive clay soil were breached by piping have been published in both soil science and soils engineering literature. These failures were determined to occur soon after either the first filling of a reservoir, or a storm which quickly filled a flood control pool. Propagation of piping and eventual breaching of the embankment of these dams was found to occur in less than one day because of two factors which contributed to clay particle dispersion and piping. The first of these was the presence of horizontal cracks in the embankment caused by construction joints, dessication, and differential settlement. The other factor found to

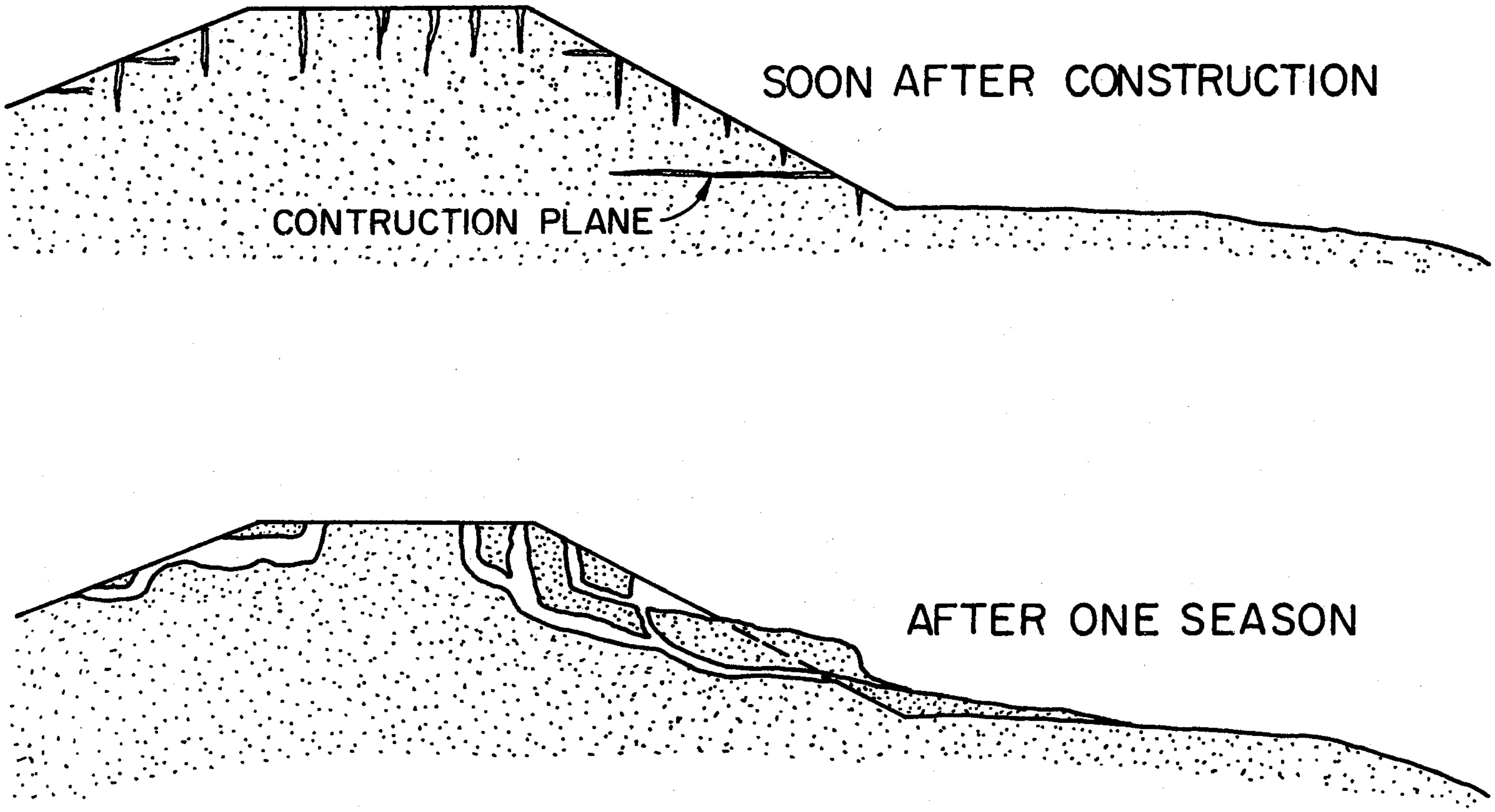

Figure 1.4. Slope Failures in Embankments Constructed of Dispersive Clay Soils

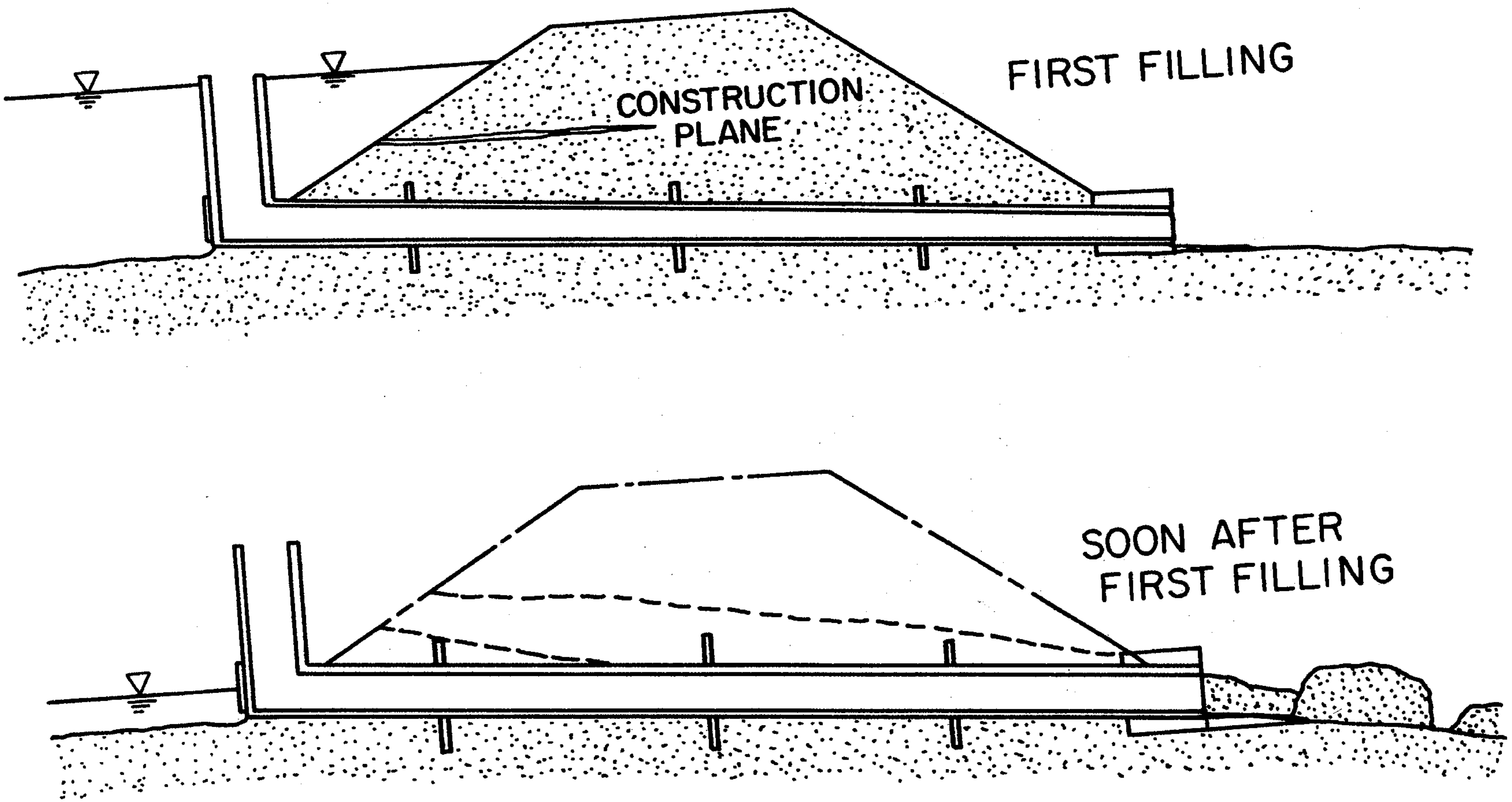

Figure 1.5. Typical Failure of a Homogeneous Earth Dam Constructed of Dispersive Clay Soils

accelerate the formation of pipes and eventual breaching of the embankment was determined to be the existence of relative high hydraulic head which could open horizontal cracks wider and cause seepage velocities great enough to move dispersed clay particles out of the embankment.

Because of the desire to design and construct both safe and stable structures of earth, including dispersive clay soils, soils engineers and soil scientists have studied the dispersive clay phenomenon. Their research has been directed at finding a method of identifying dispersive clay soil erodibility in order to enable them to predict the field behavior of these problem soils. The methods these soils engineers and soil scientists have proposed will be discussed in detail in Chapter III. These procedures range from qualitative tests of the self dispersion of clay soils to those more quantitative tests which utilize soil chemistry properties to identify dispersive clay soil erodibility.

The difficulties associated with use of these, previously proposed, methods for identifying dispersive clay soil erodibility by soils engineers wanting to predict field behavior accurately are two-fold. First, and most important, the results obtained from the use of these methods are effectively qualitative so that accurate prediction of field behavior is not possible. Second, those methods which offer the more quantitative results are based on soil chemistry properties not understood by most soils engineers. In order to provide the measure of dispersive clay erodibility needed by soils engineers and to do so using a test method easily understood and accepted by soils engineers, a physical test to determine internal erodibility of these problem soils was needed.

Purpose and Scope of Study

The purpose of this research was threefold: 1) develop a physical erosion test and device for the measurement of the internal, or dispersive clay, erodibility of compacted clay soils, 2) use the device and test procedure developed to measure the internal erodibility of 18 samples which were known to have diverse physical, mineralogical and chemiclay properties, and 3) investigate the influence of all sample properties on the physical internal erodibility of these clay soils.

In addition, physical erosion test results were analyzed and correlated with those determined by analysis of dispersive clay erosion potential using three previously proposed methods of identification of this phenomenon. This potential internal erodibility was measured using the following methods:

1. USDA Soil Conservation Service Laboratory Dispersion Test where the percent dispersion is a measure of the self dispersion potential of a soil.

2. The measure of dispersion potential based on the percent of sodium in a soil. Two similar indicators of this were utilized:

    a. Sodium Absorption Ratio which is the concentration of sodium cations compared to that of calcium and magnesium cations in a 1 to 1 soil and water suspension (Saturation Extract).

    b. Exchangeable Sodium Percentage which is the ratio of the amount of sodium cations on the exchange complex of a soil to its Cation Exchange Capacity.

3. The measure of the dispersive clay erodibility of a soil based on the percent sodium in a 1 to 1 soil and water suspension, and on observed dispersive erosion field behavior.

CHAPTER II

RESEARCH BACKGROUND

Historical Review of Reports on Phenomenon

General

During approximately the last thirty-five years the phenomenon of self-dispersing clay soils has been of critical importance to both the agriculturalist and engineer. Prior to this time little was understood about why these soils acted in such manner and very little information concerning dispersive soil behavior was available in the literature. Since the 1930's, soils engineers and soil scientists have added greatly to their understanding of this phenomenon.

Soil Science Research 1937-1954

As early as 1937, soil scientists were aware of problems associated with dispersive clay soils. They found that small earth dams and dikes built of these soils would fail by passage of water through and under the fill. Volk found over a 90% failure rate of such structures in one area of Arizona, even though their construction was by normal dike cross section and dry compaction (42). He sought a method to evaluate the self-dispersion of moisture-saturated colloids in these soils. The method arrived at has since been modernized and is now known as the USDA Soil Conservation Service Laboratory Dispersion Test. The method chosen for rupture of soil microaggregates during testing did not break-down stable aggregates into particles of 5 μ or less in diameter, so that those smaller than 5 μ were considered to be dispersed. This arbitrary limit was picked by Volk to measure the ability of a soil to self-disperse. He determined degrees of dispersion from 44% to 90% for soils from failed structures in Arizona and New Mexico. In addition, Volk published descriptions of how this problem caused failure of these structures because of internal erosion which occurred during subsidence of fills compacted dry of optimum.

One study, reported on by Fletcher and Carroll in 1948, reported the properties and characteristics of soils in a valley of Arizona where subsurface piping channels were noted in natural deposits (16). Roughly 30% of the land in one valley had been lost to this phenomenon since 1900. Fletcher and Carroll found the percent dispersion of these soils by Volk's test to vary from 17% to 18% at 5 μ. Also, they determined that the soils involved were extremely high in exchangeable sodium and uniformly high in calcium carbonate, a situation thought unique by them. Their study indicated that piping can occur in dispersive clay soils when water has access to the soil at a greater rate than the substratum can absorb it. They also established that there must be a ready outlet for the resultant lateral flow of water, and observed such outlets as far as 0.75 mi. from the area where caving occurred.

Because of the many problems associated with saline and alkali soils, the USDA United States Salinity Laboratory conducted research and in 1954 published the Agriculture Handbook No. 60 (34). This publication describes methods for analysis and improvement of saline and alkali soils, and includes standard procedures for determination of soluble and exchangeable salts and calculation of a soil's Sodium Absorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP). These indicators of soil sodium as compared to other cations were utilized to help identify partial sodium saturation of clays, the factor which causes these soils to be highly dispersive. The handbook also described how dispersion could cause transportation of clay downward through the soil where it would accumulate at lower levels. The result of continued surface dispersion is a few inches of coarse, friable surface soil and a lower dense layer of low permeability that may have a high clay content and columnar or prismatic structure.

Products of such dispersive surface erosion were found to be non-saline-alkali soils, a type which usually exists in small irregular areas in semi-arid and arid regions. Researchers at the U.S. Salinity Laboratory concluded that the presence of critical percentages of sodium occurred when the presence of high pH (approximately 10) and carbonate ions caused calcium and magnesium to precipitate and be carried away. They also concluded that the unique physical properties associated with these soils are caused by an excess of exchangeable sodium. Materials of this type are known as nonsaline-alkali or Solonetzic soils.

Soils Engineering Studies 1949-1963

The first recorded instance of possible dispersive clay behavior in a major civil engineering structure occurred during the latter stages of construction of Wister Dam by the U.S. Army Corps of Engineers, in 1949. In 1950 Casagrande described how large quantities of water flowed through the paritally completed embankment, causing "pipes" where water flowed under a very small gradient of about 1 on 50 (9). He concluded that relatively small differential settlement cracks in the closure section, following approximately the contour lines of the old river channel, were responsible for the piping. Casagrande noted that he would have considered this dam perfectly safe if he had been asked about it before piping occurred; therefore, he was seriously disturbed that clay which was compacted at optimum moisture content did not possess the ability to follow even small differential settlements without cracking. The Corps of Engineers has several reports dating from 1949 to 1959 concerning this piping and the remedial measured used to stop seepage (41). They concluded that this piping was occurring through the embankment, with a maximum discharge of 20 cfs, and had begun when the reservoir pool rose sharply after 8 in. of rain fell on the watershed during 5 days. It was approximately two days before seeps were observed in the downstream slope. Although this dam is located in an area plagued with dispersive clay problems, the extensive remedial measures taken were of the type normally used by soils engineers to stop piping and reduce seepage problems in non-dispersive clay soils. Reports to be discussed later in this chapter will further explain current problems in this structure.

The first reported piping failures in earth dams in an arid climate were published by Australian soils engineers. In 1960 Cole and Lewis reported on several failures of water retention structures in Western Australia, built between 1910 and 1957 (11). These dams were constructed using normal Australian construction control measures, with soils characterized by relative high clay contents and low in-situ moisture content at the time of placement. Failures had been associated with a rapid filling of the reservoir either immediately after construction or subsequently after a lengthy period of drought. All failures were by piping developed through the embankments, in a relatively short period of time. Cole and Lewis noted, during model studies, that when water was introduced in the voids some swelling occurred which sealed some previous cracks and other constrictions were sealed when soil particles were brought into suspension by upward erosion and a vigorous slaking action. They concluded that piping in cohesive earth banks could be associated with in-situ moisture contents well below the plastic limit. Finally, in addition to an arid climate, they listed as contributory failure factors the soil properties of at least 25% less than 5 μ particle size, activity greater than 0.6, P.I. greater than 20 and linear shrinkage greater than 7%.

At the time Cole and Lewis published their work, other Australian researchers were in the process of analyzing this phenomenon. Aitchison was among those who felt that post-construction dispersion could lead to these progressive failures. In 1963, he, Ingles and Wood reported on results of a study focused upon the contribution made to failure by this mechanism (1). They postulated the failure mechanism to be that of dispersive clay piping through the body of the dam and, alternatively, slope failure caused by slumping or slipping from progressive softening of the upstream face. Bacause during the process of excavation and compaction particles usually never were less than coarse silt or fine sand size, they believed the resultant embankment could have pore sizes in the range of 2 to 20 μ.

Aitchison, Ingles and Wood further postulated that during construction a susceptible clay would be flocculated, because of the inter- and intra-particle electrolyte situation, causing microaggregates to be formed. Because of this a stable embankment may be built. They theorized that dispersion occurred because of electrolyte leaching by relatively pure rain water and/or reservoir water. Under conditions of seepage, dispersed particles of under 2 μ size could be transported through and out of the body of the dam, starting piping which could ultimately result in failure. When there was zero flow these dispersed particles could enter the voids, reaching final equilibrium as a gel structure in these voids. This may possibly occur throughout the whole structure, thereby softening the embankment material. Such softening, with reduced shear strength, could cause slipping on the exposed upstream face.

Based on their experience, Aitchison, Ingles and Wood concluded that two general chemical states could be associated with this clay soil dispersion. First, high sodium soils are in a flocculated state only at a relatively low soil moisture content, and sudden increase in soil moisture level leads to dispersion. Second, if water that is highly saline and calcium deficient is introduced to soil in an embankment, a dispersed condition may arise in the soil provided the soil and water are not already in chemical equilibrium. They wrote that this lack of compatability between water and soil is not revealed by standard soils engineering tests.

Aitchison et al. thought it reasonable to expect the dispersion phenomenon to exist over extensive areas, since it could not only occur in saline and alkali soils but also in widely distributed acid podzolic soils with high sodium content. They concluded it probable that any dispersed clay particles suspended in water would not be retained by conventional earth dam filter zones. Another interesting conclusion they made was that the dispersion of clay aggregates may well be accompanied by softening and swelling of the clay, even under significant effective stress.

In summary, it can be said that Atchison et al. realized that clay dispersion is related to the presence of monovalent cations (notably sodium), a deficiency of higher valence cations on the exchange complex and also the presence of water in sufficient quantity and in proper electrolyte condition. They also noted the fact that the electrolyte situation in a soil and its pore water may be time-dependent, thus a flocculated clay may become dispersed at some future time.

Soil Science Studies 1955-1964

While engineers were actively searching for better understanding of the dispersive clay soil phenomenon, soil scientists were investigating the relative concentrations of cations in these soils that caused low permeability to irrigation waters. In 1955, Quirk and Scholfield reported on tests they conducted on the decrease of permeability in cation saturated soils during leaching by different electrolyte concentrations (31). Sodium-saturated samples had large decreases in permeability during leaching, even during the first 2 hrs. while calcium-saturated samples showed about 25% of this decrease in 5 hrs. They attributed these decreases to swelling, some failure of aggregates from swelling stresses and dispersion of aggregates.

Quirk and Scholfield determined that there is an electrolyte concentration, called the threshold concentration, above which permeability is maintained for a given soil percentage of exchangeable sodium. Though their study was confined to an illite-kaolinite-vermiculite soil, they believed the concept could be applied to other soils of semi-arid and arid areas, with the exception of kaolinitic soils of low pH. Their threshold concentration concept in electrolyte is directly related to flocculation or dispersion of soil aggregates.

Collis-George and Smiles did further investigations of this subject, reporting in 1963 results of their study on determining the structural stability of soil aggregates (12). The first method they utilized, although different from that of Quirk and Scholfield, provided the same relationship of flocculation and dispersion to total cation concentration and the sodium-calcium cation ratio. Their relationship was based on the flocculation or dispersion of a clay suspension while Quirk and Scholfield utilized an experimental method of leaching soil aggregates.

Collis-George and Smiles were able to correlate their relationship to structural stability as defined by a drainage moisture method when testing specially prepared artificial aggregates. They did, however, find many discrepancies when attempting to verify their experiments with natural soils. They concluded that stabilizing factors, other than chemical, could not be predicted and that, even when these factors are of small consequence, the chemical analysis of water extracts can only be used to assess structural stability behavior if the non-steady water content conditions prevailing in the soil can be ascertained.

Collis-George and Smiles stated there was a need for methods of analysis using structural stability to include consideration for natural disrupting forces. They believed the moisture characteristic method with slow wetting was too sensitive to very small degrees of structural stability. Mechanical methods, such as aggregate analysis, were thought too insensitive. Finally, these soil scientists believed that the chemical cation-balance description method ignored all other factors.

This discussion so far has indicated that Solonetzic soils exist in arid parts of the world. These problem soils may also occur in humid areas. In 1963, four Illinois soil scientists, Wilding, Odell, Fahrenbacher and Beavers, published a study concerning the genesis of such soils in the relatively humid areas of that state (43). Previously, Smith, in 1937, had published findings about the large areas covered by "slick spot" soils in Illinois (38). He noted their presence in the Illinoian glacial plain, covered by less than 100 inches of loess. He noted soil variation with depth, relatively high percentages of sodium in the exchange complex of loess soils, and relatively poor drainage in areas where "slick spots" occurred.

Wilding et al. conducted a more detailed study than Smith into both the general and physical properties of Illinois Solonetzic soils. They concluded that the chief source of excess sodium in these Solonetzic soils was mineral sodium from the parent loess, obtained from in-situ weathering of sodium-rich feldspars, occurring where the loess cover was thinnest. It is interesting to note that the predominate clay minerals present in the affected till soils are smectite and illite. Wilding et al. speculated on the basic weathering patterns which may change loess soils into dispersed masses. The mechanism which causes weathering is the same, essentially, as that given earlier, i.e., an abrupt increase in pH occurs, accompanied by a decrease in CO_2 pressure, which causes calcium and magnesium carbonates and sulfates to be precipitated, with a corresponding increase in the relative proportion of sodium. After the relative amount of sodium reaches about 50% of the cations in solution, sodium replaces other cations on the exchange complex and dispersion occurs.

During the 1950's when greater influence had been placed upon identification of dispersive clay soils and determination of their inherent erodibility, other researchers were studying causes of all types of erosion. One such study was that reported by Emerson in 1964, describing the slaking of soil crumbs as influenced by their clay mineral composition (15). Slaking of soil grains certainly contributes to the sheet erodibility of soil masses and thereby becomes a part of internal erodibility. This occurs in a dispersive clay soil when a surface is present for water contact within the soil mass. Reaction by the surface of the soil mass to the presence of water is essentially that of soil crumbs. He described slaking as the break-up of soil crumbs into discrete fragments when immersed in water. Emerson added that this break-up may proceed further when the crumb particles are composed of dispersive clay soil. The two main causes given for slaking were replacement of entrapped air by water and internal shear stresses caused by swelling. Reviewing past research in this phenomenon, Emerson found that the severity of slaking depends on the initial dryness of the crumbs and on the particle orientation of the clay. He further stated that total swelling and the effects caused by entrapped air were dependent upon the size and shape of clay crystals.

After considering the above factors, and analyzing the results achieved, Emerson offered two general explanations concerning this phenomenon. First, in general, the more a dry clay swells on immersion, the lower the pressure developed to break-up crumbs by entrapped air. The extremes are kaolinite, where the pressure developed will be almost equal to the maximum calculated value for the initial air-filled pores, and smectite, where the air present initially remains as bubbles within the clay matrix. Second, a flake of clay will only remain intact if the shear stresses from swelling do not break the clay matrix. These stresses are relieved in smectite by bending of the very thin sheets, indicating the influence on slaking on the relative flexibility of clay particles, a property determined by clay crystal size and thickness.

In addition to these findings, Emerson discovered that immersion of crumbs in water in a vacuum produced a marked difference in results. He determined that removal of air virtually eliminated the effects of entrapped air on slaking. The only effects left were those of swelling shear stresses. Emerson related this affect to field situations where kaolinitic soil wetted slowly from the surface did not slake to any depth but when wetted quickly by a large rain did slake to appreciable depth. Water entering the subsurface soil in the first case entered in the vapor phase, thus allowing air to be displaced. Water that was quickly introduced in liquid form caused slaking. Emerson's work provides valuable understanding of how sheet erosion occurs, leaving out only those contributions stemming from unusual stress histories of soils.

Soils Engineering Studies 1965-1967

In 1965, Aitchison and Wood, building on past studies, published a state-of-the-art paper on Australian dispersive soil behavior (2). They reported an 8% failure rate in small earth dams of Australia, as a result of dispersive clay piping. These failures occurred in soil categories including soloth, solonetz, solodized solonetz, yellow podzolic and gray soil of heavy texture.

Aitchison and Wood postulated that two distinct causes of dispersive piping failure existed. The first was post-construction dispersion of soil microaggregates, and the second was the movement of the dispersed clay particles through and out of a mass with a macroporosity or high permeability. They defined border lines between dispersion and flocculation for relatively pure illite and smectite, based on the earlier studies of Quirk and Scholfield, and Collis-George and Smiles (31,12). When comparing SAR to total cation concentration in selected earth dams, Aitchison and Wood found that data from all failed dams plotted in the dispersed region and from all but one of the sound dams plotted in the flocculated region of diagrams proposed by researchers. This particular dam had been constructed of material compacted wet of optimum. These findings not only supported the significance of dispersion but also implied that the actual embankment porosity was great enough to permit seepage velocities that could cause piping of dispersed soil. The high permeability resulted from non-breakdown of clods during compaction dry of optimum moisture.

The second part of this concept was verified when Aitchison and Wood conducted laboratory permeability tests on compacted clay fill. Where an initial steady flow rate was achieved at permeabilities of 10^{-4} cm/sec or greater, a sharp increase in flow rate, accompanied by turbid outflow water, was noted after a short time. In each case an enlarged piping channel was formed in the sample. Based on these tests, they recommended a maximum permeability to prevent piping failure of 10^{-5} cm/sec, with 10^{-7} cm/sec probably needed to stop piping of dispersed soil in dams with shorter seepage paths.

Aitchison and Wood stated that a method, such as they presented, must be utilized to identify the problem soil. Then, a choice must be made between construction control to limit seepage velocity or chemical control to avoid dispersion. In their opinion, no reliance should be placed upon filters to control dispersive piping.

In the meantime, Emerson continued his research on soil crumb coherence (14). In 1966 he published the findings of a study on the classification of soil mass crumbs based on their coherence in water and the factors which affect dispersion of clay particles from these soil aggregates. He proposed a scheme of qualitative classification based on reaction of dry, natural aggregates to immersion, remolded wet aggregates to immersion, and suspended aggregates in water. Recognizing the fact that the interaction between water and clay-sized particles may determine the structural stability of the soil, Emerson chose their self-dispersion in water as a basis for recognition of soil crumb breakdown. He tested both natural soil mass aggregates and prepared mixtures consisting of selected clay minerals, silt and sand. These mixtures had varied predetermined chemical properties.

In general, Emerson found that the physical effort necessary to cause dispersion varies from none when testing dry natural aggregates to large when testing suspended particles. Required effort was indirectly proportional to the ESP of the soil, i.e., the osmotic stresses between clay-particles, which occur upon immersion in water and force dispersion of clay particles from the soil mass, must be strongest to break-up dry aggregates and need only to be small to keep clay sized particles suspended.

Emerson concluded that, in addition to suspected effects of organic matter, two factors influence dispersion. First for soil aggregates containing carbonate, as the soluble salts diffused, the percentage of exchangeable sodium present on the flocculated clay will be gradually reduced by exchange of sodium ions for calcium ions derived from the carbonate, increasing the amount of sodium and thus potential dispersibility. Second, if some of the exchange positions normally occupied by calcium actually were occupied by aluminum, the interparticle attractive forces would be increased, requiring higher sodium percentages to cause dispersion. The analysis is further complicated by variations in dispersibility, dependent on the amount of water available, i.e., how dilute the concentration of all cations is in actual situations. His final statement was that, knowing the soil pH and percentage of soluble salts present, one could classify subsoil aggregates as to dispersibility, except that in some cases a knowledge of the surface area of minerals present was needed. Further, analysis of surface soil aggregates was not possible because of the lack of knowledge concerning effects of organic matter.

The high incidence of failures in small earth dams within the Brigalow Belt prompted the Water Research Foundation of Australia to conduct an investigation, lasting from 1963 to 1965, into the nature and causes of failures of these dams. Rallings described this research in <u>Bulletin No. 10</u> of the Foundation, published in 1966 (32). Piping accounted for nearly half of the dam failures recorded. This piping was apparently caused by soil dispersion in soils lightly compacted at low moisture contents.

Rallings found that causes of piping were both physical and chemical in nature. Soils in the failed dams had high exchangeable sodium percentages and low soluble salt contents. Also, low salt concentrations in the water seeping through the dams contributed to clay dispersion. Contributory physical factors included were high linear shrinkage, high silt content and low plasticity. The most serious physical factor contributing to piping was found to be field soil mass permeabilities, which would permit movement and loss of dispersed clay-sized particles. This last factor was directly related to compaction at low moisture contents, which can also lead to settlements of embankments during saturation (another possible contribution to failure). The clay minerals Rallings found most associated with critical behavior as described above were smectite and illite. He concluded that failures could be avoided with proper control of these contributing factors.

Soils engineers and scientists in the Middle East were also conducting research on internal piping in clay soils. Kassiff and Henkin published, in 1967, descriptions of piping failures in low loess dams in the Negev (27). These piping failures were found to be related to physico-chemical characteristics of the material involved. Expecting that failures were caused by settlement in the loessial soils after construction, Kassiff and Henkin instrumented several dams. They found that the settlement which occurred could not explain the observed failures. They did, however, find that the permeabilities of natural loessial soils in the area exceeded the limits proposed by Aitchison and Wood (2), so that seepage could carry dispersed particles out of embankments even when the loess soils of low plasticity were compacted to high density.

The clay minerals found to exist in these soils were mainly smectite and some illite. In addition, the physico-chemical data for the soils tested could be plotted in the "dispersed" areas of the SAR--Total Cation Concentration curves developed by Aitchison and Wood. The data found for loess soils of the Negev, when plotted by observed field behavior, defined a new, more flat, boundary curve. Kassiff and Henkin explain that this behavior occurred because of the large amount of silt in these soils. They concluded that, with proper compaction, the effects of dispersive piping could be reduced, but that soils with total cation exchange capacities over 150 meq/liter should be avoided in small dam construction.

U.S. Soils Engineering Studies 1967-1968

In 1967, Parker and Jenne of the United States Geological Survey, Denver, presented a report on piping erosion damage endangering highway structures in Colorado, New Mexico, Arizona, Utah, and Nevada (30). They determined that the erosion was caused by three factors: dessication-stress cracks, entrainment, and variable permeability subsidence. The first of these was described by earlier authors, where dessication and stress cracks provide a convenient system for dispersion of clay-sized particles, their removal and subsequent piping of all materials. The second factor has also been discussed earlier and is caused by impounded water and relatively large hydraulic gradients which cause channelized subsurface flow, resulting in collapse of overlying structures. The last mode is that where sufficient hydraulic head exists to move dispersed clay-sized particles through and out of the affected soil mass.

Parker and Jenne describe the terrain developed by these factors working together as "pseudo-Karst." This name was picked because of the terrain has the appearacne of a miniature limestone or dolomite terrain marked by solution features. They named five requirements for occurrence of this phenomenon: enough water to fill drainable cracks, the strata must be smectitic or illitic, the strata must be dessicated at least seasonally, there must be an outlet for drainage, and the ESP must be high enough to cause instability of aggregated crumbs. Parker and Jenne added that, in reality, any subsidence that occurs greatly increases the intensity of piping because of concentration of runoff, development of stress cracks and development of lateral pipes by uneven subsidence. Within their area of study they found many occurrences of this phenomenon and suspected very many more.

Among the conclusions of Parker and Jenne, most of which have been shown above, was that, in addition to the presence of the clay minerals which promote dispersion and the presence of high percentages of exchangeable sodium, topographic factors greatly affect the propensity of these materials to erode internally. If avoidance of erodable soils was not possible, they stressed prevention of runoff concentration as the remedy to the problems encountered in these materials.

Another related report concerning piping of dispersive soil was published in 1968 by Bell of the North Dakota State Highway Department (3). This phenomenon was found to be responsible for the topography of the Badlands of North Dakota. In this area, characterized by cold wet winters and warm dry summers, the same modes of occurrence of piping exist as in the Southwestern U.S., with the addition of freeze-thaw action. Because of the long history of piping erosion of this type in this region, the pseudo-Karst topography found is usually large-scale. However, small-scale topography of similar type was also found. Bell subdivided topography into two classes: major pseudo-Karst topography and miniature pseudo-Karst or retiform areas, which develop rapidly (two years) in new cut or natural slopes.

He found much of this topography in areas of sodium-rich bentonitic materials (containing mostly smectite and some illite). In addition, he found piping in blue-gray kaolinitic clay, caused by the slaking action of this material, subsequent increased permeability and collapse. Finally, he found increased dispersibility in locations where organic acids are produced by water held and deflected by lignite beds. These organic compounds served as catalyst in the dispersion process. The overall process of topographic feature formation was found to be more complex than anywhere else because of its size and combination of more and less erodible interbedded materials. The formation process included intermittent wetting, dispersion of the bonding clay minerals, flaking or slaking of materials, freeze-thaw action and collapse of arches and blocks of material.

In concluding his report Bell indicated the importance of this phenomenon as a factor in the process of land subsidence. Interconnected piping cavities were found to contribute significantly to formation of badland topography. Finally, he described the process required to locate highways in this region.

Australian Soils Engineering Studies 1968-1970

An important case history of a large earth dam where the clay core was partially constructed of dispersive clay was presented by Ingles, Lang and Richards in late 1968 (25). The dam involved was the Flagstaff Gully Dam in Tasmania, which failed by piping in 1963. This dam had a maximum height of 51 feet and crest length of 600 feet. It consisted of upstream and downstream rockfills over filter zones which were on either side of the clay core, all on a rock foundation. The initial failure occurred because of formation of a pipe at the junction of the bedrock and the dispersive clay core. Available data strongly suggested that the dam, being reconstructed, would continue to be susceptible to this type failure.

In order to monitor the advance of the wetting front in the new section of the dam, peizometers were installed. The situation in the embankment, as of 1968, was considered good. Slow dissipation of compaction pore pressures was observed. Flow through the bedrock was significant, contributing to toe seepage and allowing infiltration of the clay core. Underseepage and infiltration of upstream water were proceeding very slowly, extending the time over which the salinity of soil water would be reduced. The observed average permeability was about 10^{-6} cm/sec (lower than the 10^{-5}cm/sec limit set by Aitchison and Wood). Flow rates were so small that swelling prevailed over the dispersive effect caused by replacement water, leading to long-term stability of the core. Equilibrium seepage flow was expected by 1973 and the stability of the structure was thought to be certain.

In 1969, Ingles and Aitchison reported on the subject of soil-water disequilibrium as a cause of subsidence (24). They noted that engineers were not aware of the cause of tunnelling erosion subsidence until the 1960's. The causes that they combined into total soil-water disequilibrium included climatic environment, land use, soil type and chemical composition, hydrological factors, and construction procedures.

Ingles and Aitchison postulated that disequilibrium occurred as a result of two factors: the existence of substantial soil porosity and the lessening of particle bond forces in the soil. The latter situation does not occur in acid soils, since hydrogen ions tend to displace aluminum ions, strongly flocculating the soils. Conversely, subsidence occurs when sodium-rich soils of high pH reach a state of disequilibrium and clay-sized particles are dispersed. They found that porosities which result in permeabilities of 10^{-2} cm/sec allow transport of particles 5.2 μ in size, while in order to stop 0.5 μ sized particles it takes permeabilities of less than 10^{-4} cm/sec. Also, it was determined that 0.05 size particles can be transported when the permeability of a soil mass is 10^{-6}cm/sec. It was pointed out that smectites and illites have small discrete particles sizes, often as low as 0.01 μ. Ingles and Wood were among the first to note that swelling action and resulting change in soil permeability was of major importance. If swelling could reduce permeability faster than dispersed clay particles were transported away, the end result would be a stable soil mass.

Ingles and Aitchison recommended the qualitative Crumb Dispersion Test of Emerson for estimation of tunneling risk, along with use of the ESP as a means of determining the severity of potential hazard. In order to assess the hydraulic risk they viewed permeabilities of higher than 10^{-5} cm/sec as potentially dangerous. Finally, they offered remedial measures to increase soil stability and diminish dispersive power of water moving through the soil. Wet of optimum compaction of these soils, coupled with measures to prevent subsequent drying, was also suggested.

Further research concerning internally erodible clay soils in Australia was reported in 1970. Two papers on this subject presented at the *Symposium on Soils and Earth Structures in Arid Climates* are of interest. The first, by Hubble and Reeve (23), was on soil salinity and stability and the second, by Reilly (33), was on post-construction experiences with urban water storages.

Hubble and Reeve reported on the soils of southwestern Queensland. Using Emerson's method for classificaiion of aggregates by coherence in water, they found most of their samples were dispersive when remolded. In addition, the frequency of this behavior was found to decrease as the depth of sample location increased.

Reilly wrote of the performance of earth dams in northwest Victoria. He found that, although most of the soils used for storage banks there dispersed in distilled and rain waters, few dispersion failures occurred because of the physico-chemical state of the stored water. He concluded that while earlier recommended laboratory tests for dispersion were valuable, reliance should be placed upon crumb and jar tests, which allow direct observation of the behavior of soils in samples of the water to be retained by these soils.

U. S. Soils Engineering Studies 1970-1973

Early in 1971, Heede, a hydraulic engineer of the USDA Forest Service, reported on the characteristics and processes of soil piping in gullies in an area of Colorado (22) observed over a five-year period. The study may be considered unique because one large pipe was inspected, surveyed and photographed from inlet to outlet. The presence of gullies, high Exchangeable Sodium Percentage, low gypsum content, and fine-textured soils with smectite clay were given as prerequisites to formation of pipes. Soil pipes were thought to be developed from cracks in soils where layer permeabilities were in the range of 10^{-6} to 10^{-8} cm/sec. An interesting fact brought out was that ESP's of soils which had fallen from gully side slopes were lower than those of stable soils. This decrease in ESP was found to continue with time. Pseudo-Karst topography was well developed in these Solonetz soils.

Three soils engineers, Sherard, Decker and Ryker, are recent contributors to knowledge concerning dispersive clay behavior in relatively low earthen dams of Oklahoma and Mississippi. They presented two papers concerning dispersive soil behavior at the June 1973 Specialty Conference on Earth and Earth-Supported Structures. One paper contained information about a mechanism they believed to contribute substantially to piping failures in dams of dispersive clay soils. Dispersive clay behavior was discussed in the other paper.

In the first paper, Sherard et al. sought to explain why these piping failures had occurred so quickly, within a few days or less after rapid reservoir filling (36). Checking the literature, they found many other cases of difficult-to-explain leaks through well-constructed dams, which had developed through cracks which were not open nor seen before the reservoir was filled. They postulated that such cracking can only develop if the minor principal stress acting within the embankment along the path of a potential leak is lower than the reservoir water pressure. This condition may cause an increase in crack width from readjustment of the embankment to this new stress condition, such that existing closed cracks might be opened and new ones formed by "hydraulic fracturing." Sherard, Decker and Ryker concluded this mechanism may have led to the development of initial leaks which caused earth dam failures in Oklahoma. They further concluded that the internal embankment stresses which led to hydraulic fracturing resulted from differential settlement and/or drying and shrinkage of the embankment during and/or after construction.

The second paper of Sherard et al. was a summary of past studies into dispersive clay behavior, the understanding of the phenomenon, and its numerous occurrences in Oklahoma (37). They concurred with earlier researchers that the main property of potentially dispersive clay was a high percentage of sodium in the pore water as compared to other cations. Soils with ESP of 7 to 10 were thought to be moderately dispersive, of 10 to 15 were believed to be potentially dispersive, and of larger than 15 were known to have critical dispersive potential. The other factor Sherard et al. noted was that the lower the quantity of dissolved salts in the water passing through the soil mass, the greater the susceptibility of the soil to dispersive piping.

Among the piping erosion indicators Sherard et al. used was the USDA-SCS Laboratory Dispersion Test. Over 30% dispersion was used to indicate a soil was moderately dispersive, while 50% to 75% or more indicated severe erosion potential. They found only limited success when correlating this method of determining piping erosion potential with observed field behavior.

Sherard, Decker and Ryker described the physical appearance of the walls of erosion channels as that of highly soluble limestone. In some locations of the study, erosive soils appeared "worm eaten" or formed large surface "alligator" cracks upon drying. One point of disagreement noted between their analyses and those of earlier researchers was the contention of Sherard et al. that the presence of protective grass worsens the problem. The grass cover was believed to accelerate drying of the soil involved, thereby increasing the size of cracks and also providing root hole channels. Another contribution to failure they discussed was the occurrence of heavy concentrated rainfall immediately following periods of dessication.

During their study, Sherard et al. concluded that when total salt concentrations of 15 milliequivalents per liter or more were in the water passing through the soil mass, dispersion of clay particles would not occur. The most nearly reliable means they found to identify piping erosion potential was by locating soil chemical data on a plot of percent sodium in the saturation extract versus the total cation concentration in the extract, divided into regions of expected behavior established by field correlation. They recommended determination of the SAR and use of readily available charts to find the ESP.

Sherard et al. recognized a need for research to improve understanding of dispersive clay soil behavior and to establish criteria and tests for use in routine design applications. They believed that the SCS Laboratory Dispersion Test needed improvement to be more nearly effective for soils engineering use. In conclusion, they recommended research into a means of identifying piping erosion potential by direct erosion testing, which would consider the combined effect of all factors influencing this erosion.

Early in 1972, Sherard published a complete report for the USDA Soil Conservation Service concerning the study described above (35). This report covers the same information of the two previously cited papers, but in more detail, featuring complete sample data and many photographs of dispersive clay soil field behavior. One additional testing technique for identification of dispersion potential was included in this report. This was the crumb test originally proposed by Emerson and modified by Sherard.

One of the most recent contributions to knowledge of dispersive soil behavior was published by Mitchell and Woodward (29). The subject of this report was an investigation into the chemistry of soils in areas of California where soils were unstable and numerous slope failures had occurred. They found, as had other researchers, that physico-chemical properties of soils vary greatly within short distances and that laboratory data varied considerably, depending upon the laboratory doing the testing. In spite of these variations, Mitchell and Woodward were able to establish that 5 of 16 samples tested had pore water chemistry favorable to dispersion. They concluded that there were insufficient data to conclusively relate the failures that occurred to loss of strength from clay dispersion, but believed that the simple chemical tests used were justified in cases of suspected clay dispersion. Finally, they placed their greatest reliance on predictions using the percent sodium-total cation concentration diagram of Sherard et al. (37).

Methods Previously Proposed for Identification of Dispersive Clay Soil

Among the methods for identification of the dispersive clay phenomenon, as discussed briefly in the first section of this chapter, are those that have been accepted as viable and useful to soil scientists and engineers. These methods may be subdivided into five groups, ranging from an early physico-chemical test still in use today to a recent method proposed by soil engineers, utilizing soil chemistry data and field behavior curves.

The first method for determining the degree of dispersion of the clay fraction of soils was proposed by Volk in 1937 (42). Since that time, it has been used with little modification by the USDA Soil Conservation Service. Originally, it was conceived for the intended purpose of testing soils of the southwest United States and has been accepted for use throughout this country and overseas.

The procedure is one to measure the amount of a sample, specifically those particles less than or equal to 5 μ size, which disperses itself upon immersion. Two soil suspensions are prepared using the same dry weight of soil, and agitated as in the hydrometer method of grain size analysis. Since only the smaller-than 5 μ fraction is to be determined, readings are taken for just that purpose. One of these suspensions is prepared utilizing a standard dispersing agent and procedure as for the hydrometer test (ASTM 2422-61T). The other suspension is prepared by placing the soil sample into a vacuum flask with about 150 ml of deionized distilled water and then applying a vacuum to the flask for 10 min. The resultant soil/water paste is poured and washed into the hydrometer cylinder for testing. The overall test procedure compares behavior of artifically dispersed and self-dispersed samples. The percentage smaller than 5 μ size in the self-dispersed sample, when divided by the similar 5 μ percentage of the artifically dispersed sample, is called the degree of dispersion of the soil, and is expressed as a percentage.

Clay-type soils with degrees of dispersion less than 30% are considered by the SCS as non-dispersive soils. Those having 30-50% dispersion are believed to be moderately dispersive and could present critical field behavior under appropriate circumstances. If soils have degrees of dispersion between 50% and 75% they are known to be dispersive and are very likely to exhibit dispersive behavior with resulting internal erosion. When this index of behavior exceeds 75%, the soil tested almost surely will exhibit all of the critical problems occurring in these problem soils. By use of this test, the SCS postulated that field behavior may be inferred directly from the results of this quantitative physico-chemical test.

The next step in identification of the dispersive clay phenomenon was made in 1954 by the USDA United States Salinity Laboratory staff (34). In their report, edited by Richards, they postulated that the real reason that clay fractions of such soils disperse is an inordinate percentage of sodium ions in the total environment surrounding the clay particles, relative to other cation quantities. These soils were defined as nonsaline alkali soils.

They chose to present two indices which may be used to illustrate the percentage of sodium ions in the saturation extract or on the exchange complex of the soil. The Sodium Absorption Ratio (SAR) is defined as the concentration of sodium ions in the saturation extract divided by the square root of the average of concentrations of calcium and magnesium ions in this extract, all expressed in milliquivalents per liter of extract, i.e.,

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{\mathrm{Ca + Mg}}{2}}} \quad \mathrm{meq/L} \tag{2.1}$$

The second index is called the Exchangeable Sodium Percentage (ESP), and is determined by dividing the concentration of sodium ions on the exchange complex by the Cation Exchange Capacity (CEC) of the soil. Both are expressed in milliequivalents per 100 grams of dry soil, thus

$$\mathrm{ESP} = \frac{\overline{\mathrm{Na}}}{\mathrm{CEC}} \quad \mathrm{meq/100\ gms} \tag{2.2}$$

An emperical relationship developed between these indices (for most soils) has been widely accepted. Since the SAR is easier to determine than the ESP, it has become standard practice to find the SAR and extrapolate the ESP for the soil from the SAR. A standard 1:1 saturation extract is prepared and cation concentrations are then determined by one of several standard soil chemistry methods. The relationship between SAR and ESP is shown in Equation (2.3).

$$\mathrm{ESP} = \frac{100\ (-0.0126 + 0.01475\ \mathrm{SAR})}{1 + (-0.0126 + 0.01475\ \mathrm{SAR})} \tag{2.3}$$

In general, soils are thought by soil scientists to be moderately dispersive in a soil mass through which relatively pure water is moving if their ESP values are between 7 and 10. Conversely, when their ESP's are 15 or more, soils are believed to have serious piping potential when exposed to water having less than 15 meq/L dissolved salts. The determination of predicted field behavior using this method is, therefore, based on the chemical situation found in the total soil sample and on the dissolved salt concentration in water seeping through the soil mass.

The next, logical, direction for research was in the establishment of a relationship between the percentage of sodium in a soil extract and the total cation concentration in the percolating water. Such a relationship would define the boundary between flocculation and dispersion of clay particles.

In 1955, Quirk and Scholfield defined such a relationship for selected illitic soils, using the breakdown of permeability during constant leaching (31). Collis-George and Smiles verified this relationship, using illitic soils and the stability of soil aggregates concept, in 1963 (12). Also in 1963, a similar relationship was defined for smectitic soils by Rowell. These two relationships are shown in Figure 2.1. Aitchison, Ingles and Wood published a similar diagram in 1963, which was based on the study by Quirk and Scholfield (1). This last diagram showed relatively clear-cut zones of flocculation and dispersion and a broad zone of partial instability. Later, in 1969, Ingles and Aitchison expanded this zoned diagram to include behavior of smectite

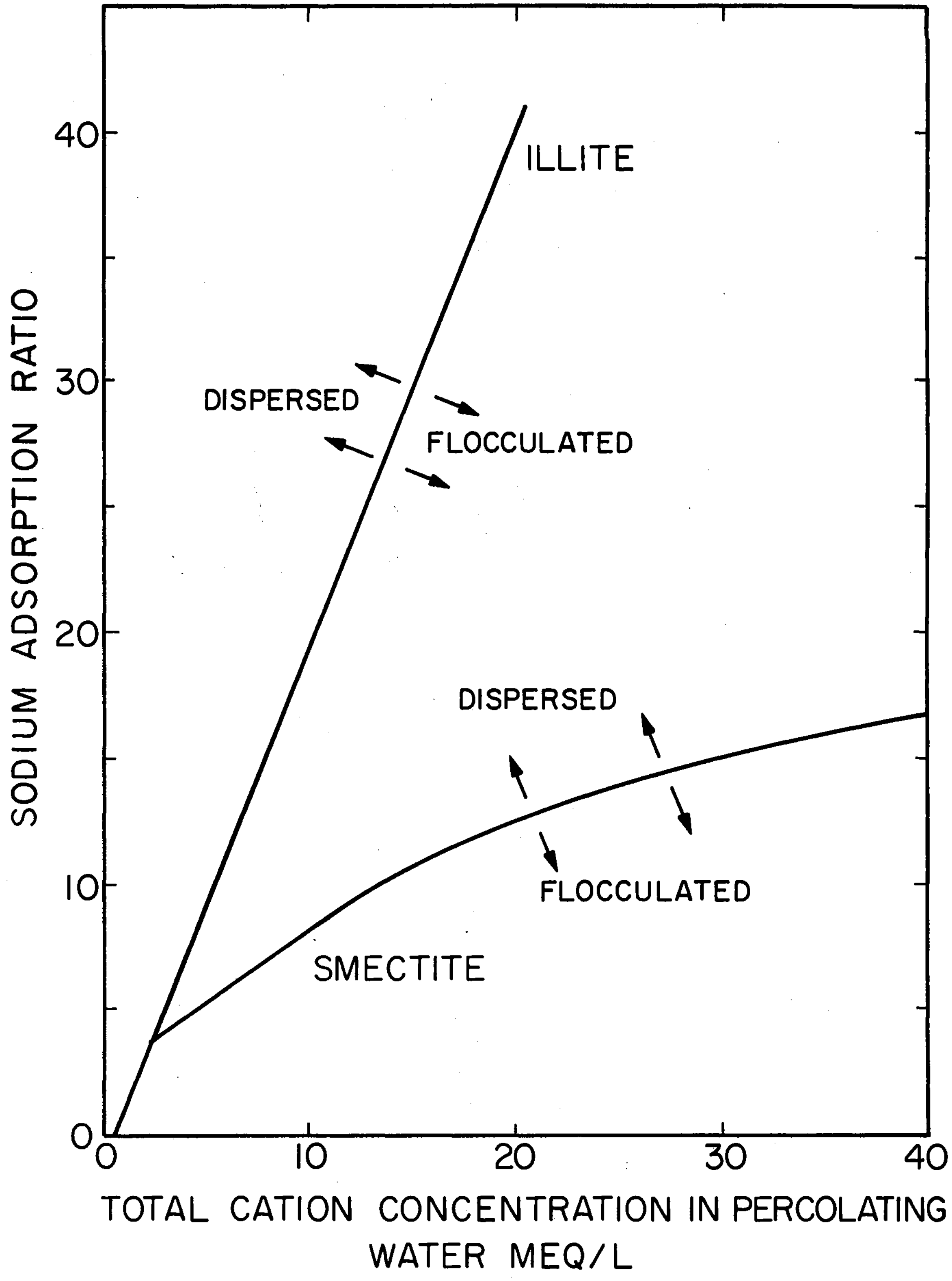

Figure 2.1. Boundary Between Flocculated and Dispersed States for Illite and Smectite Clay Soils (After Aitchison and Wood, 1965)

soils (24). Both diagrams are shown in Figure 2.2. One modification to the original relationships developed by Quirk and Scholfield and Rowell was presented by Kassiff and Henkin in 1967 (27), based on field observations of behavior of loessial soils in Negev dams. This modification is shown in Figure 2.3.

The data necessary to utilize these relationships and thus predict field behavior of clay soils are the percentage of sodium in a saturation extract and the total cation concentration of expected percolating water. Since the relationships were developed for soils containing predominately one clay mineral, it is up to the user to interpret them for the mixture of clay minerals found in his sample. These defined boundaries or zones of dispersive behavior are based completely on soil chemistry properties of the total soil and percolating water.

Another method, almost purely physical, was proposed by Emerson in 1967 (14), based on the dispersion of the clay fraction of soil aggregates in water. Because it requires the experimenter to judge whether or not dispersion is taking place, his method is a qualitative identification scheme. The reactions Emerson used to establish behavior were based on immersion of dry soil aggregates in water, immersion of wet remolded aggregates in water and suspension of aggregates in water. During the development process he tested both naturally occurring soils and prepared soils of predetermined clay mineralogy, chemical make-up and grain size. The derived classification procedure allows one to place a soil sample into one of 8 classes, according to characteristic behavior. A diagram of Emerson's scheme of classification may be seen in Figure 2.4.

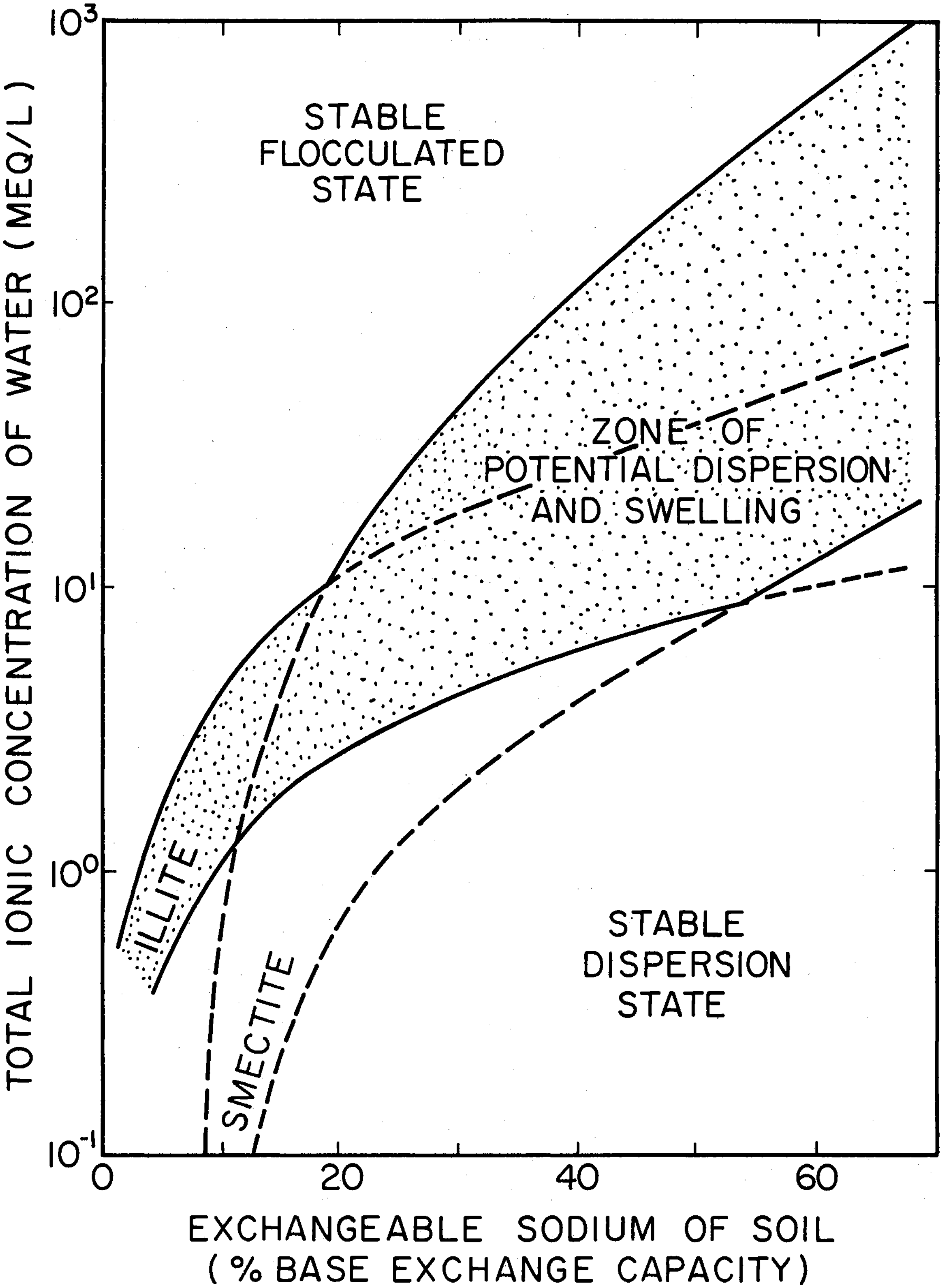

Figure 2.2. Graph for Estimating Soil-Water Instability Conditions (After Ingles and Aitchison, 1969)

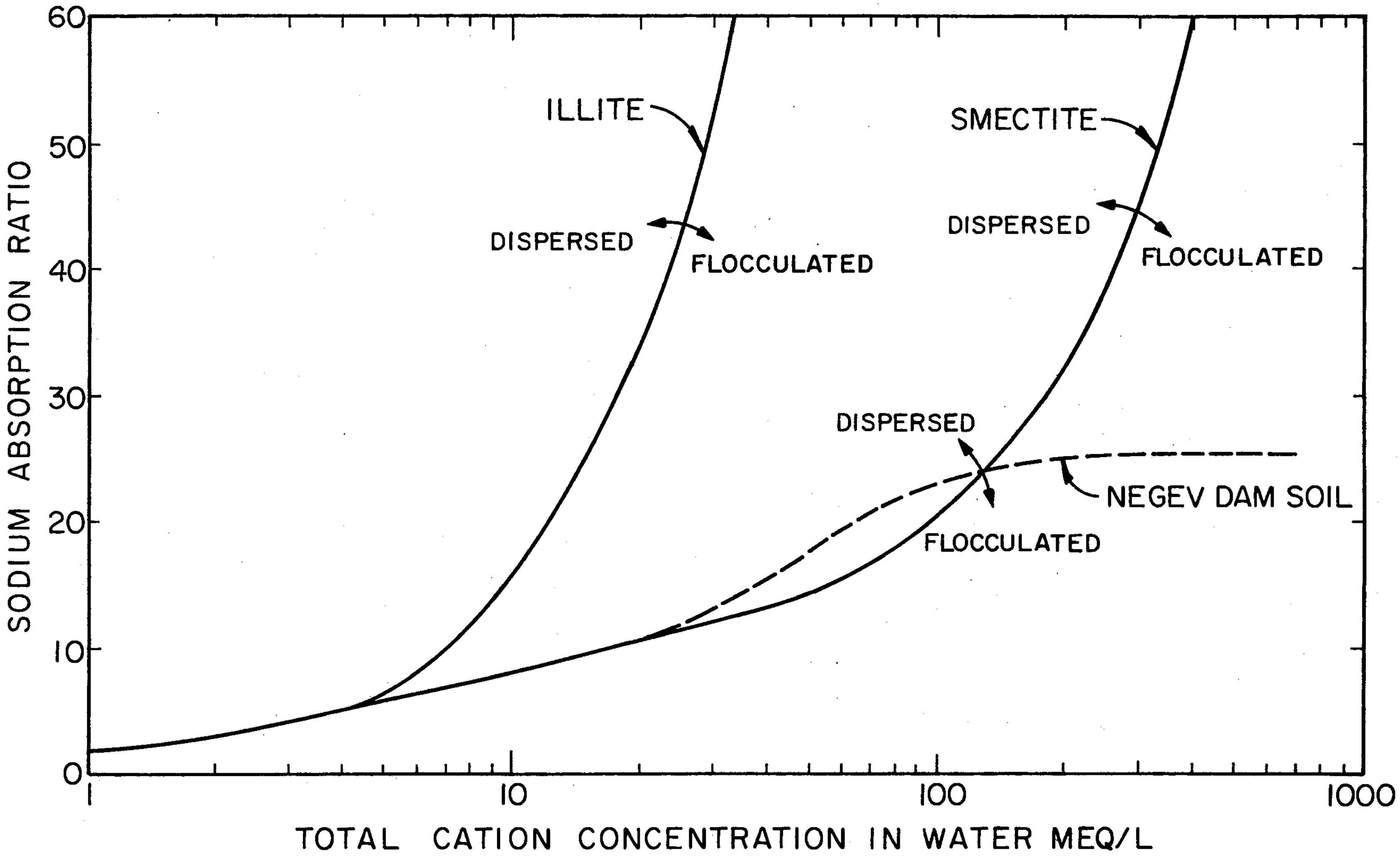

Figure 2.3. Soil-Water Instability Conditions (After Kassiff and Henkin, 1967)

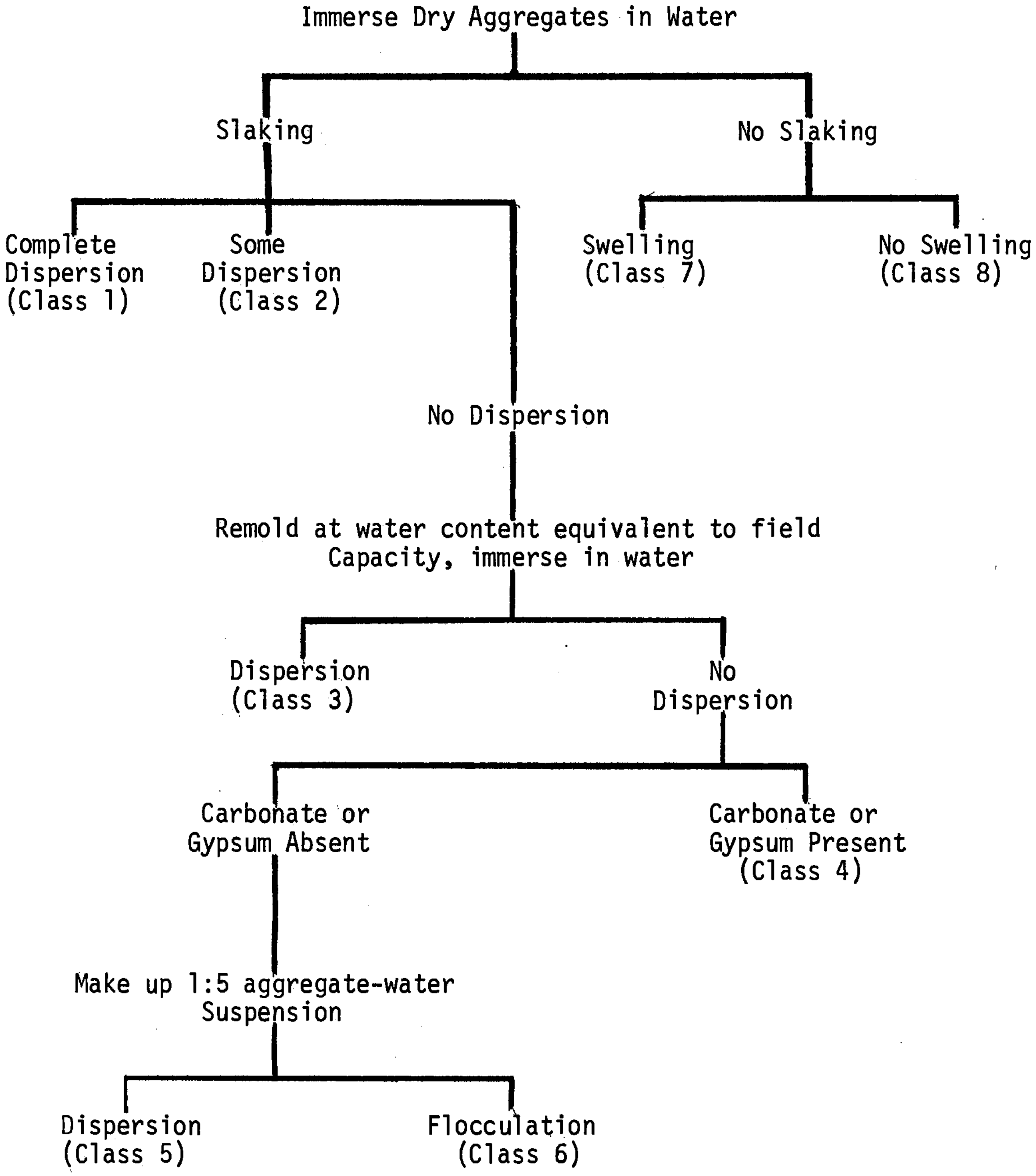

Figure 2.4. Scheme for Classification of Soil Aggregates by Coherence in Water (After Emerson, 1966)

Aggregates in Classes 1 and 2 had appreciable ESP values ranging from 17-55, with a median of 32 for Class 1. Class 2 had a minimum ESP of 7. Class 3 aggregates had ESP's that varied from 3 to 14, with a median of 6. The clay minerals associated with soils of these first three classes were illite and smectite. Aggregates in Class 4 were non-dispersive because of high concentrations of calcium and magnesium present. The soils of Classes 5 and 6 were acidic, had ESP's of 3, and very low total soluble salts. Class 5 soils contained only some illites and Class 6 soils had kaoline as their clay fraction. The remaining Classes, 7 and 8 were made up of soils which would not slake, because of natural cementation, and thus could not disperse. Those classifications which are of particular use in identification of potentially dispersive clay fractions of soils include Classes 1 through 3.

Information derived from this type of test is qualitative. If the soil being tested has behavior that places it in Class 1, it will have a relatively high ESP and exhibit very critical field behavior. Class 2 soils have moderate ESP's and may well present field problems. Conversely soils which have behavior characteristics of Class 3 are problem soils when remolded. All other classes represent soil which have no dispersive tendencies or none that might be applied to predicting internal erosion field behavior.

A refinement of Emerson's aggregate coherence test was presented by Sherard in 1972 (35). It was called the Rapid Dispersion Test or Crumb Test, and consists 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. He reported that, based upon his experience, a demineralized water immersion solution was practical and acceptable. Unlike the aforementioned classification system this method has only four grades of reaction, all directly applicable to qualitative field analyses.

Grade 1, no reaction, means that, even though a sample may slake and run out in a pile in the beaker, no sign of cloudy water is present. The slight reaction of Grade 2 is a bare hint of a cloud in the water at the surface of the crumb, whether it slakes or not. A Grade 3 or moderate reaction occurs when an easily recognizable cloud of colloids is in suspension. This cloud is usually in thin streaks on the bottom of the beaker but does not cover the entire bottom of the small beaker. The final, or Grade 4, strong reaction included a colloidal cloud covering nearly all of the bottom of the beaker, usually in a very thin skin. However, in extreme cases it may cloud the water in the beaker. These grades were visualized as directly representing field behavior, assuming the crumb tested represented the remolded or natural soil whose behavior was being predicted.

The final method to be discussed for identifying dispersive clay field behavior is that proposed by Sherard, Decker and Ryker in 1972 (37). Using test data from 99 samples of varying physical and chemical properties and known field behavior, they developed a plot of selected soil chemistry datacontaining zones of soil behavior. This plot has percent sodium in the saturation extract plotted arithmetically on the vertical axis and total soluble salts in the saturation extract plotted logarithmically on the horizontal axis. The plot is divided into three zones of behavior. Soils which have data located in the top zone are considered to be critically dispersive. Soils with data located in the middle, or transition, zone are believed to be moderately dispersive and those having data plotted in the lowest zone are thought to be non-dispersive. It should be pointed out that Sherard, Decker and Ryker did define these three zones from known field behavior and, therefore, the plot could conceivably be used for prediction of field dispersive clay behavior. Their emperically-derived plot is shown in Figure 2.5.

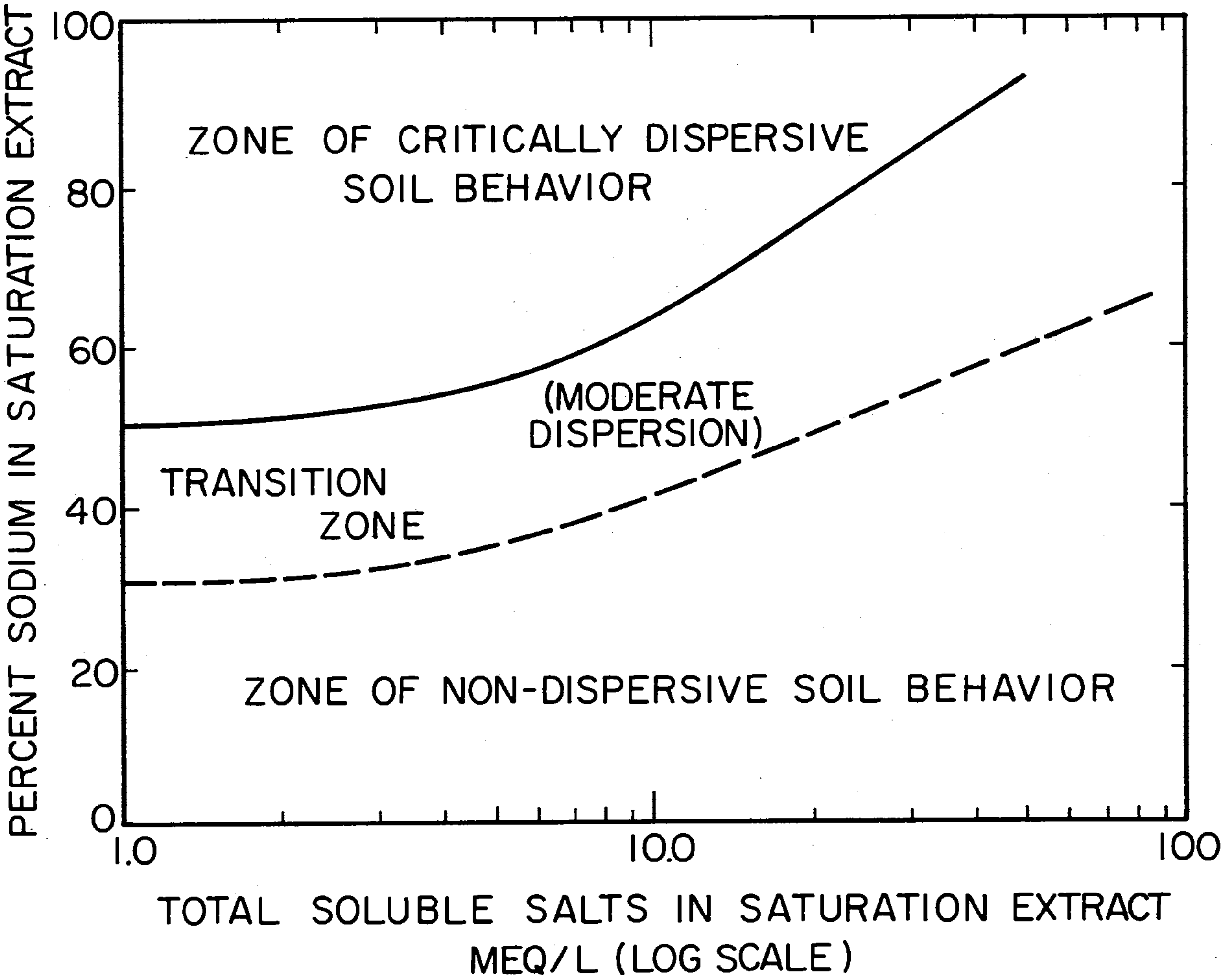

Figure 2.5. Graph for Determination of Dispersive Clay Soil Behavior (After Sherard et al., 1972)

CHAPTER III

ANALYSIS OF METHODS FOR IDENTIFICATION OF DISPERSIVE CLAY SOILS

Previously Proposed Methods

In order to be widely accepted by soils engineers, an identification method must have certain attributes. Generally speaking, these include the following:

1. Its basic underlying principles and the results obtained should be easily understood,
2. It should be practical and economical to use,
3. It should result in a quantitative measure of the desired variable, of which there should be only one, and
4. It must provide a valid result that can be readily transformed into predicted field behavior.

Perhaps the most crucial element in a laboratory testing program that would result in identification of potential internal erodibility is that of field sampling. Since the occurrence of dispersive clay is directly related to chemical conditions in the soil, which are highly variable, it is necessary that a well-planned and comprehensive sampling program be utilized, if the results from any method of identification are to be of useful significance. The engineer must be aware of the variability of this soil property and properly sample the material of interest so as to ascertain its total field behavior.

The oldest and probably most used method for identification of clay particle dispersion is the Laboratory Dispersion Test (LDT). Since its adoption by the USDA Soil Conservation Service (SCS) it has been utilized nationwide, with mixed success. Currently it is under study for modification by the SCS.

The similarity of this test to the hydrometer method of grain size analysis makes it easily understood by soils engineers. The procedures used for preparation of both soil suspensions are relatively simple and straightforward, using apparatus normally available. A possible misunderstanding that may occur is the use of 5 μ as a point of measure rather than 2 μ, since this smaller grain size is considered by most engineers the upper limit of clay. When it is the dispersion of the clay fraction that causes poor field behavior, the engineer would, perhaps, be more likely to accept measurement of minus 2 μ size particles in suspension. Conversely, this test is of relatively short duration and the results obtained are easily computed from test data, so that its use may be both practical and economically feasible.

The property measured during this test, as mentioned previously, is the percentage of minus 5 μ size particles in a suspension that has self-dispersed, divided by the same percentage of minus 5 μ particles in an artificially dispersed suspension. This dispersion is a relative measure and is thus dependent on both minus 5 μ fractions and their variation. Any difference in the amount or type of artificial dispersion may result in very different final dispersion values. The largest variations appear to be caused by differences in natural properties of the self-dispersed samples.

All the factors which affect coherence of aggregates as outlined by Emerson (14), except the chemical situation that disperses clay particles, may contribute partially or completely to the self-dispersion process during the LDT. A single factor, not necessarily existing in field situations, that has an effect is the water content of tested samples. In order to eliminate variations in test results caused by this factor, the SCS stipulates that all tests be run at natural water content. "Natural" water content is that found in the material when sampled in the field. This factor causes some uncertainty, since sampling can take place at any time throughout the year and since the delivery to the lab of samples at "natural" water content is often highly questionable. It would seem that, with all possible care taken to ensure "natural" water content, the final results may be determined for soil at other water contents and very possibly not at the one causing the most critical dispersion.

It also seems unlikely that the soil aggregates tested would closely represent the in-situ mass of the same soil. Samples for testing would very likely be disturbed and possibly remolded. This fact, along with no correction for differences in clay mineralogy and stress history, makes the prediction of field behavior doubtful from the LDT.

It has been noted above that there are two variables measured to arrive at the results of this test, making it difficult to assess the exact dispersion. In addition, although it has a quantitative result, there can be only four categories or qualities of field behavior: no, low, moderate, and high dispersion. Thus, accurate prediction of field behavior is almost impossible.

When comparing laboratory dispersion test results with known chemical indicators of dispersibility, no correlation is found (Figure 3.1). Also, when comparing LDT results to the field behavior curves developed by Sherard et al. (37), low LDT results (0-33%) plot in all three zones of behavior and the only proper field behavior correlation that can be found is when LDT results are very high (Figure 3.2). In summary, it may be said that this method of identification is not very suitable for use by soils engineers for its intended purpose of accurately predicting field behavior.

The next method to be discussed is that based solely on the soil chemistry of the material being tested and consists of using one of two determinations of the percent of sodium in the environment affecting the clay particles. It is of interest to note that a relatively small variation in percent sodium may cause a large variation in field behavior. It should also be pointed out that, because of practical and economic reasons, engineers are already determining the simpler SAR and extrapolating the ESP for use as an indicator of field behavior.

Although this simplification of procedure is available and easy analysis of results is possible, most engineers would not understand the principles behind or the true meaning of soil chemistry tests. Such procedures are foreign to them and their soils laboratory personnel, so that it may be neither practical nor economical for soil mechanics and foundation engineering firms to do such testing themselves. The testing could be contracted out to soil chemistry laboratories, but the engineer would remain separated from the determination of results and the cost would be an additional factor to be considered.

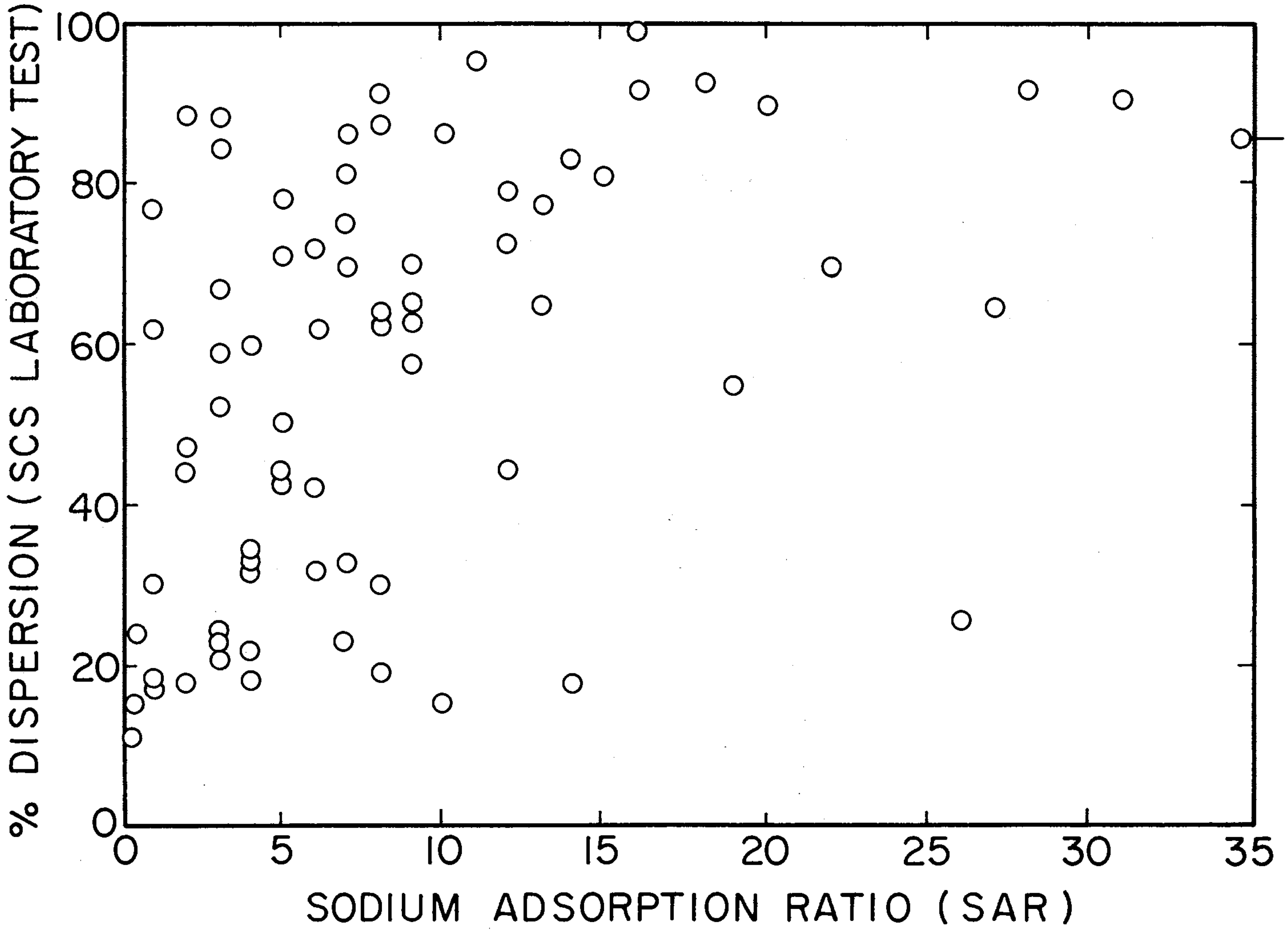

Figure 3.1. Laboratory Dispersion Test Results as Related to SAR For Samples Coming From Areas Where Critical Dispersive Erosion was Observed (After Sherard, 1972)

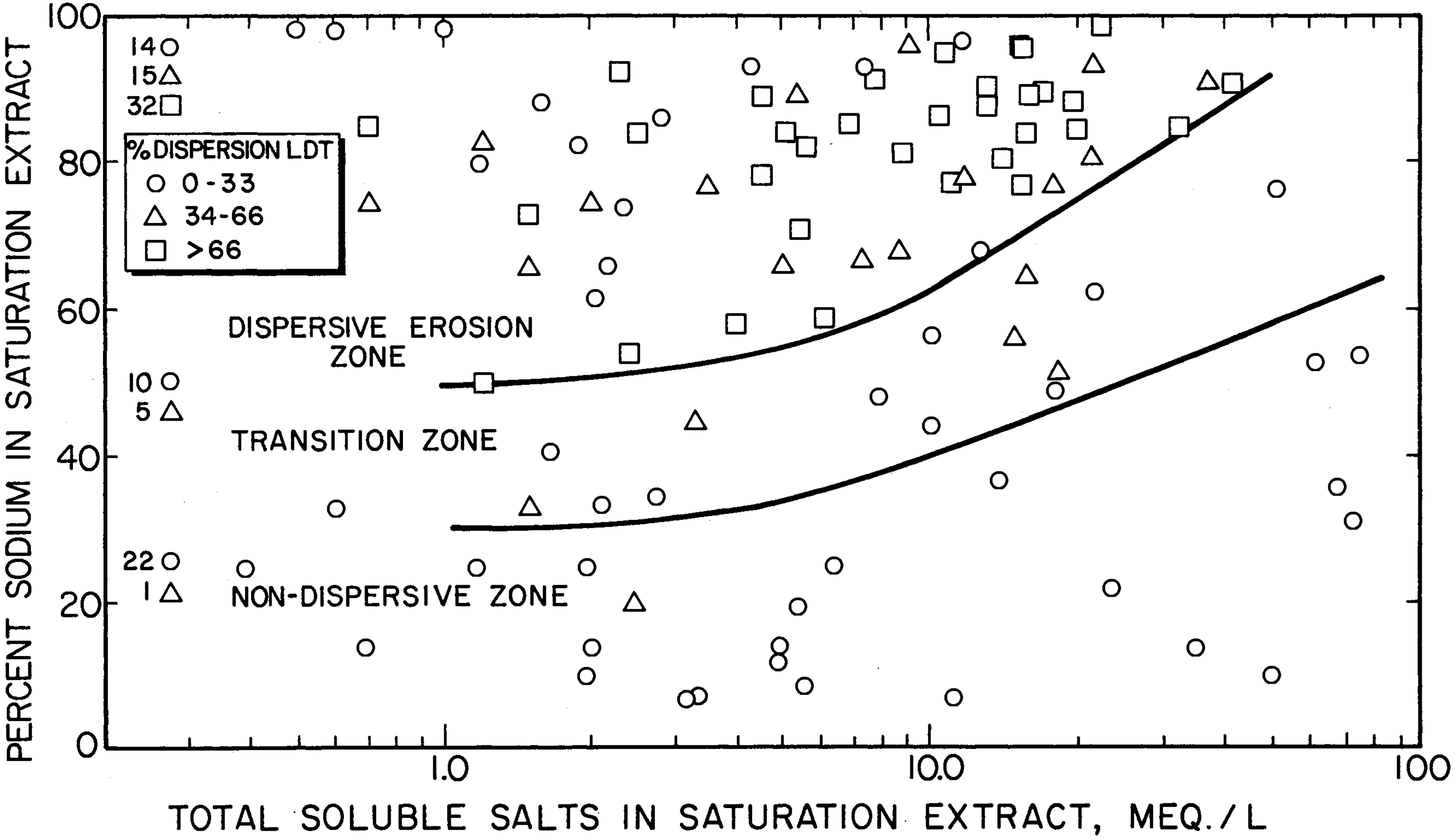

Figure 3.2. Laboratory Dispersion Test Results as Related to Pore Water Chemistry and Observed Field Behavior (After Sherard, 1972)

Both of the measures of percent sodium mentioned above are based on the total soil sample. The reasons for this are of consequence to the soil scientist, yet are not relevant to the engineer who is interested primarily in the properties of only the clay fraction, causing dispersion. In addition, even though the results obtained are a quantitative measure of one variable, their application to prediction of field behavior may be characterized as only qualitative.

Soils engineers who have studied dispersive soil behavior and soil scientists who have recently done research involving identification of this phenomenon agree that soil chemistry investigations alone ignore all other contributions to behavior under field conditions. With the foregoing analysis in mind, it is not difficult to understand why other methods have been proposed for identification of potential soil dispersion. The same reasons make this method, by itself, unacceptable to the engineer for accurate prediction of field behavior.

The third method that has been proposed for identification of dispersive soil behavior is based on chemical analyses of both the soil and water which may interact with it. The lack of understanding by the soils engineer of basic methodology, plus practical and economic problems mentioned previously are directly applicable here. This method deals with the interaction of these two purely chemical relationships and how they affect soil behavior.

Understanding the effects of this interaction on coherence of the soil mass is a step in the right direction, that of improving prediction of field behavior. More important than the other problems associated with chemical methods of identification is the fact that their results are not adequate as a basis for prediction of field behavior. In at least one case the relationships derived were adjusted so as to agree with known field behavior. While a logical endeavor, the relationship developed is probably relevant only to that singular case.

There are, basically, two elements of this method that make it less than satisfactory for use by soils engineers. The first of these is the need for sampling of water that will move through the soil mass. This may be no problem in some cases but in the majority of cases of interest to engineers this water is not available during the design analysis. This, coupled with the continuous possibility of change in chemical properties of the water make this method essentially useless to the engineer except as an aid in after-the-fact determination of causes of failures in earth structures. In conclusion, it should be noted that the relationships established and presented in Chapter II are either applicable to single clay mineral types or are useful in prediction of behavior in a relatively isolated and specific location.

One of the more recently developed identification methods is the crumb test. The results of this test are dependent on all the factors which influence break-up and clay particle dispersion of crumbs of soil aggregates. Even though this method seems simple and is easily comprehended, an understanding of all aggregate coherence factors is needed in order to analyze test results. In addition, interpretation of results is based primarily on experience of the viewer.

This method is certainly economical and practical from the standpoint of equipment and training required for preparation of samples. It has been proposed as a field test used to establish whether a material needs further testing and may fulfill this role to some extent, provided well-trained and experienced personnel do the testing.

Both of the aggregate coherence methods described earlier use three general types of reactions to determine all forms of dispersive clay behavior. This means that they are actually qualitative tests, which may be good indicators of aggregate reaction, but do not provide the engineer the information needed to accurately predict field behavior.

In his report to the SCS, Sherard (35) indicated that good correlations were found between crumb test and Laboratory Dispersion Test results on the same soils. This means that these two essentially qualitative methods agree within their general zones of determination of behavior. He included in his report a very complete description of the crumb test and specifically how one classifies aggregate reactions. This listing includes several sections that require judgement and experience for adequate interpretation, such as density of cloud of colloids, size of cloud, type of cloud, etc.

The variations in results, caused not only by overall aggregate coherence but also from interpretation of aggregate reaction, are sufficient to prohibit soils engineers from depending on such a test. Variables such as density and type of colloid coloration, temperature of immersion water, size of container used, and volume of water used have not been addressed by those proposing these methods. All of these variables may be added to the overall problems facing one who wishes to utilize such tests in the field or the laboratory. Although the proposed crumb tests may provide some indication as to general field behavior of soils, they cannot be considered adequate for use in predicting quantitative field behavior.

The last previously proposed method for identification of dispersive clay field behavior to be discussed is that developed by Sherard, Decker and Ryker (37). This one is founded on the chemistry of the soil pore water and how it relates to observed field behavior of clay soils. These two factors make this method the most acceptable for use by engineers, yet, at the same time, it does not have all the characteristics desired by engineers.

The procedures used to determine pore water (or saturation extract) chemical constituents are lengthy and require specialized techniques and equipment foreign to engineers and engineering laboratories. This portion of the overall analysis can be done at any soil chemistry laboratory, if one is prepared to accept their results and pay the additional cost. This question of acceptance is not relative to the competance of the laboratory, but is based on the willingness of an engineer to accept results he does not understand and then utilize them in his design analysis.

Since the zones of behavior associated with this method were developed by observation of field behavior, results obtained may be directly utilized to predict field behavior, if the designer believes his field situations are similar to those from which the original zones of behavior were developed, and if he wishes to know into what general zones of behavior his data fall.

However, if the designer wishes to predict more nearly quantitative behavior for his soil, he may be unable to do so, because this chemically-based method, even with zones of behavior included, cannot deal with other physical factors that affect field behavior. Among these are internal and external structure of field soil masses, mixture and kinds of clay minerals present, presence of relatively large percentages of sand

and/or silt, stress history of the soil and the climatic environment imposed on the soil mass.

When considering all the foregoing, it may be said that the last method is the most nearly acceptable for use by soils engineers; however, those using it should fully realize that its application for accurate prediction of field behavior is limited. It is interesting to note that those engineers who proposed this method also recommended that research was needed into a physical method of identification that would include consideration of all factors influencing dispersive clay soil field behavior.

Proposed Physical Identification Method

The current study was conceived because of a desire to develop a method of identifying dispersive clay soil field behavior that would be acceptable to soils engineers. It was believed that this method should consist of a physical test, such as was recommended by Sherard et al. (37). Soils engineers are familiar with physical testing principles and techniques, making this a logical choice. In addition, during this type of test the reactions of the proposed soil mass can be studied directly and become more easily understood and thus accepted.

In order to be accepted, a physical test must also conform to the other characteristics of an effective materials test. This means that it should be practical, require a relatively small sample, have a short preparation and testing time and use familiar laboratory apparatus. In addition, the test needs to be economical, to allow enough testing to adequately cover soil areas of large extent within normal testing budgets.

Also, it is very important for this method to provide sufficient information so that its result may be used to accurately predict field behavior. The test should be designed in such a way as to measure the one variable of interest while other possible variations are controlled. It is almost mandatory that the result measured be relatively precise or quantitative. Finally, the result has to be readily transformed into meaningful field behavior.

During the beginning stages of development of this identification method much thought was directed at making the procedure as acceptable as possible. It was decided that the simplest and most direct approach to field simulation would be the optimum one to accomplish this objective.

The field situation that allows propogation of internal dispersive clay soil erosion is a potentially dispersive soil mass at some normally acceptable field density with a system of cracks or holes into or through it. When relatively pure water enters these fissures, clay particles disperse into the water and are carried out of the soil mass at a faster rate than swelling can close off the cracks or holes. In the field, then, for dispersive behavior, there have to be cracks or holes, relatively pure water and soil permeability large enough to allow seepage under relatively small hydraulic gradients. If the clay in the soil mass is dispersive and physical factors are critical, there will be internal erosion, piping, etc. If the soil mass is stable and clay particles flocculated, natural cracks will close by swelling and holes will eventually be filled. The phenomenon of surface erosion via air expulsion and swelling shear stresses has similar effects in both cases.

The "soil mass" chosen for this laboratory simulation was a Harvard miniature size cylinder (diameter 1.31 in., length 2.80 in), compacted to specifications normally utilized for field density control by soils engineers. It was believed that with proper control of both density and compaction water content these cylinders of soil would well represent the physical soil mass in the field.

After many tests utilizing normal curing times after water addition and before compaction, it was decided that the variations in test reactions caused by this moisture curing introduced a variable quantity not separately determinable. In order to eliminate this variability, relating to other than the behavior which was to be measured, it was decided to compact all samples immediately following addition of compaction water. Also, in order not to introduce unwanted chemical constituents into the soil mass, it was decided that all compaction water should be distilled demineralized water.

A program of investigation was carried out to ascertain the effects of post-compaction curing. The curing periods investigated were no curing, 24 hr. curing and 48 hr. curing. The curing situations included testing just after compaction, after air dry curing, after sealed curing, after moist room atmospheric curing and after curing in an evacuated moist atmosphere. The results of this preliminary study indicated that all curing combinations imparted variant levels of behavior to the soil mass. Since these variable effects on erosion behavior were not related to the quantity being measured, it was decided that the procedure for the proposed test would include no post-compaction curing.

Longitudinal holes were used to simulate the cracks in the soil mass where relatively pure water could be introduced in sufficient quantities to cause clay particle dispersion. During preliminary testing, these holes, drilled vertically through the cylinders, performed this function well. It was also found that they provided a channel through which distilled water could be moved to flush out dispersed clay particle suspensions and renew a relatively pure water source for continued clay particle dispersion. This flushing and renewal action was included as a simulation of intermittent water introduction found in the field.

The required number and size of holes in sample cylinders were determined by trial and error, aimed at simulating field behavior. First, there had to be sufficient internal surface area available and a sufficient volume of water available for adequate clay particle dispersion to occur. Second, the location of these holes in the cross section of the cylinder had to include consideration for reducing straight through flow of water and for maintaining structural coherence of the cylinder. Finally, their size had to be such that those soils capable of swelling and closing the cracks or slumping and sealing the cracks before significant erosion occurred could react as in the field soil mass. Also, there was some consideration included for keeping their size and location practical and economical. After preliminary testing using soils of varying dispersive and swelling properties, a configuration of three 0.125 in. holes spaced evenly throughout the cross section of the cylinder was chosen. This particular cross section is shown in Chapter IV and functioned very well during testing, satisfying all the requirements listed above.

Because of the large quantities of relatively pure water needed, distilled water was chosen for use during all testing. The pH of this water was close to that of distilled demineralized water. Its use was considered justified since its chemical makeup closely simulated that of rain water.

During preliminary testing, two schemes of water movement were investigated. These were very slow continuous flow and intermittent flow. This part of the development process demonstrated that it made no essential difference which scheme was utilized. In order to limit the quantities of distilled water required, an intermittent flow system was chosen. This system provided stationary water in the hole system of the soil cylinder, which was flushed and replaced for about 7 sec. each 6 min.

In order to provide a closed environment surrounding the soil cylinder, in which movement of water could be controlled, cylinders were placed in lucite cells. Compacted cylinders were slightly compressed and centered in the cell to insure adherence to the cell walls and proper spacing at each end for water distribution and collection. Longitudinal holes were drilled and cleaned out following this operation.

Although the desire to simulate field soil mass environment was the most important consideration in adoption of this method, practical and economical considerations also influenced its development. It was believed that this method should provide reliable estimates of field behavior in a relatively short time, thus the internal erosion process had to be accelerated to provide, in hours of testing, results that took months to occur in the field. This was part of the reasoning behind the size and number of holes used; but, more important, it meant that back pressure was needed to reduce the time for water movement into the soil mass surrounding each hole and to accelerate the disintegration of the soil cylinder.

Two factors were found to influence the movement of water into the disintegration of the compacted soil cylinder. The first of these was the pressure at which water was introduced into the hole system of the soil cylinders. Because of observed surface "membrane" action during introduction of pressurized water, this technique reduced the movement of water into the soil cylinder. Surface aggregates tended to seal off the pore system from water under this situation. When water was introduced to the hole system of the soil cylinder by gravitational flow it moved into the soil by normal capillary tension, with effects similar to those that occur in the field. If water was introduced to the soil cylinder in an evacuated environment, the factors affecting differences in surface erosion behavior were negated and overall reaction of all soils to internal erosion was very much reduced. After studying these observations, it was clear that to simulate field behavior water had to be introduced by gravitational flow. A second factor was found to influence disintegration of the soil mass. This was pressurization of the total water system to accelerate movement of water into the soil after its initial gravity introduction. This pressurization was also essential to the flushing and renewal of water in the soil cylinder hole system.

Determination of a preferred test water pressure was included as part of the preliminary testing process. As it took about 5 psi to provide the necessary flow for flushing and to ensure closure of the solenoid valves used for control of water flow, this value was chosen as a lower limit of possible test water pressure. In general, it was found that, as final test back pressure was increased, observed internal erosion increased. In order to keep from overpressurizing the soil mass, the upper limit was chosen to be 20 psi. After many test cycles, a pattern of erosion versus test pressure was observed that indicated the optimum test water pressure for soils of different properties was about 15 psi. This value was then utilized for all research testing.

Another problem that arose during preliminary testing was related to differentiation of internal erosion caused by surface erosion factors from that caused by clay particle dispersion. There were, for instance, some soils which had critical surface erosion properties yet showed no internal erosion in the field. The converse was also found to be true, to some extent, in certain other soils. The accelerated erosion process described above affected both types of erosion in approximately the same way. It was necessary, then, to define dispersive clay erosion by placing some device in the test cell. It should be noted that aggregates of soil containing flocculated clay particles were found structurally coherent even under the flow conditions which were imposed in the test cells, while aggregates of soil containing dispersible clay particles were found to "melt." As a reference for defining coherence or melting of soil aggregates a sieve was placed below the soil cylinder in the cell. Because of its standard use by soils engineers and also relative availability, U.S. No. 40 sieve wire was utilized. This method of differentiating between aggregate coherence or disintegration proved to be effective and acceptable.

Determination of the length of test needed to observe long term internal erodibility utilizing this procedure was carried out while the other factors included above were studied. This was done by keeping records of estimated erosion noted at intervals during each test. Since these tests were on soils of varying dispersive properties, many possible internal erosion situations were studied. It was found that, for soils which had critical internal erodibility, four hours was the optimum time for a test to measure this behavior. Because of this, as well as a desire to set the time of test so that two sequences could be done each day of testing, a 4 hr. test period was chosen.

The final decision made concerned the quantity to be measured. This quantity had to be readily applicable in determination of field behavior and precise enough to be considered quantitative. Since it was possible to determine easily the initial and final dry weight of soil in the cell, a relationship based on these values was selected. The "percent of erosion" selected was thus defined as the ratio of the weight of dry soil lost during the test to the initial dry weight of soil in the cell, expressed as a percentage. This result was found to be directly related to potential internal field erosion.

It is believed that this proposed method for indentification conforms reasonably well to the desired characteristics of an engineering materials test. It should be easily understood by engineers because it utilizes a physical test procedure. It has been designed to be both practical and economical. Because all variables except the one being measured are controlled, it provides an acceptable quantitative result. Finally, this valid result can be readily transformed into a prediction of field behavior, as will be shown in subsequent chapters.

CHAPTER IV

MATERIALS, LABORATORY EQUIPMENT, AND PROCEDURES

Introduction

This chapter includes the description of the soils, the equipment and the procedures utilized during this research into the physical identification of dispersive clay erodibility. The general physical properties, soil series classification and geologic units of the eighteen soils tested are introduced. The section concerning equipment presents the specially manufactured apparatus used during this study. Descriptions covering equipment of a general or standardized nature is omitted. Sample preparation and testing procedures are presented, with emphasis placed on detailed descriptions of research-developed procedures.

Materials

The research program was conducted on eighteen soils of varying physical properties, soil classifications and geologic histories, native to Oklahoma, Arkansas, Mississippi, and Georgia. Fifteen of these were picked for this study because of the tendencies of their related soil masses to exhibit dispersive clay erosion in the field. The remaining soils were added to provide a measure of control to this study, since their related soil masses do not show this tendency. In order to simplify laboratory testing, all soils were numerically identified as samples 101 through 118. Pertinent engineering properties of all samples are given in Table 4.1.

Samples 101 through 105 were soils of varying color and properties taken from naturally occurring deposits located adjacent to the Konawa power generating facility owned by the Oklahoma Gas and Electric Company. They were near-surface samples from areas adjacent to the intake channel, railway spur and oil tank farm of the plant. All were samples taken from soil masses that were weakened by piping and jugging, and had relatively large slip failures in their slope faces.

Four of these five soils are of low plasticity and fairly well graded with percentages of clay in the low twenties. These soils possess a moderate tendency to shrink and swell with changes of moisture. Soil number 105 is of medium plasticity and well-graded, with thirty-six percent clay. This sample shows a moderately high shrink and swell potential. These five samples vary in color from dark brown to gray brown to light gray or yellow brown. Their textures vary from silty clay to sandy silty clay.

All of these soils are most likely of the Carytown soil series. They have developed in material weathered from shale high in exchange sodium and have neutral or alkaline lower subsoils. They occupy large broad slightly depressional low-lying upland areas that are in places connected by saddles across ridges. These areas are generally poorly drained, having low permeability and slow runoff. Soils of the Carytown series were formerly classified as Solonetz. Lime concretions and gypsum crystals are present in the lower part of the subsoil in most places. Finally, these soils have a very friable A horizon of grayish brown

TABLE 4.1

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	0.005mm	0.02mm	0.05mm	#200	#140	#60	#40	γd pcf	ω	γd pcf	ω
101	2.69	35	18	17	9%	24%	21	31	51	76	84	87	97	100	104.5	17.8	114.9	14.5
102	2.69	41	19	22	11%	29%	25	38	55	75	84	88	97	100	102.0	19.2	112.5	15.8
103	2.69	37	18	19	10%	27%	25	34	49	67	78	84	97	100	105.9	17.5	117.0	14.5
104	2.69	33	13	20	11%	30%	23	28	43	58	67	76	92	100	111.4	16.3	117.5	10.1
105	2.72	54	20	34	17%	44%	36	48	65	78	84	88	96	100	95.7	21.8	110.6	17.5
106	2.70	45	18	27	14%	37%	31	41	70	90	97	98	100	---	103.7	19.0	114.9	15.4
107	2.70	44	16	28	16%	40%	36	49	60	87	90	91	96	100	99.4	17.0	114.5	14.2
108	2.69	42	22	20	13%	34%	41	60	78	80	86	89	97	100	98.7	22.5	110.5	18.3
109	2.68	22	14	8	9%	25%	23	29	42	55	65	73	92	100	117.5	13.7	125.8	9.9
110	2.68	21	13	8	8%	21%	17	20	32	43	52	63	91	100	121.7	12.0	128.1	8.6
111	2.68	23	13	10	9%	26%	22	27	45	63	75	82	95	100	118.3	13.3	127.2	9.5
112	2.72	47	16	31	17%	46%	36	51	69	82	86	87	100	---	106.5	16.9	115.6	15.0
113	2.72	63	19	44	17%	47%	30	73	83	86	87	100	---	---	96.2	20.0	107.7	19.0
114	2.63	68	34	34	16%	53%	62	78	93	95	97	100	---	---	84.7	32.7	93.2	27.4
115	2.77	42	22	20	12%	54%	36	69	97	100	---	---	---	---	108.0	19.0	121.1	14.6
116	2.70	32	20	12	9%	35%	25	40	68	84	93	100	---	---	100.5	21.5	116.1	15.2
117	2.67	32	22	10	5%	21%	13	18	54	89	91	92	93	94	100.5	20.0	115	14.2
118	2.67	28	17	11	6%	20%	17	21	47	71	77	80	95	99	109.0	17.0	122.5	11.5

color which grades into a columnar, then very fine blocky structure of the mottled clayey soil B horizon.

These soils are underlain by the Vanoss geologic unit of the Pennsylvanian Period. This area of Oklahoma is within the geologic feature designated as the Prairie Plains Homocline. This is a broad structural feature involving the gently westward-dipping geologic beds of the mid-continent region west of the Ozark Dome of northern Arkansas and southern Missouri. The westward dip of the homocline is generally less than 100 feet per mile. Outcrops of geologic units trend north-south in Seminole County. The Vanoss unit outcrops from the area adjacent to the Arbuckle Mountains, northward to about the middle of Seminole County. This unit consists of alternating moderately soft to moderately hard sandstones, conglomerates, shales, and a few thin limestones. Parts of this unit which occur at the site of sampling are weathered shales and moderately soft sandstones. The topography is gently rolling.

Samples 106 through 108 were obtained from a relatively shallow highway cut about 7.6 miles East of Ponca City on the road that leads to the Kaw Dam area. Soils of similar physical properties and varying color were taken from areas of this cut in natural deposits where serious internal erssion was occurring. Piping, jugging and collapsed arch-gullies caused by internal erosion were distinct features of the cut.

These three soils are of medium plasticity and possess a moderately high shrink swell potential. They are fairly well-graded with percentages of clay ranging from 31 to 41. Soil 106 overlaid 107 which overlaid 108, and they graded in color from yellow-medium brown to medium brown and abruptly to light gray in color. The top two soils are silty clay with some sand and the light gray soil is a silty clay.

The soil profile at this highway cut is most likely a combination of Newtonian silt loam overlying the Song-Summit complex. The yellow-brown lower levels of the Newtonian series grade through medium brown until the cut face reaches the gray Sogn-Summit series. Newtonian silt loam occupies broad gently sloping uplands above limestone escarpments of the Sogn-Summit complex. Small slickspots occur in this series but are not mappable. The Sogn-Summit series varies in both depth and proportion of the constituent series, consisting of 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 Permian Period. These sediments are part of the Prairie Plains Homocline, discussed earlier, and dip gently westward 40 to 50 feet per mile at this location. The unit consists dominantly 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.

Samples 109 through 111 were taken in a highway cut that had suffered a large circular arc failure. This location is near Sawyer, Oklahoma in Choctaw County. These similar light yellow-brown soils of low plasticity have the texture of a sandy clay. Although fairly well graded and sandy, their relatively low percentage of about twenty percent clay provides them with a moderate tendency to shrink and swell upon changes in water content. Because of their grain size distribution these soils have relatively high compacted densities.

The soil series from which these samples come is most likely the Bowie series. This series consists of yellow podzolic soils having friable subsoils that are yellow in the upper part. The parent materials are arid moderately sandy clays. The subsoil is not dense in the natural state and allows free surface drainage and good underdrainage. Where the land is sloping, the unprotected surface erodes rapidly.

This soil has been developed from the beds of the Woodbine geologic unit. The materials within this unit were laid down during the Cretaceous Period and consist principally of cross-bedded, coarse to fine grained, loosely consolidated, reddish-yellow to brown sandstone. Interbedded with the sand are brownish-red clay lenses. These deposits are part of the Gulf Coastal Plain, which is an east-west belt of gently southward dipping sediments. At this location the dip is 50 to 100 feet per mile. The topography of this unit is that of low rolling hills.

Soil number 112 is Permian Red Clay (PRC) which was chosen to be studied because of its lack of any tendency to erode internally and its relative availability. The sample used was taken from a depth of approximately ten 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 low to medium plasticity and exhibits a moderately high tendency to shrink and swell with changes in moisture content. This material contains thirty-six percent clay and has a texture of a silty clay with some sand. Although not internally erodible it possesses a critical tendency toward sheet erosion.

This soil is an excellent example of the Vernon series. It is from the "D" horizon which normally presents itself as a compact, calcareous, massive clay of marine origin. These substrata range from very slowly permeable to nearly impervious.

The shales from which this soil is weathered are part of the Wellington-Admire geologic unit which had its origin during the Permian Period. The parent material in this area is predominantly shale which contains lenses and beds of sandstone, limestone and a few thin siltstones. This unit is several hundred feet thick and has a north-south outcrop pattern 20 to 30 miles wide. The shales of this unit form gently rolling hills.

Sample number 113 is 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 (Section 11, R25W, TWP15N). Near this location there is a near-vertical unprotected cut in this soil which has remained nearly unchanged since its construction. This sample, containing about thirty percent clay, exhibits a moderately high tendency to shrink and swell with changes in water content. The textural classification of this soil characterizes it as a sandy silty clay of high plasticity.

This material is from the subsoil of the 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 is possibly more nearly correct to say that this sample comes from the Brownfield series, that is mapped with the Nobscot series in this county. This would explain the larger amount of clay found since Brownfield soils are more clayey. Soils of this series, located at this depth, are moderately alkaline and calcareous. The description given also includes some that are formed from shale, since they can be coarse to medium blocky with a firm consistency when moist. The topography of these series is nearly flat to undulating.

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

The third soil chosen for this research as a material which would not erode internally was Georgia Kaolinite, number 114. This sample, known to consist of nearly all Kaolinite clay, is nearly white in color. It was made up of minus U.S. No. 200 sieve size material with sixty-two percent clay sized particles. While possessing a relatively high liquid limit, because of the high amount of clay present, this soil has moderate plasticity. It did exhibit a moderately high ability to shrink when dried from near its liquid limit and was difficult to mix and compact as shown by its compaction properties. The texture of this soil is that of a "fat" clay. The soil series and geologic data of this sample are not available. This particular material is mined for commercial use in Georgia.

The last four samples tested during this research were chosen from those available at the School of Agronomy of Oklahoma State University, and were part of those included in the recent study by Sherard et al.

(37). They were chosen, as nearly as possible, to represent dispersive clay soils tested during that research.

Sample number 115 of this study is part of soil sample S-29 of the referenced study. It was one of over forty such samples taken from Soil Conservation Service dams in Oklahoma that were damage by piping. This material comes from a borrow pit upstream from the Owl Creek dam site number thirteen. Its color is bright red and it has moderately high shrink-swell potential during moisture changes. This fairly well graded silty clay has low to moderate plasticity. Its propensity for self dispersion, as measured by the Laboratory Dispersion Test during the referenced study, places it within the category of probable internal erodibility. This is further supported by the ESP obtained during that research.

Sample number 116 is part of soil S-44 of the referenced research. This material was taken from Wister Dam, located in southeast Oklahoma. Previous mention of the problems of this large U.S. Corps of Engineers dam was made in Chapter II. This recent sample was taken from the wall of a vertical erosion tunnel located in the downstream slope of this dam. Many of these tunnels have formed from rainfall since the construction of this structure, in spite of good maintenance procedures. This particular sample comes from the right half of the downstream slope above the berm and from a tunnel near one of the larger jugs. It has a light gray-brown color and the texture of a sandy silty clay. Although low in plasticity, the material possesses a moderate tendency to shrink and swell with changes in water content. This soil would probably erode internally, as measured by the referenced study, using the Laboratory

Dispersion Test. The ESP found for this soil during that research also substantiates this erodibility.

Sample number 117 of the current study is part of sample S-79 from the referenced research. It is one of several taken from three low homogeneous clay dams in Arkansas which have moderate damage by vertical tunnel erosion caused by rainfall. The dam from which this material is taken is near Wynn, Arkansas, in an area of a relatively localized geologic feature called the Crowley Ridge. This ridge consists of fine grained alluvial soils capped with loess. This area is the only location in Arkansas where the Soil Conservation Service has experienced such problems. The dam involved is at Caney Creek site number six and the original sample was taken from the wall of a large jug at mid-length of the downstream slope. The color of this material is light brown and it has the texture of a silty clay. This soil is fairly well-graded, containing thirteen percent clay size particles. It has low plasticity and exhibits a low to moderate shrink-swell potential during changes in moisture content. Although its ESP measured during the referenced study indicates that it is only on the borderline of being an internally erodible soil, its Laboratory Dispersion Test results, determined then, show it to possess critical internal erodibility.

The remaining sample, number 118, used for this research is part of number S-87 from the referenced study. It was taken from a typical Soil Conservation Service dam located in an area of Mississippi where most such dams are damaged by tunnel erosion from rainfall. In this region a greater number of dams are affected, and with more severe damage, than in Oklahoma. This sample was originally taken from the immediate vicinity of jugs in the upstream slope, near the crest, on the dam at

Big Sand site number eight. The color of this sandy silty clay is yellow-brown. It is a fairly well-graded soil containing seventeen percent clay sized particles. This sample has low plasticity and exhibits a low to moderate potential to shrink and swell upon changes in water content. The test results of both the Laboratory Dispersion Test and ESP obtained during the referenced study show it to have a critical propensity to erode internally.

The pertinent engineering properties of all materials tested during this research are included in tabulated form for ease of comparison (Table 4.1). Grain size distribution curves and compaction curves determined during this study are explained in Chapter V. Related soil chemistry data for all samples may be found in Chapter V.

Equipment

During the development of a physical identification method for dispersive clay erodibility, discussed in Chapter II, special equipment was designed and constructed to accomplish procedural tasks. An important part of the overall research program was to develop an erosion device to enable the simulation of field situations, yet accelerate dispersive erosion so that it could be measured during a relatively short test period. Several pieces of auxiliary equipment were built to assist during the preparation of samples for testing. As a preliminary development project, a miniature compaction machine was designed and constructed, to aid in the elimination of variables that would affect test results. Prior to describing these special apparatuses, a brief discussion of of standard equipment utilized will be presented.

Initial sample preparation included the use of gravity drying ovens (110° C), a soil grinding machine, U.S. No. 40 sieve, and balance (0.001g sensitivity). Standard soil mechanics equipment was utilized during determination of liquid and plastic limits and grain size distribution of each soil. Linear and volumetric shrinkage were found with the use of the Texas Highway Department Bar Shrinkage apparatus. A Fisher Model 260 differential thermalyzer was utilized for differential thermal analysis to determine the clay minerals present in each sample. The pH of all soils was found through the use of Sargeant-Welch Model NX pH meter. Laboratory Dispersion Tests were carried out using soil mechanics laboratory equipment normally utilized for hydrometer analyses, with the addition of a vacuum dispersion apparatus. Other soil chemistry investigations were done with equipment normally used to make saturation extracts, ion content determinations, illite clay mineral studies and X-ray diffraction analyses.

During prior research endeavors at Oklahoma State University, miniature sleeved compaction hammers had been developed to simulate both Standard and Modified Proctor compaction efforts. These were designed and built to extend the usefulness of miniaturized testing apparatus.

In order to eliminate as much operator variation as possible during compaction of specimens and to ensure a uniform distribution of compaction energy over the specimen surface, a miniature compaction machine was built. The concept of this device is a falling hammer similar to those developed earlier and a rack and pinion gear arrangement for lifting the hammer. Standard Proctor Compaction effort is applied to a specimen by 19 blows of the hammer falling 4 inches on each of 4 layers (Figure 4.1). Modified Proctor Compaction effort is achieved when a

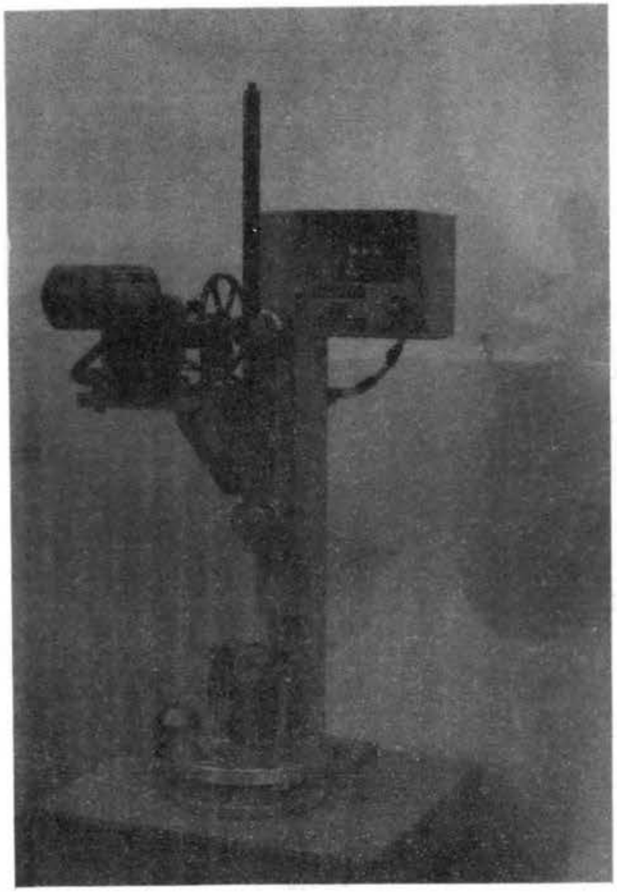

Figure 4.1. OSU Miniature Compaction Machine - Standard Proctor Operation

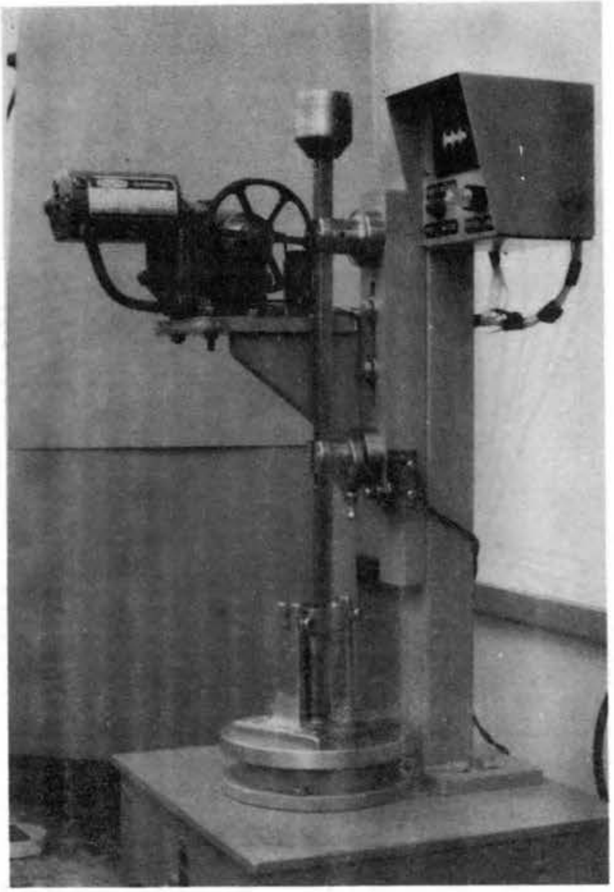

Figure 4.2. OSU Miniature Compaction Machine - Modified Proctor Operation

weight is added to the top of the hammer (Figure 4.2) and 25 blows are delivered from 4 inches on each of 5 layers. The table upon which the mold and supporting base sits is rotated by an electric motor, actuated momentarily while the hammer is lifted, so that hammer blows are distributed evenly over the surface of the soil being compacted. Although this device is still in the final development stage, it performed well during this research, and proved the original concept to be sound. A full-view of this device is shown in Figure 4.3.

Inherent in the purpose of this research, as outlined in Chapter I, was the development of a test apparatus to simulate field internal erosion and to do so at an accelerated rate. The erosion device was constructed by extensive modification of an existing device used in determination of permeability of clay soils.

The most important part of this apparatus is a "cell" constructed of lucite, into which a Harvard-miniature sized cylinder of soil is placed after compaction, slightly compressed and perforated with longitudinal holes. The completed cell, with soil cylinder, is shown in Figure 4.4. Water enters the top of this enclosure through a 1/4 inch O.D. tube and is distributed over the top of the soil. Below the soil cylinder a disc of U.S. No. 40 sieve wire is placed and is supported by a porous disc and support ring. Water collects under this porous disc and exits the cell through 1/4 inch O.D. tube.

In order to store sufficient quantities of distilled water under pressure, to distribute it to four cells during test, and to collect exiting suspension, a water flow system was added to the erosion device. This system includes primary and secondary holding tanks, an air pressure

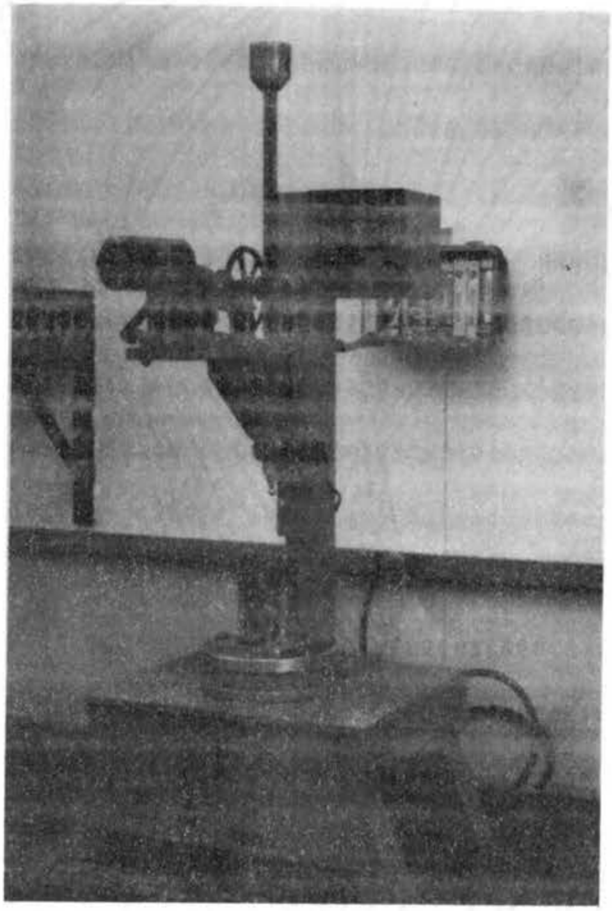

Figure 4.3. OSU Miniature Compaction Machine - Full View

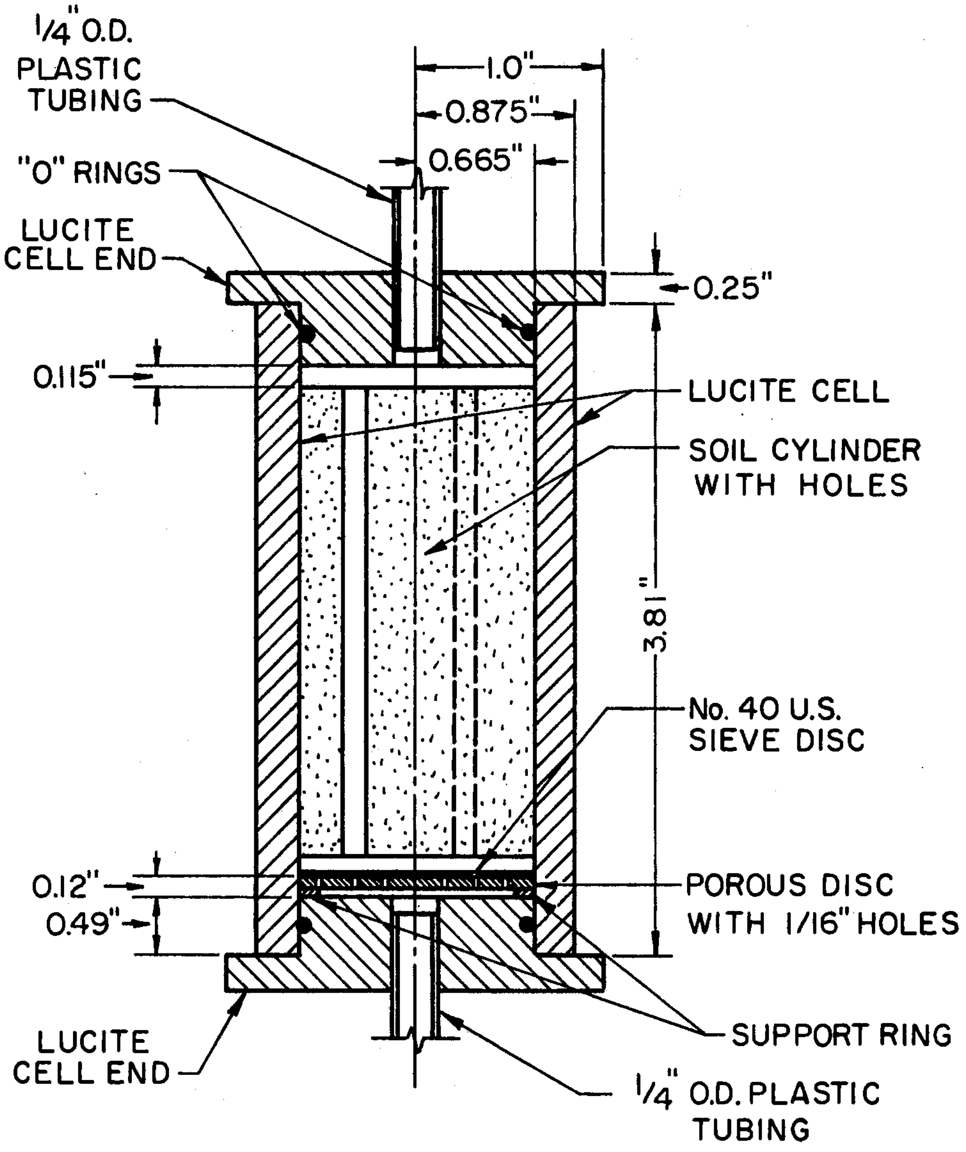

Figure 4.4. Assembled Erosion Device Cell With Soil Cylinder - Cross Section

regulating unit, a distribution manifold, two waste water containers, and associated valves and fittings.

The primary holding tank is a galvanized steel container with an effective capacity of twenty-five gallons. It was outfitted with valves and fittings for filling, pressurization, and venting of pressure. It was necessary to fill this tank before every other test sequence.

The secondary holding tank of lucite, has a capacity of about 500 ml, and is positioned at the top of the erosion device. The output of the primary holding tank is routed to the top of this tank where there are fittings and valves for shut off of input, monitoring of water pressure or input of prepared solutions, and venting of pressure. This reservoir, when filled and vented to the atmosphere, was used during primary sample filling, and served as a water observation point and pressure difference dampening chamber during testing.

The air pressure regulating unit consisted of a regulator of 100 psi capacity, an air pressure gage and water pressure gage of similar capacity. The air pressure gage was used to monitor the air pressure on top of the column of water in the primary holding tank. The water pressure gage was affixed 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 water pressure being introduced into the cells. This unit assured the near constant pressure regulation essential for testing.

The balance of this system consisted of a pressurized water distribution manifold, tubing required to allow for routing of waste water, and two receptacles for the collection of waste water. The manifold was constructed of half inch steel pipe, brass fittings and a valve for each of the four cell units, so that water from the secondary holding tank was distributed and controlled for each cell unit. All tubing used for construction of the erosion device was 1/4 inch O.D. plastic. Waste water collection receptacles were two 5 gallon PVC containers. A detailed diagram of this system is provided in Figure 4.5.

The third and final system constructed as a necessary part of the erosion device was that for timing and control of waste water outflow from the cells. The rationale for control of this outflow is discussed in Chapter III, so that this discussion is directed to its accomplishment. Units of this system include power supply and switching, timing, settling basin, and solenoid operated valves. Together, these units assure the necessary intermittent flow of suspension from the cells.

The primary part of the power supply and switching unit consists of four switches, one for each cell, through which 110 volt, 60 Hz power is routed and with which it is controlled. The output from these switches powers each corresponding timer motor and is routed through the microswitches of these timers to their respective solenoid valves. When the switches are turned on, the timers of each cell are energized and power is available to operate the respective solenoid valves as each microswitch is closed.

Timing units are simple devices consisting of a constant speed motor with an adjustable cam mounted on its shaft which either holds the integrated microswitch open or allows it to close. The total cycle time available with this device is six minutes. The cams of all units were adjusted for a closed switch time of seven seconds, during which power is routed to the respective solenoid valve to keep it open. The resultant timing is continuous (agreeing to the second over all research work)

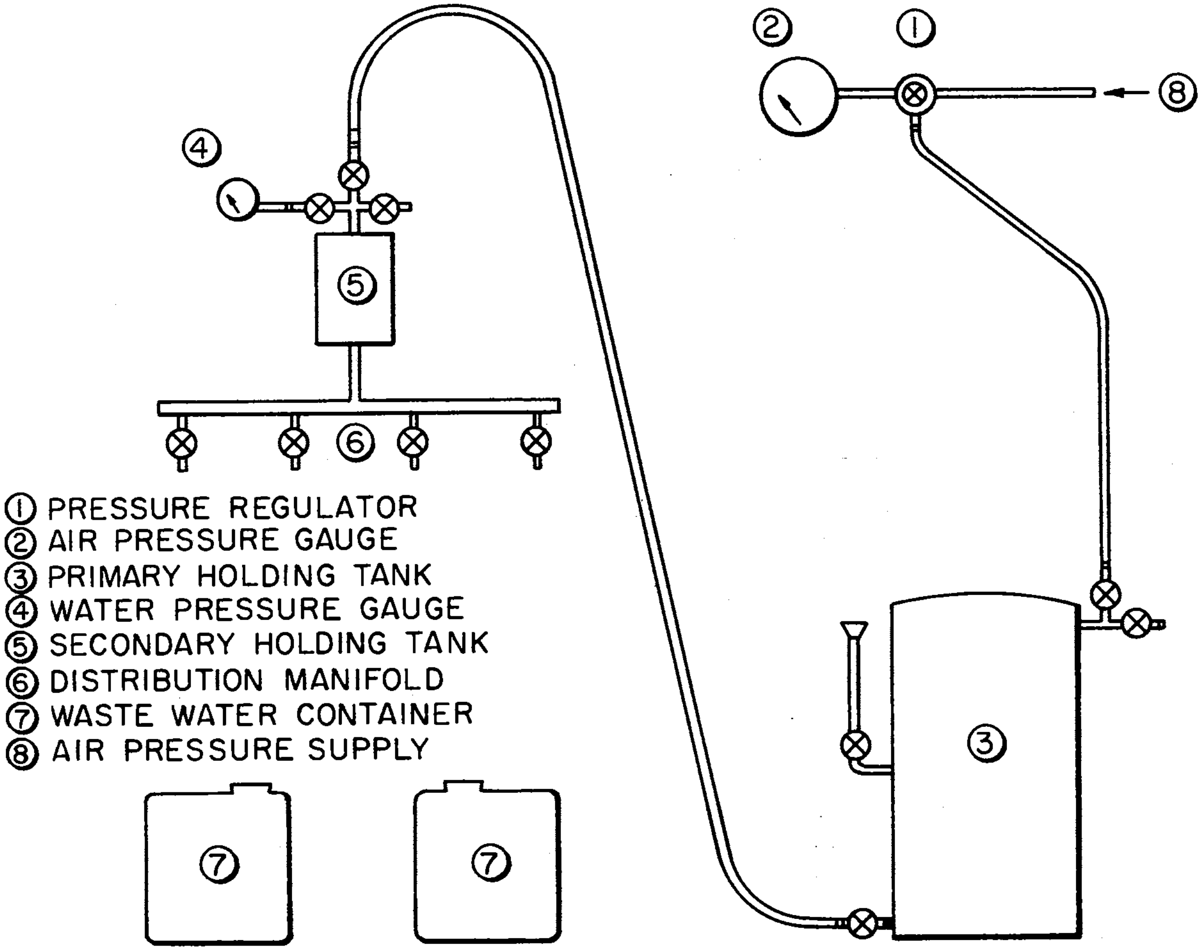

Figure 4.5. Erosion Device Water Flow System

holding open the microswitches five minutes and fifty-three seconds then closing them for seven seconds.

In order to allow for the largest number of test cycles between cleaning of the solenoid valves (which took one hour to complete) and to provide adequate operation of these valves, a settling basin was provided between each cell and 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 these tanks. This type of basin was chosen because of its availability and because of its ease of cleaning, which was necessary at the end of every sixth testing cycle.

All the above units were essential so that each solenoid valve would open and close in the prescribed pattern. These valves operated on 110 volt, 60 Hz power and are in the closed position unless energized. The main ball valve orifice of these valves are 1/2 inch in diameter. The aforementioned settling basins were essential because the control orifices of these valves are 3/32 inch in diameter. These valves operated efficiently as long as they were kept relatively clean.

The circuit diagram and suspension circulation scheme of this system are included in Figure 4.6. A photo of the complete erosion device is shown in Figure 4.7.

There was various auxiliary equipment needed to assist in extraction and trimming of compacted cylinders, slightly compress compacted soil cylinder specimens in the cells, space them vertically, locate the desired hole pattern and cut longitudinal holes through the cylinders. These are shown pictorially in Figure 4.8. The 1/4 in. Lucite sample extraction spacer is shown in operation in Figure 4.9.

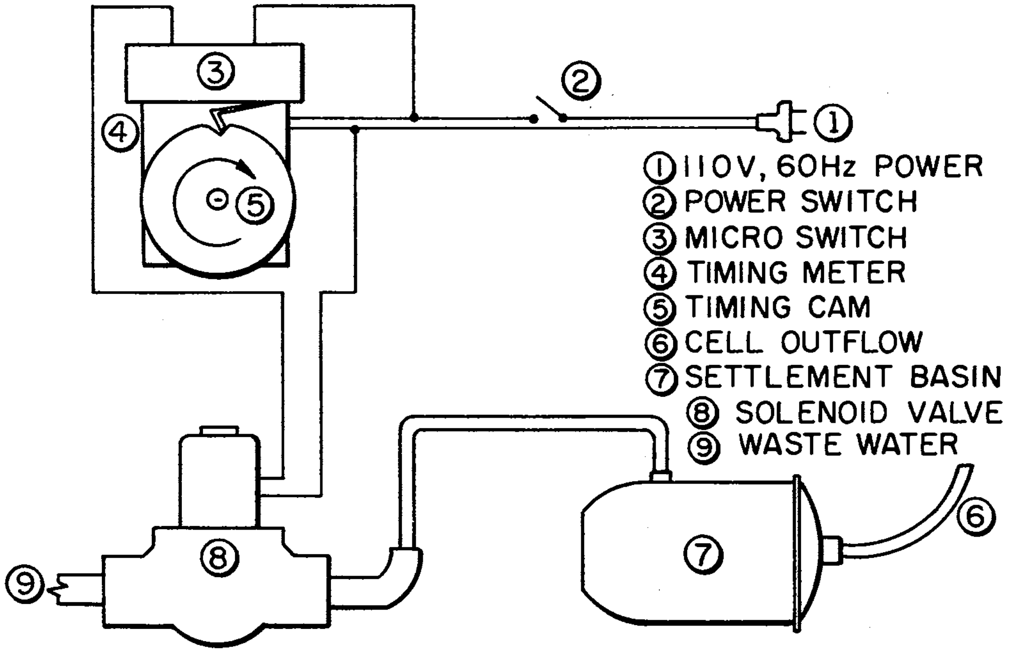

Figure 4.6. Schematic of One Unit of the Erosion Device Timing and Control System

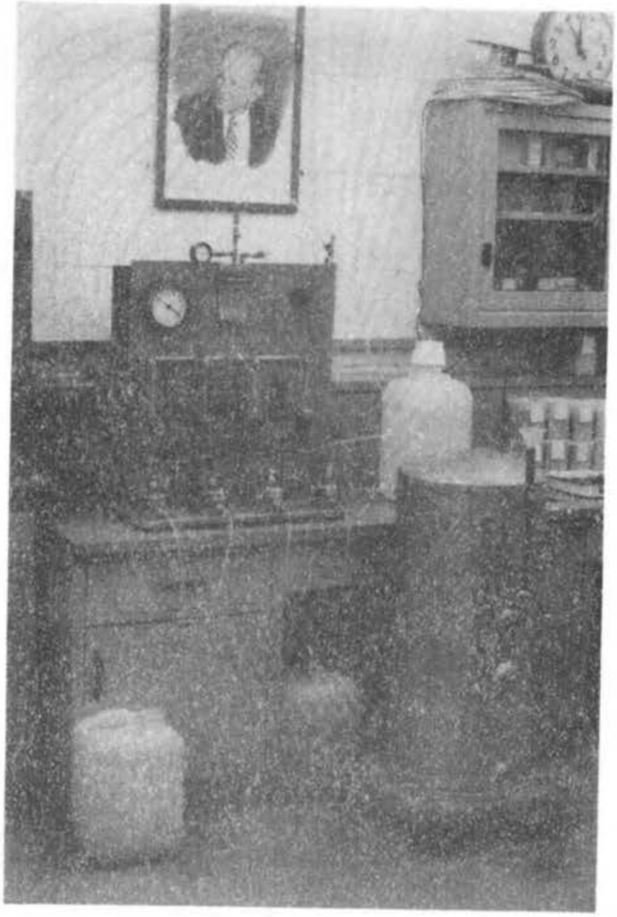

Figure 4.7. Erosion Device - Full View

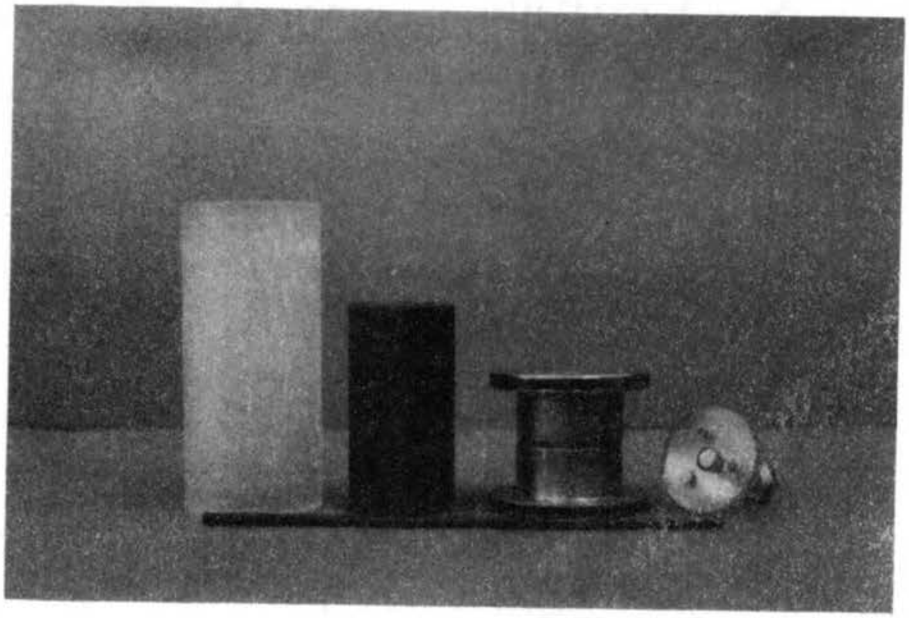

Figure 4.8. Auxiliary Equipment Used During Erosion Testing

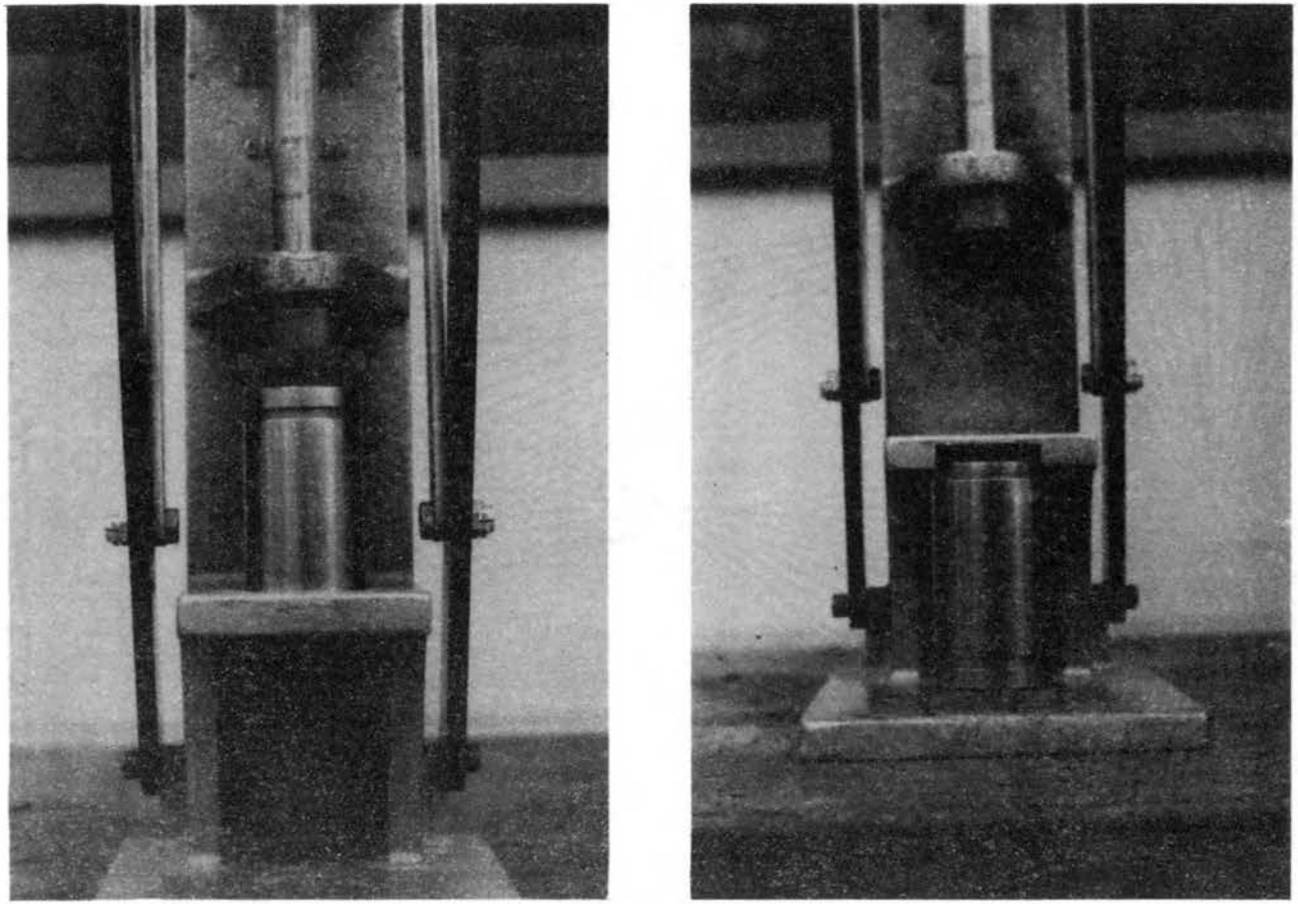

Figure 4.9. Use of Sample Extraction Spacer

Slight compression of soil cylinders (in order to attach them to the cell walls) and vertical spacing were accomplished simultaneously. Two brass compression/spacing blocks were constructed to fit into the cell on each end. The top and bottom spacings were chosen so that the open space left between the end of the compressed cylinder and the top of the completed cell and top of the sieve disc at the bottom of the completed cell would be the same. This space was chosen to be 0.125 in. Compression of the soil cylinder was accomplished by a hydraulic press. A detailed diagram of the spacing blocks used is given in Figure 4.10. A photo of the cell with soil, cylinder, and spacing blocks in place is given in Figure 4.11. A photo of the compression process is shown in Figure 4.12.

Hole locations were 120° apart and located at one-half the radius of the cell cross section (Figure 4.13). Their spacing was marked on the top of each compressed cylinder using the device shown in Figure 4.14.

Longitudinally cut holes 0.125 inch in diameter were made, where marked on the top of each cylinder, using a drill press and specially purchased drill bit. A picture of the drill bit utilized is included in Figure 4.8. Each hole was cleaned with a pipe cleaner before the complete cell was assembled. Figure 4.15 shows the first step in assembly and also the sieve, porous disc and support ring of the cell.

The special equipment outlined above was constructed either within the facilities of the School of Civil Engineering or, where required, by the Research Apparatus Development Laboratory at Oklahoma State University. Where possible, commercially available parts were incorporated in their design.

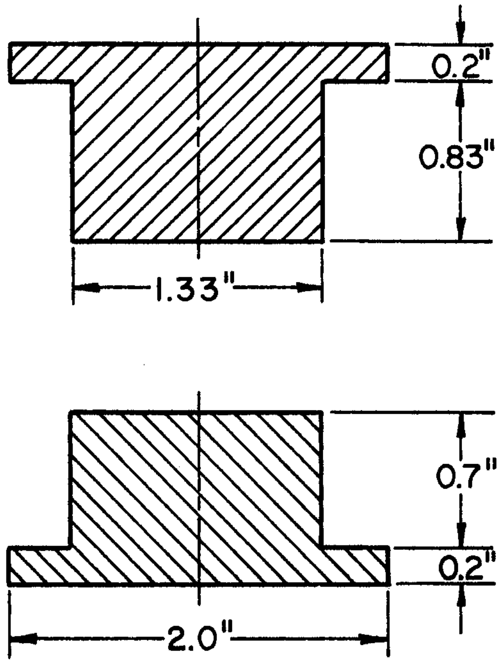

Figure 4.10. Cross Section of Spacing - Compression Blocks

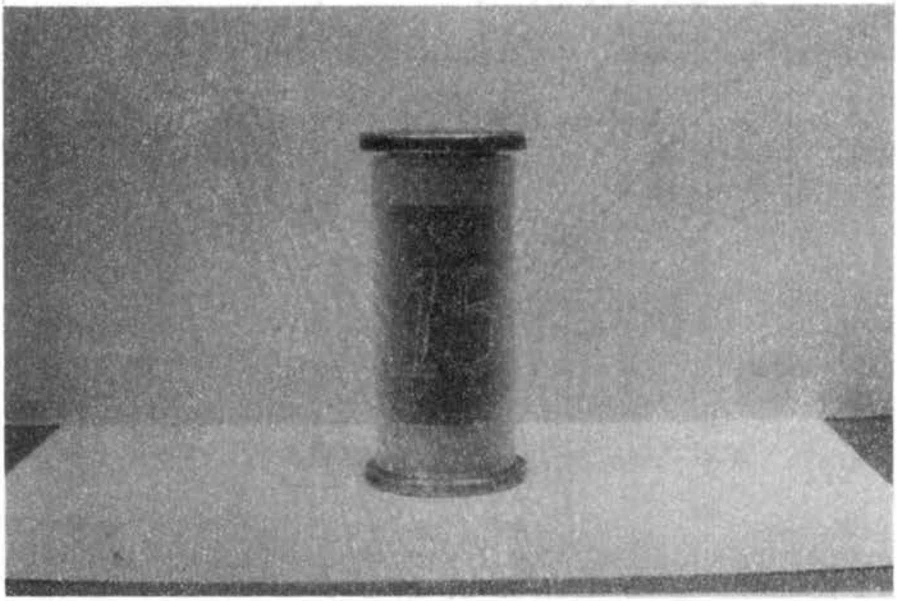

Figure 4.11. Cell With Soil Cylinder and Spacing Compression Blocks Prior to Compression

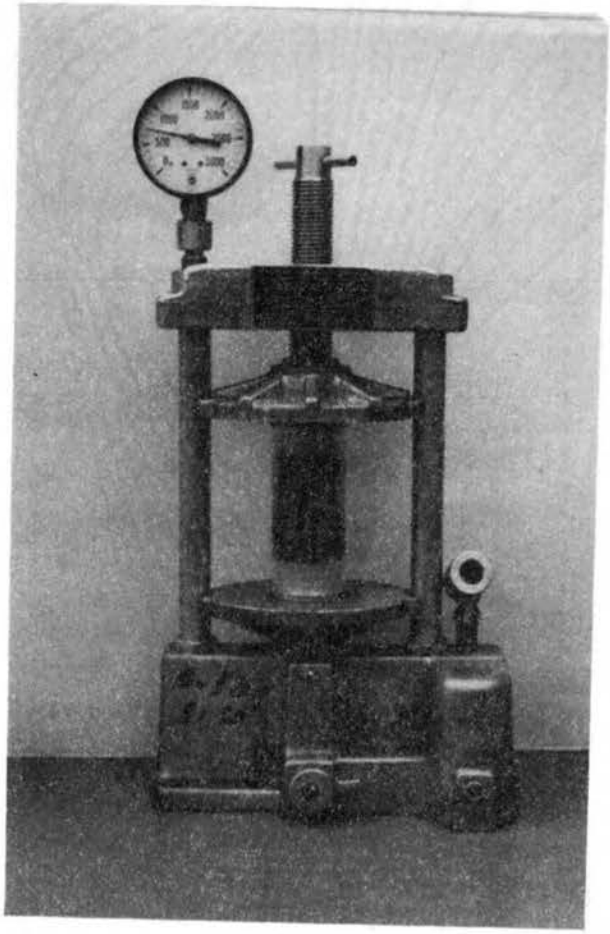

Figure 4.12. Compression Process

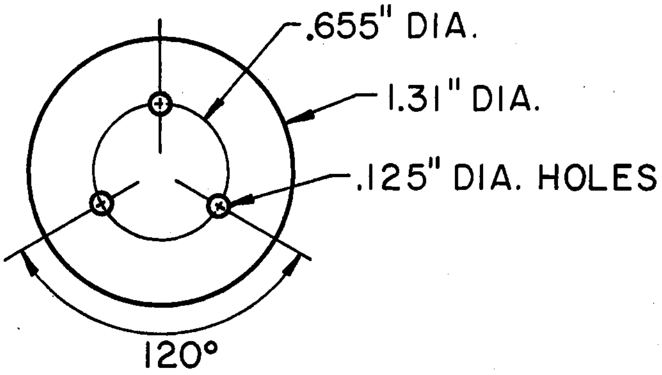

Figure 4.13. Longitudinal Hole Locations

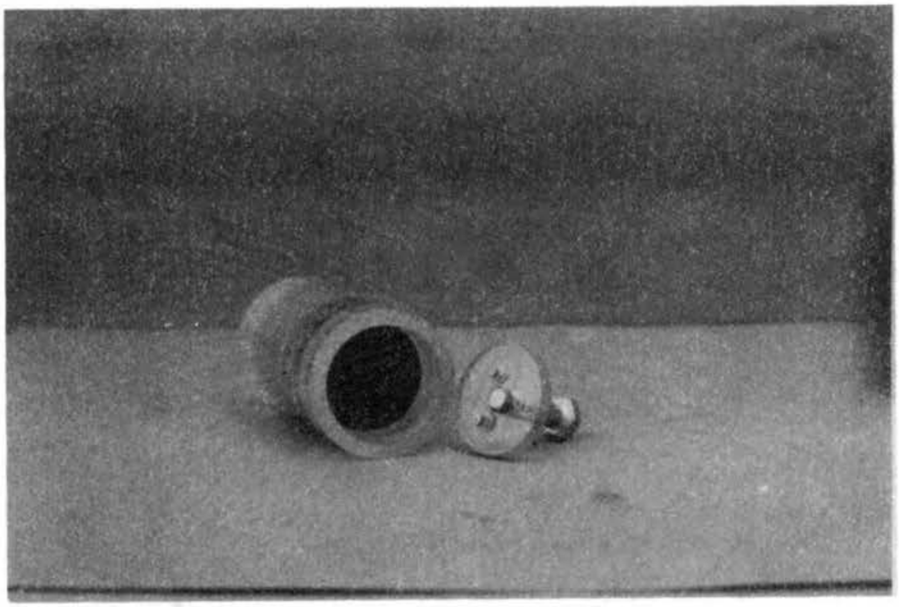

Figure 4.14. Hole Location Marking Device and Marked Cylinder

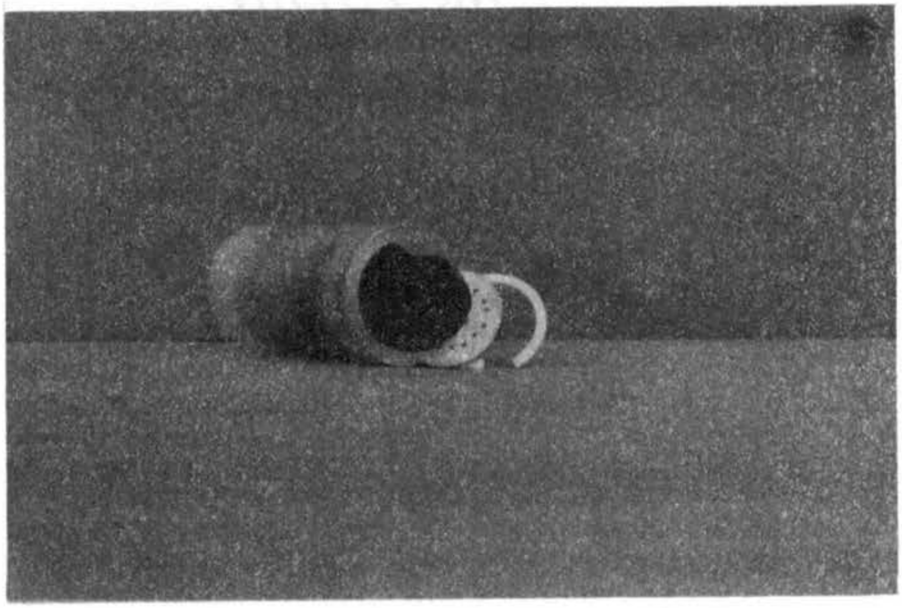

Figure 4.15. Cell With Sieve, Porous Disc and Spacing Ring

Procedures

The discussion of procedures utilized during this program of research will be presented in four parts: sample preparation, soil chemistry tests, engineering tests, and erodibility testing. Procedures used for the engineering and soil chemistry were accepted standardized testing techniques, modified where necessary to use available equipment. The sample testing procedural flow diagram that was followed is shown in Figure 4.16.

Sample Preparation

All samples were obtained in a disturbed state. From each of those which arrived at or near their natural water content, a sample large enough to use in the Soil Conservation Service Laboratory Dispersion Test (SCS-LDT) was taken. These SCS-LDT samples were carefully stored in order to prevent loss of moisture. The remaining portion of these field samples and the field samples which arrived much drier than their natural water content were oven dried at 110° C in a gravity oven. After drying, all were ground and the portion which passed a U.S. No. 40 sieve was stored to be used in all of the following tests. The exceptions to this are those field samples which were from the original SCS study (35). Only modified Proctor compaction, Differential Thermal Analysis, and erodibility testing were done on these samples.

Soil Chemistry Tests

The chemical properties desired were pH, soluble salts, and results of standard and modified SCS laboratory dispersion tests. The pH test was accomplished using a one to two suspension of soil and distilled

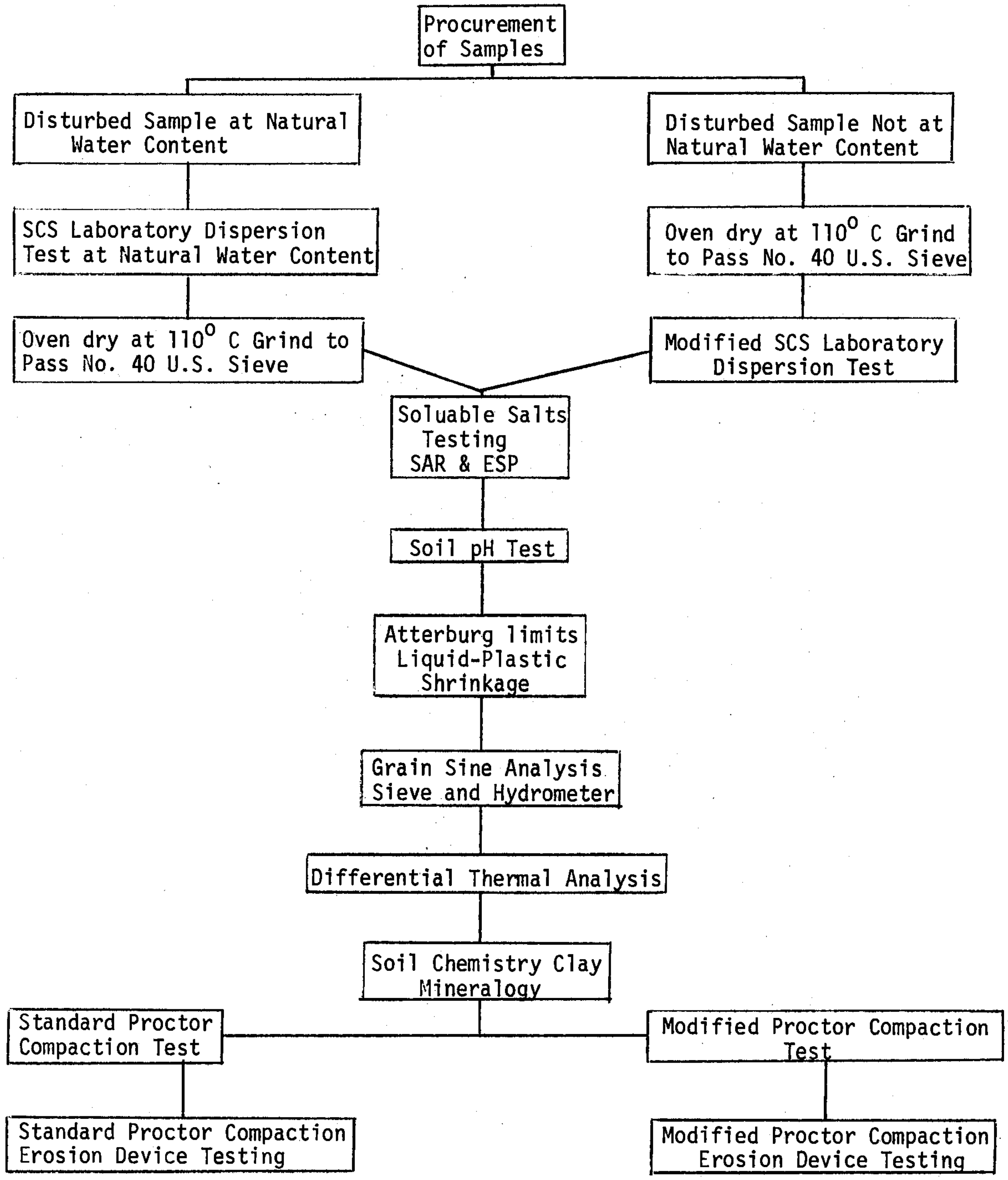

Figure 4.16. Sample Testing Procedural Flow Diagram

deionized water. Analyses to determine the quantities of Calcium, Magnezium, Potassium and Sodium in the pore water of each sample, plus their Sodium Absorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP), were done by the Soil and Water Service Laboratory of the Agronomy Department at Oklahoma State University. Laboratory Dispersion Tests were made utilizing two different procedures, dependent upon the moisture content of samples obtained.

Those field samples that arrived at or near their natural water content were tested for dispersibility using the Soil Conservation Service Laboratory Dispersion Test (SCS-LDT) procedure as original outlined by Volk in 1937 (42). Following preparation, field samples which arrived much drier than their natural water content were tested utilizing the SCS-LDT procedure after 24 hours of prior saturation in distilled deionized water.

Engineering Tests

Engineering properties of the samples were obtained to aid in data correlation and to provide background for erodibility testing. Tests performed included Atterburg limits, grain size distribution, probable clay mineralogy, and Standard Proctor and Modified Proctor compaction.

Liquid and plastic limits were determined using ASTM D423-61T and D425-59. 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 differences in test and hydrometer calibration temperature, change in specific gravity of the liquid by addition of dispersing agent, and the height of meniscus rise on the hydrometer stem.

The probable clay mineralogy of all samples was first determined by differential thermal analysis (DTA). The differential thermalyzer used was a Fisher Scientific Company Model 260. The procedure used was that outlined by the unit instruction manual and by the operating manual for this published by the soil mechanics laboratory, School of Civil Engineering, Oklahoma State University (7). Analysis of thermograms was accomplished primarily with the aid of relatively pure clay mineral thermograms made by this unit, on file in the soil mechanics laboratory. In addition, example thermograms presented by Grim were utilized (17).

Further research into the clay mineralogy of the samples tested was accomplished in the soil chemistry laboratory at Oklahoma State University. The purpose of this segment of the study was to determine the percentages of illite in the clay fraction and to find the X-ray diffraction properties of the clay fractions of selected samples. The X-ray diffraction analysis was aimed at determination of smectite.

In order to establish the percent illite in these samples as potassium determination procedure was utilized. Selected samples, about which further information was needed, were prepared for X-ray diffraction analysis. Standard soil chemistry methods, such as proposed by Jackson (26), were utilized.

X-ray diffraction analysis was carried out utilizing a General Electric Model XRD-C apparatus with an SPG-2 spectrogoniometer using Ni_a filtered Co radiation. Interpretation of X-ray diffraction results was done following methods outlined by Grim (17) and Carroll (8).

Compaction properties were found for use during erodibility testing utilizing both Standard and Modified Proctor efforts. The tests were run using Harvard miniature size molds, mold collors and bases. Compaction was accomplished with OSU soil mechanics laboratory miniature sleeved hammers and the OSU soil mechanics laboratory miniature compaction machine. The number of blows per layer and number of layers were established for each apparatus used, to provide the same maximum dry density and optimum water content obtainable from standard full size compaction tests. This was done for both Standard and Modified Proctor efforts using the applicable OSU miniature apparatuses (Figures 4.1, 4.2, 4.3). Maximum dry censities and optimum water contents were established for all samples. General procedures followed conform to those given in ASTM D698-S8T and D1557-58.

Erodibility Testing

The procedure followed during this research during erodibility testing is given in detail in Appendix A. It is included to present a complete record of how this testing was accomplished and a guide for future studies using this method of testing.

Prior to this phase of testing two things were required of the experimenter. The first was a thorough working knowledge of the erosion device and the second was to have available the Standard and Modified Proctor compaction properties of all samples.

Erodibility testing was carried out on four samples at a time, when possible. This was done so that each of the eight cylinders compacted from each soil was tested during a separate test sequence, to give the results obtained optimum independence. In addition, the cylinders tested of a given sample were placed in the erosion device so that each of the four positions were utilized twice. This was done to eliminate the effects of variation in the results caused by the apparatus.

The parameters controlled during this test were compaction effort and water content of samples during compaction. Four cylinders were compacted using each amount of effort. Two of these were at optimum water content and two were at optimum water content minus two percent. Using this scheme expected field situations were simulated during determination of erodibility.

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.

$$\text{Percent Erosion} = \frac{\text{Initial dry weight - Ending dry weight}}{\text{Initial dry weight}} \times 100$$

CHAPTER V

PRESENTATION AND DISCUSSION OF RESULTS

Engineering Properties

A general summary of the engineering properties determined for all samples is contained in Chapter IV and Table 5.1. The following detailed presentations were found useful for analyses of sample similarities and of the effects of engineering properties on erodibility. Their combined contributions to erodibility are discussed later in this chapter.

The first engineering property studied for comparison was the grain size distribution of samples. During initial preparation each sample was oven-dried, ground and sieved through a U.S. No. 40 sieve. In all but two cases the entire sample passed through this sieve. The results of the grain size analyses are shown in Table 5.1.

Comparison of grain size properties of these samples indicated that all were fairly well-graded, yet pointed out the variety of materials tested. The percentage of sand found in samples varied from none to 48% with an average of 17%. The sample with no sand in it was from the area of a failed SCS dam in Oklahoma and the samples with the most sand came from the site near Hugo, Oklahoma. The samples obtained near Konawa, Oklahoma had from 16% to 33% sand, while those from the area overlooking Kaw Dam had percents of sand ranging from 3% to 14%. Percentages of sand in the Oklahoma control soils were 13% and 14% and the Georgia

TABLE 5.1

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
101	100	84	51	31	21	15	16	63	21
102	100	84	55	38	25	13	16	59	25
103	100	78	49	34	25	18	22	53	25
104	100	67	43	28	23	13	33	44	23
105	100	84	65	48	36	27	16	48	36
106	100	97	70	41	31	25	3	66	31
107	100	90	60	49	36	27	10	54	36
108	100	86	78	60	41	28	14	45	41
109	100	65	42	29	23	17	35	42	23
110	100	52	32	20	17	9	48	35	17
111	100	75	45	27	22	14	25	53	22
112	100	86	69	51	36	23	14	50	36
113	100	87	83	73	30	4	13	57	30

TABLE 5.1 (CONT'D)

	Percent Passing						Percent		
Sample	No. 40	No. 200	0.02mm	0.005mm	0.002mm	0.001mm	Sand	Silt	Clay
114	100	97	93	78	62	51	3	35	62
115	100	100	97	69	36	25	0	64	36
116	100	93	68	40	25	17	7	68	25
117	93	91	54	18	13	12	9	78	13
118	99	77	47	21	17	15	23	60	17

Kaolinite sample contained 3%. The sample from Wister Dam had 7% sand, that from Arkansas had 9% sand and the sample from Mississippi had 23% sand. Although diversity existed between sampling location, the percentage of sand within these last four samples was similar.

Percentages of silt in these samples was less variant. It ranged from 35% to 78% with an average of 54%. Patterns of inter and intra location variety were found to be similar to those discussed for the percentage of sand.

Variation in the percent of clay was found to be much smaller than for the other fractions. After the data concerning Georgia Kaolinite, a relatively pure clay soil, was removed, those that remained were all of naturally occurring soils. These data ranged from 13% to 41% and had an average value of 27%. In general, inter-area variations of clay percentages were found to exceed intra-area variations.

These grain size distribution patterns of variety would logically lead one to deduce that other physical properties of these samples would be considerably variant. Actually, the relationships between physical properties are more complex than may be derived by grain size analysis alone.

Among the most accepted indicators of physical behavior of soils are the Atterburg Indices. Those determined for all research soils included the liquid limit, plastic limit, amount of linear shrinkage and extent of volumetric shrinkage. Pertinent data derived from this testing are shown in Table 5.2.

Inspection of the data given in Table 5.2, reveals that these properties are somewhat independent of the grain size distribution of samples. It was noted that the inter and intra-location variations of the

TABLE 5.2

PROPERTIES OF SAMPLES DERIVED FROM ATTERBURG LIMITS DATA

Sample Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Liquid Limit	34	41	37	33	54	45	44	42	22	21	23	47	63	68	42	32	32	38
Plastic Index	17	22	19	20	34	27	28	20	8	8	10	31	44	34	20	12	10	11
Volumetric Shrinkage	24	29	27	30	44	37	40	34	25	21	26	46	47	53	54	35	21	20
Classification	CL	CL	CL	CL	CH	CL	CL	CL	CL	CL	CL	CL	CH	MH	CL	CL	CL	CL

percentage of clay in samples differed from and were greater than the variations in these properties. The types and relative amounts of constituent clay minerals were suspected to be the cause of this difference in behavior.

Most of the samples tested had properties representative of clay soils with low plasticity. The exceptions to this were one sample from near Konawa, Roger Mills Gray Clay, and Georgia Kaolinite. The first two of these were clay soils of high plasticity. Georgia Kaolinite was classified as a silt soil of high plasticity, even though it contained 62% clay. The silt-like behavior of Georgia Kaolinite is believed to be caused by the relatively large size and thickness of its clay particles. Reasons for the difference of properties for these soils are not apparent from the data in Tables 5.1 and 5.2. It is interesting to note, at this time, the similarity of Atterburg Limits for the samples tested.

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. This means that other factors, such as type and mixture of clay minerals present, nature of the chemical solution surrounding clay particles and location where the samples were found, influenced this property of the samples tested.

The remaining engineering properties obtained were Standard and Modified Proctor compaction curves, and associated results. These were found to vary primarily because of material properties other than those associated with the location of samples. In order to compare these results compaction curves were characterized by type, width at 2 and 5 pounds below maximum density, and distance away from the zero air voids curve (ZAV). The results of these factors, plus maximum dry densities and optimum water contents, are given in Table 5.3. In general, Modified Proctor curves were found to be more narrow and closer to the zero air voids curves. The values shown are averages of data from both Standard and Modified Proctor curves, since these will accurately describe the general shape and location of the compaction curves of each sample.

Several general emperical rules were utilized during compaction of the results shown in Table 5.3. The relative difficulty of field compaction increases when the maximum dry density obtained in these laboratory tests decreases. This is normally accompanied by an increase in optimum water content, which also adds to the problems of good field compaction. Samples with relatively steep sided compaction curves are those which require close control of field water content during compaction to obtain the dry densities specified. Soils whose compaction curves pass close to the ZAV will be more difficult to work with in the field, since they need to be relatively saturated during compaction. The shape of both slopes of compaction curves graphically illustrate how the physical and mineralogical properties of the soil interact to affect the amount of water needed to reach a given dry density during compaction. In general, samples with more precipitous (concave to linear) curve slope are more sensitive to differences of moisture content during compaction, near the optimum, than those samples with less steep (convex) curve slopes. Finally, those soils which have broader curves, with a lesser defined peak, are more plastic than those having peaked narrow curves.

TABLE 5.3

COMPACTION CHARACTERISTICS OF RESEARCH SAMPLES

	SPC		MPC		Curve Slopes				
Sample No.	γ_{dmax} pcf	ω_{opt} %	γ_{dmax} pcf	ω_{opt} %	Leading	Trailing	% M.C. Width at -2 pcf	% M.C. Width at -5 pcf	% M.C. Away From ZAV
101	104.5	18.0	115.0	14.5	Convex	Convex	4.2	6.5	3.0
102	102.0	19.0	112.5	16.0	Convex	Convex	5.7	8.5	2.1
103	106.0	17.5	117.0	14.5	Concave	Linear	4.2	7.1	2.3
104	111.5	16.5	117.5	10.0	Convex	Convex	3.7	6.1	3.4
105	95.5	22.0	110.5	17.5	Linear	Concave	3.7	8.9	4.3
106	103.5	19.0	115.0	15.5	Convex	Convex	4.5	7.7	2.3
107	99.5	17.0	114.5	14.0	Convex	Convex	4.9	8.4	4.4
108	98.5	22.5	110.5	18.5	Linear	Convex	4.1	8.2	1.6
109	117.5	13.5	126.0	10.0	Convex	Linear	3.8	6.2	1.3
110	121.5	12.0	128.0	8.5	Convex	Linear	3.2	5.0	1.3
111	118.5	13.5	127.0	9.5	Linear	Linear	3.7	6.5	1.3
112	106.5	17.0	115.5	15.0	Convex	Convex	2.8	4.7	1.7*

TABLE 5.3 (CONT'D)

Sample No.	SPC		MPC		Curve Slopes		% M.C. Width at -2 pcf	% M.C. Width at -5 pcf	% M.C. Away From ZAV
	γ_{dmax} pcf	ω_{opt} %	γ_{dmax} pcf	ω_{opt} %	Leading	Trailing			
113	96.0	20.0	107.5	19.0	Convex	Linear	5.2	8.5	1.1*
114	84.5	32.5	93.0	27.5	Convex	Linear	3.7	6.7	1.6
115	108.0	19.0	121.0	14.5	Linear	Linear	2.3	5.0	0.6*
116	100.5	21.5	116.0	15.0	Convex	Convex	3.5	5.8	0.7*
117	100.5	20.0	115.0	14.0	Convex	Convex	4.3	6.8	1.5*
118	109.0	17.0	122.5	11.5	Convex	Convex	3.5	6.0	0.9*

*Curve data shown are from MPC curve.

This means that siltier soils are more sensitive to compaction water content differences than clayier soils.

When these results were being compared, it was noted that the compaction characteristics of these samples represent a relatively broad range of behavior patterns. The samples obtained from the area near Konawa have somewhat higher maximum dry densities and narrower curves than those of the samples from near Kaw Dam. Within these local groups the only difference that became apparent was the lower maximum dry densities found for sample 105, which had more clay in it than the other samples from Konawa. In this way sample 105 was more like those from near Kaw Dam. On the other hand the samples from near Hugo, which had more noncohesive and, especially, sandy material in them, had very high maximum dry densities and much more narrow curves than any of the other samples. The samples which had originally been part of a previous study were found to have compaction characteristics near the average for all the samples tested during this research.

It is interesting to note that the compaction properties of the control soils tested represented three distinctly different behavior patterns. The PRC sample studied had maximum dry densities near the average for all samples, and, because of its stress history and other unique physical properties, had compaction curves representative of a silty soil. Alternatively, the RMGC sample tested, having a smaller clay fraction, had compaction characteristics more like a clayey soil. This was evidenced by somewhat lower maximum dry densities and broader compaction curves. The problems associated with compaction of the Georgia Kaolinite sample were shown in its low maximum dry densities and high optimum water contents. Although it was composed of mostly clay, its compaction curves were found to be more narrow than those for the RMGC sample.

The compaction characteristics of all samples were influenced by the combinations of physical properties present. A further illustration of this is in the relative proximities of sample compaction curves to the ZAV curve. Most of the samples tested had curves relatively separated from the ZAV curve, because the combinations of properties in these cases affected compaction behavior in such a way as to assist compaction. In the other cases one property or another was relatively detrimental to compaction. These properties included low plasticity and relatively high sand fractions in the samples from near Hugo, high plasticity clay in the RMGC sample, and low plasticity and large silt fractions in samples 115 through 118.

The foregoing discussion concerning the engineering properties of the samples tested illustrates the variety of material included in this research. It is interesting to note how these diverse properties combine to define the behavior of the samples studied, and together produce similar physical behavior patterns. How compaction characteristics affect the internal erodibility of these samples will be discussed later in this chapter.

Clay Mineralogy

Several of those who have studied the dispersive clay phenomenon investigated the clay minerology of samples in order to find what affect it had on internal erodibility. In every study smectite was found to be the clay mineral most associated with this phenomenon. The only other clay mineral found to be connected with dispersive clay behavior was illite. It was one of the objectives of this research to determine if these clay minerals were present in the samples tested. Another part of this study, which shall be discussed later in this chapter, was an analysis of how mixtures of clay minerals influence internal erodibility.

The primary means used to identify clay minerals was differential thermal analysis. All but one of the tested soils contained either smectite, or illite or both. The one, very obvious, exception to these findings was the Georgia Kaolinite sample. Because differential thermal analysis was felt to be of significance as a qualitative procedure, the results of this part of the research are given as only clay mineral types in Table 5.4. Those clay minerals shown in parentheses were partially identified by this method.

It became apparent during the initial analysis of erosion test results that more information about the type and amount of clay minerals found in the samples tested could be useful during correlation of these results with other identification means. This, additional, research was into further determination of smectite and illite. The results obtained are presented in Table 5.4. This table illustrates the composite outcome of all clay mineralogy analyses. Clay minerals are presented in relative order of desending percentages in the clay fraction of the samples tested.

During the determination of the combined probable clay mineralogies given in Table 5.4 several general procedures were followed. DTA and X-ray diffraction traces were interpreted to be meaningful only where significant peaks occurred. Since both of these types of tests provide qualitative results, the relative size of peaks as compared to all

TABLE 5.4

SAMPLE CLAY MINERALOGY

Sample No.	DTA Results	% Mica In Soil	% of Soil -2 micron	X-Ray Analysis	X-Ray Diffraction Results	Combined Probable Clay Mineralogy
101	Chlorite, Illite (Smectite)	10	21	Yes	Chlorite, Smectite Illite	Mostly Chlorite, Balance Smectite, Little Illite
102	Smectite, Chlorite	13	25	Yes	Smectite, Chlorite (Illite)	Mostly Smectite, Balance Chlorite, very little Illite
103	Chlorite, Illite	10	25	No	———	Mostly Chlorite, Balance Illite
104	Smectite, Illite	9	23	No	———	Mostly Smectite, Balance Illite
105	Smectite, Chlorite	10	36	Yes	Smectite, Chlorite	Even Balance Smectite and Chlorite, very little Illite
106	Smectite, Illite	19	31	No	———	Mostly Smectite, Balance Illite
107	Smectite, Illite	20	36	No	———	Mostly Smectite, Balance Illite
108	Illite, Smectite (Chlorite)	24	41	Yes	Illite, Chlorite	Mostly Illite, Balance Chlorite
109	Smectite, Illite	8	23	No	———	Mostly Smectite, Small Balance Illite

TABLE 5.4 (CONT'D)

Sample No.	DTA Results	% Mica In Soil	% of Soil -2 micron	X-Ray Analysis	X-Ray Diffraction Results	Combined Probable Clay Mineralogy
110	Smectite, Illite	9	17	No	————	Mostly Smectite, Small Balance Illite
111	Chlorite, Illite Smectite	12	22	Yes	Chlorite, Illite (Smectite)	Mostly Chlorite, Balance Illite, Little Smectite
112	Chlorite, Illite Smectite	11	36	Yes	Chlorite, Smectite Illite	Mostly Chlorite, Balance Smectite, some Illite
113	Smectite, Illite	13	30	No	————	Mostly Smectite, Balance Illite
114	Kaolinite	--	62	No	————	Kaolinite
115	Smectite, Illite	22	36	No	————	Mostly Smectite, Balance Illite
116	Chlorite, Illite (Smectite)	17	25	Yes	Chlorite, Smectite Illite	Mostly Chlorite, Balance Illite and Smectite
117	Illite, Smectite	20	13	No	————	Mostly Illite, Balance Smectite
118	Smectite, Illite	11	17	No	————	Smectite and Illite Even

traces was utilized to test for significance. Also, relative prominence of these features was used to decide upon relative percentages of clay minerals. The percent mica in each sample is an indication of the amount of illite present and, when compared to the percent clay, was included as an important factor during the analyses of relative percentages of clay minerals. The combined results shown may be developed into approximate percentages as in the following explanation. A sample with mostly one clay mineral present contains more than one-third of that mineral, if two others were found, and more than one-half of that mineral, if only one other was found. Other clay minerals mentioned in each case were not believed to be as prevalent as the first one. In some cases an even balance of clay minerial percentages was found. When little or very little of a clay mineral is indicated, it means that a relatively small percentage or only a slight indication of that mineral was found.

It can be said that comparatively many variations in clay mineralogy were found among these samples. Although variation of mineralogies between locations of samples was determined to be significant, it was found to be no greater than intra-location variation. The existence of meaningful percentages of smectite and/or illite in all but one kaolinite sample was established by this research.

The behaviors of the clay fractions of these soils are dependent upon the type and amount of clay minerals present. Characteristics of clay minerals pertinent to this study include ability to retain cations (Cation Exchange Capacity), range of plasticity, shrink-swell potential, and influence on soil mass break-up when water is introduced to and air expelled from its voids. Among the clay minerals found in test samples, smectite exhibits the highest CEC, plasticity, and shrink-swell potential, while causing its respective soil mass to have the highest resistance to break-up during absorption of water. The level of all these characteristics found for other clay minerals ranges from somewhat lower than smectite for illite, to significantly lower for chlorite, and to lowest for kaolinite. How each of these characteristics, plus each of the mixtures of clay minerals found contribute to internal erodibility will be discussed for each sample later in this chapter.

Soil Chemistry Properties

The soil chemistry characteristics determined for all tested samples were those needed during correlation of erosion testing results with other proposed methods of identification. These included SCS Laboratory Dispersion Test results and soluble salts analyses results. These properties are available for comparison and correlation in Table 5.5. An interesting property analyzed, the ESP divided by the percent clay in each soil, has been included. This is believed by the author to be superior to the total soil ESP in representing the chemical environment surrounding clay particles in the soil mass.

$$\mathrm{ESP(clay)} = \frac{\mathrm{ESP}}{\%\ \mathrm{clay}/100} \qquad (5.1)$$

The lowest LDT percent dispersion determined was 39% for Permian Red Clay and for other control soils was 44% and 70%. On the other hand, the highest percent dispersion found was 95% for the soil from Mississippi. The variation of this index of dispersion was found to be independent of the location where samples were obtained. Indeed, local variation in this and other chemical properties supported that found by all

TABLE 5.5

SELECTED SOIL CHEMISTRY PROPERTIES OF RESEARCH SOILS

		In Saturation Extract					
Sample No.	% Dispersion LDT	meq/L Sodium	meq/L Total Cations	% Sodium	SAR	ESP	ESP (Clay)
101	50	3.3	21.6	15.3	1.0	0.4	1.9
102	44	2.0	13.2	15.2	0.8	0.2	0.8
103	43	1.1	11.4	9.6	0.5	0.0	0.0
104	56	13.5	18.0	75.0	9.1	11.0	47.8
105	49	15.2	23.8	63.9	7.4	8.6	23.9
106	90	19.2	20.9	91.9	21.7	23.5	73.5
107	62	12.6	17.2	73.3	8.4	10.0	27.8
108	49	9.1	10.7	85.0	10.8	13.0	31.7
109	65	8.9	18.7	47.6	4.1	4.5	19.6
110	95	4.0	4.6	87.0	8.0	9.5	55.9
111	90	4.0	4.4	90.9	10.2	12.0	54.5
112	39	4.3	21.5	20.0	1.5	0.8	2.2
113	44	10.2	28.4	35.9	3.5	3.8	12.7
114	70	0.3	1.6	18.8	0.4	0.0	0.0
115	81	33.8	37.0	91.4	27.0	29.0	80.6
116	63	4.7	5.3	88.7	9.0	9.0	36.0
117	78	2.1	2.5	84.0	5.0	6.0	46.2
118	95	10.9	13.0	83.8	11.0	13.0	76.5

previous investigators of this phenomenon. It is interesting to note that the variations in LDT results do not relate to variations in other chemical properties.

Since sample SAR, and thereby ESP, was determined by comparing sodium concentration to the square root of the average of calcium and magnesium concentrations, these properties do not directly relate to percent sodium in the saturation extract. There was found, however, a general correlation in the variations of these properties. Because another variable, the percent clay in each sample, was utilized in finding the ESP(clay), this property does not relate, except in a very general way, to other chemical characteristics. The overall variation in soil chemistry properties of test samples was found to illustrate the variety of dispersive clay erosion behavior to be expected later during erosion tested. How these properties were found to contribute to internal erosion will be discussed later in this chapter.

Physical Erosion Test Results

During this final and most important part of the research undertaken, all samples were tested for internal erodibility eight times. The total number of specimens prepared and examined with the erosion device was 114. Half of these specimens were compacted with Standard and half with Modified Proctor efforts. Among these specimens prepared with each of these compaction efforts half were at approximately the optimum water content and half were near optimum minus two percent. Desired sample water content and related compacted dry densities were found to be well within acceptable limits, so that the erosion test results obtained were believed significant. Detailed physical erosion test results are included as Appendix B.

Close inspection and analysis of the detailed results obtained during erosion testing revealed several pertinent facts. The first of these was that, within the limits of water contents tested for each compactive effort, a relatively small difference was found in dry density of the tested cylinders. This means that for cylinders of a sample prepared at each of the two compaction efforts there was generally no dependence of internal erodibility upon dry density. The second fact was a general dependence of percent erosion on compaction water content. In almost all cases as this moisture content increased, the amount of erosion decreased. The relationship of internal erodibility to water content agrees directly with the findings of many past investigators. This is believed to occur because of the changes in structure of the soil mass related to increase in compaction water content.

The third, and most significant, fact was that the average percent erosion in the Standard Proctor compacted specimens was approximately the same as in those specimens compacted using Modified Proctor effort. The explanation for this is based on the combination of two factors that influence internal erodibility. It has generally been found that a substantial increase in dry density, such as results from increased compactive effort, leads to a decreased susceptibility to internal erosion. On the other hand, the lower water contents associated with optimum compaction under increased compaction effort tends to increase erodibility. When both of these influences on behavior of a soil mass occurred simultaneously, the result was no general change in average percent erosion. This is illustrated in Table 5.6.

TABLE 5.6

AVERAGE PHYSICAL EROSION TEST RESULTS

Sample No.	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Percent Erosion at SPC	3.3	1.4	1.5	47.7	18.9	78.7	61.0	49.7	19.3	64.4	86.0	38.3	18.8	14.0	51.8	28.5	55.4	79.9
Percent Erosion at MPC	5.0	6.7	2.1	43.5	30.9	33.5	70.1	32.5	30.1	60.5	75.3	32.5	14.6	15.3	35.9	33.8	61.1	71.7

Among the steps taken to limit the variations in properties of each sample were compaction water content control, regulation of amount and application of compaction effort, and continuity of preparation procedure. The outcome of these as measured during analyses of detailed physical erosion test results was found to be acceptable. In addition, the probability of dependence of these test results for a given sample upon particular test sequence and equipment irregularities was believed to be minimized by the program of testing followed. Therefore, the variations in test results were thought to be primarily related to the particular physico-chemical situation present in each soil cylinder. It was decided that, even though the ranges of results as shown in Figures 5.1 and 5.2 were obtained during testing, the average percent erosion found for each sample and compaction effort could be utilized for final comparison and correlation of physical erosion test results. These variations in test results were considered representative of those normally found during analysis of field behavior. The physical properties of test specimens were believed to be less variant than those found under field conditions. In conclusion, it may be said that the percent erosion determined by averaging all 8 test results might best represent the field behavior of each sample.

The ways in which the soil mass cylinders reacted during erosion testing also represent probable field behavior of the soil masses. During these tests the progress of sample break-up and internal erosion was visually monitored. The rate at which this occurred was found to be determined by the natural properties of the sample and not by the particular laboratory procedure that was used to prepare soil cylinders.

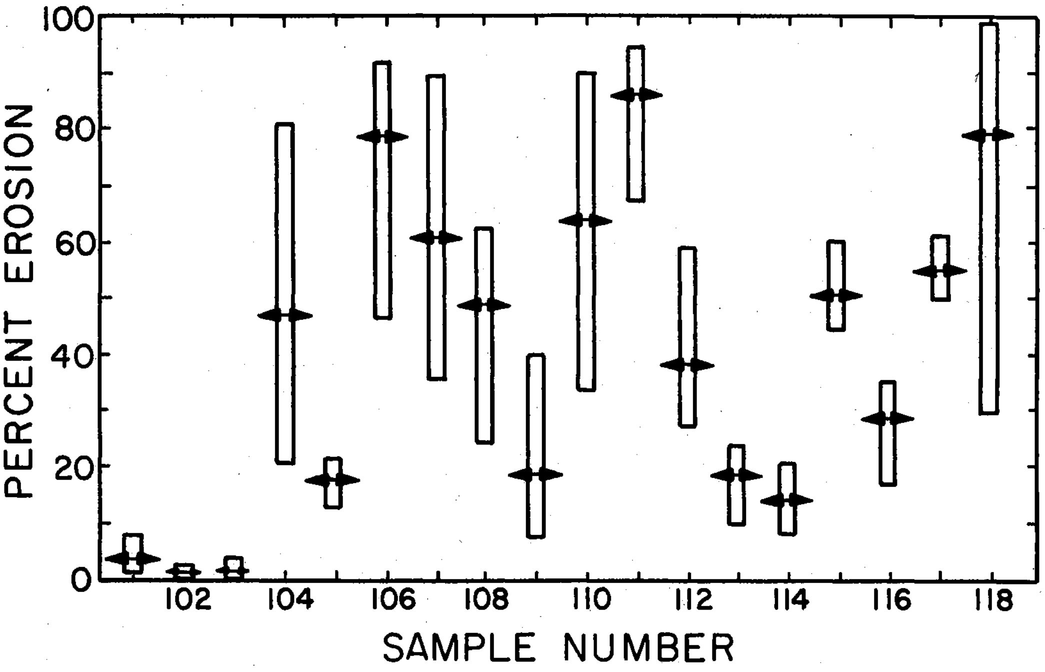

Figure 5.1. Average and Range of Percent Erosion for Standard Proctor Testing

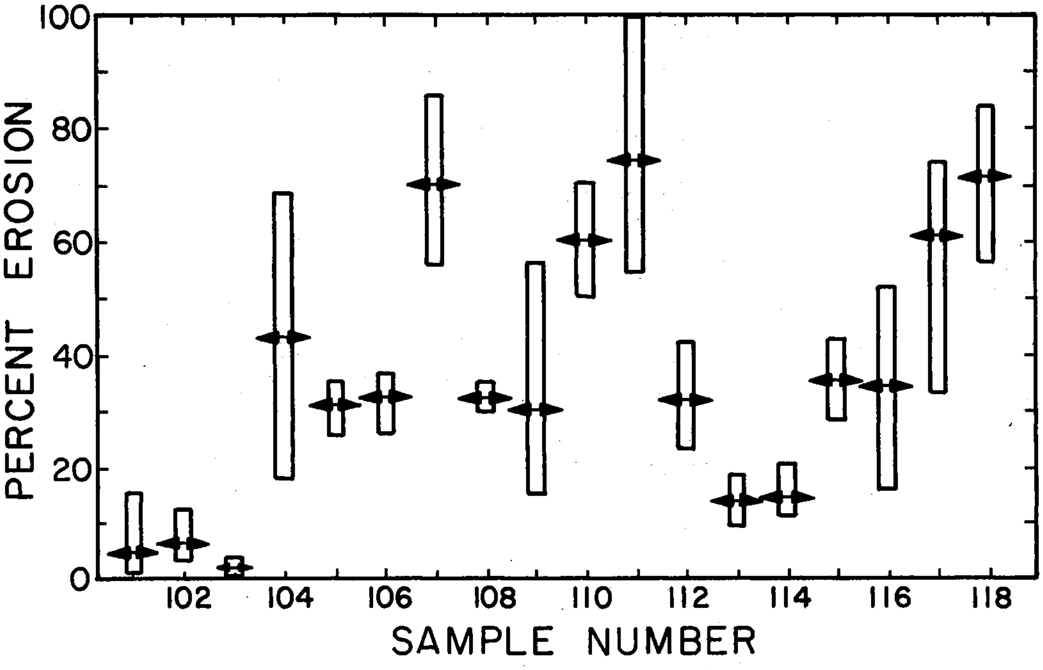

Figure 5.2. Average and Range of Percent Erosion for Modified Proctor Testing

These rates were as varied as the constituent properties of the tested samples. Generally they may be segregated into the following: those which started reacting immediately and continued for the 4 hour test period, those which began with no delay and then ceased eroding during the test, those which started reacting after a significant part of the test period had elapsed and continued until the test was terminated, and those which appeared to react little during the entire test. The range of behavior noted, as shown in Figure 5.1 and 5.2, was no loss to approximately 100 percent loss in 4 hours of testing.

It should be noted, at this point, that the total loss or percent erosion was chosen to be the indicator of field behavior because it could be measured quantitatively. While the rate of sample break-up and internal erosion was interesting, it is a qualitative behavior indicator of only limited value. In fact, when erosion device cells were dismantled and before their contents were removed, the amount of internal erosion that had occurred was not always that observed from outside of the cell during testing.

A summary of the effects of all properties on internal erodibility and correlation of these results with those obtained by other identification methods are included in the last two sections of this chapter.

Figures 5.3 and 5.4 illustrate the progress of and final extent of erosion determined for samples 109 and 112. Samples 109 through 111, in the first three positions on the erosion device, are those obtained near Hugo, Oklahoma. The remaining sample, in the last position, is Permian Red Clay. The first three of these samples were observed to erode progressively during the entire test period, while PRC initially eroded and then ceased to erode significantly after a relatively short time.

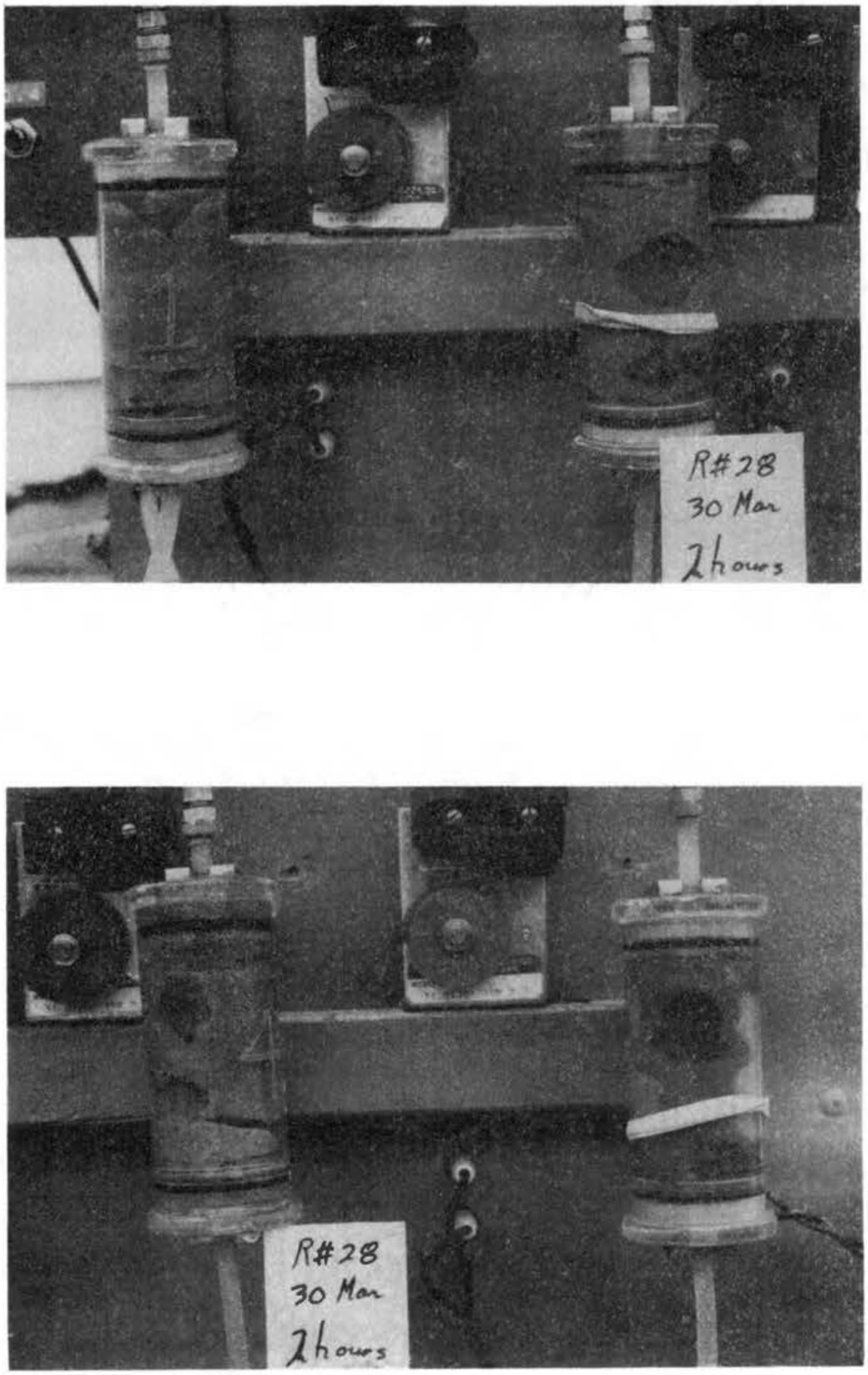

Figure 5.3. Typical Observed Erosion After 2 Hours of Erosion Testing for Samples 109-112

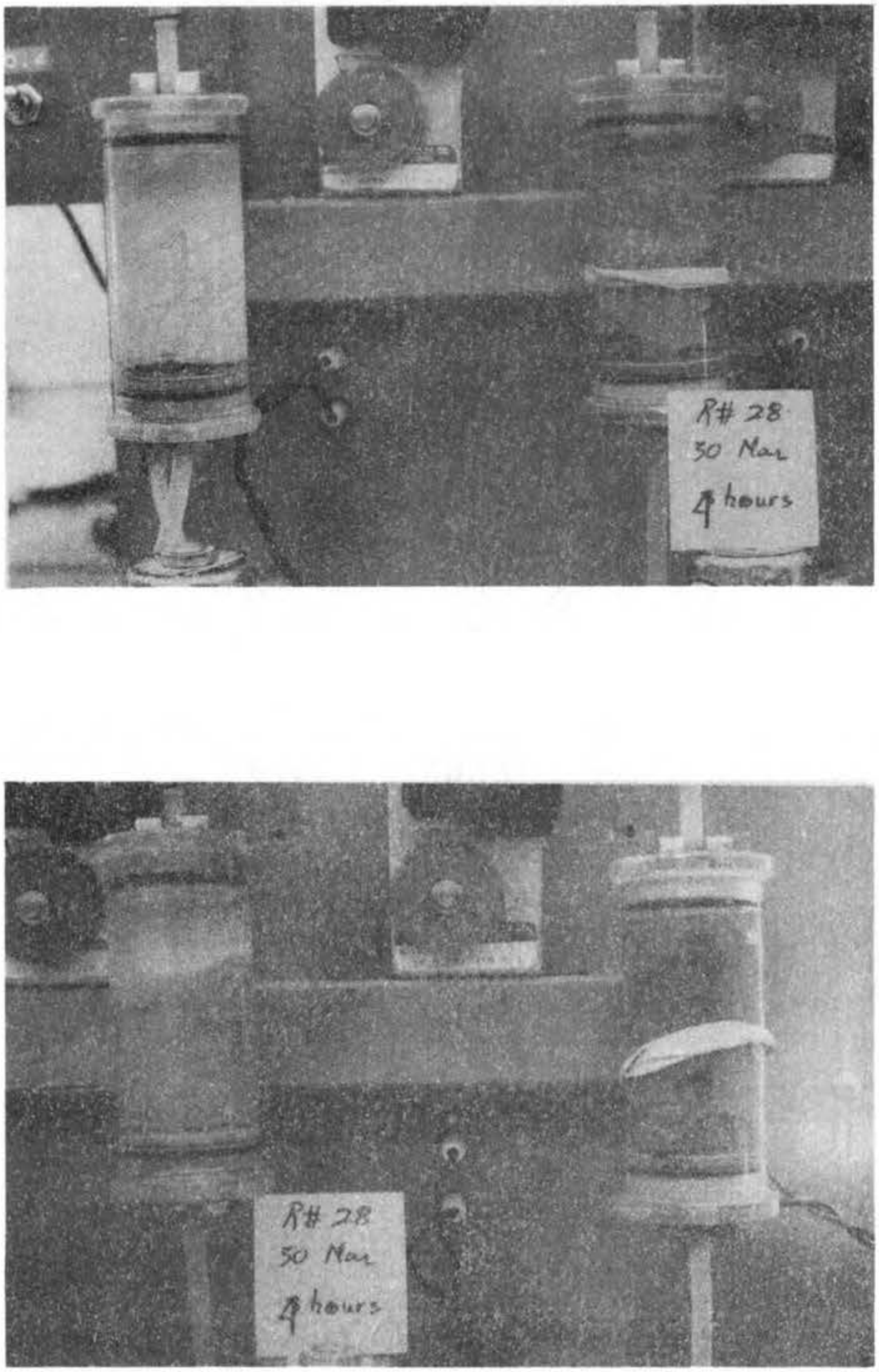

Figure 5.4. Typical Observed Erosion At End of Erosion Testing for Samples 109-112

The two pictures of erosion testing shown in Figure 5.5 illustrate the lack of erosion reaction found during testing of Roger Mills Gray Clay (sample 113) and Georgia Kaolinite (sample 114). RMGC was observed to swell and close 2 of 3 holes drilled through it and also erode little from each end. The Georgia Kaolinite cylinders were found to neither close up their holes nor erode much from each end.

The most diverse rates of erosion progress observed during testing were those observed during tests on samples 115 through 118. These were the samples selected from the available soils which were originally examined for their dispersive clay behavior by Sherard et al. (37). The variety of their observed behaviors may be at least partially explained by the fact that they came from four widely separated locations. All of these samples were found to initiate erosion at the beginning of the test period and progressively lose material at diverse rates by internal erosion until the test was terminated. Pictorial illustrations of typical erosion progress in these samples at 2, 3 and 4 hours of testing are shown in Figures 5.6, 5.7, and 5.8.

The most precise indicator of the progress of internal erosion, outside of the percent erosion, was found to be visual inspection of the soil cylinder mass after each cell was dismantled. Although interesting, analysis of this sort is strictly qualitative and not thought useful for prediction of field behavior. Descriptions of the several different hole configurations found during this research may be found below.

Three examples of internal holes not perceptible outside of the assembled cells are illustrated by Figure 5.9. The samples shown eroded primarily by continuous solution of the soil mass surfaces in direct contact with water. This process, also found in some dispersive clay

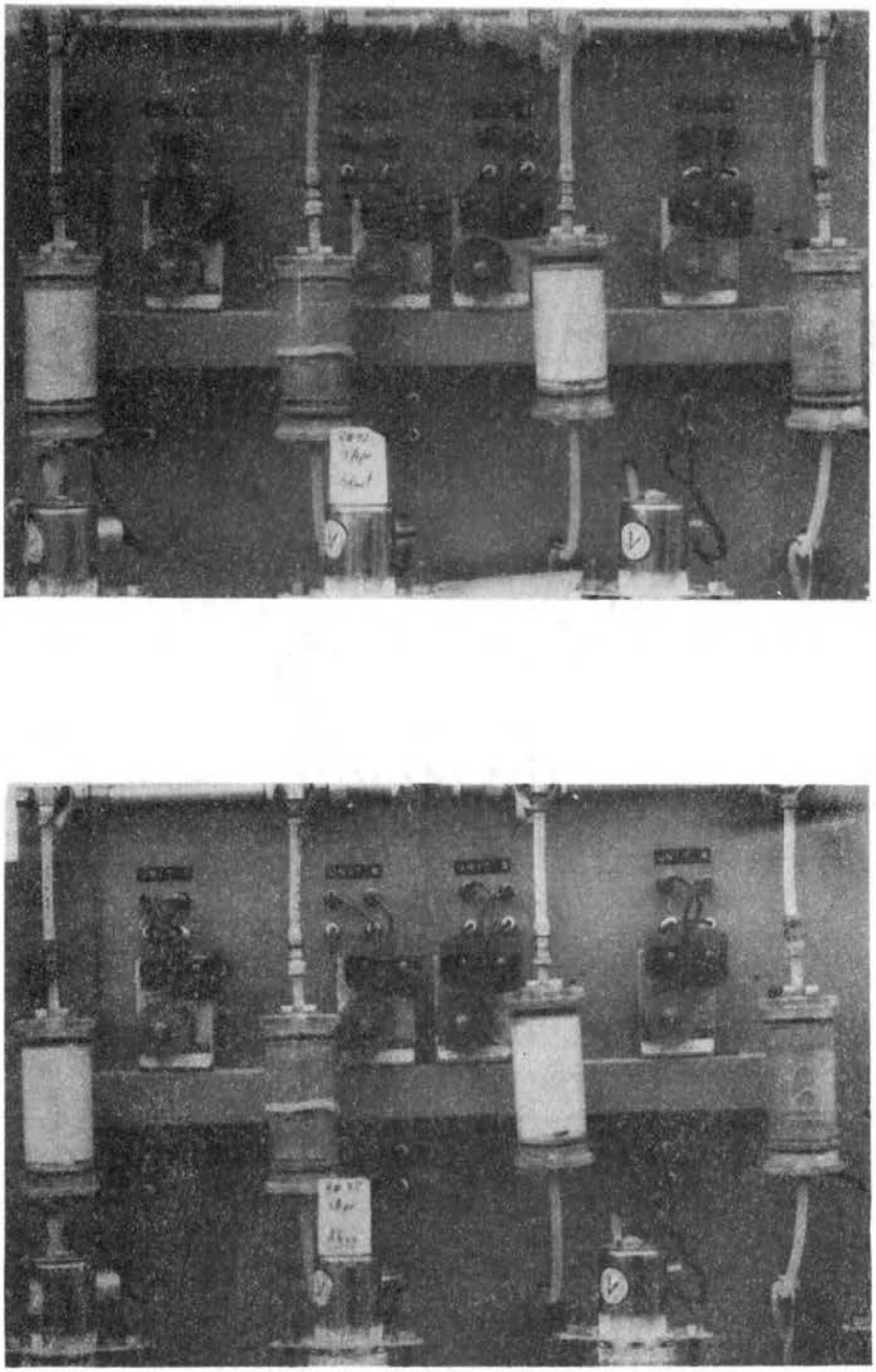

Figure 5.5. Typical Erosion Test Observations at the Start and End of Testing for Control Samples 113 and 114

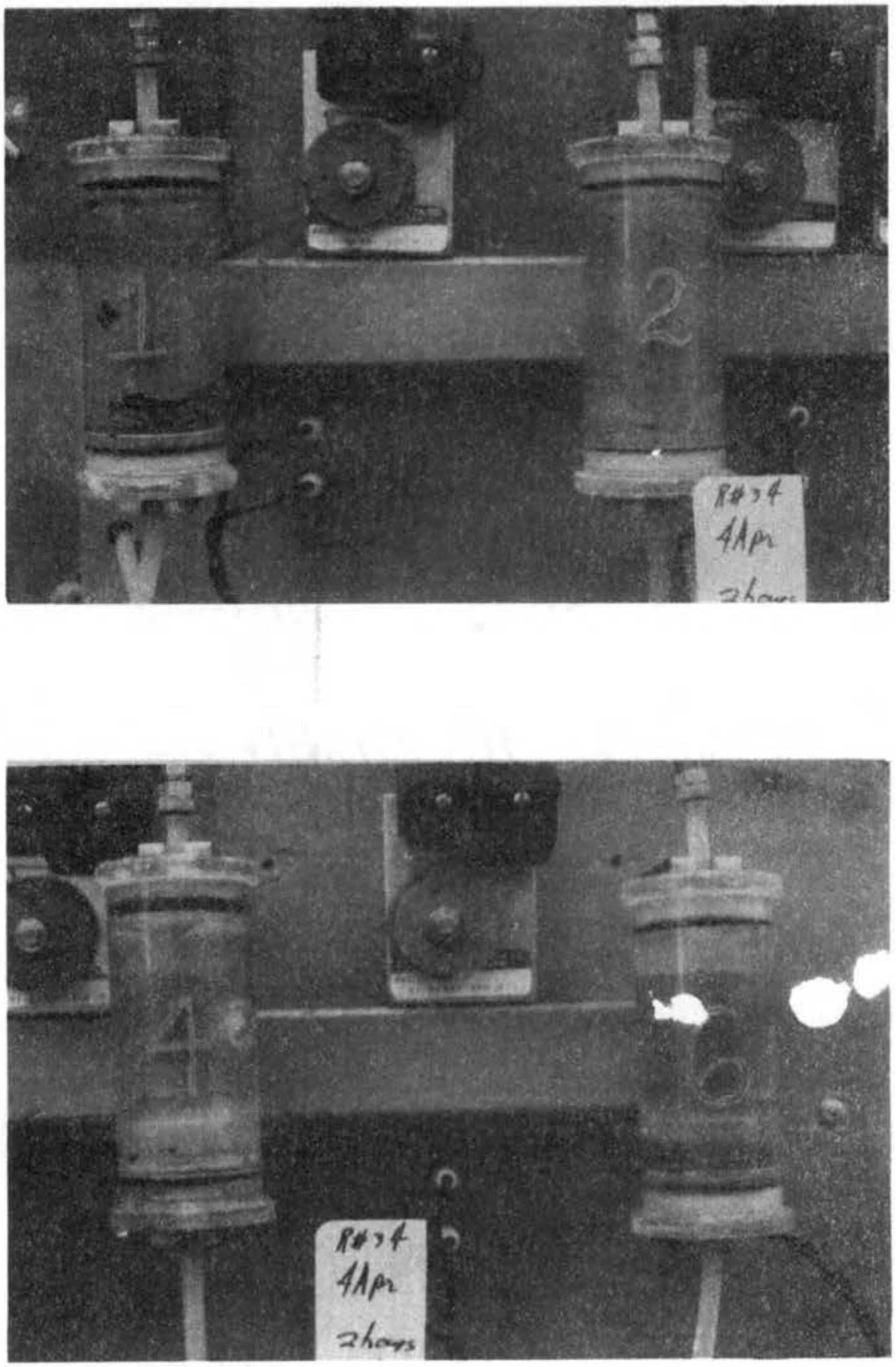

Figure 5.6. Typical Observed Erosion After 2 Hours of Erosion Testing for Samples 115-118

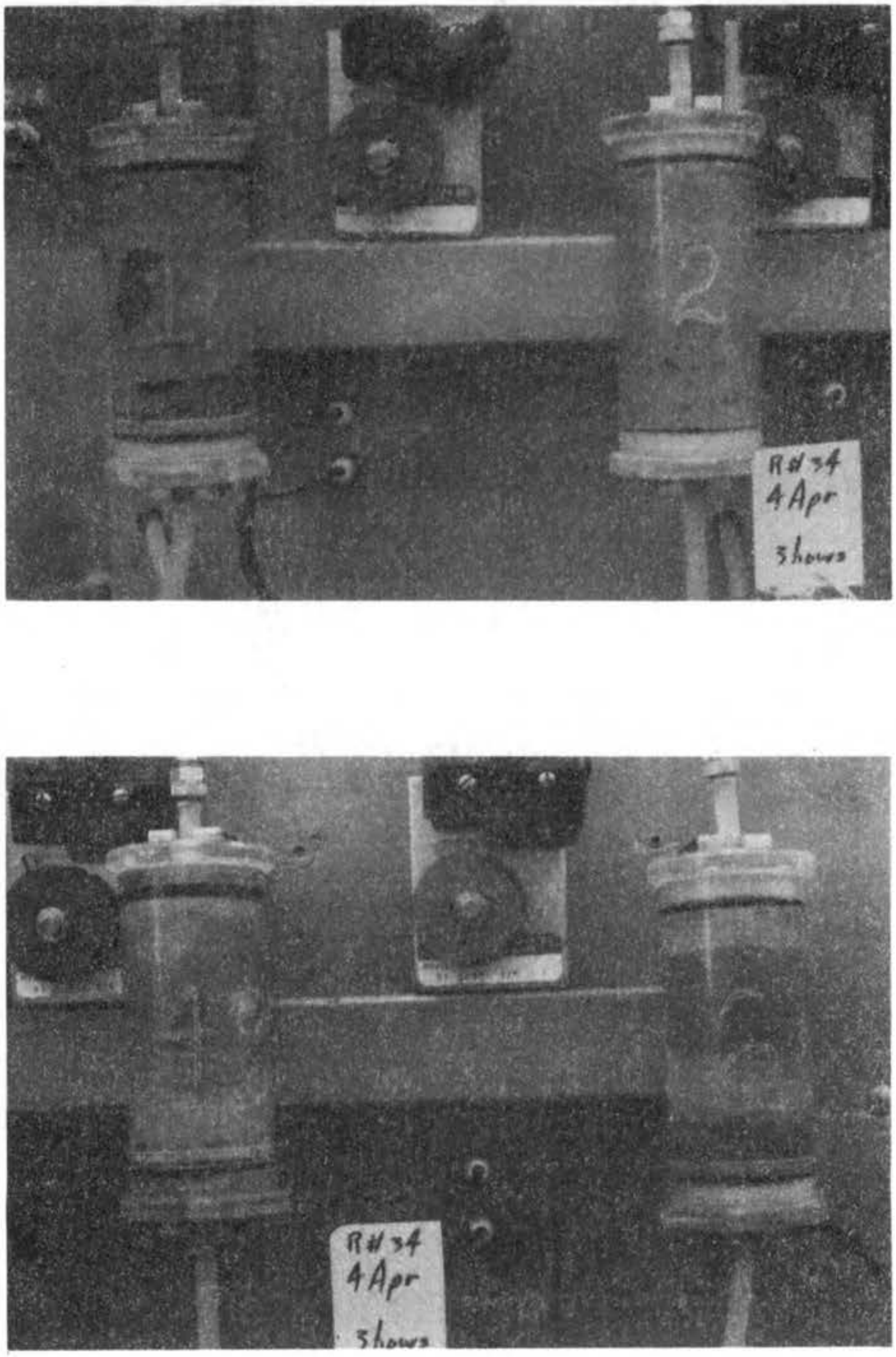

Figure 5.7. Typical Observed Erosion After 3 Hours of Erosion Testing for Samples 115-118

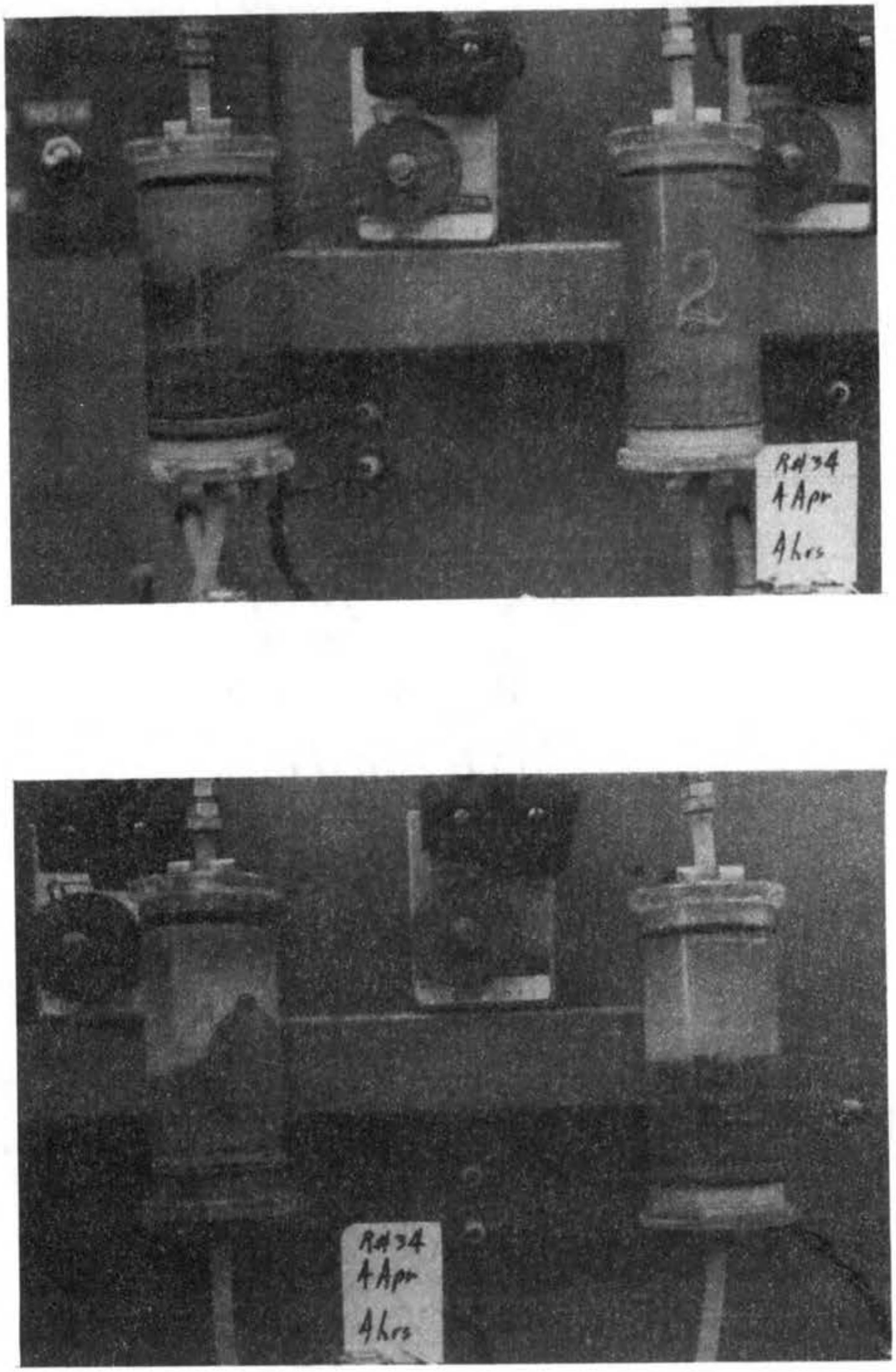

Figure 5.8. Typical Observed Erosion After 4 Hours of Erosion Testing for Samples 115-118

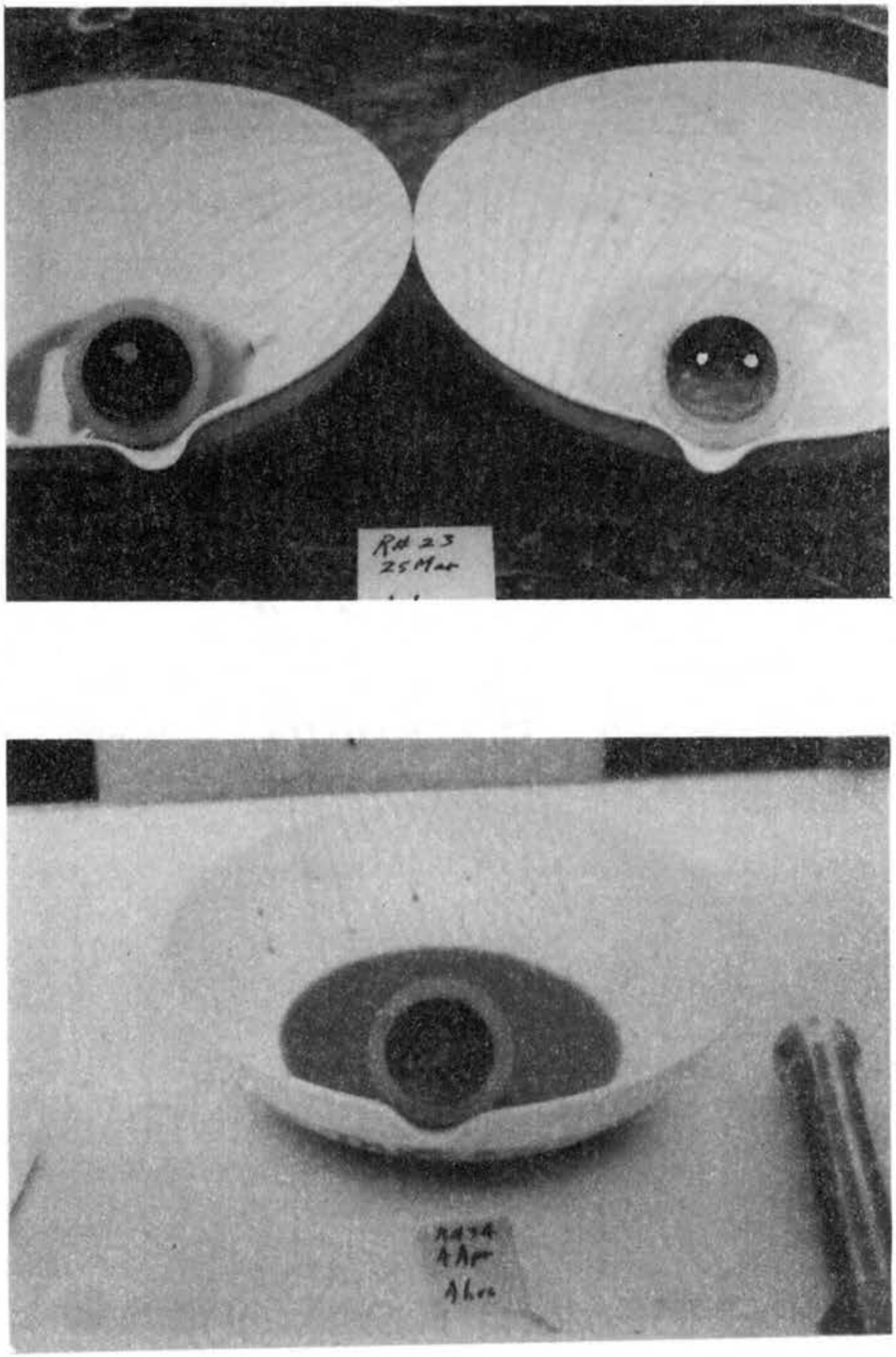

Figure 5.9. Examples of Internal Erosion Not Perceptible Outside Assembled Cells

soils in the field, is similar in appearance to solution of limestone. The three cases shown include one where two holes have been plugged and one hole has become a large pipe, one where two holes were enlarged into pipes, and one where all three holes were significantly eroded by this process.

Examples of how some soil mass cylinders broke up into small aggregates which were carried down to the bottom of the cell and melted are shown in Figure 5.10. In all cases shown, large jugs were noted from outside the assembled cells, even though the holes shown for entrance water are not all large.

Three of the four examples of internal erosion behavior shown in Figure 5.11 were found in limited number during this research. This behavior of non-swelling (essentially non-erodible) soils was indicated by no change in hole size or number and little surface erosion on each end of the cylinder.

Summary of Effects of Properties on Erodibility

The most direct and least confusing method of total analysis on the effects of properties on internal erodibility was determined to be one which consists of comparisons of small groups of samples. The samples tested and their inherent behaviors may be divided into several clusters by their physical erosion test results.

The first set of samples to be considered have very similar grain size distributions, plasticity, shrinkage and compaction characteristics. They have the three lowest percents erosion. They may be classified in order 103, 102, and 101 by this behavior. Their ESP's and ESP's by clay fraction fall into this order, also. Sample 103 would be expected to

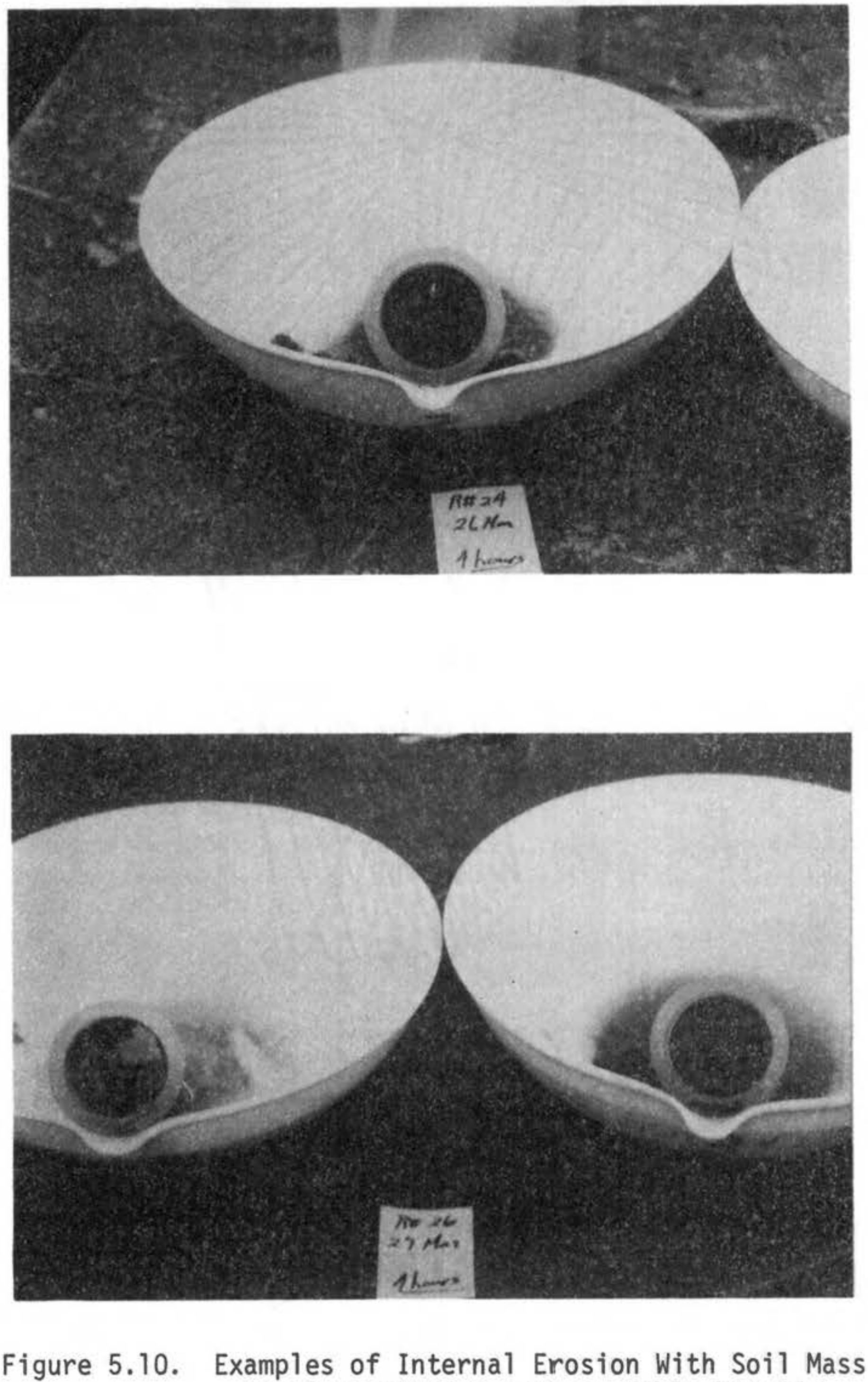

Figure 5.10. Examples of Internal Erosion With Soil Mass Break-up Which was Perceptible Outside Assembled Cells

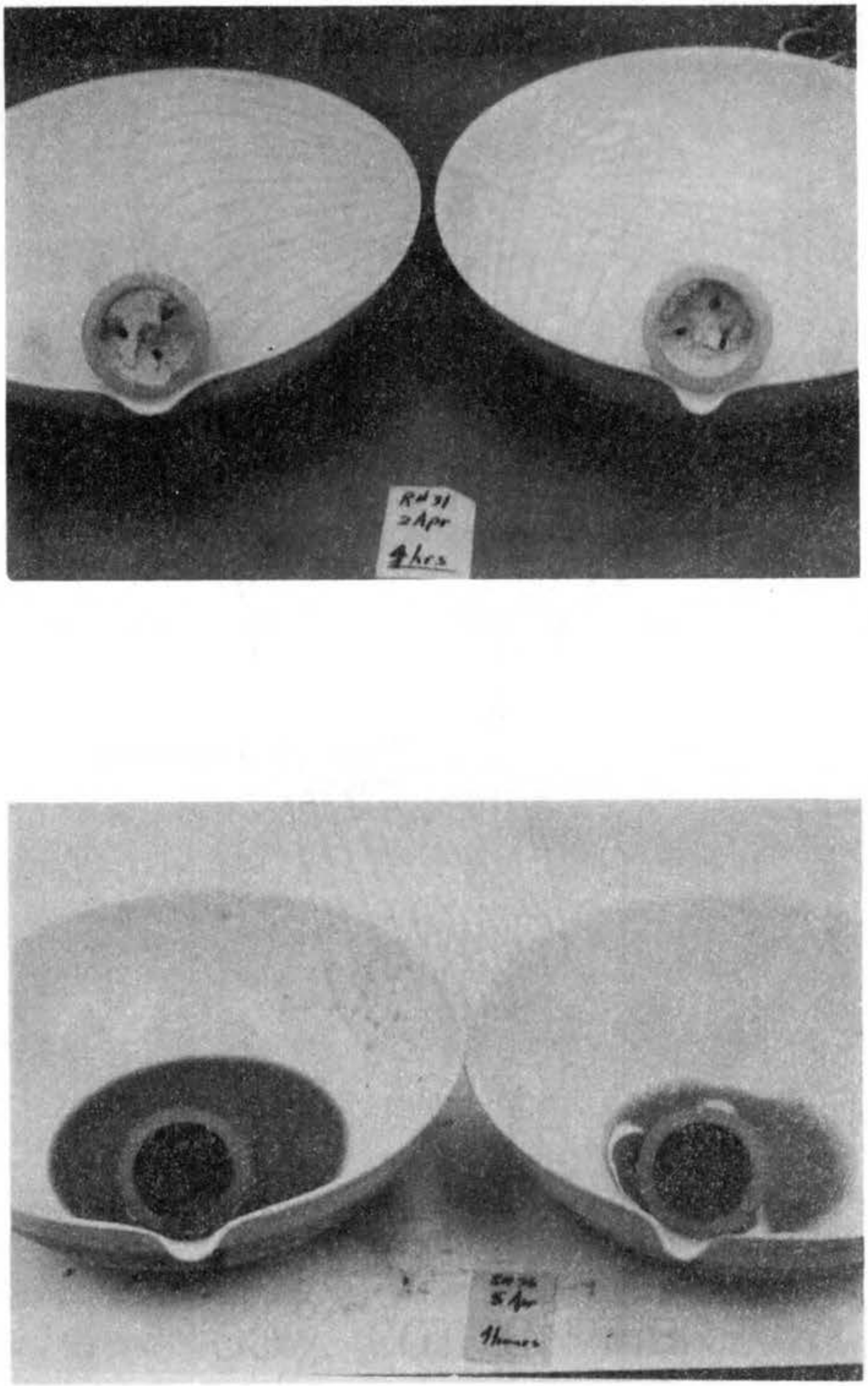

Figure 5.11. Examples of Internal Erosion With No Hole Enlargement

have the lowest internal erosion potential of these and all samples since its ESP and ESP(clay) are zero. It also contains less chemically reactive clay minerals than the other two, being mostly chlorite and the rest illite. The summation of its characteristics places it as a low plasticity silty clay of low activity with no chemical reason to disperse, hence its internal erodibility of less than 2%. Sample 102 is similar in most respects to 103 but it contains mostly smectite with most of the rest being chlorite. This, and its ESP of 0.2 and ESP(clay) of 0.8 together account for its difference of internal erodibility of 2.3%. Together they make this sample's erosion 4.1%. Sample 103 is also similar to the other two, except its mineralogy is mostly chlorite with the rest mostly smectite and its ESP and ESP(clay) are 0.4 and 1.9 respectively. One might expect the internal erodibility of 101 to be much greater than that of 102, but it is only 4.2%, because of the lower chemically reactive clay mineralogy present.

Soils number four and five by increasing internal erodibility are 114 and 113, respectively. Although these are both control soils for this research, they have significantly different reasons for displaying their similar erodibilities of 14.7 and 16.7%, and for these to be higher than those for the first three samples discussed. They are similar in that they have high plasticity and similar shrinkage properties, both higher than those of the first three samples. Sample 114, Georgia Kaolinite, owes its plasticity, shrinkage and compaction characteristics to the high percentage of clay present. Its internal erodibility cannot be supported by its ESP's of zero but is due almost entirely to the clay mineral present and its reaction during expulsion of entrapped air when it is exposed to water. The severity of this reaction may be noticed when comparing the erodibility determined for 103 with that for 114. On the other hand, 113 (RMGC) has compaction characteristics of a silty clay because of its grain size distribution and a clay mineralogy of mostly smectite with the rest illite. These two factors work together to make this soil act according to its ESP of 3.8 and more nearly to its ESP (clay) of 12.7. Based on this analysis, it may be said that RMGC would internally erode as indicated by its ESP(clay).

The next two samples in order of increasing internal erodibility are 109 and 105. These are separated from the previous set by 8% erosion, yet have similar erodibilities of 24.7 and 24.9%. These two have widely different physical and mineralogical properties and only come close to having the same chemical properties. Sample 109 is a sandy silty clay of low plasticity and shrinkage potential. The combination of these properties and the existence of mostly smectite with some illite make this soil more internally erodible than expected by its ESP of 4.5 and ESP(clay) of 19.6. Although it has low shrinkage, which reduces cracking, it also has the structure of a sandy silty clay and the most chemically reactive clay minerals, both of which promote internal erosion. Alternatively, sample 105 is a silty clay of high plasticity and shrinkage with clay mineralogy of fairly equal amounts of smectite and chlorite. This sample is somewhat like 113 in its reaction to the chemical balance in its soil mass, in that its internal erodibility follows closely its ESP(clay). It is less responsive to chemical situations which cause clay particle dispersion than 113 and 109 because of its less active clay fraction and than 105 because of its more stable structure.

There were two samples which were determined to have internal erodibilities between 30 and 40 percent. These were 116 with 31.2% and 112 with 35.4% average percent erosion. These two samples are both silty clays of low plasticity with similar clay mineralogy, i.e., mostly chlorite with both smectite and illite present. Sample 116 has a tendency to erode internally less than would be indicated by its ESP of 9.0 and ESP(clay) of 36.0. Its large silt fraction and clay mineralogy combine to cause this level of reaction to the chemical environment present. The relative nonreaction of its clay fraction to chemical changes in the soil is just about totally offset by its lack of cohesive structure. A very different reaction to physical and chemical properties was determined for sample 112. This control sample of Permian Red Clay was found to have internal erodibility much greater than its ESP of 0.8 and ESP (clay) of 3.2 indicate. Its shrinkage potential is higher than that of both similar samples, 101 and 116, because of its larger clay fraction. It has soil chemistry properties like those of 101 and erosion properties like those of 116, yet one would expect it to erode somewhat less than these because of its more cohesive mass.

The reasons for this unexpected occurrence are two-fold. First, chlorite clay is more subject to break-up by entrapped air than either smectite or illite and as the clay fraction gets larger, this reaction gets more severe. Second, and very much more important, this particular material has a relatively unusual stress history. It has been formed by weathering of highly overconsolidated clay-shale. The surface erosion potential caused by stress release and chlorite reaction to entrapped air upon contact of the soil mass with water is felt severe enough to cause the internal erodibility measured in this sample by this test.

Contributions to internal erodibility, as measured by this test, rarely may be separated into surface erosion and dispersive clay erosion.

During this research five samples of different properties and very low ESP(clays) provided a measure of the range of surface erosion to be expected in the field and how surface erosion affects internal erosion measured during this test. These include 103, 102, 101, 114, and 112.

Those samples which had average percents of erosion between 40 and 50 were 108 with 41.1%, 115 with 43.9%, and 104 with 45.6%. Other than the fact that they all have low plasticity and similar erosion tendencies, they are quite different. Samples 108, with a relatively large clay fraction of mostly illite with chlorite, was found to have the compaction characteristics of a clay with some silt. Its medium shrinkage potential is indicative of the activity of its clay fraction; however, its average internal erodibility is higher than that expected because its sensitivity to the chemical environment present plus surface erosion properties cause it to erode more severely than indicated by its ESP (clay). Sample 115 has an active enough clay fraction of mostly smectite with illite to have relatively high shrinkage potential, but it also has a relatively large silt fraction so that its compaction characteristics are those of a silty clay. It does have an internal erosion potential somewhat lower than that indicated by its ESP of 29 and ESP(clay) of 80.6. This was believed to occur because of (1) the reduced permeability of the mass, (2) low surface erosion potential and (3) swelling characteristics caused by the clay minerals present. It is the particular combination of these factors as affected by the soil chemistry properties, which dictates the sample's erosion potential. On the other hand, sample 104 has an easily predictable erodibility. The combination of a relatively active clay fraction of mostly smectite with illite and a grain size distribution which causes this soil to act during compaction like a sandy silty clay makes this sample's internal erosion predictable. Its percent erosion of 45.6 may be directly determined from its ESP of 11 or ESP(clay) of 47.8.

Samples 106 and 117 were determined to have internal erosion potentials of 56.1 and 58.3%, respectively. Sample 106 has properties which are almost identical to those of 115, except that it has a somewhat lower shrinkage potential. These facts are thought to adequately explain why this soil reacts to chemical properties in a way very similar to 115. However, it has internal erodibility that agrees better with its ESP of 23.5 and ESP(clay) of 73.5. Sample 117, with a low percentage of clay and relatively low shrinkage potential, has an internal erodibility even more predictable than that of 106. This soil has a somewhat active clay fraction of mostly illite with smectite and a relatively large noncohesive structure which in combination result in 58.3% erosion when its ESP is 6 and the more descriptive ESP(clay) is 46.2.

The next two soils in this order of increasing internal erodibility are 110 with 62.5% and 107 with 65.6% average internal erosion. Even though these soils both have low plasticities and similar clay mineralogy, their levels of erodibility come from the combined effects of very different properties. Since 110 has almost all smectite with some illite, it has plasticity and shrinkage higher than that expected from such a small clay fraction. Its compaction characteristics of a sandy silty clay are directly related to its large sand fraction. The combination of a mostly noncohesive structure and a clay fraction both chemically reactive and which swells markedly causes this soil to have higher than expected internal erodibility. Its ESP is 9.5 and ESP(clay) is 55.9. The combination of properties which brings the internal erodibility of 107 up to this level is somewhat different than any discussed thus far. Although its average sized clay fraction is composed of mostly smectite with illite and causes this soil to have moderately high shrinkage potential, this soil has low plasticity. This interaction of physical properties is best described by its compaction characteristics of a clay with some silt. The combination, which in this case results in 65.6% erosion, with an ESP of 10 and ESP(clay) of 27.7, is a chemically reactive clay fraction and a compacted structure with great enough permeability to allow water access to the soil mass.

The two soils which were found to have the highest average internal erosion potential are 118 with 75.8% erosion and 111 with 80.7% erosion. Although these two samples have low plasticity and shrinkage potential and compaction behavior characteristic of a sandy silty clay, the combination of all their physical properties affects their reaction to their chemical properties differently. Sample 118 has a small clay fraction of smectite and illite, and a large silt fraction. These act together to determine its other physical properties but, more importantly, affect its internal erodibility so that it may be somewhat predicted by its ESP of 13 and very closely predicted by its ESP(clay) of 76.5. This is done by a balance of its mostly cohesionless structure by clay minerals that exhibit relatively high cohesion, low surface erosion and high swelling potential. Alternatively, sample 111 was determined more internally erodible than its ESP of 12 and ESP(clay) of 54.5 would indicate. The different and more severe reaction of this soil to its chemical properties may be explained by its somewhat small clay fraction of mostly chlorite with illite and a little smectite. The noncohesive nature of the structure of its soil mass, in combination with its clay fraction having low swelling potential and high surface erosion potential, cause this sample to overreact to its chemical properties.

In final summary, it may be said that although a sample's chemical properties have the most important influence on internal erodibility of its soil mass, the combined effects of its physical and mineralogical properties definitely influence this behavior. The grain size distribution and clay mineralogy affect its structure, which determines porosity and stability. The type and amount of clay minerals determine its swelling, chemical reactivity, and surface erosion potentials. The particular combination of these physical and mineralogical properties is what determines how a soil will react to its chemical properties. It is interesting to note that in all cases the ESP(clay) of the samples tested better represented the effects of these chemical properties than their total soil ESP's.

Correlations of Results With Previous Methods of Identification

Among the previously proposed methods of identification, those felt most practical and oriented for use by soils engineers were included in this research. Because of its adoption and widespread use by the SCS, their Laboratory Dispersion Test (LDT) was run on the samples tested. Since the percent of sodium in the soil as compared to other cations as defined by the ESP had been accepted as an indicator of internal erodibility, the necessary testing was done to obtain this indicator for all samples used. The method found to be most applicable by soils engineers, involving the use of saturation extract data and curves based on observed field behavior, was the final one studied during correlation of physical erosion test results.

The outcome of correlation of average percent erosion by the Physical Erosion Test (PET) to percent dispersion by the LDT is shown in Figure 5.12. This graph illustrates that there was no relationship determined between the qualitative results from the LDT and the quantitative results from the PET. This further indicates that the properties of soils which influence dispersion of the type measured in the LDT are not those which influence and determine internal erodibility as measured by the PET. In conclusion, it may be said that these quantities are not significantly related.

The second analysis of correlation was directed at determining if a relationship could be found between the Physical Erosion Test results and the exchangeable sodium percentage of these samples. The average percents of erosion determined by testing these soils at Standard Proctor and Modified Proctor compactions were plotted, so that 36 points would be available for analysis. The graph shown in Figure 5.13 illustrates the absence of a significant relationship between the results found by these two methods. Since the ESP of a sample is an indicator of the chemical environment present in the total soil, it is not surprising that it does not relate to the percent erosion found by a physical test. This percent erosion is related to the chemical environment of the clay particles and influence of other physical properties of the sample.

In order to improve the correlation of Physical Erosion Test results with chemical properties of soils, the use of a modified ESP was studied. This quantity, called the Exchangeable Sodium Percentage of the clay fraction (ESP(clay)), was found to represent better the chemical

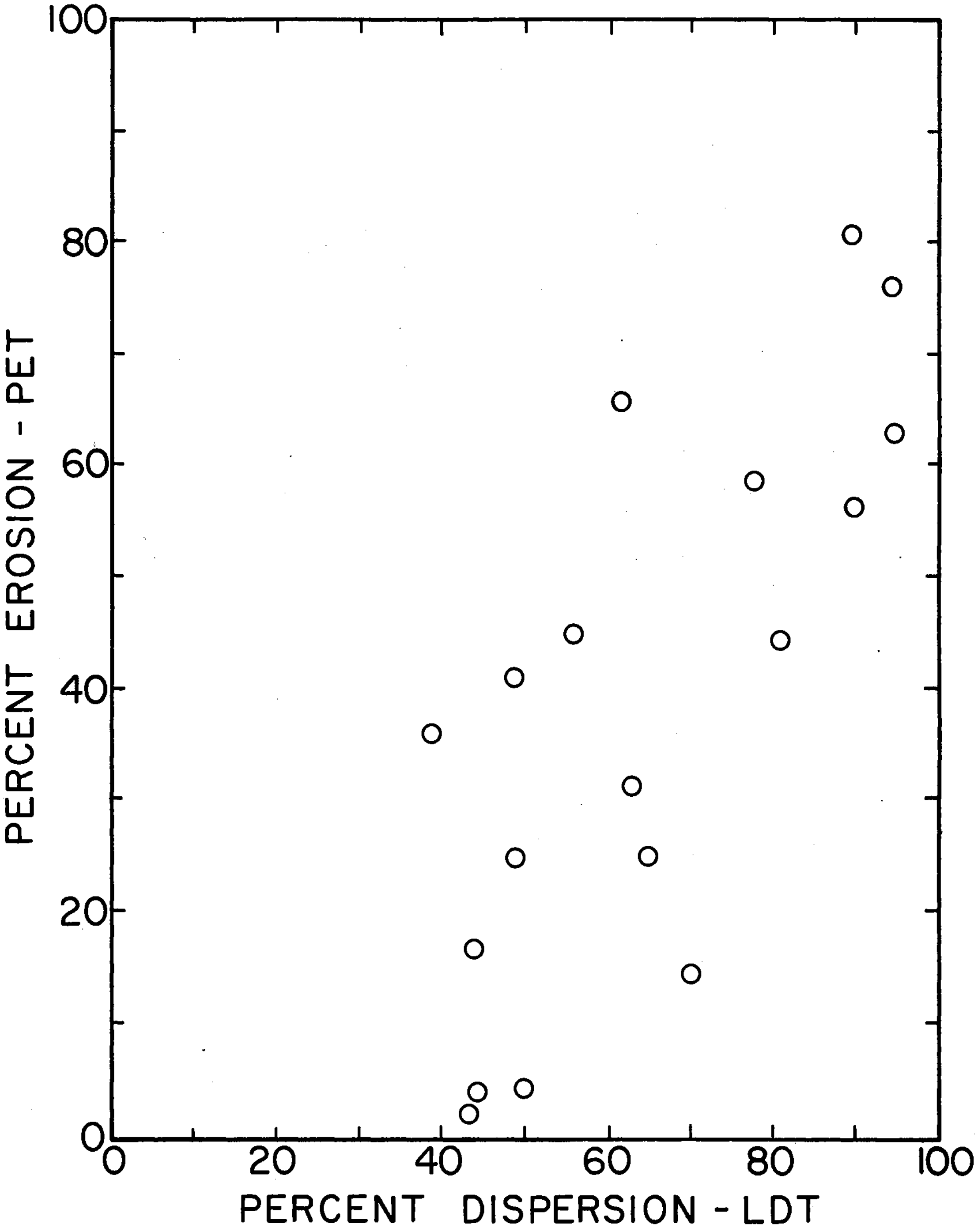

Figure 5.12. Correlation of Results From Physical Erosion Tests and Laboratory Dispersion Tests

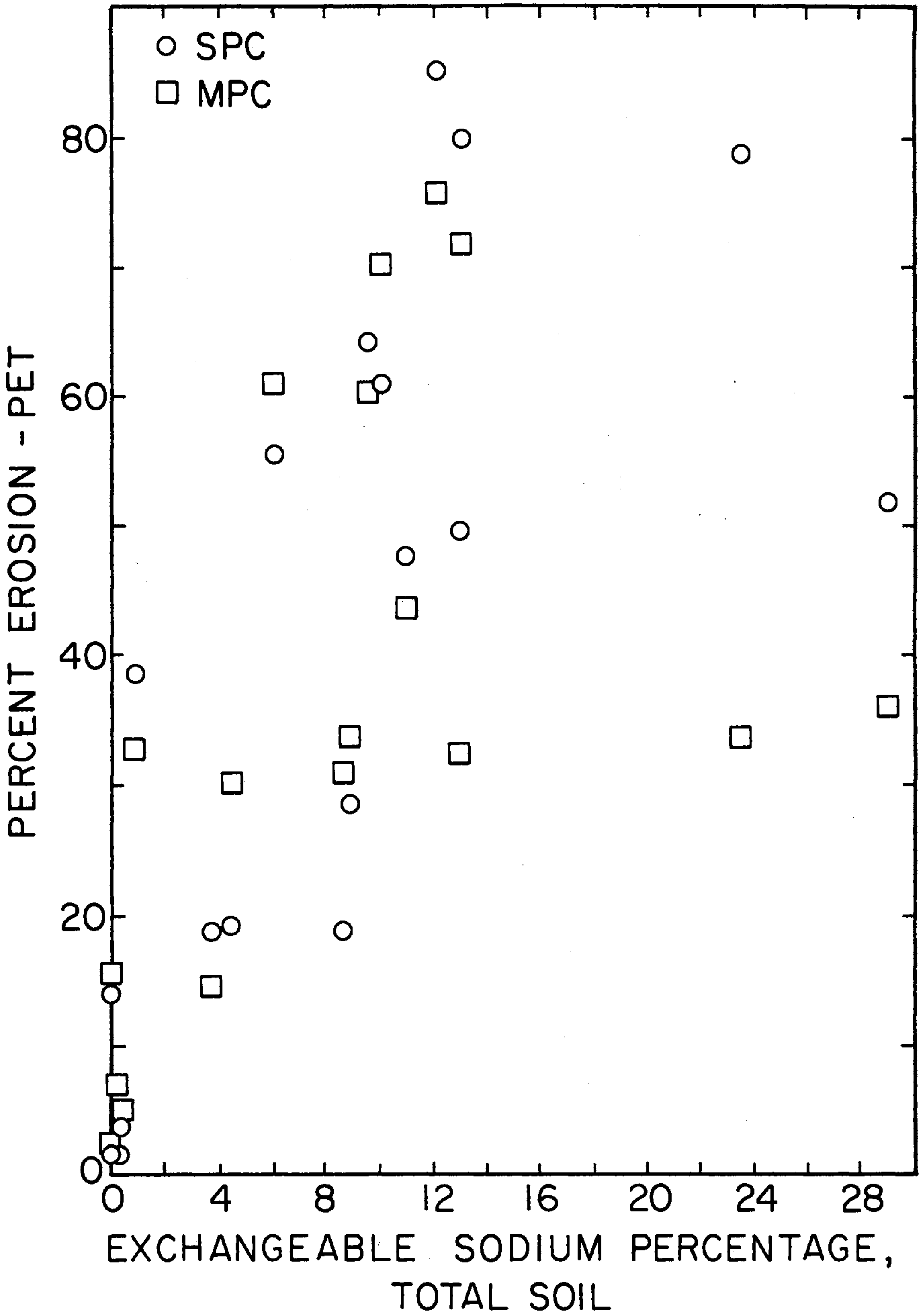

Figure 5.13. Correlation of Results From Physical Erosion Tests to Total Soil ESP's

environment of the clay particles in the samples tested. The relationship of the average percent erosion found for each compaction effort to the ESP(clay) of all samples tested is shown in Figure 5.14. When comparing the relationships illustrated by Figures 5.13 and 5.14, the significance of utilizing ESP(clay) to predict internal erosion is evident. Although this modification to the ESP does not include consideration for the physical properties of soils, it does provide a more adequate description of the effect of chemical properties on their clay fraction and definitely improves the relationship between chemical properties and observed internal erodibility. The relevance of using this relationship, rather than that found with ESP, is further supported by the fact that the method of identification thought to be most acceptable to soils engineers utilizes chemical properties which are descriptive of the environment belonging to the clay fraction.

The relationship indicated by the plotted points in Figure 5.14 was believed to be meaningful and worthy of further study. The pattern found seemed to indicate a linear relationship with some intercept of the percent erosion axis. The coordinates of all 36 points were analyzed by a method of linear regression to arrive at the formula of this relationship. The line, which was not restrained to a set intercept or slope, is that best fitting all the points. This line, included in Figure 5.14, has an intercept of 14.7 percent erosion and an inclination of 35.5° from the horizontal or ESP(clay) axis. The analysis made to find this line also indicated that the ESP(clay) of these samples could account for approximately 58% of the variations of plotted points from the line. This last information seems to, once again, point out the need for a Physical Erosion Test.

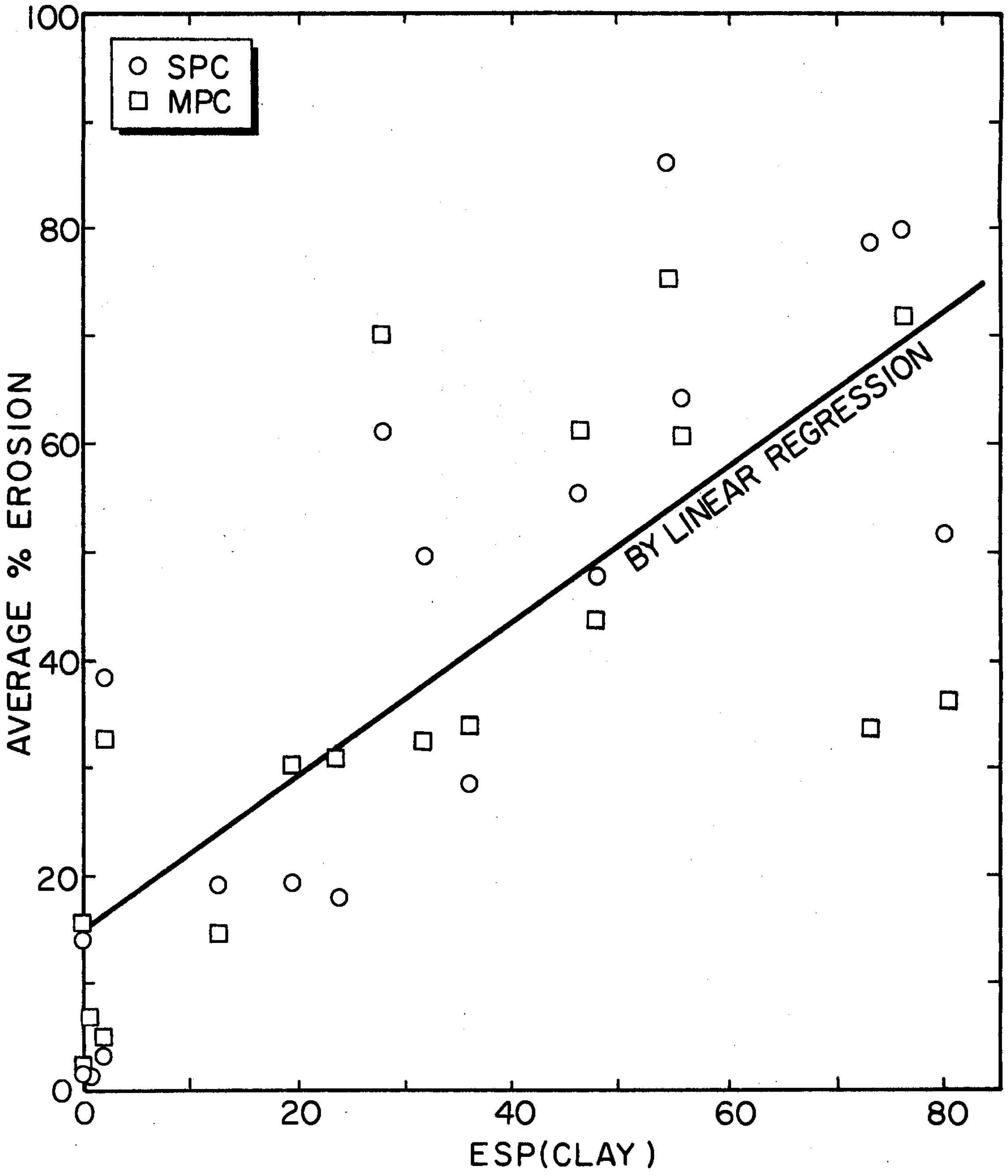

Figure 5.14. Correlation of Results From Physical Erosion Tests to ESP(Clay)'s

Further correlation of the percent erosion to the ESP(clay) was done on results determined during this research to find what effect different types of mixtures of clay minerals would have on this relationship. The samples were segregated into four groups and the results of each group were studied separately.

The first group consisted of samples which had chlorite as the main clay mineral with mixtures of illite and smectite making up the balance of the clay fraction. The relationship found for this group, samples 101, 111, 112, and 116, is shown in Figure 5.15. It has an intercept of 28% erosion and is inclined approximately 40°. The second, smaller group of samples, 102 and 105, had smectite as their main clay mineral with the balance being chlorite. The relationship determined for this group, as shown in Figure 5.15, has an intercept of 3.5% erosion and is inclined at about 42°. The third group had clay mineralogy consisting of mixtures of chlorite and illite. The relationship found for these soils, 103 and 108, is inclined at approximately 52° and has an intercept of 1.8% erosion. These lines of correlation are based on relatively few data points so that only a general analysis may be made based on the results found for the samples tested.

Since all three of these linear relationships are inclined at angles larger than that found when all samples were combined, the general influence of chlorite to increase sensitivity of the clay fraction to changes in chemical properties may be seen. In addition, when chlorite was the main clay mineral present, its increase of surface erosion potential may be seen in a significantly large intercept value. Lastly, it is interesting to note the greater sensivitity to changes in chemical properties of samples which had chlorite and illite as clay minerals.

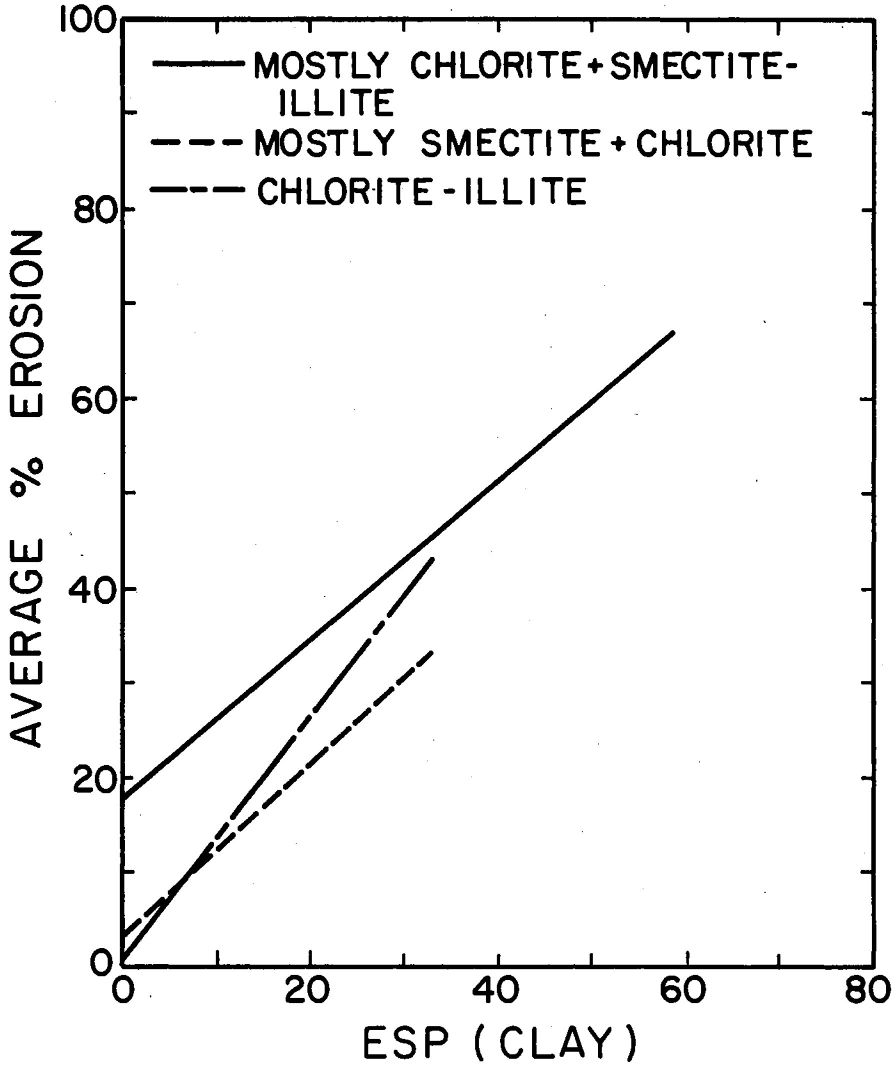

Figure 5.15. Percent Erosion Versus ESP(Clay) for Clay Mineral Mixtures Other Than Smectite-Illite

Although this analysis is based on relatively few samples, the influence of clay mineralogy on internal erodibility is evident.

A similar analysis was conducted on the fourth group of samples. This group was made up of all the samples not mentioned above, except Georgia Kaolinite, which had clay fractions consisting of mixtures of smectite and illite. The relationship found for this group is shown in Figure 5.16. This line was determined by a linear regression procedure such as that used to find the relationship for the combined samples. The smectite-illite line has an intercept of 27% erosion and is inclined at 25°. When comparing this relationship to that found for all samples, the particular reaction of this sample group of soils to changes in chemical properties of their clay fractions is apparent. The presence of mixtures of smectite and illite in the clay fractions of these samples and the influence on internal erodibility of their physical properties have combined to produce this relationship. The combined effects of their physical properties are believed to have brought about the higher-than-average intercept of this relationship. The lower-than-average slope of this linear relationship is felt to be caused by the high swelling potential of smectite and illite.

The final correlation of the results of Physical Erosion Testing to those found by previously proposed methods of identification was accomplished by plotting selected sample chemical properties on the field behavior-saturation extract graph proposed by Sherard et al. (37). The way in which these chemical properties are plotted on this graph makes the results represent the chemical environment of the total soil and clay fraction on the same plot. As discussed earlier, the curves which form the boundaries of zones of behavior in this graph were determined by

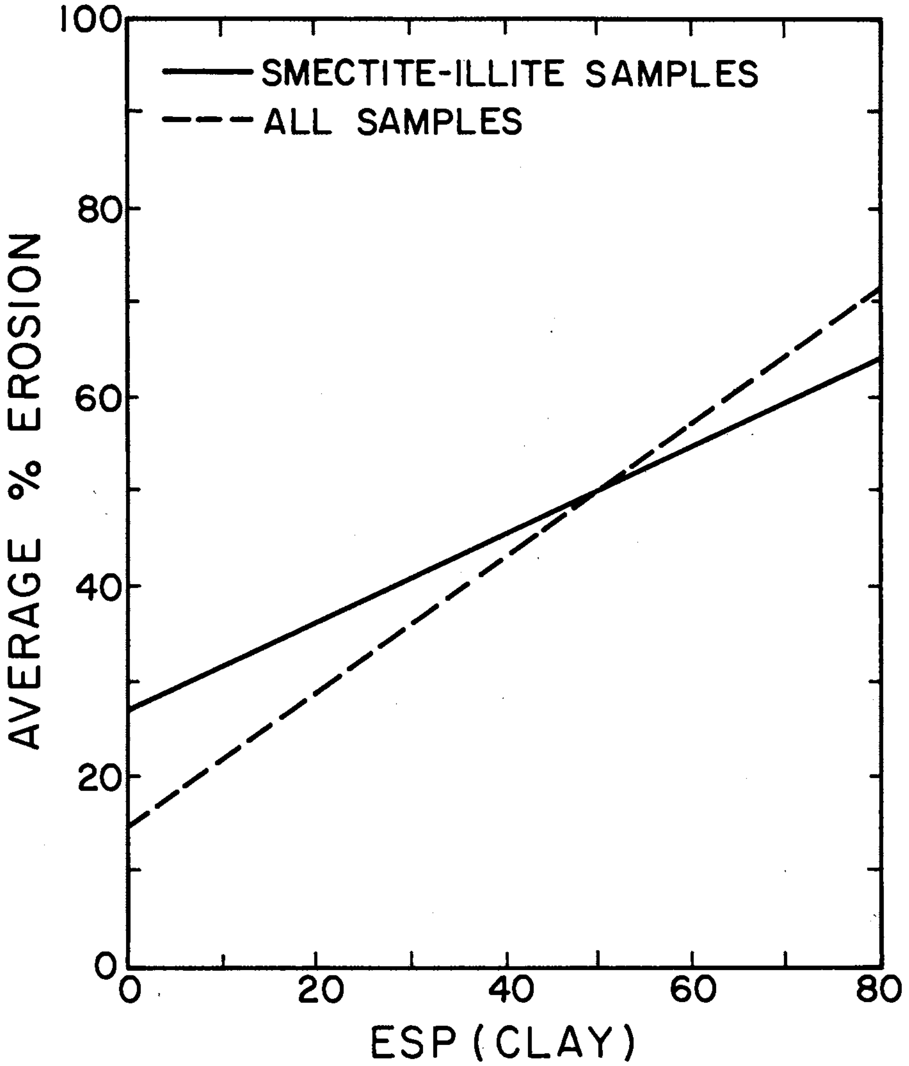

Figure 5.16. Percent Erosion Versus ESP(Clay) for Clay Mineral Mixtures of Smectite and Illite

observing field behavior. In order to relate percent erosion to these zones of behavior, the results of this research were arbitrarily divided into three groups as had been done to LDT results. These groups were 0 to 33%, 34 to 66%, and 67 to 100% erosion. An illustration of the saturation extract chemical properties of the samples tested plotted on the referenced graph (using symbols to indicate percent erosion groups) is included as Figure 5.17.

The correlation of Physical Erosion Test results to the behavior zones of this plot is significant. Six of the eight samples with percents of erosion from 0-33% have chemical data which plots in the non-dispersive zone. The data of one out of these eight samples plots in the transition zone. The one sample out of this group whose data places it in the dispersive erosion zone had an average percent erosion of 31.2%. In addition, its ESP(clay) was 36.

The group which had 34 to 66% average erosion, also consisted of eight samples. The chemical data of all but one of these was found to be plotted in the dispersive erosion zone. The sample whose data plotted in the non-dispersive zone was Permain Red Clay. The reasons for this occurrence have been included earlier in this chapter. Finally, the chemical data of the two samples which had more than 66% average erosion was found to plot in the dispersive erosion zone. It is interesting to note that both of these samples have data which indicates their erosion behavior to be more severe than that of all the other samples.

Correlation of Physical Erosion Test results with the behavior by this method of identification was believed to be most important because of its acceptibility for use by soils engineers. The results of the analysis of correlation discussed above indicate that the physical

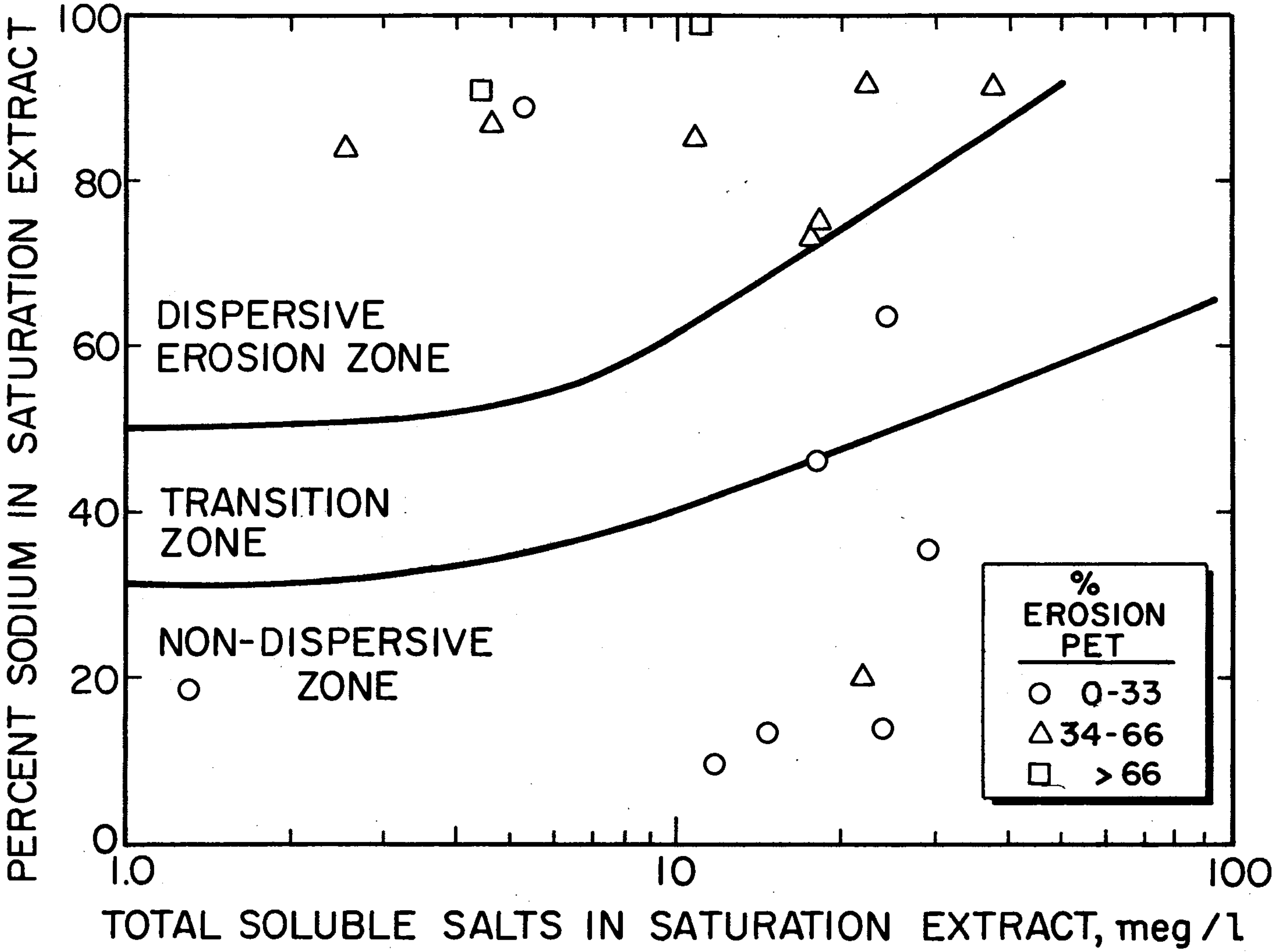

Figure 5.17. Correlation of Physical Erosion Test Results to Field Behavior as Determined by Saturation Extract Chemical Properties

erosion test method, studied during this research, is a significant addition to those previously proposed. It supplies a quantitative result which may be utilized to assess the combined effects of physical and chemical properties on dispersive clay erosion potential and to predict field behavior.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

During the past 20 years, dispersive clay soil erosion has been viewed with increasing awareness by soils engineers as a pheomenon causing failures in earth structures. As a result, the need for a method of identifying dispersive clay soil erodibility that would be acceptible for use by soils engineers when predicting field behavior became apparent. This research included the development of a Physical Erosion Test apparatus and procedure to measure internal dispersive clay erodibility in a manner useful to soils engineers. Eighteen soils were tested using this procedure and other previously proposed methods for identification of dispersive clay erodibility. The relationships between the proposed Physical Erosion Test and the other methods were also investigated. Based on the experimental data and discussions presented in previous chapters, it may be concluded that:

1. Dispersive clay soil erosion is a phenomenon resulting from dispersion and piping of clay particles, and often includes piping of sand and silt particles as well. Subsequently, this type of erosion can result in the failure of an earth structure.

2. The occurrences of this phenomenon may be found in arid, semi-arid and semi-humid areas of the world.

3. Either smectite and/or illite clay minerals are present in all dispersive clay soils.

4. The results of dispersive clay soil erosion are influenced by both the chemical dispersion potential of clay particles in the soil mass and the surface erosion potential of the soil mass.

5. The severity of erosion caused by the dispersive clay soil erosion phenomenon is dependent on the combined physical, mineralogical and chemical properties of dispersive clay soils.

6. a) The properties which influence dispersive clay soil erodibility are primarily chemical in nature. Their effects may be adequately predicted by determination of the ESP(clay), as defined in this thesis.

b) Surface erosion potential is established by the type and amount of clay minerals present, and by the stress history of the soil.

c) Other properties which influence dispersive clay soil erodibility are grain size distribution, compacted structure, swelling potential, and chemical reactivity of the clay mineralogy present.

7. Dispersive clay erodibility is unaffected by relatively small variations in dry density but is somewhat influenced by relatively large variations in dry density.

8. Dispersive clay erodibility is significantly affected by changes in compaction water content.

9. For one or more reasons, previously proposed methods for identification of dispersive clay soil erodibility are unacceptable for use by soils engineers. The major disadvantages of these methods were that results are qualitative instead of quantitative, behavior is

determined by the chemical properties of the soil, and determination of behavior is based on a less than representative soil mass.

10. The correlations of Physical Erosion Test results with those obtained using the field behavior diagram of Sherard et al. and ESP(clay) method for identifying dispersive clay soil erodibility were excellent.

11. The Erosion Device and the Physical Erosion Test procedure were proven to be excellent for providing the measure of dispersive clay soil erodibility needed by soils engineers to predict accurate field behavior.

Recommendations

In order to develop a better understanding of dispersive clay soil erosion and the influences of all soil properties on this phenomenon, as well as better utilization of these problem soils in earth structures, the following recommendations for further research may prove useful:

1. Continue the use of the Erosion Device and Physical Erosion Test procedure for measurement of dispersive clay erodibility of other natural soils. This should be done on soils whose exact field behavior is already documented to prove further the validity of this device and procedure.

2. Investigate further the influence of compacted dry density on the erosion measured by the Physical Erosion Test. This should be done by varying compaction effort applied while holding compaction water content constant.

3. Further investigate the influence of compaction water content on the erosion measured by the Physical Erosion Test. This should be

by varying compaction water content, while holding applied compaction effort constant.

4. Investigate further the influence of ESP(clay) on the erosion measured by the Physical Erosion Test. This should be done by holding physical properties constant and varying the ESP(clay).

5. Investigate the influence of chemical stabilization prior to compaction on the erosion measured by the Physical Erosion Test. The addition of compounds which would provide calcium, magnesium and potassium cations should be included in this study.

6. Investigate the influence of chemical stabilization during erosion testing on the erosion measured by the Physical Erosion Test.

7. Investigate the influence of other stabilizers on the erosion measured by the Physical Erosion Test.

8. Carry out similar investigations as those above using parallel stabilization measures in laboratory and full scale field erosion research.

9. Carry out similar investigations as those outlined in 1, 6, 7, and 8 above utilizing undisturbed samples.

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APPENDIX A

THE DETAILED PROCEDURE UTILIZED DURING PHYSICAL EROSION TESTING

1. Four Harvard miniature mold cylinders of each sample were compacted at given water contents for the two compactive efforts. The water contents used were at optimum and two percent below optimum. Thus, eight cylinders were prepared from each sample, four each at Standard and Modified Proctor efforts. Erosion testing was done, where possible, on four soils during each test sequence.

2. A sample to be compacted at the desired water content was taken from each of four of the eighteen samples to be tested. The selected sample was large enough to fill the mold with compacted soil and provide enough excess for water content determination.

3. Just prior to compaction enough distilled deionized water was added to each sample to bring it up to the desired water content.

4. A Erodibility Test Data Sheet (Figure A.1) was prepared to include description of samples, weight and volume of compaction mold, number and weight of tare cans, and number and weight of cells used.

5. Prior to compaction each moist soil sample was mixed thoroughly to insure homogeniety. Care was taken not to lose any sample and to minimize moisture loss during mixing. The final mixed moist sample was broken down such that all particles were smaller than U.S. No. 10 sieve size.

6. Each sample was then compacted into a cylinder with the desired compaction effort and procedure, using the OSU soil mechanics laboratory Miniature Compaction Machine.

7. After compaction, the sample was carefully trimmed level with Harvard miniature mold. The soil cylinder and mold were weighed to the nearest 0.01 gram and this weight recorded.

School of Civil Engineering
Oklahoma State University
Soil Mechanics Laboratory

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				
Wt. Compacted Soil & Mold				
Wt. Mold				
Wt. Compacted Soil				

Figure A.1. Erodibility Test Data Sheet

8. The remainder of the moist sample was placed in a tare can and its water content determined by drying in an 110° C gravity oven.

9. Each finished cylinder was partially extracted from the mold using a small spacing block (Figure 4.9) with the top end down. The top of the cylinder was once again trimmed level with the top of the mold. The shortened cylinder was then extracted, bottom down. These steps were done carefully so as to prevent damage to the cylinder. This shortening was done to prevent later overcompression of cylinders.

10. After the cylinders were extracted, they were placed into cells of the Erosion Device. Cell assignment for cylinders was done prior to compaction. For each pair of cylinders prepared from each soil at the same water content and compaction effort, cell assignments included one outside cell (1 or 4) and one inside cell (2 or 3). Cylinders were oriented so that the top of the cylinders were at the top of the cells. During testing samples at each compaction effort were placed in all four positions on the Erosion Device.

11. 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 and so that soil cylinder compression would be the same at each end.

12. The soil cylinders were compressed into the cells with the hydraulic press by pushing each compression and spacing block into the cell to its limit. This was carefully done to insure that the soil cylinder was compressed the same amount on each end. The assemblage was then removed from the press and the blocks were removed.

13. The positions for longitudinal holes were marked in the tops of cylinders after compression and each cell was then placed in plastic

wrap to prevent loss of moisture while the other cylinders were compressed.

14. Three (3) 0.125 inch diameter holes were then drilled longitudinal through each cylinder. The twist drill bits used were placed in a drill press to insure alignment, and were cleaned after each hole was completed. Drilling proceeded at such a speed as to minimize disturbance of the soil cylinder.

15. After drilling, each hole was cleaned and the drill "polishing" removed by a pipe cleaner. Each cell and sample cylinder was then weighed to the nearest 0.01 grams.

16. Prior to mounting the prepared cells and soil cylinders into the Erosion Device, the apparatus was prepared for testing. This process included the following:

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

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

c. The primary water tank was filled with enough distilled water to complete the 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 device was then pressurized so that 15 psi water pressure was available in the now filled secondary water tank. Water under this pressure was also available to the valves of the manifold directly above the cells.

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

g. All unit timers were set to begin their six minute cycle with all solenoid actuated valves closed and all power switches in the off position.

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

18. When the Erosion Device was ready and final preparation of the removable portion of the cell was complete each cell was placed into the device top up. This operation included 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. At this same time all tubing connections were checked.

19. At this time the secondary holding tank was filled and pressure vented. Five minutes prior to the time selected to begin the test, manifold-cell valves were progressively opened. The valve for unit 1 was opened, then 15 seconds later the valve for unit 2 was opened, etc., until valves for all units were open. During this time the voids in each cell, in turn, became filled with water and the soil cylinders started becoming saturated with water under atmospheric pressure. The secondary holding tank was kept at least one-half full of water during this time and was filled and put under test pressure of 15 psi, along with the whole device, at the beginning of the test.

20. The test was begun at the selected time by progressively turning on each unit's timer. Unit one's timer was turned on and each other unit's timer was turned on at 15 second intervals thereafter, such as

was done previously with their manifold valves. These 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 cylinders holes and the cell, and replace it with fresh distilled water.

21. After four (4) hours of elapsed testing time, each unit timer was turned off. Just 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.

22. After all power switches were turned off, the water pressure input valve on the secondary holding tank was closed and this tank was vented. If testing was completed for the day, the primary tank system was also vented and the pressure system shut down.

23. The water supply lines for each cell were then quickly disconnected from the manifold valves and the cells were placed in a horizontal position to prevent further loss of eroded material from the cylinders. The cells were left in their "C" brackets to facilitate this operation.

24. The cell ends were then removed and all of the soil cylinder left in the cell was carefully pushed, scraped and washed into a preweighed tare dish. This dish, with soil and water, was then placed in an 110° C oven to dry. When dry it was removed, cooled in a desicator, and weighed to the nearest 0.01 gram. The dry weight of soil left, after erosion, was used to determine the erodibility of the sample.

The important data recorded on the Erodibility Test Data Sheet are each cylinder's compacted dry density, compaction water content, dry weight before erosion and dry weight after erosion. The final step in this procedure was to determine each cylinder's erodibility by comparing its loss of dry weight of soil during erosion to its original dry weight of soil. This was expressed as a percentage loss.

APPENDIX B

DETAILED RESULTS FROM PHYSICAL EROSION TESTING

Standard Proctor Compaction (R #1-18)

	Water Content			Dry Density pcf		Percent Erosion	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
101	15.26	15.8	-2.5	105.70	+1.2	2.2	3.3
	14.90		-2.9	103.78	-0.7	8.1	
	18.35	17.8	+0.6	105.49	+1.0	1.6	
	17.84		+0.0	105.71	+1.2	1.1	
102	16.12	17.2	-3.1	104.49	+2.5	2.5	1.4
	16.39		-2.8	107.60	+5.6	1.1	
	16.69	19.2	-2.5	103.66	+1.7	0.4	
	18.66		-0.5	103.13	+1.1	1.4	
103	14.31	15.5	-3.2	107.62	+1.7	1.1	1.5
	14.54		-3.0	106.44	+0.5	3.4	
	19.01	17.5	+1.5	106.83	+0.9	---	
	17.40		-0.1	107.77	+1.9	1.4	
104	13.22	14.3	-3.1	112.10	+0.7	57.2	47.7
	13.04		-3.3	112.70	+1.3	80.8	
	16.95	16.3	+0.7	110.58	-0.8	20.2	
	16.25		+0.0	111.04	-0.4	32.4	
105	19.72	19.8	-2.1	99.05	+3.4	21.5	17.9
	21.68		-0.1	96.98	+1.3	18.4	
	21.48	21.8	-0.3	98.63	+2.9	12.6	
	21.47		-0.3	98.68	+3.0	19.0	

Standard Proctor Compaction (R #1-18) (Cont'd.)

	Water Content			Dry Density pcf		Percent Erosion	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
106	16.74	17.0	-2.3	103.91	+0.2	88.9	78.7
	17.22		-1.8	104.22	+0.5	46.5	
	19.46	19.0	+0.5	104.12	+0.4	87.3	
	18.59		-0.4	104.47	+0.8	92.1	
107	14.50	15.0	-2.5	101.53	+2.1	35.3	61.0
	16.10		-0.9	100.59	+1.2	89.9	
	17.60	17.0	+0.6	100.85	+1.5	81.1	
	16.79		-0.2	101.23	+1.8	37.8	
108	20.20	20.5	-2.3	99.99	+1.3	51.7	49.7
	20.87		-1.6	99.74	+1.0	62.3	
	22.97	22.5	+0.5	98.81	+0.1	23.5	
	21.85		-0.6	99.47	+0.8	61.2	
109	11.82	11.7	-1.9	117.45	+0.0	17.0	19.3
	12.08		-1.6	115.48	-2.0	40.0	
	14.04	13.7	+0.3	116.00	-1.5	12.6	
	13.44		-0.3	116.20	-1.3	7.4	
110	10.43	10.0	-1.6	119.76	-1.9	59.0	64.4
	10.24		-1.8	120.50	-1.2	73.7	
	12.47	12.0	+0.5	119.43	-2.3	90.5	
	12.10		+0.1	119.84	-1.9	34.2	

Standard Proctor Compaction (R #1-18) (Cont'd.)

	Water Content			Dry Density pcf		Percent Erosion	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
111	11.04	11.3	-2.3	119.78	+1.5	67.0	86.0
	11.65		-1.6	119.75	+1.5	95.1	
	13.17	13.3	-0.1	118.54	+0.2	87.1	
	14.06		+0.8	117.23	-1.1	94.9	
112	14.92	14.9	-2.0	104.22	-2.3	59.1	38.3
	15.55		-1.3	104.32	-2.2	36.0	
	16.99	16.9	+0.1	104.81	-1.7	31.1	
	17.45		+0.6	103.88	-2.6	27.0	
113	18.58	18.0	-1.4	95.09	-1.1	24.0	18.8
	18.50		-1.5	93.80	-2.4	10.1	
	20.59	20.0	+0.6	95.01	-1.2	17.1	
	18.63		-1.4	96.19	+0.0	24.0	
114	31.01	30.7	-1.7	81.83	-2.9	12.4	14.0
	30.38		-2.3	82.59	-2.1	21.2	
	34.24	32.7	+1.5	82.20	-2.5	14.3	
	31.67		-1.0	83.63	-1.1	8.1	
115	17.06	17.0	-1.9	109.13	+1.1	43.2	51.8
	16.82		-2.2	109.09	+1.1	46.0	
	19.07	19.0	+0.1	108.84	+0.8	57.4	
	18.42		-0.6	108.90	+0.9	60.4	

Standard Proctor Compaction (R #1-18) (Cont'd.)

	Water Content			Dry Density pcf		Percent Average	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
116	19.24	19.5	-2.3	106.78	+6.3	34.4	28.5
	19.71		-1.8	106.14	+5.6	16.4	
	21.61	21.5	+0.1	102.35	+1.9	35.3	
	21.16		-0.3	102.12	+1.6	27.9	
117	15.74	18.0	-4.3	110.64	+10.1	53.9	55.4
	18.14		-1.9	106.78	+6.3	61.4	
	19.85	20.0	-0.1	102.60	+2.1	49.8	
	19.02		-1.0	102.92	+2.4	56.6	
118	14.76	15.0	-2.2	113.11	+4.1	98.0	79.9
	15.50		-1.5	111.78	+2.8	98.5	
	17.09	17.0	+0.1	110.76	+1.8	93.2	
	16.92		-0.1	110.74	+1.7	29.8	

Modified Proctor Compaction (R #19-36)

	Water Content			Dry Density pcf		Percent Erosion	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
101	11.85	12.5	-2.6	115.86	+1.0	15.5	5.0
	13.10		-1.4	115.52	+0.6	1.0	
	14.53	14.5	+0.0	115.48	+0.6	1.6	
	13.88		-0.6	116.22	+1.3	1.9	
102	12.95	13.8	-2.8	116.70	+4.2	12.3	6.7
	13.19		-2.6	116.87	+4.4	7.6	
	15.98	15.8	+0.2	113.75	+1.3	3.7	
	15.89		+0.1	113.87	+1.4	3.2	
103	11.88	12.5	-2.6	119.65	+2.7	3.7	2.1
	12.23		-2.3	118.34	+2.3	3.0	
	14.92	14.5	+0.4	116.47	-0.5	1.3	
	14.78		+0.3	116.50	-0.5	0.2	
104	7.49	8.1	-2.6	119.09	+1.6	38.3	43.5
	8.03		-2.1	118.54	+1.0	17.7	
	10.00	10.1	-0.1	120.97	+3.5	48.6	
	10.09		+0.0	121.68	+4.2	69.3	
105	15.59	15.5	-1.9	112.31	+1.7	35.3	30.9
	16.06		-1.4	111.97	+1.4	34.8	
	16.35	17.5	-1.1	112.50	+1.9	27.4	
	18.34		+0.8	108.57	-2.0	25.9	

Modified Proctor Compaction (R #19-36) (Cont'd.)

	Water Content			Dry Density pcf		Percent Erosion	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
106	11.55	13.4	-3.8	116.25	+1.4	34.7	33.5
	14.40		-1.0	116.10	+1.2	37.4	
	14.66	15.4	-0.7	116.69	+1.8	35.3	
	15.89		+0.5	114.16	-0.7	26.5	
107	11.71	12.2	-2.5	115.76	+1.3	85.8	70.1
	12.83		-1.4	115.54	+1.0	80.4	
	13.33	14.2	-0.9	117.16	+2.7	58.6	
	15.09		+0.9	115.52	+1.0	55.6	
108	15.68	16.3	-2.6	112.50	+2.0	30.3	32.5
	16.84		-1.5	112.33	+1.8	34.1	
	18.13	18.3	-0.2	110.78	+0.3	30.0	
	18.58		+0.3	110.81	+0.3	35.5	
109	8.31	7.9	-1.6	124.24	-1.6	23.6	30.1
	7.76		-2.1	125.75	+0.0	56.2	
	9.04	9.9	-0.9	129.35	+3.6	25.1	
	10.31		+0.4	127.05	+1.3	15.6	
110	-----	6.6	----	------	----	----	60.5
	6.60		-2.0	127.94	-0.2	50.3	
	7.59	8.6	-1.0	132.21	+4.1	70.7	
	-----		----	------	----	----	

Modified Proctor Compaction (R #19-36) (Cont'd.)

	Water Content			Dry Density pcf		Percent Erosion	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
111	7.73	7.5	-1.8	126.63	-0.6	82.4	75.3
	7.32		-2.2	127.29	+0.1	99.3	
	8.22	9.5	-1.3	131.34	+4.1	54.8	
	10.65		+1.1	127.32	+0.1	64.5	
112	12.90	13.0	-2.1	118.69	+3.1	35.0	32.5
	12.74		-2.3	119.41	+3.8	42.2	
	13.15	15.0	-1.8	121.33	+5.7	23.4	
	15.36		+0.4	113.84	-1.8	29.5	
113	15.95	17.0	-3.0	110.50	+2.8	18.5	14.6
	17.19		-1.8	110.11	+2.4	18.2	
	18.46	19.0	-0.5	109.07	+1.4	9.2	
	19.05		+0.1	108.51	+0.8	12.3	
114	24.69	25.4	-2.7	94.17	+1.0	14.7	15.3
	25.38		-2.0	94.15	+1.0	15.3	
	26.92	27.4	-0.5	93.31	+0.1	20.4	
	27.12		-0.3	92.78	-0.4	10.8	
115	12.72	12.6	-1.9	123.00	+1.9	42.4	35.9
	11.88		-2.7	124.12	+3.0	42.3	
	14.24	14.6	-0.4	121.42	+0.3	30.7	
	14.75		+0.2	121.00	-0.1	28.3	

Modified Proctor Compaction (R #19-36) (Cont'd.)

	Water Content			Dry Density pcf		Percent Erosion	
Sample	Test	Desired	+ - From Optimum	Test	+ - From Maximum	Test	Average
116	12.91	13.2	-2.3	118.90	+2.8	51.6	33.8
	12.67		-2.5	119.23	+3.1	51.6	
	15.47	15.2	+0.3	116.40	+0.3	15.9	
	15.94		+0.7	115.54	-0.6	15.9	
117	11.86	12.2	-2.3	116.28	+1.3	74.1	61.1
	11.56		-2.6	117.29	+2.3	66.3	
	12.98	14.2	-1.2	116.18	+1.2	32.6	
	15.12		+0.9	113.25	-1.7	71.2	
118	8.46	9.5	-3.0	122.13	-0.4	55.4	71.7
	9.83		-1.7	123.81	+1.3	83.6	
	12.00	11.5	+0.5	122.46	+0.0	66.3	
	11.87		+0.4	122.10	-0.4	81.3	

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VITA

Thomas Merton Petry

Candidate for the Degree of

Doctor of Philosophy

Thesis: IDENTIFICATION OF DISPERSIVE CLAY SOILS BY A PHYSICAL TEST

Major Field: Civil Engineering

Biographical:

Personal Data: Born in San Pedro, California, September 25, 1944, the son of Mr. and Mrs. Oscar H. Petry.

Education: Graduated from Jefferson City Senior High School, Jefferson City, Missouri, in May, 1962; received the Bachelor of Science in Civil Engineering from The University of Missouri at Rolla, Rolla, Missouri, in May of 1967; received the Master of Science in Civil Engineering from The University of Missouri at Columbia, Columbia, Missouri in May of 1968; completed the requirements for the Doctor of Philosophy degree at Oklahoma State University in July, 1974.

Professional Experience: Surveying Rodman, Summer 1963 and 1964, Compaction Inspector, Summer, 1965, Missouri State Highway Department, Civil Engineer (soil mechanics and materials laboratory), Illinois Highway Department, Summer, 1967; Graduate Teaching Assistant (soil mechanics laboratory), Department of Civil Engineering, University of Missouri at Columbia, January 1967 to May 1968; Design Engineer on the staff of the Command Engineer, U.S. Army Korea Support Command, Taegu, Korea, March 1971 to July 1971; Laboratory Testing Technician, Parcher-Haliburton-Heiliger, Foundation Consultants, Stillwater, Oklahome, March 1972 to May 1974; Graduate Research Assistant (NSF Local Government Problems in Solid Waste Disposal), June 1972 to August 1972, (OHD Bituminous Mixes) August 1972, Graduate Instructor Assistant (soil mechanics) September 1972 to May 1973, Graduate Research Assistant (OHD Bituminous Mixes) August 1973, Instructor, Part-time, in Civil Engineering (soil mechanics and foundation engineering), September 1973 to May 1974, School of Civil Engineering, Oklahoma State University, Civil Engineer, Parcher-Haliburton-Heiliger, Foundation Consultants, Stillwater, Oklahoma, June and July 1974.

Professional Societies: Member, Chi Epsilon Fraternity, E.I.T. No. 13762-E, Missouri.