Clay Mineralogy and Soil Stabilization

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MEMO TO: Dean D. V. Terrell  
Director of Research

From time to time as conditions have permitted, the Research Laboratory has carried on some fundamental investigations of soils, particularly from the standpoint of chemical and mineralogical composition of the true clay factions and their effects on physical properties of commonly-occurring soils. On two previous occasions, progress reports of this work have been presented at annual meetings of the Highway Research Board in Washington, D.C., and in December, 1948, a copy of one of these two was presented to our Research Committee as information.

The attached report by Messrs. Havens and Goodwin, entitled, "Clay Mineralogy and Soil Stabilization," represents the latest information developed in our studies, and it is presented here for record and for the information of anyone on our Research Committee who is interested. In essentially this form, the report was given last October at the 1951 annual convention of the American Society of Civil Engineers, where it was well received.

The title, to some extent is a misnomer since the work has not been specifically directed toward soil stabilization in its usual sense. However, stabilization was the subject of the symposium on which the paper was placed and it fitted well with the descriptions of stabilization with an acrylic resin and with aniline-furural as developed by the Army and Navy in their research for military applications.

Our fundamental research projects are very much subordinate to the investigational or expedient type work which logically demands most of our time and efforts. Still, I am certain that everyone recognizes the value of the fundamental and favors our giving these long-time objectives as much attention as possible. In the field of clay chemistry and mineralogy, for example, the Department is widely recognized as a leader on this type research so far as engineering uses of soil are concerned. In a similar but more restricted way, we have managed to contribute to the fundamental knowledge of aggregates, bituminous materials, and night driving conditions (through research on sign surfaces, paints, and headlights). Some of these studies have had almost immediate applications in acceptance tests, specifications, or design. All, of course, have these uses as an ultimate objective.

Comments concerning this report and our fundamental research program in general are solicited.

Respectfully submitted,

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Assistant Director of Research

Copies to: Research Committee  
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CLAY MINERALOGY AND SOIL STABILIZATION

by

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SYNOPSIS

This paper attempts to resolve a general concept of soil rheology from the standpoint of clay mineralogy, ion-exchange, properties of clay-water systems, and volume relationships existing between clay-water systems and granular structures. Both theory and experimental data are presented.

In the experimental phase, synthetic soils of varying clay contents were prepared from carefully fractionated soil constituents. These were subjected to combined-stress analyses, tests for plasticity characteristics, and determinations of other physical properties.

INTRODUCTION

The purpose of this treatise is to describe and attempt to integrate some of the elementary principles, theories and concepts of clays as they are related to soil mechanics and consequently to soil stabilization. The intent is to progressively develop a comprehensive concept of soil rheology from the standpoint of soil composition, clay mineralogy, ion-exchange, and granular structure.

Water under certain conditions, is known to be a very effective binder of sands, silts, and other granular materials. A stack of glass plates separated by water films may be distorted by a force as shown in A of Fig. 1. When the force is released, the plates rebound with considerable agility to condition B.
Obviously the tension resisting deformation in A is a function of external water surfaces. If the stack is completely immersed in water, there is no such tendency exhibited because those exterior water-surfaces no longer exist. The same is true of beach sands when flooded by wave-action. After the wave recedes, drainage re-creates the exterior surfaces within the pores of the sand and a high degree of rigidity is restored. If drainage is persistent, the pore-water first forms an exterior surface around a somewhat spherical air-void created by the vacating water. This condition is sometimes referred to as the "funicular" stage. Further drainage breaks or ruptures the envelope and the water then forms discrete rings around the points of contact between the particles. This condition is then referred to as the "pendular" stage, and no further drainage can take place. Loss of moisture thereafter can only be achieved by evaporation. Thus, the "pendular" stage may logically be regarded as the most stable condition for water-bound granular materials.

If sufficient normal stress is applied to the plates in the above illustration, the water is extruded-out and physical contact between the plates introduces frictional resistance to the deformation in addition to the tension of the water. In this case, both interior and exterior surfaces act to resist deformations. Clay, commonly found in
soils are also minute plates, but no clay has even been known to rebound as do the glass plates. It must, therefore, be assumed that either those tensile forces due to meniscus water are no longer present or else the internal forces are considerably greater in magnitude. Accordingly, it seems logical to assume that complete saturation excludes any possibility of deriving shear-resistance from that source.

IONIC BINDERS

If the interior surfaces of the plates above were electrostatically charged, then Coulomb's forces would come into play. If similarly charged and the space between them evacuated, then the force would be repulsive in direction and would vary inversely as the square of the distance separating them. Actually, silicious surfaces such as clays have been shown to be negatively charged (1) and, as such, they are natural receptors of positively charged ions such as $\text{H}^+$, $\text{Li}^+$, $\text{K}^+$, $\text{Na}^+$, $\text{Ca}^{+2}$, $\text{NH}_4^+$, etc. Because of this, numerous complexities develop in natural clay-soils by the random prevalence of ions available for absorption. The influences of these surface charges is best illustrated by another idealized concept portrayed in Fig. 2. In this drawing, two negatively charged surfaces are separated by an interposed layer of positive charges. Without the positively charged layer, the negative surfaces would be mutually repulsive; but now, they are mutually attracted to the positive charges and are, in effect, bonded together by a positive-charge linkage.

* - Numbers in parentheses refer to list of references at the end of this paper.
Further inspection of Fig. 2 from the standpoint of Coulomb's Law obviates the necessity for extremely intimate proximity between the surfaces. This concept is not too remotely analogous to the action of

![Diagram](image)

Fig. 2 - Idealized concept of ionic binding (2).

K\(^+\), in binding mica sheets together. In dilute suspensions of clay in water, the solid surfaces are envisaged as being bound to the water by the same forces. It is generally believed that the water immediately adjacent to the surface is held so firmly that it is essentially immobilized. There is also, a progressive diminution of immobility with increasing distance from the solid surface. The greater the thickness of the immobilized shell and the farther the diminution-effects project into the water, the more the clay particles take on the characteristics of the water. In one sense, this explains why some clays enter readily into suspension while others do not. Absorbed ions such as Na\(^+\) and Li\(^+\) are capable of creating thicker shells of loosely bound water than are H\(^+\), K\(^+\), or Ca\(^+\) ions, hence, the dispersive action of the former and the flocculative action of the latter. The actual mechanisms involved are
still subject to disagreement (3, 4 and 5), consequently no great risk arises from integrating certain parts of several concepts into a somewhat generalized one.

From electrolytic conductances and transference numbers, it is known that these ions are considerably larger in aqueous solutions than would be expected from their atomic diameters. Since water molecules themselves are polar and since the presence of ions may further induce the polarity, the ion may be envisaged as capable of orienting about itself a cluster of water molecules. When ionic additions are made to a suspension of clay in water, the surface-forces of the clay are then competing with the hydration tendencies of the water. If the hydration shell is small with respect to the charge on the ion, then the ion may reach a closer proximity to the clay surface than if the shell were large, and thereby strengthen its Coulomb-attraction to the surface to such a degree that the ion would then slip out of its water envelope and cleave almost entirely to the clay surface. This would leave the water with a smaller but ever-present tendency to recover the ion from its now comparatively secure position on the clay surface. In contrast, an ion with a very large hydration shell can not approach the clay surface to the point where its attraction there becomes greater than the hydration forces of the water, unless the size of the shell can be reduced by some means.

This concept derives some substantiation from observed "cation fixation" effects wherein air-drying produces marked differences in the physical properties of the clay on re-wetting. Evaporation would then be one means of eliminating hydration water from the ions. Another means, with further reference to Fig. 1, would be to collapse the water
shell mechanically; that is, to consolidate the plates under compressive load until the water shell becomes so flattened that a stronger bond is created between the ion and the solid surface. The remaining water comprising the inter-layer then consists almost entirely of hydration-water bound to the ion in a more-or-less rigid, but unequilibrated condition, plus additional oriented-water held by other stray forces deep within the crystal and possibly by hydroxyl ions on the surface. It should be remembered in all cases that once a high degree of consolidation has been attained, that the reformation of a thick water inter-layer is opposed by the permeability of the mass. In this respect Li- and Na-clays are much less permeable than Ca-clays. Also, Ca-clays exhibit greater cohesion in the moist condition whereas Na-clays are the more cohesive on air-drying. This seems to indicate, in the case of Ca-clays, the water in some way acts as an intermediate connector in forming a cross-linkage between the clay particles. Because of its di-valent nature a Ca+ ion is much more capable of accommodating an intermediate connector than is the uni-valent Na+. Obviously any cross-linkage of this type calls for preferential orientation which can only be achieved through strong natural or induced dipoles, whether inorganic or organic. Hydrogen bonding, which is known to be a mechanism by which dimers and even polymers are produced, has been suggested as a coupling mechanism. Linkage through hydroxyl ions on the surface with a di-valent cation acting as the intermediate connector has also been proposed.

These examples serve only to emphasize the great need for further research on this specific problem, for therein undoubtedly resides the key to successful cationic stabilization.
EXCHANGE REACTIONS:

A H-clay that is a clay whose surface capacity is saturated with H⁺, exhibits reaction characteristic of an acid. In water, it dissociates to some degree and its reactions appear to obey the law of mass action. To illustrate:

\[
\begin{align*}
\text{H-clay} + \text{NaOH} \quad \text{aqueous} & \quad \rightarrow \quad \text{Na-clay} + \text{H}_2\text{O} \\
\text{Na-clay} + \text{HCl} \quad \text{(excess)} & \quad \rightarrow \quad \text{H-clay} + \text{NaCl} + \text{HCl} \\
\text{Na-clay} \quad \text{electro-dialysis} & \quad \rightarrow \quad \text{H-clay} + \text{NaCl}
\end{align*}
\]

Consequently a Na-clay may be converted to a Ca-clay by first converting it to a H-clay and then neutralizing its acidity with the Ca(OH)$_2$ base. In some cases almost complete replacement may be effected directly, depending on the relative replaceability of the two cations. Accordingly, Ca$^{+2}$ will replace a large portion of the Na$^+$ on a clay; but a Ca-clay may only be partially converted to a Na-clay in the presence of an excess of Na$^+$ ions. Therefore, the relative replaceability or permanence of the ion, in addition to the physical properties it imparts to the clay, is a factor to be considered with respect to its use in stabilization.

RHEOLOGY OF CLAYS

The strength of the plastic clays is manifest in a "threshold" stress required to produce viscous flow. This rather general concept is represented diagrammatically in Fig. 3.
When the plasticity values are corrected by the amount of the "threshold" stress, the plastic flow curve compares favorably to the dimensions of viscosity. As a further analogy, the plastic-flow curve is similar in most respects to the usual stress-strain curve.

Some further insight into the effect of varying thickness of water films on the "threshold" stress, or "yield point" as it is termed above, may be derived from experimental data (6) relating moisture content to the amount of power required to extrude the mixture with an auger machine. In Fig. 4, the "threshold" stress is, for the purpose of this comparison, considered analogous to the units of power.

Fig. 4 - Relation of tempering water in clay and the power necessary to extrude clays through an auger machine (by Grim).
The inflections in the curves clearly indicate a critical water content which may be interpreted as the boundary between the firmly held water and the loosely held water between the plates. Consequently, a very definite correlation would be expected to exist between the critical point on this type of curve and the Plastic Limit of the clay. It is, also, indicated that maximum strength occurs in a comparatively narrow range of moisture content about or below its Plastic Limit.

CHARACTERISTICS OF CLAY MINERALS

From the standpoint of occurrence, only Kaolinite, Illite, and Montmorillonite need be considered of great importance in soil mechanics. Of these three, Illite probably enjoys greatest distribution, but rarely does a soil contain only one clay mineral. Usually Illite is the predominating constituent mixed with lesser amounts of Kaolinite and Montmorillonite.

Kaolinite exhibits the smallest capacity of cation-exchange, usually 3 to 15 milliequivalents per 100 grams. It exhibits more perfect crystallization, occurs in larger particle sizes; and consequently is less capable of orienting a thick layer of water about its surfaces. Its plastic properties differ only slightly from those of quartz ground to equivalent sizes. It is more permeable due to its larger sizes and the absence of thick oriented water films.

Illite has an exchange capacity of from 20 to 40 milliequivalents. It appears as thin leaf-like flakes with ragged edges. The flakes tend to aggregate on drying and to separate again on re-wetting, depending, of course, on the binding strength of their absorbed cation. It occurs in smaller sizes than Kaolinite; and, since it exposes greater surface areas
and has a higher exchange capacity, it should bind water films more rigidly and in the lower moisture contents, it should be more cohesive than kaolinite.

Montmorillonite has a base-exchange capacity of from 60 to 100; it is also flaky; its mean particle size is much smaller than either kaolinite or illite; its crystallization is more imperfect, and its flakes exhibit ragged edges. Montmorillonite differs from the other two by its characteristic swelling. Not only is it able to accommodate thicker water films on its exterior surfaces, but it is, also, able to take water into its intra-planar surfaces to produce swelling of the crystal along the axis normal to the planar surface. In this respect, the absorbed cation has a much more pronounced effect on its plastic properties than on the other two clays. Thus, a Na-Montmorillonite expands tremendously more than a Ca-Montmorillonite, as explained before. The binding force of the Ca++ between the intra-planar surfaces hold them so tightly together that little space is available for occupation by water. Because of its capacity to retain greater quantities of firmly held water, it is expected to maintain its plastic properties over a wider range of moisture content and to be more cohesive in the lower moisture contents than the other two clays.

THEORETICAL ASPECTS OF GRANULAR STRUCTURES

Whereas clays are definitely flat and flaky, the coarser components of soils range from angular to spherical. The combined influences of clay and granular materials are best understood by first considering them separately and then collectively. This treatment is based on idealized spherical soil particles which in a condition rarely approached by sand and silt grains.
Fig. 5 shows three methods of packing uniform spheres. A represents the loosest arrangement, B the densest arrangement, and C represents an intermediate stage. All three conditions are independent of size and quantity of spheres so long as they are uniform. (7, 8, and 9).

Fig. 5 - Packing of uniform spheres

A has a calculated porosity of 47.6%, B - 26%, and C - 39.7%. A can accommodate, in its interstices, an equivalent number of spheres whose sizes are 0.732 x the diameter of the large spheres. These smaller spheres reduce the porosity of A to 27%. C will accommodate an equivalent number of small spheres 0.528 x D, but they only reduce its porosity to 31.8%. B, which is the densest arrangement to begin with, will accommodate two sizes of small spheres, 0.414 x D and 0.225 x D. Together, they reduce the porosity of B to only 19.86%. The average for all conditions in which the small spheres are included is 26% voids; whereas, without the small spheres, the average for all three conditions is 37.8% voids.
Taking the average of $A$, $B$ and $C$ with their corresponding small spheres as representative of a well-graded granular material, 26% voids could well be considered typical of naturally-occurring soils. Since the range is only about 20% to 32%, the assumption of 26% is within the predictable limits of 6%.

The introduction of sizes larger than the interstices for any condition would expand the structure and increase the porosity. Further, a volume of a clay-water mixture (7) in excess of the porosity of any granular structure would tend to float the strengthening structural members and the strength of the mass thereafter would be determined by the strength of the clay-water system alone.

Although these concepts are elementary in nature and somewhat removed from the realm of clay mineralogy, they have a bearing on the later interpretation of results and, hence, should be kept in mind throughout the paper. From the standpoint of soil stabilization, clay mineralogy cannot be isolated from the physical composition of the clay and of the coarser soil with which it is associated.

SOIL RHEOLOGY

The flow characteristics of soils, as presented here are based largely upon relationships developed experimentally in connection with a long-range program of research on clays and their influences on the fundamental properties of soils. The objective of the over-all program is to develop data
on the occurrence and distribution of clays in Kentucky and to eventually correlate these findings with soil formations as well as with the engineering properties of the soils.

For this phase of the project, about forty pounds of a mixed Illite-Kaolinite clay, smaller than one micron, was separated from one soil and another forty pounds of a mixed Montmorillonite-Kaolinite Clay, also smaller than one micron, was recovered from another soil. The separations were accomplished by sedimentation procedures. About fifty pounds of silt was separated from a third soil, also by sedimentation. The recovered clays, with both Na+ and Ca++ modifications, were combined in definite proportions with the silt to form synthetic soils of known composition.

Maximum densities and optimum moisture contents, under a given method of static compaction, were determined and these formed the basis for preparation of triaxial-test samples for combined stress analysis. Further comparisons or evaluations were made through the Atterburg Limits tests.

X-ray diffraction patterns for both clays are shown in Fig. 6. Sample C-3 is a yellow clay composed of Illite and Kaolinite. Sample C-13 is a red clay composed of Montmorillonite and Kaolinite.

Fig. 7 is a photomicrograph showing the silt imbedded in a matrix of plastic clay. The silt is composed of angular quartz grains ranging in size from 5 to 75 microns, the largest portion occurring at about 25 microns. The magnification here is about 150 times.
Fig. 6 - X-ray diffraction patterns.

Fig. 7 - Photomicrograph of silt imbedded in clay matrix.
Fig. 8 shows electron micrographs of the two samples of clay. These are actually photographs of shadow-casting (11) in which the length of the shadow is five times greater than the thickness of the particles. They present an otherwise un-achievable third dimensional effect.
Cationic modifications were introduced during the process of recovery by adding to the suspension of clay, chloride salts of sodium and calcium in excess of the amount necessary to produce flocculation. The flocculated clays were separated from the remaining water by vacuum filtration. The recovered clays were then air-dried, pulverized to pass the No. 200 sieve, and combined with the silt.

Triaxial specimens were prepared by adding sufficient water to the mixtures to bring them up to optimum moisture contents. The specimens were formed in a 2-inch diameter split-mold under a compressive load of 1500 lbs. They were sealed and allowed to age a minimum of 21 days prior to testing. In terms of triaxial nomenclature, the loading conditions approximated the so-called consolidated quick-type of test in view of strain increments of 0.005 in. per minute.

The relationships derived from these tests are presented in graphic form in Fig. 9, a through f; and Fig. 10, a and b. Plots, c and d, of Fig. 10; although a part of this study program, were obtained from an Illite clay in combination with a graded granular material (12). Plots, e and f, of Fig. 10 represent findings of other investigators (13 and 14) and are included here for comparison since they have a direct bearing on the interpretations placed on the results.

The extrapolated or dashed portion of the curves represent the author's conceptions of the relationships and they lack verification by experimental data.
Fig. 9
Fig. 10
Liquid Limit versus Per Cent Clay - The Liquid Limit, although empirical, is a measure of the amount of moisture required by a clay to produce a definite rate of shear under impact forces. It is fundamentally a property of the clay. The test implies that each clay requires a definite thickness of water between its flakes to produce an exact amount of lubrication and rate of shear. Clearly, the moisture content then varies directly with the amount of clay present.

The addition of granular particles to a 100% clay does not affect the shear properties of the mass until they displace enough of the clay to establish inter-granular friction. To this point, granular particles are envisaged as simply floating in the clay-water system. Once a granular structure is established, the Liquid Limit is determined largely by the minimum porosity of the structure and the volume relationships between the clay and water occupying those pores.

In order to "quicken" the grains and produce the rate of shear implied by the Liquid Limit test, an excess hydrostatic pressure must exist within the pores of the granular structure. Therefore, that portion of the voids not occupied by clay must be filled with water. Actually, as the clay content is further reduced, the moisture content within the pores with respect to the clay may far exceed the Liquid Limit of the clay. As more and more of the clay is removed from the pores, the volume of water required to "quicken" the grains approaches the porosity of the granular structure.

The Liquid Limit as a property of the clay is clearly indicated by the different values for the 100% clays in Fig. 9-a. Since Na-Montmorillonites usually have Liquid Limits five to six times greater than
Ca-Montmorillonites, and Ca-Montmorillonites three to four times greater than Illite or Kaolinite, it is clearly shown that C-13 is not a pure Montmorillonite. That, of course, was previously shown by x-ray diffraction. Also, since the differences due to the indicated cationic modifications are not great, there is reason to believe that the degree of cationic modifications actually induced in the recovery process was fractional.

**Plastic Limit versus Per Cent Clay** - The Plastic Limit is interpreted as representing a definite thickness of water which a clay requires between its particles to produce the degree of plasticity called for by the test. Like the Liquid Limit, it is dependent upon the mineralogy of the clay and the cationic charges on its surface. Consequently, the moisture content represented as the Plastic Limit is a direct function of the surface area of the clay.

Within the range of the Plastic Limit curves, Fig. 9-b, where the clay is the controlling factor, the moisture content varies directly as the per cent clay. The relationship between Liquid Limit and Plastic Limit within this range is simply a linear function determined by their slopes (15). The lower portion of the curve is subject to the same volume relationships with respect to the minimum porosity of the granular structure as previously shown in the discussion of Liquid Limits.

The higher Plastic Limit of C-13 is accountable by the greater surface area, smaller particle size, greater surface charge-density, and intraplanar water of the Montmorillonite Clay.
Shrinkage Limit and Maximum Dry Density versus Per Cent Clay - The curves in Fig. 9-c and 9-d suggest reciprocal relationships with respect to the influence of clay content on the two properties. In one respect, both properties depend upon the maximum degree of consolidation attainable by the particles. Whereas Shrinkage Limit reflects the minimum voids, Maximum Density reflects the maximum solids. In the first case; clay, in filling the voids of the granular structures, occupies space that would otherwise be filled with water and results in a lower Shrinkage Limit value. In the latter case; the clay, in filling the voids, merely adds to the bulk density of the mass.

After sufficient clay has been added to expand the granular structure, both properties are thereafter dependent largely upon the degree of consolidation that can be attained by the clay itself. In the one case, water is the consolidated medium; while in the other, consolidation is induced by an applied force.

With regard to the influence of mineralogical identities and absorbed cations on the shrinkage properties of the clay, it is to be recalled from earlier treatment that the binding power of the Ca⁺⁺ decreased on drying while that of the Na⁺ increases. On this basis, it is expected that the Na-clays would reach a slightly higher degree of consolidation. Mineralogically, the Montmorillonite will undergo shrinkage due to evaporation of water from within its crystal lattice in addition to shrinkage by consolidation of the particles themselves.
Cohesion versus Per Cent Clay - Previous reference to "minimum porosity of the granular structure" have not defined the term specifically. With respect to the silt used in these experiments, the silt alone at maximum density, has a calculated porosity of 43%, which means that 43% of its bulk volume may be occupied by a clay-water system without disrupting its structure. This factor is particularly significant to the relationships shown in Fig. 9-e.

The silt alone is cohesive to the extent of the meniscus tension of the water within its voids. As clay is added in small increments, the water content required by optimum conditions is still very large in terms of clay content. In fact, it is so large that the clay-water system exists there in a state of fluidity incapable of contributing further cohesion to the silt. As more clay is introduced, the moisture content, with a respect to the clay only, decreases as shown in Fig. 10-b. According to Fig. 10-b, the moisture content of the clay is higher than its Liquid Limit until about 22% clay has been added. Above 22%, the clay very rapidly approaches its Plastic Limit, which serves to explain the sharp inflections in the cohesion curves.

At clay contents above the critical volume, determined by the minimum porosity of the silt, cohesion is no longer dependent upon binding the silt grains together but is dependent upon the cohesion of the clay-water system itself. Throughout this higher range of clay content, cohesion is constant provided the moisture content of the clay is constant which it is assumed to be.
The relationships in Fig. 9-e are magnified by the high porosity of the silt structure. They are further magnified by the absence of material 1 to 5 microns in size. For a well graded granular material, both inflections of the curves would be shifted toward the ordinate by decreasing the porosity of the granular structure. This is confirmed by Fig. 10-c which shows the relationship between cohesion and percentage clay derived from combinations of an Illite clay with a graded granular material including the 1 to 5 micron range.

The first flat portion of the curves is also magnified by the specific condition of optimum moisture content. In contrast to this condition, Fig. 10-f (14) serves to indicate the character of the curves that might have been obtained had the samples, so prepared, been air-dried before testing. Fig. 10-f implies that as the moisture content, in this range of clay-content, is reduced; the relationship between cohesion and clay content resolves into a direct proportionality to the point where the clay becomes the controlling factor.

Fig. 10-e (13) further exemplifies the influences of varying the moisture content of clay occupying the voids of a granular structure. The relationships shown here were derived from combinations of a Na-Montmorillonite clay and sand. Each increment of clay defines a curve relating compressive strength to per cent tempering water, expressed as per cent dry weight of the sample. Actually, Fig. 10-e can not be compared directly with Fig. 9-e since the ordinate of Fig. 10-e is in terms of compressive strengths rather than cohesion. However, Fig. 10-e is in terms of compressive strengths and shows the same general relationship
with respect to clay content as is shown for cohesion. To that extent the comparison is indirect but none-the-less important.

**Angle of Internal Friction versus Per Cent Clay** - Below the critical minimum porosity of the silt in Fig. 9-f, the angle of internal friction for the mass is determined by the degree of frictional contact existing between the silt grains. As the clay becomes more concentrated with respect to the water in the voids, it departs more and more from a state of fluidity and merges into a state of low plasticity. In doing so, it becomes increasingly capable of lubricating the silt grains which explains the proportional decrease in the angle to about 30% clay content.

As the clay content approaches the minimum porosity of the silt, the angle rapidly become less dependent upon the inter-granular friction of the silt and more dependent on the degree of friction inherent in the clay-water system. As shown in Fig. 9-f, the angle of internal friction for clay-water systems may conceivably exceed that of a granular material, such as silt; depending, of course, upon its moisture content and degree of consolidation.

**SUMMARY**

Throughout the discussion of this group of curves, the most outstanding feature common to all has been the volume relationships existing between the clay-water systems and the void volume of the granular structures. These have shown up repeatedly as critical points of inflection in the curves.
As an approach to soil stabilization, these relationships emphasize the necessity of defining a soil in terms of its clay-water system and granular structure. As an approach to the evaluation of clay-water systems, they confirm the necessity of testing them independently of a granular structure. When tested independently, they demonstrate the profound characteristics inherent in the mineralogical identity of the clay and the extent to which cationic modifications influence the physical properties of clay-water systems.
REFERENCES


