

Engineering Pedology and Soil Stabilization

F. L. D. WOOLTORTON, Planning Engineer
Public Works Department of Nairobi, Kenya Colony, East Africa

Introductory Remarks by the Chairman: The chairman became acquainted with Wooltorton's work during the early thirties when the colonel wrestled with problems of road construction in tropical regions as executive engineer in Shwebo, Burma. At that time, American and Western soil engineering did not appreciate or even recognize the extreme phenomena occurring in the formation of tropical soils and in roads built on and of such soils.

Wooltorton learned the hard way about the nonapplicability to his problems of many of our "standard" tests and procedures and about the limitations of soil mechanics as commonly conceived. His search for understanding as a basis of rational design methods led him to the use of pedological information and methodology. The latter, however, were often in a form alien to the civil engineering practitioner. To bring them into such form required many years of intensive studies and of hard practical work. How well Wooltorton has succeeded is evident from his recent book on "The Scientific Basis of Road Design," and in his contribution to this symposium.

While other engineers have been employing pedological tools for better and more-economical road construction, this use was in the main restricted to pedological soil-identification procedures and to the supplementation of the information contained in pedological soil maps with more quantitative engineering data. Wooltorton's contribution goes much farther than this. He realized that the dynamic factors that formed a soil and gave it its pedological characteristics continue to act, though in a modified form, in the soil-subgrade-base-pavement system and determine to a large extent the quality and the durability of this system. As the result mainly of his efforts, a new engineering discipline, "engineering pedology" was born. What this discipline is and what it can do for scientific soil stabilization is ably presented in the paper which follows.

● THERE is some confusion over what is meant by the word "pedology."¹ The appropriate root is the Greek word 'pedo' meaning 'ground'. Pedology is described by one of the greatest teachers Jacob S. Joffe (1) as "a branch of soil science of the science of soils. Its scope is the study of the phenomena presented to us by the soil body in its natural position." By "natural position" is meant that particular position in which it is desired to study the phenomena presented. In pure pedology, this position would be the undisturbed insitu position. In road engineering it would be either the undisturbed (as in cuttings) or some variation of the disturbed state (as in embankments).

Engineering pedology thus becomes the science of investigating soil engineering problems, making use of all natural laws known to be operative under the particular and specific conditions prevailing.

As, in its wider sense, soil material includes rock and any other soil-forming

¹The word is pēdology and not pēdology or paedology used for the study of children.

material, engineering pedology may be considered to embrace the study of all problems pertaining to any structural unit in any type of road pavement. It is true that cement, bitumen, and other chemical additives of various kinds cannot be included amongst the soil-forming materials, but the laws governing the behavior of a road unit into which they may have been incorporated are, in general, the same as those pertaining to units formed entirely of soil. Such natural laws as those governing ionic exchange, dipole exchange, adhesion, cohesion, energy conditions as illustrated by changes in moisture content, friction and permeability etc; or, in other words, those natural laws governing stability and changes in stability are applicable, in varying degrees, to all such materials.

It is not intended to suggest that engineering pedology supplants road soil mechanics, for it does not. In the overall picture the two are complementary.

Engineering pedology supplies the scientific background to road soil mechanics, acts as a guide and control in the general

application or soil mechanics, and supplies a medium for a type of basic research and of testing generally outside the scope of orthodox soil mechanics.

CONCEPT OF ENGINEERING PEDOLOGY

It is impossible to say who was the first researcher to use pedology as an aid in solving road problems. The approach, however, is not a new one. It is known that Olaf Stokstad of the Michigan Highway Department made use of pedology in engineering studies of highway problems as related to soils as early as 1924;² that its use was advocated during the Montana National Bituminous Conference, 1938; that L.D. Hicks of the North Carolina State Highway and Public Works Commission used it in the early forties, if not before; that a large number of states have made use of its methods; that Hans F. Winterkorn, of Princeton University, has constantly made use of this approach since the early 30's; and that it featured materially in a report by Harold Allen, of the Bureau of Public Roads, in 1945. During 1934 Wooltorton was forced to adopt the pedological approach for investigating a problem of soil movements, because the soil mechanics of those days was unable to assist him towards a solution.

The conception of the expression "engineering pedology" can, it is believed, be accredited to Winterkorn, who first used the term early in 1944. It is likely that the science, as a science, first took form and evolved its philosophy during discussions at Princeton later in the same year, at which time a program of basic research necessary for its development was outlined.

It is only right to record here that such an approach to the solution of soil-engineering problems has been persistently advocated in the past by many soil scientists, and that one of the first engineers to encourage its use was the greatly experienced and far-sighted American road engineer the late C. A. Hogentogler of the Bureau of Public Roads.

NECESSITY FOR ENGINEERING PEDOLOGY

Objection may be taken to the use of the expression "engineering pedology" with

²In 1926 Charles Kellogg made a detailed soil survey of roads in and on behalf of Michigan and included a comprehensive report on the engineering significance of the soils encountered.

reference to road design on the grounds that a satisfactory one exists in that of "soil mechanics."

The author wishes to make it clear that his views on design are founded on his experience of conditions prevailing in tropical countries, where the design-outlook must frequently differ from that tenable in more-temperate regions. And because there cannot be one science of design applicable to tropical climates and another applicable only to temperate climates, he believes there should be only one science, applicable universally, in which design under any climatic condition implies a shift from the consideration of one set of variables to another in the overall scale of variables controlling design, as an all-embracing science.

Consider for one moment the trouble sometimes caused by roads in a temperate region as a result of one of those occasional long droughts. Under some tropical conditions desiccation is a yearly occurrence.

Consider also what may happen to some lateritic soils on being worked when the soil may change from one which is non-plastic to one with a plastic index of 100 with an accompanying change in an F. M. E. of 60 to one of 250.

The author has recently been informed³ that the swelling pressure of a red Nigerian lateritic soil, containing considerably more montmorillonite than kaolinite, has been measured at 11.5 tons per sq. ft.

Such phenomena are not commonly encountered under temperate climates, but the possibility of their occurrence should be provided for in the science of design and testing.

And yet, orthodox design recommendations, excellent as they are for use in temperate regions, are based on the presence of the moderately active clay mineral illite and the general absence of desiccation, despite, in the latter instance, the warning given to the dangers attendant on desiccation by H. Allen (1a) in 1945.

In terms of testing, orthodox recommendations do not always appear to be satisfactory in the tropics as regards: (1) applicability of base course recommendations for grading and plastic index; (2) reliability of C. B. R. values (determined according to standard specifications); it would seem that they are as likely to be too low as too high; and (3) specifications for the ex-

³By Alexandre Ceresa, consulting engineer, Brussels.

pansion test which do not take cognizance of the possibility of soil desiccation.

Additionally, there is no known scientific background to soil mechanics which will indicate the type of chemical additive (including cement, bitumen, etc.) likely to be most successful in the stabilization of a given soil—which is also a chemical.

For such reasons there is, it is considered, a clear case for a design science which will at once indicate which of the many variables require special consideration and how any specific problem may be most economically solved. In other words, there is a necessity for a scientific background to design based on soil properties. Without such a background successful soil stabilization would appear to be fraught with difficulties and uncertainties.

This requirement is fulfilled by pedology, which, to quote G. W. Robinson (2), "is the study of the soil from the standpoint and by the methods of pure science." It embraces "the study of the physical and chemical properties of a complicated colloidal system" by which soil engineering properties are determined.

These properties are the summation of those of the soil's primary and secondary minerals and the soil's organic matter as modified by the soil's air, containing impurities; the soil's moisture, containing substances in colloidal and true solution; and by the soil's artificial or natural structure.

With the exception of those of the primary minerals, dependent on the nature of the parent material, the properties are functions of the parent material and the climate, the movement of moisture within the soil profile, and the maximum and minimum values of the moisture content at the level under consideration.

The climatic and other controls mean that the overall properties will vary with the great soil group to which the soil belongs and with the horizon from which any sample may be obtained. This has been recognized, in particular, by the State of Michigan.

With such a philosophy, the emphasis is more on the properties suggested by the great soil group to which any sample belongs, which indicate the nature of the desirable testing, than on a standardized system of testing expected to indicate these properties.

It is realized that all the phenomena discussed in this paper are known and have all been investigated. In fact, much of the information utilized in the statements made has been obtained from U.S. research publications. It is also, however, known that the only specifications widely publicized are those really only applicable to the more-temperate climates; and that no instance can be brought to mind where any country outside Europe and the United States has not experienced an extensive crop of road failures following the introduction of modern methods of road design.

Roads sincerely designed and as conscientiously constructed have failed.

There are a number of reasons for such failures not obvious from the soil mechanics approach to design:

1. Those resulting from variations from the general conditions of design as some climatic condition not envisaged under the orthodox design recommendations.

Looked at from a slightly different angle, road soil mechanics is a habit which has been tailored to fit a specific body or set of conditions. When the body differs appreciably from the specific body, the habit no longer comfortably fits and some modification becomes necessary.

Road soil mechanics has been developed for use in connection with the so-called average or leached podsollic soils of the United States and Western Europe, where certain conditions represented by aspects of moisture content variations, the nature of predominant clay minerals, the base exchange capacity and the kind of replaceable bases present, tend to follow a similar pattern and to imply the presence of a constant in the various design correlations. The importance of these conditions existing as an apriori to the applicability of orthodox design recommendations cannot be ignored. If this pattern does not pertain then additional variables are introduced and design procedure may logically have to be modified.

Designers, working on new ground outside the United States and Western Europe, tend to be unconscious, though not necessarily unaware, of all the various phenomena which may, in general, be active under any given set of conditions; they forget the physical implications of the empirical tests and, consequently, fail to analyze how far these implications satisfy the requirements of the possible variables.

Such phenomena, arising out of climatic conditions differing from those normally associated with "average" soils, are considered responsible for occasional failures in temperate regions and for more frequent failures in the tropics.

2. Those resulting from insufficient attention being given to incremental stability, or micro-design.

Micro-design concerns the relative stability of various combinations of adjoining ions, molecules, ultramicrons, micelles or particles etc. in both two phase and, when water may be present, in three phase systems.

Micro-design possibly plays a more important part in road design than in any other branch of structural design and, unfortunately, is an aspect of design generally scamped by the limitations of normal design procedure. In soil stabilization designs, it is an aspect which increases in importance as the properties of the soil material diverge from those of average soils.

Soil science and the chemical sciences supply the chemical and surface-chemical properties of the ingredients of any soil material and those of any additive. From these data the physical chemist can estimate, by the application of the principles of surface chemistry, such properties as adhesion and cohesion in any mixture of the two.

The properties of the constituents of various mixtures enable the different combinations to be graded, in a predictive way, in their probable relative order of suitability for any road structural unit. In particular, they make it possible to eliminate certain combinations as positively unsuitable. This, in itself, is a great time saver by avoiding unproductive experiments.

Additionally, for any given soil material, surface-chemistry predicts the type of properties required by an additive to ensure permanent stability and will indicate, when its applications are more developed, which one of the various types of additives will give the best and most permanent results.

This aspect of research and design which is in the process of being developed in several parts of the world is leading up to an electro-chemical theory of road design. The necessity for engineering pedology or for pedological engineering, as it will henceforth be referred to, is the

necessity for a philosophy, a theory of the strength of road-making materials, and a theory of design which can be applied to any type of material under any climatic condition. A philosophy which will avoid, with reasonable constructional care, the possibility of any failure: a philosophy which will enable a road pavement to be designed and built with the same ease and certitude of economy and safety applicable to any building in structural steel or reinforced concrete.

It would be incorrect to suggest that all these aims have been achieved. It would, however, be fair to claim that during the short period of 10 years, during which the science of engineering pedology has been under development, much of its required theory has been outlined and great inroads have been made towards an understanding of certain aspects of this theory.

The purpose of this paper is to present the author's outlook on the design approach with a view to eliminate the repetition of certain types of road failure believed to be of a climatic origin; the excuse is the unprecedented contribution to the good of mankind expressed by American goodwill in aid to undeveloped countries.

It is impossible to review all aspects of the design approach; some only, representing those of more-common application, will be considered. Further information is obtainable from "The Scientific Basis of Road Design" (3) and, doubtless, from other sections of this symposium.

PEDOLOGICAL ENGINEERING AS APPLIED TO SHALLOW FOUNDATIONS

Philosophy of Pedological Engineering

The philosophy of pedological engineering does not admit that the properties of soils can always be adequately determined by a fixed routine of testing in the same way as is applicable to other engineering materials as concrete or steelwork. On a national basis, where there is not necessarily a great variation in soil material, this may perhaps be possible, but pedology knows no boundaries, its scope is global and it embraces all kinds of soil.

Soils representative of the great soil groups are, to the pedologist, each a different material with differing characteristics which do not necessarily respond to a standardized and simplified system of

testing. Like the human body, with which soils have been so frequently likened, the actions and reactions of such soils are not subject to precise prediction from a knowledge of a few of their characteristics but must be treated more as those of individuals, each subject to divergent environmental influences.

In many respects the representatives may be considered as complex chemical substances. The closer one approaches the tropics and the more intense the weathering process, the more-obvious this comparison becomes. It is in such regions that one is most likely to find extremes of character or extensive horizons of secondary silicates, oxides, and hydroxides.

Each of these soils, formed and found under differing climatic and drainage conditions, varies in some way or ways from the others. They vary in their genesis, in their structure, and in their physical and chemical properties where all are in a great measure functions of their environment—their external and internal climate.

It is the summation of these characteristics and properties which is so important in all problems associated with shallow foundations.

Pedological engineering bases its investigations on such data and tends to treat each problem as initially one of soil chemistry and soil physics. It is in this respect that the pedological engineering approach differs so much from that of soil mechanics.

The following examples illustrate what the pedological engineer has in mind by these climatic, structural and chemical factors:

1. Under temperate climates, where rain falls intermittently throughout the year, the moisture content of the undisturbed subsoil does not fluctuate appreciably from the soil's plastic limit. This tends to imply the presence of a constant in the design formulas and the possibility of appreciable differential moisture changes, with their attendant volume changes, is ignored and ignored with impunity until one of those cyclical droughts occurs. There is then trouble for the engineer.

Under other climates, as the hot monsoon climate, this virtual constancy of the subsoil moisture content is seldom met. The permanent ground-water table is very low, though a perched water table may exist, during certain months, at a high level.

The result is that the moisture content within an embankment may vary during the year, from some high value to some very low value, comparable more with the shrinkage limit than with the plastic limit. In other words, a moisture-content variable, which cannot be ignored, has now been introduced as an adjunct to design considerations.

(The thought occurs: Is this the real explanation for the more-common occurrence of embankments under tropical than under temperate climates rather than the greater likelihood of flooding?)

2. Though yellow adobe, underlying black adobe soil in California, and yellow kyatti, underlying black cotton soil in Burma are, on the basis of normal testing procedure, very unsuitable soils for a subgrade, yet they can sometimes be successfully used as such or even as a subbase course, provided they are not disturbed and are covered immediately to prevent desiccation, i. e. provided their natural structure and their natural resistance to moisture and volume change are not damaged.

3. The pedological engineer knows that if he has to stabilize a highly active electro-negative clay colloid, as organic-matter-free bentonite, it is unwise to try and use an additive which is also electronegative unless, perhaps, the additive is a complex ionizable salt whose anion contains a strong water-repellant dipole. The simplest solution is to use an electro-positive stabilizer. If he must use an electronegative additive, then he must first change the sign of the colloid to be stabilized by the addition of a chemical reagent. Thus an electro-negative bentonitic clay soil is not likely to be satisfactorily stabilized by an electro-negative bitumen, though it is likely it can be if the sign of the colloid is first changed by the addition of lime—a fact long ago established by Texas Highway Department engineers. Bitumen, on the other hand, would be expected to be a good stabilizer for pure organic-matter-free laterite soils in the same way as it is known to be a good adhesive for crushed limestone.

Some organic matter, oxides and hydroxides, which may themselves be stabilizers, may form coatings around the clay micelles and change the sign of the colloid. Such adventitious matter must, in consequence, be recognized.

Qualifications of a Pedological Engineer

The most-essential asset of a pedological engineer is to know how to interpret data and especially empirical data; to realize fully the conditions under which the data are applicable; to visualize clearly what this data implies; and to know how to interpret the data, which may not be engineering data, into engineering terms.

As examples may be quoted:

The practical and theoretical conditions under which the C. B. R. and similar data are likely to give most reliable information.

The implication of the P. I. data in physical terms with an understandable meaning; and what is meant by saying the P. I. should not exceed a certain value for some specific purpose as, for example, in base course design.

How to interpret and convert the research of soil scientists or, say, the physical-chemist on adhesives into engineering terms and apply these results to further the advance of soil engineering.

The second essential is to know the life history of the individual soil from its embryological stage to that of maturity; to know its anatomy and its circulatory system; to know the various compounds of which it is composed; and to know the properties of those substances. This is not so great a task as might be imagined once the fundamentals of soil genetics have been assimilated.

The important factors here are soil chemistry (especially surface chemistry), soil structure, what controls the movement of moisture, and the equilibrium value of the moisture moved.

The third essential is to know what he is aiming at, what the requirements for a particular design must be and how to effect those requirements.

For design involving embankments and cuttings these are, in general, to determine or to be able to estimate the maximum and minimum moisture contents for the most-vulnerable layer directly below the subgrade, the shear resistance or bearing value of this layer at its maximum moisture content, and the magnitude of the maximum possible distortion of the subgrade under differential moisture changes.

For the simplest types of base course, featuring only mechanical stabilization, the requirements are the avoidance of any

overall volume change and a sufficiency of mechanical strength to be provided by the coarse fraction.

For stabilized units, involving the incorporation of chemical admixtures, the problem is initially one of chemical design to be proven later in volume change, strength, and durability by testing.

In each instance the maximum possible moisture content is important. In consequence, the laws promoting moisture flow and controlling moisture equilibrium are of importance. Chemistry tends to eliminate the trial-and-error methods associated with road soil mechanics and indicates the kind of stabilizer most likely to give the best results.

THE GREAT SOIL GROUPS

Weathering of Soil-Forming Material

Soil is formed by the physical and chemical weathering of such soil-forming parent material as solid rock, boulders, gravel, sand loess, and alluvium.

By physical weathering is meant the disintegrating effects of various physical forces as those produced by frost action, temperature changes, differential swelling (as within parent rock material on the decomposition of some of its mineral constituents), the erosive action of winds, glaciers, rivers and seas, and the volume change effects of roots, lichens, etc.

Chemical weathering, or decomposition, includes the processes of solution, hydration, dehydration, carbonation, decarbonation, oxidation and reduction in which microorganic activity may play an important role. Of these processes, hydrolysis is generally by far the most-important factor.

Chemical weathering is sustained by moisture within the soil and is accelerated by increase in the mean annual temperature, i. e., it can be many times more rapid under a tropical than under a temperate climate for comparable conditions of rainfall.

Moisture is introduced into the soil profile by rain or by flooding, when it tends to percolate and flow down the profile under gravity and capillary forces and, possibly, under film and vapor flow. The more permeable the soil and the greater the rainfall—provided it is not in the form of heavy tropical downpours of high intensity but of

short duration when comparatively little will (under reasonably good surface drainage conditions) enter the profile—the deeper will the moisture penetrate.

In addition to this downward movement there is an often equally important upward flow from the permanent water table or from some temporary perched water table.

In both instances there appears to be some interchangeability between the various phases in which the moisture flows.

Moisture, other than that actually in the vapor state, moving in either direction contains chemical substances in solution which may accelerate hydrolysis.

Rainwater contains impurities of an acidic nature dissolved from the atmosphere. On entering the soil profile, its acidity and carbon dioxide content may be increased on passing through any layer of humus, or partly decomposed organic matter. As this moisture, which may now also contain humic acids, flows down the profile of a young soil, it dissolves out some of the more-soluble salts (as the chlorides and sulphates of the alkali metals) to remove them in soil drainage or to deposit them, with any humic residues in suspension, reversibly or irreversibly, in an horizon at the limits of downward movement.

As weathering proceeds and the profile matures, the tendency (especially under a temperate climate) is for these salts to be wholly removed. With the removal of the more-soluble salts from the upper horizons, the neutralizing effects which these salts may have on the acidity of the soil moisture decreases. With the usually accompanying increased acidity of the surface layer containing humic substances, the downward flowing soil moisture tends to become more acid. The less-soluble salts, as the sulphates and carbonates of calcium, are then attacked, mobilized, translocated and deposited at some lower depth to be gradually removed by drainage as the soil ages.

Finally, the clay particles themselves are subjected to hydrolysis or decomposition forces in which the complex silicates tend to be broken down into sesquioxides and silica. Under suitable conditions promoting high acidity, or low pH value, the sesquioxides may also be translocated. If the reaction is alkaline, the silica and not the sesquioxides may be removed.

In contrast to the acidic nature of the

downward-moving moisture stream, the upward-moving stream will tend to be of an alkaline reaction, where the pH generally will be the greater the younger the soil. The effect of this flow, which only occurs during fine weather, will be to return the more-soluble and incidentally more-alkaline products of hydrolysis, as sodium and calcium hydroxide, temporarily to a higher zone. The effect of this upward movement of an alkaline solution containing hydroxides is a tendency towards a destruction of any soil structure and a dispersion of the clay fraction. If the solution be weakly acid, instead of alkaline, there will be a tendency to dissolve iron and aluminum salts from the lower layers, to translocate them in an upward direction, and as evaporation proceeds, to deposit them irreversibly in an horizon of accumulation.

In addition to the more-mechanical effects of leaching and deposition discussed, there is another aspect of soil weathering which is of importance.

The soil fraction most susceptible to weathering effects is the clay fraction composed of small particles, or micelles, of a crystalline mineral nature. The surfaces of these particles contain unsatisfied electrical charges which are satisfied by relatively loosely held ions. These ions may be cations or anions, depending on the sign of the charges, but for most clay minerals they are preponderatingly cations. The ions so adsorbed are partly dissociated when the soil is in an aqueous solution and are available for exchange by ions with a greater affinity for the mineral surface than is possessed by such ions.

In general terms, the more-common clay minerals may be considered as hydrated alumino-silicates in which the nucleous, or the mass of the micelle, may be considered to be a rather complex electro-negatively charged silicate acting as an anion. Around the surface of this nucleous are attached, by electrostatic force, electropositive cations of the earth bases (as in a young cohesive soil) of sodium, potassium, calcium, and magnesium.

These mineral units, though in equilibrium with their aqueous phase for the prevailing pH conditions, are still chemically active. If the pH changes, then the mineralogical character of the micelle changes. It thus happens that the clay mineral is but seldom one of the known pure clay minerals

but is more generally an impure mineral occupying some intermediate position in the scale of pure minerals. Likewise, the surface-adsorbed bases are subject to change.

Of the adsorbed bases, one is usually in predominance and imparts to the clay fraction the properties attributable to a clay fraction composed entirely of clay saturated with that base, though there are examples where the properties of the fraction are controlled by more than one base.

Young clay fractions are generally saturated either with sodium or calcium, depending to some extent on the nature of the parent material.

As the soil solution containing acids and dissolved bases moves through the soil profile, it reacts on the surfaces of the clay material, by base exchange, and the tendency is to change, as weathering proceeds and the pH decreases, the surface adsorbed bases progressively from, say, sodium to calcium to hydrogen (sometimes more accurately given as aluminum) with an accompanying change in physical as well as in chemical properties.

As soon as hydrogen-ions begin to replace cations of the earth bases, the clay is said to be unsaturated. This can only occur after all free calcium carbonate has been leached out of the soil profile.

When all the adsorbed earth bases are replaced by hydrogen, the clay is desaturated and acid hydrolysis is most active.

Some heavily weathered soils, as the lateritic soils of the humid tropics, are amphoteric. Their makeup is such that below a certain pH value, known as the isoelectric point, they act as electropositive colloids and dissociate mainly anions, while for pH values above the isoelectric point they act as electronegative colloids and dissociate mainly cations. This characteristic is of importance when seeking a stabilizer for such soils.

The most-mature soils of the humid tropics contain an horizon of sesquioxide material, or pure laterites. This material, though of a mineral nature, is not colloidal but forms a solid. It acts as if electropositively charged in much the same way as does limestone.

Soil Weathering or Soil-Forming Processes

The overall effect of any particular process will depend upon the relative impor-

tance to be given to the two movements of soil solution, i. e., the downward- and the upward-moving solutions.

This, of course, is a function of the climate—the amount of rainfall and the lengths of fine periods together with the temperature. The various processes have been classified as follows:

1. Salinization. Occurs in semiarid and arid regions under a neutral to slightly alkaline weathering process active in soils supporting little vegetation. The downward flow of moisture is of minor importance, and weathering is controlled more by the upward flow carrying sodium salts, calcium, and, sometimes magnesium sulphate and chloride. Evaporation causes an accumulation of these salts at the top of the coarse capillary fringe over the water table. This accumulation layer may be on the surface or fairly deep down the profile, depending on the level of the permanent or the temporary perched water table.

If sodium carbonate or bicarbonate is present, there will be replaceable sodium among the soil bases, and the clay will tend to be dispersed when wet and to be of a single grain type of structure when dry. With appreciable replaceable calcium or magnesium and free salts other than sodium carbonate, the soil may be slightly aggregated and faintly permeable when dry. The little rain which permeates the profile will carry down colloidal clay particles and form a clay-pan horizon under such conditions. Dissolved organic matter residues and calcium salts tend to convert this clay pan to a hard pan by a strong cementation action.

Because of limited rainfall and the impermeable nature of the wet profile, these soils are badly drained. If abundant calcium sulphate and chloride are present, drainage is much better.

2. Alkalization. A weathering process whereby the salts of those soils formed under a process of salinization are removed consequent on improved drainage conditions. As soon as replaceable sodium becomes the predominant replaceable base and the free salts are removed, the clay particles hydrolyze with the liberation of sodium hydroxide, which causes the clay to disperse and become impermeable in the presence of water (by swelling effects). There is then a tendency at the beginning of the rains for clay migration and the formation of a clay pan. The degree of per-

meability may vary during the year. Thus certain salts translocated upwards during the dry season may lead to some aggregation.

3. Dealkalization. With a further improvement in the drainage under which alkalization is operative, the replaceable sodium is removed. If free calcium carbonate is available in the profile, the clay becomes saturated with calcium and possibly subject to the weathering process of calcification. If no calcium is present, the soil will be degraded to a hydrogen soil.

4. Gleization. A process productive, in poorly drained areas, of peat-type soils. Such soils are formed from parent materials which are almost impervious or are normally inundated. If alternatively wet and dry, which is probably more common in the tropics, iron compounds are reduced, causing calcium magnesium and manganese compounds to become soluble. A calcium saturation of about 50 percent is necessary for microbes to effect iron reduction.⁴ In sandy soils the process is somewhat analogous to podsolization and results in the formation of ground-water podsoils in temperate regions, characterized by the presence of a hardpan of organic matter or ironstone above low water level and of ground-water laterites in tropical areas.

5. Laterization. Occurs in the humid tropics under an alkaline changing to acid weathering process or in an area of alternating wet and dry seasons under alternating acid and alkaline leaching conditions. The process infers the decomposition of ferro-alumino-silicate clay minerals and the removal of silica under alkaline weathering. Iron and aluminum remain in the profile, and the accumulation may increase under acid leaching. It thus involves some podzolization. It occurs under forest cover, usually in the hills and more frequently over a suitable rock parent material.

Kaolinitic clays are sometimes found overlying the cemented horizon containing dehydrated sesquioxides of iron and aluminum and generally known to engineers as lateritic soils, the layer above the sesquioxide material may contain montmorillonite.

Under such tropical conditions, the organic matter is rapidly decomposed and plays no part in any cementation process.

6. Calcification. The weathering of a soil profile still containing free calcium

carbonate. It may occur in both temperate and tropical climates of moderate effective rainfall. The free calcium carbonate maintains the colloidal clay in a base-saturated condition and imparts an aggregated granular structure to the soil, hindering the eluviation of clay material and the formation of any pan. Weathering occurs in a slightly alkaline to slightly acid medium and causes the translocation of carbonates to a lower level. The humus is mild and easily decomposed.

Soils formed under such a process are classified as pedocals, i. e., they contain an horizon of carbonates. Representatives are differentiated on the basis of color, organic matter content and the extent and amount of carbonate accumulation (i. e., to a large extent on the effective rainfall).

7. Podsolization. After the removal of free carbonates, the clay complex tends to become unsaturated, and the soil solution increases in acidity. Podsolization occurs in humid tropical or temperate areas and takes place in an acid medium. An acid organic-matter surface layer is formed. The clay fraction is desaturated, dispersed, and hydrolized, resulting in the translocation of clay material, ferro-aluminum, and iron compounds to be deposited at lower and different levels.

In the absence of calcium, the surface organic matter does not support a high bacterial population and its decomposition is thus very slow. Part of the decomposed organic matter dissolves in a favorable medium and combines with iron to form ferrous humates. As such, it is mobile and easily translocated down the profile to be deposited at the limit of translocation.

Soils containing an accumulation layer of iron or aluminum compounds are known as pedolfers.

Azonal Soils

Physical weathering results in the production of very-young soils containing very little clay material and, more generally, consisting of relatively coarse particles. It is responsible for the formation of the azonal (or very young) soils possessing no well-developed profiles and included within the great soil groups under lithosols (rock fragments), sands (dry) and alluvial (mud) soils. Their characteristics are similar to those of their parent materials.

As the size of these particles decreases,

⁴Information supplied by Hans F. Winterkorn (letter).

the surface area per unit of mass increases, and they become more susceptible to chemical weathering. Continued weathering, now of a more-selective nature, gradually reduces the size of the smaller particles. With the accompanying rapid increase in surface area, chemical weathering is greatly accelerated and the tendency is for the finest particles to be converted into material of clay size, though not necessarily yet possessing the properties of colloidal clay. In due course the clay fraction emerges as a clay mineral, generally with the properties of a colloidal clay.

The effects of rain or floodwater on young soils will depend upon whether drainage is relatively free or impeded.

If the drainage is impeded, or initially free but changing to imperfect, the effect is to translocate the finer particles from the surface layer, or Horizon A, to form an accumulation layer, or Horizon B, below. The density depth, and thickness of this accumulation layer will depend upon the intensity and amount of rainfall, or on the frequency and amount of floodwater, the permeability of the parent material, and the stage in weathering reached. Intrazonal soils, or those soils in which normal weathering under the appropriate processes of chemical weathering is hindered by poor drainage or by the absence of free drainage or those soils whose properties are still largely controlled by those of the parent material, are now in the process of formation. They are generally to be found associated with two or more zonal, or mature, soils formed under reasonably good drainage conditions.

Intrazonal Soils

Most of the soils of stunted growth are characterized by an accumulation layer forming a hard pan or clay pan which may be cemented by oxides of iron or silica, by calcium carbonate, or by organic matter. An important factor in such soils is that any clay pan formed may not be sufficiently weathered to exhibit appreciably the properties of a colloidal clay. This particularly applies to the great soil group of planosols.

From here on the weathering of most soil-forming material is mainly chemical and becomes very much a function of the climate (temperature, rainfall, and humidity), which controls the type of vegetation and organic matter produced, and of

drainage conditions.

As long periods of geological time are involved in weathering, it must be realized that changes in topography may occur and that the climatic and drainage conditions under which a soil is initially formed may change with a change in the active weathering process. This results in the ultimate production of a matured soil having characteristics differing from those to be expected from a consideration of the forces originally operative.

Soil profiles, i. e., the soil down to the unweathered parent material, may or may not include a water table. If they do, then in humid regions the controlling movement of the weathering solution is in a downward direction and of an acidic nature. Under such conditions a range of intrazonal soils, included in the great soil groups under the names of "alpine meadow soils" and "meadow soils" (Wiesenböden) are formed under mixed gleization and calcification processes; bog soils are formed under gleization planosols formed under mixed podsolization or laterization and gleization processes; ground-water podsoils are formed under podsolization; and ground-water laterites formed under podsolization and laterization processes are formed where the particular soil formed will depend upon the temperature, rainfall, degree of imperfection of drainage, and profile age.

Under semiarid and arid climates a permanent ground-water table has less opportunity of forming within the depth of the soil profile than under humid conditions. The tendency is then for the downward and upward (from a temporary perched water-table) weathering solutions to be of equal importance or even for the upward leaching to be more important than the downward weathering. Though weathering proceeds, it now tends to do so in an alkaline medium and to maintain the salts within the profile. Under such conditions, the intrazonal soils include the great soil groups of solonchaks or saline soils (salinization), solonetz or alkaline soils (alkalization) and soloths or solote or degraded alkaline soils (dealcalization).

Among the intrazonal soils are also included two very young soils formed under good drainage conditions whose parent material contains sufficient free calcium to enable the clay fraction to remain base saturated under the prevailing weathering system. They are the brown forest soils,

(Braunerde), formed under forest cover of the temperate climates and the rendzinas formed over calcareous material under grass cover in cool to hot, humid to semi-arid climates. In neither instance is there any appreciable accumulation of clay material within the profile.

Zonal Soils

Under original or subsequent conditions of good drainage, the appropriate soil-

forming processes may operate unhindered. The particular process or, sometimes, processes, active in any specific area will depend upon climatic conditions and the age of the soil. In the latter instance one or more processes may have been completed to be followed by the process now observable. These soils have little in common with the parent material from which they are formed.

Consideration of the great soils groups, on the basis of those formed under the

TABLE 1

<u>Rainfall</u>	<u>Temperature Calcification</u>	<u>Great Soil Group</u>
Arid	Temperate to cool	Desert Soils
Arid	Temperate to cool	Sierozems
Arid	Warm-temperate to hot	Red Desert Soils
Arid to semi-arid	Temperate to cool	Brown Soils
Arid to semi-arid	Temperate to hot	Reddish-brown Soils
Semi-arid	Temperate to cool	Chestnut Soils
Semi-arid	Warm-temperate	Reddish-chestnut Soils
Subhumid	Temperate to cool	Chernozem Soils
<u>Calcification with weak Podsolization</u>		
Humid	Temperate to cool	Prairie Soils
Humid to Subhumid	Warm-temperate	Reddish Prairie Soils
<u>Calcification followed by Podsolization</u>		
Sub-humid to humid	Temperate and cool	Degraded Chernozems
<u>Weak Podsolization and some Calcification</u>		
Sub-humid to semiarid	Temperate to warm	Shantung Brown Soils
<u>Podsolization</u>		
Humid	Cool-temperate	Podsols
Humid	Cool-temperate	Brown Podsollic Soils
Humid	Temperate	Gray-Brown Podsollic Soils
<u>Podsolization with some Laterization</u>		
Humid	Warm-temperate to tropical	Yellow Podsollic Soils
<u>Podsolization and Laterization</u>		
Humid	Warm-temperate to tropical	Red Podsollic Soils
Humid (with wet and dry seasons)	Tropical	Yellowish-brown, Reddish-brown Lateritic Soils
Humid (with wet and dry seasons)	Tropical	Laterite

Where:

- Arid infers only sufficient rainfall to support sparse vegetation.
- Humid infers rainfall sufficient to support forest vegetation
- Semiarid infers an intermediate condition of rainfall between arid and sub-humid supporting only scattered short grass or shrubs
- Semihumid infers a rainfall intermediate between semi-arid and humid supporting a moderate to dense growth of short to tall grasses
- Wet infers a rainfall sufficient to support rain-forest vegetation.

various soil forming processes, gives the information in Table 1.

An important factor in design is to recognize, and this is possible from a knowledge of the great soil group to which the soil in question belongs, whether or not the subgrade layer or embankment or cutting is likely to become desiccated.

THE SOIL-GROUP MINERALS

The colloidal clay silicate minerals may be divided within three groups depending upon their activity or ability to adsorb soil bases including moisture:

<u>Clay Mineral Group</u>	<u>Base Exchange Capacity</u>
Kaolin-like	3 - 15 m. e.
Illite-like	20 - 40 m. e.
Montmorillonite-like	60 - 100 m. e.

The secondary clay minerals produced in any soil profile depend upon the nature of the weathering process and the pH of the soil solution.

Minerals of the kaolin group are produced under intensive acid hydrolysis and may characterize such soils as the podsol, podsol, laterite, and lateritic soils. Those of the montmorillonite group characterize such young soils formed under an alkaline weathering system, active in warm to hot climates, as the chestnut, chernozem, degraded chernozem, and solonetz soils.

Illite is more usually found in the soils of intermediate weathering, especially under colder climates. There are beliefs that its presence may be partly due to its existence in the parent material and that under some unknown conditions it may change to montmorillonite (and vice-versa). Illite may be present in lateritic, podsol and podsol soils as an alternative to montmorillonite. Both illite and montmorillonite may be present together in chernozem, gray semi-desert and chestnut soils. Montmorillonite may be found together with kaolin in some laterite and lateritic soils.

The clay minerals can be identified by methods involving X-ray diffraction, dehydration curves, and thermal analysis. These methods, are sometimes used by soil-engineering researchers, but more generally it is considered that the time necessary for their performance is un-

justified. Short cuts are therefore adopted.

With the possible exception of those instances when it is possible to estimate the clay mineral present on the basis of data available from, say, agricultural-research stations, this short-cut approach is to be deplored, for it can lead to false conclusions being drawn from the short-cut data.

If only one clay mineral is present, it can be given a group-name from its base-exchange capacity. In general, however, there is more than one soil mineral present, and properties of the soils may be so different, as a mixture of kaolin and montmorillonite, that it is impossible to determine presence of the soils from such data unless, of course, one is present only in very-small quantities.

The method used more generally is the determination of silica-sesquioxide ratio. This is not so much for recognizing the clay minerals present as for giving an idea of the overall effect of those clay minerals. Thus, a value of less than 1.33 indicates a well-formed laterite and the presence of a clay mineral of the kaolin group; whereas a high value in excess of three will indicate the presence of a mineral of the montmorillonite group and that the clay will have the properties of a montmorillonitic clay. It does not necessarily preclude the presence of other minerals.

In practice, it is not necessary that there be more montmorillonite than kaolinite, for example, to ensure that the clay has the overall properties of a montmorillonitic clay. Very-small proportions are generally sufficient for this.

The base-exchange capacity of a pure clay material containing only one clay mineral is a measure of the electrostatic charges carried by the colloid at the particular pH, usually 7, at which the base-exchange capacity is determined.

The more active the clay, the higher is the base-exchange capacity and the greater the charge held. It would appear that the highly active clays, which are the most-difficult to stabilize, should be fairly easy to stabilize provided a suitable stabilizer is added in sufficient quantities to the soil to neutralize these charges and turn the mixture into a hydrophobic material.

It must be remembered, however, that the amount of stabilizer added is more normally a function of the surface of soil aggregates than of the surface of the clay particles and that design provides for a

controlled amount of moisture absorption for supplying a reserve of cohesion to be drawn upon during dry spells. The number of charges, or the base exchange capacity varies with the pH of the solution in contact with the clay particles and increases with increase in the pH.

It would appear possible that a stabilized mixture found satisfactory under laboratory test might not be found satisfactory in the field. This might be expected to apply most specifically to highly active soils in which detrimental replaceable sodium is most likely to be encountered.

Some lateritic-type soils contain a highly active clay mineral coated with ferric oxide. Such soils are likely to be amphoteric. It is important to select a stabilizer for such soils which will be effective under the pH conditions likely to pertain in the completed pavement or, perhaps, to add a catalyst which will ensure the pH remaining within an optimum range.

ORGANIC MATTER AND HUMUS

Organic matter, or the residue of living matter, consists of carbohydrates (cellulose, hemicellulose, and lignin); proteins, fats, resins, waxes, ash, etc. Cellulose, hemicellulose, and the proteins are readily decomposed, whereas lignin, fats, resins, waxes, and ash are more resistant to decomposition.

Under optimum conditions these residues will rapidly mineralize into water, carbon dioxide, and mineral salts. Under other than ideal conditions, however, an intermediate product is formed known as humus, which may be very resistant to further decomposition.

Humus is a mixture of complex materials, some of which act as natural soil stabilizers. Winterkorn (4) has fully appreciated this possibility and has made use of it in stabilization proposals.

Organic matter may be destroyed by oxidation or other chemical processes. Destruction by oxidation is brought about mainly by the action of such microorganisms as bacteria and fungi.

Bacteria flourish best in a moist but well-aerated soil containing free calcium, which is one of their principle sources of energy and which implies a granular soil structure promoting good aeration. Since oxidation increases with increase in temperature, it is likely to be more rapid in

tropical than temperate climates. Excess moisture prevents good aeration, supports a less-active type of bacteria, and delays decomposition.

Under ideal conditions the decomposition of carbohydrates and proteins is rapid, and little humus is formed. Acids resulting from the percolation of water through such decomposing organic matter are, thus, in the main, restricted to carbonic acid. Under other than ideal conditions, decomposition is slower, and the acids of the percolating soil solution may also include the very-strong humic acid.

Under anaerobic conditions chemical changes occur in the residues of aquatic vegetation, irrespective of the presence or absence of free calcium, to produce the often-acid humus, or the peat, of bog soils. Such humus may contain little or much cellulose. The rate of humus formation increases with temperature.

Under humid conditions favoring natural coniferous forest, i. e., for soils deficient in soil bases, there is a collection of considerable organic matter on the soil surface, all of it poor in bases, and some accumulation down the soil profile from decaying roots. Decomposition occurs in an acid medium and is promoted by fungi rather than by bacteria. Mineralization is rapid, and little humus is formed. What humus is formed is frequently of the nature of semidecomposed raw humus dispersed throughout the profile. It differs in properties from that formed under anaerobic conditions.

Under a semiarid climate promoting a grassland-type of vegetation, lower moisture contents increase aeration. Decomposition is thus potentially more rapid. This is so under semiarid forest cover, and even less humus is produced than for forests in the more-humid regions. With decreasing rainfall, steppe- and prairie-type vegetation replace forest land. Decomposition, still potentially rapid, is halted by cold and frosty or hot and dry seasons and tends to be limited to that of the celluloses. These interruptions allow humus to form and to accumulate. The high base status of such soils enables the acid nature of the humus to be neutralized by base-exchange phenomena. Such soils as the chernozems, black earths, rendzinas and prairie soils are typical. The black color of such soils is not a reliable indica-

tion of the amount of humus contained in them, however.

Under hot desert conditions supporting shrub vegetation, the small amount of organic matter produced is rapidly decomposed. Such humus as is produced is dispersed down the profile by virtue of the long roots characterizing such conditions.

The heavier soils of the humid tropics are not so low in organic matter as might be imagined. The humus produced apparently combines with iron to form humates and is preserved as such on dehydration. Lighter soils, however, are low in organic matter.

The constitution of humus is still somewhat of a surmise. It contains a number of acids, the most important of which is generally referred to as humic acid, and various partly decomposed compounds of organic matter.

Organic matter is believed to be reduced to humus by three processes: the oxidation of lignin, the fixation of ammonia, and the combination of the resulting colloidal complex, lignin-humus or humic acid, with protein and hemicellulose colloids by adsorption.

The oxidation of lignin requires air and takes place more rapidly in an alkaline medium. During oxidation the number of carboxyl groups, causing acidity, is increased. This results in an increased base-exchange capacity. The fixation of nitrogen from ammonia imparts a resistance to further decomposition.

Hemicellulose and proteins are hydrolysable; but on combining with humic acid, they appear to be held tightly to the surface, as if they were exchangeable bases, and in such a way that they are orientated to make the hydrolysable groups inaccessible to organic catalysts. Some polymerisation may occur. It will be noted that such complex compounds are not only ionisable but contain strong carboxyl dipoles, whose effects will become more obvious with decreasing base-exchange capacity.

The properties of humus will thus depend upon the nature and ratios of its components and will vary with the soil with which it is associated. Thus, lignin-humus is believed to predominate in chestnut soils and proteins in gray soils. Hemicellulose is found in the former but not in the latter. The base-exchange capacity varies with the pH at which the humus is formed. The

humus of chernozems, formed under neutral to slightly acid weathering, has a higher base exchange capacity than that of the podsoles formed under acid conditions. For the same reason the humus of the chernozems would be expected to adsorb more moisture than that of the podsoles.

Humus is electronegative and strongly acid when its bases are removed. Iron and aluminum colloids may impart to it amphoteric properties if sufficient basic groups be present.

Humus is only slightly soluble in water, but it may adsorb sufficient water to render it mobile. Translocation is thus, in the main, mechanical or in suspension. It is, however, very mobile, if not soluble, in an alkaline solution and is found fairly uniformly distributed to considerable depths in some tropical soils, where it appears to act as a protecting sheath around soil particles aggregates. It becomes very water-resistant once dehydrated.

It is adsorbed by clay particles, probably through the medium of calcium cations or by base exchange and dipole orientation.

Humus has an important modifying effect on soil structure by promoting, in the presence of replaceable calcium, a granular structure. It also effects the consistency and moisture relationships by increasing the liquid limit and plastic limit but not materially affecting the plastic index.

Cellulose and hemicellulose, found in soils, as the podsol soils, formed under low bacterial activity, are detrimental to bitumen, lime, cement, and resin stabilization by virtue of promoting bacterial activity, which extends to the decomposition of the stabilizers themselves.

SOIL STRUCTURE

Soil structure includes macrostructure and microstructure.

The macrostructure of a cohesive soil refers to the natural elements into which the virgin soil breaks down into on drying, i. e., periodic desiccation is essential if the macrostructure is to be well developed.

On wetting from the dry condition, soil cracks or the air spaces around the boundaries of these elements tend to disappear. Part of the space is filled by extraneous material and slaked soil, and the remainder as the elements adsorb moisture and swell. Nevertheless, it is doubtful whether these boundary faces do, in general, dis-

appear to permit the soil structure to reform a continuous whole. It seems more likely that the size and shape of the elements is maintained and that subsequent drying causes the same boundary surfaces to reappear. There are exceptions, of course, as with the less-cohesive soils and some slaking alkali clay soils.

The presence of these air spaces, or cracks, is an important factor. They permit percolation during the early stages of rewetting and offer the possibility of organic matter being deposited on the surfaces of the elements.

The shape and size of these elements is a function of the soil group to which the soil belongs and of the horizon from which the element be taken. Both are believed to be dependent on the soil's chemistry, though the shape is sometimes modified by shear stresses as in glei structure. The shape is also thought to be, in some way, connected with the clay particle shape and with differences between the coefficients of horizontal and vertical swelling (5).

Weathering processes conducive of natural consolidation and the nature of the soil's microstructure, i.e., volume changes and shear resistance, are presumably responsible for the size of the elements of dispersed clay soils.

Under Baver's classification system (6) for soil macrostructure, there are three main types: cube-like (caused by granulation), prism-like and plate-like (caused by fragmentation), and single grain (caused by deflocculation). Structures within, or between which, he classifies, as examples, chernozems; laterites and humid prairie soils; brown forest and red and yellow forest soils; desert soils; and gray forest soils.

The difference between the coefficients of horizontal and vertical shrinkage would appear to be the basis of the Nikiforoff (7) system of: (1) plate-like, in which the natural cracks are mainly horizontal; (2) prismatic, in which vertical cracks predominate, the surfaces are smooth and the edges are sharp; (3) blocky, in which horizontal and vertical cracks are equally well developed, the surfaces are smooth and the edges are sharp; and (4) granular, as blocky but surfaces are more rounded and not so smooth and edges are not sharp.

The microstructure, or the structural skeleton of a cohesive soil material, is the result of weathering processes productive

of leaching (causing eluviation of clay particles and cementing colloids), flocculation and deflocculation (causing clay particles to be deposited in a random way or in an orientated way between coarser particles), natural consolidations as by drying and wetting cycles (where by its colloidal clay particles may be brought, if slaking occurs, into closer contact and possibly within the range of intermolecular forces), cementation (on dehydration of natural cements) which result in the creation of a resistance to water-deterioration.

On the above basis, Kubiena (8) has classified soil microstructure as shown in Table 2.

Natural soil cements are believed to include orientated clay particles; oxides of iron and silica; organic matter residues as fats, waxes, resins, and certain other humic compounds which are considered to become attached to the surfaces of clay particles largely through the process of base- and dipole-exchange-adsorption effects (some authorities consider the attachment to be through the medium of calcium and aluminum ions); certain gum products of microbial metabolism; certain microorganisms; and certain grass roots.

The nature of the soil micro-structure will thus tend to vary with the soil group and the particle grading.

Microstructure tends to increase the soil's resistance to shear deformation and to make the soil material water resistant. Some soil structures are quickly reestablished after disturbance; some are never reestablished; while others may occupy some intermediate condition.

Some structures lead to fine-aggregate soils, which are normally permeable; some to coarse-aggregate soils, which may or may not be permeable; while others lead to the formation of dense, impermeable soils. The various soils represent gradations between the conditions of permeability and impermeability, between aggregation and dispersion in their natural densification, in their amount of cementation and in their resistance to water deterioration.

So long as wetting is slow, as it normally is under a road pavement, soil macrostructure does not usually disintegrate, though it may develop the already incipient internal planes of weakness when cementing agents are weaker than the disintegrating forces. Exceptions may occur in soils rich in replaceable sodium and, possibly, mag-

nesium, when the clay particles may disperse and in doing so repel each other with a force greater than the resistance of any cementing agents. The displacement of air from a dry soil by water at a faster rate than it can escape increases slaking effects. Clays low in organic matter tend to form hard clods, especially when exchangeable sodium is high and the free salt content is low, whereas those rich in organic matter are aggregated into crumbs possessing pronounced microstructure.

saturated sample containing no air.

For such conditions, the rewetting curve will retrace the drying curve, provided the soil is not dried to a moisture content below the plastic limit, i. e., provided air does not enter during the drying process.

Should the soil dry out to a moisture content below the plastic limit, so that some air enters and desiccation occurs, then the rewetting curve moves away from the basic curve and the engineering shrinkage limit decreases. The soil opens out and the

TABLE 2

Coating of mineral grains	Arrangement of fabric	Occurrence
	Grains embedded loosely in a dense ground mass	Lateritic Soils
Grains not coated	Grains united by intergranular braces	Chernozems, Brown Earths, Lateritic Soils
	Intergranular spaces containing loose deposits of flocculent material	Sandy Prairie Soils
Grains coated	Grains cemented in a dense ground mass	Desert Crusts Podsol B-horizons
	Grains united by intergranular braces	B-horizons of Podsolized Brown Forest Soils
	Inter-granular spaces empty	B-horizons of iron and humus Podsoils.

When a soil possessing appreciable microstructure is incorporated into an embankment and compacted, the small aggregates may still retain much of their microstructure and their water repelling properties.

SOIL STRUCTURE AND VOLUME CHANGE

Volume or density changes are affected by soil structure, as evidenced by both density and microstructure and by desiccation.

Powdered and Unrestrained Cohesive Soils

As long as the air content is small, it would appear that the normally determined shrinkage curve (volume in cc. per 100 gms. of dry soil versus moisture content in percent of dry weight) for a saturated sample closely follows and parallels the basic shrinkage curve for a pulverized

permanent structure is in the process of being formed.

When the air content increases to a value above a critical value of about 4 percent (at the maximum density and optimum moisture content), the form of the drying and wetting curves becomes pronouncedly sigmoid and there is hysteresis. An equilibrium condition is eventually reached, which is apparently determined by the activity of the clay fraction and the neutralization effects of the various forms of molecular forces, cementation, and other structure-forming processes. Some of these, as the presence of organic matter and oxides, may be already inherent in the mixture. The minimum density is thus stabilized, provided conditions favorable to slaking are absent.

For densities within the range of field relative compactions and for a soil material with a well-defined upper limit to moisture adsorption (no slaking), it would appear that the overall volume change per unit weight of

a cohesive, but not too-highly plastic, soil between zero and saturation moisture contents, is the same irrespective of the relative compaction.

By contrast, the density changes between these maximum and minimum moisture-content limits increases with increase in density, while the moisture-content range increases to some maximum value and there is a decrease in the value of the engineering shrinkage limit with decreased density.

For this constancy of volume change to occur, air must be free to escape during wetting. Air cannot always freely escape from some highly plastic soils, however. The volume change per unit weight may then increase with decreased density. Such volume change curves tend to be irregular and may include a coarse capillary range, i. e., a change in moisture content may occur without a change in volume.

Density and desiccation would thus appear to affect the shape of the volume-change curves, while density, desiccation and microstructure affect the value of the maximum moisture content and the value of the site shrinkage limit.

Restraint and static loading tend to reduce volume changes, while dynamic loading tends to increase the density by forcing out the contained air.

Undisturbed Cohesive Soils

If the soil is always completely or nearly completely saturated, volume-change curves are apparently of the same type as those for powdered samples containing little or no air. On drying and wetting over a range above the effective plastic limit, the curve closely follows and parallels the zero-air-void curve for a powdered sample. The difference between the two conditions of undisturbed and disturbed is that the structure of an undisturbed sample has built up a resistance to volume change, reducing the maximum moisture content, and the site shrinkage limit is in excess of the test value.

Under conditions of desiccation, the curves would seem, according to the author's views, to follow either the basic or the sigmoid pattern, according to the properties and the amount of the clay fraction, while the maximum and minimum dry densities would appear to be determined by structural forming processes and, in particular, may be influenced by the value of

the test shrinkage limit.

As long as the natural soil structure is not allowed to deteriorate during the construction of a road, it does not appear that applied loading and restraint exert any appreciable influence over the unloaded natural volume-change cycle.

The internal structure of a road pavement may be considered, as regards volume changes, to be rigid for base courses of the macadam type, semirigid for base courses of the stabilized-soil type, while that of compacted-embankment soils may be considered as flexible and generally subject to measurable volume change.

STABILITY REQUIREMENTS

The stability of any road structural unit will depend upon: (1) overall properties of the unit as controlled by the internal climate at the time of study; (2) properties of each of the various individual constituents making up the structural unit; and (3) variations in the internal climate which, apart from having a direct influence on the overall properties, may be accompanied by variations in the properties of one or more of the constituents and thus exert a further indirect influence on the overall properties.

The field of soil mechanics embraces the study of stability in relation to the overall properties for some assumed condition of internal climate considered to represent the worst possible condition. This approach, on a global basis, may not: (1) be sufficiently comprehensive as there may in effect be more than one worst condition. (2) give, for some soils, the worst condition which it is assumed to represent. (3) give, for other soils, an economic solution, i. e., the worst site condition may not be so severe as it is assumed to be.

The field of pedological engineering embraces a study of the natural laws operative in any structural unit, the requirements for satisfactory design, how far these requirements are met by orthodox design (i. e., an interpretation of the assumptions inherent in orthodox design), the properties of the various constituents of a structural unit, and the effect of variations in climate on the properties of these constituents.

The overall properties of any structural unit of given composition will vary with moisture content and, sometimes, with internal temperature. External temperature

may have a direct effect on moisture content conditions.

Orthodox design is frequently based on a condition of minimum shear resistance as represented by some laboratory condition of saturation as, for example, attained during the expansion test used in conjunction with the C. B. R. determination.

Such an approach assumes four stipulations which may or may not be fulfilled: (1) minimum shear resistance is the only criterion; (2) minimum shear resistance measured is not greater than the minimum shear resistance existing in the field; (3) minimum shear resistance is not appreciably less than the minimum shear resistance existing in the field; and (4) there is a factor of safety involved in any relationship, between test data and satisfactory performance, used.

SWELLING PRESSURE MAY HAVE TO BE CONSIDERED

Pedological studies have shown that a condition of minimum shear resistance is not always the only design criterion. The reverse condition, implying the possibility of differential raising of the structure instead of the more-common differential sinking of a structure may be of even greater importance (9).

Whether design should be based on the former or on the latter or on both possibilities depends on the nature of the materials comprising the unit structure and on the external climate. In other words, in addition to the natural laws controlling moisture changes, the natural laws governing changes in internal-pressure conditions occurring during moisture-content changes is, or may be, a subject for consideration. The phenomenon to be measured and controlled is the effect of a change in internal-pressure conditions resulting in swelling pressure.

The seat of swelling is, more generally, in any clay material present and swelling pressure is liberated when dry clay takes up moisture. The maximum value of the swelling pressure will vary with the nature of the clay mineral and of the adsorbed bases. It will increase with the activity of the clay mineral. In general terms, it will tend to increase as the external climate changes from temperate to tropical. The amount of swelling pressure released, for any given clay material

will increase with decreased initial moisture content, i. e. with desiccation, and appears to approach a maximum for the shrinkage limit as determined from the site shrinkage curve, which depends on the structural condition of the material. It is a minimum or zero when swelling ceases, which is at some moisture content value approaching the field capacity determined for the particular structural condition.

In practice, however, the maximum value appears to be dependent more on the amount of desiccation and possibly on the effects of the replaceable bases than on the nature of the clay mineral (10).

Under temperate climates, where it has been shown by experience that the moisture content under a pavement seldom falls much below the plastic limit, except possibly during droughts, the pressure effect is usually unimportant, and the minimum shear resistance is the design criterion. Under tropical conditions, swelling pressure may be the controlling design factor for some desiccated A-6 soils, and both factors may have to receive consideration in any design involving the presence of certain A-7 soils.

The implications of minimum moisture-content conditions may be as important as those of maximum moisture content.

MOISTURE MOVEMENTS AND MAXIMUM MOISTURE CONTENT UNDER A PAVEMENT

An investigation into the causes of moisture movement was one of the first tasks of the pedological engineer. It was stimulated by the report in 1935 of the Imperial Valley road failure in California, (11), when free water was found under the pavement although the yearly rainfall did not exceed 1 or 2 inches; and by some moisture content data in 1936 from Burma (9), showing moisture increases occurring towards the end of the long, hot, dry season preceeding the monsoon rains.

It was generally suspected that moisture under a pavement might reach some equilibrium value approximating the plastic limit in temperate climates but that under tropical climates the maximum value might reach considerably greater values. There was, however, no way of estimating the magnitude of the equilibrium value.

The study of the natural laws under which moisture moves in soils was inaugurated

almost simultaneously in England and the United States. In the latter country the date is fixed by the setting up of the Highway Research Board Subcommittee on "Nongravitational Flow of Water Through Soils" in 1944. Its object was the determination of the laws controlling moisture movement and the equilibrium value of the moisture content under a pavement.

In the United States the problem was undertaken by Winterkorn and Eyring in 1945 (12) and by Winterkorn in 1947 (13). Working on the basis that moisture equilibrium was determined by energy considerations, they considered that, of the various ways in which moisture could flow, i. e., by surface-tension differences, vapor diffusion, vapor convection, and by film flow, the most likely and most generally applicable way was in the film phase, though it was possible that some moisture also moved in the capillary and vapor states. Of the energies which could be responsible for moisture movement, i. e., surface energy caused by the presence around the colloidal clay particles of replaceable ions, capillary energy arising out of surface-tension forces, kinetic energy or vapor-pressure differences, and thermal energy caused by a temperature gradient. Winterkorn considered that the most important cause of moisture flow, when applicable, was a thermal gradient which resulted in film flow due to change in the water affinity of particle surfaces with change in temperature. Winterkorn thus supported the Bouyoucos concept and developed this concept into his theory of the thermoosmotic flow of moisture in soils (14).

Though many had denied that an appreciable movement of moisture could occur in soils under a temperature gradient, as had been suggested by Lebedev, Chaptal, and Bouyoucos, this natural law was clearly and cleanly confirmed, by the Road Research Laboratory in England (15), as an important factor in determining moisture movements in desiccated soils.⁵ The results agree with those of Bouyoucos, showing that there was an optimum moisture content approximately equal to the plastic limit at which a maximum amount of moisture is moved, but the Road Research Laboratory differed from Bouyoucos and Winterkorn in believing that the moisture movement occurred in the vapor phase and

⁵See also "Climate and Highways," H. F. Winterkorn, Trans. A. Geophys. U., June 1, 1944.

not in the film phase.

The mode of attack then changed. The emphasis was now more on the magnitude of the equilibrium moisture content than on the means by which such a value was reached. The United States, as represented by Spangler in 1945 (16) and England, as represented by the Road Research Laboratory (15), turned to the development of the more-thermodynamic aspect as originally developed mathematically in California by Edlefsen and Anderson in 1943 (17).

This approach has been so developed in England that it is believed that it is now possible to estimate the moisture equilibrium values in saturated and nonsaturated soils under any condition of loading. The approach used, based on suction-pressure differences, appears to apply more to a study of the natural laws controlling moisture-equilibrium values than to the natural laws promoting moisture movement. As regards the latter, the mechanism is presumably considered to be some sort of vapor-pressure gradient.

It is apparently not believed that thermoosmosis plays an important part in moisture flow in England, as most of the studies made in that country seem to have been based on conditions of constant temperature. This may well be so in England where conditions (relatively high water table, relatively high minimum soil-moisture contents, and relatively low temperatures) tend to be more conducive of capillary than film or vapor flow; but it is not likely to be so in tropical regions where conditions (low water tables, relatively low minimum soil-moisture contents, and relatively high temperatures) tend to favor movement in the vapor or film states.

Though the ultimate soil-moisture-content distribution does not appear to be dependent on the state in which moisture flows, the actual state in which it moves in desiccated soils, i. e., in the vapor or film phase, is nevertheless of importance to road engineers. If movement occurs in the film phase, then the total amount of water moved within a given time is proportional to the particle surface area per unit volume and hence increases with density (12); whereas if it occurs in the vapor phase, vapor movement occurs less readily in well-compacted soils than in loose soils of the same moisture content (15).

From a purely soil-science point of

view, it would appear reasonably certain that, in the instance of a powdered and saturated sample being compacted under natural drying forces, the sample will, on slowly rewetting from a moisture content not less than the shrinkage limit, take up moisture by vapor flow to a moisture content just below the plastic limit and thereafter by film flow till the sample be wet enough to enable capillary flow to occur. But in the instance of artificially compacted and undisturbed cohesive soils, all containing appreciable imprisoned air, it is believed that the film-flow stage may extend over a considerable range and persist up to the last few percentages of saturation for some soils.

From the point of view of the stability of the soil material, Winterkorn (18) has pointed out that the rate of soil structural deterioration is really more important than the rate of water penetration.

For predictory purposes, a fraction of the field moisture equivalent (which varies from about 0.7 for compacted A-6 sodium clays to about 0.9 for A-7 calcium clays) appears to give a good estimate of the maximum moisture content of a cohesive subgrade soil likely to occur under the center of a covered pavement.

FACTOR OF SAFETY IN DESIGN

It is known that standard testing procedure may not give the minimum C. B. R. or the maximum moisture intake of some A-7 soils (as for some calcium black-cotton soils) because of the limited time factor involved in the soaking tests; and it is known that some A-6 soils (as some sodium black-cotton soils) will never be in the disadvantageous condition implied by the standard method used for determining the soaked C. B. R.

Any factor of safety inherent in the C. B. R. method of design obviously depends on whether the minimum site C. B. R. is greater or less than the test value.

Pedological thought suggests that, under the meticulous care and conditions of design and construction prevailing in California at the time this design method was developed, there was an implied factor of safety which may be absent under more-modern methods of design. These latter would seem to permit the use of poor A-7 soils in embankments and under conditions which do not presuppose any control over embankment height.

It has been suggested (3) that the minimum value of the factor of safety may, with reservations, be indicated by

$$\frac{L. L. - P. L.}{F. M. E. - P. L.} \quad \text{or} \quad \frac{L. L. - S. L.}{F. M. E. - S. L.}$$

according to climatic conditions. Under conditions of good design, an adequate height of subgrade above ground-water table and as impervious surfacing, the factor of safety would be expected to increase above the values quoted.

PROPERTIES OF THE STRUCTURAL CONSTITUENTS

The most-active constituents of a road structural unit are the clay and organic-matter contents. Other constituents are active but to a lesser degree, and their effects are not so obvious. It is only now that the properties of these others are being given more considerations.

Colloidal clay is composed of secondary clay minerals, with a crystalline structure, formed from the parent material during its weathering and the process of soil formation. Because of boundary conditions, the nature of and the way in which ions are arranged, a number of valences or electro-lines of force associated with the ions situated in external and internal (cleavage-plane) surfaces of the minerals are unsatisfied by ions forming part of the crystalline material and are free to adsorb adventitious ions.

There are, in general terms, two classes of clay minerals: the silicate minerals (as of the montmorillonite, illite, and kaolin groups) and the oxide minerals (as hydrated ferric, aluminum, and other oxides).

The silicate minerals are found more commonly under temperate climates and the oxide minerals in tropical areas, though the most active of the silicate minerals (montmorillonite) is encountered more usually in the tropics.

The clay minerals to be found in any soil are a function of the soil-forming processes and of the great soil group to which the soil belongs.

The silicate minerals are electronegatively charged colloids and dissociate adsorbed positive ions when in aqueous solution, whereas the pure oxide minerals are electropositively charged and dissociate adsorbed negative ions. In the latter instance, however, the intensity of the anionic field

may be so low that the effect of any dipole groups situated on the surface of the minerals may be more-effective electrically than that of the dissociated ions, i. e., the oxide surfaces may behave more as a solid surface than as a colloidal surface.

The complete range of soil clay minerals varies between the highly active minerals of the montmorillonite group, carrying an intense field of negative charges, down to the slightly active members of the kaolin group, carrying but a few negative charges, and on to the positively charged oxides.

Among the members of the oxide group are sometimes included lateritic soil minerals, which occupy a place in both classes. They may be amphoteric. Though basically silicates (possibly of the montmorillonitic group) and electronegatively charged, their micelles are sheathed with a coating of iron oxide. Under alkaline conditions the iron is insoluble and the colloids act as if electronegatively charged and dissociate cations; but when the soil solution is acid, as is more usual for such soils, the iron becomes soluble, goes into colloidal solution, and ionises. The colloid then acts as if electropositively charged and will dissociate anions. The dividing line, as regards sign of resultant charge, does not necessarily occur when the soil solution is neutral but may occur on the acid side of neutrality at a condition of the soil solution known as the isoelectric point. The resultant charge carried is then zero.

This amphoteric property is believed to be an important one in the understanding of some stabilization phenomena. It possibly supplies an explanation of the successful part played by some catalysts in certain soil-resin combinations (19).

Colloidal organic matter acts much in the same way as an electronegatively charged clay colloid. The intensity of the surface field may, however, be several times greater than that surrounding the most-active clay colloid.

When a silicate clay or organic matter colloid is in aqueous solution, the adsorbed ions will dissociate or partly leave the colloidal surface, where the firmness with which they are held generally decreases with decrease in the valency of the adsorbed ion. If the adsorbed ion happens to be a sodium ion, it becomes almost free from surface restraint and is easily displaced.

In general, two phenomena are likely to occur in a soil-water solution: (1) the ad-

sorbed ions become hydrated and are separate from immediate contact with the particle surface and (2) this ionic hydration, by partially releasing the ions from the colloidal particle surface, permits the surface itself to become hydrated. The former process is referred to as hydration, or ionic hydration, which is accompanied by the release of the heat of wetting; the latter is referred to as osmotic hydration, since osmosis is considered to be involved at this stage with the hydrated ions forming an osmotic membrane. The amount of each form of hydration will depend upon the chemistry and the shape of the clay mineral micelles.

Oxide minerals possess relatively little attraction for water, and pure laterite is insoluble and nonplastic.

If the solution be an electrolytic solution other than a water solution, then the adsorbed cations on the silicate clay surface may be replaced by cations from the electrolyte according to known laws of cationic, or base, exchange. By leaching with a suitable electrolytic solution, a sodium-clay colloid with a high affinity for water may be changed to a calcium clay with less affinity for water and lower plastic index.

Base exchange features in a number of stabilization processes.

Similar laws of replacement apply to electropositively charged clay colloids, but the process involved is not yet fully understood.

The deleterious properties of clay depend upon the amount and activity of the colloidal clay and colloidal organic matter present. While some forms of organic matter are beneficial by virtue of acting as a waterproofer, other forms and all clay material are in varying degrees detrimental.

Primarily, the potential activity of the clay material (its capacity for adsorbing bases including water) increases with its base-exchange capacity or as the clay mineral changes from an almost inactive kaolin to a highly active montmorillonite.

Secondly, the potential activity varies with the adsorbed bases, which are mainly those of calcium, hydrogen, sodium, and magnesium.

Thirdly, the effective activity will appreciably depend upon the structure of the soil fabric, i. e., upon whether the soil be undisturbed, disturbed, naturally compacted or artificially compacted and, if so,

the relative compaction.

In addition to the phenomenon of ionic exchange, there is another and somewhat similar form of exchange which (though not of such importance in the field of soil science, because of the lower forces involved and the slower rate at which it occurs) may often be of prime importance in the field of soil stabilization. That is dipole exchange by which an ion containing a dipole group will replace another ion containing a dipole group of lower dipole moment. This phenomenon is believed of prime importance in the field of stabilization involving the use of organic compounds containing carboxyl and similar groups, which are able to replace those of water possessing a lower dipole moment.

Stabilization, in the chemical sense, consists essentially of adding to a soil material an optimum percentage of another material of opposite polarity to produce, by exchange phenomena, a mixture of greater cohesion or a mixture in which the deleterious clay particles or aggregates are surrounded by an insoluble sheath resistant to moisture penetration. The problem is essentially a surface-chemical problem. Thus, an optimum percentage of laterite clay will increase the cohesion of a podsollic clay, and a cationic detergent will stabilize an acid and siliceous soil, i. e., an electronegative clay colloid.

STABILIZATION

Stabilization in the sense of maintaining a minimum desirable shear resistance may be divided into three categories: (1) stabilization by compaction alone; (2) mechanical stabilization not specifically providing for moisture stabilization; and (3) moisture stabilization involving the incorporation of some chemical substance.

Stabilization by Compaction

The process of artificial soil compaction may have a stabilizing effect only when suitable soil material is used and when climatic conditions are favorable.

Much depends, as regards the suitability of the material, on the nature of the microstructure, i. e., on the nature of the clay mineral and of the replaceable bases, on the presence and nature of protecting sheaths of organic matter and oxides, and whether these media are dispersed around

single grains or around compound particles forming aggregates. Whether or not the cementing agents are reversible is another factor to be considered.

Many a laboratory possesses as an exhibit compacted soil material which has been kept in water for a long period without showing any sign of disintegration. But this characteristic does not apply to all compacted soils. It is possible with some naturally stabilized soils and with some A-6 clays but is less likely to be possible with cohesionless materials, silts, and A-7 clays.

There is an upper limit to moisture adsorption dependent on energy conditions. If the water table is very high, it is determined by the surface energy of the particles plus the capillary energy and corresponds to complete saturation. If the water table is very low, this upper limit is reduced to almost that corresponding to the surface energy of the particles. Between the two extremes is a moisture content known as the lentocapillary point, representing the upper limit to saturation, above which, under constant temperature conditions, moisture moves slowly in the fine capillaries and in the film or in the vapor phase.

Highly active clays, especially of the high-surface-energy calcium variety, may, after compaction at optimum moisture content, adsorb moisture from a nearby free-water surface so that ultimately the cohesive bonds between the clay micelles and aggregates are weakened and some slaking occurs irrespective of the percentage compaction. This condition is sometimes brought about or accelerated by the presence of appreciable percentages of carbonates and certain types of organic matter. Such soils, when compacted to maximum density and unloaded, will take up moisture, if available, to approximately their liquid limit. The possibility of some loss of structure occurring appears to be indicated by a relatively high field moisture equivalent. Such soils are not appreciably stabilized by compaction.

The maximum subgrade moisture content in an embankment is controlled to some extent by external loading, tending to suppress moisture adsorption and swelling, and by the length of the path the moisture has to travel, whereby it may be removed by evaporation, transpiration, etc., before it has an opportunity to accumulate in dan-

gerous amounts. But, with such highly active subgrade materials, there always exists the possibility of a loss of stability not necessarily indicated by the 4-day C.B.R. value. Such soils may continue to adsorb moisture and lose stability for periods far in excess of 4 days.

The presence of replaceable sodium in both A-6 and A-7 clays delays and may prevent the condition of incipient slaking by closing the soil pores with swollen clay, provided external energy is not available to work the moisture into the soil material. This delaying action is frequently sufficient to prevent structural deterioration by reason of the time interval during which moisture is available to cause damage.

With other clays, more common in the A-6 group and believed indicated by a relatively low field-moisture equivalent, the maximum moisture content, as controlled by the effective energy available to cause moisture adsorption, is not so greatly in excess of the optimum moisture content and decreases from the maximum value as the density of compaction approaches a maximum. Compaction tends to stabilize such soils.

When the energy available to cause moisture adsorption is satisfied, any excess moisture which may tend to accumulate (as by percolation through blacktop) will drain away if enabled. If the excess moisture is unable to drain away by virtue of the densification of a dispersed type of subgrade material, some additional softening of the subgrade may occur.

If the moisture content of the soil be appreciably below the standard optimum, or the plastic limit, when ample free water becomes available, few soils (unloaded), other than certain A-6 active sodium clays, can resist the disruptive action of rapid water entry, and slaking occurs by a dynamic action irrespective of the value of the field moisture equivalent. Under conditions of slow adsorption, as from a low water table, the colloidal cohesive braces can often adjust themselves to the slow volume changes without severe deterioration. One of the first to draw attention to this phenomenon was Henry Porter of the Texas State Highway Department (20).

The above discussion specifically refers to soils which have been disturbed before testing. Many soils with high moisture-adsorption characteristics by virtue of their physical and chemical structure will re-

main at a safe moisture content when disturbed, provided their natural structure is not destroyed and they are not allowed to dry out before being covered.

Some soils tend to be stabilized by compaction. This stabilization increases with increased density. It must be remembered however, that the amount of densification attainable in highly plastic clays is often limited by a kind of elastic phenomenon consequent on the imprisonment of air within the soil structure during compaction. Also, the load-carrying capacity of other less-plastic soils may depreciate on over-compaction, due to the breaking down of their natural microstructure.

A climate is favorable to stabilization by compaction when it results in the production of soil material resistant to water adsorption and when it does not encourage excessive pavement distortion.

It appears that, for all soil material normally resistant to slaking, the volume change occurring during cycles of slow wetting and drying, between saturation and the air dry conditions, does not vary appreciably with density. H. Porter of Texas is also believed to have been the first to note this characteristic (20).

For soils compacted at optimum moisture content under temperate climatic conditions, i. e., where the moisture content in the subsoil does not usually fall much below the plastic limit, the moisture intake, above the optimum, and the accompanying volume change for all but the highly active clays and silts, decreases as the percentage compaction increases. This is a stabilizing factor. When soil desiccation occurs, however, this stabilizing effect of decreased volume change with increased density disappears, insofar as the volume change becomes less dependent on density and there is a tendency to introduce slaking conditions and excessive differential volume changes or pavement distortion.

Mechanical Stabilization

The requirements for a satisfactory design of a road structural unit may be expressed in terms of the suitability of the material in the particular unit as well as in terms directly implying adequate shear resistance, such as in the empirical manner based on material recognition, classification, and rating (mechanical analysis and plasticity data) which has

become the standard, though not necessarily the most popular, method used in the United States.

Such a method relies on the statistical analysis of an immense amount of experience and data for its correlations between test requirements and satisfactory performance.

The method in mind is that originally introduced by H. Allen of the Bureau of Public Roads in 1942 for the classification and rating of embankment materials and for the determination of the total thickness for subbase, base, and surfacing relative to the various ratings. This method was built up, extended, and developed to give the present standard specifications of the American Association of State Highway Officials for materials for embankments, base courses, and surface courses.

The various specifications for surface and base-course materials include a control over the grading of the material and over the liquid limit and plastic index of its fines content. Specifications for subbase courses generally require that the materials used should give good densities when compacted and that their plastic index should not exceed some stipulated value. For embankment materials the control is mainly concerned with relative compaction. For all structural units a plastic-index control features either directly or indirectly.

The implications of such design recommendations were examined pedologically in a letter to Winterkorn by Wooltorton in 1947 (22), which concluded that: (1) a plastic index control was in effect a direct control over the maximum possible volume change (i. e., under conditions of slaking); (2) a liquid limit control expressed the same requirements on a moisture content change basis and that the permissible maximum value of the liquid limit varied with the specific gravity of the particles, the apparent density and the percentage of fines; (3) such design recommendations could only logically apply to the particular "average" or leached podsollic soils for which the statistical data, leading to such recommendations, referred; and (4) the general problem could not be solved for the want of some additional condition or control. The missing condition was considered to be the logical one of limiting the actual volume change to some permissible value.

Thus for base courses or any structural

unit in which no overall swelling would be permissible: Plastic index times fines content (measuring the maximum value of possible swelling) should not exceed the volume of voids available within the compacted material to accommodate such swelling. For other structural units: plastic index times fines content should not exceed some predetermined value implying some overall swelling is permissible in the unloaded condition but which may in part or in whole be suppressed by the external loading.

The logical conclusions from this analysis were that: (1) under certain conditions where slaking was not encouraged as it is within the fines of a coarse granular base course, some allowance could be made for the nature of the soil structure in fixing permissible limits for the plastic index or maximum possible volume change and (2) the permissible maximum value of the fines content varied inversely as the plastic index, i. e., for any particular material so that, ignoring any structural effects, this permissible percentage, which features in present design recommendations or grading tables, varies with the nature of the soil colloids and decreases with increase in the colloidal activity, i. e., the tendency is for any permissible percentage to change with the soil group to which the soil belongs.

The validity of this reasoning was investigated by Winterkorn (18, 21) in connection with the addition of portland cement, lime, asphalt, tar, aniline-furfural, Resin 321, and abietic acid to synthetic soils composed of 65 percent sand, 25 percent silt (ground feldspar), and 10 percent clay (illite, kaolinite, montmorillonite) to which percentages of salt were added. He found that for small percentages of additives the best results were not obtained when kaolinite formed the clay fraction but when the more active illite was used.

The low surface activity of untreated kaolinite mixtures resulted in a high air-voids volume when they were fully saturated, whereas the higher surface activity of untreated illite lead to a small air-voids volume on saturation. Mixtures containing kaolin would thus require considerably more additives to prevent detrimental moisture adsorption leading to softening, stripping, etc. The moisture adsorption for the samples containing bentonite was sufficient to exceed the pore space available and to cause overall swelling, thereby

weakening binding and water-proofing effects.

Chemical Stabilization

The principles governing the electrochemical theory of stabilization have already been referred to. It is not proposed to consider further the development of this approach as so much has yet to be learned about the properties of the various complex compounds used and the various reactions which occur, during stabilization, between these compounds and the colloidal clay particles. The intent is only to refer to those aspects of the development concerning which something has already been learned by experiment and experience.

It should be kept in mind during the following discussions that the efficiency of any particular stabilizer, as a stabilizer, and the economy of using such a stabilizer are two considerations which the author believes should be kept separate initially.

In general, the more active the clay fraction and the finer the soil material be pulverized, i. e., the greater the number of forces associated with particle surfaces to be stabilized, the greater will be the percentage of additive required. For this latter reason, cohesive materials are not usually completely pulverized but are broken down into small aggregates of an optimum size. Unfortunately, factors other than those of surface chemistry have to be considered with the result that expectations arising out of the electrochemical approach have often to be modified.

Cement Stabilization. The additive cement is used for: (1) reducing, by surface-chemical phenomena, the moisture affinity of clay materials and (2) promoting cementation sufficient to create a semirigid framework within the structural unit, though not for creating a completely solid or rigid structure as characterizes a cement-concrete pavement.

In the instance of cement stabilization, two requirements often have to be fulfilled. In such instances the surface-chemical effects are not necessarily the controlling factors.

From the electrochemical point-of-view cement would be expected to be very effective in the stabilization of those organic-matter-free clays acting as electronegatively charged materials, though this does not imply that any such clay can be sta-

bilized by the incorporation of only a small percentage of cement. On the contrary, the percentage would be expected to increase with increase in the activity of the clay. Small percentages are only likely to be applicable with low-activity clays or with nonactive soil material where little more than cementation or mechanical stabilization is required and not moisture plus mechanical stabilization.

In addition to the nature of the colloidal complex itself, that of the exchangeable ions must be considered, though the actual part played by these ions is not yet fully understood. Tests (23) indicate that the effect of the replaceable bases increases with the silica-sesquioxide ratio, whereas the most-desirable controlling replaceable base depends upon the base-exchange capacity and is most likely to be a monovalent ion. Such a base appears (25) to be indicated by that cation which, for a monionic variation of that cation, gives a minimum value for the expression: optimum moisture content less the shrinkage limit.

The general effect of organic matter is one of modifying the effective activity of the clay particles where this may be accompanied by reactions, of a nature dependent on the chemistry of the organic matter, which may deter the process of stabilization. Some acid organic matter, especially that associated with podsoles and podsol soils, is detrimental by delaying or preventing the setting of the cement, while that organic matter associated with some lateritic soils has not been found to be detrimental.

It may be added here that it is often difficult to find a satisfactory stabilizer for some lateritic soils. It is believed that there are a number of reasons for this, among which the amphoteric nature of such materials must feature.

In addition to the considerations of surface chemistry and chemistry controlling the efficiency of soil-cement stabilizations, there are also certain physical factors having an influence on the process. Grain-size distribution, pore space, moisture-density relationships and, compressive strength are of importance. The gross effect of these appears to be a modification of the results to be expected from the electrochemical approach. This grows in importance as the activity of the clay material increases and results in there being an optimum value of the activity for most-

efficient stabilization.

Some salts (e. g., sulphates of sodium and magnesium) are detrimental by virtue of interacting with the cement to form expanding compounds leading to disintegration of the mixture.

Much pioneer work has been done on the pedological study of soil-cement stabilization by Hicks (24), Mills (25), Catton (26), and Winterkorn (23). Much of this has been used by the Highway Research Board (26a).

Bitumen Stabilization. Bitumen may be used for the purpose of supplying cohesion for nonmechanically stabilized granular materials, for waterproofing mechanically stabilized granular mixtures or for waterproofing cohesive soils.

The principle controlling the stabilization of granular materials is one of coating such particle with a film of bitumen, of an optimum thickness, sufficient to supply adequate cohesion without, at the same time, destroying the natural frictional resistance of the particles.

For cohesive materials, the principle is of adding sufficient bitumen to block the capillaries within the small soil aggregates to hinder moisture changes within these aggregates and partly to sheath these aggregates. Complete waterproofing of the aggregates is considered to be neither necessary nor desirable.

The amount of bitumen required depends essentially on the affinity of the bitumen for the soil material. As bitumen predominantly acts as an electronegatively charged colloid, the amount of bitumen required increases with the number of electronegative charges located on the surface of the material to be stabilized. In the instance of a clay soil and a given particle grading, the percentage of bitumen required increases with the activity of the clay material as represented by its base-exchange capacity or its silica-sesquioxide ratio. It also increases with decrease in the valency of the adsorbed ions and with increase in the amount of organic matter.

Of the possibly adsorbed ions, sodium is usually detrimental. The presence of acid organic matter from leached forest soils is frequently so; but the basic organic matter associated with the chernozems is not. Free calcium leads to detrimental conditions by promoting bacterial activity leading to the decomposition of the bitumen.

This particularly applies to heavy clay soils (37).

The percentage of bitumen required varies with a number of other factors, e. g., voids-ratio, climate, and type and the source of bitumen used.

The relatively hydrophobic soils and rocks, containing carbonates and oxides, are the most-easily wetted by bitumen to produce good adhesion and (when once protected by bitumen) a substantial resistance to moisture penetration into the bitumen-soil material interface.

Adhesion between bitumen and the relatively hydrophilic materials (as clay and rock silicates) is generally poor, and water, if it can reach the bitumen-soil material interface, quickly replaces the bitumen as a sheath around such particles. Therefore, the incorporation of a small percentage of wetting agent whose function is a surface-chemical reaction to change the sign of the electrostatic force field on the particle surfaces is usually essential with such materials. Types of wetting agents used include lime, cement, aniline-furfural, and the like. Bitumens containing a high wax content, cracked oils, and high-temperature tars may sometimes be used without a wetting agent. The desired percentage of wetting agent has been found to vary with climate and the base-exchange capacity of the clay material.

The pedological approach to soil-bitumen stabilization has been furthered by a number of investigators, including McLeod (27), of Canada; the Road Research Laboratory, England (15); and H. F. Winterkorn (28). The Highway Research Board has made use of some of the results of such research (29).

Resin Stabilization. Resins are used more generally for moisture stabilization. Resin and resin derivatives do not add to soil stability by providing cohesive resistance, though some synthetic resins (e. g., phenol-formaldehyde) may lead to an increase in strength.

Natural rosins have a constitution somewhat similar to abietic acid. The molecules contain hydrophilic acid and bulky hydrophobic hydrocarbon groups (the latter acting as strong dipoles). They are insoluble in an acid solution and almost insoluble in pure water, but their solubility increases in an alkaline medium.

Rosin derivatives, such as the complex compounds of sodium abietate and abietic

acid, apparently can feature in both base-exchange and dipole-orientation phenomena. The same applies to the synthetic resins which have commonly featured in stabilization research.

In a water medium, partly neutralized, powdered natural resins break down into smaller particles of ultramicro size. These ultramicros attach themselves to or orientate themselves about the surfaces of clay aggregates or particles so that, in the process of stabilization, the hydrophobic groups are directed outwards from the clay surfaces, thus repelling the entry of water. The presence of a film of moisture around the clay particles appears to be necessary for the success of this operation, i. e., presumably to enable effective orientation to take place—particularly so when natural resins are used.

Natural resins are known to stabilize some acid soils and chalk. The mechanism by which stabilization is so achieved is not fully understood, and it has been said that several phenomena are probably involved in the operation. As a surmise it appears that natural resin particles carry a residual negative charge by which they can become attached to the surface of, say, a particle of chalk which carries secondary positive charges.

Similarly, in the case of the very-acid soils (pH 4 to 6) of an amphoteric nature or which have been treated to obtain hydrogen, aluminum, or iron modifications, the surface of the clay silicates act as if positively charged and thus encourage the attachment to themselves of particles of insoluble resins.

In the instance of partly soluble sodium derivatives, anionic exchange may occur to produce an insoluble sheath around the soil material.

Synthetic resins, as aniline-furfural, appear to attach themselves to an electro-negatively charged surface by a process more similar to base exchange. They may be efficient as moisture stabilizers over a wide pH range, but they appear to be most efficient in an acid medium.

Research on the use of resin stabilizers has been largely sponsored by Winterkorn (30) and his co-workers. Some useful basic research has been reported on by the Road Research Laboratory, England (15). The practicability of the use of aniline-furfural has been described by Mueller (31).

Use of Electrolytes in Stabilization. A

number of electrolytes, as calcium chloride, sodium chloride, hydrated lime, ferric chloride, and sodium silicate, can play an important, though generally limited, role in stabilization. The common principle involved is ionic exchange, though such others may feature as a change in hygroscopicity, a lowering of the freezing point, the possibility of increased maximum densities and shearing resistance, and retardation of evaporation by crystallization within the capillaries.

In addition to its deliquescent properties, calcium chloride can, by leaching, change a highly water-retentive clay, as a sodium clay, into a calcium clay by base-exchange phenomenon, thereby reducing the plastic index and volume change. The benefit achieved by this process increases with increase in the silica-sesquioxide ration.

Hydrated lime may behave similarly with the added advantage of acting as a wetting agent to change the effective sign of highly active clay colloids. In the presence of natural pozzolanic materials, there is also a cementation effect.

The effect of the addition of a suitable percentage of silicate of soda to appropriate soils is to increase water-stable aggregation and resistance to crushing and to decrease the plastic limit, plastic index, and swelling. The process involved is apparently that of anionic exchange, resulting in the formation of insoluble silicate sheaths around the soil particles and accompanied by cementation effects.

There is a considerable field of literature on the use of electrolytic semistabilizers, but it is only proposed to refer to a believed important publication by Laws and Page which appears to have escaped attention (32). It is felt that there is scope for silicate of soda stabilization, as distinct from its sole use as a cementation agent, in the tropics.

As the silicates are electronegatively charged, they could not be expected to stabilize active clays. This is borne out by Reference 32, in which it is shown that the efficiency of the additive increases with decrease in the activity of the clay, i. e., with decrease in the silica-sesquioxide ration. It is likely to be most efficient with those soils of an electropositive character or with those active clays which have had imposed on them an electropositive nature by virtue of coatings of iron compounds.

In conclusion, attention is drawn to the work of Winterkorn and his associates Moorman Chandrasekharan, Silberg, and Goodpaster, of the problems associated with the stabilization of soils belonging to specified soil groups, i. e.,

podsollic (33), loess pampeano (34), lateritic (21), saline (35), alkaline (36), and beach soils (30). Attention is also drawn to Winterkorn's more-general paper on the stabilization of cohesive soils (37).

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