

PHYSICO-CHEMICAL PHENOMENA OF
SOIL MATERIALS

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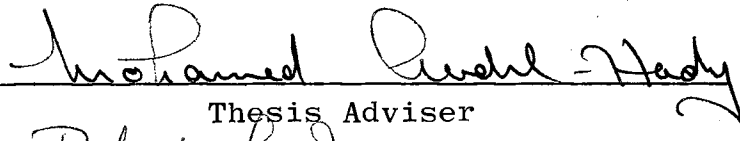
Submitted to the faculty of the Graduate
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in partial fulfillment of the
requirements for the degree of
DOCTOR OF PHILOSOPHY
July, 1966

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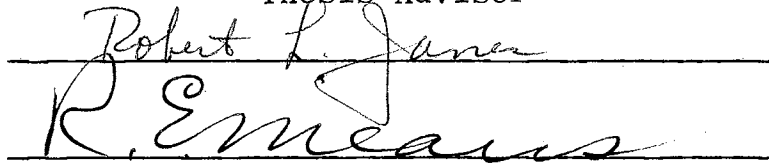
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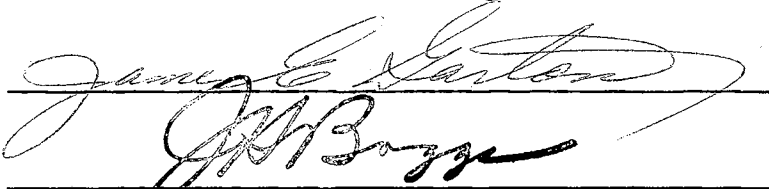
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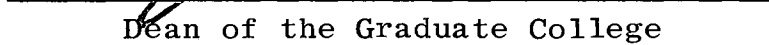
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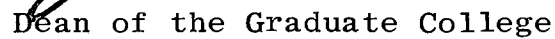


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ACKNOWLEDGEMENTS

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

To his major professor and adviser, Professor J. V. Parcher, for his inspiration and valuable leadership.

To the chairman of his committee, M. Abdel-Hady, for the sincere manner in which he accepted the supervision of the final preparation of this thesis during the absence of Professor Parcher.

To his committee members, R. L. Janes, James E. Garton, and R. E. Means.

To Professors Jan J. Tuma and Lester W. Reed for their assistance and encouragement.

To his fellow classmates, Assad F. Abdul-Baki and E. W. LeFevre, for their valuable assistance and encouragement in the development of this project.

To his mother for her inspiration and encouragement toward a higher education.

To Mrs. Rita Hill for her careful typing of this dissertation.

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CHAPTER I

INTRODUCTION

General

A definite need exists in engineering practice for a method which will enable the engineer to predict the physical and especially the mechanical properties of soils on the basis of fundamental concepts and easily performed tests. The general behavior of soils is of paramount concern to the soil scientist, the geologist, and the soils engineer. With the ever increasing use of soil and its conservation, it has become more apparent with the advance of modern technology that each of these scientific groups must cooperate in order to obtain a more comprehensive understanding of the nature of soil.

There are two main approaches to the understanding of the strength properties of cohesive soils. The first of these is evaluation of soil shearing strength in a macroscopic strength test. It has received the majority of effort because of the urgency for practical solutions to problems involving the strength of the soil. It is not difficult to devise a piece of apparatus in which some property of the soil related to the strength is measured under a variety of

conditions. Unfortunately, it is much more difficult to relate such a property either to the behavior of the soil in the field or to the fundamental soil parameters which control its strength, and it is virtually impossible to derive from these properties general relationships for other soils under other conditions. Most of the effort put into studies of soil strength up to the present has been focused on the design and exhaustive testing of apparatus rather than soil, since the defects of equipment have placed major restrictions on the evaluation of test results.

The second approach concentrates on the study of the fundamental aspects of interparticle behavior with the object of relating the macroscopic strength and strain characteristics of the soil to the physico-chemical properties of its constituents including the pore fluid. Most studies on macroscopic shear strength undertaken with some form of testing apparatus develop conclusions which are limited by properties under investigation which have not been thoroughly examined or reported. Only in few investigations have both approaches been employed to give a wider view of the factors controlling strength and deformation of some soils.

Fine-grained soils lend themselves to the study of physico-chemical phenomena on a microscopic scale due to the electrical unbalance and the high specific surface of the crystalline clay minerals. The electrical unbalance allows the clay mineral to adsorb certain cations and anions and

relate these in an exchangeable state; that is, the adsorbed ion on a clay particle may be exchanged by treatment with other ions in an aqueous solution.

There are several reasons why the engineer should be concerned with cation exchange. The properties of cohesive soils have been shown to vary with the nature of the exchangeable ion (Thomson, 1963; Grim, 1942)*. Knowing the possible changes in the geotechnical properties when chemically modified and knowing the properties desired in the soil mass, it appears feasible that the soils engineer should be able to tailor the soil to some extent to fulfill his needs. Winterkorn (1953) relates incidents of failures which occurred due to changes in soil properties as a result of ion exchanges during and following construction. The nature of the exchangeable ion may affect the reactivity of the soil with other substances; e.g., it influences the reaction with portland cement in cement-stabilized soils.

Problem

The general problem to be considered concerns the effects of physical-chemical phenomena on the shear strength of clay materials. Specifically, the problem consists of determining the shear strength characteristics of isotrop-

*References are indicated by author and year of publication and are listed in the bibliography.

ically consolidated artificial clays that have been modified by saturation of the exchange complex with sodium, potassium, calcium, and magnesium cations. Unconfined shear testing was augmented by hydrometer analyses, specific gravity determinations, and a study of the Atterberg limits. There are many cations that may be investigated, but the program that forms the basis of this thesis was restricted to the cations normally found in nature; namely, calcium, magnesium, sodium, and potassium. The data of Table I-I is presented on the following page to illustrate the predominance of these cations.

It should be noted that the bodies of water used in the following table represent large amounts of water and, consequently, the salt concentration is much lower than would be found in the more arid areas. For an example of areas of much higher salt concentration, the reader is referred to, "A Study of Saline-Alkali Soils in Oklahoma," (Reed, 1962).

TABLE I-I
THE CHEMICAL ANALYSIS* OF SOME REPRESENTATIVE NATURAL WATERS

| Source | St. Lawrence River (Montreal) | Lake Ontario | Niagara River | Detroit River | Lake Superior | Red River | Regina City |
|-------------------------------------|-------------------------------------|-----------------|------------------|------------------|------------------|--------------|----------------|
| pH | 7.6 | 8.1 | 8.0 | 8.1 | 7.4 | -- | -- |
| Dissolved O ₂ , ml/l. | 6.5 | 5.4 | 6.0 | 4.9 | 7.5 | -- | -- |
| Dissolved Solids | 143.0 | 157.8 | 170.4 | 114.6 | 68.0 | 864.0 | 1128.0 |
| Ca | 27.6 | 36.4 | 33.7 | 26.1 | 14.3 | 98.0 | 163.6 |
| Mg | 6.8 | 8.4 | 8.2 | 7.4 | 4.6 | 40.0 | 86.5 |
| Fe | 0.06 | 0.06 | 0.05 | 0.05 | 0.06 | 0.34 | 0.12 |
| Na and K | 6.1 | 9.5 | 4.6 | 2.6 | 2.9 | 134.0 | -- |
| Si O ₂ | 9.2 | 2.5 | 7.0 | 5.0 | 8.0 | 14.8 | 21.0 |
| (H CO ₃)' | 89.4 | 105.0 | 122.0 | 105.0 | 47.0 | 223.0 | 543.0 |
| (SO ₄)'' | 17.4 | 20.7 | 18.1 | 10.9 | 4.3 | 202.0 | 424.0 |
| (Cl)' | 13.1 | 16.5 | 13.5 | 5.3 | 11.8 | 211.5 | 9.0 |
| (NO ₃)' | 0.2 | 1.9 | 0.5 | 1.2 | 0.2 | 0.9 | 0.5 |
| Total Hardness | 96.9 | 125.4 | 128.0 | 95.6 | 54.7 | 409.0 | 622.3 |

*Chemical analysis obtained from Munro (1964).

CHAPTER II

SOIL SCIENCE AND ENGINEERING

The use of homionic soils in research may be open to question since they are not found in nature. However, it has been stated (Winterkorn, 1952) that it is not necessary to work with homionic soils in the field; e.g., sodium-soil characteristics can be achieved with about 15 per cent sodium saturation of the exchange complex. The term homionic in this study is defined as the condition when all the exchange positions of a clay mineral are satisfied by one type of cation; e.g., Na^+ .

In research, when one is investigating a particular question, all other variables should be eliminated or minimized. As a step towards the study of natural soils, one must first determine the characteristics of a pure state and then go to more complex systems. Therefore, despite the fact that it is difficult to produce 100 per cent homionic soils, it seems scientifically correct to attempt to do so in order to eliminate extraneous factors.

The agronomist has been aware of the importance of cation exchange for over a century and has been intensively investigating it for at least fifty years. Engineering has

only begun to appreciate its significance to any large extent in the past decade. The outline of the cases involving cation exchange cited in the following paragraphs have the further purpose of providing a practical background and to suggest to the engineer that alien material is often of useful significance in understanding the behavior of clay soils. In order that subsequent suggested explanations of the observed data may be more readily visualized, a brief review of the applicable concepts of the fields of Clay Mineralogy, Physical Chemistry, and Soil Physics are reviewed.

Clay Mineralogy

Most of the clay minerals (Grim, 1953) have sheet or layered structures although a few have tubular or fibrous structures. Argillaceous material may be considered as being comprised of very small particles, each of which is either a book of sheet-like units or a bundle of tubes or fibers. Individual clay soils may contain a mixture of book-like units or books and bundles along with other components such as the normal rock-forming minerals.

The fundamental building blocks of the clay minerals are the silica tetrahedron and the alumina octahedron. The silica tetrahedron consists of a central silica atom surrounded by four oxygens or hydroxyls in the form of a pyramid. The alumina octahedron may be considered as an aluminum atom surrounded by six hydroxyls in octahedral coordination. The

silica or alumina atom may be substituted by other minerals and this phenomenon is referred to as isomorphous substitution. The net negative charge of the clay minerals is satisfied by the adsorption of cations.

The main clay minerals are kaolinite, montmorillonite, and illite or hydrous mica. Kaolinite consists of a single layer of octahedrons with a superimposed layer of tetrahedrons intergrown in such a manner that the tips of the tetrahedrons and apices of the octahedrons form a common layer. The mineral kaolinite is a stacking of such units tied together by hydrogen bonding. There is very little substitution within the lattices; hence, the cation exchange capacity is in the order of 5 to 15 milliequivalents per 100 grams of air dried soil.

The montmorillonite unit is composed of an octahedral sheet enclosed by two tetrahedral sheets such that the tips of the tetrahedrons point inwards. In the mineral montmorillonite, the oxygen layers of the bases of the tetrahedrons are adjacent to each other which gives rise to a weak bond and excellent cleavage. An outstanding feature of this mineral is the ability of water molecules and cations to enter between the unit-layers causing expansion of the lattice in the "c" direction. There is always substitution within the lattice of montmorillonite resulting in a high base exchange capacity of 80 to 100 m.e./100 grams soil.

The structural unit of illite or hydrous mica is the

same as for montmorillonite except that some of the silicas are always replaced by aluminums in the tetrahedral layers and the resulting charge deficiency is balanced by adsorbed potassium ions. These ions tie the structural units together very effectively. The mineral illite which leads to the favoring of the term hydrous mica in the general classification appears to be a gradational stage between kaolinite and montmorillonite.

Mixed layer minerals arise from the fact that most clays are composed of more than one clay mineral that may be mixed in any of several ways. There may be discrete interlayering of pure minerals and such particles may cleave easily, particularly through montmorillonite layers. Another mixture possibility is interstratification between layers of similar clay minerals. These mixtures are as stable as pure minerals.

Physical Chemistry

The concepts needed from the broad field of physical chemistry to be considered here are relatively few. An important idea is that of the various types of bonding that can occur in molecular units. Ionic bonding (Grim, 1953; Munro, 1964) involves the outright transfer of electrons from one atom to another. The covalent bond is the sharing of electrons in pairs, each electron pair corresponding to a single valence. In certain compounds, a hydrogen already bound by two electrons to an atom may further coordinate two more elec-

trons to form another bond. This is termed hydrogen bonding. The hydrogen bond is weaker than the ionic and covalent bonds.

When a molecule is placed between two charged plates, a phenomenon termed polarization occurs. The anode attracts the electrons and the cathode attracts the nuclei. If the polarization disappears when the electric field is removed, the dipole is referred to as induced and the molecule is termed non-polar. If the centers of positive and negative charge within the molecule do not coincide, then the molecule possesses a permanent dipole and is termed a polar molecule. Water is an example of polar fluid.

Intermolecular or Van der Waals forces consist of both attractive and repulsive forces. Attractive forces arise from attractions of permanent and induced dipoles and the vibrations of electron clouds with respect to the nuclei of atoms in a molecule. A repulsive force arises from the approach of electron atmospheres and nuclei of the atoms of one molecule with those of another. Coulombic forces result from the electrical interaction of two charges. All of these forces are susceptible to mathematical expression.

Soil Physics

The behavior of colloids (Baver, 1956) is predominantly a function of the surface area of the particles comprising the colloid. There are three factors influencing surface area; namely, particle size, particle shape, and the material

of which the particles are composed. Subdivision of a particle into many smaller particles increases surface area per unit volume, changing the particle from an equi-dimensional to disc shape which further increases the surface area for a given volume. The classic illustration of the effect of the material comprising the colloid is the comparison of colloidal suspensions of gold and clay. The former are stable, but suspensions of clay often must be chemically treated to insure stability.

Grim (1953) gives the causes of cation exchange as broken bonds at the edges of crystals, substitutions within the lattice structure and the possible replacement of the hydrogen of an exposed hydroxyl group at the edges of the crystal by an exchangeable cation. For kaolinite, broken bonds play the major part in exchange capacity. In illite, broken bonds contribute strongly, but there is also some isomorphous substitution. Broken bonds account for about 20 per cent of the high exchange capacity of montmorillonite and the remainder is due to isomorphous substitution.

In addition to adsorbing cations, the clay particle also hydrates by the formation of hydrogen bonds between surface hydroxyls, or oxygens, and the water molecules. Succeeding layers of water are held by similar bonds to the preceding layer. In this manner an adsorbed water film, or hull, is built up around the clay particle. A thick adsorbed hull on the clay particle is associated with adsorbed sodium ions

and a thin hull with calcium and magnesium ions. The presence of extraneous cations and anions (or salts) in the pore water has the effect of depressing the thickness of the adsorbed water film around a clay particle. The thickness of the water hull is dependent on the type of adsorbed cation and the charge density of the particle.

The adsorbed cations are not in contact with the particle surface but diffuse away from it in such a way that the concentrations of cations decrease as the distance from the particle surface increases. This concept is referred to as the diffuse double layer. The inner of the two layers is composed of the negative charge associated with the clay particle and some cations adsorbed so strongly as to be considered immobile. The outer layer is comprised of the mobile and exchangeable cations. The clay particle and its adsorbed cations is an electrically neutral system which may be considered to be bounded by the particle surface and the outer edge of the diffuse double layer. The distance between these boundaries is a direct measure of a quantity termed the zeta potential. The higher the zeta potential, the greater the distance between the two boundaries.

The general applicability of the Law of Mass Action is assumed in the production of a homionic clay. The equilibrium that exists between cations adsorbed by the clay particle and those in pore water is continually shifted toward the homionic state by successive replacement of the pore

water by a solution containing only the ions that one desires to have adsorbed. One method for the measurement of the cation exchange is a leaching procedure in which the exchangeable positions are filled with ammonia cations. A determination of the retained ammonia yields the exchange capacity.

Origin of Clays

Clay minerals are a secondary product of the weathering or alteration of rock-forming minerals. They may be considered to be formed in-situ and may undergo transportation by the natural agencies of the geologic cycle. The B horizon of the agronomists is the zone accumulation of materials removed from the upper horizon including a concentration of weathered products, some of which are the clay minerals. Typical weathering processes include oxidation, hydration, hydrolysis, and the formation of soluble salts. However, as well as being a product of soil weathering, sedimentation and metamorphism also play a part in clay mineralogy.

CHAPTER III

LITERATURE REVIEW OF APPLICATIONS OF CATION EXCHANGE TO SOIL ENGINEERING

General

Recent and past research relating physico-chemical phenomena to soil mechanics presents many complex difficulties in correlation due to variations in soil type, soil structure, and testing procedure.

Studies have been made on clay-water suspensions, homionic soils, and naturally occurring soils. A natural soil used to investigate a particular problem; e.g., effect of electrolyte concentration, introduces serious unknowns with respect to quantities and type of ions either adsorbed or present in the free water. Also, it does not seem feasible to compare directly the results of a research program concerned with clay-water suspensions to that of the plastic clay-water mass normally associated with soil mechanics (Lambe, 1958).

The evaluation of shear strength is an exceedingly complex problem due to the number of variables involved. A correlation of shear strength as determined by such techniques as direct shear, vane shear, drop cone, unconfined

compression, and triaxial testing is difficult when encountered in regular research problems, thus when coupled with physico-chemical effects additional difficulties arise.

Behavior of the microscopic state has been viewed in the light of interparticle forces by Lambe (1960) and Warkentin (1962), polarizability of the adsorbed cations by Rosenqvist (1955), and structure by Lambe (1958). There are numerous postulates, but there appears to be a common thread running throughout these ideas, and it is hoped that research will tie them together to form a comprehensive picture.

Treatment of a Gravel Road

One of the earliest direct field applications was carried out by Winterkorn (1933) on a gravel road in Missouri. The gravel surfacing material had a clay binder, which, according to its Atterberg limits, should have been suitable. On the road, however, it behaved like a silt; softening in the rain and exhibiting a high permeability. Excessive amounts of water entered the subgrade which resulted in many surface failures. Laboratory tests indicated practically all of the exchange positions to be filled with calcium ions. Test sections of the road were treated with solutions of the chlorides of calcium, potassium, and sodium. The latter two salts improved the road considerably but the calcium treated section became even worse. Further laboratory tests indicated that the dispersive effects of the sodium and potassium

cations were responsible for decreasing the permeability. The calcium caused further aggregation which made the condition worse. It would appear that the replacement of adsorbed calcium by sodium caused an increase in thickness of the adsorbed water hull on the clay particles; hence, a decrease in the permeability.

Decreasing Permeability

As part of the San Francisco Exposition of 1940, a shallow lagoon was to form a scenic area. It was to be fresh water with evaporation and seepage losses replaced from the city water supply. Seepage proved to be beyond tolerable limits and a remedy was sought. A thicker blanket of clay was not economical since the clay had to be hauled in. Lee (1940) took advantage of cation exchange simply by replacing the fresh water by sodium-rich sea water. The latter was left in place until a seepage of about forty inches of the salt water had occurred. The salt water was drained and fresh water pumped in. Subsequent tests and observations showed the permeability of the treated blanket to be about 10 per cent of the original value. This decrease in permeability as sodium became adsorbed is also reported in the recent investigations of Hamilton (1961) and Thomson (1963).

Liming of Soils

In the field of portland cement stabilization of soils,

it is advantageous to have calcium as the adsorbed cation rather than sodium. In the hardening process of cement, lime (CaO) is released to re-enter the reactions at later stages. If sodium is present in the adsorbed phase, an exchange takes place in which calcium replaces the sodium. This removes calcium from the hydration process of the cement and results in much lower strengths. "Liming," that is the addition of a small per cent of lime (1% to 3%) to the soil before addition of the portland cement, is often advantageous.

Hydrometer Suspensions

Another application of cation exchange that is more familiar to the soils engineer is the stabilization of hydrometer suspensions by the addition of calgon [sodium hexameta phosphate, $\text{Na}_6 (\text{PO}_4)_3$]. It is known (Grim, 1953) that calcium soils, i.e., those soils having a majority of the cation exchange positions filled with calcium, tend to form large particles and that these particles are attracted to one another to form flocs which settle out quickly. The reason for this is the low zeta potential (Baver, 1956) of the calcium clays which allows the particles to come close together. The addition of the sodium salt (calgon) has two effects. The first is a partial cation exchange with an accompanying increase in the zeta potential. The second effect is the removal of calcium cations by the formation of

complex phosphates (Van Olphen, 1950). The over-all result is a stabilization of the suspension. A point of interest with regard to montmorillonite clays is that the adsorption of monovalent sodium ions may cause sufficient swelling to disrupt the clay particle. In any event, cleavage takes place with relative ease between the structural sheets of some clay minerals during the dispersion phase of preparing a hydrometer sample. Grim (1939) concludes that:

Mechanical analysis of kaolinite and some illite clays give a fair picture of the composition of the natural clay. Similar analyses of montmorillonite and other illite clays measure little more than the degree of disaggregation.

It would appear necessary that every sample be treated in an absolutely identical manner if comparisons between different soils are to be made.

Artificially Sedimented Clays

An interesting set of experiments was reported by Bjerrum and Rosenqvist (1956). In these tests, a series of artificially sedimented clays were produced with sedimentation taking place in salt water and in fresh water. The sensitivity of the salt samples was about five when the salts were present in the pore water. Subsequently, these samples were leached with fresh water and the salt content reduced from 32 to 5 grams per liter. The sensitivity increased from the original value of five to an average value of 110, with individual values ranging from 70 to 180. The liquid limit was

reduced from 40 per cent to 20 per cent. The undrained shear strength of the leached samples was some 40 per cent less than that of the unleached samples. The fresh-water clays were characterized by a dense structure and a relatively high shear strength with the sensitivity varying from five to six. In analyzing this data, Bjerrum and Rosenqvist attributed the decrease in strength to the pore pressure parameter (defined as the ratio of increase in pore pressure to increase in deviator stress under undrained loading). This, in turn, postulates high pore pressures which were considered plausible due to a partial collapse of the unstable soil structure. Sedimentation in salt water leads to flocculation due largely to the ion content of the water. The flocculation may also be aided by preferential absorption of ions other than sodium (e.g., calcium or magnesium) by the clay particles. As a consequence, particles of all sizes tend to settle out at similar rates; that is, clay flocs settle at a rate roughly equal to silt particles. This leads to homogeneous deposits of high sensitivity. On the other hand, sedimentation in pure water would result in little, if any, flocculation. Particle size segregation would occur due to different settling velocities and one would expect the product of such sedimentation to be a gradual gradation of particle sizes from coarse at the bottom to fine at the top of the layer.

Landslide in Japan

Matsuo (1957) investigated a landslide near Kashio, Japan and concluded that cation exchange played a major role in the slope failure. An analysis of rain water entering the slope revealed a calcium ion content of 0.07 milliequivalents per liter while the ground water issuing from the toe of the slope contained 1.13 m.e. per liter. Shear strength tests were carried out which indicated the natural soil to be weaker than a calcium soil. Stability calculations based on the test results gave a factor of safety of the slope for the natural soil of 0.6 and the calcium soil of 1.3. Matsuo concluded that the initially stable slope was predominantly a calcium soil and subsequent leaching reduced the adsorbed calcium which led to strength reduction and ultimate slope failure. It was suggested that calcium salts injected at the top of the slope would maintain stability. There was no mention of the quantity of salts in the pore water or of actual determinations of the adsorbed cation complex; thus, no observations can be made other than the suggestion that the changes in zeta potential due to leaching out of the pore water salts may have been a factor in the slope stability.

Lambe's Equation

Lambe (1960) presented the following equation as appli-

cable to a saturated fine-grained soil system:

$$\sigma' = \sigma + A - u - R$$

where:

σ' = effective normal stress on the shear plane

σ = total normal stress on the shear plane

u = stress in the pore water

R = repulsive forces between the clay particles

A = attractive forces between the clay particles.

The adsorbed cation complex affects both the repulsive and attractive forces, probably by differing amounts, which leads to strength variations. The higher the zeta potential, the greater the repulsive forces; hence, the lower the strength. The converse would also appear to hold. If the zeta potential is suppressed by the presence of salts in the pore water and then these salts are removed without a volume change taking place, the resulting repulsive forces must increase. If, however, volume changes do occur, the repulsive forces change further and as a result so will the strength.

CHAPTER IV

PREPARATION OF SYNTHETIC SOIL AND TESTING PROGRAM

Synthetic Soil Used

From the review of previous soil testing research it becomes apparent that it is extremely difficult to correlate much of the data available. There is wide variation of testing procedures and also wide variety of the soils used throughout the nation, such as Boston clay, Weald clay of England, Norwegian quick clays, Alberta clay of Canada, Venezuela clay, Mexico City clay, and others. The results of physical tests of these materials are extensively used in the attempt to develop better design methods and procedures.

The application of mechanics to noncohesive soils gives relatively good results, but with the cohesive soils, unfortunately, the results are often very disappointing and give unreliable design information.

In this investigation, it was attempted to use the mineralogical and chemical characteristics as controlled variables by using so-called synthetic soils. These soils were prepared by using the clay minerals, bentonite, kaolinite, and illite in various combinations with a fine sand. The combinations used are shown in Tables IV-I and IV-II. A

TABLE IV-I
COMPOSITION OF BENTONITE-KAOLINITE-SAND MIXTURE

| Soil Mix | 70% Clay Fraction | | 30% Fine Sand Passing the 100 Mesh Screen |
|----------|-----------------------|-----------------------|--|
| | Per Cent Bentonite | Per Cent Kaolinite | |
| 1 | 5 | 95 | |
| 2 | 10 | 90 | |
| 3 | 15 | 85 | |

TABLE IV-II
COMPOSITION OF BENTONITE-ILLITE-SAND MIXTURE

| Soil Mix | 70% Clay Fraction | | 30% Fine Sand Passing the 100 Mesh Screen |
|----------|-----------------------|--------------------|--|
| | Per Cent Bentonite | Per Cent Illite | |
| 4 | 5 | 95 | |
| 5 | 10 | 90 | |
| 6 | 15 | 85 | |

sample from each of these mixes was treated with a chloride solution of the following cations: sodium, magnesium, calcium, and potassium—six mineral mixes with four cations to form a total of 24 homionic soil samples.

Source of Materials

The clay minerals, bentonite, kaolinite, and illite, were obtained from the University of Oklahoma Geology Department. From the X-ray diffraction results these minerals were rated to be of commercial grade in purity. The sand used was obtained by crushing standard Ottawa sand to pass the 100 mesh sieve. This sand was about equally proportioned on the 80, 100, 200, and the pan.

The bentonite and illite were received in lump form as they were quarried. The kaolinite was a Georgia paper grade processed to pass the 270 mesh sieve. Each of these minerals was tested with 0.75 normal hydrochloric acid and there was no perceptible effervescence; therefore, carbonate content was considered to be negligible and no treatment was considered necessary for the removal of carbonates. The bentonite and illite were first crushed to pass the 40 mesh sieve and then boiled in distilled water until dispersed. This procedure was successful for the bentonite, but not with the illite. The illite required crushing to pass the 100 mesh, then with boiling only about 30 to 40 per cent was dispersed. Repeated grinding of the residue was required for three

cycles. An electric portable cake mixer used while boiling greatly assisted in getting the mix to go into solution. About one week of work was required before the illite was dispersed and it is still doubtful to the author that proper dispersion of the illite was achieved.

Preparation to Obtain Homionic Soils

Each of the mineral groups were separated equally into four containers (12 quart enamel dishpans). The groups were then proportioned to give 24 samples of 700 grams each. At this stage there was placed 325 grams of bentonite, 1500 grams of kaolinite, and 1500 grams of illite in each of the four pans. Distilled water was added to fill the container to about three-fourths full and thoroughly dispersed with the electric mixer. The container was then left to settle so the clear solution could be siphoned off and the cation solutions added. After several days, it became obvious that settlement was almost negligible. The mixes were then placed into drying ovens and left for 36 hours at 65°C at which time enough evaporation and settlement had occurred that four liters of the chloride solution was added and mixed for about five minutes with the electric mixer. Then the 36 hours cycle in the oven was repeated. The cycle of adding the chlorides was repeated four times in order to assure that complete ionic exchange had occurred. A 2.0 normal solution of the chloride was used.

After the last chloride treatment, the samples were washed with methol alcohol to remove the excess salts. The procedure for washing was to add approximately four liters of alcohol, mix with an electric mixer for three to five minutes and let settle for 24 hours, then drain off the supernatant solution. This washing with alcohol was repeated five times. Settlement was sufficient with the kaolinite and illite, but the bentonite remained in solution. In order to remove the alcohol wash solution, diatomaceous filters were submerged and connected to an air ejector. The filter used was two and one-half inches O.D. by eight inches long. It would remove about four liters of wash solution in about 20 to 24 hours.

The above procedure for preparing homionic soil was developed by Dr. Lester W. Reed, of the Soil Science Section, Agronomy Department, Oklahoma State University.

After the last alcohol wash, the materials were air dried to a moisture content of about two to three per cent, then recrushed to pass the 100 mesh sieve. Some difficulty was again experienced in getting the material pulverized. This is attributed to the cementing effect of the adsorbed water from the air. It is believed that this problem could have been eliminated by oven drying the material at 60°C after the last alcohol wash. The material should then be screened immediately before moisture adsorption from the air takes place. The material was then weighed and mixed to form

the synthetic soils with 700 grams per sample. Tables IV-III and IV-IV show the proportions of the combinations used.

There were now twenty-four 700 gm. samples, six mineral combinations each treated to form a homionic soil with each of the four cations used (sodium, potassium, calcium, and magnesium).

Isotropic Compaction and Consolidation

With the hope of simulating compaction as it would occur in nature, the triaxial cell was modified to isotropically consolidate the sample. The upper drainage cap and plunger were removed from the cell leaving the bottom drainage pedestal. Latex membranes were fabricated, two and one-half inches in diameter by five inches long and funneled down to one and one-eighth inch diameter neck, one and one-fourth inch long which would fit the bottom drainage pedestal. The membranes were made by using a glass mandrel prepared by the glass shop to the above dimensions. The mandrels were dipped into a synthetic rubber solution (Vultex I-V-10-General Latex and Chemical Corp., Ashland, Ohio). The mix used was seven parts latex and one part water. Ten coats or applications were used to give the desired thickness and strength. With each successive dip, the mandrel was alternately reversed from upright position to the upside down position in order to obtain as uniform a coating as possible. A minimum drying time of four hours was required between successive dippings.

TABLE IV-III
BENTONITE KAOLINITE MIX

| Soil Mix | Clay Fraction | | Fine Sand gms | Total gms |
|-----------|------------------|------------------|------------------|--------------|
| | Bentonite gms | Kaolinite gms | | |
| 1 | 24.5 | 465.5 | 210.0 | 700 |
| 2 | 49.0 | 441.0 | 210.0 | 700 |
| 3 | 73.5 | 416.5 | 210.0 | 700 |
| Sub Total | 147.0 | 1323.0 | 630.0 | 2,100 |

TABLE IV-IV
BENTONITE ILLITE MIX

| Soil Mix | Clay Fraction | | Fine Sand gms | Total gms |
|-----------|------------------|---------------|------------------|--------------|
| | Bentonite gms | Illite gms | | |
| 4 | 24.5 | 465.5 | 210.0 | 700 |
| 5 | 49.0 | 441.0 | 210.0 | 700 |
| 6 | 73.5 | 416.5 | 210.0 | 700 |
| Sub Total | 147.0 | 1323.0 | 630.0 | 2,100 |

After the samples (700 gm.) had been weighed to the proper proportion, they were thoroughly mixed, and distilled water added to about five per cent above the liquid limit. After setting for approximately 48 hours, the samples were remixed and water added to bring water back to approximately the above moisture content. The membranes were placed into a loading template which consisted of a glass cylinder two and one-half inches in diameter by five inches long. The membranes were then filled with the use of a modified plunger type grease gun from which the cone end had been sawed off. The plunger chamber was filled with the plastic soil with a spatula, then extruded to fill the membrane. This procedure seemed to be very satisfactory as there were no air pockets found in the samples when they were trimmed after consolidation. The neck and cone end of the membrane were now peeled from the glass sleeve into the upright position, then the cone section was filled with Ottawa sand to act as a filter and to insure drainage. Next, the base of the triaxial cell with a porous stone in the drainage pedestal was inverted and lowered in place and the pedestal inserted into the membrane and sealed by wrapping and tying with an elastic band. The specimen and base were then turned right side up, then the chamber and top mounted and filled with distilled water. To the sample drainage connection was attached a 50 cc. burette used to measure the volume reduction of the sample. A battery of six cells was used simultaneously for a complete

cycle for each cation group. Thus, four cycles were required for each of the 24 samples. The six cells were then connected to an air supply at a pressure of 4.5 kilograms per square centimeter. Time-burette readings were recorded so that a typical time consolidation curve could be plotted. The test was continued until the curve indicated that 100 per cent primary consolidation had been achieved.

Unconfined Shear Test

When the change of volume versus the logarithm of time curve indicated secondary consolidation had been reached, the set-up was dismantled and the consolidated specimen was trimmed to 1.4 inches in diameter by 2.8 inches long. The shear strength was determined by the unconfined shear test using a strain rate of one per cent per minute.

After failure, the specimen was removed and the angle of rupture was measured with a protractor. A moisture sample was taken from the center of each specimen for moisture content determination. The remainder of the specimen and the trimmings were used for specific gravity determinations, hydrometer analyses, and Atterberg limits tests.

CHAPTER V

PRESENTATION AND DISCUSSION OF TEST RESULTS

General

In this chapter, the results of the tests are presented and tentative explanations are offered for the actions based on physical chemical concepts. Although shear strength was considered to be the primary parameter, other factors were studied, such as specific gravity, hydrometer analysis, Atterberg limits, and the activity number. Each of these will be considered in following sections.

Specific Gravity of Soil Solids

Table V-I lists the results of specific gravity tests determined by the standard pycnometer procedure. The variation in the results seems to be significant when one considers the source of this variation. It is generally conceded that the specific gravity is indicative of the predominate mineral present. Two other apparent factors influencing these values are the presence of salts in the pore water and the adsorbed cation complex.

In natural soils, the salt content of the pore water is as variable as the number of locations available; therefore,

it is interesting to consider the basic formula for calculating the specific gravity of soil solids (Taylor, 1949).

$$G_s = \frac{W_s G_t}{W_s + W_{b+w} - W_{b+w+s}}$$

where

W_s = weight of soil particles as measured,

W_{b+w} = weight of pycnometer plus water

W_{b+w+s} = weight of pycnometer plus water plus
soil as measured

G_t = specific gravity of water at the temperature
of the test.

For any given soil or soil modification, soluble salts in the pore water will increase the weight of dry soil by the weight of the salts. Let the dry weight of soluble salts be dW . For small amounts of soluble salts, there is practically no weight loss when they are dissolved in water. To clarify this statement further, if one gram of soluble salt (e.g., NaCl) is added to 500 grams of water, the total weight will be their sum; that is, 501 grams. To obtain the specific gravity, the formula would appear as follows:

$$G_{sm} = \frac{(W_s + dW)_m \cdot G_t}{(W_s + dW)_m + W_b + w - (W_{b+w+s} + dW)_m}$$

$$= \frac{(W_s + dW)_m \cdot G_t}{W_s + W_{b+w} + W_{b+w+s}}$$

in which the subscript "m" refers to a measured quantity. It is apparent that the presence of soluble salts in the pore water increases the observed value of the specific gravity of the soil solids. In this investigation, the salt content of the pore water was purposely kept negligible.

TABLE V-I
SPECIFIC GRAVITY FOR SOIL MODIFICATIONS

| Group | Soil Mix | Specific Gravity | | | |
|-------|--------------------------------|------------------|------|------|------|
| | | Na | K | Mg | Ca |
| 1 | 5% Bentonite 95% Kaolinite | 2.65 | 2.63 | -- | 2.67 |
| 2 | 10% Bentonite 90% Kaolinite | 2.65 | 2.63 | 2.65 | 2.69 |
| 3 | 15% Bentonite 85% Kaolinite | 2.65 | 2.65 | 2.63 | 2.65 |
| 4 | 5% Bentonite 95% Illite | 2.82 | 2.76 | 2.77 | 2.78 |
| 5 | 10% Bentonite 90% Illite | 2.82 | 2.73 | 2.77 | 2.77 |
| 6 | 15% Bentonite 85% Illite | 2.82 | 2.74 | 2.73 | 2.77 |

The other major factor that may influence the specific gravity of the soil particles is the weight of the adsorbed cations. Thomson (1963) found that by multiplying the cation exchange capacity of the soil by the weight of one milli-equivalent of the adsorbed cation, the total weight of the

amount of a given cation adsorbed may be determined. The results of such calculations indicate that 100 grams of the soil used in Thomson's study with the Alberta clay would adsorb 1.23 grams of potassium or 0.63 grams of calcium or 0.72 grams of sodium or 0.38 grams of magnesium. It is of interest to note that the results of this study gives the following specific gravities for soil modifications, Na - 2.79, K - 2.71, Mg - 2.68, and Ca - 2.73. This is in close agreement with the results for the synthetic illite soil group from Table V-I which give Na - 2.82, K - 2.72, Mg - 2.77, and Ca - 2.77.

There is an interplay of all factors discussed to such an extent that it is difficult to evaluate the effects of each factor separately. Further, there is insufficient data to assess which of the factors is predominate for a given set of conditions. The hydration of the soil particles and the adsorbed cations as well as the amount of the cations adsorbed are factors that depend, to a large extent, on the surface activity of the soil. Therefore, it is the clay soils, particularly those with high montmorillonite, that would reveal the largest variations in observed specific gravity. Further research in this area should prove to be most valuable.

Changes of the adsorbed cations or concentration of salts in the pore water will lead to variations in the value of specific gravity and, indirectly, calculations of the

void ratio and degree of saturation. Thus, if water is percolating through the soil along preferred paths, for example tension cracks or thin silt seams, the specific gravity is changing due to salt removal; hence, calculated void ratios are apt to be in error unless determined on soil samples having a salt content corresponding to that in-situ. In reality, this is another way of saying that the void ratio is changing due to a change in the adsorbed water film. The point is that the specific gravity is used to calculate the value of the void ratio. Another interesting factor pointed out by Grim (1962) is that the exchange of one cation for another may have no effect on the adsorbed layer up to a certain ratio of adsorbed cations at which point there is an abrupt change in the thickness of the adsorbed layer.

Hydrometer Analysis

In the early days of soil mechanics, it was generally thought that the size of individual particles of a soil would prove to be its most important characteristic. Results of ensuing years of research and experience have failed to substantiate this belief. The hydrometer method of analysis is based upon the assumption that Stokes' Law,

$$D = \sqrt{\frac{1800 \eta v}{\gamma_s - \gamma_f}},$$

is valid for the particular case of settlement of soil grains

in a suspension. For soils which are nearly all finer than a 200 mesh, the hydrometer test is recommended. Sometimes reliable indications of the type of clay mineral may be obtained from the grain size distribution curve (Lambe, 1960). For particles finer than approximately 0.0002 mm., the use of the hydrometer test is in question. A centrifuge or supercentrifuge can be used in conjunction with Stokes' equation for size analyses of grains smaller than 0.002 mm. Water film thicknesses varying from 13 Å to over 1000 Å have been reported (East, 1942). The thickness of water films on soil particles have not yet been measured directly; the thicknesses to date have been obtained by procedures using various assumptions. The thicknesses appear to depend on the type of mineral, exchangeable ions, and the pressure acting on the films.

The results of hydrometer analyses of this study are presented in Figures 5-1 through 5-6. These data seem to substantiate the above findings. It is pointed out that no appreciable differences appear until the residue in suspension begins to approach the colloidal size range. Therefore, when it is desired to study grain size effects in relation to ion exchange effects, one of the more elaborate methods should be used. The results obtained in this data seem to give valuable results from which the per cent finer than two microns was useful in the determination of activity numbers. This will be considered in a later section.

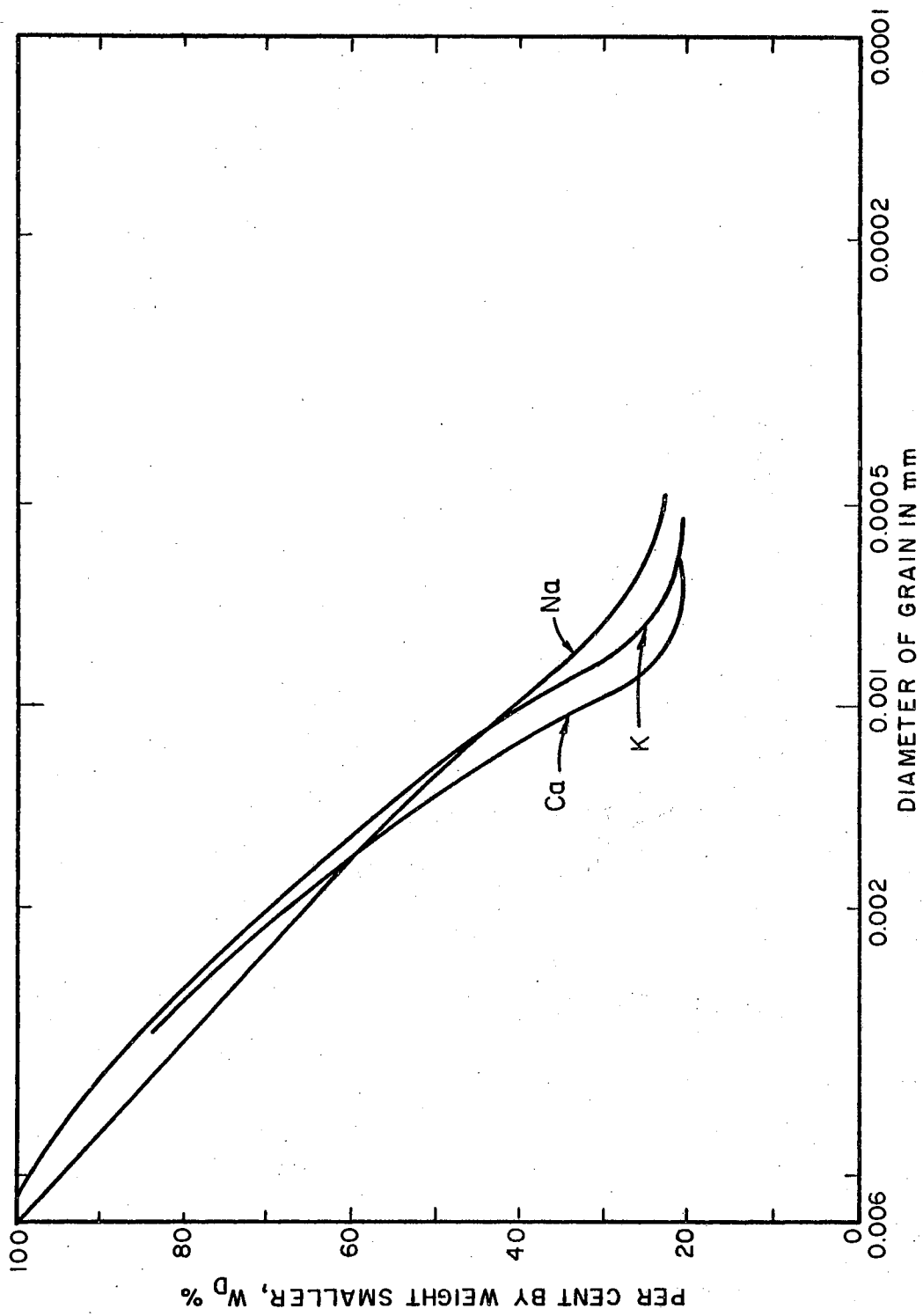


Figure 5-1. Grain Size Distribution for 5% Bentonite and 95% Kaolinite.

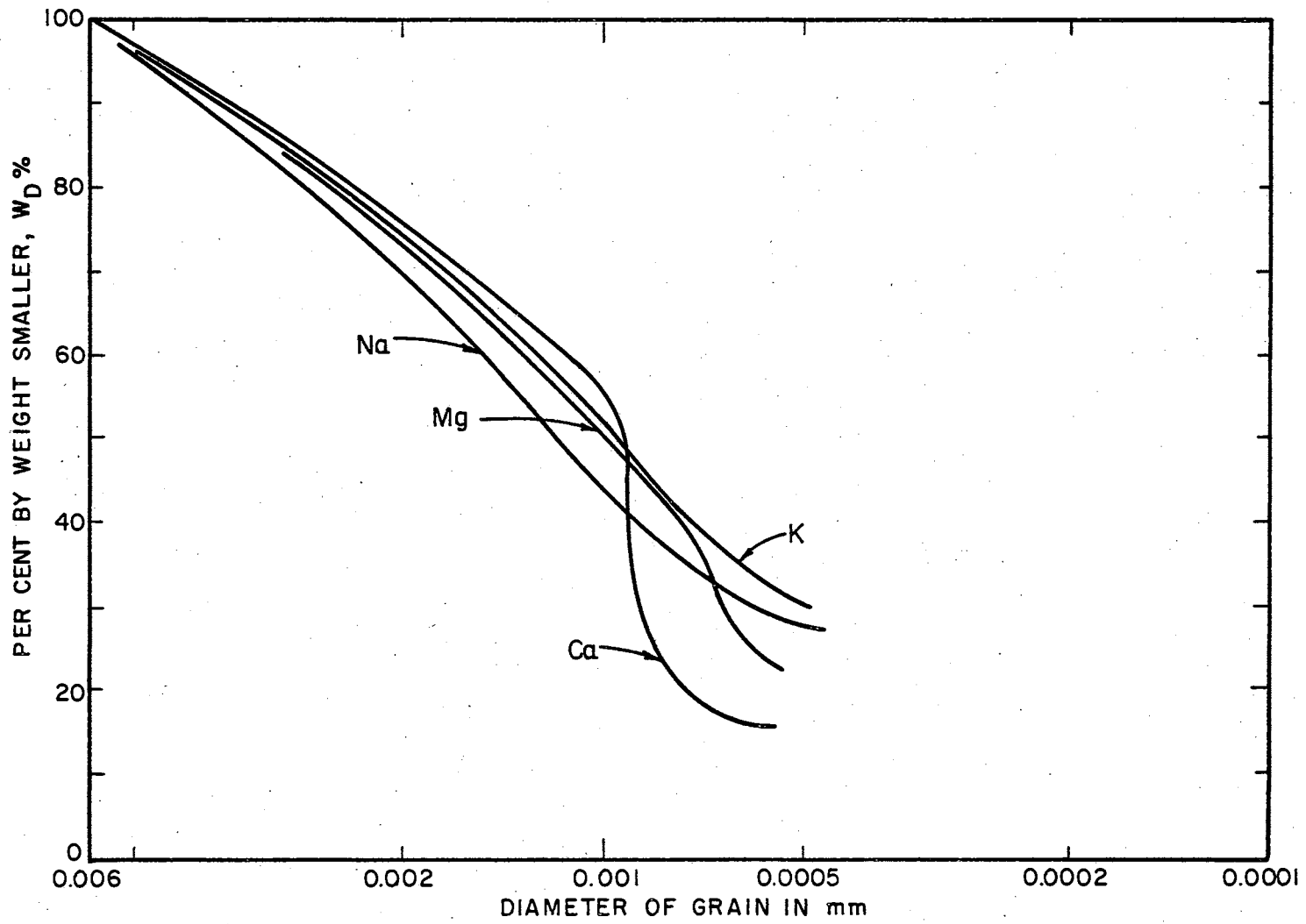


Figure 5-2. Grain Size Distribution for 10% Bentonite and 90% Kaolinite.

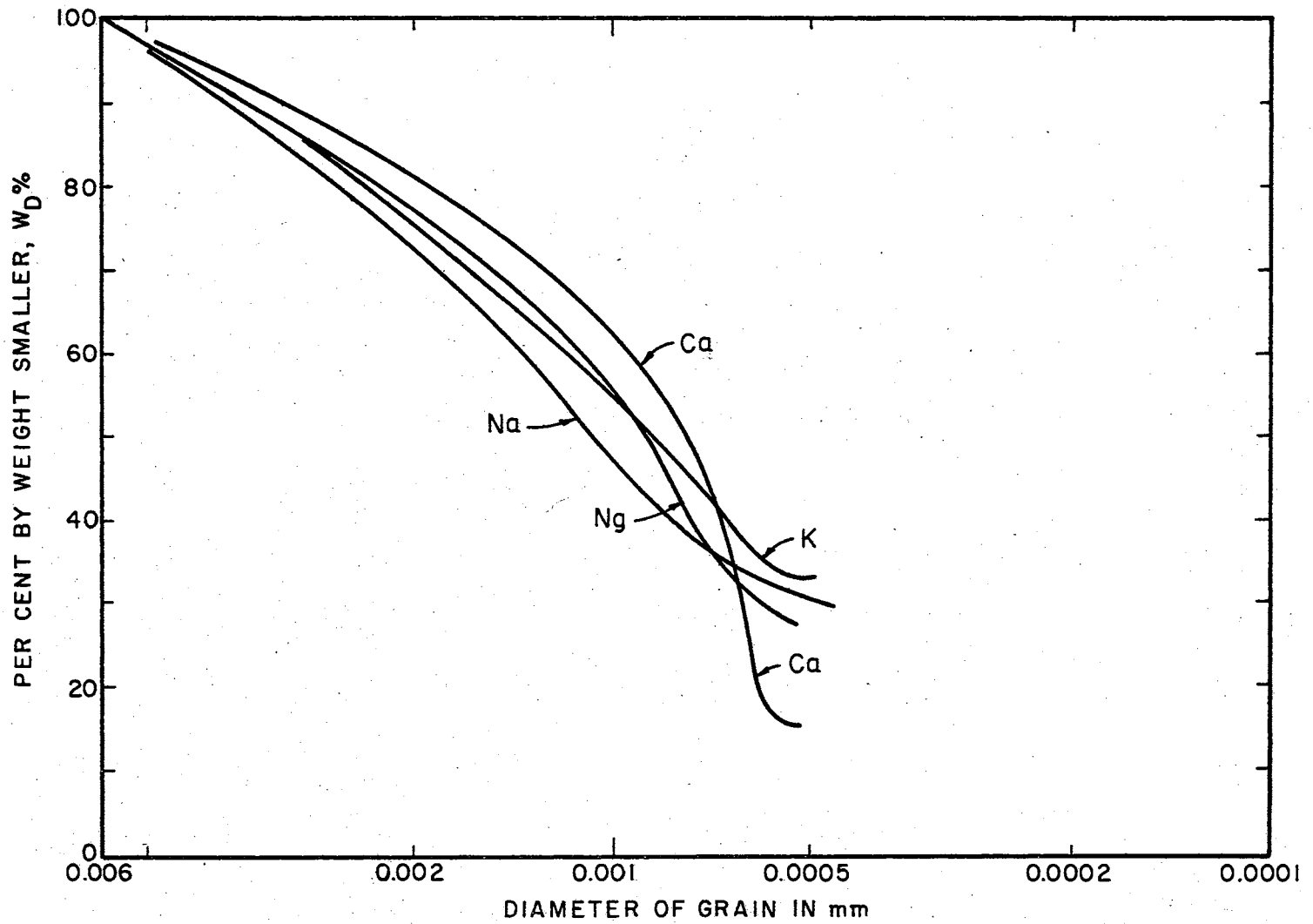


Figure 5-3. Grain Size Distribution for 15% Bentonite and 85% Kaolinite.

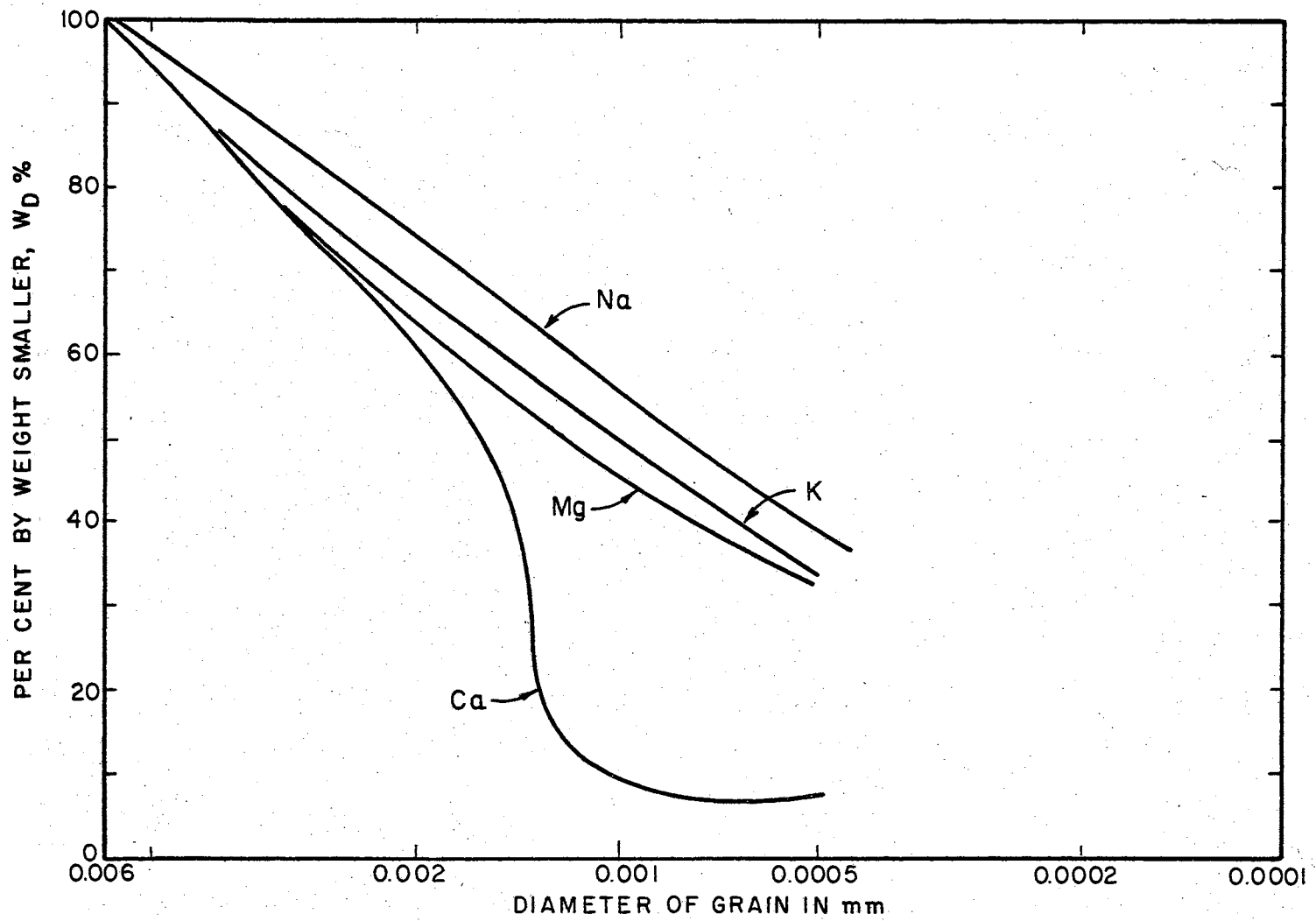


Figure 5-4. Grain Size Distribution for 5% Bentonite and 95% Illite.

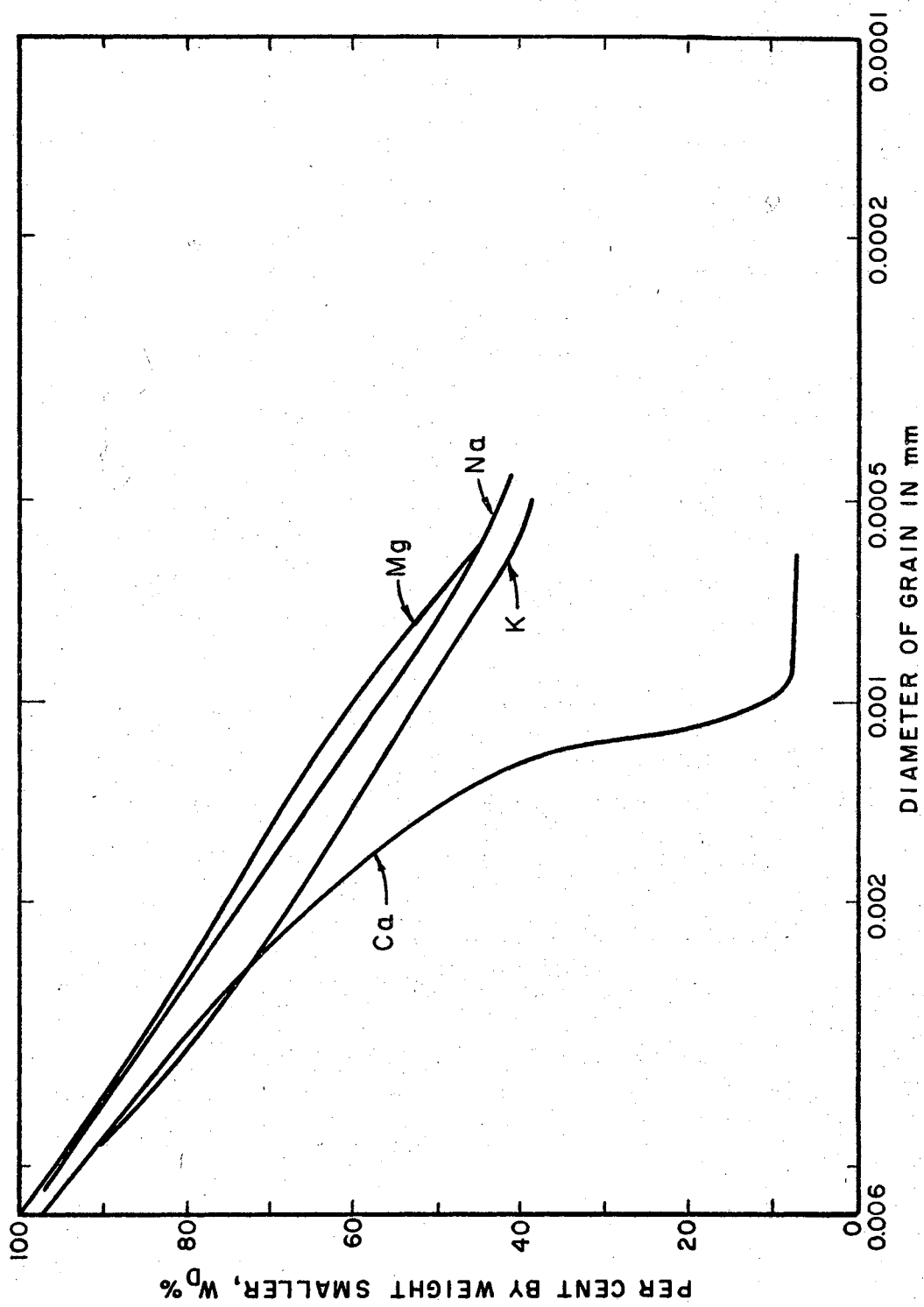


Figure 5-5. Grain Size Distribution for 10% Bentonite and 90% Illite.

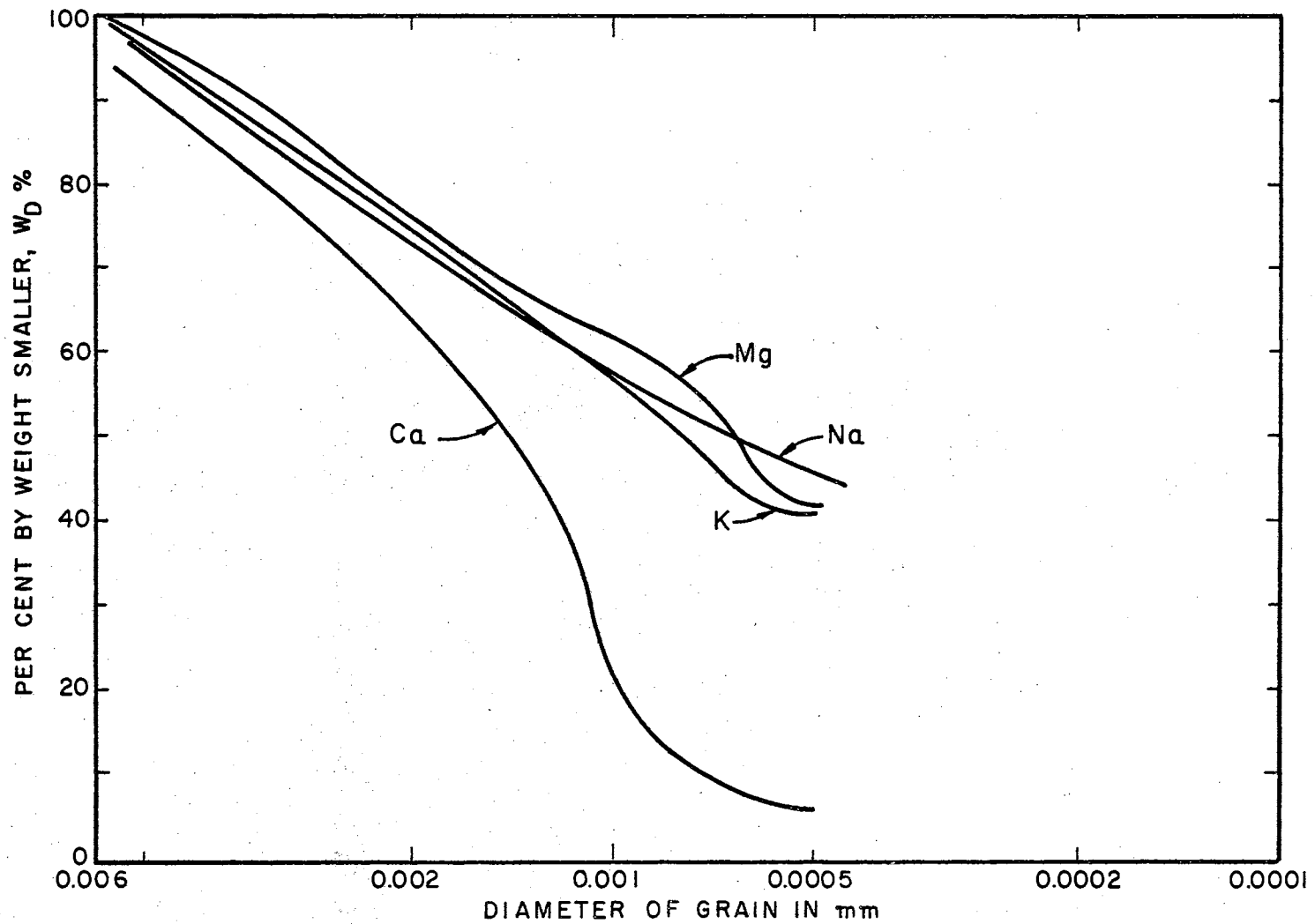


Figure 5-6. Grain Size Distribution for 15% Bentonite and 85% Illite.

The results of hydrometer data show considerable difference in the sodium and calcium homionic soils. This variance is attributed to the difference of the effects of the adsorbed ions.

The adsorbed ions promote disorder in the water hull (Low, 1961). If the ion is small and monovalent, e.g., Na^+ it may move through the adsorbed water hull without causing disorder. Due to this fact, the presence of Na^+ as the adsorbed ion allows the formation of very thick adsorbed water layers if the water is available. With Na^+ , the oriented water net is not excessively rigid, but is very thick and there is a gradual transition from oriented water to the free water (Grim, 1958). With a large or multivalent ion, e.g., Ca^{++} , there is a large disordering effect because the hydrated Ca^{++} is the adsorbed cation, the water layer is thin, and there is a sharp break between the oriented water and the pore water.

To prevent flocculation of the soil suspension during the hydrometer analysis, a chemical is added. In most clays (Thomson, 1963), the chemical is usually calgon [sodium hexametaphosphate, $\text{Na}_6(\text{PO}_4)_3$] which has the effect of increasing the zeta potential presumably due to adsorption of the sodium cation. The very act of adding any chemical adds a large number of ions to the suspension in addition to any present in the soil sample. Since the suspension can be made stable, it follows that the salts in the pore water of

the original sample have little influence on the hydrometer analysis. This statement must be taken as applicable to "normal" samples. There are soils with high salt contents whose suspensions cannot be stabilized unless intolerable amounts of calgon are added. Manipulations of the formulas used in the hydrometer analysis with various assumptions concerning variation of the film thickness and specific gravity for a given size of solid particle indicate that the influence of the adsorbed cation complex on the water hull of a clay particle does not have a very significant influence on the resulting grain size curve. Grim (1953) concludes that the reason for the increase in the per cent clay sizes is the greater tendency for particles to break down along cleavage planes during dispersion when sodium occupies a high per cent of the exchange positions.

What constitutes an intolerable amount of calgon to be added still seems to be somewhat indeterminate. The easiest way (Lambe, 1951) to select the best amount of deflocculant to use for a given soil is by trial. The change in hydrometer reading required to prevent flocculation (Means and Parcher, 1963) is usually in the range from 0.0002 to 0.0005 in the hydrometer reading. It is of special interest to point out here that with the homionic soils used in this study, the amount of calgon required as determined by trial gave an initial change in the hydrometer reading of 0.0035 for the kaolinite group and of 0.0010 for the illite group.

In view of the previous discussion in regard to the problems of an intolerable amount of calgon, it appears that more study and research is essential on this subject.

Atterberg Limits

Plasticity is a major characteristic of the cohesive soils. It is the property that enables a material to undergo rapid deformation without noticeable elastic recovery, and without cracking or crumpling, and without volume change. Many methods, mainly arbitrary, exist for determining the plasticity of soils. The tests due to Atterberg (1911) originally developed for agricultural work, have been widely used in soil mechanics since their potential value was first indicated by Terzaghi (1943). Although the limit values are based on simple empirical tests, they have been found to be very useful as index properties which may be correlated with more fundamental properties, such as shear strength and compressibility. Also, as will be shown in the succeeding paragraphs, they reveal fundamental attributes of clay minerals saturated with various cations.

Values for the plastic limit, liquid limits, and plastic index for homionic soils used in this study are given in Table V-II.

Figures 5-7 through 5-10 show moisture contents of the limit values plotted versus per cent bentonite. It is significant to note that the plastic limits show very little

TABLE V-II

ATTERBERG LIMITS AND ACTIVITY NUMBER FOR SOIL MODIFICATIONS

| Soil Group | Mix | Liquid Limit | | | | Plastic Limit | | | | Plastic Index | | | | Activity Number | | | |
|------------|--------------------------------|--------------|------|------|------|---------------|------|------|------|---------------|------|------|------|-----------------|------|-----|------|
| | | Na | K | Mg | Ca | Na | K | Mg | Ca | Na | K | Mg | Ca | Na | K | Mg | Ca |
| 1 | 5% Bentonite 95% Kaolinite | 37.1 | 42.2 | -- | 35.9 | 21.6 | 24.9 | -- | 18.9 | 15.5 | 17.3 | -- | 17.0 | 0.38 | 0.38 | -- | 0.40 |
| 2 | 10% Bentonite 90% Kaolinite | 42.9 | 47.8 | 45.4 | 40.2 | 21.4 | 28.2 | 21.1 | 20.1 | 21.5 | 19.6 | 24.3 | 20.1 | .50 | .42 | .50 | .41 |
| 3 | 15% Bentonite 85% Kaolinite | 54.3 | 56.4 | 51.9 | 45.6 | 21.9 | 27.1 | 20.7 | 20.5 | 32.4 | 29.3 | 31.2 | 25.1 | .73 | .60 | .64 | .49 |
| 4 | 5% Bentonite 95% Illite | 32.2 | 35.5 | 37.1 | 36.8 | 18.1 | 22.4 | 20.7 | 20.7 | 14.1 | 13.1 | 16.7 | 16.1 | .46 | .41 | .54 | .57 |
| 5 | 10% Bentonite 90% Illite | 46.0 | 41.2 | 44.0 | 41.5 | 16.7 | 24.5 | 21.9 | 22.4 | 29.3 | 16.7 | 22.1 | 19.1 | .93 | .53 | .70 | .61 |
| 6 | 15% Bentonite 85% Illite | 71.8 | 46.5 | 51.4 | 43.5 | 17.9 | 24.4 | 20.1 | 21.4 | 53.9 | 22.1 | 31.3 | 22.1 | 1.70 | .69 | .93 | .87 |

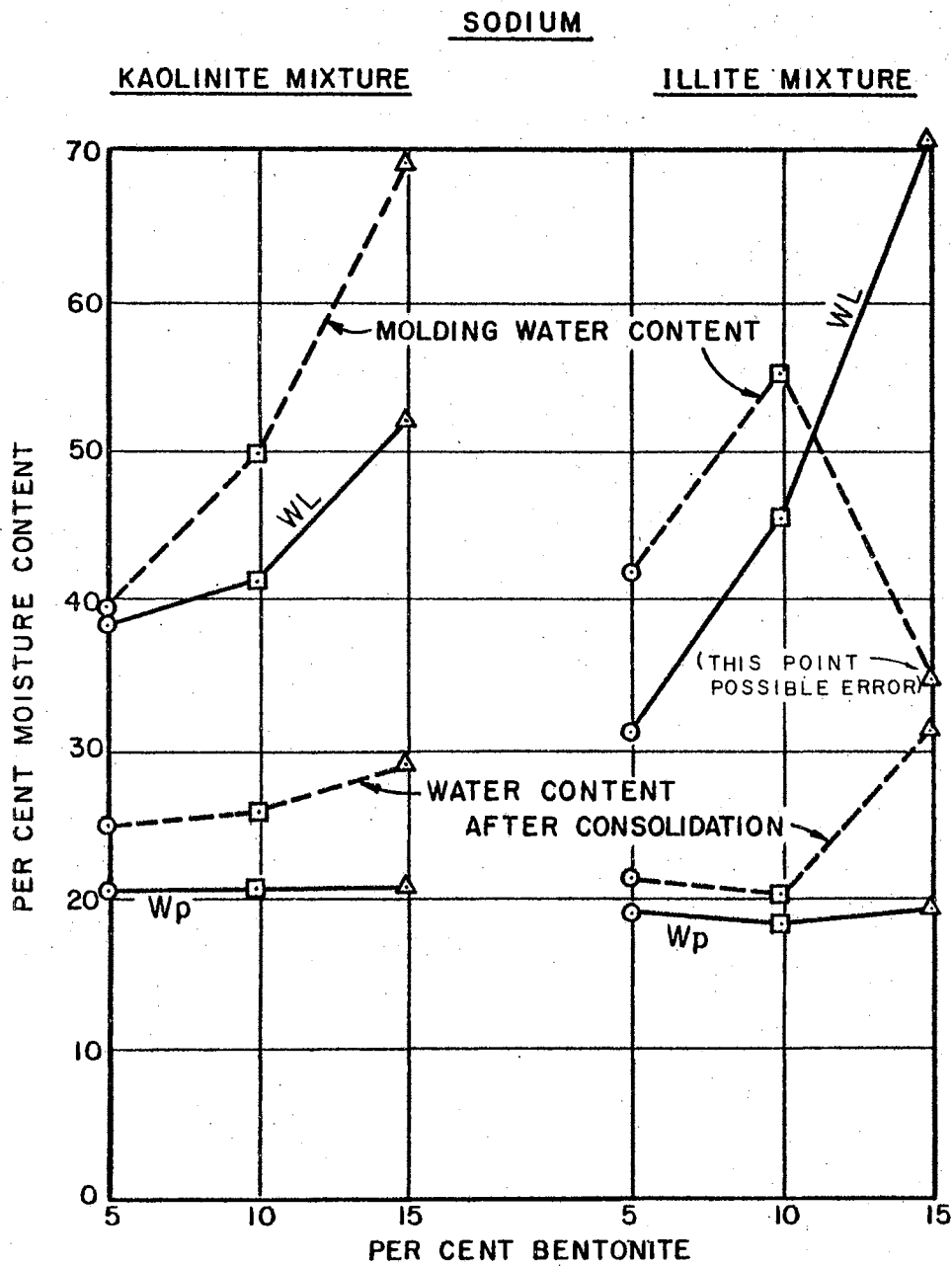


Figure 5-7. Moisture Content Versus Per Cent Bentonite with Sodium.

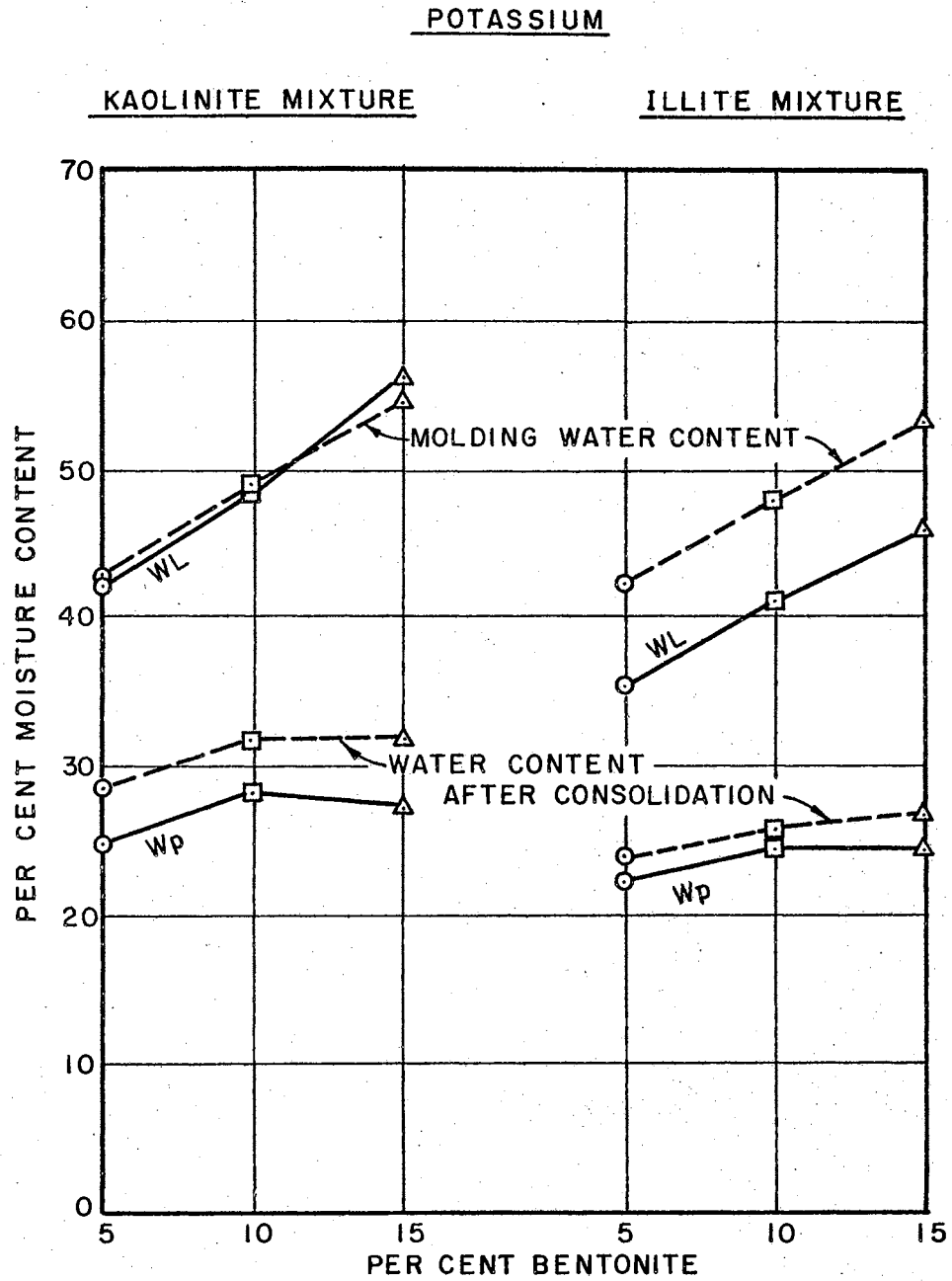


Figure 5-8. Moisture Content Versus Per Cent Bentonite With Potassium.

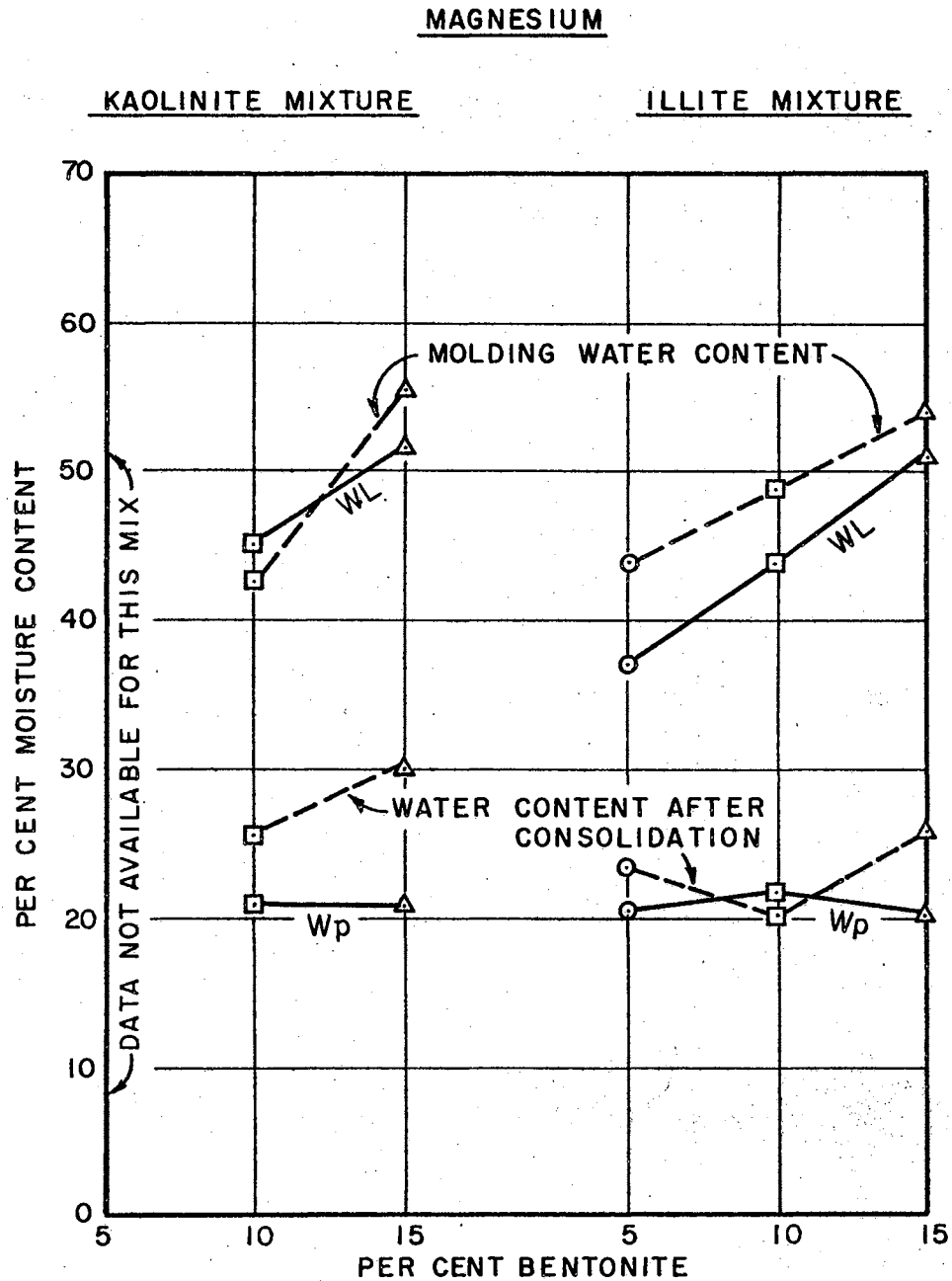


Figure 5-9. Per Cent Bentonite Moisture Content Versus Per Cent Bentonite With Magnesium.

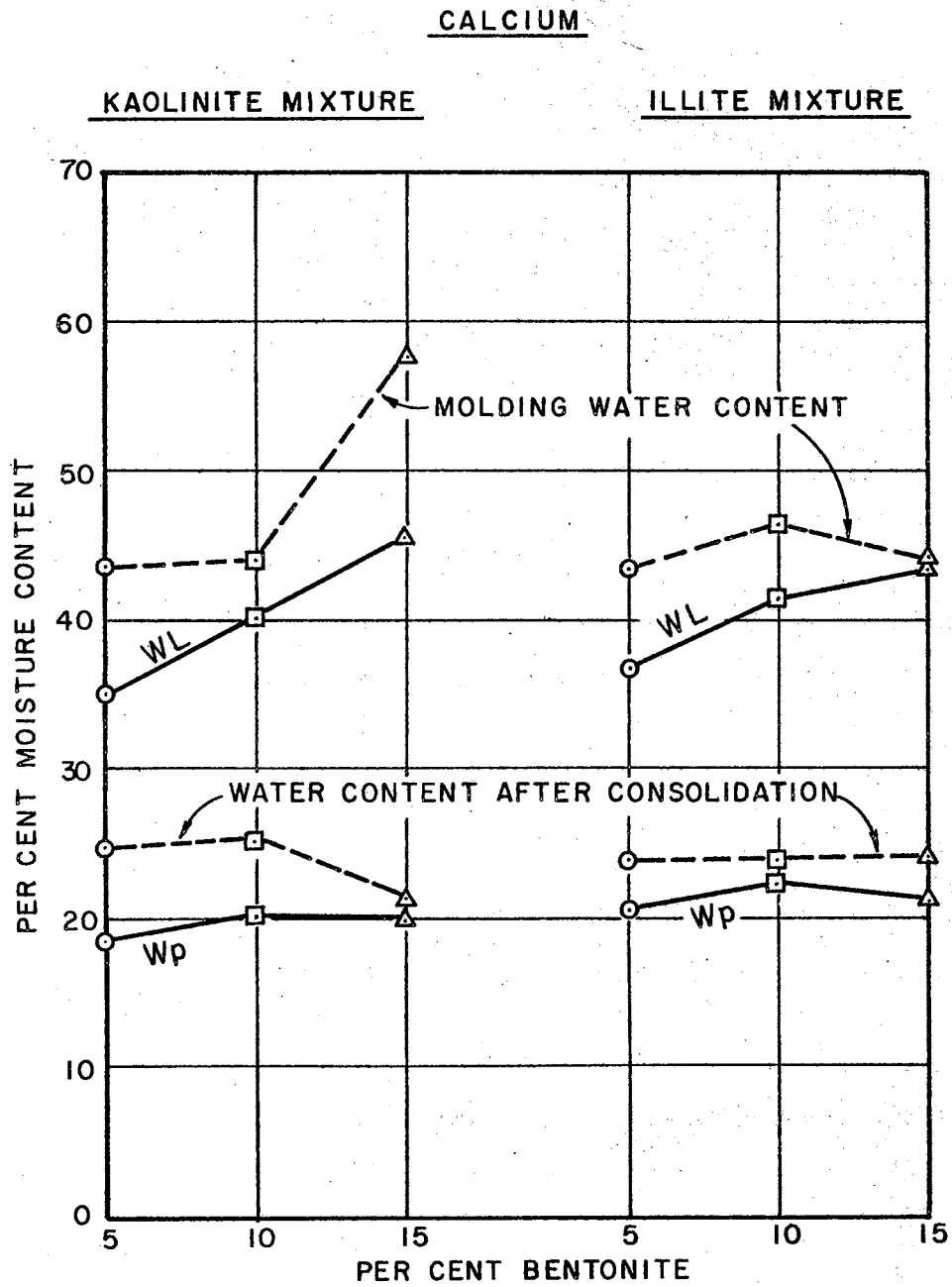


Figure 5-10. Moisture Content Versus Per Cent Bentonite With Calcium.

variation; also, the moisture after 100% primary consolidation, which was the moisture content at which the shear test was performed, shows very little variation. However, the liquid limits show a very pronounced variation. As the percent bentonite is varied from five to fifteen per cent, the liquid limit has the following ratios of variation:

For the kaolinite group

Na - 1.47, K - 1.34, Mg - 1.34, Ca - 1.24

For the illite group

Na - 2.23, K - 1.31, Mg - 1.38, Ca - 1.18.

As noted from the figures, the variation is very near a straight line. Thomson (1960) found that the plastic and liquid limits for non-homionic soils varied appreciably for periods of up to thirty-three days after mixing. The soil solution used in Thomson's work, however, contained extraneous cations as his method of preparation did not include removal of cations from the pore solution. It was concluded by Thomson that cations were being continually exchanged between the soil and the soil solution until chemical equilibrium was finally achieved. Up to this equilibrium time, variations in Atterberg limits were observed.

For the present investigation, homionic soils were used and distilled water was employed as pore fluid. Thus, it was concluded that no time effects were likely to occur as a result of the exchange of cations between the soil and the pore solution. However, it is possible that a long term

change could occur after the addition of water to the sample. This possible change in the limits with time could be caused by the slow growth of water hulls around the adsorbed cations. This slow completion of cation hydration is to be expected in a highly impervious clay soil. In a surface area research study currently being conducted by Mr. E. W. LeFevre, of Oklahoma State University, liquid limits for the same homionic soils will again be evaluated, it will be interesting to follow his results and to see what magnitude time, drying and wetting, and possible additional hydration will have on these properties.

The results of the Atterberg limit tests for the homionic synthetic clay were plotted for comparison purposes on the Casagrande charts of Figures 5-11 and 5-12. In general, the results fall slightly above the A-Line and in the CL classification, except for most of the fifteen per cent bentonite mixes which fall in the CH classification. For both the kaolinite and the illite groups, the potassium soils plotted closer to the A-Line than the others, thus indicating that the potassium treated group should exhibit less toughness and dry strength and greater permeability. It has been found by Coates (1954), that homionic modification for Leda clay plotted as a straight line, parallel to the A-Line on the plasticity chart. Hamilton (1961) found that homionic modifications for the Alberta clay plotted as a straight line, but deviated slightly upward from the A-Line as the

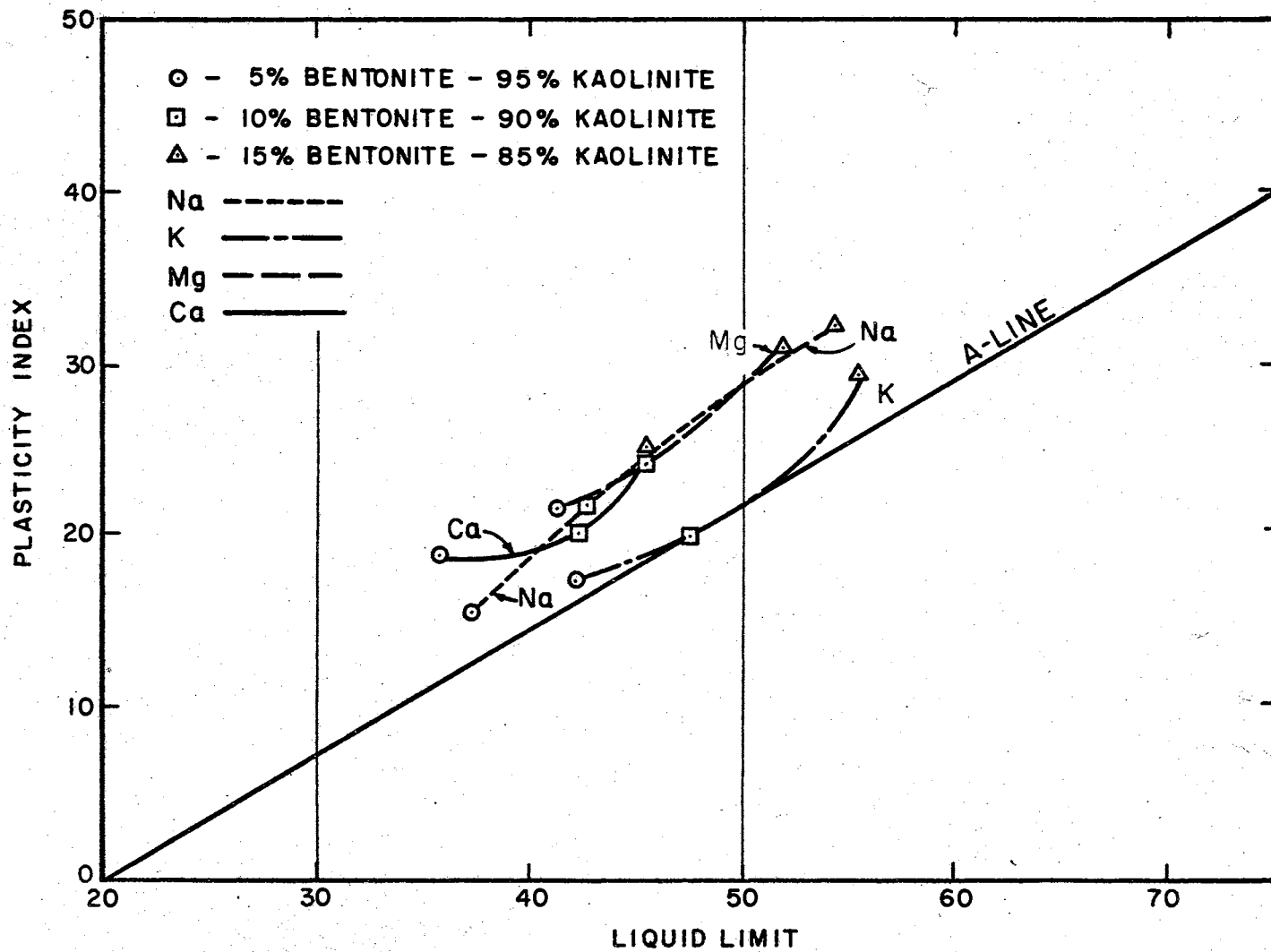


Figure 5-II. Plasticity Chart for Kaolinite Group.

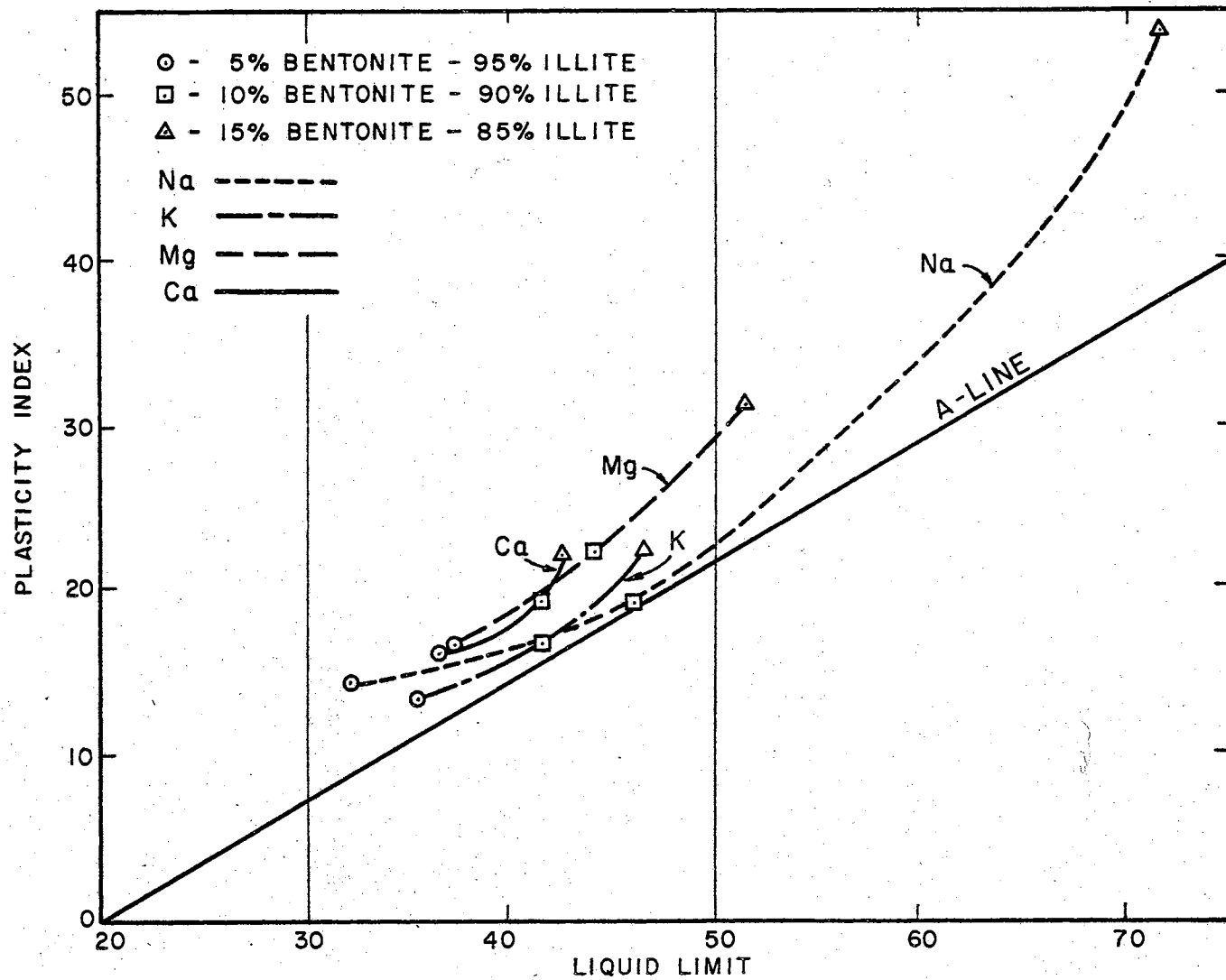


Figure 5-12. Plasticity Chart for Illite Group.

results move to the right. This present investigation indicates slight curvature from the A-Line as one moves to the right on the plasticity chart which seems to agree reasonably well with the test results of Coates and Hamilton if one could justify combining their results into a combined pseudo curve.

Activity

Skempton (1953) found that in any particular clay stratum, the ratio of the plasticity index to the clay fraction content is approximately constant and may be defined as the "activity" of the clay, and this direct linear relationship to be expressed by the ratio:

$$\text{Activity} = \frac{\text{plasticity index}}{\text{clay fraction}} .$$

Here, the clay fraction is defined as the percentage by weight of particles finer than two microns. From his investigation, the following classifications were established in terms of the ratio PI/clay fraction:

inactive clays - activity < 0.75

normal clays - activity 0.75 to 1.25

active clays - activity > 1.25.

Skempton cites Samuels (1950), who found that base exchange has only a minor influence on kaolinite. Samuels further states that at that time no base exchanges were

known to have been made on illite, but predicted that since the mineral illite shows moderate activity, the effect would probably be appreciable.

In this investigation (Figure 5-13), which compared the activity for both kaolinite and illite, it is clear that the prediction made by Samuels was apparently correct and logical. Figure 5-14 is included to illustrate the effects of different cations upon activity ratio.

In the paper by Skempton, he states:

The properties of a clay are determined fundamentally by the physio-chemical characteristics of the various constituent minerals and by the relative proportions in which the minerals are present. The determination of these characteristics is a lengthy and difficult process requiring the use of an X-ray spectrometer, thermal analysis, etc., and it is evident that such techniques can never become part of the normal laboratory procedure in soil mechanics. Some simple tests are therefore required that give a quantitative measure of the composite effects of all the basic properties of a clay and, as is well known, the Atterberg limits fulfill this function in large measure. But they are not wholly sufficient, and in the present paper evidence is given which shows that valuable additional information is provided by an index property combining the Atterberg limits and the particle size distribution of a clay; yet requiring for its determination only the results of these routine tests.

In the original concept of this investigation, it was not planned to study the activity ratio, but from the results presented in Table V-II and Figures 5-13 and 5-15, it is concluded that the activity ratio is a very significant soil parameter and merits further study.

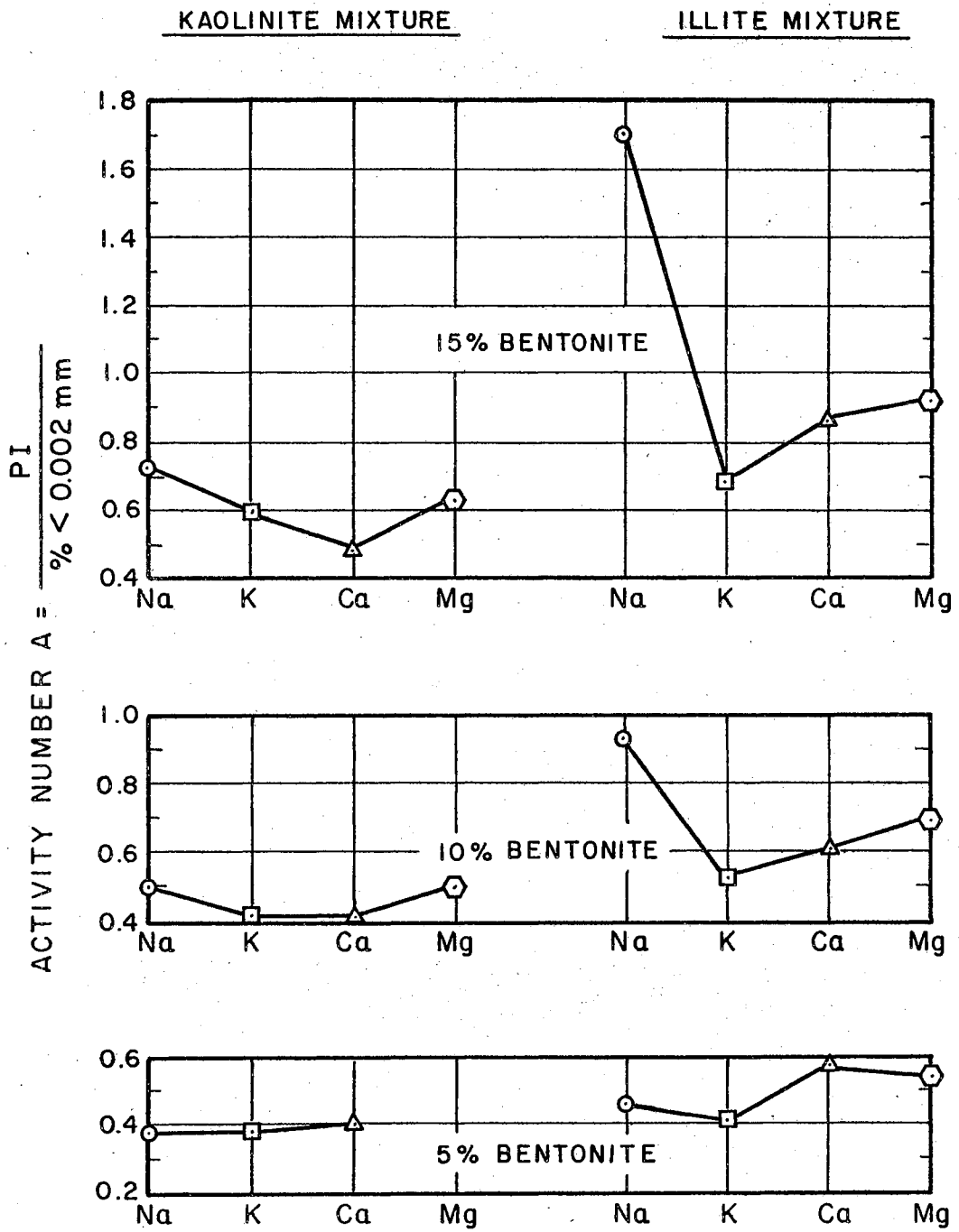


Figure 5-13. Activity Number Versus Saturation Cation.

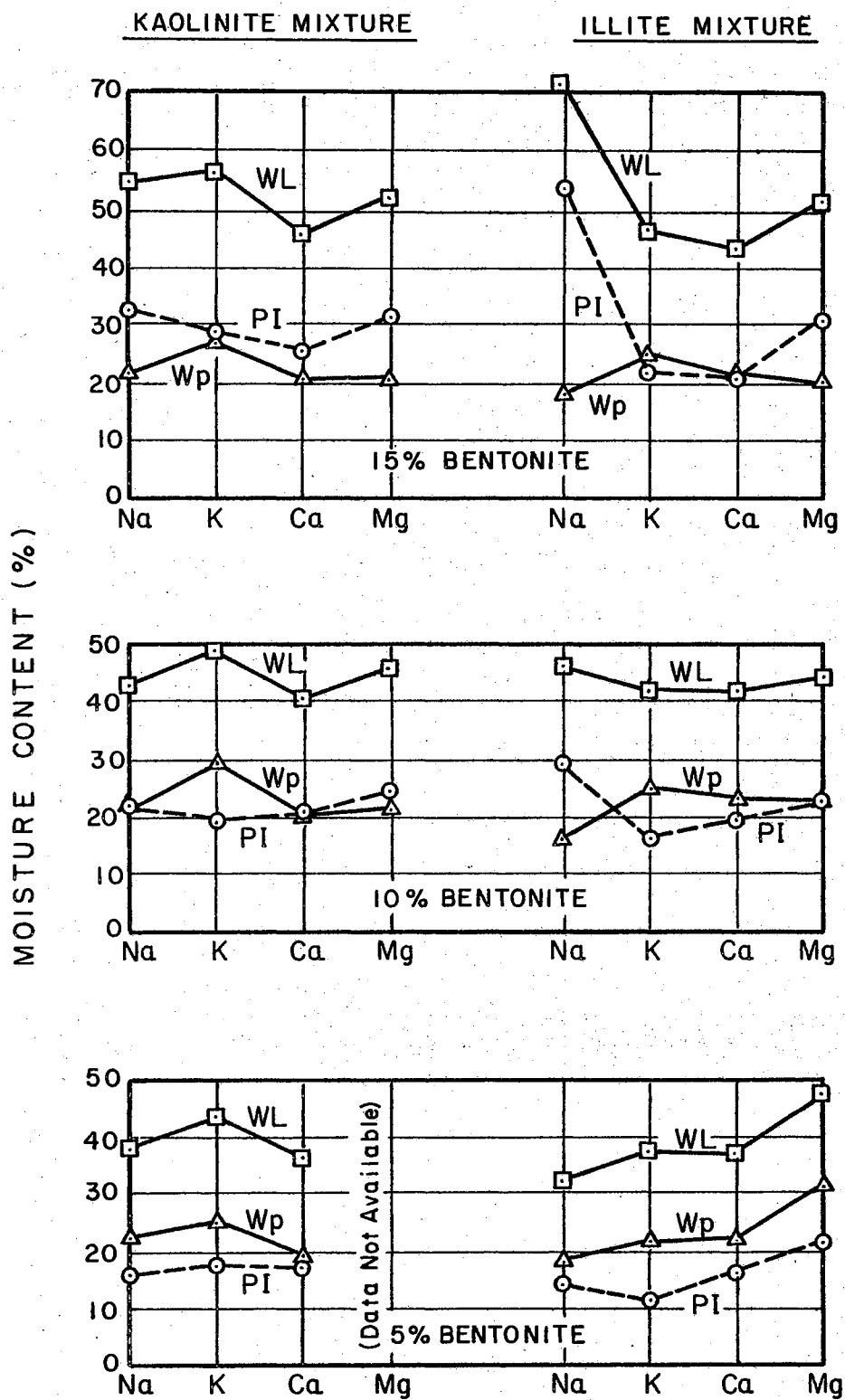


Figure 5-14. Moisture Content Versus Saturation Cation.

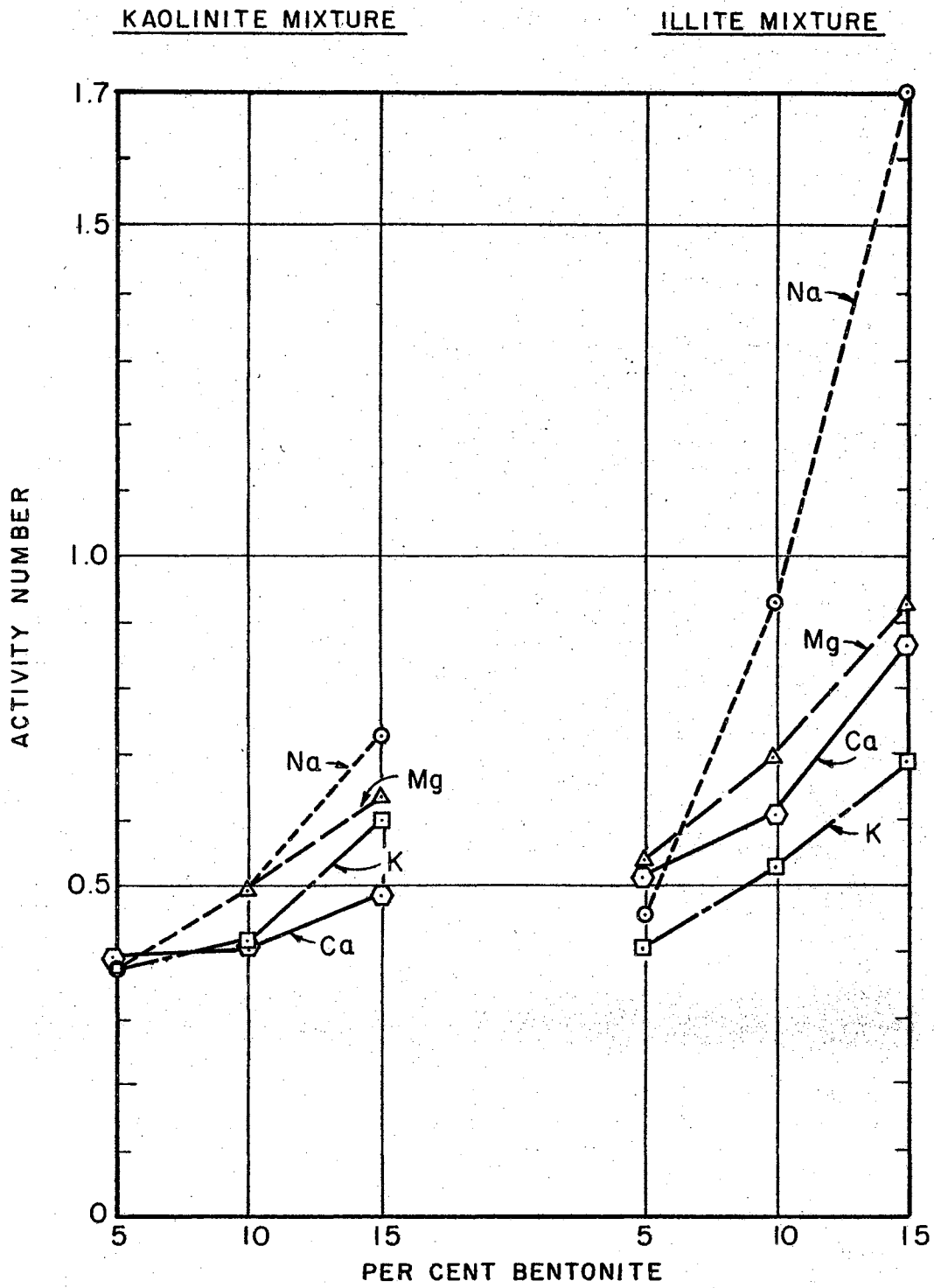


Figure 5-15. Activity Number Versus Per Cent Bentonite.

Time of Consolidation

The method of compaction or consolidation utilized a modified triaxial cell. The material was placed in a latex membrane; then a cell pressure of 4.5 kg. per cm.² was applied and held constant until a plot of burette reading versus the logarithm of time indicated 100 per cent consolidation. From Table V-III and Figures 5-16 through 5-22, it is apparent that the time-rate of consolidation is strongly influenced by both the cations adsorbed on the clay complexes and by the mineral composition:

1. Kaolinite group with 15% bentonite
Sodium > magnesium > calcium > potassium.
2. Illite group with 15% bentonite
Sodium > potassium > magnesium > calcium.

It is of interest to note that the results reported by Lambe (1955) and Thomson (1963) agree with the illite group above (Na > K > Mg > Ca). They were using natural soils for which it is difficult to correlate and compare all of the physical, chemical, and mineralogical quantities. It is significant to observe the ratio maximum and minimum variations of time for consolidation:

For sodium and 95% kaolinite 42,000 seconds.

For sodium and 85% illite 450,000 seconds.

A ratio of 11 to 1.

For calcium and 95% illite 21,600 seconds.

TABLE V-III
SOIL PARAMETERS OF SOIL MODIFICATIONS

| Group | Mix | Time of Consolidation Seconds x 10 ³ | | | | Coefficient of Permeability k x 10 ⁻⁷ | | | | Compression Index C _c = 0.009(W _L - 10) | | | |
|-------|--------------------------------|--|-------|-------|------|---|-----|-----|-----|--|------|------|------|
| | | Na | K | Mg | Ca | Na | K | Mg | Ca | Na | K | Mg | Ca |
| 1 | 5% Bentonite 95% Kaolinite | 42.0 | 11.4 | -- | 30.6 | 1.1 | 6.0 | - | 1.9 | 0.33 | 0.28 | -- | 0.23 |
| 2 | 10% Bentonite 90% Kaolinite | 84.0 | 14.2 | 30.0 | 27.0 | 0.8 | 4.1 | 2.1 | 2.2 | 0.39 | 0.34 | 0.32 | 0.27 |
| 3 | 15% Bentonite 85% Kaolinite | 126.0 | 15.0 | 54.0 | 43.0 | 0.6 | 2.2 | 1.5 | 1.1 | 0.49 | 0.42 | 0.38 | 0.33 |
| 4 | 5% Bentonite 95% Illite | 162.0 | 27.0 | 18.0 | 21.6 | 0.2 | 2.6 | 3.5 | 3.8 | 0.29 | 0.23 | 0.24 | 0.24 |
| 5 | 10% Bentonite 90% Illite | 390.0 | 105.0 | 69.0 | 42.0 | 0.1 | 0.6 | 1.2 | 1.5 | 0.41 | 0.28 | 0.30 | 0.28 |
| 6 | 15% Bentonite 85% Illite | 450.0 | 216.0 | 138.0 | 66.0 | 0.1 | 0.4 | 0.6 | 1.4 | 0.65 | 0.33 | 0.37 | 0.30 |

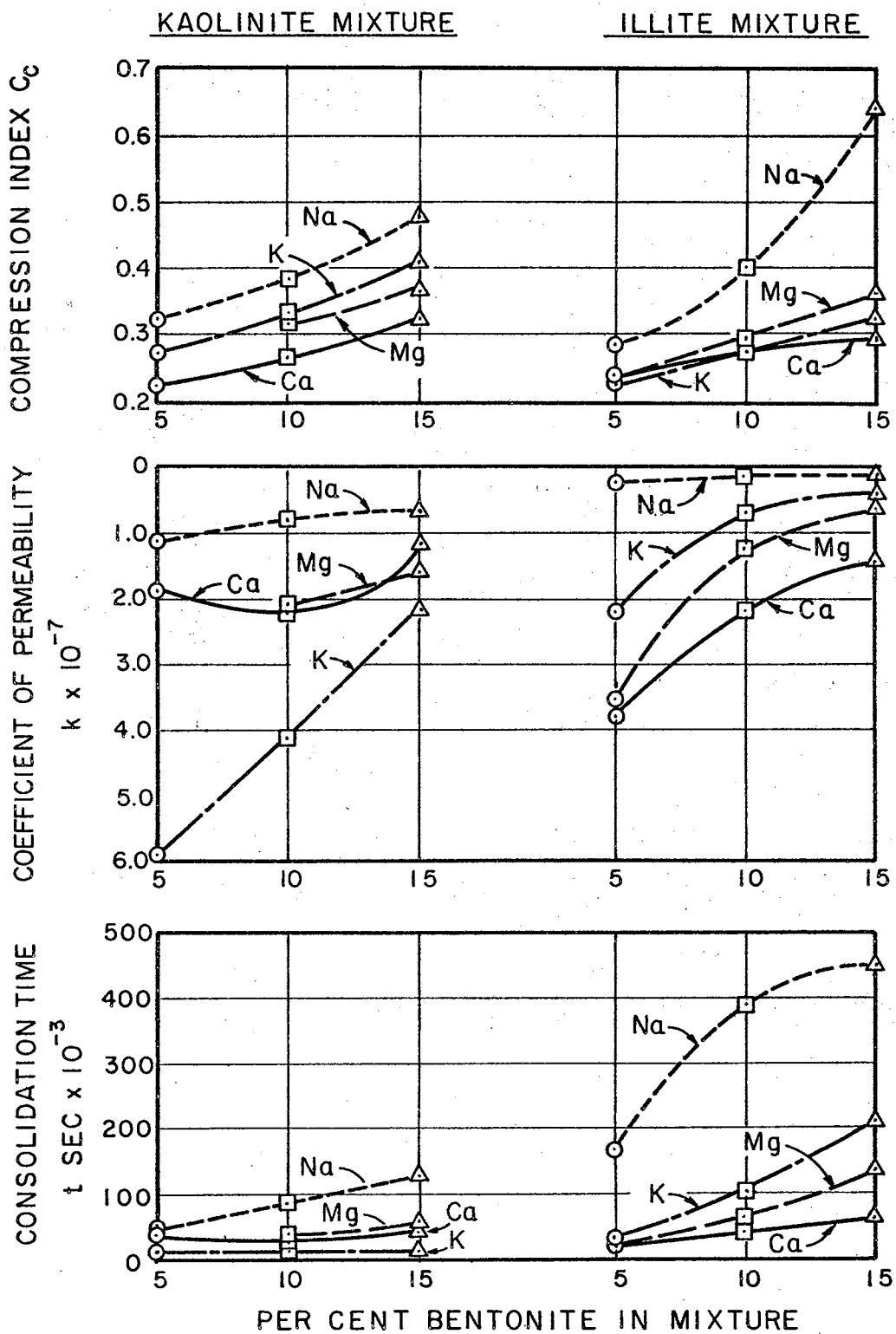


Figure 5-16. Soil Parameters Versus Per Cent Bentonite.

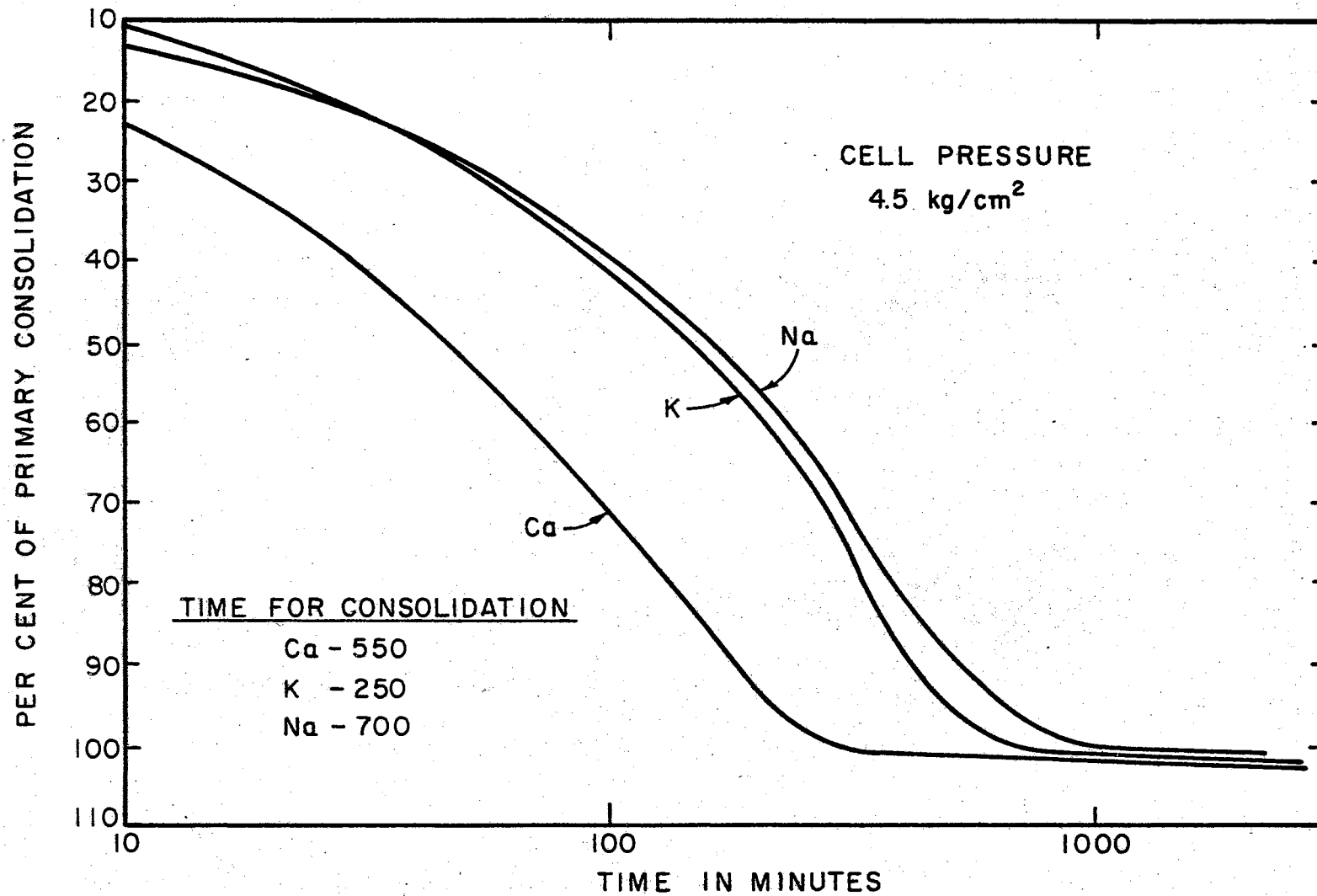


Figure 5-17. Isotropic Consolidation and Compaction for the 5% Bentonite + 95% Kaolinite Group.

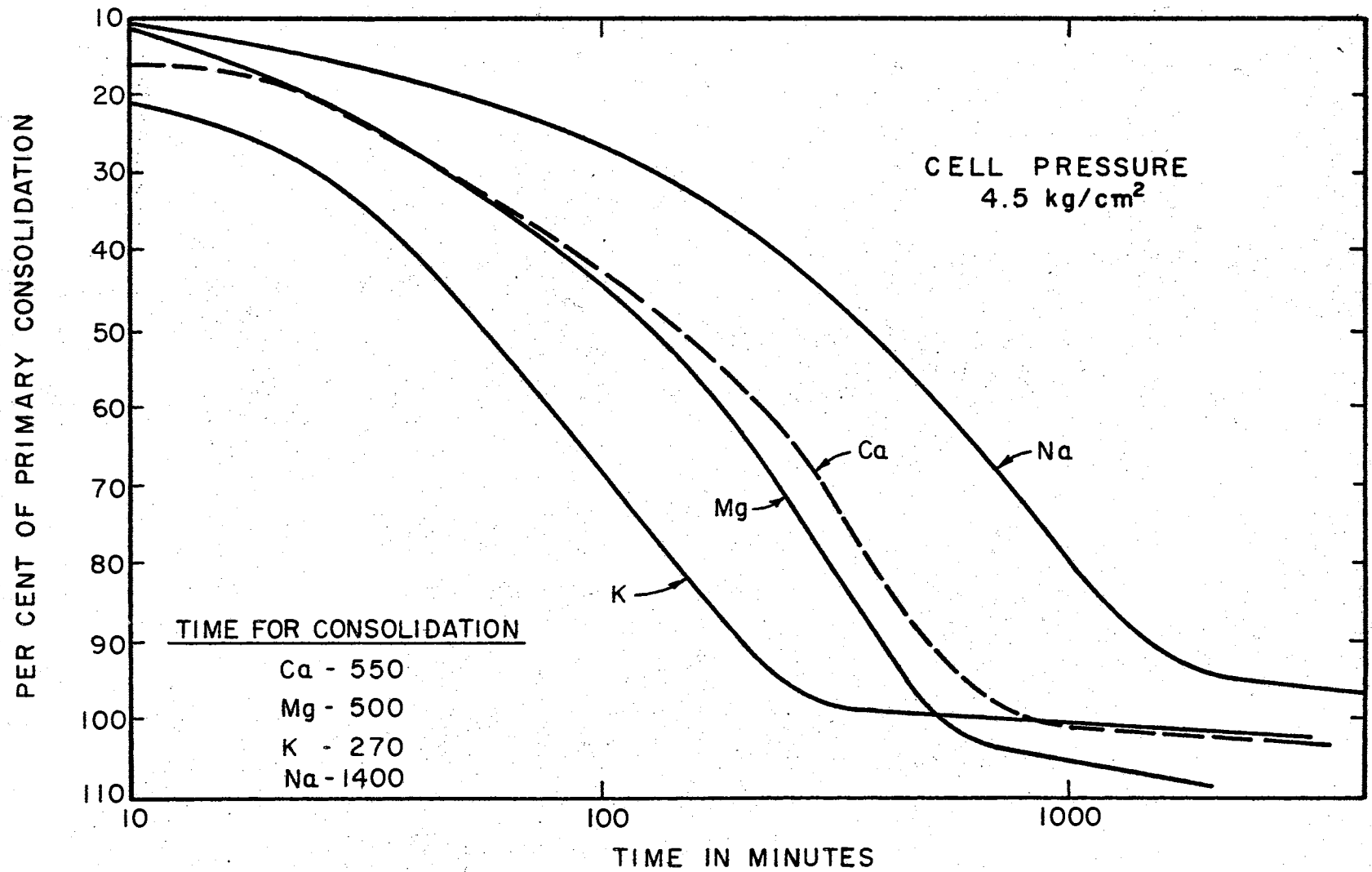


Figure 5-18. Isotropic Consolidation and Compaction for the 10% Bentonite + 90% Kaolinite Group.

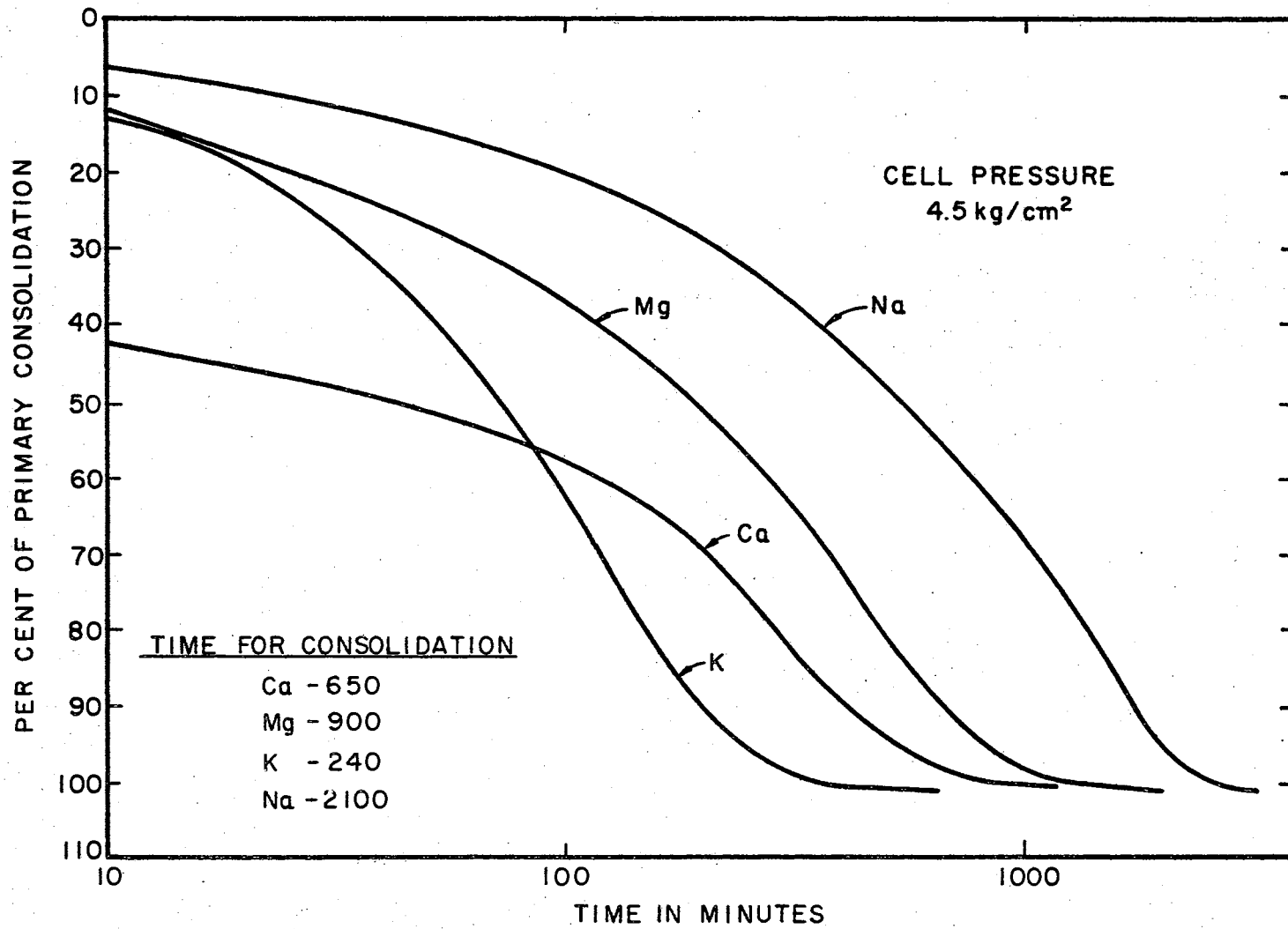


Figure 5-19. Isotropic Consolidation and Compaction for the 15% Bentonite + 85% Kaolinite Group.

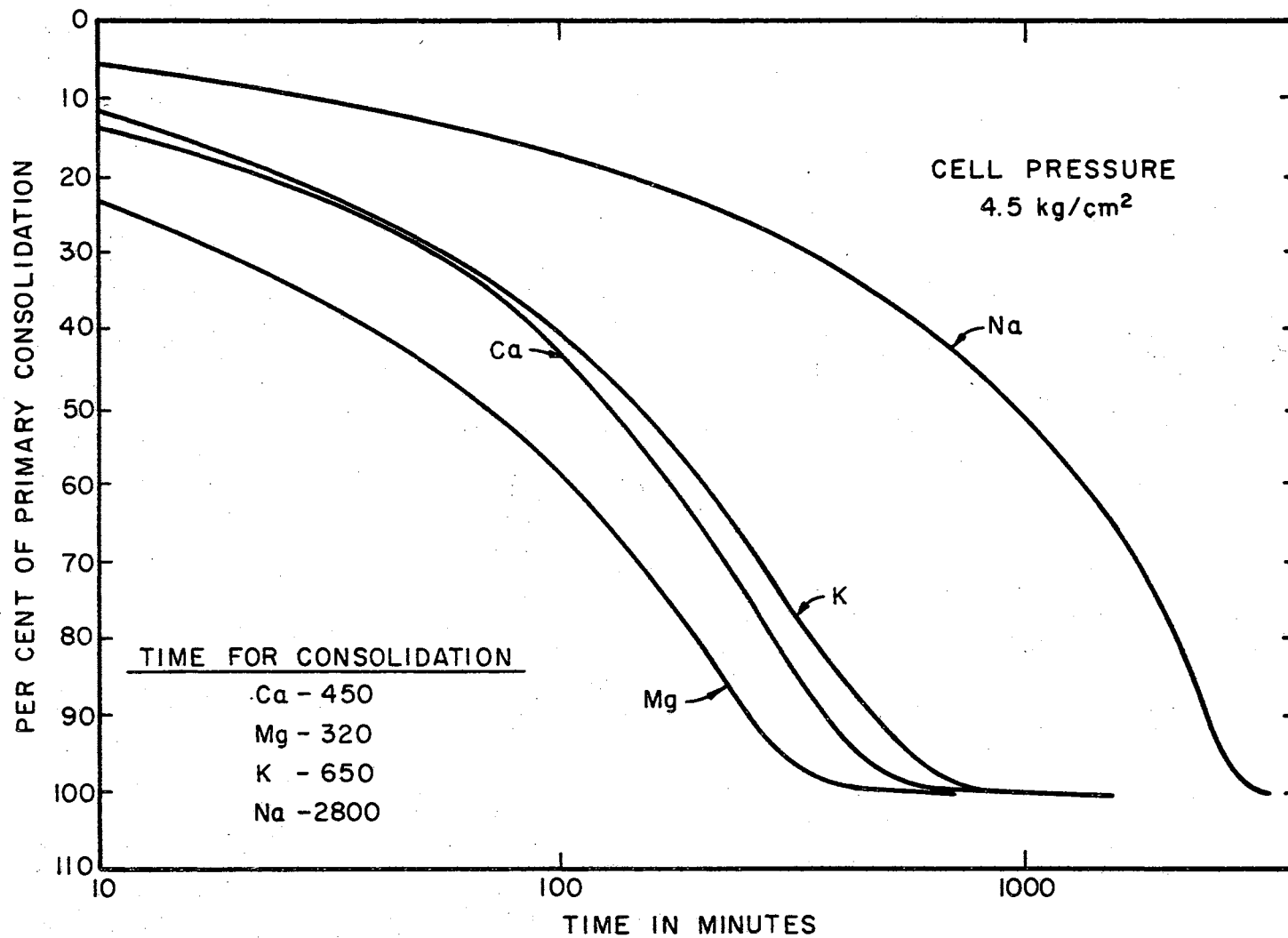


Figure 5-20. Isotropic Consolidation and Compaction for 5% Bentonite + 95% Illite Group.

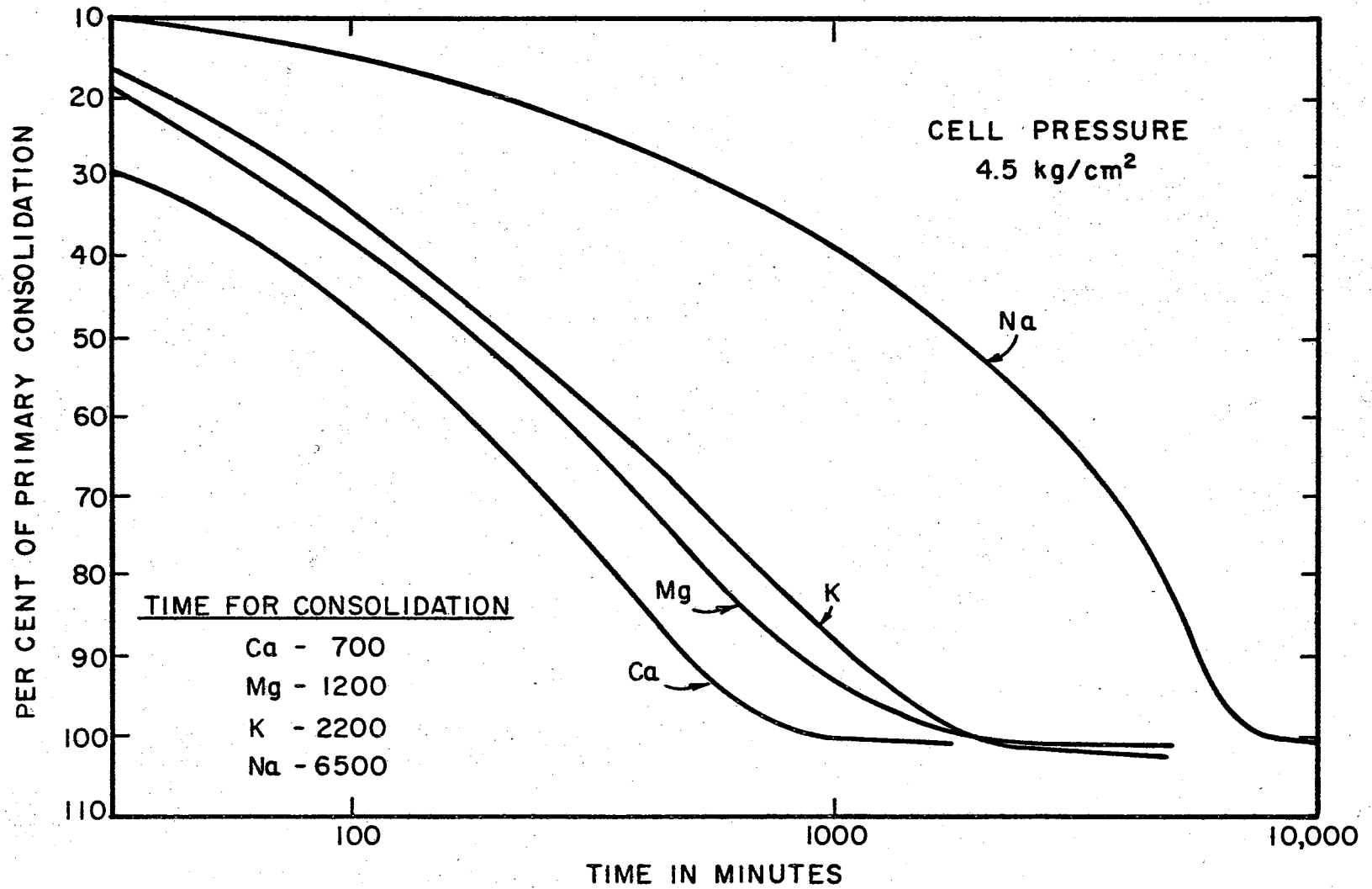


Figure 5-21. Isotropic Consolidation and Compaction for 10% Bentonite + 90% Illite Group.

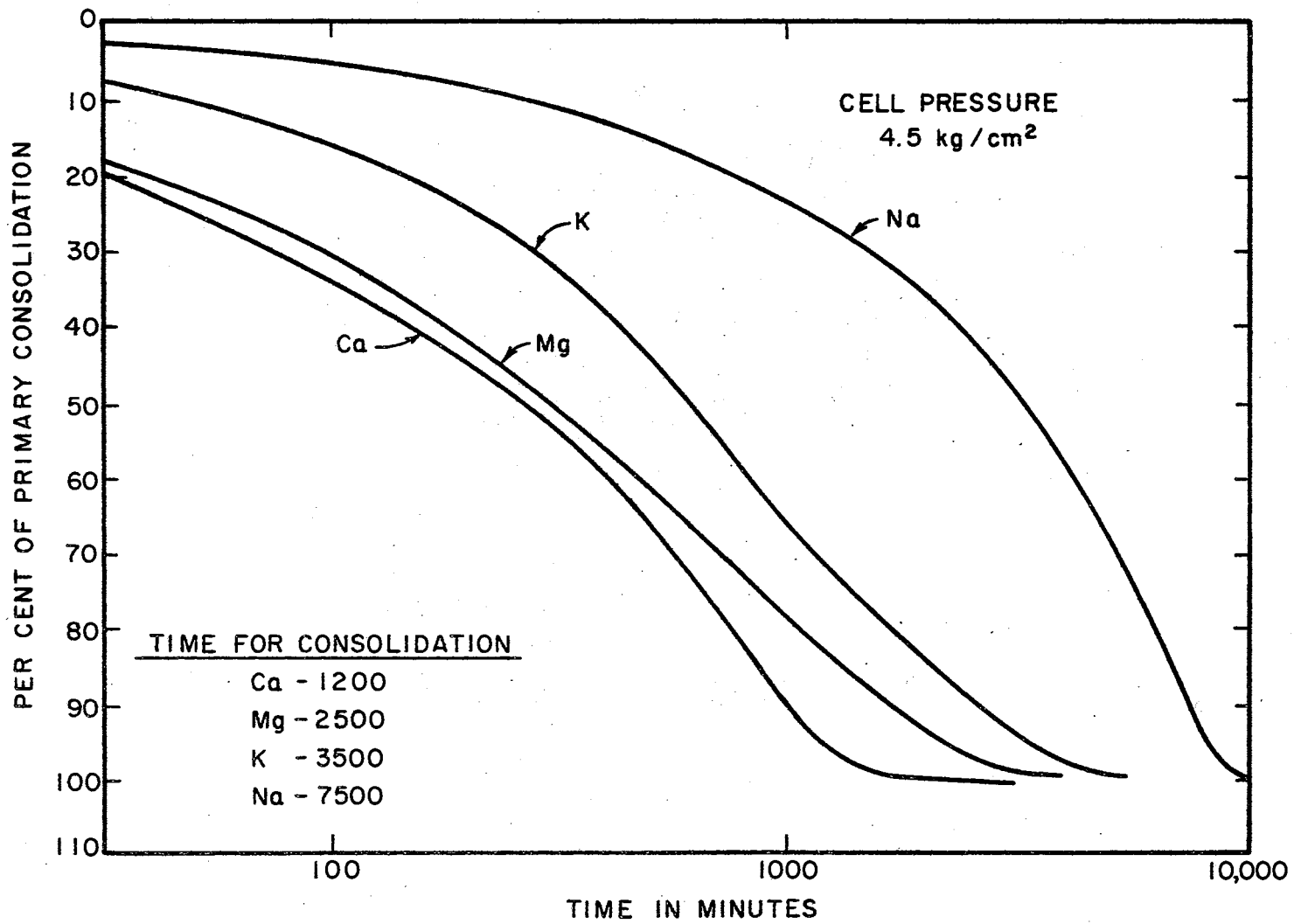


Figure 5-22. Isotropic Consolidation and Compaction for the 15% Bentonite + 85% Illite.

For calcium and 85% illite 66,000 seconds.

A ratio of 3 to 1.

Other relative variations are shown in Figure 5-16.

Coefficient of Permeability

The results shown in Figure 5-16 show a definite parallel trend between time of consolidation and the coefficient of permeability. Baver (1956) shows that the size, density, and hydration of the particles have great effects upon the permeability. Baver cites Lutz (1934) has demonstrated that the permeability of clays increases as hydration of the particles decreases, and the nature of the adsorbed ion also affects hydration and permeability.

Table V-III shows for the fifteen per cent bentonite mixture, the following variations in permeability:

For sodium-kaolinite, $k = 6 \times 10^{-8}$.

For calcium-kaolinite, $k = 1.1 \times 10^{-7}$.

A ratio of approximately 20 to 1.

For sodium-illite, $k = 1 \times 10^{-8}$.

For calcium-illite, $k = 1.4 \times 10^{-7}$.

A ratio of 14 to 1.

Compression Index

The compression index given in Table V-III and Figure 5-16 is estimated from the empirical relationship based upon the liquid limit given by Terzaghi and Peck (1948) as

$C_c = 0.009 (W_L - 10)$. These empirical values are presented only to show relative effects for variations of physical and chemical properties on the compression index which is a major parameter in making a settlement analysis for a foundation problem.

Unconfined Compression Shear Strength

The results of the unconfined shear tests are presented in Table V-IV and Figures 5-23 through 5-27.

The unconfined compression test is a special case of the triaxial compression test of soils where the compressive and shear strengths of a soil prism, or cylinder, are measured under zero lateral stress ($\sigma_2 = \sigma_3 = 0$). The test is based on the assumption that there is no moisture loss during the test.

In this study the soil specimens were removed from the triaxial consolidation cells, the latex membranes removed and the samples immediately trimmed to the standard dimensions of 1.4 inches diameter by 2.8 inches long, then placed in the loading machine. The rate of strain was held constant at one per cent per minute.

Figure 5-23 shows the unconfined shear strength plotted versus the cations used for the five, ten, and fifteen per cent bentonite mixes respectively. For five per cent bentonite mixes there is no apparent significant variation. For the various cations used, the ten per cent bentonite mixes

TABLE V-IV
UNCONFINED SHEAR STRESS, $(0.5q_u)$
FOR SOIL MODIFICATIONS

| Soil | | Unconfined Shear Stress $(0.5q_u)$ kg/cm ² | | | |
|-------|--------------------------------|--|------|------|------|
| Group | Mix | Na | K | Mg | Ca |
| 1 | 5% Bentonite 95% Kaolinite | 0.99 | 1.10 | --- | 0.95 |
| 2 | 10% Bentonite 90% Kaolinite | 0.89 | 0.86 | 1.64 | 0.93 |
| 3 | 15% Bentonite 85% Kaolinite | 0.88 | 1.19 | 1.13 | 0.78 |
| 4 | 5% Bentonite 95% Illite | 1.10 | 1.20 | 1.08 | 0.87 |
| 5 | 10% Bentonite 90% Illite | 1.47 | 1.14 | 1.10 | 1.06 |
| 6 | 15% Bentonite 85% Illite | 0.38 | 1.02 | 1.32 | 1.19 |

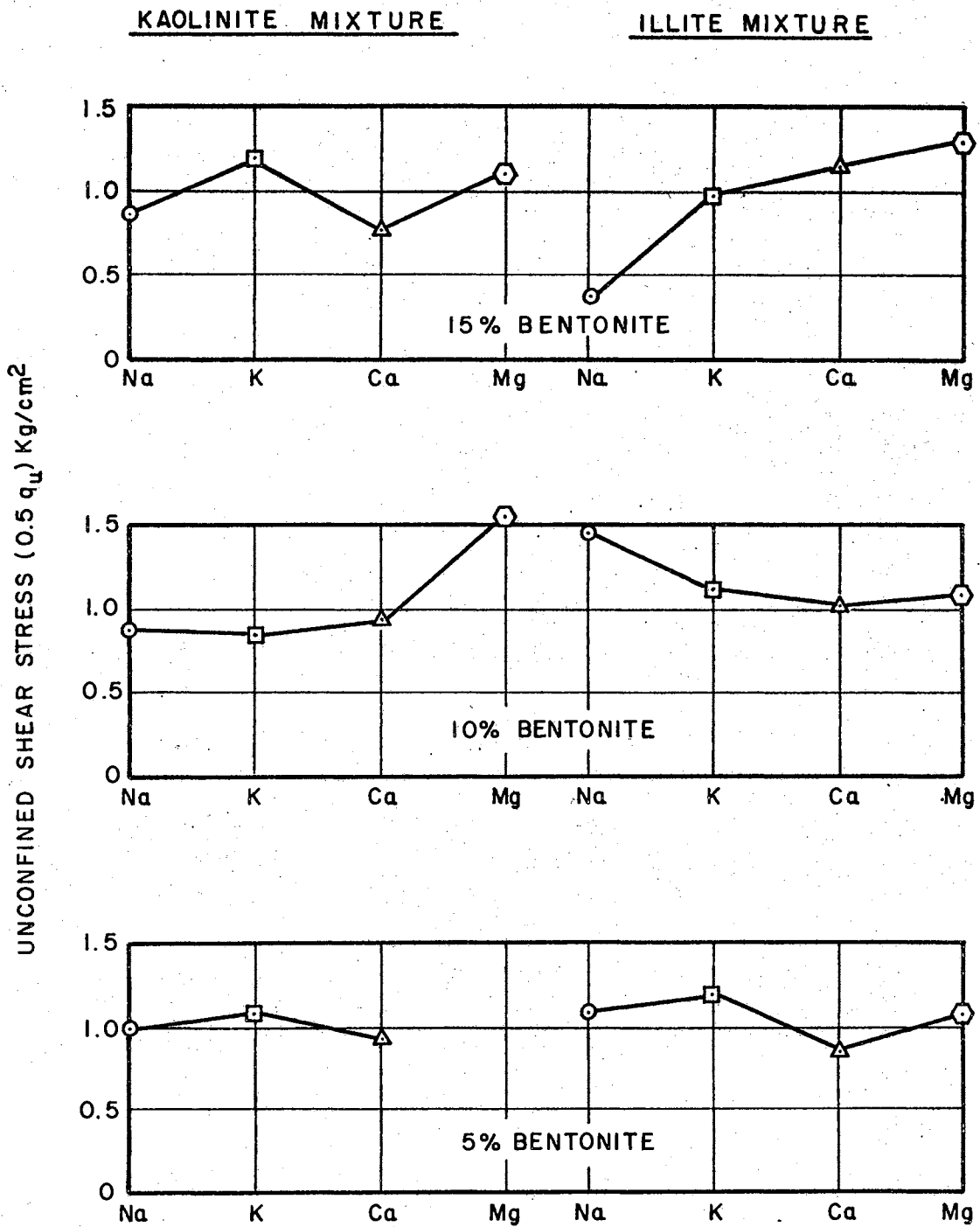


Figure 5-23. Shear Stress Versus Saturation Cation.

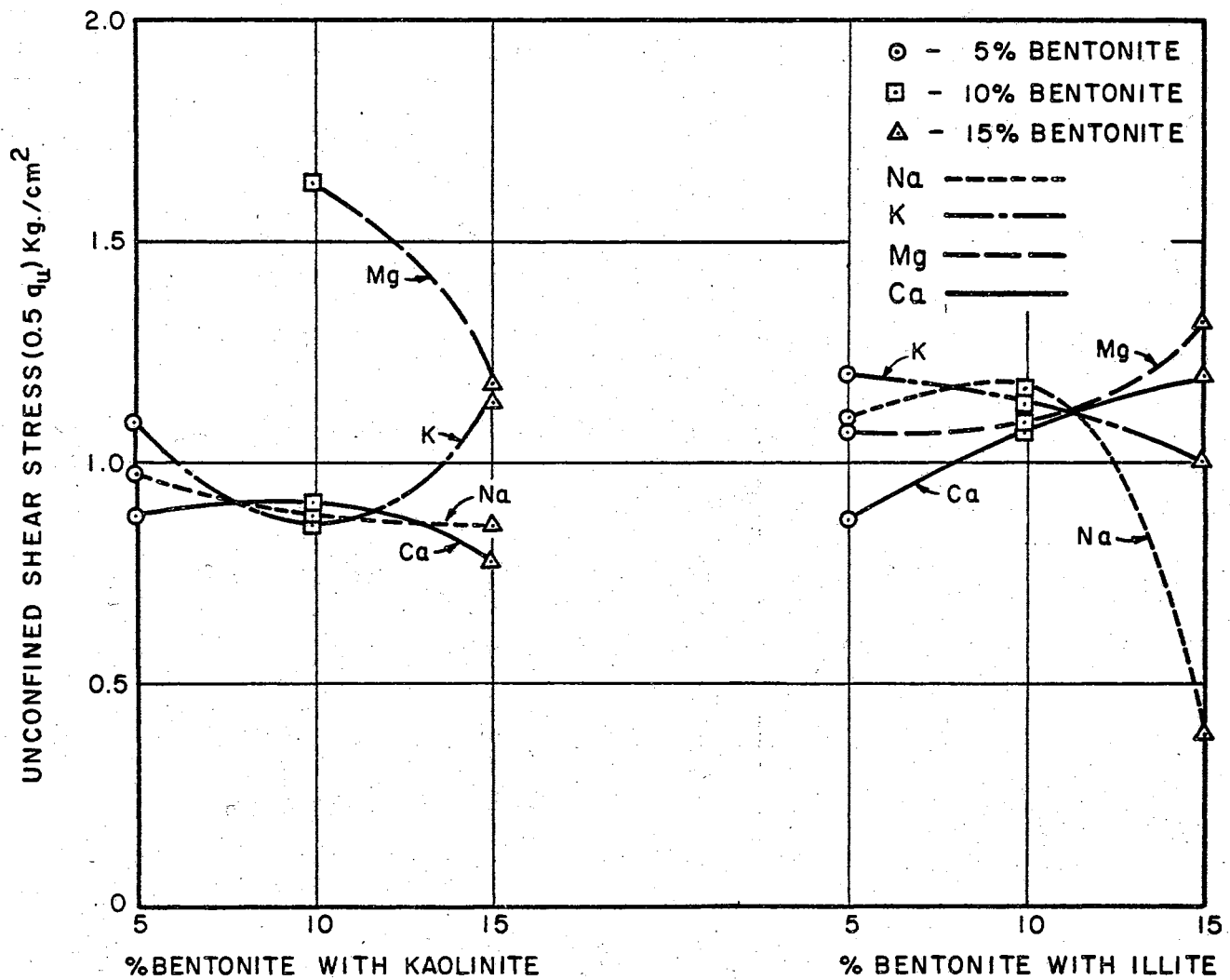


Figure 5-24. Stress Versus Per Cent Bentonite.

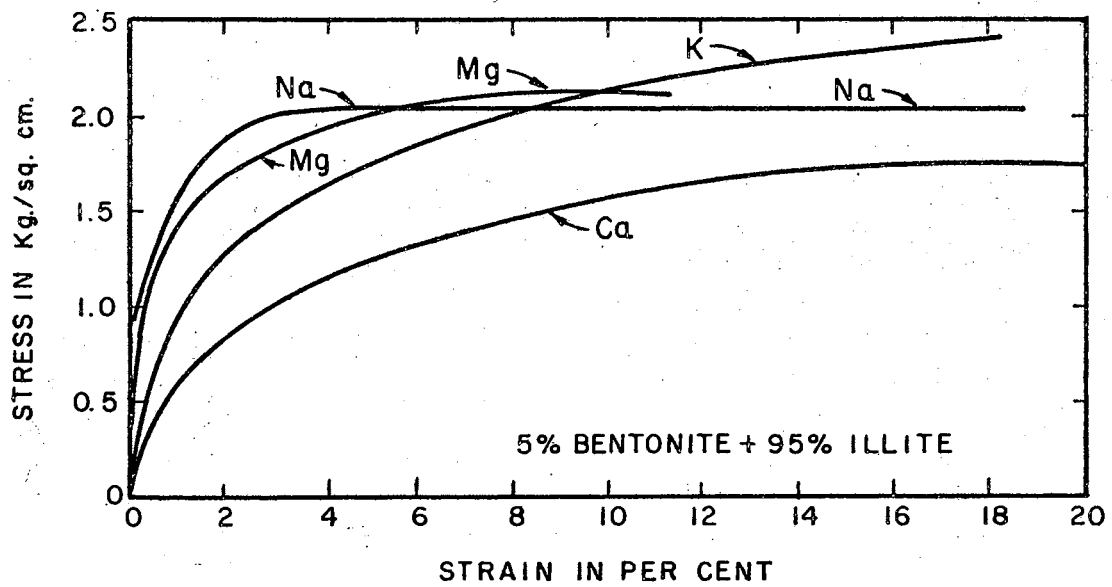
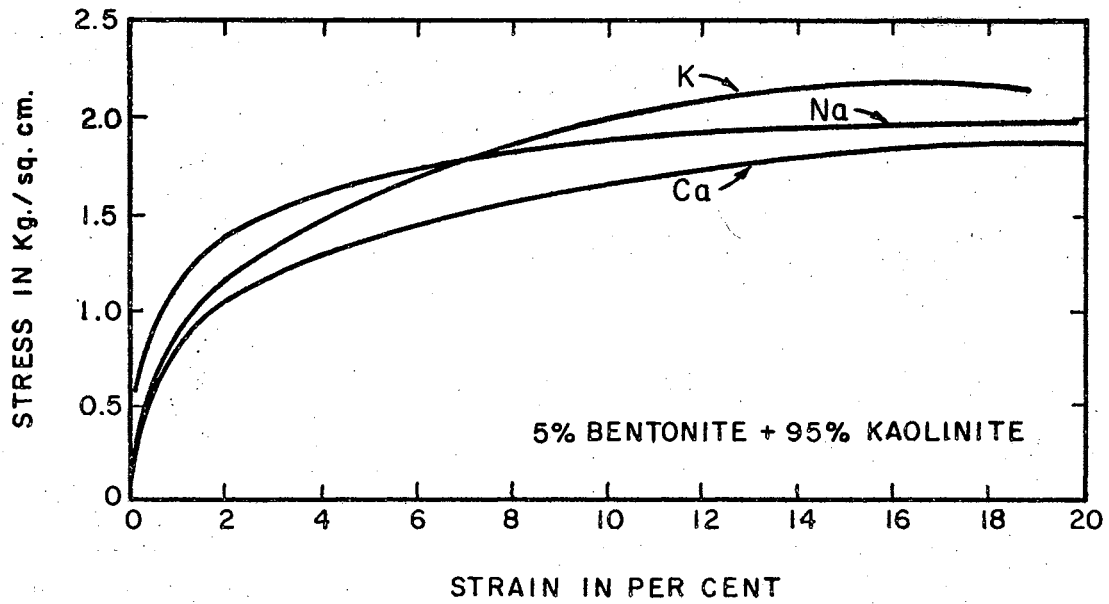


Figure 5-25. Stress Versus Strain

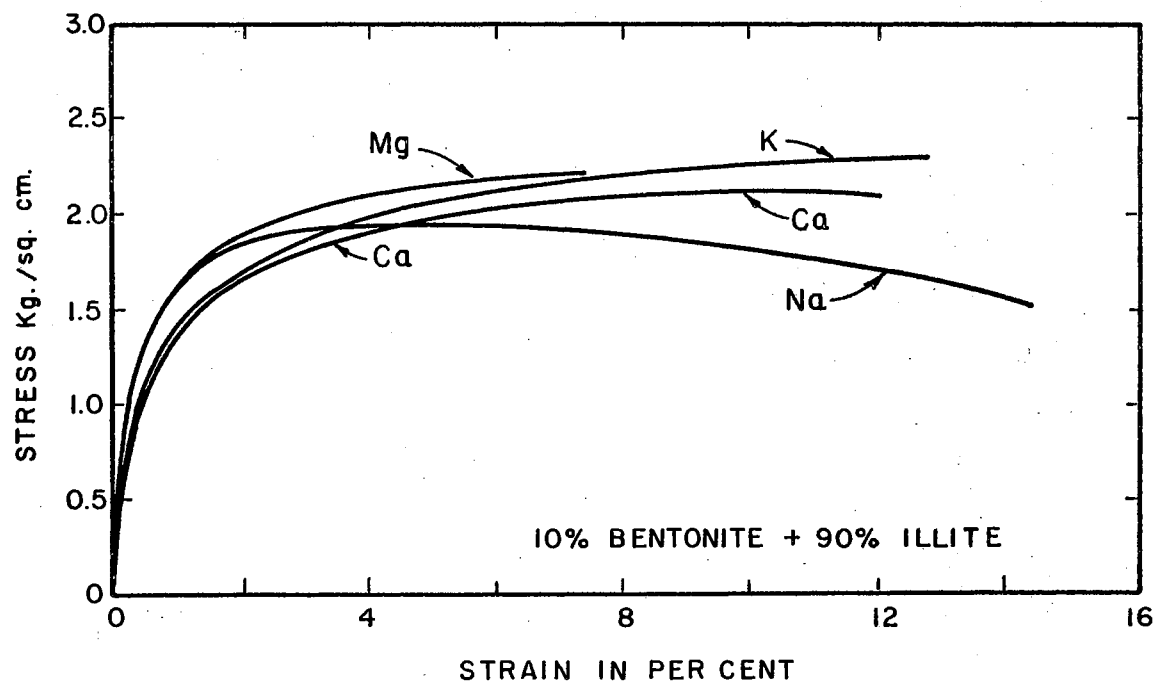
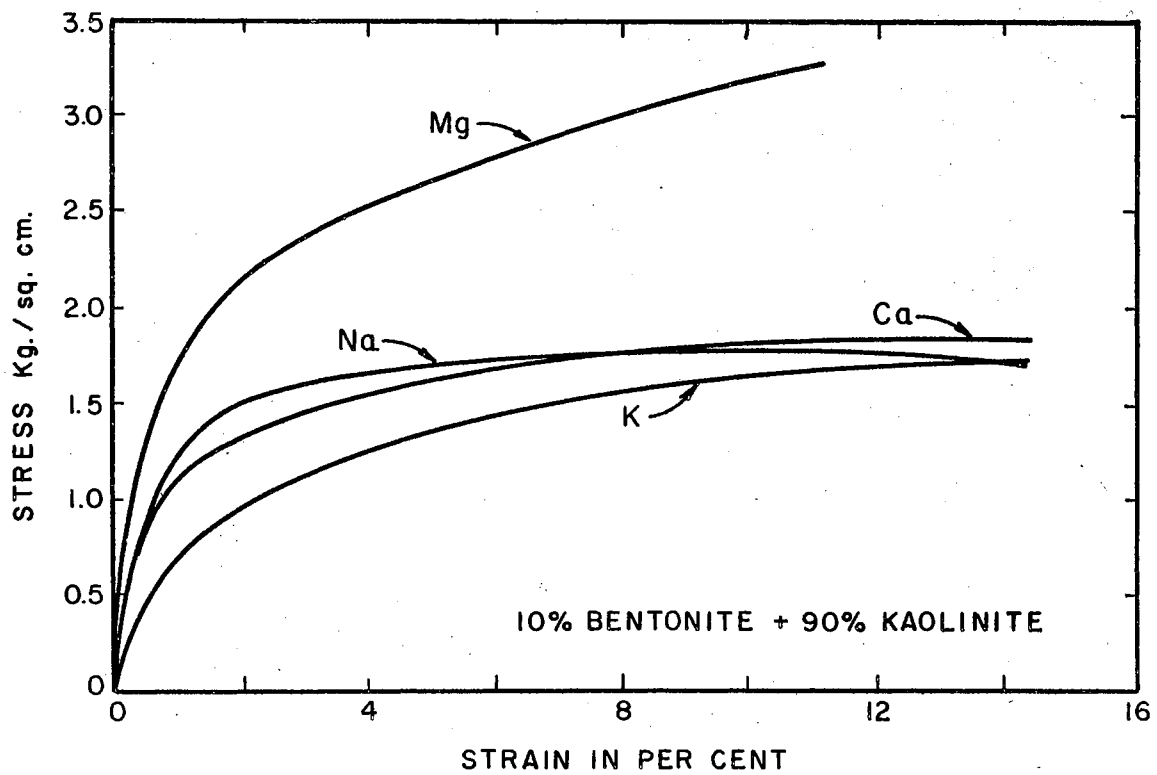


Figure 5-26. Stress Versus Strain

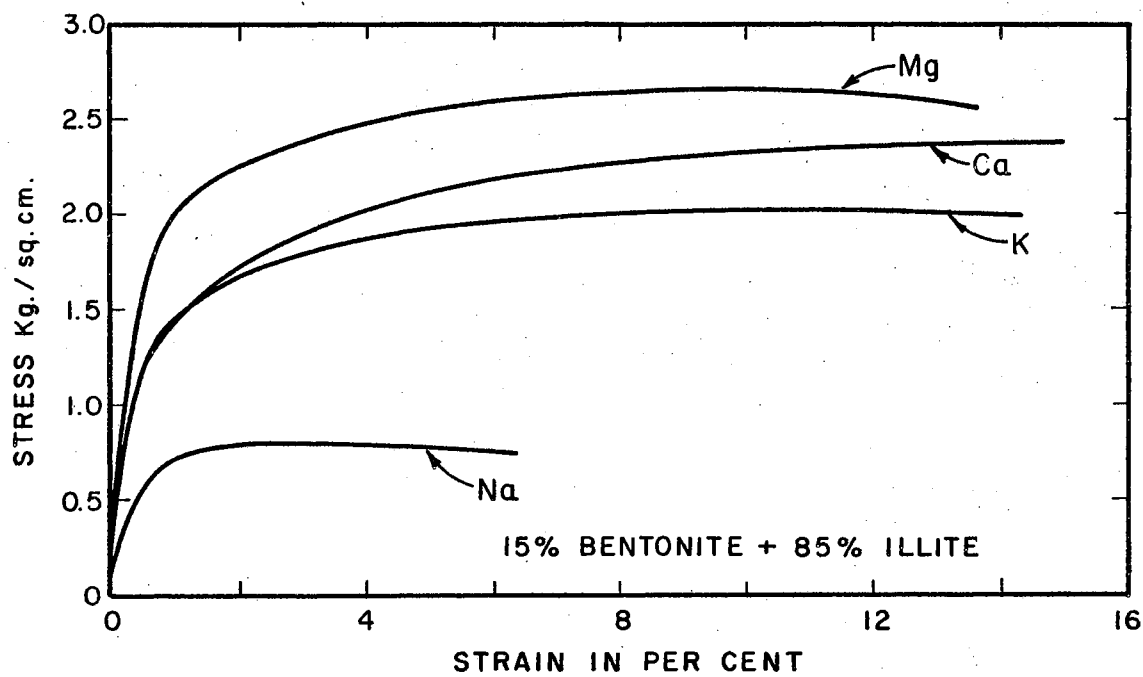
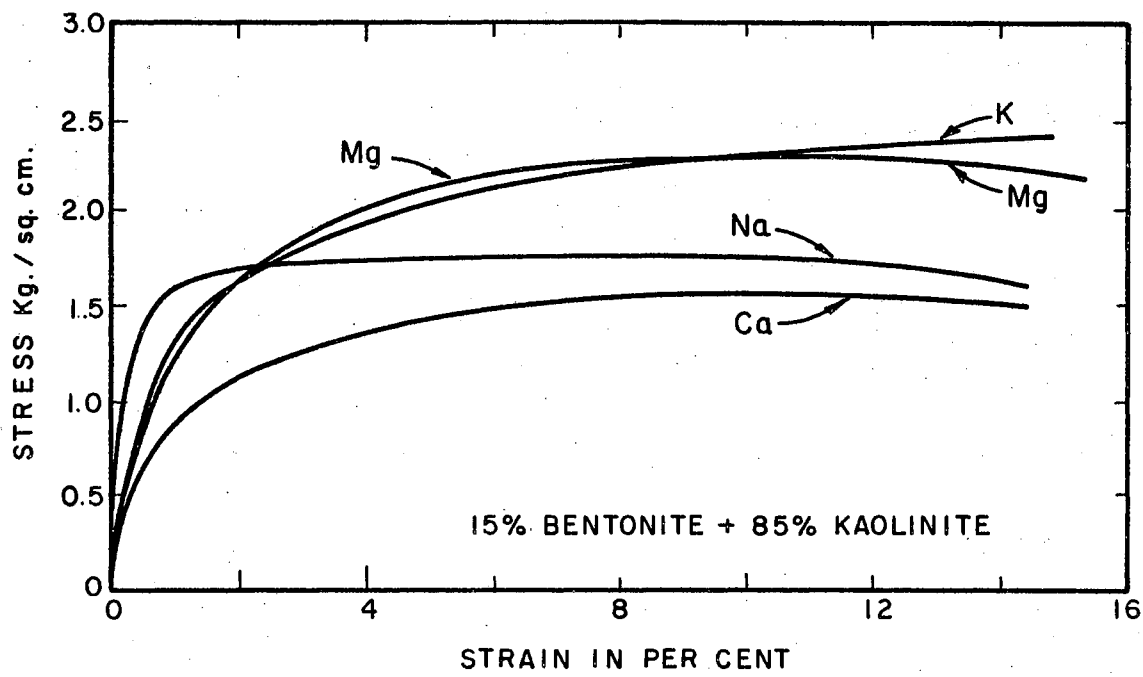


Figure 5-27. Stress Versus Strain

show some variation but not enough so that specific or definite conclusions would be justified. With the fifteen per cent bentonite mix the kaolinite group shows variations with the different cations used; however, additional testing would be required before specific predictions could be established. In the fifteen per cent bentonite illite group there is a very definite indication of strength variation with the sodium giving the lowest value, increasing in the following order:

$$\text{Na} < \text{K} < \text{Ca} < \text{Mg} .$$

From the data of this figure it would seem worthwhile for further research to be extended to include increased percentages of bentonite, such as 20 and 25 per cent mixes.

Figure 5-24 shows the unconfined shear strength plotted versus the per cent bentonite for the various cations used. It is significant to note for five per cent bentonite that calcium gives the lowest strength for the kaolinite and the illite groups and that potassium gives the highest value.

The ten per cent bentonite mix is interesting in that all of the strength values cross at about this value and approach very closely the same strength value.

The fifteen per cent bentonite mixes show the beginning of a rapid dispersion of strength values, indicating that for fifteen per cent, and greater, amounts of bentonite, the effects of the exchangeable cation is very prominent and that this region merits more extensive research.

Figures 5-25 through 5-27 show the individual stress-strain relation for each soil sample, the results of which have already been summarized in Figures 5-23 and 5-24. Again, it is pointed out that further research should include higher percentages of bentonite. At the beginning of this study the feasibility of additional mixes with increased bentonite was considered but abandoned because of the concern for the time factor required for the consolidation of samples with additional bentonite. In planning future research the results contained herein should prove helpful in estimating the extended time periods needed for carrying out this type of experimentation.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The problem of this study was the investigation of the feasibility of using synthetic soil mixtures to establish index groups that could be used for evaluating the physical properties of natural soils. The problem is composed of two general aspects: (1) preparation of the synthetic soil using varying proportions of the most common occurring clay minerals, bentonite, kaolinite, and illite and, (2) to convert each of the selected soil mixtures to a homionic soil by using the four most frequently occurring salts, sodium, calcium, potassium, and magnesium, adsorbed by soils in their natural state.

Hypotheses were: (1) A definite correlation exists between the mineral content of a clay soil and its physical strength characteristics, and that these characteristics can be predicted and evaluated by the use of mineral and cation identification tests. (2) These strength characteristics are altered in varying degrees by the nature of the adsorbed cations, and that with the identification of cations of the predominating salts additional evaluation can be made of the soils performance for engineering design purposes.

A review was made of the related literature and a need for the study was substantiated. Methods were developed for preparing synthetic homionic soils. These soils were then tested by the established physical tests. The correlations of these tests show good possibility of utilizing synthetic soil for indices as a method of evaluating the engineering properties of natural soils.

Conclusions were drawn, and recommendations for further study are given.

Conclusions

The following conclusions were delineated from the data:

1. This study has made a quantitative evaluation of the influence of the different cations upon soil properties.
2. The cation exchange reaction is exceedingly complex and is influenced by a great number of factors.
3. The practical applications of cation exchange to improve the engineering properties of a soil have so far been restricted to the treatment of surface deposits such as canal and lagoon linings and base course stabilization. As yet, no method has been devised to treat relatively large volumes of undisturbed soil.
4. Homionic soil may be produced successfully in the laboratory if the soil is leached or washed contin-

uously with a solution containing the desired cation, until all extraneous cations have been removed from the soil and pore solution. Producing large quantities of homionic soil in the laboratory is expensive and time consuming, therefore, it requires a very well planned testing program in order to obtain the utmost value of the data gathered.

5. The study of homionic soils requires adoption of tests not normally associated with a soils laboratory, such as cation exchange capacity, flame photometer and X-ray diffraction analyses. The cation exchange capacity is a more direct measure of the activity of the clay sizes. The flame photometer shows the proportion of each cation that is adsorbed on the clay complex and indirectly the salt content of the pore water; hence, one can assess the probable behavior of the soil. X-ray diffraction studies will yield approximate percentages of each of the main clay mineral classes present. The presence of members of the montmorillonite family are indicative of large changes in geotechnical properties as physical-chemical changes occur.

Recommendations

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

1. Additional research on the same basic problem should be performed using homionic modifications of other cations found in nature, such as hydrogen, lithium, and barium.
2. Investigation of the effect of one cation upon another should be studied with various percentages of Ca and Na adsorbed and various percentages of Ca and Mg adsorbed.
3. The effects of anions on physical properties should also be investigated such as Cl , PO_4 , SO_4 . These anions may be found in the adsorbed state or present in the pore water. Lambe has stated that adsorbed anions can influence the shear strength of a soil.
4. At present the practical applications of cation exchange are restricted mainly to the treatment of subgrade and embankment materials. Thus it is recommended that the effects of cation exchange on the compaction characteristics be investigated. The use of the miniature Harvard compaction apparatus is recommended as this apparatus requires only small quantities of soil.
5. Since cohesion may be an integral part of the strength of a soil, this property should be investigated. It is recommended that a program be carried out on the soil modifications using the technique of Schmertman and Osterberg (1960) to

study the variation of cohesion and angle of internal friction with strain. These results should be correlated with strength tests such as determined by unconfined compression or the vane shear tests.

6. Although not arising solely from this program, it is apparent that some knowledge of the fundamental concepts of clay mineralogy, soil physics, and soil chemistry is necessary if one is to understand more fully the geotechnical behavior of the fine grained soils. It is, therefore, recommended that consideration be given to the inclusion of the fundamentals of clay mineralogy, soil physics, and soil chemistry in the training of engineers specializing in the field of soil mechanics.
7. All work in this investigation was performed in a constant temperature environment, further research is recommended in order to determine effects of temperature variation.

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