

# A FUNDAMENTAL APPROACH TO THE STABILIZATION OF COHESIVE SOILS

HANS F. WINTERKORN, *Princeton University*

## SYNOPSIS

Structural, physico-chemical and bacteriological factors entering into the problem of successfully and practically stabilizing cohesive soils are discussed, and ways are shown by which soil stabilization can be extended to cover heavy soil types which at the present time are outside the realm of recommended practice for soil-bitumen and soil-cement.

This paper is concerned with cohesive soils and particularly with that large and important group of cohesive soils which falls outside the realm of presently recommended practice for soil-cement and soil-bitumen. Representatives of this group have more than 50 percent of their component particles passing the 200 mesh sieve, and are possessed of liquid limits and plasticity indices in excess of 40 and 18, respectively (1).<sup>1</sup>

The physical meaning of these limits is that soils exceeding them do not possess an internal skeleton of grains of sand and larger-sized particles touching each other or interlocking with each other.

With graded granular materials about 65 percent are necessary to provide this skeleton. This coincides with the lower limit of the granular soil group according to the classifications of the Public Roads Administration and of the U. S. Engineers. With uniformly sized granular material the lower limit is about 55 percent coinciding with the respective lower limit of the Civil aeronautics Classification (2).

It is significant that in soils and soil mixtures not possessing an internal granular skeleton, the plasticity properties cannot be calculated by extrapolation from the percentage and the plasticity characteristics of the clay fraction (7).

It is the dream of every public-spirited road builder to make a good construction material out of the soil found on location. For the purpose of the present paper this soil is of the cohesive type introduced above. A good construction material combines strength with durability and economy.

<sup>1</sup> Italicized figures in parentheses refer to the list of references at the end of the paper.

## GENERAL THEORY OF CONSTRUCTION MATERIALS

Almost every construction material whether it be stone, concrete, lumber, metal or one of our modern plastics consists of some kind of particles bound together by some sort of cementing agent. The particles may be represented by sand grains, pieces of gravel, metal crystals, cellulose fibers, or any other imaginable particles. The cementing agent is normally composed of particles which are smaller than those which are cemented together. These cements may be liquid, plastic, or solid.

The terms "liquid" and "solid" describe conditions of state. These conditions are functions of temperature, pressure, and concentration. Consequently, a change of one or several of the environmental parameters may change the actual state of the cement from liquid to plastic and solid or in the reverse order. Plasticizing and liquifying effects of increase in temperature are commonly observed with organic cementing materials; plasticizing effects of increase in moisture content, i.e. decrease in concentrations are commonly observed in the case of inorganic cements.

The strength and durability of a construction material depend on the type of particle, the type of cementing agent, and the method of compounding. The particles are usually called aggregate or filler. If the aggregate is graded to achieve a high dry density of the cemented system, the latter is called a concrete. The specific name of a concrete derives from the type of glue or cementing material used, viz.: portland-cement-concrete, asphaltic concrete, tar-concrete, resin-concrete and clay concrete. The concrete type of

structure is also possessed to a certain extent by the bearing metals. Because of their similarity in structure, concretes of the different types possess a number of properties in common. They vary with respect to those properties which depend on the consistency of the cementing agent and on the strength and shape of the aggregate or filler particles.

If the system is open-graded, i.e. if the particles are of a more or less uniform size, such materials as bituminous macadam, metal pieces made by powder metallurgy, and others are obtained. Again, these systems possess a number of properties in common. Such systems may be subdivided into those which possess pore-spaces of larger than capillary size and those with pore sizes in the capillary and subcapillary range.

Coordination of cemented construction materials into a few categories distinct by their basic structures is not an idle game. Rather, it makes available for the larger category the individual knowledge acquired on specific materials falling within that category. Thus the knowledge acquired and the theory developed for creep of metals is applicable '*mutatis mutandis*' to plastic flow in portland cement concrete. Also, fatigue and especially corrosion fatigue as recognized for metals has an important counter-part in the durability of inorganic construction materials.

Chemical engineering owes its existence and its magnificent performance to the recognition that the production of all kinds of chemicals involves only a relatively small number of distinct unit processes. The same method of attack can be applied profitably to understanding the functioning and failure of all types of construction materials.

#### STABILIZATION OF COHESIVE SOILS

Cohesive soils of the type considered can take practically any load imposed by plane or vehicle as long as they are dry. In this dry condition the clay particles stick strongly to each other and form a high-strength solid body.

When these soils become wet, the individual particles tend to surround themselves with a water film that acts like a lubricant, resulting in a plastic and sticky mass. Killing the tendency of the clay particles to absorb these water films also destroys their ability to serve as strong binders at very low moisture contents.

The compacted dry weight of typical cohesive soils is usually below 100 lb. per cu. ft. Assuming a specific gravity of 2.65 for the individual soil particles, such a soil system possesses a pore space of about 40 percent. To fill this pore space completely requires a weight percentage of cementing material equivalent to the product of the porosity of the compacted soil and the specific gravity of the cementing agent. An additional requirement for obtaining such a non-porous system is that the largest particles in the cementing agent must be smaller than the pore size of the compacted soil.

Such a non-porous system would be uneconomical because of the large percentage of cementing agent required. Furthermore its strength characteristics would vary greatly if the cementing material were possessed either of water affinity (inducing swelling) or of a thermal expansion coefficient larger than that of the solid particles, especially in the case of thermoplastic cements.

Accordingly, the systems to be established will be of capillary and subcapillary porosity. There are several ways of producing structural materials from cohesive soils, *viz.*:

- (a) cementing the soil particles together by means of inorganic binders;
- (b) cementing by means of organic binders;
- (c) maintaining part of the natural water-cohesion of the soil and water-proofing it.

#### CEMENTATION BY MEANS OF INORGANIC BINDERS

Most inorganic binders such as portland cement, lime, plaster of Paris, etc., have particle sizes of the same order of magnitude or larger than the component particles of cohesive soils. For this reason stabilization with reasonable amounts of binder involves (a) formation of secondary soil particles by cementation of soil particles in a cluster around grains and micelles of the cementing agent and (b) cementing together of the clusters into the structural material. Success of this method depends upon ability to pulverize the soil fine enough to permit formation of strong and water-resistant clusters. This becomes increasingly difficult the more cohesive the soils are. The practical limit for soil-cement has been stated previously. Pushing this limit further into the realm of cohesive soils will have to be based on further development of

knowledge concerning surface activity of the cohesive soil systems (8).

#### CEMENTING BY MEANS OF ORGANIC BINDERS

The theoretical goal of this process is to deprive the primary and secondary clay particles of their water-affinity and to cement these particles together. These two functions may be filled by one and the same organic material or by a mixture of two or more materials. The ideal binder is hydrophobic and possesses greater affinity to the internal soil surface involved than is possessed by water; it is resistant to oxidation and to attack by soil bacteria and fungi; it is applicable as a liquid of low viscosity and forms a plastic or solid cement within reasonable and controllable time.

#### WATERPROOFING OF COHESIVE SOILS

Theoretically and economically the most attractive solution of the problem is to maintain as much as possible of the water-induced cohesion of the soil, and to protect it by waterproofing from taking in additional water which may result in swelling and lowering of the mechanical strength of the system.

While theoretically we may separate cementing and water-proofing stabilization, in any actual system both forms will undoubtedly be present. However, one or the other will usually prevail. These two methods of stabilization and all the possible combinations are, of course, extension of the theory and practice of soil-bitumen into an area in which pure soil-bitumen has shown weakness and is therefore not recommended at the present time.

The basic deficiencies of bitumen in this type of system are: (a) insufficient activity to destroy the water-affinity of most heavy soils if used in amounts which do not render the system plastic at the higher ranges of environmental temperatures; (b) susceptibility of the bitumen to oxidation and attack by soil bacteria and fungi (9).

The problem of the adhesiveness of bitumen to mineral surfaces has received wide and intensive study and several methods of improving this adhesiveness have been developed. These are concerned with (a) changing the chemical character of the mineral surface, (b) admixing surface-active substances to the bitumen, (c) changing both the mineral surface and the bitumen composition.

As an example of the effectiveness of changing the chemical character of the mineral surfaces, reference is made to the results of an extensive study undertaken by the Missouri State Highway Department. This study covered nine cationic modifications each of six heavy clay soils of widely differing character and twenty-one different bituminous materials (10). It was found that each one of these soils could be stabilized with a reasonable (less than 7.5 percent) amount of bitumen if the mineral surfaces were treated with iron or aluminum cations. However, there was a tendency, especially in the iron-treated soils, toward loss of life or oxidation of the bitumen. Incidentally, the Ca-treated soils showed strong bacterial activity during the submersion tests.

There is a large literature—especially patent literature—concerning admixtures to bitumen for improvement of its coating power and stripping resistance. In the main, these admixtures represent amines and other organic derivatives of ammonia, fatty, naphthenic, resinous and similar organic acids and their salts with bi-, tri-, and tetravalent metal ions, sulfonated organic materials and their metal salts, cation-active bonding agents, and related types of organic materials possessed of a relatively large molecular size and of well expressed polarity and surface activity (4). Only relatively few of the patented materials seem to have found their way into practice, and of these a number have been found of limited service life, being susceptible especially in soils to destruction by oxidation and by microbial activity.

The combined method of changing the mineral surface and the bitumen is normally based on adsorption of tri- and higher valent cations on the surface and reaction of at least one of the valences of these cations with an organic anion of high molecular weight contained in the bitumen.

There can be little doubt that most of the recommended auxiliary treatments and admixtures give considerable improvement in the performance of the bituminous binder or waterproofing agent when examined in the laboratory in short-time water exposure and weathering tests. On the other hand, many cases have been observed in which the service life of stabilized soil was considerably shorter than would have been expected from the results of laboratory tests. In fact, with

time some of the "stabilized soils" become less stable than the untreated natural soils.

The fact that short-time laboratory tests do not always reveal the inherent weakness of the systems indicated that the cause for the weakness is the microbial destruction of the natural organic matter contained in the soil or (and) of the added organic binder or water-proofing agent. The soil microbe population normally requires a certain period of time (about four weeks minimum) before it adjusts itself to the new environment established by the admixture of the binder or water-proofing agent and the mechanical procedures involved in the construction of the respective soil structures (5).

Observation of the detrimental action of soil microbes has not been restricted to bases and surfaces; it has also been found that normal bacterial oxidation of organic matter in a natural soil may become changed into anaerobic fermentation, if this soil is employed as a subgrade, with resulting slimy decomposition products that greatly reduce the load carrying capacity of the subgrade. This is the reason, of course, why in practice surface soils containing organic matter are not employed as fill or subgrade material.

Inspection of the evidence available from the laboratory and the field indicates that it is possible to extend bituminous soil stabilization into the area of pure cohesive soils by means of surface-active admixtures, but that the resulting systems must be protected against microbial attack.

Because of the great importance of bacteria in highway performance and since highway engineers cannot normally be expected to be expert in bacteriology, the role of soil microbes especially as affecting soils and their stabilization is summarized in the following.

#### SOIL BACTERIA

According to Waksman "the microscopic plant world is represented in the soil by the algae, fungi, and bacteria, named in the order of their increasing importance of numbers and activities (6). Because bacteria predominate in numbers and variety of activities over all the other groups of micro-organisms the earlier micro-biologists gave the name of "soil bacteriology" to the whole field of soil microbiology.

Bacteria are subdivided into those that

derive their energy from the oxidation of purely inorganic substances and those which consume compounds of plants and animals for their energy and growth.

These microbes play a most important role as scavengers in freeing the earth of the otherwise accumulating debris of plants and animal cadavers. From this role it is easy to visualize that soils are provided with microbes and microbe-associations which either singly, but in most cases, through cooperative effort, are able to destroy every substance synthesized in the plant or animal body, and also partial decomposition products of such substances. This decomposition is being produced by numbers of bacteria which range into millions per gram of a rich soil.

It is not the purpose of this section to write a book on soil-microbiology, but to point out: (a) the tremendous role which microbial life plays in the destruction of organic substances either found naturally in or which have been added to a soil; and (b) the fact that these microbes are able to destroy not only such materials as celluloses, hemicelluloses, fats, proteins, lignin, etc., but also substances which are commonly considered as resistant to bacterial attack or even as bactericidal or bacteriostatic.

It is now well known that soil bacteria can attack the whole range of hydro-carbons, from waxes and asphalts, through lubricating oils and kerosenes, down to the gasolines and naphthas, including such aromatic substances as benzene, naphthaline and anthracene. Very interesting, especially in view of the later discussion on the effectiveness of "bactericides", is the decomposition of phenol by bacteria which is now used industrially for the cleaning of phenol-containing waste water, and the case reported by Zo Bell of bacteria decomposing the "poisonous" tetraethyl lead in high-octane gasoline and changing it to the insoluble lead sulfide by means of sulfur taken out of other compounds present in the gasoline (12).

The rate of decomposition of water-insoluble, waxy, fatty, asphaltic, oily, and similar substances depends upon the exposed surface per unit mass, i.e. their degree of dispersion, emulsification, or distribution as film over solid substances. It should be kept in mind that the dispersion incidental to soil stabilization represents an optimum condition

for destruction of the organic binder or waterproofing agent. Consequently, it is not surprising that bacterial activity often accounts for the early destruction of organic substances, bituminous, resinous or others, which have been dispersed in soils for the purposes of waterproofing and binding (6). It follows that organic waterproofing or binding materials or both should have germicidal properties or should be employed together with germicidal substances. However, it is not easy practically to apply this conclusion, since no substance exists which is germicidal under all environmental conditions.

#### ACTION OF GERMICIDAL SUBSTANCES

The effectiveness of germicidal substances depends on the type of micro-organisms involved and on the physical and chemical composition of the other components of the system under consideration. The factors which are important with respect to germicidal action in soils can be easily understood from study of the action mechanism of germicides and antiseptics. Germicidal action may be due to:

- (a) oxidation (chlorine, hypochlorites, chlorates;
- (b) hydrolysis of the cells (strong acids and bases)
- (c) change of permeability of cell walls (tannic acid) etc.;
- (d) direct chemical union with the cell preceded in some cases by absorption; the cell is killed as a result and the protoplasm in some cases is coagulated or precipitated (formaldehyde, mercuric chloride, water-soluble heavy metal salts);
- (e) mechanical disruption or injury to the cell, as a result of osmotic phenomena (effect of strong brines and syrups).

It is of interest here to consider the germicidal action of specific chemicals, which might come to mind as potential admixtures in soil stabilization.

#### *Salts of heavy metals:*

The soluble salts of heavy metals—mercury, silver, lead, copper, iron,—are more or less effective disinfectants. It should be noticed that it is the soluble salt which is effective, this means it is the metal ion rather than the salt which is germicidal. This is especially

evident from the fact that mercuric chloride dissolved in absolute alcohol is less efficient as a bactericide than when dissolved in water, in which the salt is ionized to a greater degree. Also, the ionized mercuric chloride is a strong poison while the much less ionized mercurous chloride is only a mild intestinal disinfectant. It is, therefore not surprising that non-ionized compounds of the same metals, which as ions are highly poisonous, are not only not germicidal but may even serve as food suppliers to germs if the remaining part of the compound is of organic character such as the radical of a fatty acid.

#### *Organic Compounds:*

Most commonly used are: formaldehyde, chloroform, iodoform, alcohol, phenol and its derivatives, aniline dyes, organic acids, toluene, and a few of the essential oils. Some of these, like formaldehyde, owe their effectiveness to direct chemical action on the protein of the cell, others, like the aniline dyes and the poly-atomic organic acids, to adsorption and hindering of the normal life processes; the organic acids of low numbers of carbon atoms act through their hydrogen-ion concentration, while solvents like toluene, alcohol, chloroform and others probably attack the fatty parts of the structure of the germ cells.

It has been shown that germicidal action is due to definite physical and chemical interaction between the germ and the germicide. In order that this interaction may prove lethal the germicide must be available in sufficient active concentration. Whenever the germicide forms insoluble compounds with other components of the system it becomes inactive. In fact it is known that even as potent a germicide as mercuric chloride is apt to form an impervious coating over the surface of solid particles and protect the bacteria in the interior from injury. Also it is known that sodium soap may react with the Ca-ion in hard water to form protective crusts of insoluble Ca-soaps over streptococci colonies.

Normal cohesive soils possess a large internal surface composed of multifarious organic and inorganic substances, which may absorb, react with, or otherwise render inactive variable amounts of added germicidal substances. Therefore, it is impossible to prescribe without

test the right amount and the right type of germicidal substances with definite assurance of effectiveness, or even with assurance that they do not adversely affect the physical or service properties of a treated soil system. It should be evident from the facts presented that no "general composition of matter" even if containing one or another "bactericidal"

- (a) The taking of representative soil samples and their handling and storing.
- (b) The preliminary selection of the germicidal agent (or agents) on the basis of the physico-chemical character of the soil and of the waterproofing agent chosen;
- (c) Final selection and dosing of the germicidal agent on the basis of laboratory tests.

TABLE 1  
RECOMMENDED TREATMENTS FOR DIFFERENT CLIMATIC SOIL CATEGORIES

Character of internal soil surface	Complementary chemicals
1. Complex iron and aluminum silicates with $SiO_2/R_2O_3 > 2$ . Typical of cool moist climates. The clay particles are predominantly negative in electric charge	Organic cations (derivatives of $NH_4^+$ ; also substances which may react with particle surfaces through hydrogen linkage.
2. Complex iron and aluminum silicates with $SiO_2/R_2O_3 < 2$ and complex hydrous iron and aluminum oxides. Typical of warm and hot moist climates. Increase in sesquioxides results in a decrease of negative charges and an increase of positive charges on the clay particles	There are sufficient positive charges to react with negative organic ions, such as those of soluble soaps, saturated and unsaturated fatty acids, resin acids, et alia. The high prevailing temperature and the presence of the catalytic iron oxides makes use of antioxidants desirable if not essential for durability.
3. The internal soil surface is covered by lignaceous and proteinaceous organic matter. Typical for climatic conditions (favorable to growth of grasses) under which evaporation equals precipitation	Substances which form synthetic resins with the humus materials.
4. Desert, saline and alkaline soils. Typical for climatic conditions under which evaporation exceeds precipitation	This field is largely unexplored.
5. Peats and bogs	Substances which form synthetic resins with the organic matter or which themselves form synthetic resins including the organic matter as filler.

CHEMICAL AND PHYSICO-CHEMICAL CONSIDERATIONS

Having considered at some length the problem posed by the activity of soil bacteria, consideration will be given to surface chemical phenomena playing a role in both binding and waterproofing stabilization.

Previously, examples have been presented showing how change of the surface chemical character of the soil particles, by replacement of the naturally occurring cations with iron and aluminum ions, resulted in easy stabilization of heavy clay soils of widely differing character. Such replacement is often difficult or impossible of achievement in the field.

On the other hand, the types of admixtures mentioned as employed or recommended for the bitumen possess different chemical characteristics. The logical and easiest way of making certain of a desirable reaction between components of the binder or waterproofing agent and the surface of the soil particles is to ascertain the surface-chemical character of the soil and employ as binder or admixture to the binder substances which react with the surface.

For best possible selection of the reacting substance the chemical character of the soil in question should be well known. This indicates the probable desirability of developing a surface-chemical classification method complete with tests to be employed in the stabilization of cohesive soils. Fortunately, the general climatic soil classification is, to a certain extent, a chemical one, and the different pedological soil series also possess distinct surface-chemical characteristics.

This scheme of a general approach to the problem is illustrated in the correlation of the simplified climatic soil classification with the types of available surface-active substances in Table 1.

substance can be considered as giving a definite protection against microbial decomposition of a waterproofing agent added to a soil for stabilizing purposes.

*Practical Application of Knowledge on Soil Bacteria and on the Action of Germicides:*

It seems to be evident from the preceding facts and arguments that with the bacterial factor entering the picture of soil stabilization, new techniques of sampling and testing must be developed. While it would be premature to describe or propose such techniques in detail, they must cover the following phases:

These complementary chemicals can be used as admixtures to low-priced organic binders such as asphalt and tar, or if economically feasible, they can be employed by themselves. In the latter case, they must be able to function as binders in addition to their role as surface modifiers. A considerable number of the admixtures which have been suggested for bitumen cannot serve as binders, especially the derivatives of high-molecular-weight organic acids and the ammonia derivatives if used by themselves. However, these materials possess interesting potentialities in the waterproofing of cohesive soils, especially if it is desirable to keep the total percentage of the waterproofing agent at a minimum.

#### THE WATERPROOFING OF SOILS (11)

The basic principle of waterproofing soils is to maintain part of the cohesion-giving water-affinity of the soil particles and to make part of the internal soil surface water-repellent. As is well known from the use of air-entraining concrete, small amounts of resinous or other surface-active materials can give considerable wetting resistance to porous inorganic construction materials. This wetting resistance is especially strong against capillary infiltration without hydrostatic head of the water source; hence the satisfactory functioning of air-entrained concretes.

In a waterproofed soil, cohesion is due primarily to the thin undisturbed water films between particles. By definition of the waterproofed system and as can be concluded from the small amounts of waterproofing agents employed, the latter do not cover the total internal surface. Rather they provide non-wettable barriers in a number of places in such a system. These barriers are not plugs, but thin surface coatings. While liquid water cannot pass these barriers, water vapor can pass over them. Consequently water vapor can, under favorable conditions, enter such systems and the vapor can add to the films of cohesion-water making the system swell and lose its cohesion. Also, water under a hydrostatic head can be made to slip over the water-repellent parts of the internal surface. In fact, "water-proofed" soils may have a greater permeability with respect to water under a certain head than do the non-waterproofed soils. This indicates the inherent

limitations of "waterproofing" with small (<2%) amounts of surface active chemicals. Such systems are not really waterproofed, only the rate of water intake is reduced in the absence of hydrostatic heads. Except, where waterproofed systems possess a well functioning internal granular skeleton as in waterproofed mechanical stabilization or in a waterproofed sand-clay, they should not be employed under a pavement of low water-permeability where danger of water-accumulation due to migration in the vapor phase exists. In other words, they should be employed only in locations where moisture is present in active form (as vapor or under a head) for a much shorter time than would be required for detrimental penetration of the moisture into the system.

Despite these limitations, waterproofing of soils has definite potentialities with respect to the great problem of building the lowest-cost type of farm-to-market roads if the right kind of surface can be developed. This surface should be thin but abrasion resistant, furthermore, it should be pervious to water-vapor and impervious to liquid water. Examples of the type of system desired are the human skin, or, perhaps even better, the frog skin.

#### CONCLUSIONS

Critical appraisal of available theoretical and experimental evidence permits the conclusion that satisfactory and practical waterproofing and cementing stabilization methods can be developed for soils that fall outside the limits of presently recommended practice for soil-cement and soil bitumen.

In the practical use of such methods optimum results can be expected only if the reactive organic materials are selected on the basis of thorough understanding of the physico-chemical character of the internal surface of the soil under consideration.

With respect to durability of such stabilized systems attention must be given to the activity of soil bacteria.

#### REFERENCES

- (1) Current Road Problems Bulletins Nos. 7 and 12, Highway Research Board, 1943, 1946.
- (2) Report of Committee on Classification of Materials for Subgrades and Granular

- Type Roads. *Proceedings, Highway Research Board*, Vol. 25, p. 376-392 (1946).
- (3) Buchanan, E. D. and R. E., *Bacteriology*, MacMillan Company, New York, 1938.
  - (4) Eckert, George W., "Surveys of patent and periodic literature on bituminous materials." *Roads and Streets*, March 1937, 1938. *Proceedings, Assoc. Asphalt Paving Technologists* 10, 1938; 11, 1939; 12, 1940; 13, 1941. Further references in *Chemical Abstracts*.
  - (5) Jones, P. C. T., "The Microbial Decomposition of Resinous Stabilizing Agents in Soil," *Proceedings, 2nd Int. Conf. Soil Mechanics and Foundation Engineering IV*, 280-284, Rotterdam, 1948.
  - (6) Waksman, Selman A., *Principles of Soil Microbiology*, Williams & Wilkins, Baltimore 1927.
  - (7) Winterkorn, Hans F., *Physico-chemical Properties of Soils; Proceedings, 2nd Int. Conf. S.M. and F.E. I*, 23-29, Rotterdam, Holland, 1948.
  - (8) Winterkorn, Hans F., Gibbs, Harold J. and Ferrman, R. G., "Surface-chemical Factors of Importance in the Hardening of Soils by Means of Portland Cement." *Proceedings, Highway Research Board*, Vol. 22, 385-414 (1942).
  - (9) Winterkorn, Hans F., *Principios Sobre Moderna Estabilizacion de Suelos. Caminos No. 70, Enero-Febrero, Buenos Aires* (1947).
  - (10) *Physico-chemical Factors of importance in Bituminous Soil Stabilization. Proceedings, A. Asph. P.T. 11*, 204-257 (1940).
  - (11) Winterkorn, Hans F., Fehrman, R. G. and McAlpin, George W., "Water-proofing Cohesive Soils by Resinous Treatment." *Proceedings, Soil Sc. Soc. of A. 10*, 458-460, 1945.
  - (12) Zo Bell, Claude E., *Princeton Lectures 1948*, see also *Marine Microbiology, Chronica Botanica, Co., Waltham, Massachusetts*, 1946.

## OBSERVATIONS OF MOISTURE CONTENTS AND DENSITIES OF SOIL TYPE BASES AND THEIR SUBGRADES

L. D. HICKS, *Chief Soils Engineer, State Highway and Public Works Commission, North Carolina*

### SYNOPSIS

This paper is a report of a survey made in North Carolina during 1947 of the moisture contents and densities of soil type bases and their subgrades. The report describes the survey procedure and contains photographs showing the various operations. Charts are used to show the monthly fluctuations in moisture contents of the bases and subgrades expressed in terms of the standard optimum and plastic limit of the soils and in terms of the degree of saturation of the existing base and subgrade. The average relative densities of the bases are given and the influence the degree of relative density has upon the moisture absorbed is shown. The subgrades are divided into two types, granular type and silt-clay type, and their average relative densities given and the influence the degree of relative density has upon the moisture absorbed is also shown.

The data in this report reveal certain pertinent facts regarding the moisture soil bases and subgrades will contain under service conditions. Also, the relative densities the bases and the various types of subgrades develop under traffic is revealed. This information is very important to the designing engineer who must have or assume the moisture and density of a soil before determining its bearing value.

The amount of moisture a mass of soil contains is probably the most influential factor governing its stability. The use of soil type materials for base courses placed on soil subgrades has caused this fact to be of great concern to engineers engaged in pavement design. Many designing engineers assume that the soils composing the base courses and sub-

grades become saturated with moisture during service and base their designs on this assumption.

The degree of compaction required for base courses and subgrades, in order to prevent additional consolidation by traffic, is another problem with which engineers are concerned. Consolidation under traffic causes rough riding