SOIL PLASTICITY DEPENDENCY

ON SURFACE AREA

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CHAPTER I

INTRODUCTION

In nature the weathering processes by which rock masses are reduced to soil are very complex with both mechanical and chemical processes occurring simultaneously. The end product of many chemical weathering processes is a group of very small crystalline minerals called clay. Behavior of these clays is influenced primarily by the attractive or repulsive forces between their particles. In contrast larger particles such as sand are mainly influenced by the forces of gravity. Delineation of the relationships between physico-chemical properties of clay minerals and those engineering properties, as determined by soil mechanics studies, is of major importance. Literature indicates much study on both specific and general clay mineral properties but very little research into their effects on engineering properties. Specifically, it is the aim of this study to examine the correlation between specific surface area and the plasticity characteristics as measured by the Atterberg Limit methods. This plasticity dependency will be determined on a series of laboratory-altered clay mixtures and then tested on several natural soil clays.

General

Clay mineral composition, particle size distribution, non-clay mineral composition, organic material, and geologic history control

1

the engineering properties of cohesive soils and shales. With such a multitude of variable parameters, it is impossible to classify soil clays or even to predict their behavior entirely on the basis of clay mineral composition. Much of soils engineering necessitates broad assumptions of engineering properties which are, for cohesive soils, partially controlled by mineralogical makeup. A knowledge of clay mineral composition and its resultant engineering behavior will help greatly to evaluate the many empirical test data from standard soil mechanics testing (Grim, 1962).

Two requisites for successful soils engineering practice are a knowledge of analytical soil mechanics design procedures and the experience, plus judgment, necessary to predict changed conditions. The former is routinely learned as an academic discipline. The latter is considerably more involved in that it requires prediction of future events and how they will relate to the situation. One of the aids in such predictions is a fundamental knowledge of physico-chemical properties of various soil constituents. This knowledge can provide a concept of the basic causes of particular soil properties and aid in interpreting soils engineering laboratory data.

The term "clay" has many meanings dependent upon the particular using agency. For purposes of this report, clay shall be defined as small mineral particles which usually exhibit plasticity when combined with small amounts of water. Not all small mineral particles possess plasticity, which is a phenomenon related to surface chemistry (Scott, 1963). These particles which fall into the forementioned definition of clay are referred to as clay minerals that are discussed in more detail in the next chapter.

In most engineering soil classification systems, an extremely small amount of clay will affect the properties of the entire soil mass. For example, in the Unified Soil Classification System, this effect is noticeable at values of clay fraction in excess of five per cent by weight. When twelve per cent is present, the properties of the soil mass are controlled by the clay behavior (Corps of Engineers, 1953). Proper identification of the particular clay mineral or minerals present is necessary if valid predictions of future behavior are to be made. Whereas soil science and geological data cannot be applied quantitatively to soil engineering design situations at this time, any information which may be used to understand and appreciate the materials used in engineering construction will ultimately lead to a more comprehensive design that will adequately fulfill the intended purpose.

Problem

Plasticity of soil materials is one of the major indices by which the soils engineer obtains an indication of the engineering design values for both the present and future condition. It is also the prime indicator of how much and how rapidly the present engineering properties may change in the future under various external conditions (Scott, 1963). Plasticity is defined as that property of certain materials in which the deformation resulting from a certain sudden stress is retained after removal of that stress with no resultant volume change. Plasticity of cohesive soils is a surface chemistry property in which the inter-particle forces and the liquid between determine the behavior. Atterberg (1911) postulated several consistency states and their limiting boundaries. Casagrande (1932) refined and enlarged the theory of soil plasticity that

is generally accepted today. He further standardized laboratory procedures to be used in this regard. Further discussion of these consistency states and their boundaries is considered in the next chapter.

The Atterberg plasticity limits are functions of the adsorbed cation(s), clay mineral types, size and shape of particle, crystallinity, and many other related factors (Grim, 1962). Since plasticity is primarily surface chemistry dependent, the hypothesis of this research is that specific surface area is the major controlling factor in the behavior of soil masses when in the plastic consistency state. All other factors merely influence the amount of surface area available for liquid adsorption.

CHAPTER II

SOILS ENGINEERING-SCIENCE

Soils engineering-science is defined as that field of soils engineering which recognizes the contributions of both soil mechanics and soil science to the creation of the final project design.

Clay Mineralogy

Clay minerals are extremely small crystalline forms of hydrous aluminum silicates. Most of the natural clay minerals may be grouped into three main families based on crystalline structure. Within each structural type, crystalline perfection varies as do some of the constituents within the crystal lattice. Present bonding theories and ionic-geometry considerations have been used to predict the "academic" clay mineral structure for each type. Variations within the crystal lattice give the explanation for other minerals of the same family.

The molecular structures of clay minerals have been studied by many people. Until the advent of X-ray analysis little was known about these tiny particles. Much of our understanding of crystal structure depends on works reported by Pauling (1940) whose theories on bonding and ionic-induced geometry have been the basis for much of our present knowledge. Differential thermal analysis, X-ray diffraction, and electron microscopy have been of great benefit in testing the hypotheses so developed. Chemists, soil scientists, engineers, clay mineralogists,

and many others have filled books with data on genesis, morphology, structure, and occurrence of natural clay mineral deposits. An excellent reference on early clay mineral concepts is Clay Mineralogy (Grim, 1953). An examination of the crystal structure of the three main clay mineral families is a natural introduction to the fundamental behavior of clays from an engineering standpoint.

Basic Structural Units

Although the molecular structures of clay mineral silicates appear complex, repeated investigations have shown that they are composed of two basic structural units combined in different manners to give the different clay mineral types. One of the important considerations is the role of ionic size and coordination in silicate structure. Valence is secondary for these in contrast to being a primary factor in normal simple inorganic salts.

One of the basic structural units is the silica tetrahedron. It consists of a single silicon cation in tetrahedral coordination with four oxygen anions. When four anions surround a central cation so that they all touch one another, a regular tetrahedron is formed where three anions have their centers at the three corners of the base of the tetrahedron and the fourth anion is at the apex of the tetrahedron and rests on the other three anions. The cation lies in the vacant space inside and touches all four anions. From geometry it can be shown that a cation of radius 0.225 R can be surrounded by four anions of radius R. Therefore, oxygen anions in tetrahedral coordination with a cation of radius 0.337 A would meet these requirements. The silicon cation in tetrahedral coordination with four oxygen anions is found in nature in abundance thereby

implying great stability of this unit. Aluminum cations may proxy for the silicon and hydroxide anions may occasionally proxy for the oxygen. Regardless of the particular ions, the cation is equidistant from the four anions. A number of these tetrahedrons combine to form a sheet-like layer with indefinite lateral dimensions. The individual tetrahedron is shown in Figure 2-1 (a) and the combined configuration is shown in Figure 2-1(b). Another way to visualize this unit is to consider a perforated

ALUMINA

(c)

(d)

SILICA

(a)

(b)

O OXYGEN   ◑ ALUMINUM   ⊛ OXYGEN ATOMS COMMON
                                     TO BOTH SILICA AND
◎ HYDROXYL   ● SILICON   ALUMINA SHEETS WHEN
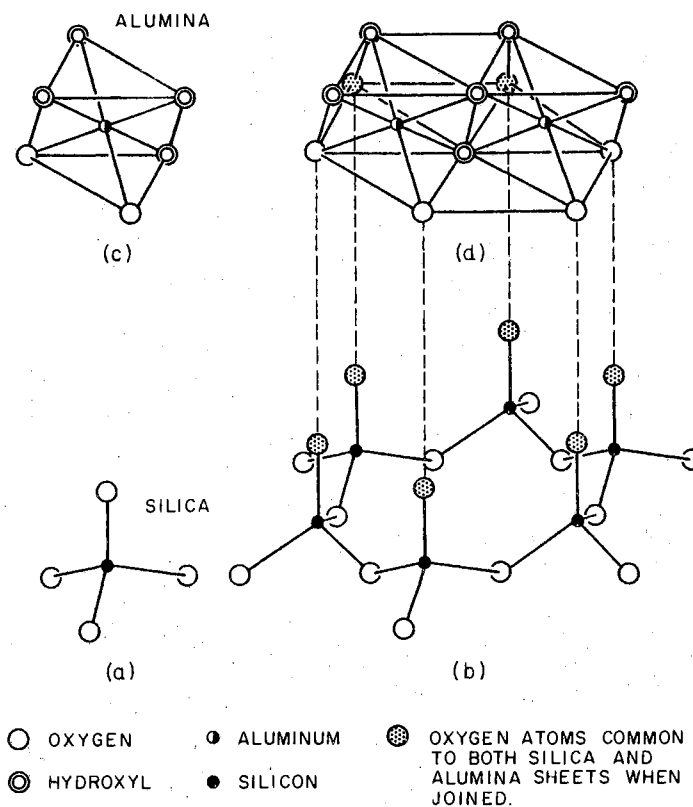   JOINED.

Figure 2-1.   Molecular structure of silica and
              alumina sheets (Scott, 1963)

basal plane of oxygens, a hexagonal network of silicon cations at the

center, and a plane of oxygens or hydroxides located directly above the cations. The thickness of the unit in most clay minerals is about 4.93 Å. This tetrahedral structural unit is considered to be an extremely stable form (Grim, 1953) (Gilreath, 1958).

The other basic structural unit in common clay minerals is composed of two layers of closely packed oxygens or hydroxides with various metallic cations enclosed in octahedral coordination. When six anions surround a central cation so that all anions touch four other anions, each anion is at the corner of a regular octahedron (eight-sided figure). Four of the anions and the cation are in the same plane with the other two anions located centrally above and below the cation. From geometry it can be shown that a cation of radius 0.414 R can be surrounded by six anions of radius R; therefore, six oxygens in octahedral coordination with a cation of radius 0.546 Å would meet these requirements (Gilreath, 1958).

The common cations are aluminum, ferric and ferrous iron, and magnesium. Other cations could fulfill this size requirement. The octahedral units may also be combined into sheet structure of indefinite lateral dimensions. When two-thirds of the octahedral vacancies (normally with Al^{+++}) are filled, the structure is called dioctahedral; when all octahedral vacancies are filled (normally with Mg^{++}), the structure is called trioctahedral. The single octahedral unit is shown in Figure 2-1 (c) and the combined sheet layer is shown in Figure 2-1 (d). The thickness of the unit is 4.93 Å in most clay minerals. (Grim, 1962).

The lateral dimensions of both the tetrahedral and the octahedral units are similar so that they combine into stable minerals in several manners. One such combination may be visualized by the dashed lines

between Figure 2-1 (b) and (d). Various stacking patterns, substitutions within the lattices of both units, and various adsorbed cations give rise to the structure of particular clay minerals. The three common families of clay minerals are montmorillonite, illite, and kaolinite. The seemingly small differences in their makeup are the key to explaining and understanding many of their properties.

Montmorillonite Family of Clay Minerals

The most commonly accepted structure of montmorillonite minerals is a combination of two silica tetrahedral sheets with a central alumina octahedral sheet. The tips of the tetrahedral units all point toward the central alumina sheet. The tetrahedral and octahedral sheets are so combined to form a common layer of the oxygen tips and one of the hydroxyl layers. The atoms common to both sheets are oxygens (Grim, 1962). The resulting sheet layer is continuous laterally and is stacked in the third direction. Successive sheets may be stacked on top of each other in different ways, resulting in the polymorphic mineral variations of montmorillonite (Scott, 1963). Figure 2-2 shows the molecular structure of montmorillonite type minerals.

Since unit cell stacking places two basal tetrahedral layers of oxygen adjacent, only weak bonds are formed between the sheets. This is an inherent plane of weakness and exhibits excellent cleavage. Several sheets may form an aggregation but water, as a polar molecule, may enter between the sheets forcing them apart. This swelling phenomenon is called an expanding lattice.

The theoretical formula for the montmorillonite mineral group is $(OH)_4 Si_8 Al_4 O_{20}$ (Grim, 1953). The actual situation always varies

OCTAHEDRAL COORDINATION

TETRAHEDRAL COORDINATION

$6O^{--}$

$4Si^{++++}$

$4O^{--} + 2OH^{-}$

$4Al^{+++}$

$4O^{--} + 2OH^{-}$

$4Si^{++++}$

$6O^{--}$

A

C

$10\overset{\circ}{A}.$

○ ANIONS ● CATIONS

O^{--}

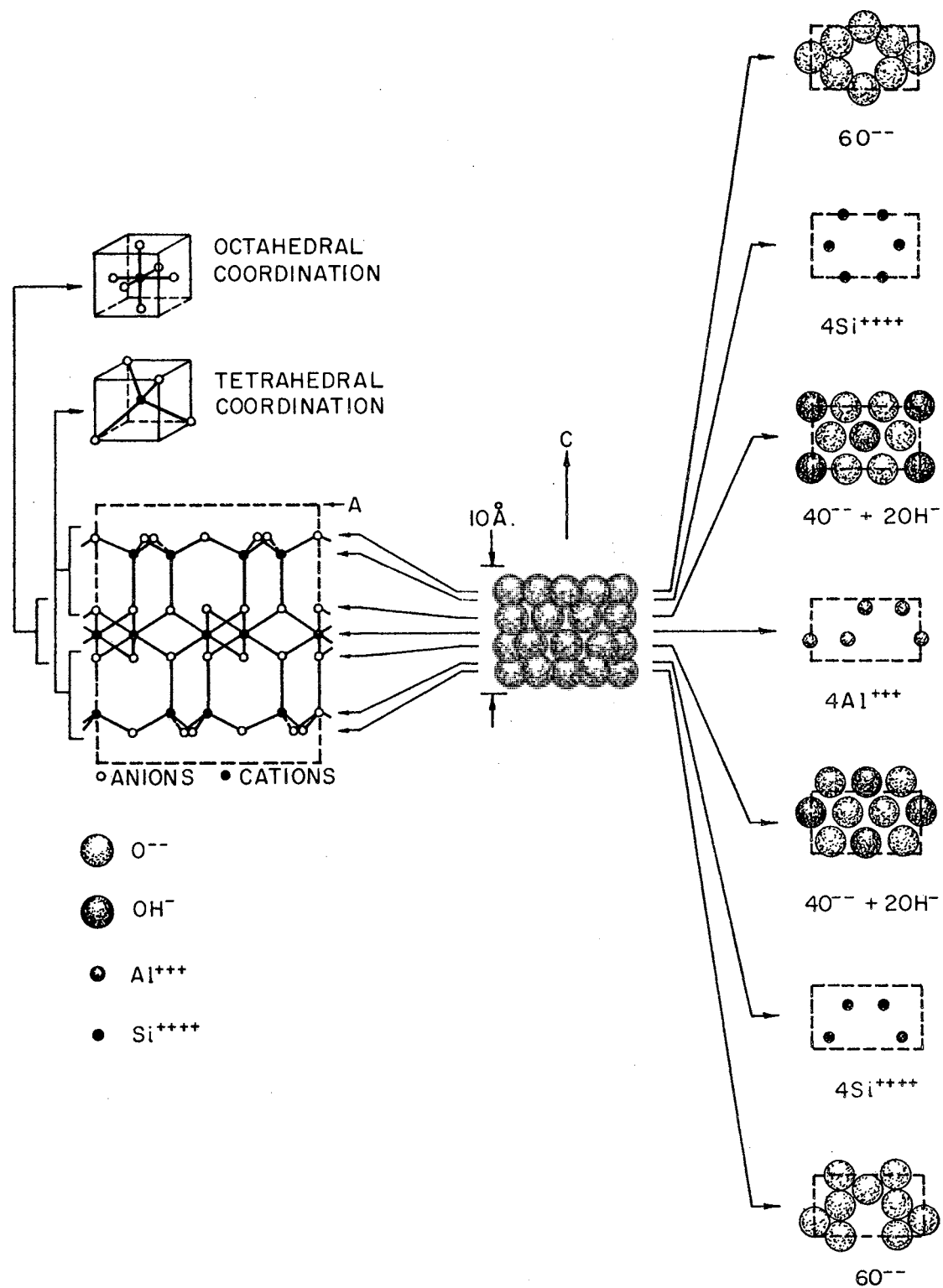OH^{-}

Al^{+++}

Si^{++++}

Figure 2-2. Molecular structure of montmorillonite (Norton, 1952)

from that composition because of substitutions within the lattice of aluminum for silicon in tetrahedral coordination and/or magnesium, iron, zinc, nickle, lithium, etc., for aluminum in octahedral coordination. Each set of substitutions gives rise to a different montmorillonite mineral. As is the situation with the other two clay mineral groups, the theoretical clay mineral of the group has, as its name, the group name. The montmorillonite clay mineral has one magnesium cation to five aluminum cations in the octahedral position with no other substitutions (Grim, 1953) (Scott, 1963).

It is noteworthy that regardless of the number of substitutions within the lattice between cations of different valences, the total unbalance is usually about - 0.66 per unit cell of the mineral. There is a strong possibility that additional lattice vacancies contribute to this unbalance (Grim, 1953). This charge deficiency is balanced by the adsorption of cations between units cells and around broken edges. These adsorbed cations are accessible for exchange reactions due to the bonding weakness between unit cell sheets.

Because of the poor bonding between adjacent oxygen layers, typical montmorillonite particles are extremely small and plate-like. For the bentonite mineral they are approximately 0.05 microns in diameter and have a thickness to diameter ratio of 1:400 (van Olphen, 1956). Thickness of the particles is greatly influenced by the charge and size of the adsorbed cation.

Illite Family of Clay Minerals

The basic composition of the illite minerals is similar to that of montmorillonite minerals with minor cationic differences. Some of the

tetrahedrally coordinated silicons are always replaced by aluminum with the resulting charge deficiency balanced by adsorbed potassium cations. Although these substitutions appear minor, the structural implications are major. The potassium cations are adsorbed between unit layers where they pack snugly into the spaces left in the basal tetrahedral oxygen layer. They are in 12-fold coordination with the oxygen anions of adjacent unit cells. The charge deficiency is large (from -1.30 to -1.50 per unit cell) and lies in the tetrahedral layer. The large size of the potassium cation which allows excellent coordination, the large charge deficiency, and the location of this charge deficiency tends to bond the illite units together forming larger particles which cannot be broken down by intrusion of polar liquids. Replacement of the adsorbed cations is possible only at layer edges and particle surfaces (Grim, 1953). The theoretical formula for illite is $(OH)_4 K_y Al_4 (Si_{8-y} \cdot Al_y) O_{20}$. Variation of illite is created by the amount of aluminum substitution for silicon (Iler, 1955).

Electron micrographs of illite indicate primarily small, poorly defined flakes grouped into irregular particles with ill-defined boundaries. A typical illite particle has a diameter of about 0.5 microns with a thickness to diameter ratio of 1:50 (van Olphen, 1956). Since surface chemistry is related to many clay mineral properties, those illites that are well crystallized, having minimal surface area, behave more like kaolinitic minerals whereas those poorly crystallized, but well-fractured, illites tend to montmorillonitic behavior.

Considerable controversy rages over the properties and characteristics of illite mineral structures. It is, however, different from the well-crystallized micas and from montmorillonite minerals in

behavior and structure.

Kaolinite Family of Clay Minerals

The structure of kaolinite is composed of a single tetrahedral sheet so oriented that the tips form a common layer with a face of a single octahedral sheet. Since the lateral dimensions of both unit cells are similar, composite layers are easily formed. Figure 2-3 shows the molecular structure of kaolinite minerals.

The minerals of this family are all dioctahedral with aluminum in the octahedral positions. Little, if any, substitution occurs. The dioctahedral aluminum, occupying only two of three possible sites, may be arranged in three different patterns. This may explain the different stacking patterns found in this clay mineral. The hydroxyls of the oc-tahedral layer are so positioned that each is directly in line with the perforations in the hexagonal network of basal tetragonal oxygens of the congruent layer. For this reason many hydrogen bonds may occur hold-ing the unit layers tightly together. Ordinary grinding techniques can-not destroy these bonds so that particle size is largely a function of natural crystalline occurrence (Grim, 1953, 1962) (Iler, 1955).

The theoretical formula for kaolinite is $(OH)_8 Si_4 Al_4 O_{10}$. The charges within the lattice are balanced. Cleavage occurs between unit layers with any charge deficiency being due to broken bonds at the lateral edges. Electron micrographs show well-ordered, six-sided platelets with some lateral elongation. The typical kaolinite particles have a diameter of 0.5 to 1.0 microns with an average thickness of 0.05 mi-crons (Scott, 1963).

OCTAHEDRAL
COORDINATION

TETRAHEDRAL
COORDINATION

C

14.5 Å.

°ANIONS •CATIONS

O⁻⁻

OH⁻

Al⁺⁺⁺

Si⁺⁺⁺⁺

6O⁻⁻
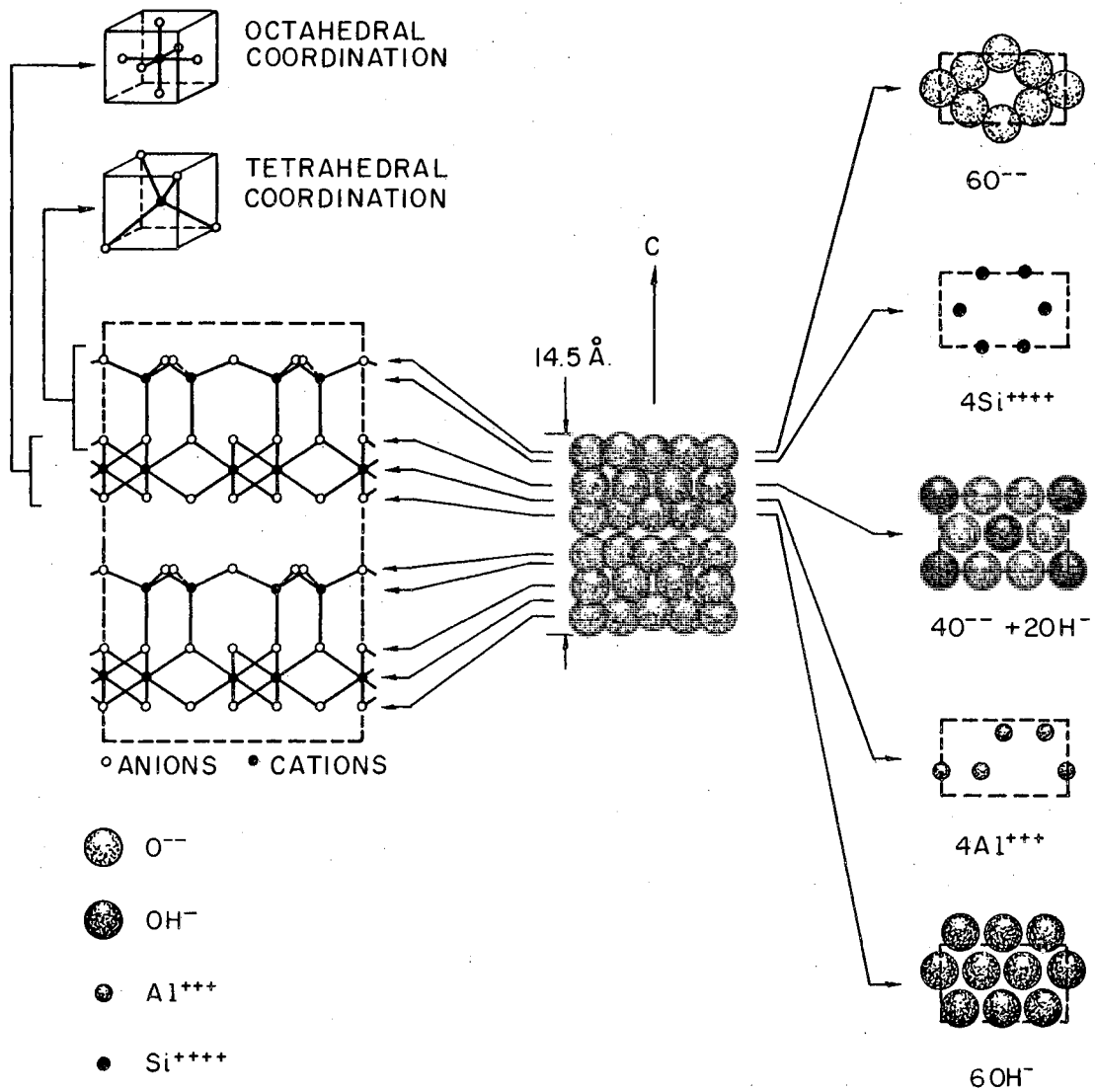
4Si⁺⁺⁺⁺

4O⁻⁻ +2OH⁻

4Al⁺⁺⁺

6OH⁻

Figure 2-3. Molecular structure of kaolinite (Norton, 1952)

Soil Chemistry

The variables to be considered in studies of clay plasticity are numerous. Those involved with soil chemistry are: the chemical nature of the particle surface, particle size and shape, the nature of the adsorbed cation, the nature of the dispersing medium, and the previous chemical history of the system. Combinations of these factors must be grasped simultaneously as their effects are inter-related (Marshall, 1964).

The surface chemistry of clay mineral particles is complex due to the involvement of several different sets of surface properties. Colloidal surface properties exist due to an atmosphere of ions about the particle. The geometrical relationships of charged silica-alumina layers to various adsorbed cations of particular ionic sizes and charges are the source of another highly involved set of properties. To complicate further the situation is the inherent variation between clay colloids in their charge geometry. The exposed planar faces may be chemically and/or electronically different, as will be the edge faces (Marshall, 1964). Perhaps the most significant aspect of this surface chemistry situation is the recognition that variance does exist and that their total effect or average effect may be more consistent than individual performance. Further study in the fields of physical, colloid, and surface chemistry plus soil mineralogy may well remove some of the confusion from this area.

Particle size and shape varies within each clay mineral family as well as between the families. Electron microscopy studies indicate that the most prevalent (but not the only) natural form is a plate-shaped

particle. Shape and size may be explained in terms of molecular structure or perhaps it is the other way around. Kaolinite with hydrogen bonding between unit layers is the largest particle of the group. The lack of isomorphous substitution may account for the regularity of lateral configuration. Montmorillonite particles are similarily shaped but are much thinner due to the unit layer bonding weakness. Illite is an intermediate size particle with much variation in thickness and diameter. The size of the adsorbed potassium cation located near the seat of the charge deficiency explains the layer bonding. Particle size is related to conditions at the time of crystal formation (van Olphen, 1956). In the consideration of particle size and shape, electron microscope technology has furnished much of our evidence. Further advances may clarify the situation even more.

The surface adsorbed cation may affect the amount and nature of the adsorbed water. It may serve as a bond to bind particles together or to limit the separation distance. It may become hydrated (form a water envelope) and interfere with or change the adsorbed water network configuration. The size and charge of the particular adsorbed cation will influence the orientation and extent of adsorbed water layers (Grim, 1962). The purpose of the adsorbed cation is to balance the electronic charge deficiency of the particle whose unbalance is due either to substitution within the lattice or broken edge bonds. Since this charge deficiency is not an integral value per unit cell, the cation is shared by several unit cells. It may be tightly or loosely bound depending on the local situation. Just how this may affect plasticity will be discussed in more detail.

For soils engineering-science purposes the dispersing medium

of primary importance is water. Water as a polar molecule has many unusual properties. Many researchers have presented evidence that the water held directly on the particle surface is in a different physical state from that of ordinary water (Grim, 1962). How far out from the particle this condition exists is not known, but it is thought to vary with any given clay mineral. The transition from bound water to ordinary water seems to be dependent upon the particular clay mineral and its particular cation. Much disagreement as to the precise nature of this bound water is found but almost every researcher states that some form of organization of the water molecules does exist (Grim, 1962).

The previous history of the system has reference to cationic changes that have occurred previously during the period of crystallization and since. This is of particular importance in laboratory evaluation of altered clay mixtures. There may be fixation of both anions and cations, geometrical (alumina oxide hydrate polymers) hindrance by exchange site blocking, and other modifications created during desiccation and grinding (Marshall, 1964).

As noted in the foregoing paragraphs, many factors are involved in the consideration of surface chemistry effects. While these may be analyzed and studied, their total effect on plasticity is difficult to predict precisely. The thickness and orientation of the plasticity-producing water layers may well be a function of particle surface area. The amount of particle surface area available is determined by the surface chemistry phenomenon.

Soil Plasticity

The most conspicious physical property of a clay soil is its

plasticity. It has been used to distinguish between clays and nonplastic soils and to classify different clays according to the degree of plasticity (Casagrande, 1947). Atterberg (1911) devised simple empirical methods for determining relative plasticity of clay. Casagrande (1932), under a Bureau of Public Roads grant, standardized these procedures and gave them engineering significance. This development of standard procedures was followed by wide acceptance and use of the plasticity properties as an index to the engineering properties of clay soils. Plasticity limits and indices are derived from test data on remolded samples and are at best an indication of the behavior of the natural undisturbed soil mass. Many engineering projects such as highway construction require remolding of soil in which case the plasticity values are more significant. For other engineering projects the plasticity characteristics alone are insufficient for design criteria. Soil structure and stress history normally are the physical conditions that dictate the actual stress-deformation characteristics needed for design. However, the plasticity limits and indices are valuable in prediction of future behavior (Means and Parcher, 1963).

As an aid in eliminating the personal factor in soil consistency descriptions, Atterberg defined four states of consistency for fine-grained soils. These are defined in terms of strength behavior as liquid, plastic, semi-solid, and solid. Consider a clay soil with a high initial water content which behaves as a liquid ("muddy" water). As the soil dries from the liquid state it reaches a point at which it ceases to behave as a liquid and acquires the properties of a plastic material. This change is necessarily a gradual one and is not a point but a zone. A point within this zone as determined by laboratory procedure is called

the liquid limit. Similarily, at a further lower water content, the soil commences to acquire some elastic properties. A point within that zone is defined by laboratory testing as the plastic limit. Eventually a point is reached where the volume of the soil mass becomes constant. This is defined as the shrinkage limit. The soil mass is then assumed to exhibit only elastic properties. The three limits are called the Atterberg limits and are given in terms of water content. The difference between the values of liquid limit and plastic limit (the width of the plastic state) is called the plasticity index. Similarily, the difference between the plastic and shrinkage limits is called the shrinkage index. The plastic limit, liquid limit, and the plasticity index are the more common values used in predicting engineering properties (Hough, 1957) so this research is confined to those three.

The laboratory procedures used for determination of these limits are given in detail in the next chapter. It must be recognized that the Atterberg limits are idealistic and empirically determined. The fact that they have been accepted and widely used since 1932 provides us with much data on their correlation with engineering properties and hence are of value.

It should be remembered that the use of plasticity characteristics will vary from situation to situation since in design they are only an index of engineering properties. Several general comments can be made, however. Theoretically, the in-place water content when used with the limits could be used to classify the consistency of the natural soil mass. However, the laboratory condition may be radically different from the field condition. Natural soil masses may gain strength through particle orientation that is destroyed by laboratory procedures. This may well

account for sudden loss of strength of field soils upon remolding. The Atterberg limits for this type of soil are indicative of the worst condition rather than the natural condition. In highway and airfield work much of the soil strength is from the remolded condition. Atterberg limits are widely used as materials specifications for this type of construction.

The liquid limit is used as an index of compressibility. A high liquid limit indicates a major proportion of the soil volume is water adsorbed onto the particle which may be forced out under load. The liquid limit laboratory determination is sensitive to many factors involved in preparation of the sample. Extreme desiccation, grinding procedure, and time allowed for wetting all influence the final results. The amount of surface area available for adsorption and the water equilibrium are affected by the forementioned procedures.

The plastic limit has its primary function in defining the plasticity index. The plasticity index denotes the range of the plastic consistency state. A large value for the plasticity index indicates a soil that may swell or shrink excessively. The liquid limit and the plasticity index are used in many soil classification systems. Casagrande (1947) devised a plasticity chart utilizing these plasticity characteristics to group clays into engineering behavior classifications. This chart is shown in Figure 2-4. The chart is a part of the Unified Classification System which is used to classify fine-grained materials according to general engineering properties (Corps of Engineers, 1953).

The plasticity characteristics of soils may be used to identify soil strata which may undergo color and consistency change from one location to another. It is impractical to perform engineering design
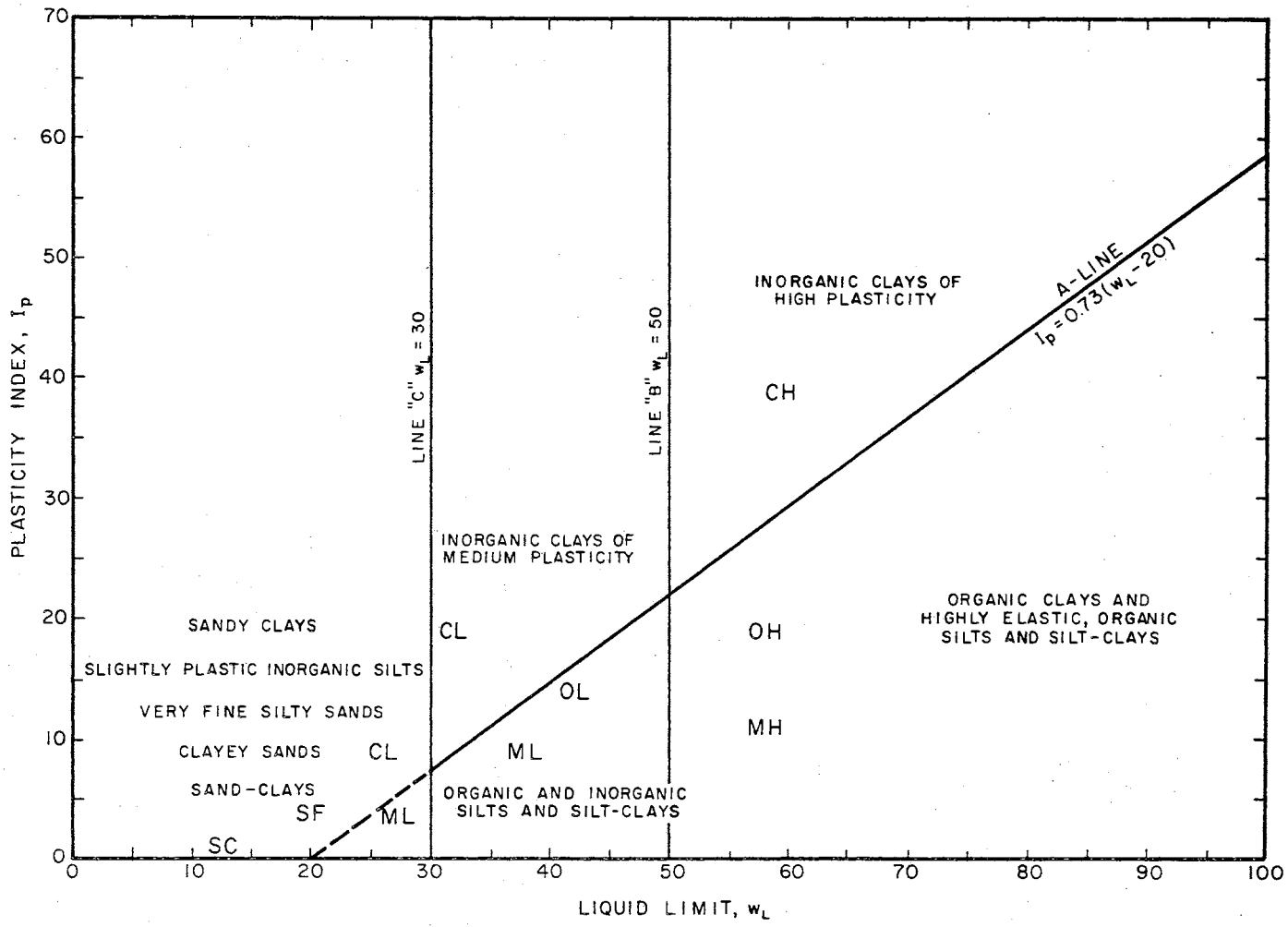
Figure 2-4. Casagrande Plasticity Chart (A. Casagrande, 1947)

data tests on all soil strata beneath a particular site unless it can be shown that each is different. The plasticity tests are simple and quick in contrast to the testing of undisturbed samples. The index proper-ties may be used to denote differences which would require additional testing (Means and Parcher, 1963).

Plasticity tests should be performed on samples at the natural water content in order to obtain valid results. Desiccation and grinding of the samples could change the results. These tests should be per-formed in a standard manner in which the data are reproducible and representative. They require a minimum of technique but laboratory integrity is essential.

Very little can be said in favor of the Atterberg theory being sub-stantiated by the laboratory tests. This actually is of minor importance. The tests are rapid, simple, and reproducible and have been used a suf-ficient time for correlations to have been properly developed between the data and engineering properties. As a predictor of present and fu-ture engineering behavior of soil masses, it is imperative that we better understand the physico-chemical background which influences these values.

CHAPTER III

LABORATORY PROCEDURES, EQUIPMENT,
AND MATERIALS

Thirty-two laboratory-altered clay mixtures were used to establish correlations between soil plasticity and surface area. Eleven natural soil clays were used to test the hypothesis of correlation. Surface area determinations were made by the ethylene glycol retention method. Modified American Society of Testing and Materials procedures were used to determine the liquid limit, plastic limit, and plasticity index.

Nature of Soils Used

The clay minerals used in preparing the laboratory-altered mixtures were bentonite, kaolinite, and illite which were obtained from the University of Oklahoma Geology Department. The fine quartz particles used were obtained by crushing standard Ottawa sand to pass the No. 100 mesh sieve. Mr. W. G. Henderson (1966), Texas Western University, prepared the samples for research on the physico-chemical phenomena of soil materials as they affect the strength characteristics. The procedure used in preparing the homionic soils was outlined by Professor L. Reed of the School of Agronomy, Oklahoma State University.

The bentonite and illite were ground, soaked, and reground until the material was finer than the No. 100 mesh sieve. The kaolinite was

received in powdered form. The clay minerals were then soaked in distilled water for several days to allow dispersion. After partial oven drying, the samples were subjected to several cycles of wetting with the appropriate cation (K^+, Na^+, Ca^{++}, Mg^{++}) chloride. Wetting, mixing, soaking, and partial drying was repeated four times to insure a high concentration of a particular cation. This should replace the natural cations with a single desired cation. The mixture was then washed with methyl alcohol to remove all excess, non-adsorbed ions. Washing procedure entailed mixing with alcohol, allowing settlement, and decantation of supernatant liquid. Diatomaceous filters were used to accelerate the removal of excess fluids. The washing process was repeated five times at which time it was assumed that the adsorbed cations were all the same. The samples were then air dried and recrushed to pass the No. 100 mesh sieve.

The particular individual samples were mixed with all samples containing thirty per cent by weight of fine quartz. Mixtures of zero bentonite, five per cent bentonite, ten per cent bentonite, and fifteen per cent bentonite were made with kaolinite and illite. The bentonite percentages are based on the clay fraction of the sample. A mixture was made for magnesium, calcium, sodium, and potassium cations. This provided homionic clay mixtures with the three most common clay minerals and the four most prevalent cations.

The particular combinations were wetted to a water content slightly above the liquid limit and allowed to soak in order to provide intimate mixtures. After remixing with additional water, the samples were isotropically consolidated until normally consolidated under 4.5 kilograms per square centimeter. From this consolidated sample Mr.

Henderson trimmed a sample for strength testing. These trimmings are the laboratory-altered clay mixtures used in this plasticity-surface area research.

Natural soil samples were obtained from several sources. Many came from the Soils Laboratory, Oklahoma State University. Others were gathered from their particular locale by the author. An effort was made to include soils from different geological and geographical areas with trace materials of various kinds. Sample 1 is a topsoil from the general area of the new Business Building on campus. Sample 2 is a sandy clay from the same area but from the bottom of one of the drilled piers. Sample 3 is a chunk of Permian red and gray clay from the over-burden of a crushed limestone base course pit near Ingalls, Oklahoma. Sample 4 is caliche spoil from a borrow pit in Concho County, Texas. Sample 5 is a very stiff clay with some trace of organic matter from Nowata, Oklahoma. Sample 6 is a stiff silty clay also from Nowata, Oklahoma. Sample 7 is a calcareous silty soil from near Panhandle A. and M. College, Oklahoma. Sample 8 is a plastic fine loess from Salina, Kansas. Sample 9 is a stiff gray clay from Massard, Arkansas. Sample 10 is a loess with some organic matter from Ulysses, Kansas. Sample 11 is a Laurentian clay with fine mica flakes. Samples 5, 6, 7, 9, 10, and 11 are from the Oklahoma State University Civil Engineering Soils Laboratory. Samples 1, 2, 3, 4, and 8 were obtained by the author from the particular area.

Preparation of Test Samples

All samples used, both the laboratory-altered mixtures and the natural soils, contained some material that was larger than that allowed

in the test procedure. In the laboratory-altered samples, the large particles were aggregates since at one point in their alteration, all material had passed the No. 100 mesh sieve. In the natural soils there were some individual particles which were not aggregates. All samples were soaked in methyl alcohol for a period not less than twenty-four hours. The larger particles in the natural soils were then discarded. The alcohol-wet samples were oven dried at a temperature of less than 140° F. Each sample was ground with mortar and rubber pestle until all material passed the No. 50 mesh sieve. Approximately three hundred grams of material was prepared for each sample. They were then stored in glass jars prior to testing.

Each sample was removed from the glass container and mixed thoroughly. Two hundred grams of dry material was mixed with distilled water to a water content of twenty per cent dry weight basis. Mixing was continued until even distribution appeared. The wetted samples were placed into a second glass jar and sealed to allow moisture equilibrium. After a period of not less than thirty-six hours, the sample was remixed and a sample removed for determination of the plastic limit. The remainder of the wetted sample was used for the liquid limit determination.

Replicate testing of specific surface area was done on the remaining dry samples. Prior to sampling each time, the sample was remixed. Extreme precaution was taken in all sampling to assure representative sampling. The particle size distribution was not determined but all particles were smaller than the No. 50 mesh sieve.

Atterberg Limits Test Procedure

Atterberg (1911) defines the liquid limit as the lower limit of viscous flow at which two sections of a soil cake barely touch but do not flow under the impact of several sharp blows. American Society of Testing and Materials Test Procedure D 423-54T (1958) defines the liquid limit as that arbitrary water content at which two halves of a soil cake will flow together along the bottom of a groove for a distance of one-half inch when the cup is dropped twenty-five times for a distance of one centimeter at the rate of two drops per second. The cup and grooving tool are part of a standard liquid limit device whose dimensions and materials of construction are specified. The Referee Test Procedure was used except ten determinations were performed in order to define the liquid limit more exactly. Linear regression analysis was used to determine the liquid limit. The primary difference in the routine test procedure and the referee procedure is the care taken to insure uniform distribution of the water.

Atterberg (1911) defined the plastic limit as the lower limit of the plastic state at which the soil crumbles when being rolled out into threads. American Society of Testing and Materials Test Procedure D 424-54T (1958) defines the plastic limit as that minimum water content at which the soil can be rolled into threads one-eighth inch in diameter without the threads breaking. Although this test appears crude, it gives surprisingly reproducible results. Several determinations were made on each sample in order to demonstrate this reproducibility statistically.

Surface Area Test Procedure

Early test procedures used nitrogen gas volume to determine specific surface area. Nitrogen was used by Platen and Winkler (1958) for studies of plasticity and surface area. This procedure is inadequate in that it does not measure the total surface area of expanding lattice minerals. The procedure used in this research was the ethylene glycol adsorption method proposed by Morin and Jacobs (1964). Under specified conditions a monolayer of ethylene glycol is adsorbed on the particle surface. Research indicates that 0.00031 grams of ethylene glycol have a monolayer surface of one square meter (Dyal and Hendricks, 1950).

Curtin technical grade No. 370 mesh bentonite was used in preparation of buffer and as a standard. The buffer was prepared by mixing four hundred grams of oven-dry bentonite with enough ethylene gylcol to give a monolayer on each bentonite surface. Theoretically, bentonite should retain two hundred sixty milligrams of ethylene glycol per gram of oven-dry material (Dyal and Hendricks, 1950). The buffer was so prepared with curing in a vacuum desiccator at a pressure of less than one millimeter Hg. After eight hours it was removed, remixed, and passed through a No. 50 mesh sieve and returned to the desiccator at the same pressure to remain for three days. Six samples of unwetted bentonite were used to verify the monolayer condition of the buffer. During the testing the buffer adsorbed excess ethylene glycol and additional bentonite was added to compensate.

Three vacuum desiccators were placed in assembly-line fashion connected to a manifold. The first desiccator contained phosphorous

pentoxide and was used for drying the sample. Tare cans were dried in the same manner and reweighed for each run. The second desiccator contained reagent-grade ethylene glycol and was used for vapor wetting of the sample. The third desiccator contained the buffer sample and was used for curing the sample to the monolayer point. Release of vacuum was done very slowly by drawing air through a column filled with activated alumina and calcium chloride desiccants to provide dry air.

The test procedure required a minimum curing time of twenty-four hours. The time in the first two desiccators was adjusted so that the entire procedure for a single run took seventy-two hours. Three-ounce aluminum tare cans were used without lids. Each can had a number and a fixed position on the desiccator plate. Weighing always proceeded in the same order at a set rate. Development of this rate and a weighing procedure was an extremely important aspect to attaining reproducible data.

Each set of tare cans provided for twelve unknown samples with two standards. The washed, oven-dried, warm tare cans were placed into the drying desiccator; the pressure was reduced and maintained at less than one millimeter Hg for at least two hours. The vacuum was released with dry air and the can weighed. All weighings were to the nearest tenth of a milligram. The cans were taken to the balance in the desiccator and removed one at a time for weighing in the standard order at the set rate.

The cans were filled with one to two grams of sample. The first three cans had replicate material; the fourth contained a bentonite standard; the fifth, sixth and seventh cans held a second material type; the eighth, ninth, and tenth cans held a third sample type; the eleventh can

contained a bentonite standard; the last three cans held a fourth material type. The loaded cans were replaced in the first desiccator; the pressure was reduced and maintained at less than one millimeter Hg for a period in excess of twelve hours.

After the drying cycle was completed, the cans with samples were reweighed to determine the dry weight of the sample. At this stage in the procedure, the samples were in an extreme state of desiccation so that the moisture from the air was quickly adsorbed. Samples of bentonite standard were observed to gain twenty milligrams per gram sample in a thirty minute period. This is a possible source of major error for soils with appreciable surface area. The weighing rate and order were standardized to minimize this error. Further consideration should be given to use of a "dry" room for weighings to reduce this source of error.

The cans were placed in the second desiccator with ethylene glycol present; the pressure was reduced and maintained at less than one millimeter Hg. This pressure vaporized the ethylene glycol and the samples were vapor wetted to a point in excess of the monolayer condition. The original procedure called for the samples to remain in this desiccator for twenty-four hours. In some cases this time length over-wetted the samples which required a longer curing period and shortened the buffer life. After many repetitions of the surface area test, it became obvious when the proper wetted condition had been reached. The physical appearance of the standard bentonite sample achieved a dull glossy texture and some balling was noticed with an increase in excessive ethylene glycol adsorption.

After proper wetting of the samples, they were removed from

the second desiccator and placed into the third. They were left on the desiccator plate and moved as a group. The third desiccator, with the samples on the desiccator plate directly above the buffer sample, was evacuated to a pressure of less than one millimeter Hg and sealed for at least twenty-three hours. The samples were then taken to the balance and the first bentonite standard was weighed to determine if monolayer equilibrium had been reached. The sample was replaced and the desiccator was again evacuated for one hour if equilibrium had been reached and longer if it had not. All weighings were done with sample handling performed by tongs.

Once equilibrium conditions were established the samples were weighed in the standard manner. The tare cans were emptied, washed, oven-dried, and placed warm into the first desiccator in preparation for the next run. Approximately forty-five days of testing were required for the establishment of a standard technique and procedure that would give reproducible results. Each clay was tested twelve times utilizing different positions on the desiccator plate each time. Once the technique and procedure were standardized, excellent reproducibility was obtained.

The method by which the specific surface area was determined is shown in the following equation:

$$SSA = (EG_{sample}) \ (260/EG_{standard}) \ / \ (0.31 \ mg/m^2)$$

$$= \text{square meters per gram soil solids}$$

where SSA = specific surface area in m^2/g solids

EG = ethylene glycol retained in milligrams
per gram solids

Rapid and accurate determinations of specific surface area can be made by the vapor wetting procedure in contrast to methods previously

used. It is especially adapted to those situations where numerous samples are to be tested. It is free of the effects of sample size, temperature fluccuations, and moisture present in buffer, sample, or ethylene glycol (Morin and Jacobs, 1964). The only difficulty is that of technique and procedure which can be acquired with practice. Although it is more complex than most soil mechanics laboratory tests, it is a relatively simple chemical quantitative procedure.

CHAPTER IV

PRESENTATION AND DISCUSSION
OF RESULTS

A statistical approach was used to analyze the test data. A confidence level of ninety-five per cent was selected and the student "t" distribution was assumed. The magnitude of the plus and minus values so obtained was used to demonstrate reproducibility of data. This should not be confused with accuracy.

The summarized data for the laboratory-altered clay mixtures are shown in Tables IV-I and IV-II. The data for the natural soils are shown in Table IV-IV. Table IV-III outlines the order of increasing magnitude of surface area, liquid limit, and plasticity index with respect to the particular adsorbed cations. Figures 4-1 through 4-3 show graphically the relationships between surface area, liquid limit, and plasticity index with regard to the percentage of bentonite admixture and adsorbed cation. Figure 4-4 indicates the positions of the samples plotted on the plasticity chart. The particular relationships of specific surface area to the plasticity characteristics are shown in Figures 4-5 through 4-6.

Statements and equations relating to behavior of the test samples should not be extrapolated to be conclusive for all natural soil clay mixtures. Only the general trends are significant. Further testing of various clay mixtures will be required prior to establishment of a valid equation for all natural soils.

SAMPLE DESCRIPTION (Per cent of clay fraction)	SURFACE AREA (m^2/g solids)				PLASTICITY INDEX (per cent)			
	Cation				Cation			
	K^+	Na^+	Ca^{++}	Mg^{++}	K^+	Na^+	Ca^{++}	Mg^{++}
100% Kaolinite - 0% Bentonite	7.5 + 2.0	18.1 + 3.5	37.9 + 3.4	51.3 + 2.4	8.6 + 1.4	7.8 + 1.6	8.9 + 1.7	8.9 + 1.2
95% Kaolinite - 5% Bentonite	14.0 + 1.8	38.7 + 3.5	48.3 + 2.6	65.4 + 3.7	13.4 + 1.4	13.7 + 1.3	13.4 + 1.6	14.6 + 2.9
90% Kaolinite - 10% Bentonite	25.6 + 1.3	56.8 + 2.8	60.6 + 2.7	78.8 + 4.8	16.2 + 2.0	20.0 + 1.8	18.0 + 0.8	20.3 + 1.3
85% Kaolinite - 15% Bentonite	39.0 + 2.9	77.4 + 2.4	74.1 + 4.7	107.7 + 4.8	26.1 + 1.2	27.2 + 2.3	22.7 + 1.1	28.6 + 1.9
100% Illite - 0% Bentonite	16.1 + 2.0	35.5 + 4.1	41.4 + 3.2	34.2 + 2.7	6.2 + 0.6	6.1 + 2.0	12.5 + 1.8	10.2 + 2.0
95% Illite - 5% Bentonite	25.1 + 2.3	54.5 + 4.0	57.5 + 4.8	47.2 + 2.5	9.5 + 0.7	11.2 + 0.4	15.4 + 2.5	14.3 + 1.9
90% Illite - 10% Bentonite	36.6 + 1.7	75.7 + 1.7	73.1 + 4.8	62.9 + 7.0	14.3 + 1.8	21.9 + 0.7	18.8 + 1.4	20.6 + 1.9
85% Illite - 15% Bentonite	46.5 + 1.0	95.5 + 4.6	91.1 + 4.4	102.8 + 2.1	18.8 + 1.3	34.3 + 1.9	22.7 + 0.8	26.8 + 2.0

NOTE: Confidence Level = 95 % Student "t" distribution

TABLE IV-I

LABORATORY-ALTERED CLAY MIXTURES PARAMETERS

SAMPLE DESCRIPTION (Per cent of clay fraction)	LIQUID LIMIT (per cent) Cation				PLASTIC LIMIT (per cent) Cation			
	K^+	Na^+	Ca^{++}	Mg^{++}	K^+	Na^+	Ca^{++}	Mg^{++}
100% Kaolinite - 0% Bentonite	35.6 + 0.8	29.0 + 0.9	28.1 + 1.0	30.0 + 0.5	27.0 + 0.6	21.2 + 0.7	19.2 + 0.7	21.1 + 0.7
95% Kaolinite - 5% Bentonite	40.1 + 0.7	34.9 + 0.4	32.3 + 0.9	35.5 + 1.7	26.7 + 0.7	21.2 + 0.9	18.9 + 0.7	20.9 + 1.2
90% Kaolinite - 10% Bentonite	43.5 + 1.0	41.4 + 1.4	37.4 + 0.3	41.7 + 0.9	27.3 + 1.0	21.4 + 0.4	19.4 + 0.5	21.4 + 0.4
85% Kaolinite - 15% Bentonite	52.7 + 0.3	48.6 + 1.0	42.9 + 0.7	50.3 + 1.3	26.6 + 0.9	21.4 + 1.3	20.2 + 0.4	21.7 + 0.6
100% Illite - 0% Bentonite	27.0 + 0.1	24.0 + 0.8	32.2 + 0.8	30.1 + 1.5	20.8 + 0.5	17.9 + 1.2	19.7 + 1.0	19.9 + 0.5
95% Illite - 5% Bentonite	32.1 + 0.6	29.6 + 0.2	34.8 + 1.2	35.3 + 1.2	22.6 + 0.1	18.4 + 0.2	19.4 + 1.3	21.0 + 0.7
90% Illite - 10% Bentonite	38.0 + 1.0	39.6 + 0.6	38.9 + 0.6	41.4 + 1.2	23.7 + 0.2	17.7 + 0.1	20.1 + 0.8	20.8 + 0.7
85% Illite - 15% Bentonite	42.8 + 0.9	53.4 + 1.4	42.2 + 0.7	48.0 + 1.6	24.0 + 0.4	19.1 + 0.5	19.5 + 0.1	21.2 + 0.4

NOTE: Confidence Level = 95 % Student "t" distribution

TABLE IV-II

LABORATORY-ALTERED CLAY MIXTURES - ATTERBERG LIMITS

SAMPLE DESCRIPTION (Per cent of clay fraction)	Order of Increasing Specific Surface Area with Cation	Order of Increasing Liquid Limit with Cation	Order of Increasing Plasticity Index with Cation
100% Kaolinite - 0% Bentonite	K < Na < Ca < Mg	Ca < Na < Mg < K	Na < K < Ca, Mg
95% Kaolinite - 5% Bentonite	K < Na < Ca < Mg	Ca < Na < Mg < K	K, Ca < Na < Mg
90% Kaolinite - 10% Bentonite	K < Na < Ca < Mg	Ca < Na < Mg < K	K < Ca < Na < Mg
85% Kaolinite - 15% Bentonite	K < Ca < Na < Mg	Ca < Na < Mg < K	Ca < K < Na < Mg
100% Illite - 0% Bentonite	K < Mg < Na < Ca	Na < K < Mg < Ca	Na < K < Mg < Ca
95% Illite - 5% Bentonite	K < Mg < Na < Ca	Na < K < Ca < Mg	K < Na < Mg < Ca
90% Illite - 10% Bentonite	K < Mg < Ca < Na	K < Ca < Na < Mg	K < Ca < Mg < Na
85% Illite - 15% Bentonite	K < Ca < Na < Mg	Ca < K < Mg < Na	K < Ca < Mg < Na

TABLE IV-III

CATIONIC EFFECT ON SPECIFIC SURFACE AREA, LIQUID LIMIT, AND PLASTICITY INDEX

Specific Surface Area

Specific surface area values for the laboratory-altered clay mixtures were found to vary depending upon the particular adsorbed cation and the amount of bentonite admixed. The values ranged from a low for potassium kaolinite to a high for magnesium saturated kaolinite with fifteen per cent bentonite. As would be expected, the addition of the small particle bentonite increased the surface area in every case. The rate at which the surface area increased with increasing bentonite varied with the cation and major mineral.

The surface area data summary for these clay mixtures is shown in Table IV-I. The relationship between particular cation and per cent bentonite and surface area is shown graphically in Figure 4-1. The cation order of increasing surface area is shown in Table IV-III.

As would be expected from their differences in molecular structure, the behavior of the homionic illite and kaolinite mixtures was different. The potassium and sodium saturated mixtures showed approximately the same rate increase for the two. The calcium and magnesium saturated illite mixtures showed a greater increase rate than for the kaolinite. The magnesium saturated mixtures indicate a change in surface area increase rate between the ten per cent and the fifteen per cent bentonite values. This indicates a change from interlayering to discrete mineral grouping. The potassium and calcium saturated clay mixtures showed the least rate of surface area increase. This could be explained on the basis of ionic size. The potassium and hydrated calcium ions are quite large. On the other hand the sodium and magnesium cations could be held inside of the lattice and prevented from causing aggregation.
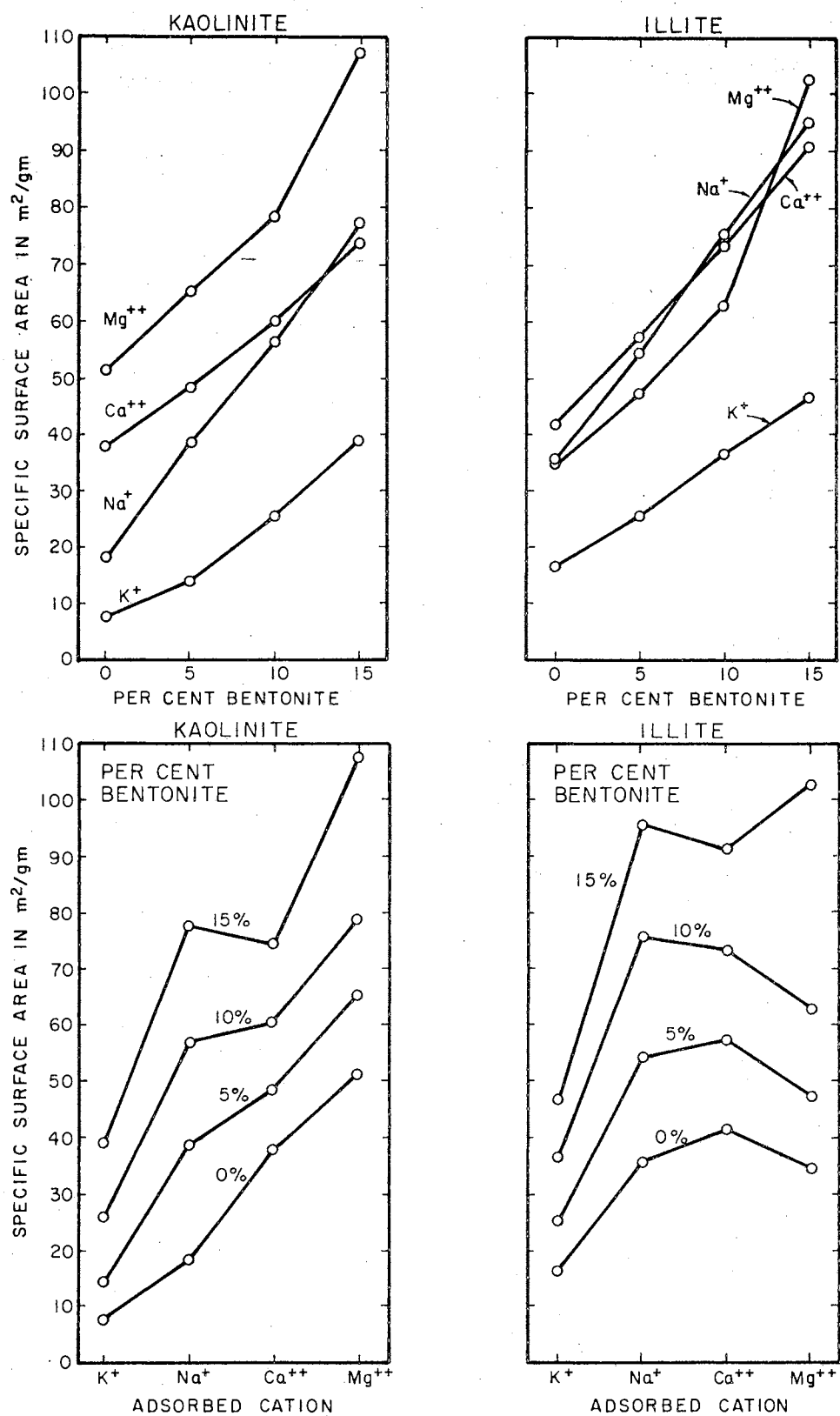
Figure 4-1. Surface Area Relationships with Adsorbed Cation and Per Cent Bentonite

The effect of adsorbed cations on clay mineral mixtures cannot be completely explained or predicted due to the multitude of parameters. The data show that ionic size, valence, and molecular structure together with an investigation of the mixed minerals present can be used to explain the simple combinations used in this research. Intimate layering and aggregation both occur with a predominance of discrete particle aggregation at the higher bentonite contents.

Liquid Limit

An interesting pattern was noted in the variation of liquid limit with an increase in bentonite. The values ranged from a low for sodium illite to a high for sodium illite with fifteen per cent bentonite. In every case an increase in bentonite corresponded to an increase in the liquid limit. The amount and nature of this increase was quite different for the different cations.

The liquid limit data summary for these clay mixtures is shown in Table IV-II. The liquid limit relationship to adsorbed cation and amount of bentonite admixed is shown graphically in Figure 4-2. The cationic order of increasing liquid limit is shown in Table IV-III.

The hydration of the calcium ion prevents the adsorbed water layer network from extending its normal distance. The kaolinitic mixtures show low liquid limits for the calcium saturated condition. For the illitic mixtures calcium has the lowest rate of liquid limit increase with addition of bentonite. Aggregation and interlayering are probably pronounced in these mixes. Sodium and magnesium saturated mixtures have higher liquid limits and high increase of liquid limit with increase of bentonite admixed. The sodium saturated illite has the highest rate
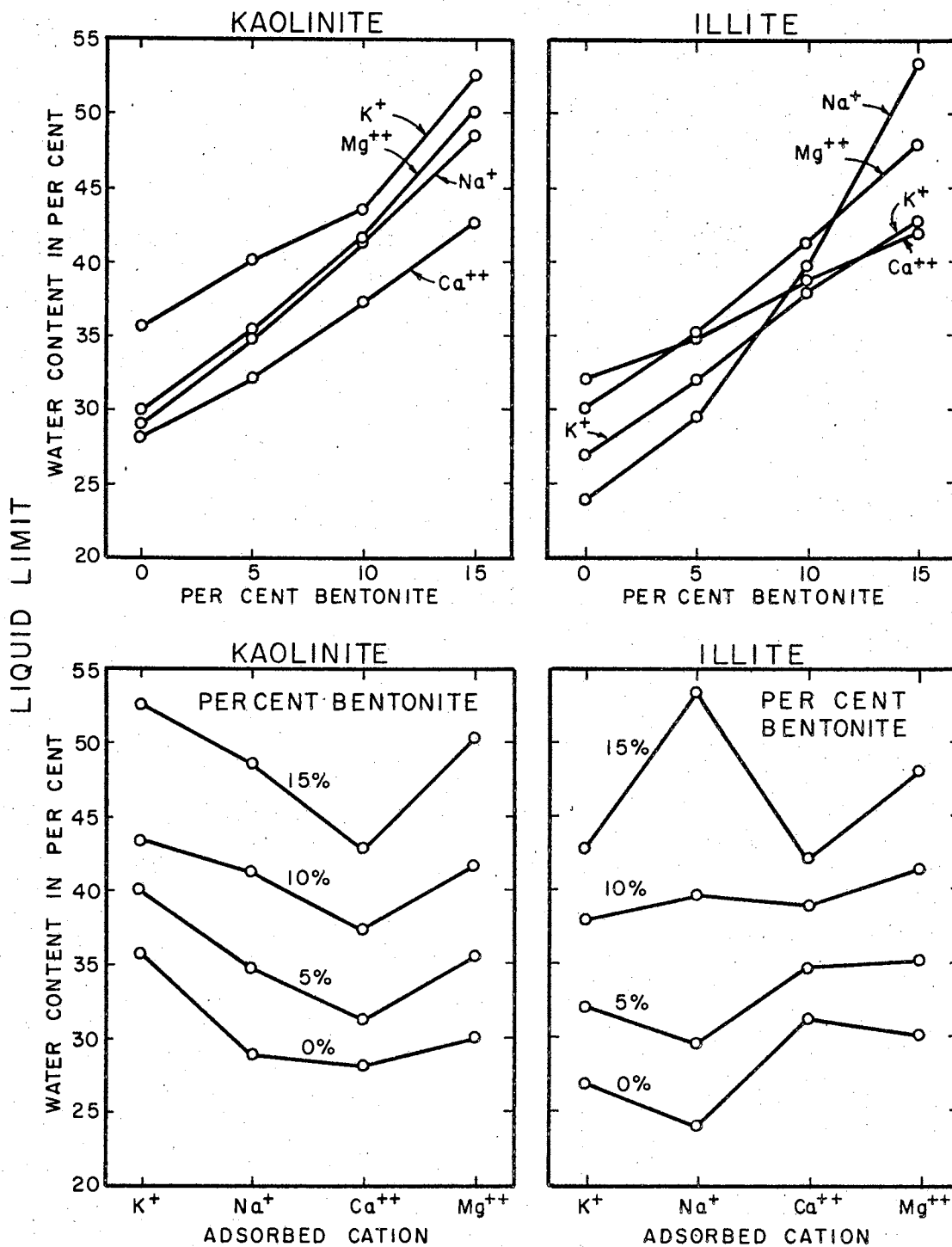
Figure 4-2.   Liquid Limit Relationships with Adsorbed Cation and
Per Cent Bentonite

increase between five and fifteen per cent bentonite. This shows a lack of interlayering in this region.

The potassium saturated kaolinite mixtures have higher liquid limits than expected. These particular mixes do not conform to the surface area correlation with plasticity shown later in this chapter. Additional testing with mineral analysis should be performed on material before conclusive evidence could be shown. Perhaps the water molecules can penetrate where the ethylene glycol molecules did not.

Little difference was noted in the samples with no bentonite present. The effects of interlayering and aggregation coupled with the effects of cation size and hydration are inter-related and difficult to analyze separately. The literature shows (Grim, 1962) that there is a wide variance in liquid limit values for different samples of similar clay minerals. For this reason only general trends should be inferred from limited testing such as this research.

<div align="center">Plastic Limit</div>

There was little variance in the values obtained for plastic limit. The potassium saturated clays had the highest values of those tested. For the sodium, calcium, and magnesium saturated mixtures, a range of four per cent was found in the plastic limits. There is not enough variation in plastic limits of those mixtures tested to warrant any definite conclusions.

<div align="center">Plasticity Index</div>

Plasticity index variation with adsorbed cation was less than the variation noted for liquid limit. There was an increase in plasticity

index for every increase in the amount of bentonite. The values ranged from a low for sodium kaolinite to a high for sodium illite with fifteen per cent bentonite added. For the kaolinite mixtures the variation of plasticity index with various adsorbed cations was very small. The potassium kaolinite did show a sudden increase from ten to fifteen per cent bentonite. This could be due to the plasticity of potassium bentonite aggregations being greater than that for potassium kaolinite-bentonite mixed layers. For the illitic mixtures the sodium illite mixtures with higher bentonite contents showed the largest increase in plasticity index with increasing bentonite. The potassium illites were low in plasticity probably due to the interlayering of the two minerals which are quite similar structurally.

The plasticity index data summary is shown in Table IV-I. The cationic order of increasing plasticity is shown in Table IV-III. The graphical representation of the changes in plasticity index with regard to cation and amount of bentonite added are presented in Figure 4-3.

Since crystallinity was not investigated in this research, it is difficult to apply the evidence presented here to conclusive statements about natural clay mixtures. The relationships between plasticity and the multitude of factors which control it are the basic reason for attempting to relate surface area and plasticity since the factors that affect one affect the other.

Natural Soil Clays

Eleven natural soil clays were tested including those with some organic matter, fine sand, fine silt, calcareous materials, micaeous materials, and loessian silt. These were taken from different geographic
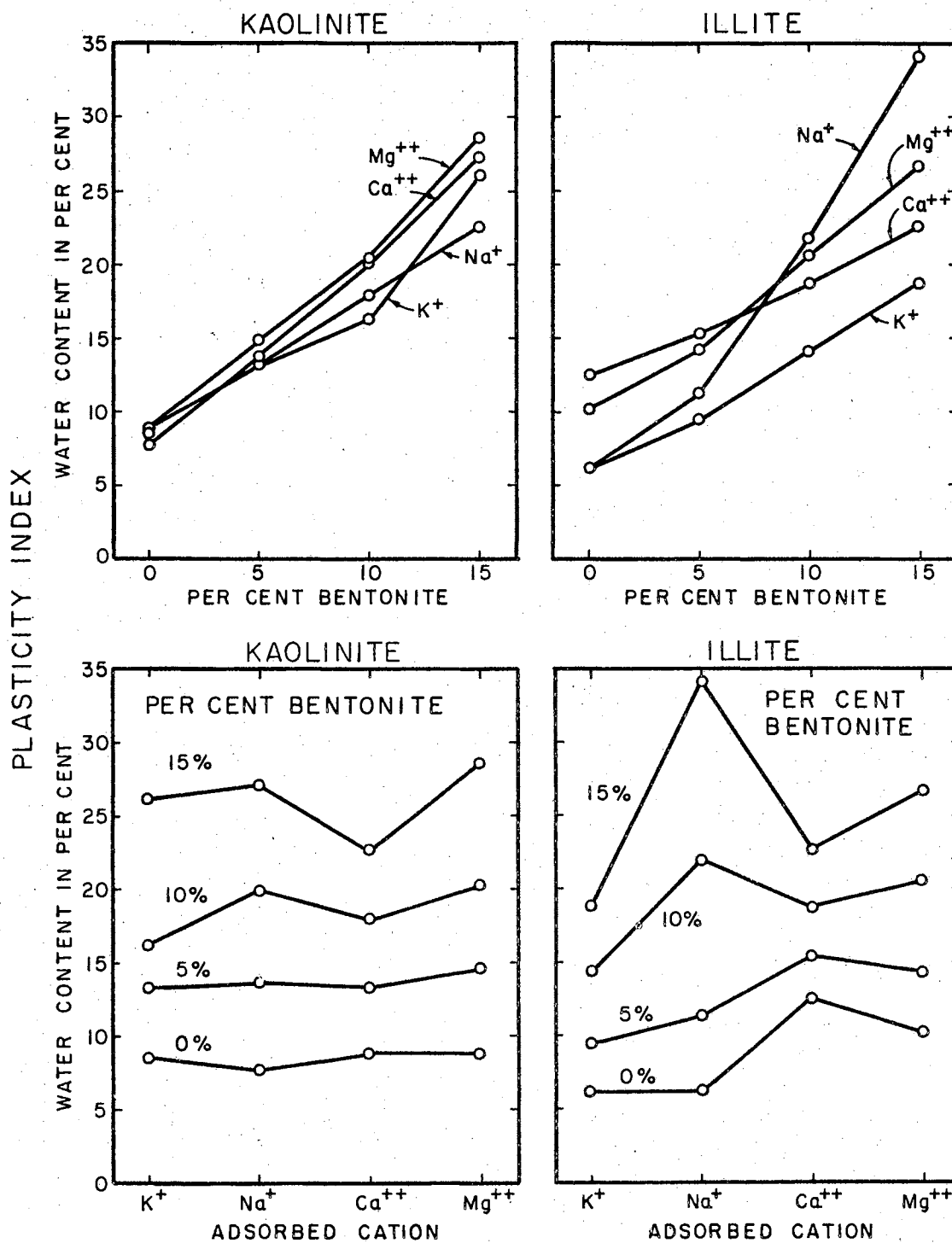
Figure 4-3. Plasticity Index Relationships with Adsorbed Cation and Per Cent Bentonite

and geologic areas. Descriptions of the samples obtained from the local Soils Laboratory were taken from their labels. The summarized data for the natural soils is shown in Table IV-IV. In order to better understand the range of soils included, they have been shown on a Plasticity Chart (Figure 4-4) as used in engineering classification. Six of these natural soils fall within the test limits of plasticity and surface area. Five additional samples were included of higher plasticity in order to test the extrapolation of the correlations. These correlations with plasticity and specific surface area will be discussed next.

Inter-relationship of Specific Surface Area and Plasticity

The multiplicity of factors that control the amount of available surface area and those that control plasticity has been discussed in the earlier sections. The hypothesis of this research is that the surface area is the major factor in controlling plasticity. Liquid limit, plastic limit, and plasticity index have been plotted separately against specific surface area to demonstrate this correlation. Those plots are shown in Figures 4-5, 4-6, and 4-7.

With the exception of the potassium saturated kaolinite-bentonite mixtures an excellent correlation is shown for liquid limit and plasticity index. The soils were selected to give a range of values for those two parameters. As a consequence, there is a narrow range of values for the plastic limit. It would appear from the plastic limit - specific surface area data that the solid friction strength overshadows the cohesive strength. The cohesive strength is area dependent but the solid friction strength is not. Additional testing of clays with a greater range of plastic limits would be necessary in order to define the correlation (if any)

	SOIL DESCRIPTION	Specific Surface Area (m²/g)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
1.	Topsoil from new Business Building Area OSU Campus, Stillwater, Oklahoma.	91.8 + 4.3	48.3 + 1.4	20.2 + 0.4	28.1 + 1.8
2.	Sandy Clay from bottom of drilled piers, new Business Building, OSU Campus, Stillwater, Oklahoma.	46.0 + 3.6	37.9 + 1.2	24.3 + 0.2	13.6 + 1.4
3.	Permian clay chunk sample from base course pit overburden, Ingalls, Okla.	132.2 + 0.8	63.2 + 1.6	19.4 + 0.7	43.8 + 2.3
4.	Caliche spoil from borrow pit, Concho County, Texas.	71.0 + 1.3	30.6 + 0.9	16.4 + 1.2	14.2 + 2.1
5.	Stiff clay with trace of organic matter, Nowata, Oklahoma.	188.4 + 6.2	73.4 + 1.1	23.1 + 0.2	50.3 + 1.3
6.	Stiff silty clay, Nowata, Oklahoma.	218.5 + 7.3	91.0 + 1.3	20.9 + 0.9	70.1 + 2.2
7.	Calcareous silty soil, Panhandle A. and M. College, Oklahoma.	67.8 + 1.9	37.8 + 0.6	18.4 + 1.1	19.4 + 1.7
8.	Fine Loess, Salina, Kansas.	138.5 + 2.7	63.2 + 1.2	20.3 + 0.7	42.9 + 1.9
9.	Stiff clay, Massard, Arkansas.	136.1 + 2.3	66.2 + 0.9	22.1 + 0.2	44.1 + 1.1
10.	Loess with trace of organic matter, Ulysses, Kansas	95.8 + 4.6	47.4 + 1.0	19.7 + 0.9	27.7 + 1.9
11.	Laurentian clay with traces of very fine mica flakes	96.0 + 0.6	50.4 + 0.8	18.6 + 1.1	31.8 + 1.9

NOTE: Confidence Level = 95 % Student "t" distribution
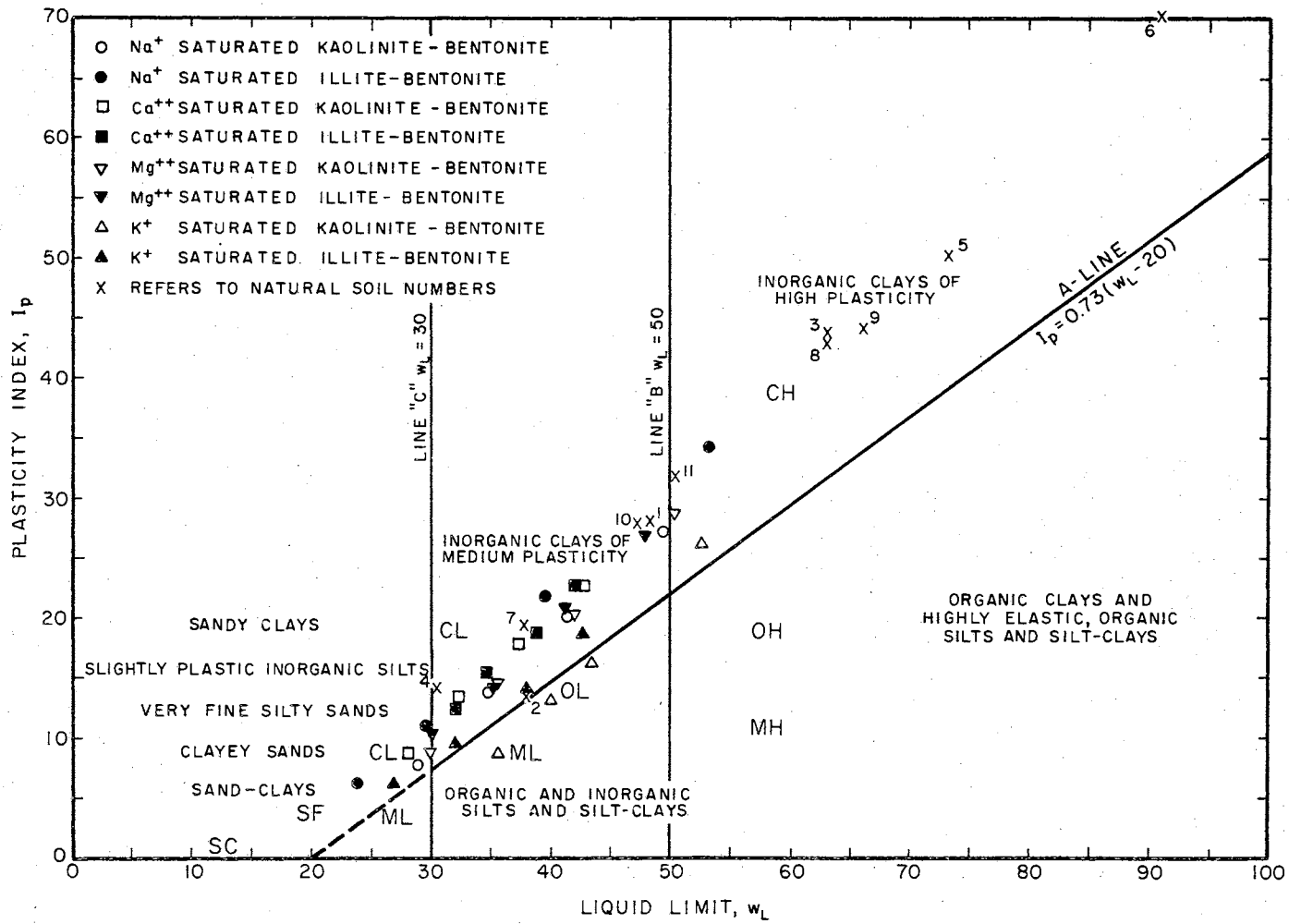
TABLE IV-IV

NATURAL SOIL CLAY PARAMETERS

Figure 4-4. Plasticity Chart Showing Plasticity Properties of All Test Samples
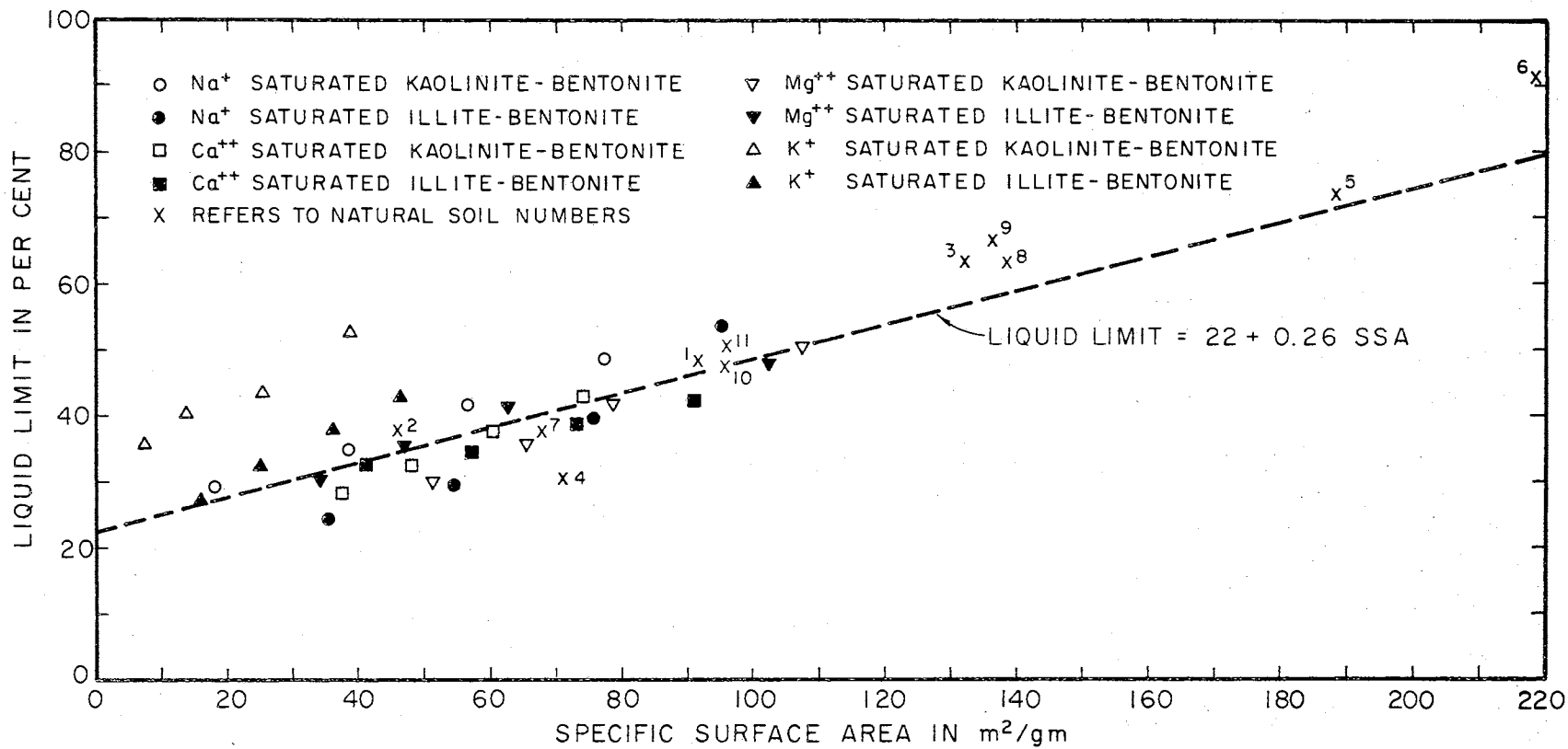
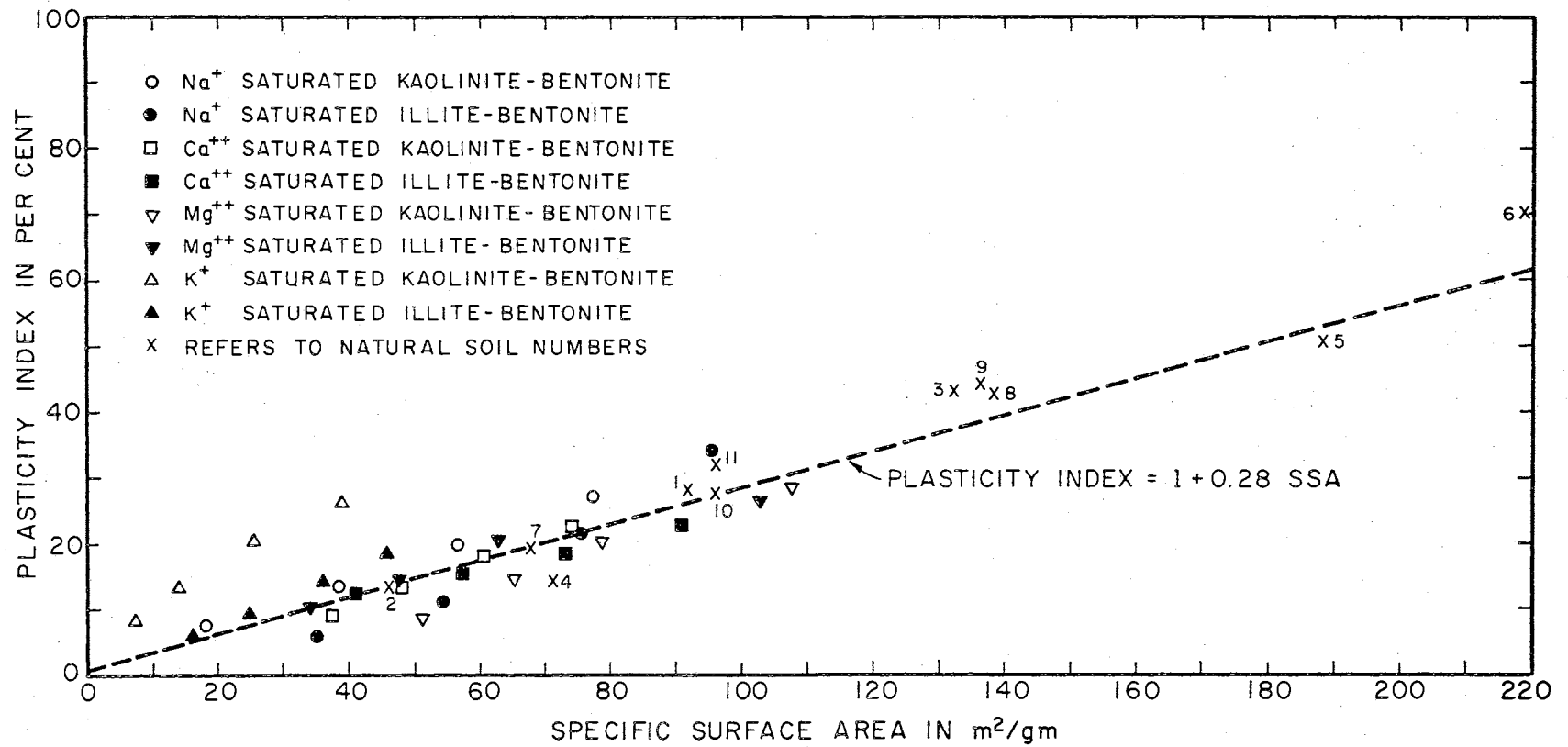Figure 4-5. Specific Surface Area Versus Liquid Limit

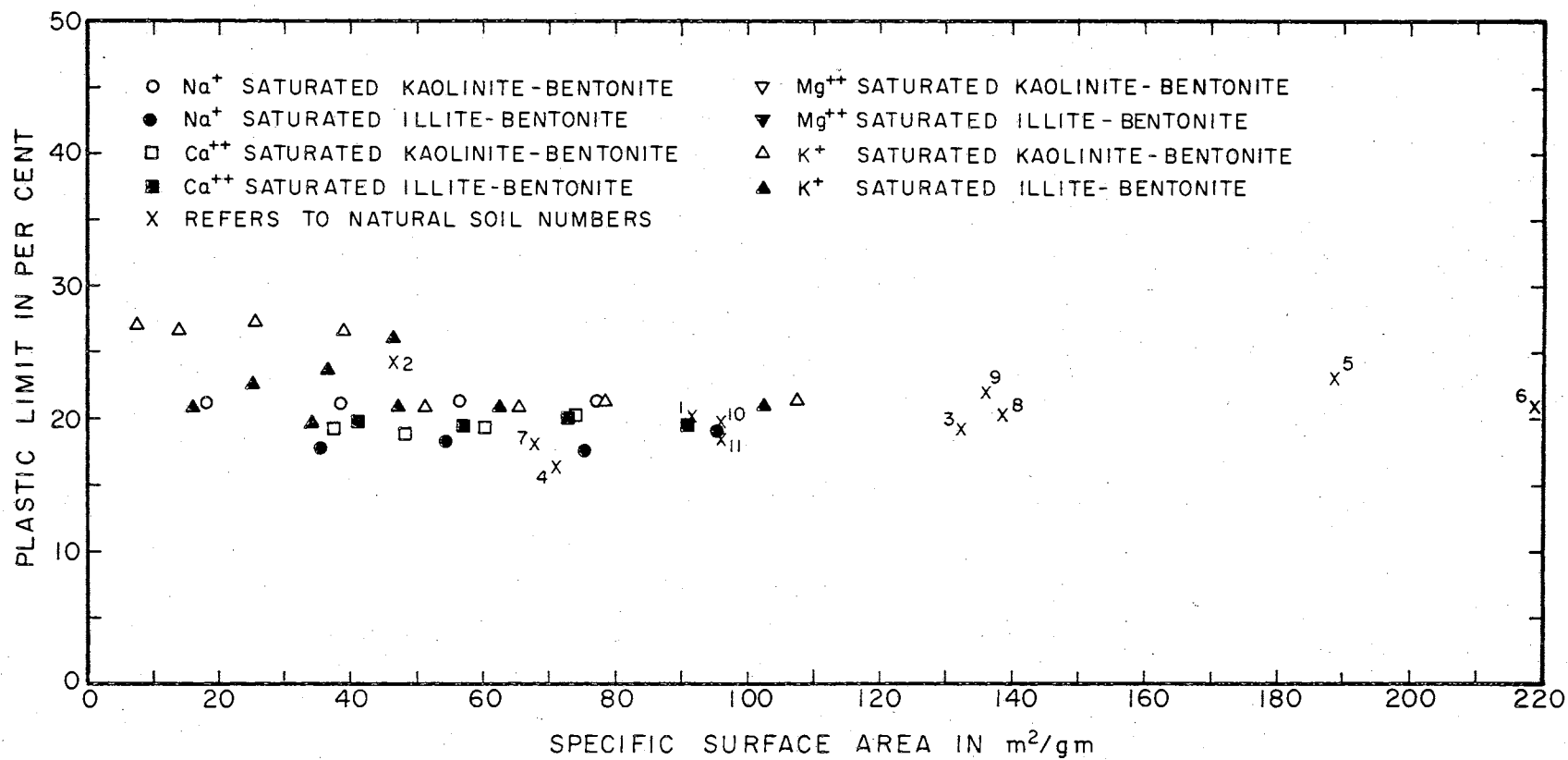Figure 4-6. Specific Surface Area Versus Plasticity Index

Figure 4-7. Specific Surface Area Versus Plastic Limit

between specific surface area and the plastic limit.

The laboratory-altered clay mixtures were tested and linear regression analyses performed on the correlations. The natural soil clays were then tested and those results used to test the hypothesized correlation. A ninety-five per cent confidence level was selected and the student "t" distribution assumed for analysis procedures. The data indicate that the distribution is normal and that the natural soils belong to the same population as the laboratory-altered clay mixtures.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Plasticity of clay soils dependency on surface area was the object of this study. It is believed that an understanding of this physico-chemical property of clay soils will aid greatly in the proper use of the index properties as determined by standard soil mechanics plasticity tests.

The major hypothesis was that a direct correlation existed between specific surface area and the Atterberg plasticity values. This relationship was developed by use of laboratory-altered samples to include the three major clay minerals (montmorillonite, kaolinite, and illite) with the four most common adsorbed cations (K^+, Na^+, Ca^{++}, and Mg^{++}). This hypothesis was tested by eleven natural soil clays of different origin and composition.

Review of soil science, ceramics, and soil engineering literature revealed a paucity of information on this subject. Laboratory-altered homionic soils were tested for plasticity according to the methods most commonly used in soils engineering. A procedure for reproducible multiple sample determination of specific surface area was developed. Replicate surface area testing of the laboratory-altered samples was accomplished and correlations developed between specific surface area

and plasticity. The effects of adsorbed cation and amount of bentonite admixture on the liquid limit, plasticity index, and specific surface area were noted. Plasticity and surface area tests were performed on the natural soil clays and their fit with the previously developed correlations was studied.

Conclusions were drawn and recommendations for further study are given.

Conclusions

The following conclusions on soil plasticity dependency on surface area were obtained from this study:

1. This study has made a quantitative evaluation of the dependency of plasticity on surface area.

2. Clay mineral molecular structure and the associated chemical phenomena are exceedingly complex for natural soil clays.

3. With some exception there is a linear relation between the liquid limit and specific surface area within the limits tested in this study.

4. With some exception there is a linear relation between the plasticity index and specific surface area within the limits tested in this study.

5. The relationship between specific surface area and the plastic limit is not defined over a sufficient range of values to warrant conclusions as to corrleation. An indication that cohesive strength is minor compared to the firction strength could be noted.

6. Potassium saturated kaolinite-bentonite mixtures do not relate surface area and plasticity in the same manner as other soils tested.

7. Surface area values for combinations of intimately mixed clay minerals are not additive. Potassium saturated mixtures have the least surface area for those tested.

8. A procedure for reproducible replicate testing of multiple soil samples is possible and requires only routine laboratory technique.

9. Soil science study is a normal extension of knowledge for the soils engineer.

Recommendations

These recommendations appear justified in light of the analysis of the data:

1. More comprehensive study on the same basic hypotheses should be performed using a wider range of adsorbed cations, a mixture of adsorbed cations, and other clay minerals.

2. Soil materials with a wider range of non-clay grain sizes should be analyzed. This would provide a wider range of plastic limit values.

3. The effects of cations and anions not in the adsorbed state upon the plasticity characteristics should be studied.

4. Investigation of the effect of one cation upon another cation should be studied with particular attention to the cations used in this research.

5. Other index properties such as grain-size distribution, specific gravity, shrinkage characteristics, and density should be included in future studies of the effect of surface area. Engineering properties such as permeability, strength, and compression might also be considered.

6. It is the strong feeling of the author that some knowledge of soil science and mineralogy is essential to the understanding of engineering behavior of soil masses. It is not intended that this knowledge will replace soil mechanics but instead to make it more comprehensive. It is therefore recommended that these subjects be integrated into the undergraduate soils engineering courses for all civil engineers with increasing importance given in courses for soils engineering graduate majors.

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