

# PHYSICO-CHEMICAL TESTING OF SOILS AND APPLICATION OF THE RESULTS IN PRACTICE

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## SYNOPSIS

The mechanics of systems composed of granular constituents, liquid and gas phases are dependent to a great extent upon the mechanical and chemical character of their internal surfaces. The electrostatic concept of chemical linkage and other attraction forces permits the formulation of simple theories concerning water affinity of soil particles, and friction and cohesion of soil systems which are in general agreement with experimentally obtained data. The theory indicates the directions in which soil properties can be changed by physico-chemically active admixtures such as soluble salts, bituminous materials and portland cement. Besides offering help for the explanation and correlation of phenomena which were hitherto thought contradictory, the theoretical concept and the accumulated experimental results may serve as valuable guides in the future development of soil stabilization.

The Committee on Physico-Chemical Testing of Soils is concerned with the exploration of the influence of the amount and character of internal surface on the physical properties of soils, and with the application of this knowledge to soil engineering. The work, thus defined, involves the application of fundamental and intrinsically simple physical and chemical principles to complex systems. Because of this complexity, a judicious attitude based upon intimate familiarity with soils is required for progress in this field beside a knowledge of physics and chemistry.

The three main questions for which answers are sought by the committee are:

(1) What factors determine the physical properties of the solid soil constituents, especially their behavior toward water?

(2) To what extent can the physical properties of soil systems be predicted from the properties of the constituent particles?

(3) What physical and chemical properties of the soil constituents determine the susceptibility of a particular soil to stabilization by the available methods?

In the following an attempt is made to give such answers to these questions as are available and can be coordinated into a simple theory at the present time.

## FACTORS DETERMINING THE THICKNESS AND STRUCTURE OF WATER FILMS ADSORBED BY SINGLE SOIL PARTICLES

Since the concept of chemical linkage as an electrostatic phenomenon has been introduced by Kossel into inorganic chemistry, the adsorptive forces which exist on the surface of solids have become easily explainable as due to surface ions or to scattered valences. In both cases, electric fields are formed surrounding the solid particle. If the solid particle is suspended in water its surface may release ions into the latter, because of the affinity of ions for water; or it may collect ions from the surrounding liquid; or it may simply attract and orient the water dipoles around itself. If the particle becomes surrounded by ions, the latter together with adsorbed water dipoles may be so strongly attached to the solid as to become part of a micelle, consisting of the solid and the surrounding swarm ions. The micelle represents a swollen soil particle. The distribution of swarm

ions around a spherical particle of uniform charge indicating its swelling capacity, has been calculated by Ducleaux (1)<sup>1</sup> under the assumption that the kinetic dispersing forces and the electric attraction forces must balance each other. This calculation gave the concentration "C" of ions as a function of the distance from the surface of the spherical particle as:

$$C = A.e^* \frac{Pp^2e^2N}{KRT} \frac{1}{r}, \text{ wherein:}$$

A = a constant

$e^*$  = base of natural logarithms

P = number of swarm ions

p = charge of swarm ions

e = elementary electric charge

N = Avogadro number

C = number of ions per unit volume

K = di-electric constant of liquid

R = gas constant

T = absolute temperature

Since most of the fine soil constituents possess a plate-like structure instead of a spherical one, Winterkorn has calculated the distribution of ions on a uniformly charged plane surface using the same assumptions concerning kinetic-electric balance as Ducleaux (2). He obtained the following expression for the ionic concentration at a distance r from the electrically charged plane surface:

$C = Br^k$ , where B and k are constants, the latter being found so small as to be practically 0, and consequently  $r^k = 1$ . This means that in the latter case the concentration of the ions is not a function of the distance from the surface. It should be kept in mind, however, that these equations are concerned with ideal cases. Actually, an ideal plane field will never be encountered on the surface of colloidal granules. Moreover, if it should exist close to the surface it would be dispersed with increasing distance, because of the limited size of the plane as well as the

fact that the electrical force lines end in the swarm ions. While the practical limitations of the presented theory must be realized, it gives a good explanation

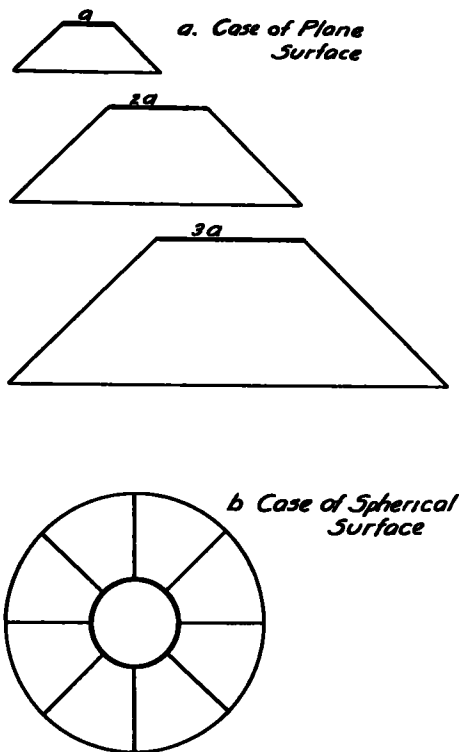


Figure 1. a. Plane surface. Decrease of potential with increasing distance from surface as a function of the size of the surface.

If. (1) Force per unit surface is constant

(2) Angle of dispersion of force = 45 deg

(3) The dispersion is uniform.

Then: Depth for reduction of unit force to one-third of its original value is a, 2a, and 3a respectively

b. Spherical surface. Rapid decrease of intensity of force-field with increasing distance from particle.

for the enormous swelling capacities which plate-shaped, uniformly charged particles like those of bentonite possess. The swelling capacities of most soil colloids lie between those treated by

<sup>1</sup> Figures in parentheses refer to list of references at end.

Ducleaux and Winterkorn, respectively. If the crystal lattice and, consequently, the electric surface structure of a soil colloid is known, calculation of the swelling capacity is theoretically possible.

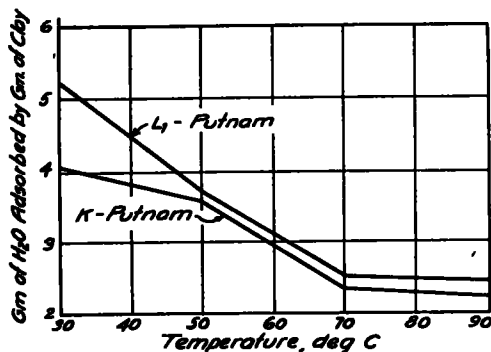


Figure 2. Energy structure of adsorbed water films as a function of type of exchange ion, as revealed by hydration at different temperatures (from viscosity data).

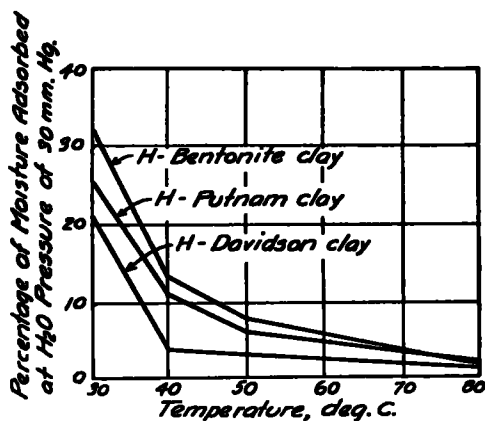


Figure 3. Energy structure of adsorbed water films as a function of colloid, revealed by adsorption from vapor phase at different temperatures.

This calculation should not present too many practical difficulties. Such a procedure should also be possible for soil particles which owe their surface field, not to definite surface ions, but to scattered valences as is the case with silica

grains. For the latter, the same general concept of the dispersion of the electric field as a function of size and shape of the particle holds true, as was treated for surfaces containing ions. The illustration in Figure 1 indicates that the thickness of water films on quartz grains, adsorbed under comparable conditions of temperature and vapor pressure, should increase with increasing particle size. The correctness of this deduction is evidenced by the data on water adsorption as related to particle size which were obtained by Dobeneck (3) as far back as 1892. The energy structure of moisture films as a function of the type of the particle and of its adsorbed ions is given in Figures 2 and 3.

#### FACTORS AFFECTING THE PHYSICAL PROPERTIES OF SYSTEMS MADE UP OF SOIL PARTICLES, AIR, AND WATER

Natural soil systems are composed of solid, liquid and gaseous phases. Every one of these contributes its share to the physical properties of the soil. The effect of the solid particles, as the most tangible component, has been most thoroughly investigated. Early, the properties of friction and interlocking were found associated with the coarser grained material, that of cohesion with the finer grained material. The latter property was found dependent on the presence of moisture films which gave rise to either:

(a) Apparent cohesion due to the water-air interfacial tension of water wedges between soil particles, vanishing with the obliteration of the interfaces;

(b) True cohesion by means of chains of oriental water dipoles connecting positive charges on one particle with negative ones on the next. These chains shorten with moisture loss at increasing temperatures and may become part of a chemical con-

nection between the particles at baking temperatures;

(c) A combination of apparent and true cohesion, this being the most common.

Since the cohesion of a soil is functionally connected with the thickness and structure of the moisture films around its constituent particles, a change of the structure of these films by changing the

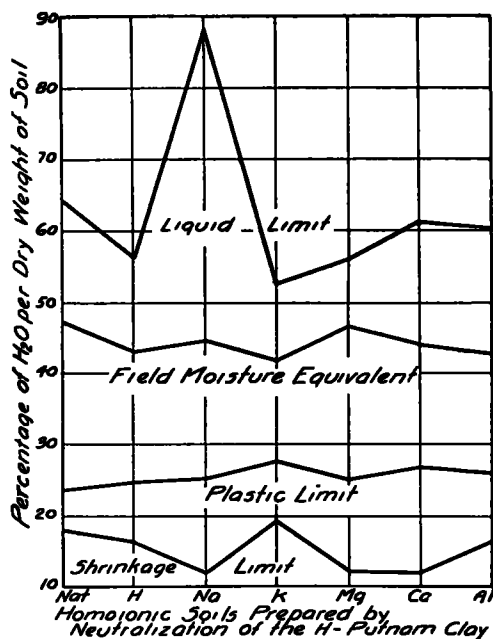


Figure 4. Effect of exchange of ions on adsorption energy for water as expressed by the subgrade soil constants.

electric surface field is bound to result in a change of the cohesion of the soil. The surface field can be changed by substitution of ions for those already present in the soil. The cohesive behavior of a soil finds its expression in its plastic and liquid limit, respectively. Data on the change of subgrade soil constants by ionic substitution have been reported previously (4). However, these did not lend themselves to thorough theoretical

analysis, since the substitution had been effected by elutriation with a possible chance of anionic effects clouding those due to the cations. Figure 4 presents data on the effect of cations on subgrade soil constants which were obtained on homoionic soils prepared by neutralization of the hydrogen system with the hydroxides of the respective cations. The consistency properties exhibited by homoionic soils are expressions of the thickness and energy structure of the water films of the component particles. The structure of the films present in the system is necessarily influenced by the electric fields of adjoining particles, and is not identical with that of a single particle suspended in water. Therefore, the quantitative prediction of the cohesive properties of soil systems based solely on the knowledge of the moisture films of their component particles meets as yet unsurmountable difficulties. However, qualitative predictions can be and have been made (5). They can be summarized as follows: particles with like and uniform electric surface fields will repel each other (no true cohesion); those with uniform but oppositely charged fields will attract each other (true cohesion); also, those with non-uniform surface fields may attract each other (true cohesion). To what extent these attractions and repulsions will take place depends upon the amounts and valencies of adsorbed ions which, together with the water dipoles, are the carriers of the electric field.

One of the important physical properties of a soil is its shear resistance. The value for shear resistance is for coarse grained materials directly proportional to the normal pressure, while for cohesive materials the shear-pressure relationship is more complex. In the early days of soil mechanics, the shearing resistance of cohesive soils was assumed to be due to two components, the frictional and

the cohesion. The relationship was expressed as follows

$$\text{Shear resistance} = \text{cohesion} + \text{normal load} \times \text{coefficient of friction}$$

Experiments soon showed that this relationship does not always hold true; the cohesion of a soil is not a constant, rather it varies with the state of consolidation. Figure 5 presents the typical relationship between shear resistance and load of compression, indicating the

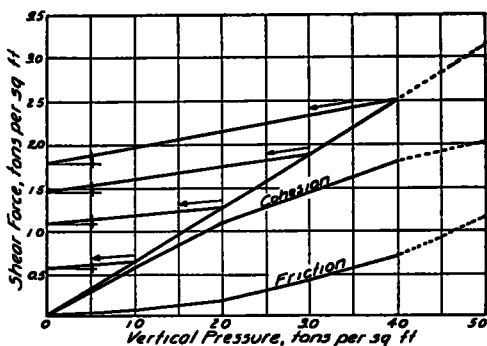


Figure 5. Friction and cohesion as functions of consolidation load (derived from typical shear test curve for cohesive soils. Hogentogler: *Engin. Prop. of Soils*, page 214). Separation and extrapolation of friction and cohesion data indicate that both, cohesion and the angle of friction increase with increasing pressure to a certain limit, whence they continue as constants.

change of cohesion and coefficient of friction with change of precompression of the specimen (6). From the data contained in this curve another set of curves can be derived, expressing the coefficient of friction and the cohesion as functions of the preconsolidation load. The cohesion increases with increasing consolidation pressure approaching a constant value, whence it appears to be unaffected by further increase in pressure. The coefficient of friction increases to a constant value which is also the coefficient of shear resistance for higher pressures. This result, which might be

surprising to the formalistically minded, is the only rational one if the film properties of the component particles are considered. If two particles connected by chains of polar ions approach each other their attraction increases up to a certain point at which their respective parts of the films are so strongly held that they behave as elastic solids. Further compression would result in rapidly rising repulsive forces. This explains the behavior of the cohesion component of the shear resistance-pressure relationship. The coefficient of friction also increases with increasing closeness of the particles. At large moisture contents and great separation of the particles from each other, for instance at the liquid limit, shearing involves only the relative movement of water layers over each other. The coefficient of friction for water is very small. At increasing closeness the plane of shear will go successively through plastic and semi-solid water films until the mineral surfaces or the solidified water layers of the particles touch each other. From this point on the coefficient of friction is a constant. It is this latter value which the engineer usually has in mind when talking about friction. Since all soil components from the finest to the coarsest sizes contain adsorbed water and/or air films, there exists no fundamental difference between frictional and non-frictional material. If a dividing line is to be established frictional material in the engineering sense might be defined as of such size and surface character that mechanical inequalities of the surface are of a greater order of magnitude than the thickness of strongly adsorbed water or air films.

The importance of the effect of adsorbed films on the engineering properties of soils is especially well demonstrated in the case of compacting cohesive soils at different moisture contents by means of a definite amount of work (Proctor compaction). In dry condition the soil

particles are kept apart by adsorbed air films. These may, in extreme cases, the water molecules. There is an intermediate condition where the soil particles

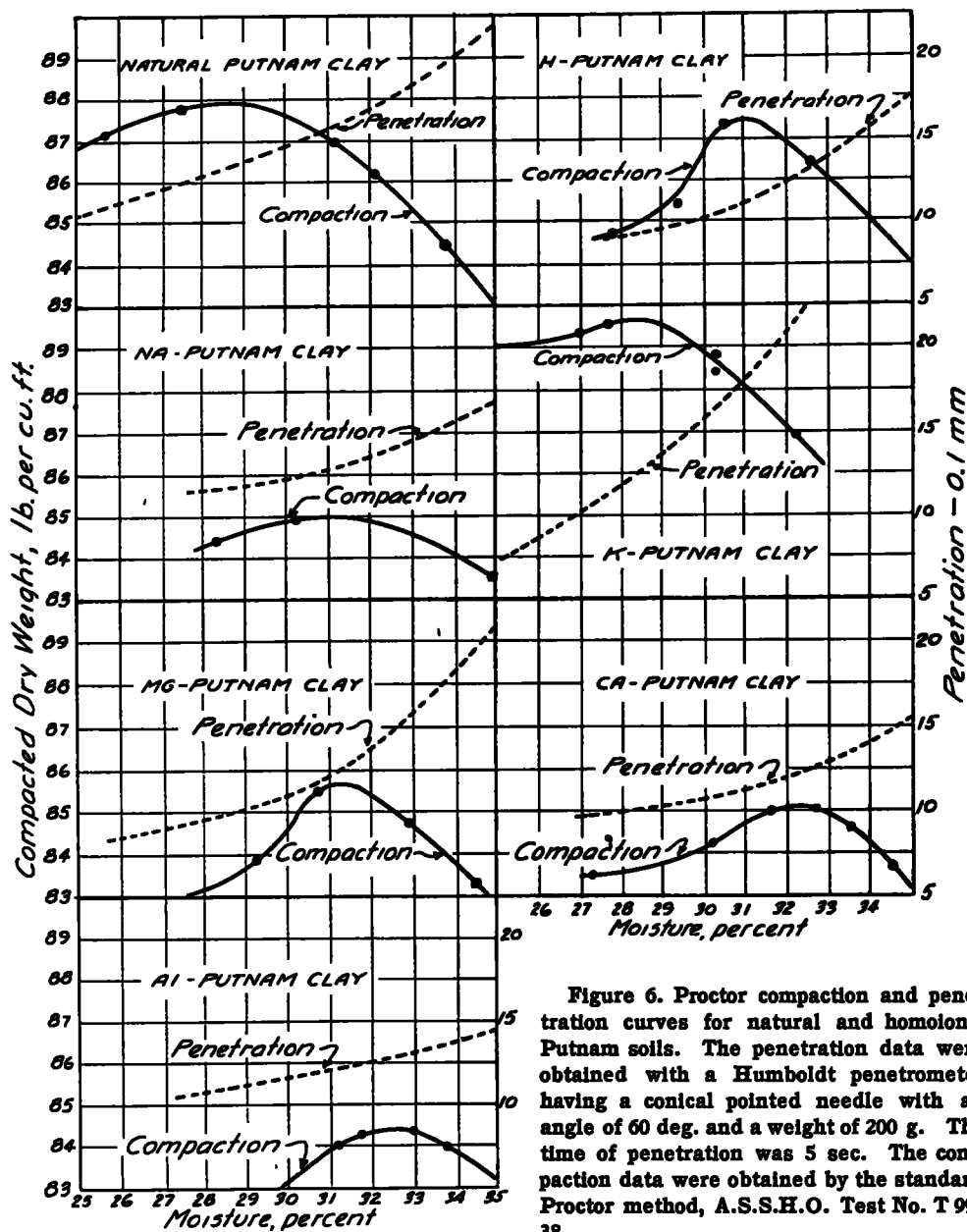


Figure 6. Proctor compaction and penetration curves for natural and homoionic Putnam soils. The penetration data were obtained with a Humboldt penetrometer having a conical pointed needle with an angle of 60 deg. and a weight of 200 g. The time of penetration was 5 sec. The compaction data were obtained by the standard Proctor method, A.S.S.H.O. Test No. T 99-38.

endow the soil with flow properties similar to those of liquids. In very wet condition the particles are kept apart by

possess water-films of such thickness and consistency of the outer layer that they can easily be moved over each other under

the applied force. This is the optimum moisture content for the specific type of compaction employed. For greater force of compaction the optimum moisture content moves, logically, toward smaller values. Since the optimum moisture content is intimately correlated with the structure of the moisture films on the soil particles it should be a function of the type and amount of exchange ions. That

organic matter in the soil. In this case the ionic effects depend to a great extent upon the amount and kind of organic material present. Thus, while the Na-ion usually increases the liquid limit, it decreased that of the surface soil of a Loess Pampaneo which was very rich in elastic organic matter. Adsorption of the Na-ion caused the organic matter to lose some of its resiliency when wet (8).

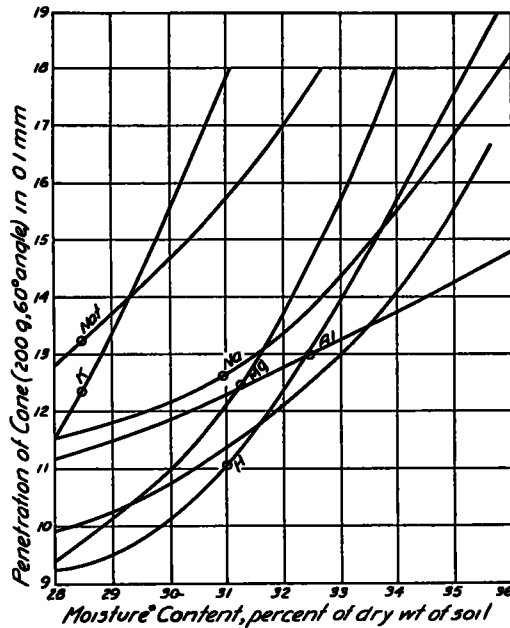


Figure 7. Relationship between penetration and moisture content of natural and homoionic Putnam clays in samples compacted by the Proctor method. Encircled points represent data at optimum moisture content.

this is the case is demonstrated by data obtained by Gibbs (7) on homoionic Putnam soils. These together with penetration data, indicating stability behavior are given in Figures 6 and 7. The theoretical and practical meaning of these data will be thoroughly discussed in a forthcoming publication. At this place it seems sufficient to show the effects of the ionic treatments.

The simple ionic effects on the physical properties of soils may become, and often are, complicated by the presence of

An interesting coordinated effect of living and dead organic matter and exchange ions was observed during the preparation of the homoionic Putnam soils in an aqueous medium.

After the homoionic soil slurries had been standing for a while it was observed that with the Ca modification the normally brownish color of the soil had been changed to a bluish tint, with an accompanying change of the physical properties of the slurry. The other soil modifications showed little (Mg) or no change in

color (A1). The following explanation suggested itself and was subsequently checked experimentally by Dr. Albrecht of the University of Missouri. The Ca-ion stimulated the growth and activity of anaerobic bacteria, which in their turn reduced the ferric compounds in the soil to the ferro-state while oxidizing

#### FACTORS AFFECTING THE STABILIZATION OF COHESIVE SOILS

In the light of the preceding discussions, it becomes clear that specifying certain consistency properties for binder-material in clay-gravel, or sand-clay stabilization specifies at the same time a certain structure of the adsorbed films in

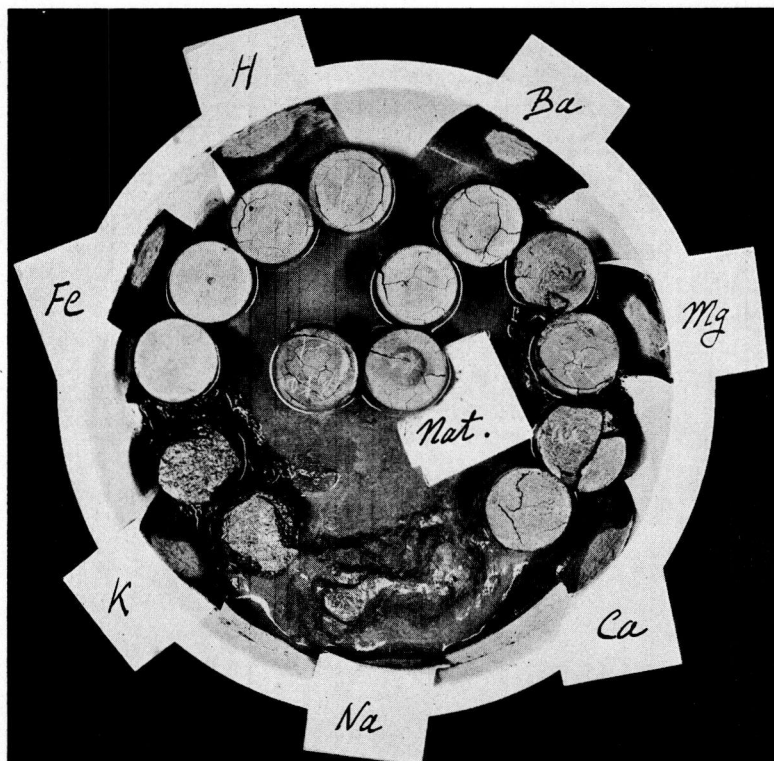


Figure 8. Effectiveness of bituminous soil stabilization as a function of the exchange ions.  
Appearance of bitumen-treated Putnam silt loam after 36 days immersion

the organic matter in the soil. Loss of organic matter and the presence of the ferro-ions changed the physical properties of the soil. Decrease of stability in earth fills containing compacted surface soil, which has recently given much trouble on some old roads in Missouri, is probably due to some such bacterial action.

the binder. Consideration of the affinity relationship of particles of different surface-chemical character indicates that for different types of sand and other aggregate different sets of specifications should be used for best results. While the effect of the surface-chemical character of the soil binder material is only an indirect one in the above described



application, it becomes direct and of greatest importance in such types of soil stabilization which involve surface-chemical and chemical reactions. Among the latter can be counted, treatment with soluble salts, which may or may not form insoluble compounds in the soil, bituminous stabilization, and hardening by means of portland cement. A recently concluded investigation on the physico-chemical factors of importance in bituminous soil stabilization (9) has shown the determining influence of the surface-chemical character of those soil components which contribute most to its internal surface. It was found that the smaller the silica-sesquioxide ratio of these particles and the greater the valency of their adsorbed ions the more easily could these soils be stabilized by means of bitumen. Figure 8 demonstrates the effect of the type of exchange ions present in the soil on its susceptibility to bituminous stabilization. With some soils containing organic matter, the Ca-modification did not quite place in accordance with the bivalent nature of their ions. This might have been due, at least in part, to the action of anaerobic bacteria similar to that described above. Exploratory work by the Missouri State Highway Department has indicated a considerable effect of the surface-chemical composition of soils on their susceptibility to stabilization by means of portland cement. Research on this problem is now being carried on cooperatively by the State Highway Department and the Engineering Experiment Station of the University of Missouri.

It is evident that this presentation of theoretical and practical results of physico-chemical testing could paint only the high-lights of the picture. Nevertheless, it is hoped it will be sufficient to stimulate interest and research in this field. If the future development of soil mechanics is envisaged, it appears probable that many of the outstanding problems must depend for their solution on the help which surface chemistry and especially the concept of linkage as an electrostatic phenomenon, can give.

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