VARIATIONS IN THE STRENGTH PROPERTIES OF A COHESIVE SUBGRADE SOIL AS A FUNCTION OF ORGANIC MATTER IN COMBINATION WITH CERTAIN SATURATING CATIONS

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THESIS

This is to certify that the

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By

JOSETTE MARJORIE PORTIGO

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Submitted to the School for Advanced Graduate Studies of
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PREFACE

The idea for this investigation originated with Olaf Stokstad of the Michigan State Highway Department who suggested that certain subgrade soils in the State of Michigan gave satisfactory results in standard tests conducted in the laboratory but failed to yield a corresponding degree of performance in the field. A research project was programmed by the Research Laboratory Division of the Michigan State Highway Department to study the problem, and Roy Leonard started the investigation of the influence of soil fines in gravel stabilization in 1954. The project was assigned in 1957 to the writer who continued the study, concentrating on the possibility that the fines of some subgrade soils combine with natural organic colloids to produce, in the soil properties, changes that are not revealed by the usual standard laboratory tests.

The writer is indebted to Dr. G. C. Blomquist for his untiring assistance and guidance, to Mr. E. A. Finney, Director of Research Laboratory Division of the Michigan State Highway Department, for permission to use the data on the Highway Research project for this thesis, to Mr. R. C. Mainfort of the Soils and Pavement Evaluation Unit of the Research Laboratory Division, whose competent direction of the Highway Research project has been a source of inspiration.

The writer also wishes to express her appreciation to Mr. E. A. Dahlman, Highway Department Soil Engineer for the Kalamazoo District, for his assistance in locating and obtaining soil samples, and to the staff of the Soils and Pavement Evaluation Unit of the Research Laboratory Division for their help in obtaining samples and carrying out the tests in the laboratory.

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JOSETTE M. PORTIGO ABSTRACT

Experiments were carried out to investigate the influence that natural soil organic matter in the subgrade would have on the plasticity, shrinkage, swelling, moisture absorption properties and compressive strength of the subgrade soil. The investigation also covered the variation in strength properties caused by certain cations saturating the base exchange capacity of the clay and colloid portion of the soil.

The soil samples used were homoionic soils prepared from Warsaw soil by leaching portions of the soil with some suitable electrolyte containing one of the cations chosen, namely hydrogen, alumimum, ferric, and calcium ions. Two kinds of organic material were used to simulate the natural soil organic matter. Lignin was used to represent organic matter in equilibrium with soil microbial activity. Humic acid, extracted in the laboratory from muck, was used to represent organic material in the process of decomposition.

The solutions containing the cations were in concentrations calculated to saturate the base exchange capacity of the soil with the cations. Lignin and humic acid were added at 1% and 2% of the dry weight of the homoionic soil sample initially and, when trends were indicated, the organic materials added were increased to 3% and 4%.

The results of the investigation are as follows:

1. The adsorption of 1% lignin on clays and colloids saturated with aluminum or ferric ions improved the plasticity, shrinkage, swelling, moisture adsorption, and unconfined compression properties of the soil.

2. Saturation of the base exchange capacity of the soil with ferric ions moderately improved the general strength characteristics of the soil.

3. 2% or greater of lignin or humic acid in soil, especially in "hydrogen" and "calcium" soils, resulted in decrease in strength of the soil.

4. Some of the lignin and humic acid samples exhibited good plasticity and shrinkage properties but displayed high swelling and low compressive strength.

The following conclusions have been drawn:

1. Lignin, adsorbed on the surface of clay and colloids, can be effective in inhibiting moisture adsorption, provided lignin is applied in amounts not exceeding that which is necessary to provide steric hindrance to water dipoles. The beneficial effect of lignin in moisture control of the cohesive soil tested could be enhanced by aluminum or ferric ions saturating the base exchange capacity of the soil.

2. Natural organic matter in the soil, if present in the relatively undecomposable form of the structure of lignin, can be beneficial if it is adsorbed on the surface of the clay and colloid portion of the soil in sufficient amounts to inhibit adsorption of water dipoles. This beneficial effect of natural lignin could be enhanced by aluminum or ferric ions saturating the base exchange capacity of the soil.

3. The determination of plasticity and shrinkage constants alone is not a sufficient criterion for evaluating cohesive soils for subgrade use. A cohesive soil is controlled by physico-chemical phenomena to such an extent that it becomes necessary to conduct other tests determining moisture relations affected by the active surface of the clay and colloid portion.

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INTRODUCTION

A roadway consists of two principal components: the pavement, which may be either rigid or flexible, and the foundation which consists of the base, which is directly under the pavement, and the subgrade on which both pavement and base rest. A subbase between base and subgrade may sometimes be necessary.

Very few people are aware of the importance, even existence, of the subgrade. To the average motorist, a roadway is mostly what he can see - pavement, shoulder, and other external features. Even to a road engineer of forty years ago, a strong pavement was the ultimate goal of highway construction. As a result, all symptoms of road deterioration such as cracks, boils, corrugations, pumping, and rutting were, for a long time, attributed to pavement deficiencies. Thicker and better pavements on some roads showed greatly improved performance but on others, particularly after 1920, failures continued to occur regardless of the high quality of the pavement and regardless of the most efficient pavement construction methods.

Subgrade research started in the United States about 1925. By 1930, there were sufficient relations

established between general roadway failure and subgrade factors. Burton and Benkelman[1] studied 107 slabs in 534 miles of pavement in Michigan and found that more than half of the failures were due to differential expansion and settlement of the subgrade. In 1934, Lang[2] showed that frost heave, capillary moisture conditions, and surface deflection - all attributed to subgrade soils - were among the direct causes for failure of bituminous surfaces. Sweet and Woods[3] in 1946 established definite correlation between mapcracking and soil texture and drainage position in 41 miles of pavement in Indiana. In the same year in Minnesota, Swanberg and Hansen[4] traced alligator cracking and rutting to yielding of the subgrade.

After a survey of the causes of pumping in Indiana, Woods and Havey[5] reported that of the three conditions necessary for pumping, two conditions had to do

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[1] V. R. Burton and A. C. Benkelman, "The Relation of Certain Frost Phenomena to the Subgrade," Highway Research Board Proceedings, X (1930), pp. 259-275.

[2] F. C. Lang, "Practical Applications of Road Soil Science in Construction of Flexible Surfaces," Highway Research Board Proceedings, XIV (Part II, 1934).

[3] Harold S. Sweet and K. B. Woods, "Mapcracking in Concrete Pavements as Influenced by Soil Textures," Highway Research Board Proceedings, XXVI (1946).

[4] J. H. Swanberg and C. C. Hansen, "Development of a Procedure for the Design of Flexible Bases," ibid.

[5] K. B. Woods and F. F. Havey, "Pumping of Subgrade through Paving Joints and Cracks," ARBA Technical Bulletin No. 103 (1946).

with the subgrade, namely, type of soil and presence of free water. In 1949, Bleck[1] found that among the causes of rigid pavement failures, those related to soil characteristics were responsible for waviness, blow-ups, faulting, longitudinal and "D" cracking.

Studies of subgrade-related pavement failures, some of which have just been mentioned, indicate one or more of the following conditions to have existed under the failed sections:

1. Presence in the subgrade of soil material with high moisture capacity, resulting in saturation and loss of cohesion.

2. High percentage of silt and very fine sand, a condition favorable to the formation at low temperatures of ice lenses which cause frost heaves and boils.

3. Excessive volume changes (swelling or shrinkage) which may be brought about by large variations in moisture content or by the presence of materials which are compressible or decomposable by soil microorganisms. Swelling may also occur in cut sections after removal of earth surcharge.

It would seem logical that the prevention and control of subgrade failures should be contingent on the conditions just stated and that whatever method is chosen

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[1]A. T. Bleck, "Pavements and Influences Affecting or Determining Their Performance," <u>Highway Research Board Bulletin</u> No. 20 (1929), p. 21.

to stabilize the road bed should, in effect, eliminate the susceptibility of the soil body to excessive water intake and volume change.

The presence of organic material in the soil complicates the problem of subgrade stabilization. Organic matter is generally believed to be compressible and easily decomposed by soil microorganisms. Organic matter is also believed to have a strong capacity for absorbing water. However, aside from the known facts about the destructive effect of organic matter on Portland cement, little is known about the effects that varying proportions of organic material in the soil have on the strength of the road bed. As a matter of fact, the writer has experienced difficulty finding in the literature cases of roadway deterioration that can be attributed directly to the presence of organic material in the subgrade. This does not indicate, by any means, that organic matter is or is not harmful to the subgrade. There could be any number of reasons for this dearth of information, and the following are suggested:

1. Organic soil has always been considered "unsuitable material" and is removed from the road bed during construction.

2. If the organic matter is found to be less than 2% of the total soil, it is generally considered harmless. Any deterioration of the subgrade that may take place afterwards, which may or may not be caused by

the organic material present, is usually attributed to other soil factors in the soil body.

3. There is at present no testing method that can quickly and efficiently determine the nature of the organic matter in the soil and its degree of decomposition.

It is the purpose of this thesis to find out what organic matter does to a subgrade soil. Stated in full, the thesis problem is as follows: To determine the variations in the strength properties of a cohesive subgrade soil as a function of organic matter in combination with certain saturating cations.

The following terms shall be defined:

1. Subgrade is "the material in excavation (cuts), embankments (fills) and embankment foundations immediately below the first layer of subbase, base or pavement and to such depth as may affect the structural design."[1]

2. Cohesive subgrade soil is a subgrade soil containing more than 15 per cent clay.[2]

3. Organic matter is decayed and partly decayed vegetable and animal material.[2]

4. Strength properties are those soil characteristics which are used as criteria in evaluating the

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[1]Robert H. Tittle, "Salvaging Old Pavements by Resurfacing," Highway Research Board Bulletin 47 (1942).

[2]F. L. D. Wooltorton, The Scientific Basis of Road Design (London: Edward Arnold Ltd, 1954), 364 pp.

suitability of subgrade or fill material. Among these properties are: compressive strength, shrinking and swelling characteristics, resistance to adsorption of moisture beyond that required for maximum compaction.

5. Saturating cation is the cation introduced to soil in such concentration as has been calculated to occupy all of the base exchange positions in the clay or other colloidal component of the soil.

6. Homoionic soil is soil with only one kind of exchangeable cation saturating its exchange positions.

The following are the premises, so to speak, in the discussion:

1. The clay and colloid content of the soil is capable of going into base exchange and adsorption activities, both of which are surface phenomena largely influencing such properties of the soil as cohesion, plasticity, structure, volume shrinkage, percolation, and water-holding capacity.[1]

2. A cohesive soil contains clay and colloidal materials in sufficient amounts to have surface phenomena influence the properties of the total soil body.

3. Water molecules are dipoles and are attracted by ions through polarization and orientation in the clay mineral either on the broken bonds or between oxygen

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[1]C. A. Hogentogler, "Report of Subcommittee on Subgrade Studies," Highway Research Board Proceedings, VII (1927), p. 97.

planes.[1]

4. The amount of water the colloids and clay take up while swelling under optimum conditions varies with the kind of adsorbed ions saturating the exchange positions.[2]

5. The principles of base exchange and adsorption permit the alteration of the surface character of soil colloids by chemical means such that the water-attracting character of the mineral surface may be changed into water-repellent properties.[2]

6. Soil organic matter has been shown to have a base exchange capacity.[3,4]

7. Clay has a protective effect on organic matter. It has been known to inhibit peptization of proteins.[5]

8. Organic matter can be used to fill up exchange positions and adsorption points on the clay which would

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[1]W. P. Kelley, H. Jenny and S. M. Brown, "The Hydration of Minerals and Soil Colloids in Relation to Crystal Structure," Soil Science, XLI (1936).

[2]H. F. Winterkorn, "Surface Chemical Factors Influencing the Engineering Properties of Soils," Highway Research Board Proceedings, XVI (1936).

[3]W. R. McGeorge, The Base Exchange Property of Organic Matter in Soils. Ariz. Exp. Sta. Bull. 30 (1930).

[4]W. Sherman Gillam, "A Study on the Chemical Nature of Humic Acid," Soil Science, XLIX (1940).

[5]L. E. Ensminger and J. E. Gieseking, "Resistance of Clay-Adsorbed Proteins to Proteolytic Hydrolysis," Soil Science, LIII (1942), pp. 205-209.

otherwise be occupied by water molecules or by easily hydrated cations.[1]

9. Of the organic materials found in the soil, lignin has been proved to be the most resistant to microbial decomposition.[2]

10. Organic material in the soil in excess of that adsorbed by the clay and colloids can, in itself, become an agent for adsorbing water molecules and hence increase the possibility of swelling.

On the basis of the premises stated, the following proposition is considered:

Variations in the strength properties of a cohesive subgrade may be produced by varying the exchangeable bases and the organic matter content. Thus there is a certain percentage of organic matter in combination with a definite saturating cation which gives optimum strength properties to the subgrade. Above or below this percentage, or in combination with other inorganic cations, the organic matter introduced will produce detrimental results in the subgrade structure.

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[1] R. E. Grim, W. H. Allaway, and F. L. Cuthbert, "Reaction of Different Clay Minerals with Organic Cations," Journal of the American Ceramic Society, XXX (1947).

[2] Selman A. Waksman and Imri J. Hutchings, "Decomposition of Lignin by Microorganisms," Soil Science XLII (1936), pp. 119-130.

CHAPTER I

THEORETICAL CONSIDERATIONS AND REVIEW OF THE LITERATURE

Roles of Subgrade Soil Components

Gravel and Coarse Sand

All soil particles having a diameter of 2 millimeters or more and retained on the No. 10 U.S. Standard Sieve are classified as gravel. Coarse sand is the portion passing the No. 10 sieve and retained on the No. 40 sieve. For the subgrade to provide adequate supporting power, there should be sufficient points of contact between the particles of gravel and coarse sand to create the necessary internal friction. If there is too little gravel and coarse sand in proportion to the clay and colloids, the coarse particles will be suspended, so to speak, in the clay and contact between the points will be lost. The loss in internal friction means a loss in supporting power.

Soil Fines

The fines constitute that portion of the soil passing the No. 40 sieve and include all particles with an approximate diameter smaller than 0.420 millimeter. The clay minerals, inorganic and organic colloids, fine sand and silt are classified among the fines.

In the same manner that the gravel and coarse sand provide the internal friction in the subgrade soil, the fines provide the cohesion. The soil-moisture relationships which are such important considerations in the subgrade are all determined in the fines. The Revised Public Roads or the Highway Research Board System of subgrade soil classification[1] uses percentage of fines as the initial criterion. The categories are narrowed down by percentage of soil passing the No. 200 sieve,[2] 35 per cent being the dividing line between what may be considered generally good and generally fair to poor subgrade materials. The liquid limit, plasticity index, and finally the group index, all three criteria being associated with soil fines, are used in the final steps of the classification.

The importance of a better understanding of the role of soil fines is appreciated if one recalls that there is a continuing battle being waged against excessive change in moisture and volume in the subgrade. The seat of this trouble is in the fines, particularly so in the portion passing the No. 200 sieve. These are the clays and the inorganic and organic colloids. Ironically

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[1]M. G. Spangler, Soil Engineering (Scranton: International Book Company, 1951), pp. 176-178.

[2]The maximum particle diameter is 0.074 mm.

the clue to the solution of the soil-moisture-volume problem is also in the understanding of the physico-chemical phenomena observed to occur in this portion of the soil.

Clay Minerals

The clay minerals are found, along with soil colloids, in the soil portion that remains in suspension after 24 hours in hydrometer analysis. The clay minerals are distinct chemical compounds capable of entering into chemical reactions. They range in size from 2 to 5 microns and despite their small size, or because of it, provide the lattice structures and tremendous surface area for the adsorption of ions, water and organic molecules, and for the exchange of cations and anions.

The clay minerals are built up from two basic structural units or "building blocks". One of these units is the silica tetrahedron - a silicon atom surrounded by four closely-packed oxygen atoms such that the silicon is equidistant from all four oxygens or hydroxyls. On a sheet, these tetrahedra are arranged so that their bases are in the same plane. Grim[1] sets the thickness of the silicon tetrahedron at 4.93 Angstrom units. The other "building block" is the aluminum

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[1]Ralph E. Grim, Clay Mineralogy (New York: McGraw-Hill Book Company, Inc., 1953).

octahedron - an aluminum atom surrounded by six closely-packed oxygen atoms or hydroxyls in an octahedral arrangement. The aluminum atom is equidistant from all six oxygens or hydroxyls. The aluminum octahedron is, according to Grim,[1] 5.05 Angstrom units thick.

Grim,[1] Baver,[2] Marshall,[3] Pauling,[4] Searle and Grimshaw,[5] and Wooltorton[6] have all studied clay minerals thoroughly and have written valuable information on the clay structure and properties. The known clay minerals may be grouped as follows:

1. The kaolin group, consisting of kaolinite, dickite, nacrite, and halloysite.

2. The montmorillonite group, consisting of montmorillonite, beidellite, and nontronite.

3. The hydrated mica or the illite group, including the chlorites and vermiculites.

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[1] Ralph E. Grim, Clay Mineralogy (New York: McGraw-Hill Book Company, Inc., 1953).

[2] L. D. Baver, Soil Physics (3d ed, New York: John Wiley & Sons, Inc., 1956).

[3] C. E. Marshall, The Colloid Chemistry of the Silicate Minerals (New York: Academic Press Inc., 1949).

[4] L. Pauling, "The Structure of the Chlorites," Proceedings of the National Academy of Sciences, XVI (1930), p. 578.

[5] A. B. Searle and R. W. Grimshaw, The Chemistry and Physics of Clays (3d ed, New York: Interscience Publishers, Inc., 1959).

[6] F. L. D. Wooltorton, The Scientific Basis of Road Design (London: Edward Arnold Publishers Ltd., 1954).

4. The impure mixed-layer clay group.

The kaolin clays are characterized by a 1:1 lattice (one silicon tetrahedral layer to one aluminum octahedral layer). The members of the group above differ only in the stacking of the units. The sheets are compact so that no ions or molecules can get between them, hence there is very little isomorphous substitution or substitution within the lattice. The external basal surfaces are relatively inert but show adsorption properties. Ionic reactions and exchange properties are found on the unsatisfied valences at the edges of the particles. Kaolin clays have slight hydration and adsorptive properties, low base exchange capacity and low cation adsorption. The principal member of the group is kaolinite, the structure of which was first suggested by Linus Pauling.[1]

The montmorillonite clays are characterized by a 2:1 lattice (2 silicon tetrahedra and 1 aluminum octahedron in between) which expands and contracts with the amount of water present. All the tips of the tetrahedral sheet point toward the center of the unit. High hydration and high cation adsorption are indicated. There is considerable lattice substitution (magnesium for aluminum, aluminum for silicon, etc.) so that the lattice

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[1]Linus Pauling, <u>op. cit.</u>

charge is always balanced. Water and other polar molecoules can enter between the layers, resulting in lattice expansion. Exchangeable ions occur between the silicate layers along with more water and other polar molecules. Montmorillonite is the principal member of this group. It contains some calcium ions, and some of its aluminum ions are replaced by magnesium which in turn may be replaced by potassium or sodium. Beidellite is characterized by considerable substitution of aluminum for silicon and by low magnesium content. Nontronite results from complete substitution of aluminum by iron, and hence is sometimes referred to as a silicate of iron.

The clay minerals in the illite group are characterized by a 2:1 lattice with the units relatively fixed in position and hence non-expanding. The silica layers carry charges due to the substitution of aluminum for silicon in the silica sheets. Potassium atoms are embedded between the alumino-silicate layers to balance this charge deficiency and to act as agents of cementation. These balancing cations are, however, not exchangeable.

The only thing that need be said for the fourth group of clay minerals is that, although their occurrence is rather widespread, they are random interstratification of clay units and hence do not have constant properties. Mixed layers of montmorillonite and illite are common.

These mixed-layer clays probably explain the numerous varieties of clay minerals which cannot seem to belong to any of the three main groups mentioned above, since their properties, like most mixtures, are very variable.

Organic Colloids

Organic matter as it may be found in the soil is defined by Waksman[1] as a "mixture of dark-colored amorphous organic compounds formed in the soil as a result of decomposition of organic matter of plant and animal origin by microorganisms, under aerobic or anaerobic conditions; it consists largely of substances which are resistant to further decomposition (largely lignins and modified lignin complexes), of substances in the process of decomposition (hemicelluloses, some celluloses, and proteins), of substances resulting from decomposition (organic acids, bases, etc.) and of microbial-synthesized substances (largely organic nitrogenous complexes and hemicelluloses)."

The products of decomposition of organic matter are usually leached away by ground water so that after a time only the most resistant of them, the lignins and lignin complexes, and some proteins are left in the soil. There is growing opinion among workers with the soil that

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[1]S. A. Waksman, "Chemical Nature of Soil Organic Matter," Transactions, 2d Commission, International Society of Soil Scientists, Volume A, p. 172.

these lignins and proteins, if found in soils containing sufficient clay, may actually be beneficial for highway use.

Physico-chemical Properties in Soil

Introduction

The clay and colloid portion of the soil is often referred to as the "active" portion. The adsorption of water molecules, adsorption of ions, exchange of ions, and other physico-chemical phenomena occur on the tremendously large surface area afforded by the clay and colloids by virtue of their particle size. It is common knowledge, although slightly incredible, that if a crystalline cubic solid one inch on the side is broken up into tiny cubes 3 microns on the side, the surface area is changed from 6 square inches to 362 square feet (or roughly the floor area of an 18 ft. by 20 ft. room) and the total length of the broken edges is 13,900 miles or about halfway around the earth at the equator.

Parker and Pate[1] have pointed out that adsorption of water by soil is due almost entirely to the soil colloids and that a relation exists between the silica-sesquioxide ratio of clay and its plasticity and moisture

[1]F. W. Parker and W. W. Pate, "Base Exchange in Soil Colloids and the Availability of Exchangeable Calcium in Different Soils," Journal of the American Society of Agronomists, XVIII (1926).

equivalent. Hogentogler[1] reported that the soil particles with colloidal properties largely determine the physical properties of the soil. Hogentogler enumerated the soil phenomena directly dependent upon the amount and activity of the colloids as follows: hygroscopic moisture attraction, adhesion, heat of wetting, freezing-point depression, water-holding capacity, capillary movement, percolation, plasticity, soil structure, and shrinkage.

Ion Adsorption and Exchange

It has been mentioned that the clay minerals are capable of adsorbing ions and polar molecules within the crystal lattice or on the electro-negatively charged surface and exchange these ions or polar molecules for those present in an electrolyte surrounding the clay mineral. Several theories have been presented to explain the mechanism of exchange that takes place between the clay or between a colloid with a known base exchange capacity and the free ions in an electrolyte. Among the earlier ones proposed is the kinetic theory of ion exchange by Hans Jenny and is given here as presented by C. E. Marshall.[2]

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[1]C. A. Hogentogler, "Report of Subcommittee on Subgrade Studies," Highway Research Board Proceedings, VII (1927), p. 97.

[2]C. E. Marshall, The Colloid Chemistry of the Silicate Minerals (New York: Academic Press Inc., Publishers, 1949), pp. 125-127.

Jenny's Kinetic Theory of Ion Exchange. Each ion is regarded as having a certain mean oscillation volume. The theory covers four principles, namely: simple exchange, complementary ion principle, surface diffusion, and contact exchange. For simple exchange, exchange is less when the oscillation volume of the added ion exceeds that of the ion on the clay, and more in the opposite case. Exchange completion is approached for high electrolytic concentration.

The complementary ion principle concerns two replaceable ions on the clay as affected by oscillation volume. The release of one of the ions on the clay is greater in proportion as the oscillation volume of the other ion on the clay is smaller.

Surface diffusion concerns overlapping of oscillation volumes upon a given surface. This part of the theory has been substantiated in zeolite and salt experiments but not in clay. Contact exchange is exchange of ions between adjacent colloidal particles due to overlapping of oscillation volumes. This principle fines application in ion diffusion from the soil to the roots of plants.

The following is how Jenny and Reitemeier[1] visualise the mechanism of ion exchange on the clay surface:

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[1]H. Jenny and R. F. Reitemeier, "Ionic Exchange in Relation to the Stability of Colloidal Systems," Journal of Physical Chemistry, XXXIX (1935), pp. 593-604.

> Colloidal clay particles are plate-shaped crystals which hold on their surfaces adsorbed cations. Owing to heat motion and Brownian movement the adsorbed ions are not at rest but oscillate, and at times are at a considerable distance from the wall. If it so happens that on account of Brownian movement a cation of an added electrolyte slips between the negative wall and the positive oscillation ion, the electrolyte cation will become "adsorbed" while the surface ion remains in the solution as an exchange ion. The more loosely an ion is held, the greater is the average distance of oscillation and the greater is the possibility of replacement or, vice versa, the more tenaciously an ion sticks to the surface the less readily it will be released by the cations of an electrolyte added to the colloidal system. The average distance of oscillation corresponds directly to the average thickness of the electric double layer, and on the basis of the picture outlined, one would conclude at once that clays with high zeta potentials contain easily exchangeable ions.

Hauser's Concept.—E. A. Hauser[1] assumes that "crystals of colloidal dimensions differ from larger sized crystals by having a composition at variance with the stoichiometric one." From this initial assumption, Hauser continues:

> ...the surface of colloidal crystals must consist to a large extent of chemically unsaturated or unevenly combined building elements. These must exhibit a high potential of unsaturation, and this is satisfied by adsorption of compensating ions from the environment. If compensating ions are not available, or if the colloidal matter is present in high concentration, rearrangement of the building units will take place in time, until stoichiometric equilibrium is reached and a system of minimum free energy is obtained....Only one constituent (of an

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[1]E. A. Hauser, Colloidal Phenomena (Massachusetts: Massachusetts Institute of Technology Press, 1954).

electrolyte) is really adsorbed, whereas the others remain in solution. Since the electrical neutrality of the system as a whole must be maintained, another ion must be substituted. This ion can either be given off by the adsorbent in exchange for one taken on, or it must be obtained by secondary reaction in the dispersion medium.

Wooltorton's Hypothetical Clay Salt.[1]—Wooltorton compares the electro-negatively charged clay micelle (with a silica-sesquioxide ratio greater than 2) to a negatively charged anion forming a nucleus surrounded by an atmosphere of positively charged cations in varying degrees of freedom. Wooltorton continues:

> These cations form, in the aggregate, the complex cation of the hypothetical clay salt.... The Helmholtz double layer conception is useful in explaining certain phenomena but is nevertheless largely empirical.
>
> The first fundamental property of the colloidal soil complex is its ability to dissociate certain ions. For electro-negative colloidal clays, the dissociated ions are cations which form the hypothetical clay cation. The remaining material may be taken, in the aggregate, to be electronegative and is thus likened to a salt anion....As described by Kelley, Dore and Brown, crystalline minerals are composed of atoms at regularly spaced distances and falling into regularly spaced planes....For any particular arrangement of the building blocks, for any given boundary conditions such as cleavage planes and end conditions, and for any given conditions of unsatisfied aluminum charges, as occur in certain arragements, there will be free bonds or charges which are available for bases or cations to attach themselves. On this hypothesis, the nature of any adsorbed ions will obviously depend, in part, upon the space available within the framework to retain them. Amongst the bases which may be absorbed or adsorbed, due

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[1]F. L. D. Wooltorton, The Scientific Basis of Road Design (London: Edward Arnold Ltd., 1954).

to the existence of unsatisfied charges, must be placed water.

The less securely the replaceable cations be held, i.e. the less their surface energy of adsorption, the greater will be the induced osmotic energy available for adsorption. The correlation curve for a powdered, low-energy sodium clay would thus be expected to exhibit a greater swelling and a higher plastic index for a given base-exchange capacity than would a calcium modification.

Effect of Replaceable Ions

Regardless of which of the numerous theories comes closest to explaining what actually happens on the clay surface, there is general agreement that most clay minerals do adsorb, absorb, and exchange ions and polar molecules. There is also general agreement that these exchangeable, or replaceable, ions affect to some measurable degree the moisture-related properties of the clay. As a matter of fact they also affect the properties of the soil of which the clay may only be a very small portion. The conclusions which have been reached regarding these effects may be a little too general, and one will notice some points of disagreement here and there. It is possible that, since there is a tremendous range of variability in clay minerals, not to speak of the greater range of variability in native soils in the different experiments carried out on clays and soils, some variable, or variables may not have been held down. This fact alone makes the degree of concurrence among the different workers on soil properties even more amazing.

Effect of Replaceable Ions on Flocculation

In 1928, Baver[1] found that substitution of sodium for calcium, magnesium, or other bases resulted in a new colloid highly dispersable in water. He also found that calcium had a flocculating effect on the soils with high percentage of clay, while hydrogen-saturated soil was less flocculated than the original soil. Sodium and potassium have a decided deflocculating action. In slaking, the presence of hydrogen ions increased the rate of disintegration, while sodium and potassium decreased the disintegration rate.

Wooltorton[2] confirms the flocculating effect of free and replaceable calcium on clay by attributing the phenomenon to the favorable influence of calcium on the growth of vegetation and organic matter which are adsorbed on the clay binding soil particles into aggregates and becoming water resistant on dehydration.

H. Jenny[3] mentions the high flocculating powers of calcium and magnesium, and the dispersive action of potassium and sodium on clay and humus colloids.

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[1]L. D. Baver, "The Relation of Exchangeable Cations to the Physical Properties of Soils," Journal of the American Society of Agronomists, XX (1928).

[2]F. L. D. Wooltorton, op. cit.

[3]H. Jenny, Factors of Soil Formation (New York: McGraw-Hill Book Company, Inc., 1941).

Effect on Atterburg Factors

The effect on the Atterburg factors of soil consistency is equivalent to the effect on shear resistance. Divalent ions tend to increase the plasticity index by either raising the liquid limit or lowering the plastic limit. According to Baver,[1] the sodium ion lowers both limits but increases the plasticity index. However, it has been reported by Belcher, McAlpin and Woods,[2] that sodium soils give the maximum liquid limit values. Winterkorn[3] found that the potassium ion tends to lower the plasticity index and that calcium, magnesium, and sodium ions tend to increase the plasticity index.

Effect on Swelling

Baver[1] shows that for Putnam clay (beidellite) swelling varies with the nature of the adsorbed cations in the order given: Li > Na > Ca > Ba > H > K. For Montmorillonite clay (bentonite) the order of swelling is as follows: Na > Li > K > Ca = Ba > H. The ultimate moisture uptake and the volume change in cubic centimeters per gram of monoionic clay has been

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[1]L. D. Baver, Soil Physics (New York: John Wiley & Sons, Inc., 1956).

[2]D. J. Belcher, G. W. McAlpin and K. B. Woods, "Current Practices in Stabilization," Purdue Conference (1940).

[3]H. F. Winterkorn, "Surface Chemical Factors Influencing the Engineering Properties of Soils," Highway Research Board Proceedings, XVI (1936).

found by Winterkorn[1] to decrease in the general order of Na > Ca > H. Sideri[2] states that the substitution of a cation by another that raises the charge of the colloid particles increases the swelling. The cations are ranked according to influence on swelling in this order: Na > K > Ca > Mg > H. Grim[3] reports that Li and N favor great swelling while Ca, Mg, Al, Fe(ic), and K tend to reduce swelling.

<u>Effect on Compressive Strength</u>

Winterkorn,[4] studying the influence of surface-chemical properties as expressed by seven different exchangeable cations on compressive strength found that Al, Fe, and H modifications always gave best results, Mg, Ca, and K modifications gave intermediate results close to those of natural soil, and Na modifications gave the worst results.

<u>Effect on Water Configuration</u>

The properties of clay-water systems such as

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[1] H. F. Winterkorn, "Adsorption Phenomena in Relation to Soil Stabilization," <u>Highway Research Board Proceedings</u>, XV (1935).

[2] D. I. Sideri, "Soil Swelling: I. The Swelling of Soil in Water Considered in Connection with the Problem of Soil Structure," <u>Soil Science</u>, XLI (1936).

[3] R. E. Grim, "Modern Concepts of Clay Minerals," <u>Journal of Geology</u>, L (1942), pp. 225-275.

[4] H.F. Winterkorn, <u>Homo-Ionic Soil Study</u>, May 31, 1946.

plasticity are affected by the bond between particles, amount of water between particles, and the nature of water adsorbed on the clay surface. Grim[1,2] asserts that the exchangeable ions determine the bond between particles thereby restricting the amount of water that can come between the particles. The nature of the exchangeable ions influences the character of the configuration of water molecules, that is, the manner in which the cation with its hydration envelope fits geometrically into the configuration. There is a suggestion that small ions tend to tighten the water net, while large ions tend to disrupt the water net. Thus, Grim suggests further, the calcium ion tends to develop four very well oriented layers of water. Sodium favors the development of very thick layers. Potassium, hydrogen, aluminum and ferric ions form tight bonds between the particles and hence have very small potential for growth of thick oriented water layers.

Effect on Hydration or Hygroscopicity

Wooltorton[3] describes hygroscopicity as "that

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[1] R. E. Grim, "Ion Exchange in Relation to Some Properties of Soil-Water Systems," ASTM Special Publication No. 142 (1952).

[2] R. E. Grim, "Organization of Water on Clay Mineral Surfaces and Its Implications for the Properties of Clay-Water Systems," Highway Research Board Special Report No. 40 (1958), pp. 17-23.

[3] F. L. D. Wooltorton, op. cit.

moisture which is adsorbed from the atmosphere and held by molecular forces close up to the surface of the particle....It consists of a film of water molecules strongly associated with the exchangeable cations and the surface of the soil micelles. It is held close to the surface by very powerful compressive forces which are considered to tend to reduce micellar swelling. These high compressive stresses result in an increase in the density of the water and impart to the film the properties of a solid... the thickness, according to Mattson, (is) not greater than 4 to 5 micromicrons and corresponds to the range of molecular attraction."

Baver[1] presents data to show that at relative humidity of 99.8 per cent, hygroscopicity increases according to: Li > Na > H > Ba > Ca > K; at relative humidity of 74.9 per cent the order is: H > Ca > Li > Na > Ba > K. Data is also presented to show that hygroscopicity increases with total exchange capacity of the colloids, although Baver warns that the relation which actually involves relative activity of ions and colloidal surface, number of ions present, etc. is not a simple one.

Soil-Organic Matter Relationships

In his experiments with Loess Pampeano soils,

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[1]L. D. Baver, op. cit.

Winterkorn[1] found that this loess containing 6.45 per cent organic matter was very favorable for waterproofing so long as further bacterial action was prevented. Analysis of the organic matter in Loess Pampeano showed a high percentage of lignins and proteins. Earlier, in 1940, Catton[2] had successfully hardened with soil cement a peaty soil having a very low density and very high organic content.

The presence of easily-decomposable proteins along with strongly resistant lignins in the same soil above needs some explanation. Lignin has been shown by Waksman and Hutchings[3] to be highly resistant to attack by fungi, bacteria and invertebrate animals living in soils, peat bogs, and composts. They assert that certain groups among the higher fungi are capable of destroying lignin in the fresh or partly decomposed plant tissue but once in the purified state, lignin becomes completely resistant to attack even by these microorganisms. Protein, on the other hand, is readily decomposed by many

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[1]H. F. Winterkorn, "Physico-Chemical Properties of Soils," Proceedings of the Second International Conference on Soil Mechanics and Foundation Design, I (Rotterdam, 1948).

[2]Miles D. Catton, "Research on the Physical Relations of Soil and Soil Cement Mixtures," Highway Research Board Proceedings, XX (1940), p. 821.

[3]Selman A. Waksman and Imri J. Hutchings, "Decomposition of Lignin by Microorganisms," Soil Science, XLII (1936), pp. 119-130.

microorganisms under most conditions. However, it is believed that protein is protected from decomposition both by the lignin and clay portion of the soil. Stabilization of protein by the more resistant lignin has been proposed by Waksman. An experiment by Waksman and Iyer cited by de Sigmond[1] showed that lignin exercises a depressive effect on the decomposition of proteins in pure and mixed cultures of microorganisms, indicating an interaction between lignin and protein molecules.

Many other workers, however, attribute this protective action to the presence of clay. Ensminger and Gieseking[2] quote Waksman as stating that clay colloids form compounds with humus colloids, thus preventing its rapid decomposition. Ensminger and Gieseking performed an experiment with colloids to which pepsin and pancreatin were added. They concluded that the adsorption of albumen and haemoglobin by base exchange clays interfered with enzymatic hydrolysis of these proteins in both acid pepsin and alkaline pancreatin suspensions, and that the degree of interference was influenced by the exchange capacity of the clay.

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[1] Alexius A. J. de Sigmond, The Principles of Soil Science. Trans. A. B. Yolland, ed. G. V. Jacks. (London: Thomas Murby & Co., 1938).

[2] L. E. Ensminger and J. E. Gieseking, "Resistance of Clay-Adsorbed Proteins to Proteolytic Hydrolysis," Soil Science, LIII (1942), pp. 204-209.

Reduction of Base Exchange Capacity

The clay-protein relationship apparently benefits both protein and clay. While the protein seeks "refuge" in the clay structure from the reach of enzymes, it covers up exchange positions in the clay lattice and on the clay surface. It may also, as suggested by Hendricks[1], orient itself between the silica-alumina sheets to keep the interplanar spacing a constant. Consequently, with most of the exchange positions inaccessible, the adsorption capacity of the clay for water and for easily hydrated cations is reduced.

This reduction of base exchange capacity has been found to be effected not only by proteins but by various large organic cations as well. Smith[2] reacted bentonite with a solution of free nicotine in water and reported that bentonite enters into base exchange with a definite chemical equivalent of organic base where saturation can be reached. The studies of Meyers[3] indicate that there is a physico-chemical union between the organic and the

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[1] S. B. Hendricks, "Base Exchange of the Clay Mineral Montmorillonite for Organic Cations and Its Dependence upon Adsorption due to Van der Waals Forces," Journal of Physical Chemistry, XLV (1941), pp. 65-81.

[2] C. R. Smith, "Base Exchange Reactions of Bentonite and Salts of Organic Bases," Journal of the American Chemical Society, LVI (1934), p. 1561.

[3] H. E. Meyers, "Physico-Chemical Reactions Between Organic and Inorganic Soil Colloids as Related to Aggregate Formation," Soil Science, XLIV (1937), p. 331.

inorganic colloids. Working with alfalfa and clay colloids, he found that, regardless of the type of organic and inorganic materials combined, a reduction in exchange capacity of the system resulted from the mixing. Gieseking[1] reported that complex organic cations were strongly adsorbed within the variable interplanar (001) spacings of montmorillonite, resulting in larger interplanar spacings. These cations were found to be exchanged by cations of approximately the same size but were not exchanged by hydrogen, which is usually very effective in replacing small cations. Gieseking also found that montmorillonite saturated with large substituted ammonium ions did not show the water adsorption, swelling, and dispersion characteristics of calcium, sodium, or hydrogen montmorillonite, nor did the new interplanar (001) spacings vary with the water content of the system. Jordan[2] reported that organic ions could be used to reduce the water-adsorbing properties of montmorillonite; the larger the ion, the greater the reduction of water-adsorbing capacity. He showed that the degree of swelling depends upon at least three factors, namely, the extent of the surface coating of the clay particles by

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[1] J. E. Gieseking, "The Mechanism of Cation Exchange in the Montmorillonite-Beidellite-Nontronite Type of Clay Minerals," Soil Science, XLVII (1939), pp. 1-11.

[2] J. W. Jordan, "Organophilic Bentonites Swelling in Organic Liquids," Journal of Physical and Colloid Chemistry , LIII (1949), pp. 294-306.

the organic matter, the degree of saturation of the base exchange capacity of the clay by organic cations, and the nature of the solvating liquid.

<u>Orientation of Organic Colloids on the Clay</u>

As is the case with any surface phenomenon in the study of soil, there are a few different theories and concepts regarding the manner in which organic colloids are held on or by the clay.

Sideri[1] describes the humus-clay cohesion as follows:

> The cohesion between the individual particles of a non-homogeneous aggregate consisting of colloidal particles and of particles of a greater size may be explained by the orientation of the molecules of the layer of adsorption only in the limited case of the closest contact between the coarse mineral elements. In most cases the orientation of the molecules of the layers of the cementing substances extends to a certain depth, there to become disorganized and to be replaced by the smectic elements of the grouping. The increase of the stability of the bond and the decrease of the solubility of the clays cannot be explained only by the influence of the adsorbed layer of humus and by the decrease of moisture capacity due to a definite orientation, as is recognized, for instance, in regard to the molecules of fatty acids. In soil we are dealing with a large accumulation of humus in an irreversible state and with the prevalence of the variable forms of the mesomorphous grouping.
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> It is highly striking, indeed, that there can be highly stable (that is, insoluble in water) non-homogeneous aggregates composed of parts which are readily soluble in water. The solution of sodium-clay after it has been dried

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[1]D. I. Sideri, "On the Formation of Structure in Soil: II. Synthesis of Aggregates; On the Bonds Uniting Clay with Sand and Clay with Humus," <u>Soil Science</u>, XLII (1936).

> at 100 degrees Centigrade readily dissolves again in water but, mixed with pure quartz sand, it becomes insoluble and acquires the character of a very tenacious cement. A similar behavior is manifested by humus-clay aggregates, obtained from a Na-clay and Na-humate material, which readily peptize under the influence of water. These aggregates acquire a remarkable resistance not only to water, but also to alkalies.

Hendricks[1] believes that organic colloids are held to the surface of silicate layers of the clay mineral not only by the coulomb forces between the ions but also by van der Waals attraction of the molecules to the surface. The values of the interplanar spacing depend upon the structure of the organic ion and the manner in which it is adsorbed upon the silicate surface. Large organic ions are held more firmly by clay than are inorganic ions, including hydrogen. Their presence markedly alters the dispersability of clay and practically destroys the lattice swelling in water.

Meyers[2] explains the reduction of exchange capacity in his polar adsorption theory:

> Surfaces possessing electrical properties polarize polar compounds. The humic compounds are polar and therefore capable of being polarized. Since they are only slightly ionized compounds, the carboxyl ends (or the end of the complex with the greater number of carboxyl groups) would be positive. The soil colloids, bentonite, quartz, and orthoclases possess electrical properties and therefor would serve as polarizing materials. They are all electronegative and therefore would attract toward

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[1] S. B. Hendricks, op. cit.

[2] H. W. Meyers, op. cit.

their surface the positive end of a polar compound. The polar adsorption should result in a close packing of the organic colloid particles on the surface of the polarizing substances. Such adsorption would result in a reduction in the exchange capacity, not because of the chemical union but because of steric hindrance to the passage of ions from the ends and sides of the organic colloids resulting from close contact either with the polarizing surface or with other polarized organic colloids. The polar adsorption not only would be a factor in reducing the base exchange capacity of the organic colloid but it would also probably cover the exchangeable cations on the surface of the inorganic colloid, thus permitting only those ions within the expanding lattice to enter into the exchange reaction.

With an amphoteric compound such as aluminum hydroxide, a chemical union may possibly exist between the positive valences of the compound and the negative valences of the colloidal organic acid. In addition there would probably be oriented packing around the aluminum hydroxide particles since the organic colloidal particles, because of their relatively large size, probably would need to be packed very closely in order to satisfy the valence requirements of the positively charged particles. This close packing would also result in steric hindrance to some of the normally exchangeable ions located on the side of the organic colloids, thus lowering the exchange capacity of the system.

Organic Cations as Additives in Soil Stabilization

Numerous pilot studies have been carried out to test the use of large organic cations by base exchange, or of organic colloids by adsorption, in improving the properties of highway base courses and subgrades. The specific uses for which these cations and colloids are tested may be grouped as follows:

1. To increase the effectiveness of currently known and used waterproofing and bonding materials (such

as asphalt, bituminous mixtures, and Portland cement) by modifying the surface properties of the soil or aggregate particles.

2. As a waterproofing agent in itself, to change the water-attracting properties of soil particles to water-repelling properties.

The results of quite a few of these studies have been encouraging as may be inferred from the research conducted by:

1. Mainfort, McAlpin, and Winterkorn[1] on salts of abietic acid;

2. Winterkorn and McAlpin[2] on rosinous materials;

3. Winterkorn[3] on aniline-furfural;

4. Grossi and Woolsey[4] on fatty quaternary ammonium salts;

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[1] R. C. Mainfort, G. W. McAlpin, and H. F. Winterkorn, A Laboratory Study of the Soil Stabilizing Effectiveness of a Complex Salt of Abietic Acid, Technical Development Note No. 32, U. S. Department of Commerce, July, 1944.

[2] H. F. Winterkorn and G. W. McAlpin, Soil Stabilization by the Use of Rosin, Technical Development Note No. 34, U.S. Department of Commerce, February, 1946.

[3] H. F. Winterkorn, A Laboratory Study of the Soil Stabilizing Effectiveness of Artificial Resins with Special Emphasis on the Aniline-Furfural Resins, Technical Development Note No. 43, U.S. Dept. of Commerce, January 1947.

[4] Frank X. Grossi and John L. Woolsey, "Effect of Fatty Quaternary Ammonium Salts on Physical Properties of Certain," Industrial and Engineering Chemistry, XLVII (1955).

5. Meunier, Williamson and Hopkins[1] on calcium acrylate;

6. Davidson and Davidson[2,3,4,5] <u>et al</u> on fatty acid amine acetate, quaternary ammonium chloride, aniline furfural, polyacids and lignin with large organic cations.

Amount of Organic Colloids Required

An important aspect of soil-organic matter relationship is the amount of organic colloids that can be used to effect the inhibition of water absorption. This amount is determined for organic cations not only by the base exchange capacity of the soil but also by the equivalent weight and structure of the cation employed.

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[1]Vincent C. Meunier, Gordon J. Williamson, and Robert P. Hopkins, "Soil-Water Relationship in Calcium Acrylate Stabilized Soil," Industrial and Engineering Chemistry, XLVII (1955).

[2]Donald T. Davidson and John E. Glab, "An Organic Compound as Stabilizing Agent for Two Soil-Aggregate Mixtures," Highway Research Board Proceedings, XLIX (1949).

[3]James H. Hoover and D. T. Davidson, Preliminary Evaluation of Some Organic Cationic Chemicals as Stabilizing Agents for Iowa Loess, Proj. 283-S, Iowa Engineering Experiment Station, 1956.

[4]J. B. Sheeler, J. C. Ogilvie, and D. T. Davidson, "Stabilization of Loess with Aniline-Furfural," Highway Research Board Proceedings, XXXVI (1957).

[5]R. L. Nicholls and D. T. Davidson, "Polyacids and Lignin Used with Large Organic Cations for Soil Stabilization," Highway Research Board Proceedings, XXXVII (1958).

It was pointed out previously that for the organic cation to reduce the water uptake of the soil, it should provide steric hindrance to water dipoles. Due to van der Waal's attraction, larger cations are generally difficult, or impossible, to replace by smaller organic cations or by inorganic cations.[1] Jordan[2] states that the larger the organic cation, the greater its effectiveness in reducing the water-adsorbing capacity of the treated soil.

It is interesting to conjecture what happens when steric hindrance at all points on the active surface is effected and an excess of organic matter is present. The writer imagines that the following would happen. Assuming that more organic matter than necessary is applied, the polar organic molecules would nevertheless crowd on the clay surface and effect steric hindrance to water dipoles and exchangeable bases. However, the excess organic colloids would then be exposed to possible combination with water dipoles. Thus, the excess organic matter would apparently increase the "water-loving" tendencies of the soil. Actually it would not be the clay or the soil surface that would take up the

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[1] S. B. Hendricks, "Base Exchange of the Clay Mineral Montmorillonite for Organic Cations and Its Dependence on Adsorption due to van der Waals Forces," Journal of Physical Chemistry, XLV (1941), pp. 65-81.

[2] J. W. Jordan, "Alteration of the Properties of Bentonite by Reaction with Amines," Mineralogy, XXVIII (1949), pp. 598-605.

water but the excess organic additives. However, the general effect on the system is the same, that is, increased potential for water uptake for a given weight of soil and organic matter.

The Effect of Natural Organic Matter

The discussion up to this point has been dealing mostly with added organic matter. The question comes up: What about the organic matter which is already present in the soil?

Most soils contain organic matter in varying degrees. The organic matter contained is usually a mixture. However, the components are definite chemical compounds in themselves, regardless of whether they are in the process of formation, of decomposition, or have reached equilibrium with respect to soil microbiological activity. A considerable proportion could exist as dissociated cations or as polar molecules, and, therefore, could be expected to behave like any pure compound of the same composition applied to the soil. Since the contention has been that organic colloids applied to the soil are effective in reducing the capacity of the soil for adsorption of water, it follows that organic colloids, already existing in the soil, and of the same chemical composition as that which would be applied, would be similarly effective in reducing such water-adsorption capacity, contingent on two important consideration: (a) the amount of natural organic matter in the soil should very nearly equal that amount which, by polar adsorption, would result in close packing of the organic colloids on the clay surface, thus covering up exchangeable bases and restricting the adsorption of water dipoles, and (b) the soil-water relationships created by the saturating or predominant replaceable inorganic cations in the soil should be clearly understood and properly evaluated with respect to the total picture.

CHAPTER II

EXPERIMENTAL PROCEDURES

General Procedure

Several samples of a cohesive soil, classified in the Michigan State Highway Department Soil Engineering Manual as Warsaw soil, were obtained at borings along the right-of-way on M-43 between the city of Kalamazoo and Richland, Kalamazoo County, Michigan. The samples, taken from part of the B horizon but mostly from the C horizon, were a yellowish brown to reddish brown coherent gritty loam.

The following data about the soil were obtained in preliminary experiments:

1. Particle size distribution
2. Specific gravity of soil grains
3. Base exchange capacity
4. Clay mineral content (qualitative) by X-Ray diffraction and by infra-red spectroscopy
5. Plastic limit, shrinkage limit, and liquid limit

The following tests were performed on the homoionic soil modifications and homoionic soil-organic matter combinations:

1. Plastic limit, liquid limit, and shrinkage limit
2. Unconfined compression strength
3. Moisture absorption in capillarity, immersion, freeze-thaw, wetting and drying cycles
4. Volume change

In the experiments of this thesis, an attempt has been made to simulate the natural organic matter in the soil with the use of lignin and humic acid. This has been found necessary as it is physically impossible to obtain, even in a large area, samples of soil belonging to the same series and classification and containing naturally occurring organic matter at different set percentages, as 1%, 2%, etc.

Lignin has been chosen to represent the organic matter in equilibrium with soil microbiological activity, that is, assumed to remain in the soil without further decomposition. Humic acid has been chosen to represent organic matter at any stage of decomposition. Inorganic cations are introduced into the soil by base exchange and it is assumed that these sations are present in the soil <u>before</u> the organic collcids enter the system.

Preparation of Homeionic Soils

<u>Materials</u>

600 lb Warsaw soil passing the No. 4 sieve;

0.2 normal hydrochloric acid solution; solutions of aluminum chloride, calcium chloride, ferric chloride; distilled water. Large jars and ceramic vats to hold the samples. Vacuum filtration system for washing the chemically-treated samples.

<u>Procedure</u>

The procedure used by H. F. Winterkorn[1] was adopted. Essentially, it consists of leaching the soil with an electrolyte containing the desired cation in such concentration as is calculated to saturate the base exchange capacity, the value of which was obtained in a preliminary experiment. An assumption has to be made that the process results in base saturation.

"Hydrogen" soil was prepared by soaking 100 lb of raw soil for a few days in a solution of 0.2 normal hydrochloric acid, then washing the treated soil on a Buchner funnel until the wash water is tested free of chlorides.

"Calcium", "ferric", and "aluminum" soils were prepared by soaking the raw soil in the corresponding chloride solutions and then leaching out the free chloride ions with distilled water.

The chloride-free homoionic samples were then

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[1]Hans F. Winterkorn, "Physico-Chemical Soil Testing," <u>Highway Research Board Proceedings</u>, XX (1940) pp. 798-806.

allowed to dry in air, the lumps broken up with a rubber-tipped mallet, and fractions of the required grain size were separated and weighed out for the necessary tests.

Preparation of Soil-Organic Matter Combinations

Each combination was prepared from the raw soil and from the homoionic soil by adding a given weight of the chosen organic material as a percentage of the dry weight of the inorganic soil. The percentage of clay in the soil, and the identification of the clay minerals in the colloid fractions were used as guides in approximating the amount of lignin or humic acid to be applied to the soil samples. Below are the 45 different combinations prepared:

Raw soil, no additive
Raw soil plus ½%, 1%, 2%, 3%, 4% lignin
Raw soil plus 1%, 2%, 3% humic acid
"Hydrogen" soil, no additive
"Hydrogen" soil plus ½%, 1%, 2%, 3%, 4% lignin
"Hydrogen" soil plus 1%, 2%, 3% humic acid
"Aluminum" soil, no additive
"Aluminum" soil plus ½%, 1%, 2%, 3%, 4% lignin
"Aluminum" soil plus 1%, 2%, 3% humic acid
"Ferric" soil, no additive
"Ferric" soil plus ½%, 1%, 2%, 3%, 4% lignin
"Ferric" soil plus 1%, 2%, 3% humic acid
"Calcium" soil, no additive

"Calcium" soil plus ½%, 1%, 2%, 3%, 4% lignin

"Calcium" soil plus 1%, 2%, 3% humic acid

Preparation of Humic Acid

<u>Materials</u>

10 lb muck, 2 lb sodium pyrophosphate crystals ($Na_4P_2O_7 \cdot 10\ H_2O$), dilute hydrochloric acid solution.

<u>Procedure</u>

The method used was that suggested in a study by J. M. Bremner.[1] A 200-gram portion of muck was placed in a beaker, treated with one liter of 0.25 molar solution of hydrochloric acid, and allowed to stand overnight. The muck was then washed on a Buchner funnel with distilled water. Two liters of a tenth molar solution of sodium pyrophosphate were added to the washed muck. The mixture was shaken intermittently for several hours, allowed to stand overnight, and the black supernatant liquid was siphoned off and passed through filter paper. The filtrate was acidified with hydrochloric acid, thereby reprecipitating the humic acid. The precipitate was washed with slightly acidified distilled water. The washed precipitate was put aside, care being taken that it was kept in a moist condition until needed.

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[1]J. M. Bremner, "Studies on Soil Organic Matter: I. The Chemical Nature of Soil Organic Matter," <u>Journal of Agricultural Science</u>, XXXIX (1949), pp. 183-193.

Testing Procedures

Mechanical Analysis

The standard method described in AASHO Designation: T 88-54[1] was used. This soil test consists of a sieve analysis for the portion of the soil that is retained on the No. 10 U.S. Standard Sieve and a hydrometer analysis for the portion passing the No. 10 sieve. Since all cationic modifications and soil-organic matter combinations were made from the portion passing the No. 4 sieve, the sieve analysis was done only on the raw soil. The hydrometer analysis, however, was carried out for all cationic soils.

Specific Gravity of Soil Grains

The specific gravity of the soil was measured by means of a pycnometer according to the standard method described in AASHO Designation: T 100-54.[2] Since this specific gravity was to be used to calculate hydrometer analysis data, only that portion passing the No. 10 sieve was tested.

Base Exchange Capacity

This test was necessary to determine the amount

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[1] Standard Specifications for Highway Materials and Methods of Sampling and Testing, Part II. Adopted by the American Association of State Highway Officials, 7th ed. (Washington, D.C., 1955), pp. 257-265.

[2] Ibid., p. 287.

and concentration of acid and salts necessary to effect a saturation, or near saturation, of the base exchange capacity of the soil. The literature presents quite a few known and accepted methods of determining base exchange capacity. The one adopted here is that of Olson and Bray's, published in 1938.[1] A brief summary is here given: Weigh 5 grams of soil and place it in a 400 cc. beaker. Add 40 ml. 15% hydrogen peroxide, cover the beaker with a watch glass and place on a steam bath. Digest for approximately one hour, remove the watch glass and completely evaporate the liquid. Now place the sample in a 250 ml. beaker and add 50 ml. normal, neutral ammonium acetate. Stir the solution occasionally for a half hour. Pour into a small Buchner funnel, pour more neutral ammonium acetate and filter by suction until a volume of 500 ml. of leachate is produced. Discard the leachate. Wash the soil on the same filter with 300 ml. absolute methanol which has been neutralised with ammonium hydroxide. Discard the washings. Now leach the soil in the filter with 300 ml. of 0.10 normal hydrochloric acid, receiving the leachate in a clean Erlenmeyer flask. Transfer the leachate to an 800 ml. Kjeldahl flask and add 5 grams sodium hydroxide into the flask. Distill the ammonia into a 500 ml. Erlenmeyer flask containing

[1] L. C. Olson and R. H. Bray, "The Determination of the Organic Base Exchange Capacity of Soils," Soil Science, XLV (1938), pp. 483-496.

50 ml. of tenth normal hydrochloric acid. The excess acid is back-titrated with 0.10 normal sodium hydroxide using an indicator. The base exchange capacity is twice the number of milliliters of 0.10 normal acid used.

X-Ray Diffraction Analysis

This test was performed using the X-Ray Diffraction apparatus of the Soil Physics Laboratory, Soil Science Department of Michigan State University. The purpose of the test was to identify the clay and colloid portion of the soil in order to be able to make an intelligent interpretation of the results of the other tests.

Infra-Red Spectroscopy

This is an additional test for identification of the clay and colloid portion of the soil sample. The test was carried out in the infra-red spectrophotometer of the Michigan State Highway Department Research Laboratory.

Atterburg Limits

The homoionic soil modifications and the soil-organic matter combinations were tested for plastic limit, liquid limit, and shrinkage limit according to standard methods and using the apparatus and materials specified in the AASHO Standard Specifications.[1] The plasticity

[1] loc cit., pp. 270-280.

index and the shrinkage ratio are calculated from the results of the tests.

Swelling Test

The method used is an adaptation of the standard method for the determination of volume change of soils, first proposed by W. K. Taylor[1] of the Bureau of Public Roads and listed in AASHO Standard Specifications[2] as AASHO Designation: T 116-54. The apparatus used in the experiment was devised from a Soiltest consolidometer body to which was added a perforated piston. A micrometer gage measures the upward movement of the piston as it is pushed up by the swelling soil which is kept in a state of saturation through the duration of each test. The sample actually used in this test is, after compaction to near-Proctor, 2½ inches in diameter and 1 inch in thickness. This is a much smaller sample than that in the AASHO Designation which is 4 inches in diameter and 1.5625 inch in thickness.

The Unconfined Compression Tests and the Weathering Test Series

The unconfined compression tests and weathering

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[1] Procedures for Testing Soils, Sponsored by ASTM Committee D-18 on Soils for Engineering Purposes (Philadelphia: American Society for Testing Materials, July 1950), pp. 131-135.

[2] AASHO, loc cit., pp. 290-294.

tests were performed on previously compacted soil cylinders. Compaction to standard density at optimum moisture was obtained by static loading in a steel mold. Loading was done on a Tinius-Olsen hydraulic press. The compacted soil cylinders measure 1.3437 inch in diameter and 2.687 inches in height. These dimensions give a height-to-diameter ratio of 2:1 and a volume of 1/453.59 of a cubic foot. When the moist or dry weight of the soil cylinder is obtained in grams, the value obtained is the numerical equivalent of wet or dry density in pounds per cubic foot.

Twenty-four soil cylinders were prepared for each of the homoionic soils or soil-organic matter combinations. Twelve of these were weighed and left in the open for 7 days. The other twelve were also weighed but were stored in an air-tight container to maintain the molding moisture for 7 days. After the 7-day curing period, 3 of the air-dried samples and 3 of the moist-cured samples were weighed and tested for unconfined compression strength.

The remaining 9 samples of air-dried soil and 9 of moist-cured soil were then placed on a 2-inch layer of saturated standard Ottawa sand for another 7 days to allow the cylinders to take up water by capillary action. The pan containing the sand was covered to prevent evaporation, and constant water level was maintained at the top of the sand layer by means of an over-flow outlet.

Water was allowed to drop into the pan to replenish that taken up by capillarity. To maintain the level of the sand in the pan, a piece of cheesecloth was laid over the sand layer and several layers of paper towels were placed on top of the cheesecloth. With this procedure, none of the sand grains could get on the soil samples and the paper towels could be peeled off as they get soiled.

The samples were taken off the capillary pad for weighing at reasonable intervals, during the 7-day period. In the meantime, the increasing moisture contents were carefully observed and plotted. Most of the samples obtained their maximum moisture uptake within 7 days. However, some samples were slow in the initial stage of moisture absorption and were still absorbing moisture by the end of the 7th day on the capillary pad. For such samples, the capillary absorption period was extended to 14 days to allow the time-moisture content curve to level off. At the end of the 7- or 14-day capillary absorption period, three of the samples originally cured by air-drying and three originally moist-cured were weighed and tested for unconfined compression strengths.

The remaining 6 samples corresponding to each method of curing were then weighed and placed in a freezer. This began 4 cycles of freezing and thawing. The samples were stored in the freezer for approximately 16 hours and placed on the capillary-absorption pad for

for approximately 8 hours, for thawing. The samples were weighed before they were put back into the freezer. One freezing and one thawing made up one cycle.

After four cycles of freezing and thawing, 3 samples corresponding to each method of curing were weighed and tested for unconfined compression strength. By this time the samples have been considerably weakened, so that some of the testing was done on a Soiltest Unconfined Compression Machine, Model U-130.

The remaining 3 samples corresponding to each method of curing were then weighed and dried in an oven at a temperature of 60 degrees Centigrade (140 degrees Fahrenheit) to constant weight. The samples were then taken out of the oven and each one was carefully lowered into a pan of water kept at room temperature. Great care was taken so that no turbulence occurred while the samples were being immersed. The pan was located on a strong, stable surface where the laboratory traffic was not likely to bump against it. Since the worst conditions were being simulated, it was decided to lower the samples into the water while still hot. A few of the samples were allowed to cool off before immersion and the relative rates of disintegration were observed and recorded for future reference.

The samples were left in the water for 8 hours. Those that did not disintegrate were taken out and dried in the oven at 60 degrees Centigrade to constant weight.

The oven-dried weights were recorded, and the samples were immersed in the water again. The initial oven-drying and the immersion constituted the first cycle. The soil samples were taken through four drying and wetting cycles. If any soil cylinders were left after four cycles, they were tested for unconfined compression strength.

CHAPTER III

RESULTS OF TESTS

Preliminary Tests

Mechanical Analysis and Classification

The results of the mechanical analysis of the raw or untreated Warsaw soil are given in Table 2. The particle size distribution plotted from mechanical analysis data is shown in Fig. 1. The soil is classified on the basis of mechanical analysis data.

Textural classification.—According to the AASHO classification, the soil sample contains 10.2 per cent gravel, 16.0 per cent coarse sand, 18.6 per cent fine sand, 21 per cent silt and 34.2 per cent clay and colloids. The raw soil is classified texturally as a clay soil.

Revised BPR or HRB system of classification.—This system, as mentioned in Chapter I, makes use of liquid limit, plasticity index, and group index as additional criteria to grain size in the classification of soils. Since the raw soil contains 80.3, 73.8, and 55.2 per cent of its total weight passing the Nos. 10, 40, and 200 sieves respectively, the soil is first tentatively clasc

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classified as an A-4, A-5, A-6, or A-7 soil. The liquid limit value of 28.0 and the plasticity index of 12.9 given in Table 3 further classify the soil as an A-6 soil. The group index of 5.2 confirms the A-6 classification. The soil is finally labeled an A-6(5.2), a clayey soil which is generally rated as poor subgrade material.

Base Exchange Capacity

The values for base exchange capacity obtained for three different fractions of the natural or raw soil are given in Table 1.

TABLE 1

BASE EXCHANGE CAPACITY OF WARSAW SOIL

Sample	Base Exchange Capacity in milliequivalents per 100 grams of sample
A. Treated with hydrogen peroxide	
1. Passing No. 20 sieve	4.35
2. Passing No. 40 sieve	6.25
3. Passing No. 140 sieve	8.60
B. Not treated with hydrogen peroxide	
1. Passing No. 20 sieve	4.90
2. Passing No. 40 sieve	7.35
3. Passing No. 140 sieve	10.80

It will be noted that the sample used contains some organic matter as shown by the loss in base exchange capacity after treatment with hydrogen peroxide. The hydrogen peroxide was used as an oxidizing agent to destroy any organic matter present in the soil samples. It is also suggested that the ammonium acetate method used in this test is expected to yield lower base exchange capacity values than another method in which sodium acetate is used.

Specific Gravity

The specific gravity of the soil grains in the portion passing the No. 10 sieve is 2.64.

Identification of Clay and Colloid Fractions

X-Ray diffraction patterns obtained of the clay and colloid fractions indicated the following components to be present: illite, kaolinite, interstratified vermiculites and chlorites, and quartz.

Infra-red absorption spectra indicated illite, kaolinite, and quartz.

The results of the standard tests follow.

Plastic Limit Tests

The results of the plastic limit tests are given in Table 3 and are shown in Figs. 2 and 3.

Effect of Ions on Plastic Limit

Both the aluminum and ferric ions indicated a tendency to increase the value of the plastic limit, while the calcium and hydrogen ions demonstrated a tendency to decrease the value of the plastic limit. The ions are ranked according to their effect on plastic limit as follows: Fe(ic) > Al > Raw soil > Ca > H.

Effect of Organic Matter on Plastic Limit

Raw soil.-The plastic limit increased with the addition of 1% and 2% lignin, and decreased with the addition of 3% and 4% lignin. The plastic limit also increased with the addition of 1%, 3%, and 2% humic acid in that order.

"Hydrogen" soil.-The plastic limit increased with the addition of 1%, 2%, 3%, and 4% lignin. Additions of 1%, 2%, and 3% humic acid increased the plastic limit to a greater extent than did 1% lignin but to a less extent than did 2%, 3%, and 4% lignin.

"Aluminum" soil.-The change in the plastic limit resulting from the addition of 1%, 3%, and 4% lignin was negligible. The addition of 2% lignin increased the plastic limit slightly. Addition of 1%, 2%, and 3% humic acid increased the plastic limit to values greater than those obtained for any of the lignin combinations.

"Ferric" soil.-All plastic limits resulting from the addition of 1%, 2%, 3%, and 4% lignin were lower than the plastic limit of non-additive "ferric" soil. All plastic limits resulting from the addition of 1%, 2%, and

3% humic acid were higher than that of non-additive "ferric" soil.

"Calcium" soil.--The addition of lignin generally increased plastic limit. The decrease in plastic limit due to the addition of 2% lignin was so slight as to be negligible. The addition of humic acid similarly increased plastic limit.

Liquid Limit Tests

The results of the liquid limit tests are given in Table 3 and are shown in Figs. 4 and 5.

Effect of Ions on Liquid Limit

Very little change in liquid limit values was caused by a change in the saturating cation. Raw soil and "calcium" soil had the same liquid limit. Both "hydrogen" soil and "aluminum" soil had slightly higher liquid limits and "ferric" soil had slightly lower liquid limit. The ions are ranked according to their influence on liquid limit as follows: Al > H > Ca = Raw soil > Fe.

Effect of Organic Matter on Liquid Limit

Raw soil.--The liquid limit decreased very slightly on addition of 1% and 2% lignin, and increased very slightly on addition of 3% lignin. Only the addition of 4% lignin registered a significant decrease in liquid limit. 1% humic acid decreased liquid limit, but 2% and

3% humic acid increased the liquid limit considerably.

"Hydrogen" soil.—Only the addition of 1% lignin caused a lowering of liquid limit. 2% to 4% lignin and 1% to 3% humic acid all raised the liquid limit.

"Aluminum" soil.—The addition of 1% to 3% lignin lowered the liquid limit. 4% lignin raised the liquid limit very slightly. 1% and 2% humic acid caused very slight decrease in liquid limit, and 3% a very slight increase. The effects appear to be negligible.

"Ferric" soil.—The effects here were more perceptible than in the case of "aluminum" soil. 1% and 2% lignin lowered, while 3% and 4% lignin raised the liquid limit. All humic acid additions raised the liquid limit.

"Calcium" soil.—With the exception of 2% lignin which lowered the liquid limit, all other additions in lignin and humic acid raised the liquid limit.

Effects on Plasticity Index

The plasticity index is indicative of the moisture-content range over which the soil is plastic and is related to the cohesive properties of the soil. The plasticity index is obtained as the difference between the liquid limit and the plastic limit of the soil. The computed values of plasticity index are given in Table 3 and are shown in Figs. 6 and 7.

Effect of Ions on Plasticity Index

The ferric ion lowered the plasticity index while

the hydrogen, aluminum, and calcium ions raised the plasticity index. The ions are ranked in the order of their effect on plasticity index as follows: H > Ca > Al > Raw soil > Fe(ic).

Effect of Organic Matter on Plasticity Index

Raw soil.—1%, 2%, and 4% lignin and 1% humic acid lowered the plasticity index. 3% lignin and 2% and 3% humic acid raised the plasticity index.

"Hydrogen" soil.—All additions of lignin and humic acid lowered the plasticity index.

"Aluminum" soil.—All additions of lignin and humic acid, with the exception of 4% lignin, lowered the plasticity index. The effect of 4% lignin is, in fact, so slight as to be negligible.

"Ferric" soil.—All additions of lignin and humic acid raised the plasticity index.

"Calcium" soil.—With the exception of 1% and 2% lignin which caused a very slight lowering of plasticity index, the addition of lignin and humic acid generally raised the plasticity index.

Shrinkage Limit Tests

The results of the shrinkage limit tests are given in Table 4 and are shown in Figs. 8 and 9.

Effect of Ions on Shrinkage Limit

Only the ferric ion increased the value of the shrinkage limit. The ions are ranked in the order of their effect on shrinkage limit as follows: Fe(ic) > Raw soil > Al > Ca > H.

Effect of Organic Matter on Shrinkage Limit

Raw soil.—All additions of lignin lowered, and all additions of humic acid raised, the shrinkage limit.

"Hydrogen" soil.—All additions of lignin and humic acid, with the exception of 1% lignin, raised the shrinkage limit. 1% lignin indicated no effect on shrinkage.

"Aluminum" soil.—All additions of lignin and humic acid raised the shrinkage limit.

"Ferric" soil.—1% and 2% lignin lowered the shrinkage limit, 3% lignin raised it, and 4% lignin indicated no effect. All humic acid additions raised the shrinkage limit.

"Calcium" soil.—1%, 2%, and 4% lignin lowered the shrinkage limit, while 3% lignin and all humic acid additions raised the shrinkage limit.

Ratio of Shrinkage Limit to Liquid Limit

The ratios, computed from shrinkage limit (SL) and liquid limit (LL) values, multiplied by 100, are given in Table 4 and are shown in Figs. 10 and 11. The ratio has been suggested as a measure of the tendency of the soil to shrink. The larger the ratio, the smaller is the t

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the tendency of the soil to shrink.[1]

Effect of Ions on the SL:LL Ratio

Only the ferric ion increased the SL:LL ratio. The ions are ranked according to their effect on the SL:LL ratio as follows: Fe > Raw soil > Ca > Al > H.

Effect of Organic Matter on the SL:LL Ratio

Raw soil.--All additions of lignin and humic acid, except 4% lignin and 1% humic acid, decreased the SL:LL ratio.

"Hydrogen" soil.--All additions of lignin and humic acid increased the SL:LL ratio.

"Aluminum" soil.--All additions of lignin and humic acid considerably increased the SL:LL ratio.

"Ferric" soil.--1%, 2%, and 4% lignin decreased the SL:LL ratio, while 3% lignin and all humic acid additions increased the ratio.

"Calcium" soil.--All additions of lignin and humic acid, except 1% humic acid, decreased the SL:LL ratio.

Swelling Tests

The results of the swelling tests are given in Tables 5 and 6 and are shown in Figs. 14 to 25. Table 5

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[1]D. T. Davidson, "Exploratory Evaluation of Some Organic Cations as Soil Stabilizing Agents," Highway Research Board Proceedings, XXIX (1949).

gives the actual swelling obtained for each soil sample compacted to a certain density and at a certain moisture content. Table 6 gives the comparative swelling computed for each of the homoionic soil-organic matter combination if it were compacted to the density and at the moisture content of the corresponding non-additive homoionic soil. The variations in the swelling curves in Figs. 16 to 25 could, therefore, indicate variations caused by different percentages of organic matter added to the soil. Table 6 was suggested by the results of the experiments conducted by Russell, Worsham, and Andrews[1] who stated that for two samples compacted at the same dry density, the volume change of the sample with the lower moisture content is proportionally greater. For two samples compacted at the same moisture content, the volume change of the sample compacted at the greater dry density is proportionally greater.

Effect of Ions on Swelling

The hydrogen, aluminum, and ferric ions reduced swelling, while the calcium ion increased swelling. The ions are ranked according to their effect on swelling as follows: Ca > Raw soil > H > Al > Fe.

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[1]H. W. Russell, W. B. Worsham, and R. K. Andrews, "Influence of Initial Moisture and Density on the Volume Change and Strength Characteristics of Two Typical Illinois Soils," Highway Research Board Proceedings, XXVI(1936).

Effect of Organic Matter on Swelling

Raw soil.--1% lignin and 3% humic acid both decreased swelling. 2% and 3% lignin and 1% and 2% humic acid increased swelling.

"Hydrogen" soil.--All lignin and humic acid additions increased swelling. The increase in swelling due to 1% lignin was very slight compared to all the others for this homoionic soil.

"Aluminum" soil.--All lignin additions up to 3% reduced swelling, especially 2% lignin which demonstrated only half as much swelling as the non-additive "aluminum" soil. 1% humic acid increased swelling, but 2% and 3% humic acid reduced swelling.

"Ferric" soil.--1% lignin and all humic acid additions reduced swelling. 2% and 3% lignin increased swelling.

"Calcium" soil.--1% lignin reduced swelling, but all other additions of lignin and humic acid increased swelling.

Weathering Test

The results of moisture absorption by capillarity and during freezing-thawing cycles are given in Table 7, and shown in Figs. 26 to 29. The results of unconfined compression tests on samples representing different stages in the weathering test are given in Table 8. The results of the wetting and drying test are summarized in t

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Effect of Ions on Moisture Absorption of Air-Dried Samples by Capillarity

The moisture absorption was reduced in each of the homoionic soil used. Moisture contents of the homoionic samples at nearly all recorded stages of the test were in the order: Raw soil > H > Al > Fe > Ca. The untreated, or raw, soil reached a maximum moisture content of 20.3% on the 7th day on the capillary absorption pad. The average moisture content for the homoionic soils at the end of the same period was 17.5%. All samples attained about 80% of their total moisture absorbed within 24 hours after they were placed on the capillary pad. As a matter of fact, the untreated soil, "hydrogen" soil, "aluminum" soil, and "ferric" soil absorbed 80% of their total moisture within 9 hours after the start of the capillary absorption test.

Effect of Ions on Moisture Absorption of Moist-Cured Samples by Capillarity

Moisture absorption was reduced in all homoionic soils tested except "calcium" soil. Moisture contents at corresponding stages of the test were in the order: Raw soil > Ca > Fe(ic) > H > Al. The absorption curve for "calcium" soil plotted very close to that of the raw soil, both reaching a moisture content close to 15.5% at the end of 7 days on the capillary absorption pad.

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"Aluminum" soil gave the lowest moisture absorption in this test. At the end of 7 days' exposure on the capillary absorption pad, the "aluminum" soil samples barely exceeded in moisture content the optimum moisture at standard density obtained on compaction of "aluminum" samples by the Harvard Miniature compaction apparatus.

Effect of Organic Matter on Moisture Absorption of Air-Dried Samples by Capillarity

Raw soil.--The addition of lignin and humic acid reduced considerably the moisture absorption. In the 14-day period on the capillary absorption pad, none of the lignin samples regained the moisture lost during the air-drying process. While the 1% humic acid addition lowered the moisture absorption in capillarity, the water uptake for this sample after 7 days on the capillary absorption pad exceeded its optimum moisture at molding.

"Hydrogen" soil.--The addition of lignin and humic acid reduced the moisture absorption. As in the case of the raw soil, none of the lignin samples regained, in the 14-day period on the capillary moisture absorption pad, the moisture lost during air-drying. 1% humic acid reduced the moisture absorption. However, the 7-day exposure on the capillary pad raised the moisture content of the 1% humic acid sample to that above the optimum moisture at molding.

"Aluminum" soil.--The addition of lignin reduced moisture absorption. None of the samples regained, after

14 days on the capillary pad, the moisture lost during the air-drying. However, 1% humic acid increased moisture absorption after the first day on the capillary pad.

"Ferric" soil.--The addition of lignin reduced moisture absorption, none of the samples regaining, in 14 days on the capillary pad, the moisture lost during air-drying. The curve for 1% humic acid plotted lower than the non-additive "ferric" soil during the first 6 hours on the capillary pad, but regained moisture to exceed the non-additive "ferric" soil moisture content at 7 days on the pad.

"Calcium" soil.--The addition of lignin reduced moisture absorption. None of the samples regained, in 14 days on the capillary pad, the moisture lost during air-drying. The 1% humic acid curve plotted lower than the non-additive "calcium" soil at the start of the capillary absorption test, but exceeded the moisture content of the latter by the 7th day on the capillary absorption pad.

Effect of Organic Matter on Moisture Absorption of Moist-Cured Samples by Capillarity

Raw soil.--The addition of 1% and 2% lignin produced no significant change in moisture absorption. The addition of 3% lignin and 1% humic acid increased moisture absorption.

"Hydrogen" soil.--All additions of lignin and humic acid increased moisture absorption. The organic

matter additions are ranked according to their influence on moisture absorption, for the 7-day period on the capillary moisture absorption pad, as follows: 3% lignin > 1% humic acid > 2% lignin > 1% lignin > "hydrogen" soil.

"Aluminum" soil.--All additions of lignin and humic acid increased moisture absorption. The organic matter additions are ranked according to their effect on moisture absorption, for the 7-day period on the capillary moisture absorption pad, as follows: 3% lignin > 1% humic acid > 2% lignin > 1% lignin > "aluminum" soil.

"Ferric" soil.--All additions of lignin and humic acid increased moisture absorption. The organic matter additions are ranked according to their effect on moisture absorption, for the 7-day period on the capillary pad, as follows: 1% humic acid > 3% lignin > 2% lignin > 1% lignin > "ferric" soil.

"Calcium" soil.--The addition of lignin and humic acid produced no significant change in the moisture absorption during the first three days on the capillary moisture absorption pad. However, 1% humic acid produced significant increase on the 7th day on the capillary absorption pad.

Effect of Ions on Moisture Absorption of Air-Dried Samples during Freezing and Thawing

No data was obtained for raw soil, "hydrogen"

soil, "aluminum" soil, and "ferric" soil. All of these samples broke apart before they could be placed in the freezer for the first half of a cycle of freezing and thawing. Only the "calcium" soil "survived" the capillary absorption test.

<u>Effect of Ions on Moisture Absorption of Moist-Cured Samples during Freezing and Thawing</u>

The ions, except calcium, recorded lower moisture contents during the four cycles. The moisture content for "calcium" soil plotted very close to that of raw soil. The increase in moisture content through the four cycles is greatest in raw soil. The ions are ranked according to their influence on increase in moisture content as follows: Raw soil > H > Ca > Al > Fe.

<u>Effect of Organic Matter on Moisture Absorption of Air-Dried Samples during Freezing and Thawing</u>

Except for "calcium" soil, no data was obtained in this portion of the test as there were no samples of the raw soil, "hydrogen" soil, "aluminum" soil, and "ferric" soil to take through the freezing and thawing test. For "calcium" soil, the moisture contents of samples containing 1% humic acid had higher moisture contents for each of the four cycles than non-additive "calcium" soil. However, the actual moisture taken up through four cycles was greatest for 1% humic acid and 1% lignin. Samples containing 2% lignin indicated

slight loss of moisture. The uptake for non-additive "calcium" soil was negligible.

Effect of Organic Matter on Moisture Absorption of Moist-Cured Samples during Freezing and Thawing

The comparisons here will be expressed in terms of the difference in moisture contents of a sample at the start of the first cycle and at the end of the fourth cycle of freezing and thawing.

Raw soil.—The organic matter additives are ranked according to their effect on moisture uptake through four cycles of freezing and thawing as follows: 1% lignin > raw soil > 2% lignin > 3% lignin. The humic acid sample broke apart on the second cycle.

"Hydrogen" soil.—The 1% lignin sample took up three times as much moisture as the non-additive "hydrogen" soil, while the 2% lignin sample lost a slight amount of moisture. No data was available for 3% lignin and 1% humic acid.

"Aluminum" soil.—The 1% lignin sample took up three times as much moisture as non-additive "aluminum" soil. The 2% lignin sample lost a negligible amount of moisture. There was no data for 3% lignin and 1% humic acid.

"Ferric" soil.—The 1% lignin sample indicated a slight loss in moisture content, while the 2% lignin sample demonstrated a slight moisture uptake. The 1%

humic acid sample took up as much moisture as the non-additive "ferric" soil, but collapsed during the third cycle. There was no data for 3% lignin.

"Calcium" soil.-The sample containing 1% humic acid absorbed more moisture than the non-additive "calcium" soil. 1% and 2% lignin samples both lost moisture during the four cycles of freezing and thawing.

Results of the Wetting-and-Drying Test

This is the most severe test in the weathering series adopted for this set of samples. However, very few of the samples survived the less severe treatments of capillary moisture absorption and alternate freezing and thawing. Furthermore, many of the samples that were started on the first cycle of wetting-and-drying failed before the conclusion of the test. In summary, the results are as follows:

Raw soil.-1% and 2% lignin samples retained about 70% of their solids after four cycles of wetting and drying.

"Hydrogen" soil.-Non-additive "hydrogen" soil completely fell apart within the first hour of initial immersion in water. 1% and 2% lignin combinations retained about 80% of their solids after four complete cycles.

"Aluminum" soil.-Non-additive "aluminum" soil disintegrated during the first immersion in water. 1% and

2% lignin combinations retained about 90% of their solids after four cycles.

"Ferric" soil.—Only the 2% lignin sample held up through the end of four cycles, retaining about 95% of their solids.

"Calcium" soil.—Only the 1% lignin sample help up through the four cycles, retaining about 50% of their solids.

No humic acid samples were taken through the wetting-drying test.

Unconfined Compression Test

The results of unconfined compression tests on the homoionic soils and soil-organic matter combinations are given in Table 8. Since this test was conducted in connection with the weathering tests, compressive strength data are grouped as follows: curing strength, strength after capillary absorption, strength after freezing-and-thawing, strength after wetting-and-drying.

Effect of Ions on Curing Strength (Air-Dried)

Ions caused a general reduction of curing strength. The ions are ranked according to their effect on curing compressive strength as follows: Raw soil $>$ Ca $>$ Fe $>$ H $>$ Al.

Effect of Ions on Curing Strength (Moist-Cured)

With the exception of calcium, which caused an

almost negligible increase in strength, the ions generally reduced curing strength. The ions are ranked according to their effect on curing strength as follows: Ca > Raw soil > Fe(ic) = H > Al. Very low strengths were obtained for all samples, the highest being 37.0 psi for "calcium" soil, and the lowest being 15.8 psi for "aluminum" soil.

<u>Effect of Organic Matter on Curing Strength (Air-Dried)</u>

<u>Raw soil</u>.–1% and 2% lignin reduced compressive strength; 3% lignin increased compressive strength, though slightly. No data was available for humic acid.

<u>"Hydrogen" soil</u>.–All lignin combinations more than doubled the compressive strength of non-additive "hydrogen" soil in the order: 2% lignin > 1% lignin > 3% lignin > "hydrogen" soil. 1% humic acid gave 3 times as much strength as non-additive "hydrogen" soil.

<u>"Aluminum" soil</u>.–All lignin combinations increased compressive strength, in the order: 3% lignin > 1% lignin > 2% lignin > "aluminum" soil. 1% humic acid gave the greatest increase in compressive strength.

<u>"Ferric" soil</u>.–All lignin combinations produced an increase in compressive strength, in the order: 3% lignin > 1% lignin > 2% lignin > "Ferric" soil.

<u>"Calcium" soil</u>.–3% lignin increased compressive strength, but 1% and 2% lignin decreased compressive strength. The lignin additives are ranked according to

their effect on compressive strength as follows: 3% lignin > "calcium" soil > 1% lignin > 2% lignin. Humic acid at 1% produced the greatest increase in compressive strength.

Effect of Organic Matter on the Compressive Strength of Moist-Cured Samples

The moist-cured samples of all lignin additions took very low compressive loads ranging from 18 psi for 3% lignin in "aluminum" soil to 45.5 psi for 2% lignin in "hydrogen" soil. "Aluminum" soil with 1% lignin took a compressive load of 69.5 psi and "hydrogen" soil with 1% lignin took a compressive load of 134.8 psi. These compressive loads are low compared to those of the air-dried samples. The lignin additions for "hydrogen", "aluminum", and "ferric" soils all produced greater compressive strengths than the corresponding non-additive soils. No data was available for humic acid samples.

Raw soil.-1% lignin slightly increased compressive strength while 2% and 3% lignin decreased compressive strength.

"Hydrogen" soil.-1% lignin produced 6 times as much compressive strength as non-additive "hydrogen" soil, 2% lignin produced twice as much compressive strength, and 3% lignin produced slightly higher compressive strength.

"Alumimum" soil.—All lignin combinations produced greater compressive strengths than the non-additive "aluminum" soil in the following order: 1% lignin > 2% lignin > 3% lignin > "aluminum" soil.

"Ferric" soil.—The lignin additions are ranked in the order of their effect on compressive strength as follows: 3% lignin > 2% lignin > 1% lignin > "ferric" soil.

"Calcium" soil.—1% and 2% lignin slightly increased compressive strength, while 3% lignin slightly decreased compressive strength.

Effect of Ions on Compressive Strength of Samples after Capillary Absorption

The raw soil and non-additive homoionic soils for both air-dried and moist-cured sets all had zero compressive strengths.

Effect of Organic Matter on Compressive Strength of Samples Cured by Air-Drying

The values of compressive strength of air-dried samples after capillary moisture absorption were within the range 0.0 psi to 28.0 psi, representing great losses of compressive strength caused by 7 to 14 days' exposure on the capillary moisture pad. Within this low range, the compressive strengths of 2% lignin samples for all homoionic soils were greater than those of the 1% lignin samples.

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The values of the compressive strength of moist-cured samples, after capillary moisture absorption, were within the range 0.0 psi to 31.4 psi. These values represent only a slight loss of compressive strength caused by 7 to 14 days' exposure on the capillary absorption pad. 2% lignin samples of raw soil, "hydrogen" soil, "aluminum" soil, and "calcium" soil had greater compressive strengths than the corresponding lignin samples. "Ferric" soil had lower compressive strength with 2% lignin than with 1% lignin.

Effect of Ions and Organic Matter on Compressive Strength after Freezing and Thawing

Zero compressive strength was recorded for all air-dried and moist-cured samples except two. "Aluminum" soil with 1% lignin had compressive strengths of 9.5 psi and 8.0 psi for the air-dried and moist-cured samples respectively, at the end of four cycles of freezing and thawing. "Calcium" soil with 1% lignin had compressive strengths of 6.2 psi and 4.8 psi for air-dried and moist-cured samples respectively.

CHAPTER IV

CONCLUSION

Table 9 gives the relative values of the strength properties of soil-organic matter combinations with respect to the properties of the corresponding non-additive homoionic soil, the values for which are expressed as unity.

Table 10 gives the relative values of the strength properties of all soils tested with respect to the properties of the raw, or untreated, soil, the values for which are expressed as unity.

Evaluation of the data in Tables 9 and 10 will be based on the following criteria:

1. A soil treatment, whether it consists of saturation with a certain cation by cation exchange, or adsorption of polar molecules on the colloidal surface, or both, is beneficial if such treatment results in (a) decrease in the values of liquid limit, plasticity index, shrinkage ratio, volume of swell, moisture absorption, and (b) increase in the values of shrinkage limit, ratio of shrinkage limit to liquid limit, and compressive strength.

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2. A soil treatment as described above is not beneficial, and may even be detrimental, if it results in (a) increase in the values of liquid limit, plasticity index, shrinkage ratio, volume of swell, moisture absorption, and (b) decrease in the values of shrinkage limit, ratio of shrinkage limit to liquid limit, and compressive strength.

The influence of the saturating cations and organic matter additives on the soil will be summarized under three main groups, namely: (a) Influence on plasticity and shrinkage properties; (b) Influence on swelling, moisture absorption in weathering, and unconfined compression; and (c) Over-all influence.

Influence of Organic Matter on Homoionic Soils

Influence on Raw Soil

Plasticity and shrinkage.--Except for causing a slight and insignificant increase in plastic limit, 1% humic acid produced the greatest improvement in plasticity and shrinkage properties of raw soil. 4% lignin was a close second with a slight decrease in shrinkage limit. 1% and 2% lignin had intermediate effects, but increased the tendency of the soil to shrink. 3% lignin and 2% and 3% humic acid produced more detrimental effects than beneficial ones.

Swelling, moisture, and strength.--Only 1% lignin pr

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produced improvement of any significance. 2% to 4% lignin and the humic acid combinations all increased swelling. An exception is 3% humic acid which reduced swelling. However, no information on moisture absorption and compressive strength was available for 3% humic acid.

Over-all influence.—1% lignin moderately improved the general strength properties of raw soil.

Influence on "Hydrogen" Soil

Plasticity and shrinkage.—1% lignin was the only treatment that resulted in a lower liquid limit than that of the standard, raw soil. However, the general rise in plastic limit resulted in low values of plasticity index for all samples. 1% lignin produced the greatest improvement. The rest of the lignin and humic acid samples produced about equal beneficial effects on "hydrogen" soil.

Swelling, moisture, and strength.—All of the lignin samples increased compressive strength for both methods of curing and decreased moisture absorption for the air-dried samples. Greater decrease in swelling was noted with increase of lignin.

Over-all influence.—1% lignin appeared to be the best treatment for "hydrogen" soil.

Influence on "Aluminum" Soil

Plasticity and shrinkage.—All lignin and humic

acid additions, except 4% lignin, produced about the same degree of improvement in aluminum soil.

Swelling, moisture, and strength.—2% lignin had the most beneficial effects, with 1% and 3% lignin close behind.

Over-all influence.—1% lignin appeared to be the most beneficial additive, followed by 2% and 3% lignin. 2% and 3% humic acid appeared promising but there were no other data available.

Influence on "Ferric" Soil

Plasticity and shrinkage.—1% and 2% lignin produced slight improvement in the properties of "ferric" soil. The humic acid samples reduced shrinkage tendencies, but raised all values of plastic limit, liquid limit, and plasticity index.

Swelling, moisture, and strength.—1% lignin demonstrated the most improvement. 2% and 3% lignin decreased moisture absorption but increased swelling.

Over-all influence.—1% lignin appeared to give "ferric" soil the most improvement in strength properties.

Influence on "Calcium" Soil

Plasticity and shrinkage.—None of the lignin and humic acid samples improved the properties of calcium soil. Although 2% lignin did better than the rest of the organic matter additions, the lignin at all four percentages increased the tendency of the "calcium" soil to

shrink.

Swelling, moisture, and strength.—1% lignin improved the properties of "calcium" soil. 2% and 3% lignin reduced moisture absorption and increased compressive strength but produced too much swelling.

Over-all influence.—1% lignin just moderately improved the strength properties of "calcium" soil.

Influence of Cations and Organic Matter on Raw Soil

Plasticity and Shrinkage Properties

There were quite a few homoionic soil-organic matter combinations with indications of improving the characteristics of the soil. Three samples gave excellent shrinkage reduction effects: (a) Raw soil plus 1% humic acid, (b) "Aluminum" soil plus 1% lignin, (c) Non-additive "ferric" soil. Plastic limits for these samples were below 10.

Two samples displayed excellent shrinkage reduction properties, but slightly lowered the shrinkage limit values: (a) Raw soil plus 4% lignin, (b) "Ferric" soil plus 1% lignin.

Two samples demonstrated satisfactory improvement of plasticity values but indicated a tendency to increase shrinkage slightly: (a) Raw soil plus 1% lignin, (b) "Ferric" soil plus 2% lignin.

Six samples displayed excellent improvement of

shrinkage properties but produced poor plasticity constants: (a) "Alumimum" soil plus 1%, 2%, 3% humic acid, (b) "Ferric" soil plus 1%, 2%, 3% humic acid.

Swelling, Moisture Absorption and Compressive Strength

The reduction in swelling was best demonstrated in raw soil plus 1% lignin and in "calcium" soil plus 1% lignin. Swelling was moderately reduced in raw soil plus 3% lignin, "hydrogen" soil plus 1% lignin, "alumimum" soil plus 1% and 2% lignin, "ferric" soil plus 1% lignin, and non-additive "calcium" soil.

Over-all Influence

"Ferric" soil may be considered the best homoionic soil as regards over-all influence on plasticity, shrinkage, swelling, moisture absorption and unconfined compression strength.

The following may be considered the best homoionic soil-organic matter combinations as regards over-all influence on plasticity, shrinkage, swelling, moisture absorption, and unconfined compression strength:

(a) Raw soil plus 1% lignin

(b) "Alumimum" soil plus 1% lignin

(c) "Ferric" soil plus 1% lignin

The following homoionic soil-organic matter combinations may be considered detrimental. They displayed poor plasticity properties and demonstrated great undei

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tendency to swell and absorb moisture:

(a) "Ferric" soil plus 3% lignin

(b) "Hydrogen" soil plus 2% lignin

(c) "Hydrogen" soil plus 3% lignin

(d) "Hydrogen" soil plus 1%, 2%, 3% humic acid

(e) Raw soil plus 3% lignin

Summary of Conclusions

On the basis of the evaluation just made, the following points are summarized:

1. The addition of 1% lignin improved the plasticity, shrinkage, swelling, moisture absorption, and unconfined compression properties of raw soil, "aluminum" soil, and "ferric" soil.

2. Saturation of the base exchange capacity of the clay and colloid portion of the soil with "ferric" ions moderately improved the general strength properties of the soil.

3. 2% lignin added to "hydrogen" soil, and 3% lignin added to "hydrogen", "ferric", and raw soil resulted in a decrease in the strength of the respective homoionic soils.

4. The presence of calcium and hydrogen ions, along with their respective lignin and humic acid combinations did not prove beneficial.

5. Most of the samples treated with humic acid

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indicated improvement of shrinkage properties but failed to improve the other strength properties of the soil.

6. A few of the samples containing organic matter had plasticity index values less than 10 and exhibited good plasticity and shrinkage properties but displayed high swelling and low compressive strength.

The following conclusions may be drawn:

1. Lignin, adsorbed on the surface of clay and colloids, can be effective in inhibiting moisture adsorption provided lignin is applied in amounts not exceeding that which is necessary to provide steric hindrance to water dipoles. The beneficial effect of lignin in moisture control of the cohesive soil tested is enhanced by aluminum or ferric ions saturating the base exchange capacity of the clay and colloid portion of the soil.

2. Natural organic matter in the soil, if present in the relatively undecomposable form of the structure of lignin, can be beneficial if it is adsorbed on the surface of the clay and colloid portion of the soil in sufficient amounts to inhibit adsorption of water dipoles. This beneficial effect of natural lignin could be enhanced by aluminum or ferric ions saturating the base exchange capacity of the soil.

3. The determination of plasticity and shrinkage constants alone is not a sufficient criterion for

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evaluating cohesive soils for subgrade use. A cohesive soil is controlled by physico-chemical phenomena to such an extent that it is necessary to conduct other tests determining moisture relations affected by the active surface of clay and colloids.

Future Research

Future research is recommended along the following lines:

1. Determining the actual percentage between zero per cent and one per cent, or between one per cent and two per cent, at which lignin in raw soil, "ferric" soil, or "aluminum" soil produces optimum properties.

2. Determining the actual phenomena that take place on the surface of clay and colloids when lignin is applied to a ferric ion- or aluminum ion-saturated soil.

3. Exploring the possibilities of a nuclear method of determining base exchange capacity.

4. Working out a quick, accurate procedure for determining the amount of natural organic matter in the soil and its state of decomposition.

APPENDIX

TABLE 2

MECHANICAL ANALYSIS OF UNTREATED SOIL

U.S. Standard Sieve Number	Particle Size in mm.	Cumulative % Passing
	Sieve Analysis	
1" - 1½"		100.0
1"		100.0
3/4"		98.7
3/8"		96.7
No. 4	4.8	94.2
No. 10	1.98	89.8
No. 20	0.833	86.3
No. 40	0.417	73.8
No. 60	0.246	64.0
No. 140	0.104	56.6
No. 200	0.074	55.2
	Hydrometer Analysis	
	0.032	54.6
	0.020	52.4
	0.012	43.9
	0.009	40.2
	0.0061	36.5
	0.0032	29.4
	0.0013	26.9

TABLE 3

EFFECT OF ORGANIC MATTER ON LIQUID LIMIT, PLASTIC LIMIT, AND PLASTICITY INDEX OF HOMOIONIC MODIFICATIONS

Sample	Liquid Limit	Plastic Limit	Plasticity Index
Raw soil	28.0	15.1	12.9
1% Lignin	27.5	15.6	11.9
2% Lignin	27.8	16.0	11.8
3% Lignin	28.5	14.5	14.0
4% Lignin	24.0	12.3	11.7
1% Humic acid	24.7	15.3	9.4
2% Humic acid	40.4	17.4	23.0
3% Humic acid	30.6	16.0	14.6
"Hydrogen" soil	29.2	10.5	18.7
1% Lignin	27.9	12.6	15.1
2% Lignin	31.7	16.4	15.3
3% Lignin	32.6	16.6	16.0
4% Lignin	33.4	16.6	16.8
1% Humic acid	31.6	15.7	15.9
2% Humic acid	30.9	16.1	14.8
3% Humic acid	31.7	15.9	15.8
"Aluminum" soil	30.8	16.8	14.0
1% Lignin	26.2	16.9	9.3
2% Lignin	29.8	17.5	12.3
3% Lignin	28.0	16.9	11.1
4% Lignin	31.2	16.6	14.6

TABLE 3—Continued.

Sample	Liquid Limit	Plastic Limit	Plasticity Index
"Aluminum" soil			
1% Humic acid	29.4	19.5	9.9
2% Humic acid	30.0	18.8	11.2
3% Humic acid	32.0	19.8	12.2
"Ferric" soil	27.0	17.3	9.7
1% Lignin	25.4	14.4	10.0
2% Lignin	25.8	16.0	9.8
3% Lignin	29.3	16.5	12.8
4% Lignin	31.4	16.2	15.2
1% Humic acid	28.8	17.7	11.1
2% Humic acid	30.3	19.5	10.8
3% Humic acid	30.4	19.4	11.0
"Calcium" soil	28.0	13.8	14.2
1% Lignin	29.2	15.3	13.9
2% Lignin	27.1	13.5	13.6
3% Lignin	34.4	17.5	16.9
4% Lignin	30.5	14.3	16.2
1% Humic acid	33.7	15.6	18.1
2% Humic acid	33.4	15.0	18.4
3% Humic acid	30.7	16.2	14.5

TABLE 4

EFFECT OF ORGANIC MATTER ON THE SHRINKAGE FACTORS OF HOMOIONIC MODIFICATIONS

Sample	Shrinkage Limit	Ratio $\frac{SL}{LL}$	Shrinkage Ratio
Raw soil	11.7	41.8	1.87
1% Lignin	10.7	38.9	1.80
2% Lignin	10.4	37.4	1.72
3% Lignin	10.3	36.1	1.68
4% Lignin	11.5	47.9	1.75
1% Humic acid	13.3	53.9	1.82
2% Humic acid	13.8	34.2	1.82
3% Humic acid	12.5	40.9	1.88
"Hydrogen" soil	9.9	35.4	1.88
1% Lignin	9.9	35.7	1.81
2% Lignin	12.2	38.5	1.75
3% Lignin	11.7	35.9	1.56
4% Lignin	12.3	36.8	1.63
1% Humic acid	13.4	42.5	1.89
2% Humic acid	14.5	47.0	1.83
3% Humic acid	13.9	43.9	1.85
"Aluminum" soil	11.6	37.7	1.84
1% Lignin	12.4	47.4	1.81
2% Lignin	12.8	43.0	1.64
3% Lignin	13.3	48.0	1.49
4% Lignin	13.1	42.0	1.72

TABLE 4-Continued.

Sample	Shrinkage Limit	Ratio $\frac{SL}{LL}$	Shrinkage Ratio
"Aluminum" soil			
1% Humic acid	16.3	55.5	1.70
2% Humic acid	13.7	45.7	1.81
3% Humic acid	15.5	48.5	1.79
"Ferric" soil	12.6	46.7	1.83
1% Lignin	10.9	43.0	1.82
2% Lignin	10.7	41.5	1.76
3% Lignin	13.8	47.8	1.62
4% Lignin	12.6	40.1	1.75
1% Humic acid	14.9	51.8	1.82
2% Humic acid	15.5	51.2	1.95
3% Humic acid	16.0	52.7	1.80
"Calcium" soil	10.8	38.6	1.91
1% Lignin	9.7	33.2	1.83
2% Lignin	9.5	35.0	1.75
3% Lignin	12.4	36.1	1.57
4% Lignin	10.3	33.8	1.57
1% Humic acid	13.3	40.0	1.86
2% Humic acid	12.7	38.0	1.86
3% Humic acid	11.5	37.5	1.90

TABLE 5

SWELLING DUE TO WATER SATURATION OF SAMPLES COMPACTED
AT OPTIMUM MOISTURE AND OPTIMUM DENSITY

Sample	Dry density in lb/cu ft	Initial moisture content in %	Vol-
			3 hours
Raw soil	119.1	13.5	.0058
1% Lignin	117.8	14.4	.0015
2% Lignin	116.0	13.8	.0037
3% Lignin	117.0	13.5	.0060
1% Humic acid	119.4	14.5	.0129
2% Humic acid	117.9	14.3	.0115
3% Humic acid	116.4	13.9	.0037
"Hydrogen" soil	125.0	11.5	.0135
1% Lignin	123.0	11.8	.0077
2% Lignin	120.7	11.4	.0112
3% Lignin	117.0	11.3	.0138
1% Humic acid	122.7	11.3	.0212
2% Humic acid	121.4	11.5	.0185
3% Humic acid	118.0	11.3	.0206
"Aluminum" soil	122.0	11.3	.0172
1% Lignin	121.0	11.3	.0071
2% Lignin	118.0	12.3	.0044
3% Lignin	121.0	11.5	.0078
1% Humic acid	121.4	10.8	.0188
2% Humic acid	120.5	11.4	.0145
3% Humic acid	118.0	11.1	.0148

TABLE 5-Continued.

ume Change in cubic centimeter per gram of dry soil					
12 hours	24 hours	36 hours	48 hours	72 hours	Maximum
.0074	.0075				.0076
.0029	.0033	.0036			.0037
.0074	.0089	.0105	.0116	.0126	.0136
.0123	.0147	.0166	.0185	.0209	.0236
.0144	.0147	.0150	.0152		.0154
.0140	.0146	.0149	.0152		.0155
.0048	.0051	.0054	.0054		.0054
.0163	.0169	.0170	.0170		.0170
.0149	.0168	.0183	.0188	.0197	.0197
.0250	.0289				Discontinued
.0350	.0445				Discontinued
.0241	.0251	.0253	.0254		.0254
.0209	.0222	.0226	.0228		.0228
.0228	.0236				.0237
.0194	.0198				.0198
.0106	.0119	.0155	.0184		.0184
.0077	.0087	.0095	.0097	.0102	.0107
.0145	.0175	.0179			.0188
.0201	.0205	.0206	.0206		.0206
.0162	.0167	.0168	.0169		.0169
.0163	.0169	.0172			.0172

TABLE 5-Continued.

Sample	Dry density in lb/cu ft	Initial moisture content in %	Vol-
			3 hours
"Ferric" soil	125.6	11.4	.0108
1% Lignin	125.4	11.8	.0043
2% Lignin	122.5	11.7	.0042
3% Lignin	121.1	11.5	.0079
1% Humic acid	120.5	11.4	.0097
2% Humic acid	122.4	11.8	.0111
3% Humic acid	120.8	12.1	.0116
"Calcium" soil	119.0	14.0	.0048
1% Lignin	116.3	14.0	.0010
2% Lignin	117.5	13.4	.0036
3% Lignin	114.1	14.2	.0057
1% Humic acid	119.0	14.4	.0088
2% Humic acid	115.3	14.4	.0088
3% Humic acid	115.0	13.8	.0161
Raw soil[a]	123.2	13.8	.0177
"Hydrogen" soil[a]	123.2	13.8	.0156
"Aluminum" soil[a]	123.0	12.6	.0114
"Ferric" soil[a]	123.3	12.9	.0095
"Calcium" soil[a]	125.2	13.0	.0193

[a]These samples were molded to a dry density as close as possible to 123.0 lb/cu ft and an initial moisture content of 13.0 per cent.

TABLE 5-Continued.

ume Change in cubic centimeter per gram of dry soil					
12 hours	24 hours	36 hours	48 hours	72 hours	Maximum
.0141	.0150	.0155	.0157	.0162	.0163
.0101	.0118	.0130	.0134		.0134
.0136	.0176	.0207	.0211		.0211
.0226	.0290	.0344	.0361		.0361
.0112	.0118	.0118			.0118
.0133	.0139	.0142	.0144		.0144
.0129	.0135				.0135
.0071	.0077	.0081	.0082		.0082
.0040	.0049	.0055	.0057		.0057
.0095	.0117	.0133	.0140		.0142
.0127	.0151	.0173	.0183		.0186
.0124	.0129	.0130	.0136		.0136
.0105	.0108	.0108	.0114		.0114
.0177	.0183				.0183
.0198	.0202	.0204	.0206		.0215
.0182	.0186	.0188	.0189		.0191
.0134	.0140	.0144	.0145		.0145
.0106	.0112	.0113	.0115		.0115
.0266	.0273				.0274

TABLE 6

EFFECT OF ORGANIC MATTER ON THE SWELLING OF COMPACTED SAMPLES TESTED IN WATER-SATURATED CONDITION

Sample	Dry density in lb/cu ft	Initial moisture content in %	Vol-
			3 hours
Raw soil	118.9	13.5	.0058
1% Lignin			.0014
2% Lignin			.0035
3% Lignin			.0059
1% Humic acid			.0122
2% Humic acid			.0108
3% Humic acid			.0035
"Hydrogen" soil	124.0	11.5	.0136
1% Lignin			.0074
2% Lignin			.0110
3% Lignin			.0139
1% Humic acid			.0214
2% Humic acid			.0181
3% Humic acid			.0200
"Aluminum" soil	122.6	11.3	.0171
1% Lignin			.0070
2% Lignin			.0039
3% Lignin			.0075
1% Humic acid			.0195
2% Humic acid			.0141
3% Humic acid			.0145

TABLE 6—Continued.

ume Change in cubic centimeter per gram of dry soil					
12 hours	24 hours	36 hours	48 hours	72 hours	Maximum
.0074	.0075				.0076
.0027	.0031	.0033			.0034
.0071	.0085	.0100	.0111	.0120	.0130
.0121	.0145	.0163	.0182	.0206	.0232
.0136	.0139	.0142	.0143		.0145
.0131	.0137	.0140	.0143		.0146
.0046	.0048	.0051	.0051		.0051
.0164	.0170	.0171	.0171		.0171
.0144	.0162	.0177	.0182	.0190	.0190
.0246	.0384				Discontinued
.0353	.0450				Discontinued
.0243	.0253	.0255	.0256		.0256
.0205	.0217	.0221	.0223		.0223
.0222	.0229				.0230
.0193	.0197				.0197
.0104	.0117	.0153	.0181		.0181
.0068	.0077	.0084	.0086	.0090	.0094
.0140	.0169	.0173			.0182
.0209	.0213	.0214	.0214		.0214
.0157	.0162	.0163	.0164		.0164
.0160	.0166	.0169			.0169

TABLE 6-Continued.

Sample	Dry density in lb/cu ft	Initial moisture content in %	Vol-
			3 hours
"Ferric" soil	125.0	11.5	.0110
1% Lignin			.0042
2% Lignin			.0040
3% Lignin			.0076
1% Humic acid			.0094
2% Humic acid			.0106
3% Humic acid			.0106
"Calcium" soil	118.5	14.0	.0048
1% Lignin			.0010
2% Lignin			.0037
3% Lignin			.0054
1% Humic acid			.0086
2% Humic acid			.0083
3% Humic acid			.0158
Raw soil[a]	123.0	13.0	.0176
"Hydrogen" soil			.0147
"Aluminum" soil			.0118
"Ferric" soil			.0096
"Calcium" soil			.0196

[a]This soil and the homoionic modifications following it were molded to a dry density as close as possible to 123.0 lb/cu ft and an initial moisture content of 13.0 per cent.

TABLE 6—Continued.

ume Change in cubic centimeter per gram of dry soil					
12 hours	24 hours	36 hours	48 hours	72 hours	Maximum
.0144	.0153	.0158	.0160	.0165	.0166
.0099	.0115	.0127	.0131		.0131
.0131	.0169	.0199	.0203		.0203
.0218	.0280	.0332	.0349		.0349
.0109	.0115	.0115			.0115
.0127	.0132	.0135	.0137		.0137
.0118	.0124				.0124
.0071	.0077	.0081	.0082		.0082
.0039	.0048	.0054	.0056		.0056
.0098	.0121	.0138	.0145		.0147
.0120	.0143	.0164	.0174		.0177
.0121	.0126	.0127	.0133		.0133
.0099	.0102	.0102	.0108		.0108
.0174	.0180				.0180
.0196	.0200	.0202	.0204		.0213
.0172	.0175	.0176	.0178		.0180
.0138	.0144	.0149	.0150		.0150
.0107	.0113	.0114	.0116		.0116
.0270	.0278				.0279

TABLE 7

EFFECT OF ORGANIC MATTER ON MOISTURE ABSORPTION IN WEATHERING TESTS

Sample	Moisture content at molding	Dry density at molding	Moisture content after curing	Moist- Cap- 3 hr	6 hr
				Cured	by
Raw soil	14.1	118.9	2.8	18.6	19.3
1% Lignin	13.1	118.4	2.1	3.6	4.1
2% Lignin	15.0	114.9	2.6	3.9	4.2
3% Lignin	15.9	115.0	0.0		
1% Humic acid	14.9	117.9	0.0		10.2
"Hydrogen" soil	10.1	127.4	1.4	14.1	14.7
1% Lignin	13.4	119.5	2.1	3.1	3.6
2% Lignin	14.1	117.2	2.2	3.0	3.3
3% Lignin	17.0	117.0	0.0		
1% Humic acid	13.5	120.4	0.7		11.0
"Aluminum" soil	11.3	122.6	1.4	13.5	13.9
1% Lignin	14.7	115.4	2.2	3.5	3.9
2% Lignin	15.1	114.3	1.4	2.6	3.2
3% Lignin	16.1	114.0	0.5		2.5
1% Humic acid	13.7	119.7	0.4		11.6
"Ferric" soil	10.3	126.4	3.4	13.2	13.6
1% Lignin	14.4	115.3	2.8	4.1	4.4

TABLE 7-Continued.

ure Content in per cent of dry weight of sample								
illary Absorption					Freeze-Thaw Cycles			
9 hr	1 da	3 da	7 da	14 da	1	2	3	4
drying in air								
19.6	20.0		20.3					
4.4	6.1	8.0	9.4	10.5	11.1	13.1	14.3	15.5
4.4	5.8	7.8	10.5	12.4	13.2	13.0	12.9	12.6
	7.0		14.4					
	16.2		17.0		18.2	18.8	19.2	19.2
15.3	15.5		18.3					
4.0	5.6	7.9	9.5	10.6	11.6	13.1	15.2	16.1
3.6	4.9	6.8	8.4	9.3	8.8	10.2	10.3	9.6
	5.1		11.1					
	16.0		15.7		17.0			
14.2	15.4		17.7					
4.3	5.1	7.1	8.4	9.4	10.3	11.0	11.9	13.1
3.7	5.3	7.2		10.6	12.3	13.3	13.4	14.2
	4.1				12.3			
	15.5		18.3		19.9			
14.5	14.9		17.1					
4.6	6.0	7.8	9.7	11.1	12.0	12.7	14.4	15.6

TABLE 7-Continued.

Sample	Moisture content at molding	Dry density at molding	Moisture content after curing	Moist-	
				Cap-	
				3 hr	6 hr
2% Lignin	15.6	114.3	1.8	2.8	3.2
3% Lignin	16.2	117.0	0.0		
1% Humic acid	14.1	119.5	1.5		11.6
"Calcium" soil	15.2	118.0	2.2	7.9	10.4
1% Lignin	13.6	118.4	2.1	2.9	3.4
2% Lignin	14.8	115.7	2.0	3.1	3.5
3% Lignin	14.5	116.0	0.0		
1% Humic acid	15.1	119.1	1.7		10.1
				Moist-	
Raw soil	13.6	119.1	14.5	14.6	14.3
1% Lignin	13.1	120.0	14.7	14.8	14.5
2% Lignin	14.7	115.9	15.8	14.7	14.4
3% Lignin	15.9	115.0	15.6		
1% Humic acid	14.9	117.9	11.6		11.7
"Hydrogen" soil	10.1	127.4	11.5	11.6	11.5
1% Lignin	14.0	117.9	14.6	14.5	14.3
2% Lignin	14.2	117.0	14.5	13.9	13.6
3% Lignin	17.0	117.0	12.8		
1% Humic acid	13.5	120.4	12.4		12.9

TABLE 7-Continued.

ure Content in per cent of dry weight of sample								
illary Absorption					Freeze-Thaw Cycles			
9 hr	1 da	3 da	7 da	14 da	1	2	3	4
3.5	4.8	6.4		8.8	9.3	9.9	9.7	10.2
	3.4		6.8					
14.5	17.5		19.1		20.4	20.7	21.2	
11.7	15.1	16.3	16.7	17.3	17.2	17.2	17.3	17.5
3.8	5.4	7.6	9.3	10.7	12.1	13.4	14.2	14.7
3.6	5.0	7.5	9.4	11.2	11.3	11.1	10.9	10.3
	4.3		8.6					
	10.8		18.0		17.8	18.8	19.5	20.5
cured								
14.2	14.3		15.3		18.1	19.5	20.3	19.9
14.3	14.1	14.3	14.9	14.9	16.1	19.2	21.3	20.0
14.3	14.2		15.0	15.9	16.7	17.6	19.2	20.5
	15.7		16.5					
	12.7		16.3		16.2	17.9	18.7	18.7
11.4	11.5		12.0		13.9	14.7	15.1	14.8
14.0	14.0	14.2	14.7	14.6	15.6	19.5	22.0	23.2
13.3	13.1	13.4		15.5	13.3	13.7	13.0	11.6
	16.2		19.6					
	13.7		15.4		16.5			

TABLE 7-Continued.

Sample	Moisture content at molding	Dry density at molding	Moisture content after curing	Moist- Cap- 3 hr	6 hr
"Aluminum" soil	9.7	129.2	9.4	9.9	9.9
1% Lignin	13.1	116.2	13.1	13.8	13.5
2% Lignin	15.6	114.0	15.5	15.4	15.2
3% Lignin	16.1	114.0	21.0		21.0
1% Humic acid	13.7	119.7	13.6		14.6
"Ferric" soil	10.3	125.9	11.3	12.3	12.4
1% Lignin	14.6	116.2	15.5	15.2	14.9
2% Lignin	14.1	114.8	15.6	15.4	15.3
3% Lignin	16.2	117.0	16.2		
1% Humic acid	14.1	119.5	11.8	12.4	12.7
"Calcium" soil	14.8	118.5	14.5	14.3	14.2
1% Lignin	14.2	117.6	14.4	14.6	14.6
2% Lignin	14.9	115.2	15.6	15.1	14.9
3% Lignin	14.5	116.0	15.5		
1% Humic acid	15.0	119.1	12.1		13.0

TABLE 7-Continued.

ure Content in per cent of dry weight of sample								
illary Absorption					Freeze-Thaw Cycles			
9 hr	1 da	3 da	7 da	14 da	1	2	3	4
9.9	10.1		10.3		11.4	12.1	12.8	12.3
13.5	13.3	13.6	14.3	15.0	17.2	18.8	20.1	21.1
15.1	14.9	15.3		16.5	16.0	16.2	16.2	16.2
	21.0		23.6		23.6			
	15.2		17.0		18.2			
12.4	12.7		12.8		14.4	14.4	15.0	14.8
14.8	14.5		15.4	16.5	16.7	16.5	16.5	15.6
15.2	15.1	15.6		17.4	18.0	18.6	18.4	19.2
	15.4		16.2					
	15.2		17.4		18.6	19.6	19.7	
14.1	14.2	14.7	15.5	16.1	17.6	17.8	18.2	18.2
14.2	14.3	14.7	15.2	15.6	15.7	15.2	15.1	
14.7	14.5		15.1	15.9	16.0	15.8	15.8	15.1
	15.5							
	14.3		16.7		16.6	16.6	19.7	20.5

TABLE 8

UNCONFINED COMPRESSION STRENGTHS IN PSI OF HOMOIONIC SOILS AND LIGNIN COMBINATIONS

Sample	after Curing		after Cap. moisture absorp.		after Freeze-thaw	
	ad[a]	mc	ad	mc	ad	mc
Raw soil	528	35.1	0	0	0	0
1% Lignin	462	37.3	1.0	1.3	0	0
2% Lignin	331	30.0	17.7	31.4	0	0
3% Lignin	550	31.0	0	0	0	0
"Hydrogen" soil	233	22.2	0	0	0	0
1% Lignin	544	134.8	0	0	0	0
2% Lignin	588	45.5	2.1	2.0	0	0
3% Lignin	520	27.0	0	0	0	0
"Aluminum" soil	220	15.8	0	0	0	0
1% Lignin	526	69.5	17.0	5.0	9.5	8.0
2% Lignin	369	38.2	20.5	27.0	0	0
3% Lignin	608	18.0	20.4	12.6	0	0
"Ferric" soil	244	22.2	0	0	0	0
1% Lignin	410	36.0	18.5	28.8	0	0
2% Lignin	339	29.6	28.0	20.0	0	0
3% Lignin	460	57.0	0	0	0	0
"Calcium" soil	392	37.0	0	0	0	0
1% Lignin	386	41.5	2.0	3.0	6.2	4.8
2% Lignin	370	33.0	15.9	29.5	0	0
3% Lignin	492	28.2	0	0	0	0

[a]Ad stands for air-dried, mc for moist-cured, samples.

TABLE 9

COMPARISON AND EVALUATION OF INFLUENCE OF ORGANIC MATTER ON SOIL PROPERTIES BASED ON HOMOIONIC SOIL DATA EXPRESSED AS UNITY

Sample	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Ratio SL:LL
Raw soil	1.00	1.00	1.00	1.00	1.00
1% Lignin	.98	1.03	.92	.91	.93
2% Lignin	.99	1.06	.91	.89	.89
3% Lignin	1.02	.96	1.08	.88	.86
4% Lignin	.86	.81	.91	.98	1.14
1% Humic acid	.88	1.01	.73	1.14	1.29
2% Humic acid	1.44	1.15	1.78	1.18	.82
3% Humic acid	1.09	1.06	1.13	1.17	.98
"Hydrogen" soil	1.00	1.00	1.00	1.00	1.00
1% Lignin	.95	1.20	.81	1.00	1.01
2% Lignin	1.08	1.56	.82	1.23	1.08
3% Lignin	1.12	1.58	.85	1.18	1.01
4% Lignin	1.14	1.58	.90	1.24	1.04
1% Humic acid	1.08	1.49	.85	1.35	1.20
2% Humic acid	1.06	1.53	.79	1.47	1.33
3% Humic acid	1.08	1.51	.84	1.41	1.24
"Aluminum" soil	1.00	1.00	1.00	1.00	1.00
1% Lignin	.85	1.00	.66	1.09	1.26
2% Lignin	.97	1.04	.88	1.12	1.14

TABLE 9-Continued.

Shrinkage ratio	Swelling	Capillary moisture absorption ad[a]	Capillary moisture absorption mc	Unconfined compression strength ad	Unconfined compression strength mc
1.00	1.00	1.00	1.00	1.00	1.00
.96	.49	.76	1.00	.88	1.06
.92	1.79	.62	1.03	.63	.85
.90	3.10	.71	.92	1.04	.88
.94					
.97	2.02	.96	.94		
.97	2.04				
1.00	.71				
1.00	1.00	1.00	1.00	1.00	1.00
.96	1.16	.88	1.54	2.33	6.07
.93	1.70	.57	1.03	2.52	2.05
.83	2.62	.64	1.30	2.23	1.22
.87					
1.00	1.49	.93	1.09		
.97	1.34				
.98	1.39				
1.00	1.00	1.00	1.00	1.00	1.00
.98	.93	.74	1.65	2.39	.44
.89	.54	.80	1.29	1.68	2.42

[a]Ad stands for air-dried, mc for moist-cured, samples.

TABLE 9-Continued.

Sample	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Ratio SL:LL
3% Lignin	.91	1.00	.79	1.17	1.27
4% Lignin	1.01	.99	1.04	1.15	1.11
1% Humic acid	.95	1.16	.71	1.43	1.47
2% Humic acid	.97	1.12	.80	1.20	1.21
3% Humic acid	1.04	1.18	.87	1.36	1.29
"Ferric" soil	1.00	1.00	1.00	1.00	1.00
1% Lignin	.94	.83	1.03	.86	.92
2% Lignin	.95	.92	1.01	.85	.89
3% Lignin	1.08	.95	1.32	1.09	1.02
4% Lignin	1.16	.93	1.57	1.00	.86
1% Humic acid	1.07	1.02	1.14	1.18	1.11
2% Humic acid	1.12	1.12	1.11	1.23	1.10
3% Humic acid	1.13	1.12	1.13	1.27	1.13
"Calcium" soil	1.00	1.00	1.00	1.00	1.00
1% Lignin	1.04	1.11	.98	.90	.86
2% Lignin	.97	.98	.96	.88	.91
3% Lignin	1.23	1.27	1.19	1.15	.93
4% Lignin	1.09	1.04	1.14	.95	.88
1% Humic acid	1.20	1.13	1.27	1.23	1.04
2% Humic acid	1.19	1.09	1.30	1.17	.98
3% Humic acid	1.10	1.17	1.02	1.06	.97

TABLE 9-Continued.

Shrink-age ratio	Swell-ing	Capillary moisture absorption ad	mc	Unconfined compression strength ad	mc
.81	.95	.70	1.84	2.76	1.14
.93					
.92	1.04	1.12	1.42		
.98	.85				
.97	.87				
1.00	1.00	1.00	1.00	1.00	1.00
.99	.82	.91	1.11	1.68	1.62
.96	1.29	.60	1.28	1.39	1.33
.88	2.21	.40	1.08	1.89	2.57
.95					
.99	.72	1.24	1.31		
1.06	.88				
.98	.83				
1.00	1.00	1.00	1.00	1.00	1.00
.96	.70	.84	.86	.98	1.12
.91	1.73	.59	.88	.94	.89
.82	2.27	.49	.85	1.25	.76
.82					
.97	1.66	1.17	1.13		
.97	1.39				
.99	2.24				

TABLE 10

COMPARISON AND EVALUATION OF TOTAL SOIL PROPERTIES BASED ON RAW SOIL DATA EXPRESSED AS UNITY

Sample	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Ratio SL:LL
Raw soil	1.00	1.00	1.00	1.00	1.00
1% Lignin	.98	1.03	.92	.91	.93
2% Lignin	.99	1.06	.91	.89	.89
3% Lignin	1.02	.96	1.08	.88	.86
4% Lignin	.86	.81	.91	.98	1.14
1% Humic acid	.88	1.01	.73	1.14	1.29
2% Humic acid	1.44	1.15	1.78	1.18	.82
3% Humic acid	1.09	1.06	1.13	1.17	.98
"Hydrogen" soil	1.04	.70	1.45	.85	.85
1% Lignin	.99	.84	1.17	.85	.85
2% Lignin	1.13	1.09	1.18	1.04	.92
3% Lignin	1.16	1.10	1.24	1.00	.86
4% Lignin	1.19	1.10	1.30	1.05	.88
1% Humic acid	1.13	1.04	1.23	1.14	1.02
2% Humic acid	1.10	1.07	1.15	1.24	1.12
3% Humic acid	1.13	1.05	1.22	1.19	1.05
"Aluminum" soil	1.10	1.11	1.08	.99	.90
1% Lignin	.93	1.12	.72	1.06	1.13
2% Lignin	1.06	1.16	.95	1.09	1.03

TABLE 10–Continued.

Shrinkage ratio	Swelling	Capillary moisture absorption ad[a]	me	Unconfined compression strength ad	me
1.00	1.00	1.00	1.00	1.00	1.00
.96	.49	.76	1.00	.88	1.06
.92	1.79	.62	1.03	.63	.85
.90	3.10	.71	.92	1.04	.88
.94					
.97	2.02	.96	.94		
.97	2.04				
1.00	.71				
1.00	2.24	.90	.76	.44	.63
.97	2.60	.79	1.17	1.03	3.84
.94	3.80	.47	.78	1.11	1.30
.83	5.85	.58	.97	.99	.77
.87					
1.01	3.34	.84	.83		
.98	3.00				
.99	3.12				
.98	2.60	.87	.64	.42	.45
.97	2.42	.64	1.06	1.00	1.98
.88	1.41	.70	.81	.70	1.09

[a]Ad stands for air-dried, and me for moist-cured, samples.

TABLE 10–Continued.

Sample	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Ratio SL:LL
3% Lignin	1.00	1.12	.86	1.14	1.15
4% Lignin	1.11	1.10	1.13	1.12	1.00
1% Humic acid	1.05	1.29	.77	1.39	1.33
2% Humic acid	1.07	1.24	.87	1.17	1.09
3% Humic acid	1.14	1.31	.94	1.32	1.16
"Ferric" soil	.96	1.15	.75	1.08	1.12
1% Lignin	.90	.95	.77	.93	1.03
2% Lignin	.92	1.06	.76	.91	.99
3% Lignin	1.05	1.09	.99	1.18	1.14
4% Lignin	1.12	1.07	1.18	1.08	.96
1% Humic acid	1.03	1.17	.86	1.27	1.24
2% Humic acid	1.08	1.29	.83	1.32	1.22
3% Humic acid	1.08	1.28	.85	1.37	1.26
"Calcium" soil	1.00	.92	1.10	.92	.92
1% Lignin	1.04	1.01	1.08	.83	.79
2% Lignin	.97	.89	1.05	.81	.84
3% Lignin	1.23	1.16	1.31	1.06	.86
4% Lignin	1.09	.95	1.25	.88	.81
1% Humic acid	1.20	1.03	1.40	1.13	.96
2% Humic acid	1.08	.99	1.42	1.08	.91
3% Humic acid	1.10	1.07	1.12	.98	.90

TABLE 10-Continued.

Shrinkage ratio	Swelling	Capillary moisture absorption ad	Capillary moisture absorption mc	Unconfined compression strength ad	Unconfined compression strength mc
.80	2.48	.61	1.16	1.15	.51
.92					
.91	2.71	.98	.91		
.97	2.22				
.96	2.26				
.98	2.14	.84	.75	.46	.63
.97	1.75	.77	.83	.78	1.03
.94	2.78	.50	.96	.64	.84
.87	4.76	.33	.80	.67	1.62
.94					
.97	1.55	1.04	.99		
1.04	1.90				
.96	1.78				
1.02	1.08	.86	.91	.75	1.05
.98	.75	.72	.79	.73	1.18
.95	1.87	.51	.80	.70	.94
.84	2.44	.42	1.01	.93	.80
.84					
.99	1.79	1.01	1.03		
.99	1.50				
1.02	2.41				

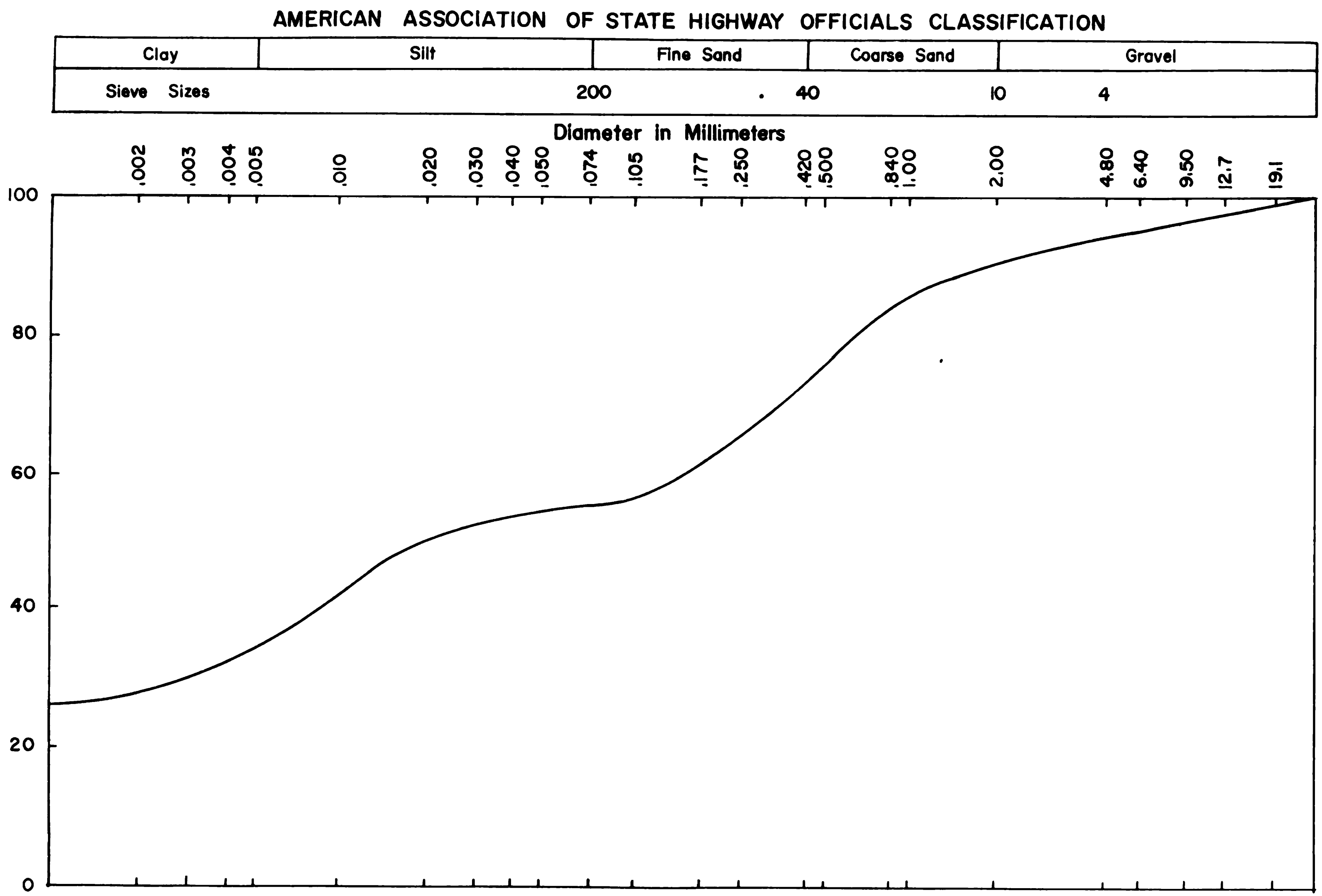

Fig. I.— Particle size distribution of Warsaw soil sample (Horizons B and C)

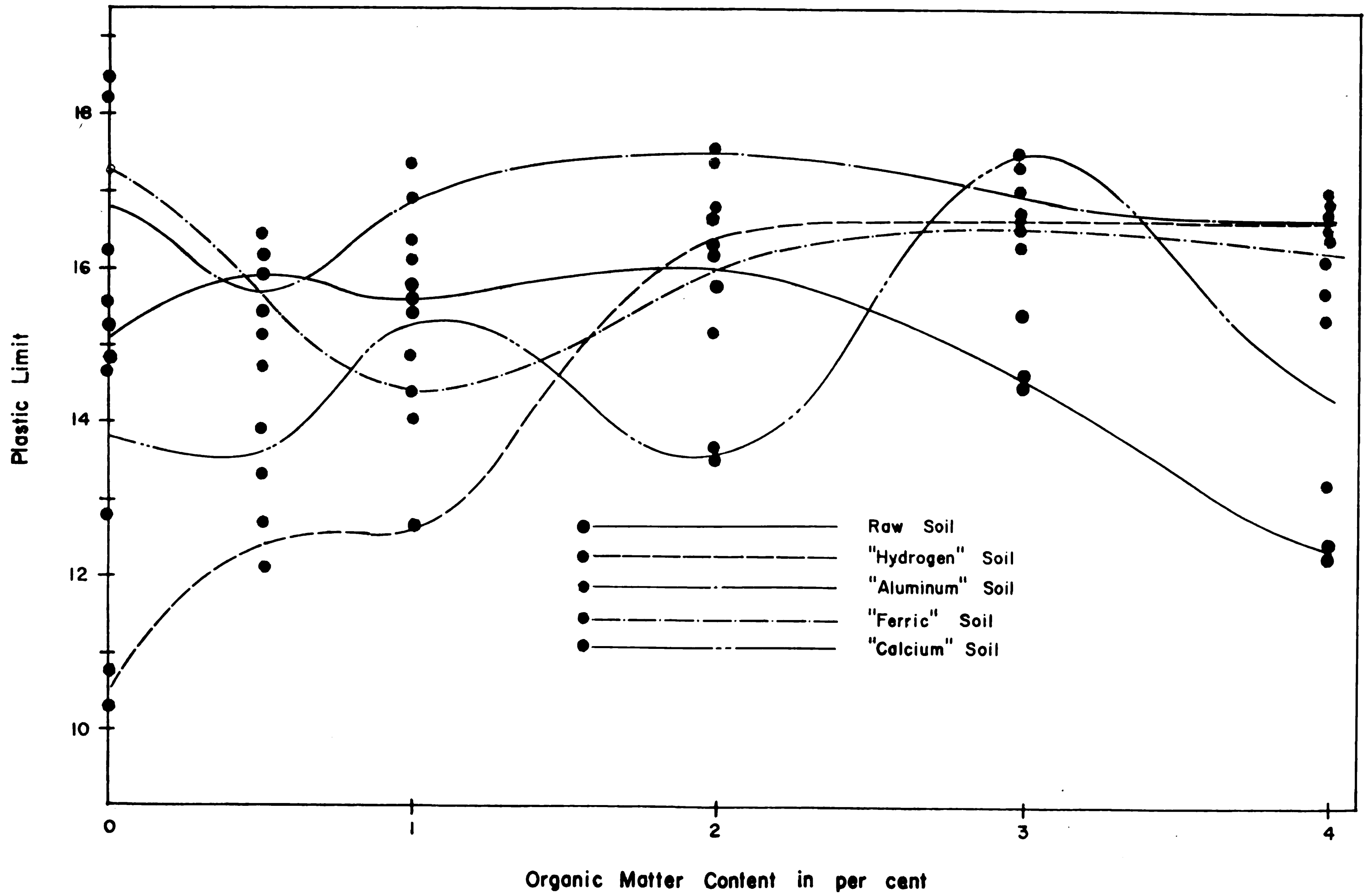

Fig. 2.-Effect of lignin on the plastic limits of homoionic soils

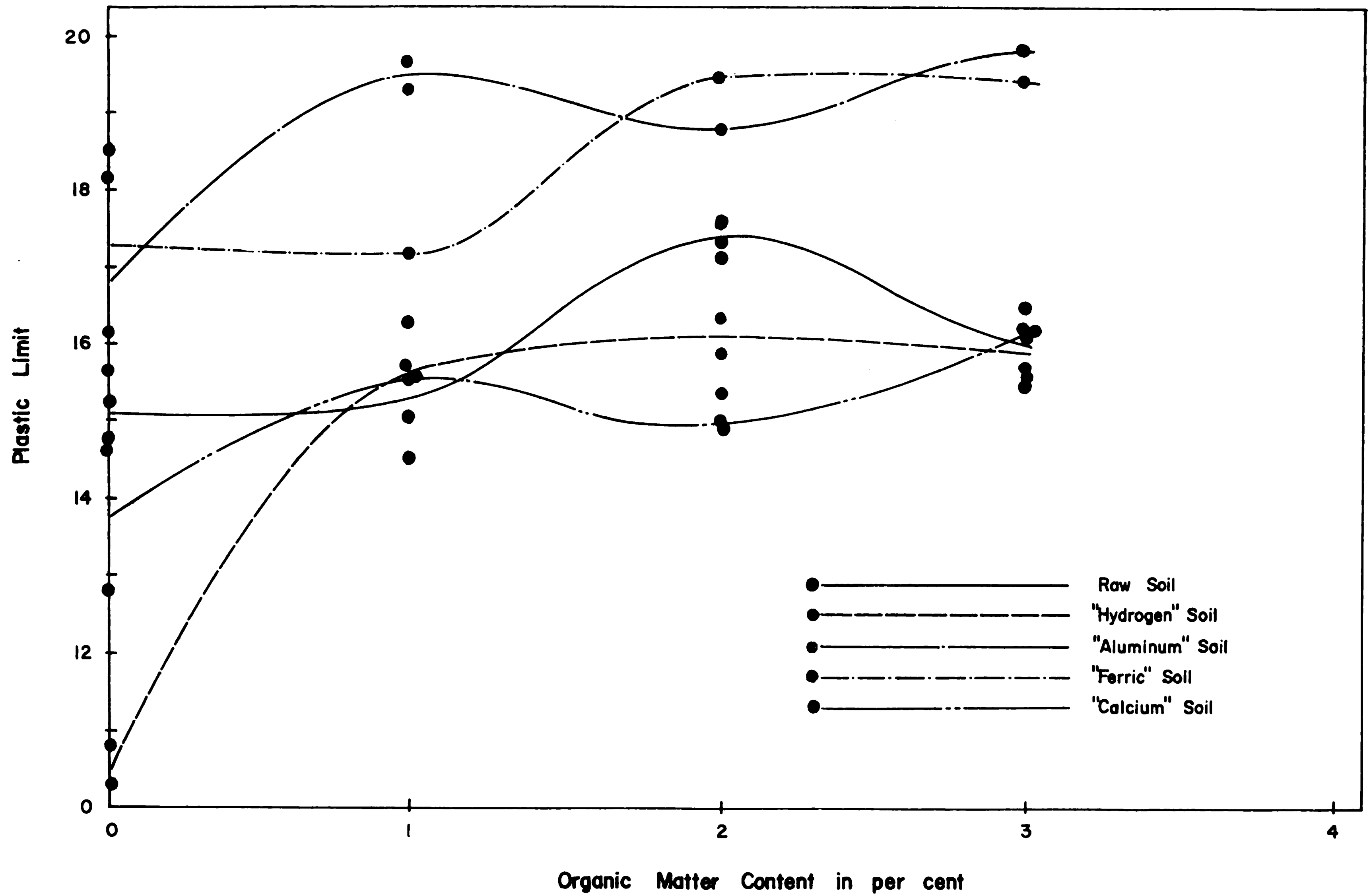

Fig. 3.—Effect of humic acid on the plastic limits of homoionic soils

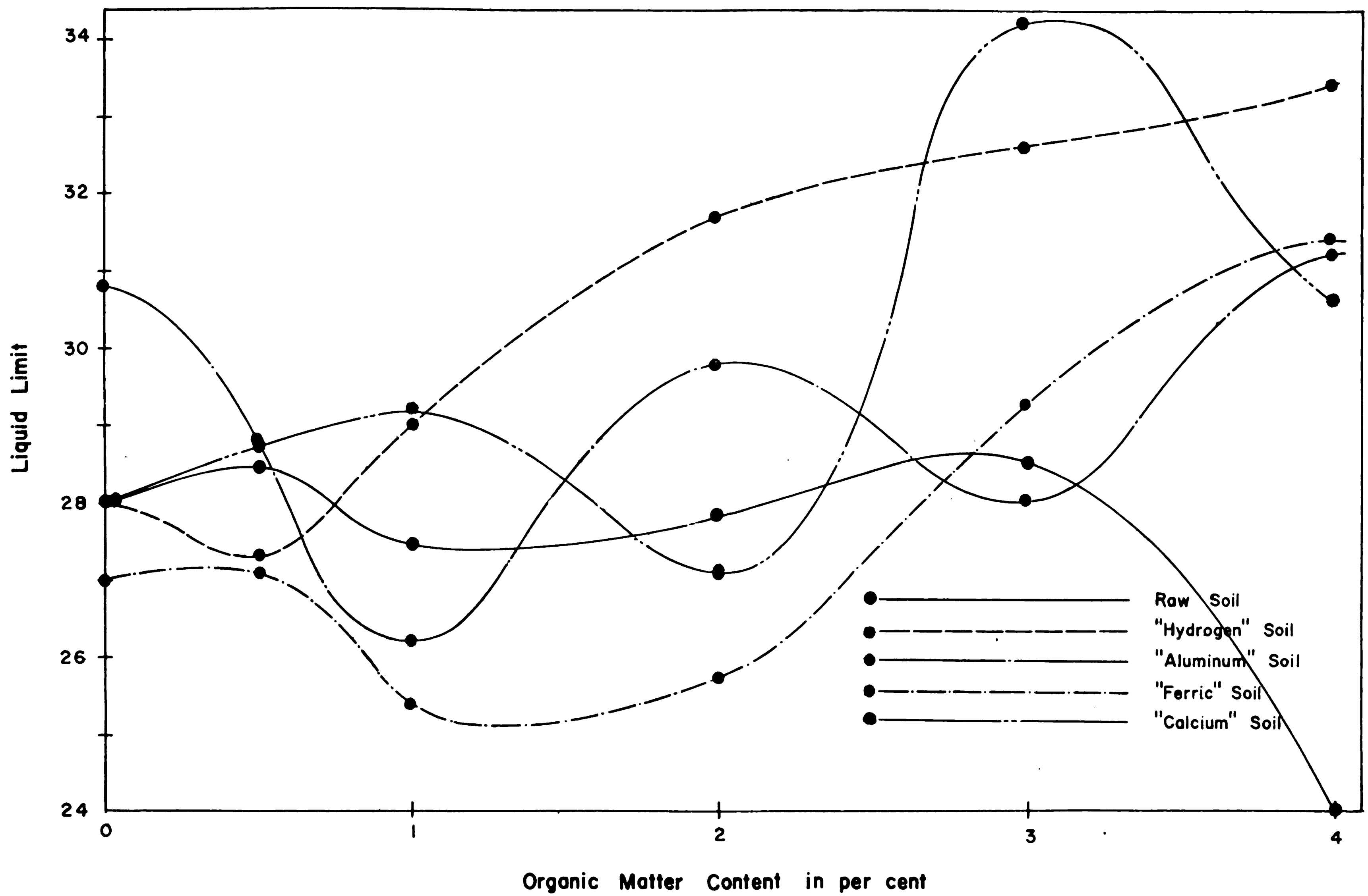

Fig. 4.—Effect of lignin on the liquid limits on homoionic soils

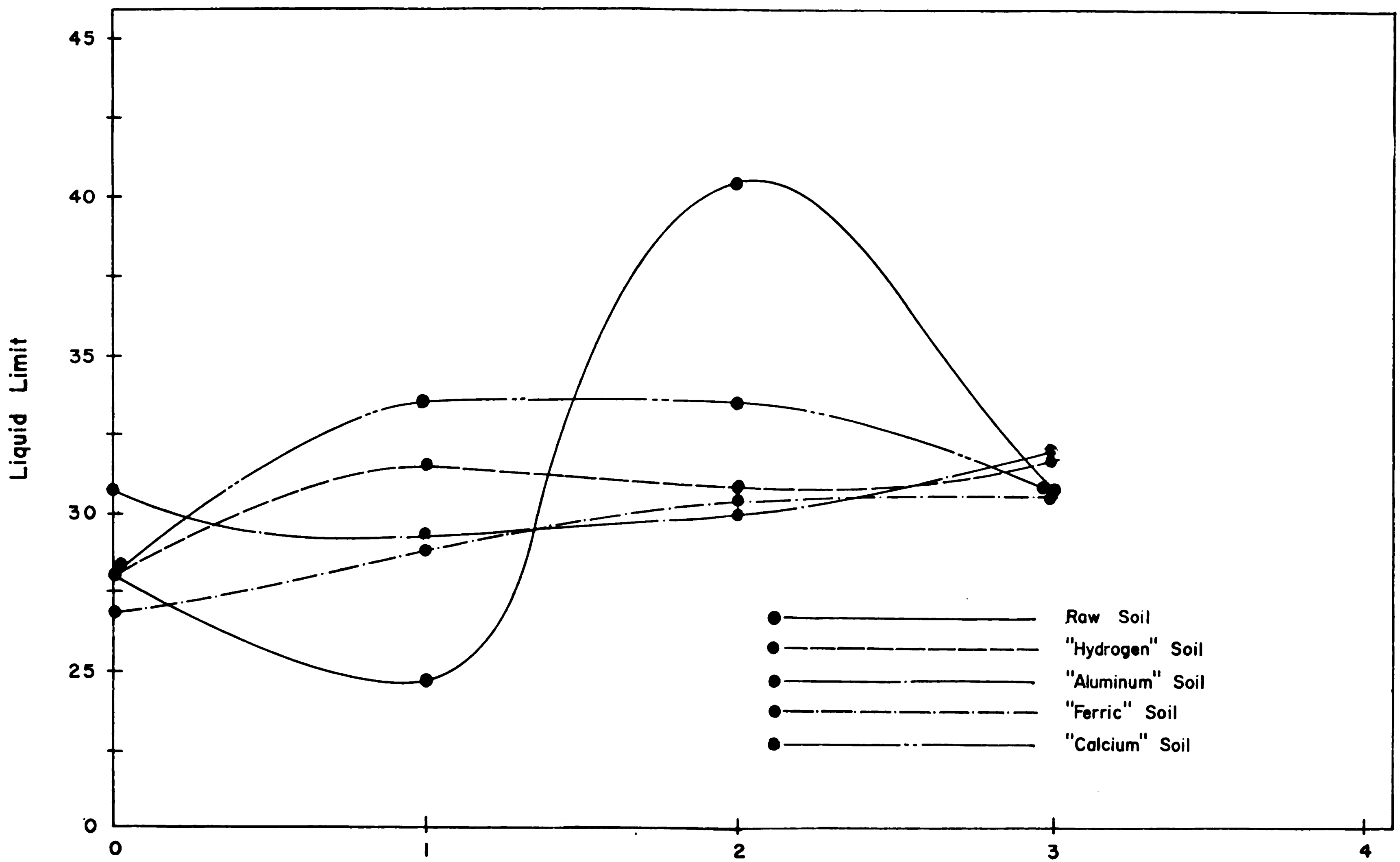

Fig. 5.—Effect of humic acid on the liquid limits of homoionic soils

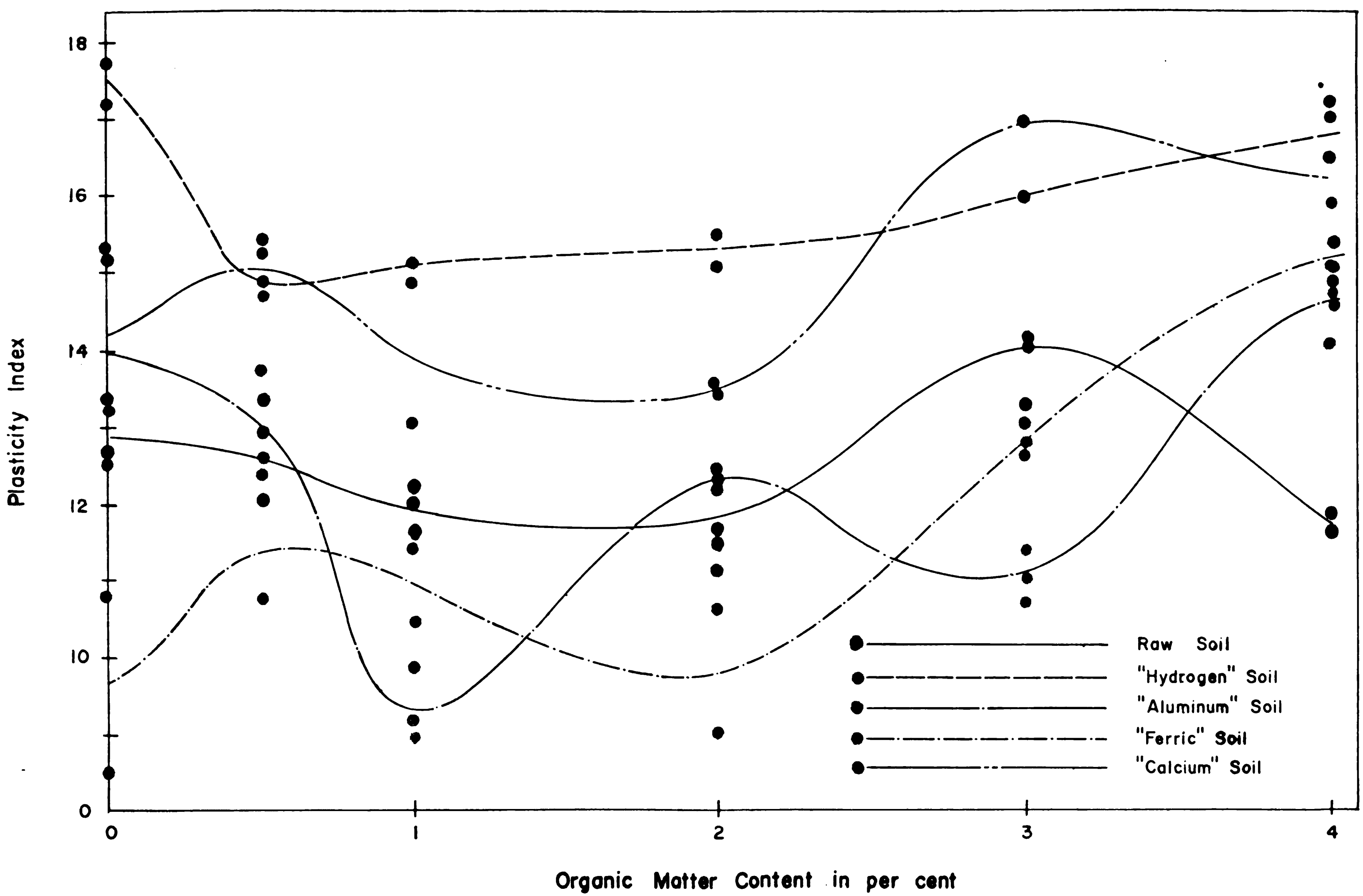

Fig. 6.-Effect of lignin on the plasticity indices of homoionic soils

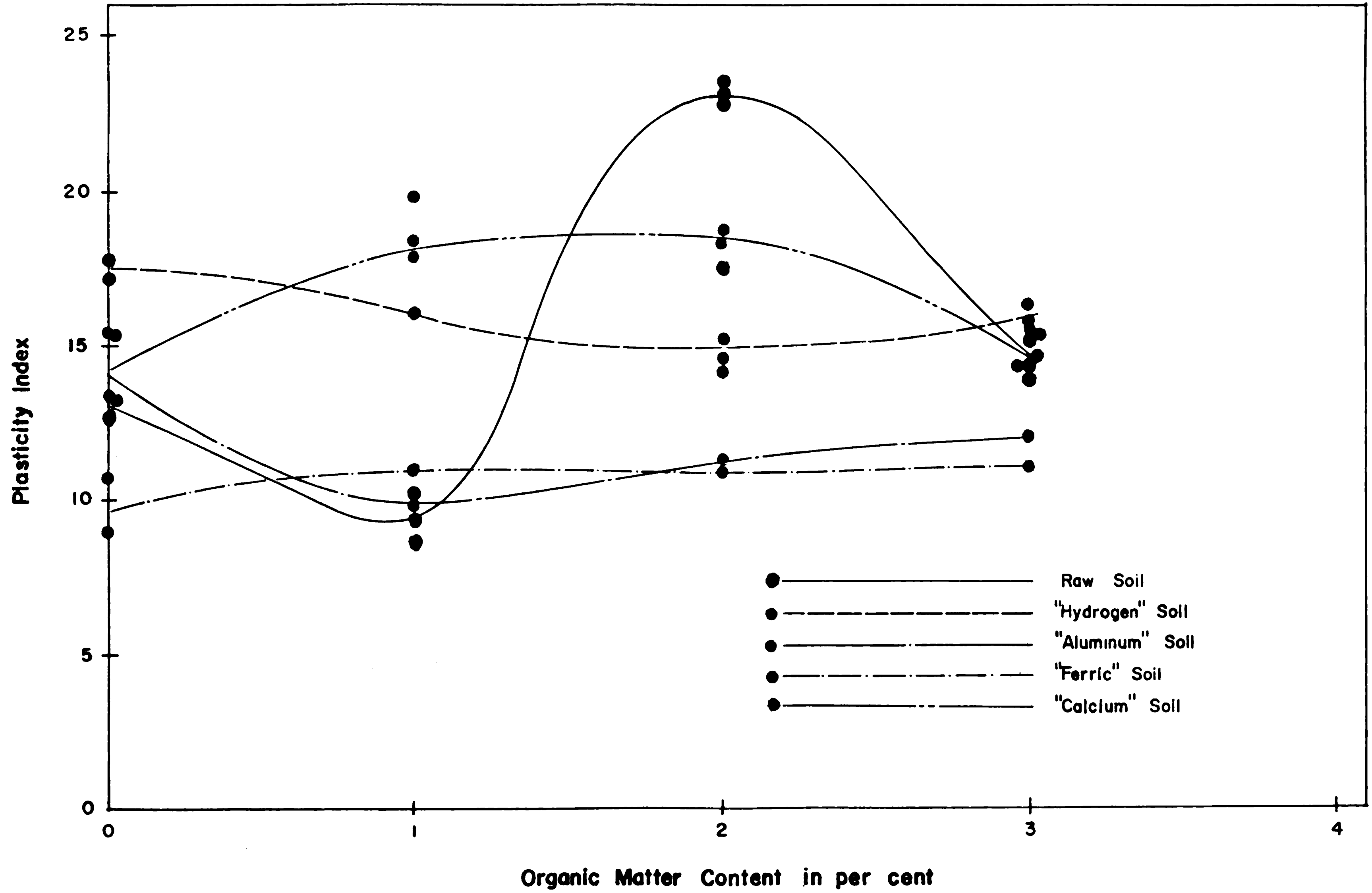

Fig. 7.- Effect of humic acid on the plasticity indices of homoionic soils

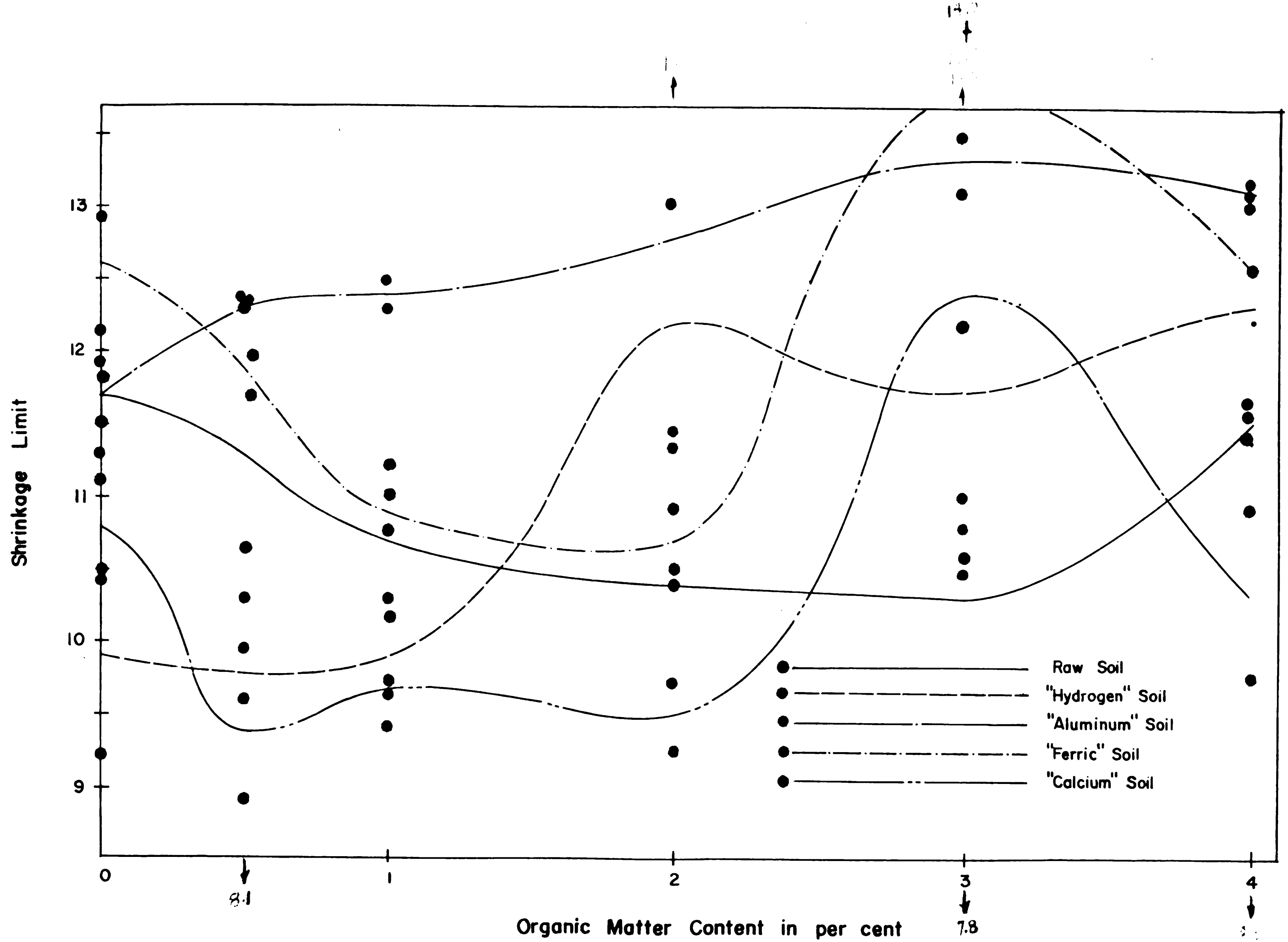

Fig. 8.—Effect of lignin on the shrinkage limits of homoionic soils

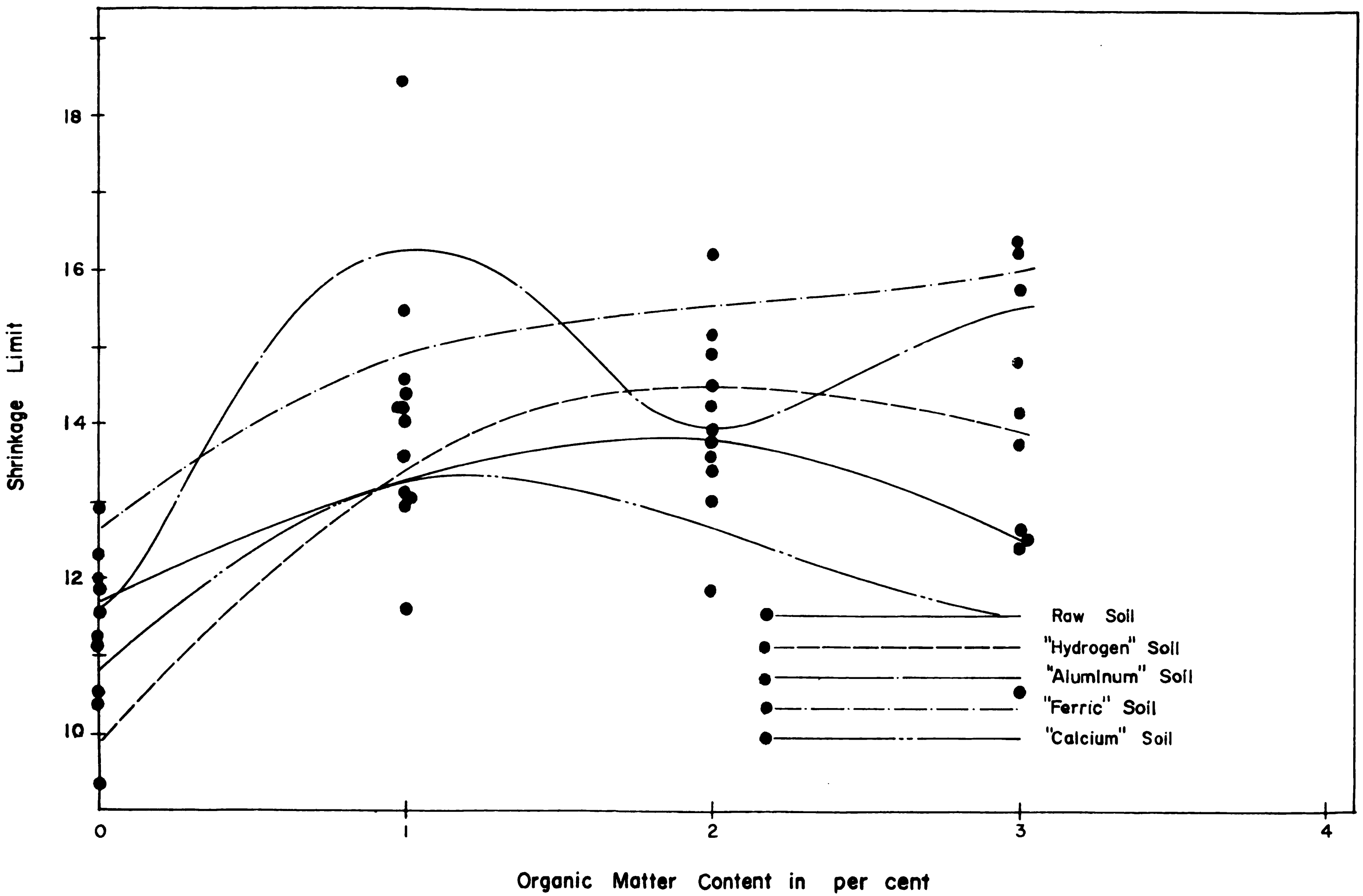

Fig. 9.—Effect of humic acid on the shrinkage limits of homoionic soils

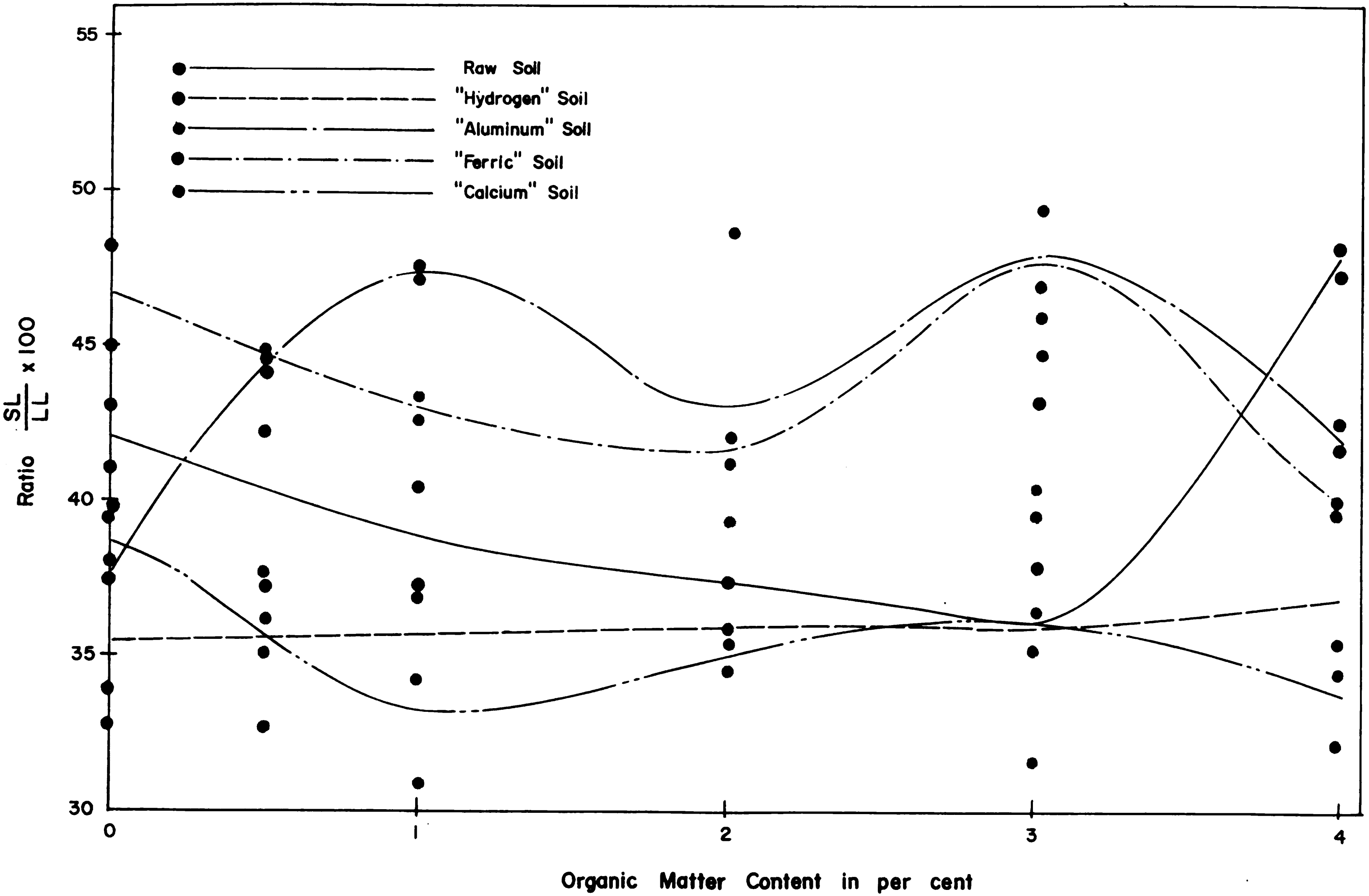

Fig. 10.—Effect of lignin on the SL:LL ratios of homoionic soils

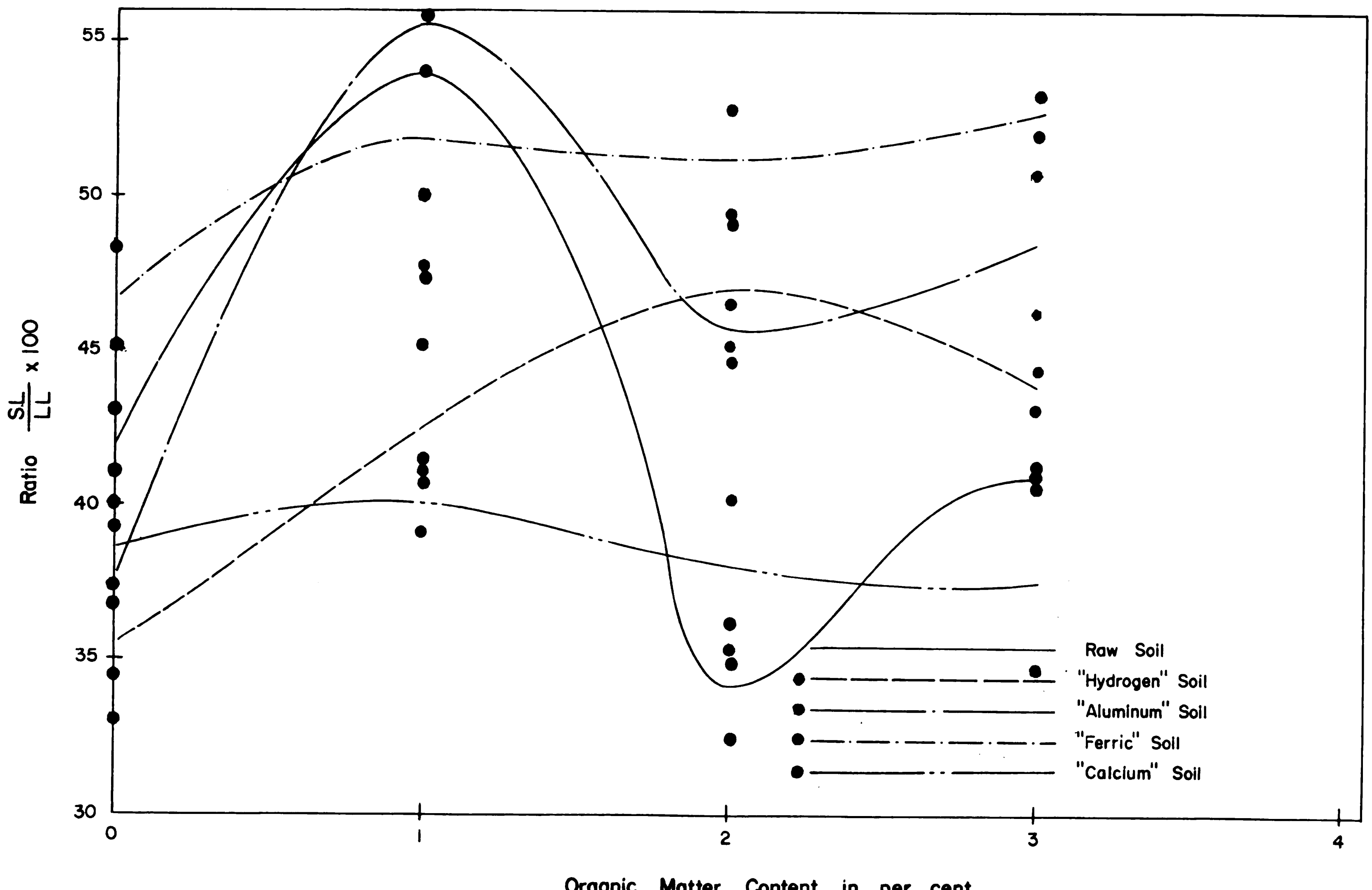

Fig. 11.—Effect of humic acid on the SL:LL ratios of homoionic soils

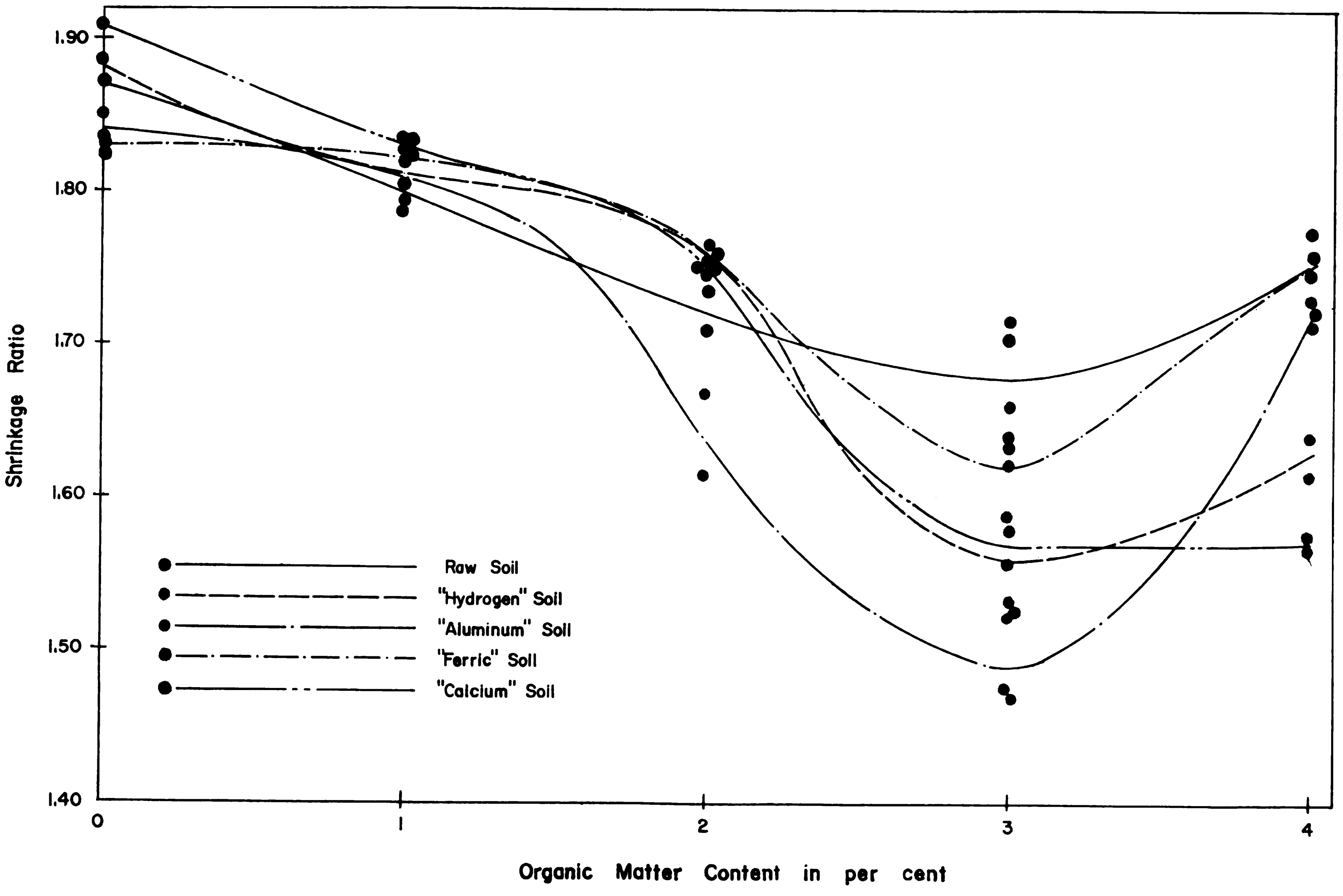

Fig. 12.-Effect of lignin on the shrinkage ratios of homoionic soils

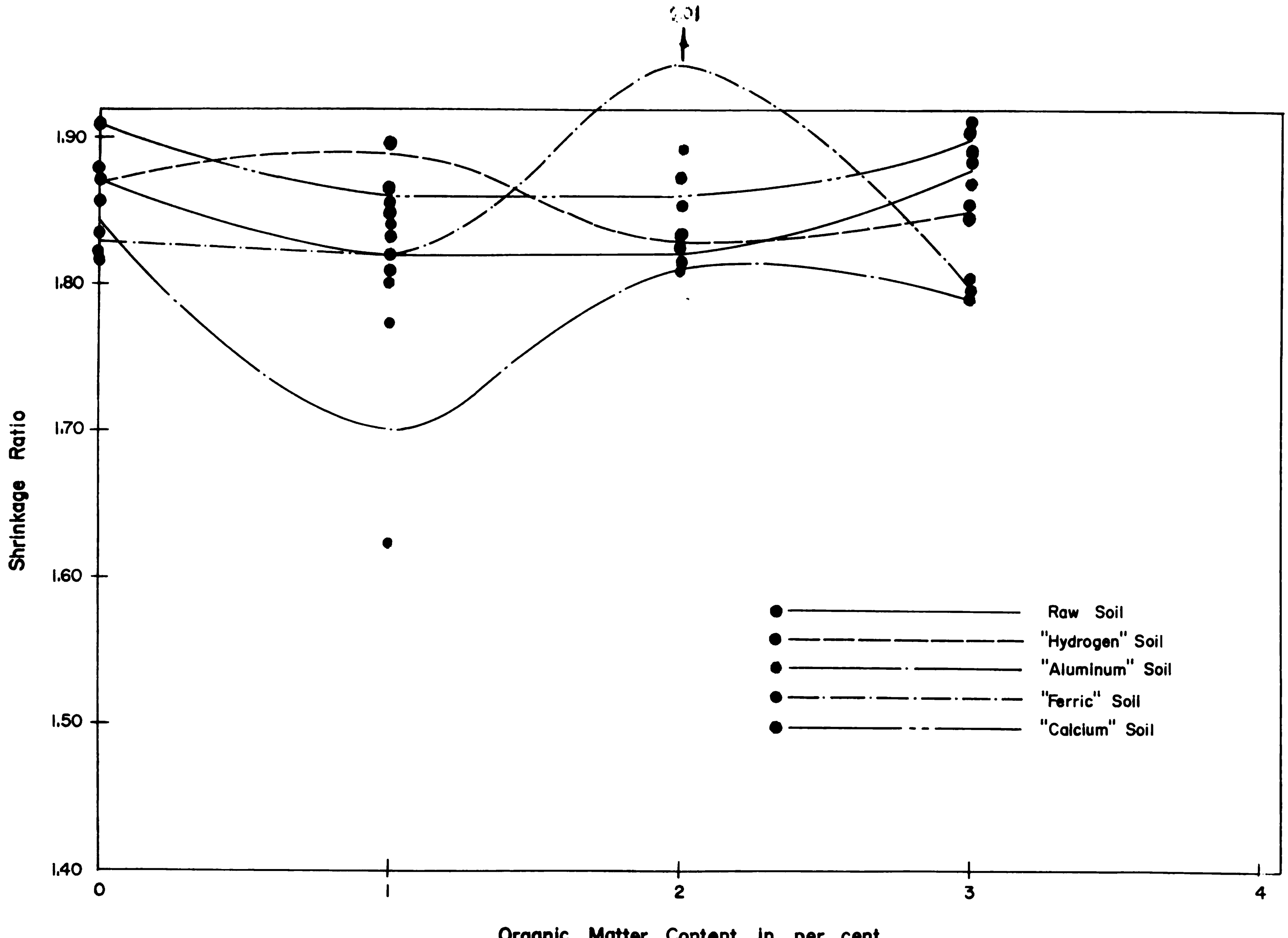

Fig. 13.—Effect of humic acid an the shrinkage ratios of homoionic soils

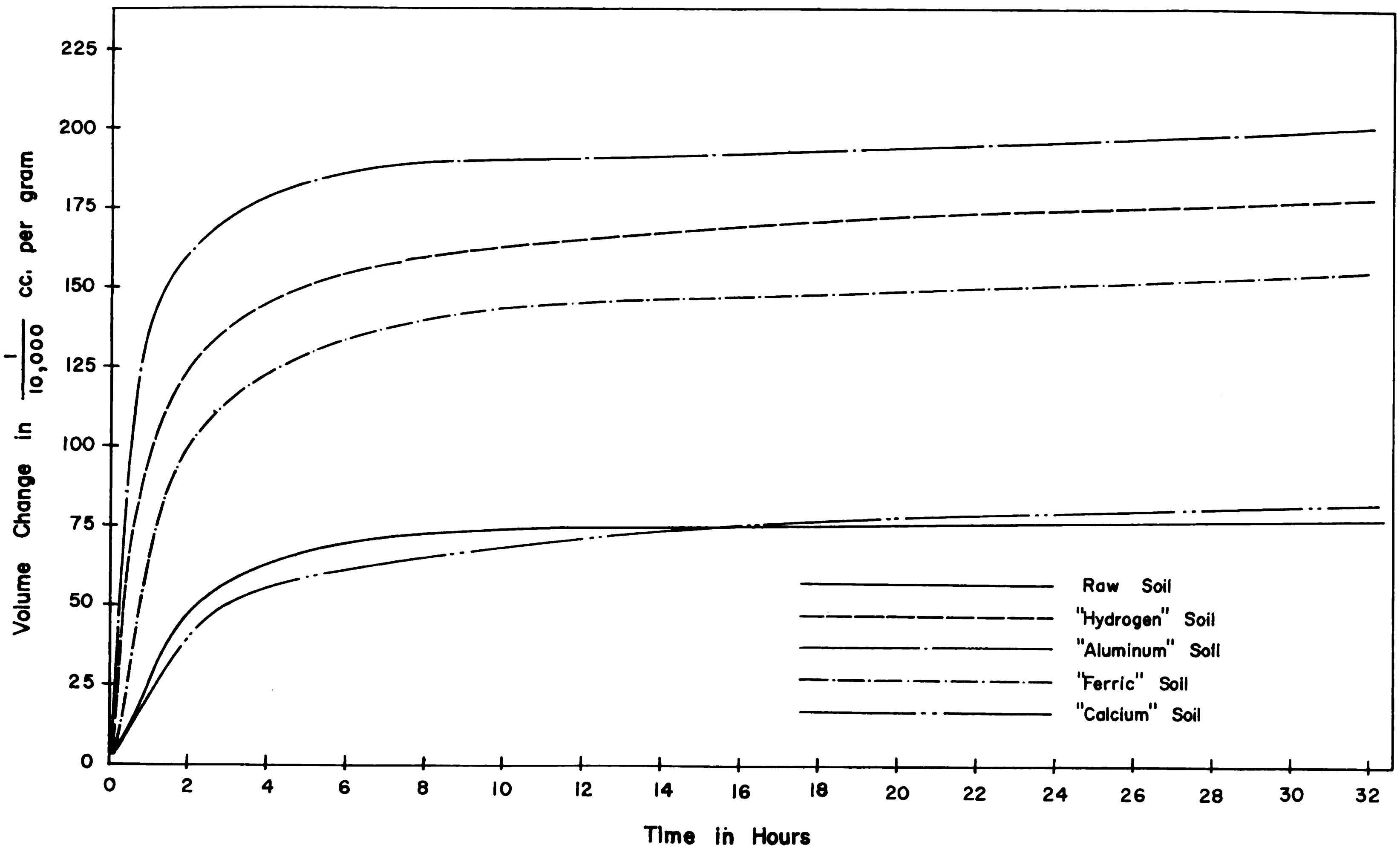

Fig. 14.- Swelling of homoionic soils compacted at their respective optimum moistures and densities

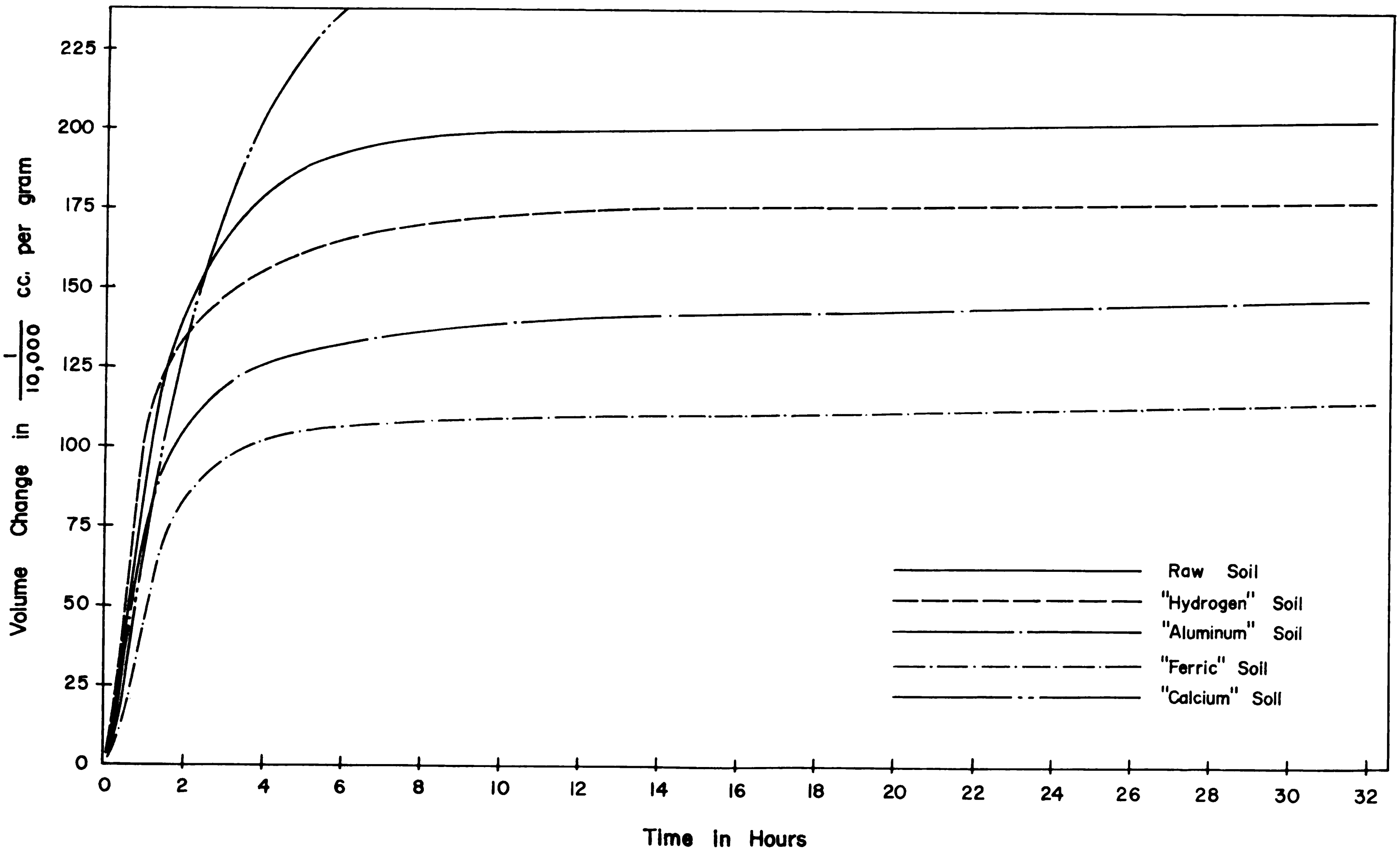

Fig. 15.– Swelling of homoionic soils compacted at a density of 123 lb per cu ft and a moisture content of 13 per cent

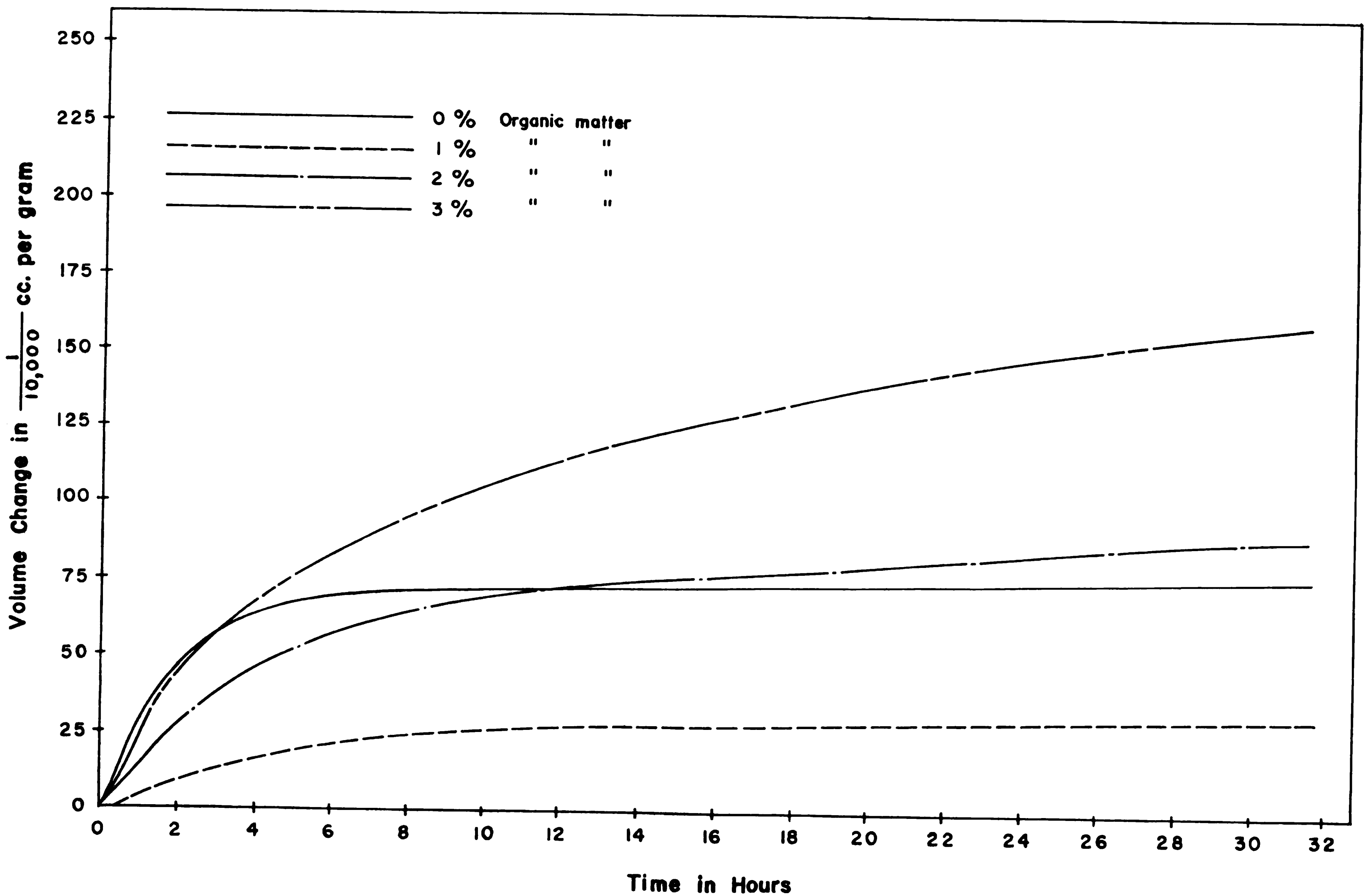

Fig. 16.— Swelling of "raw" soil at various percentages of lignin

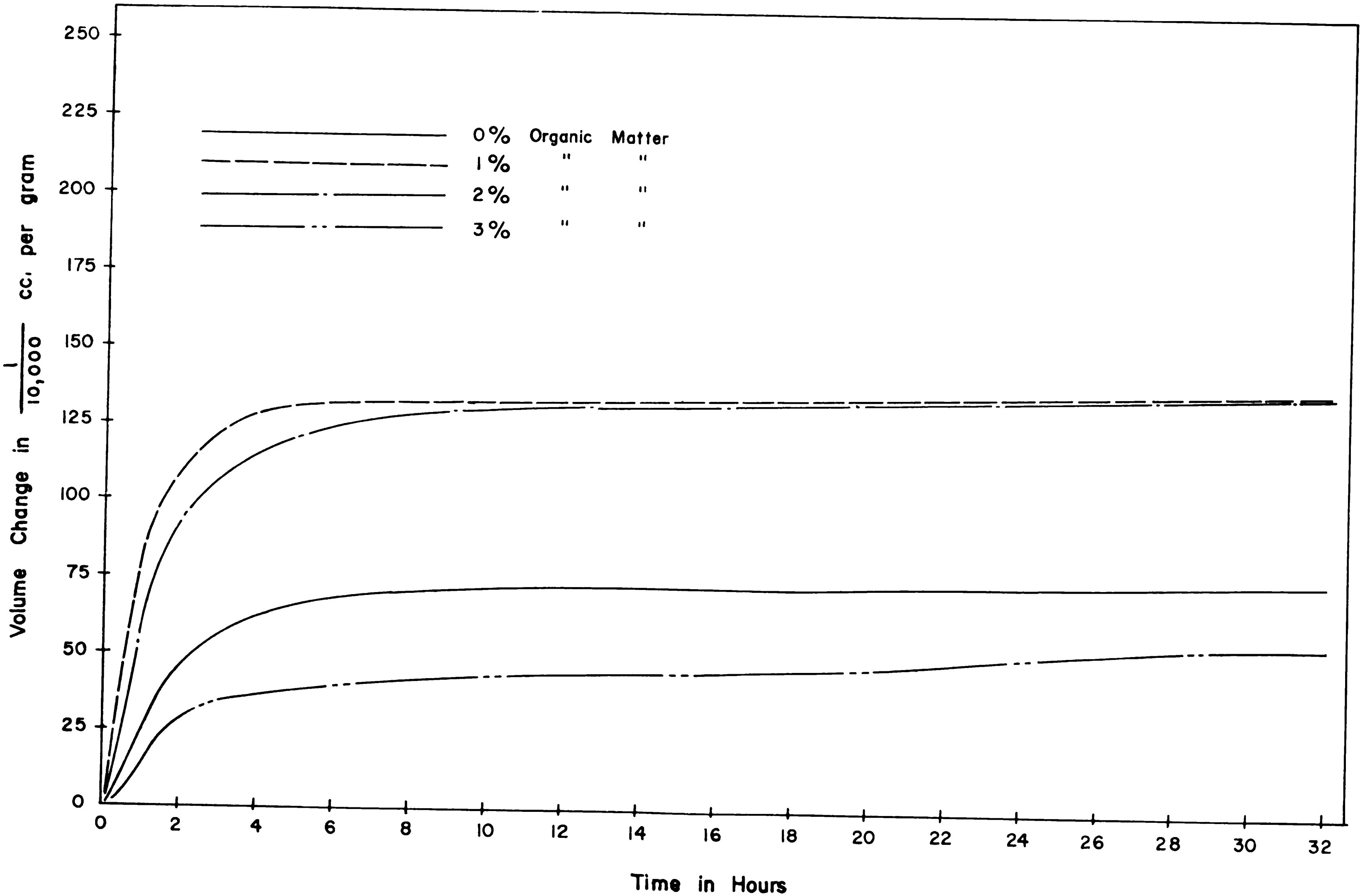

Fig. 17. — Swelling of "raw" soil at various percentages of humic acid

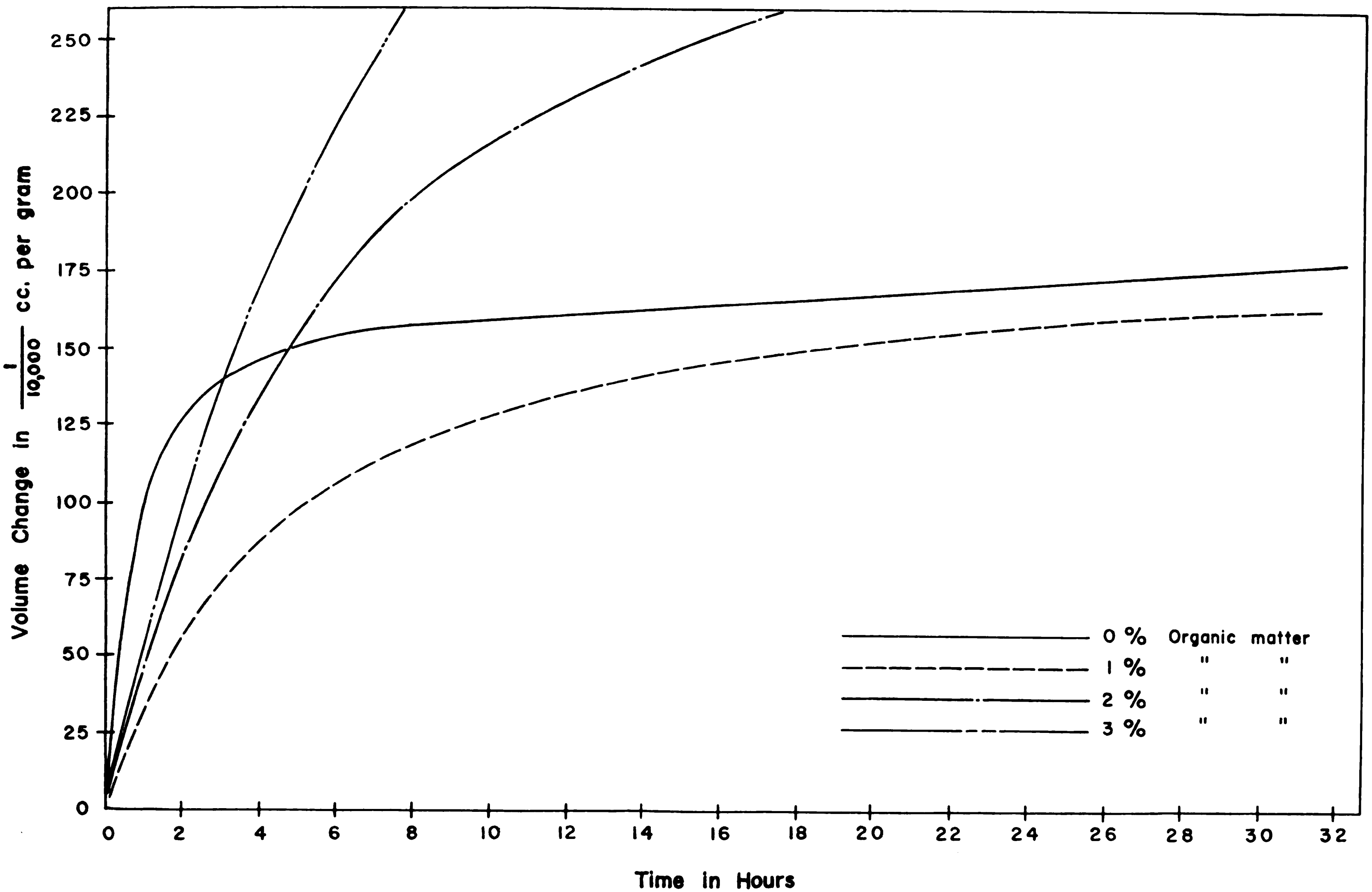

Fig. 18. — Swelling of "hydrogen" soil at various percentages of lignin

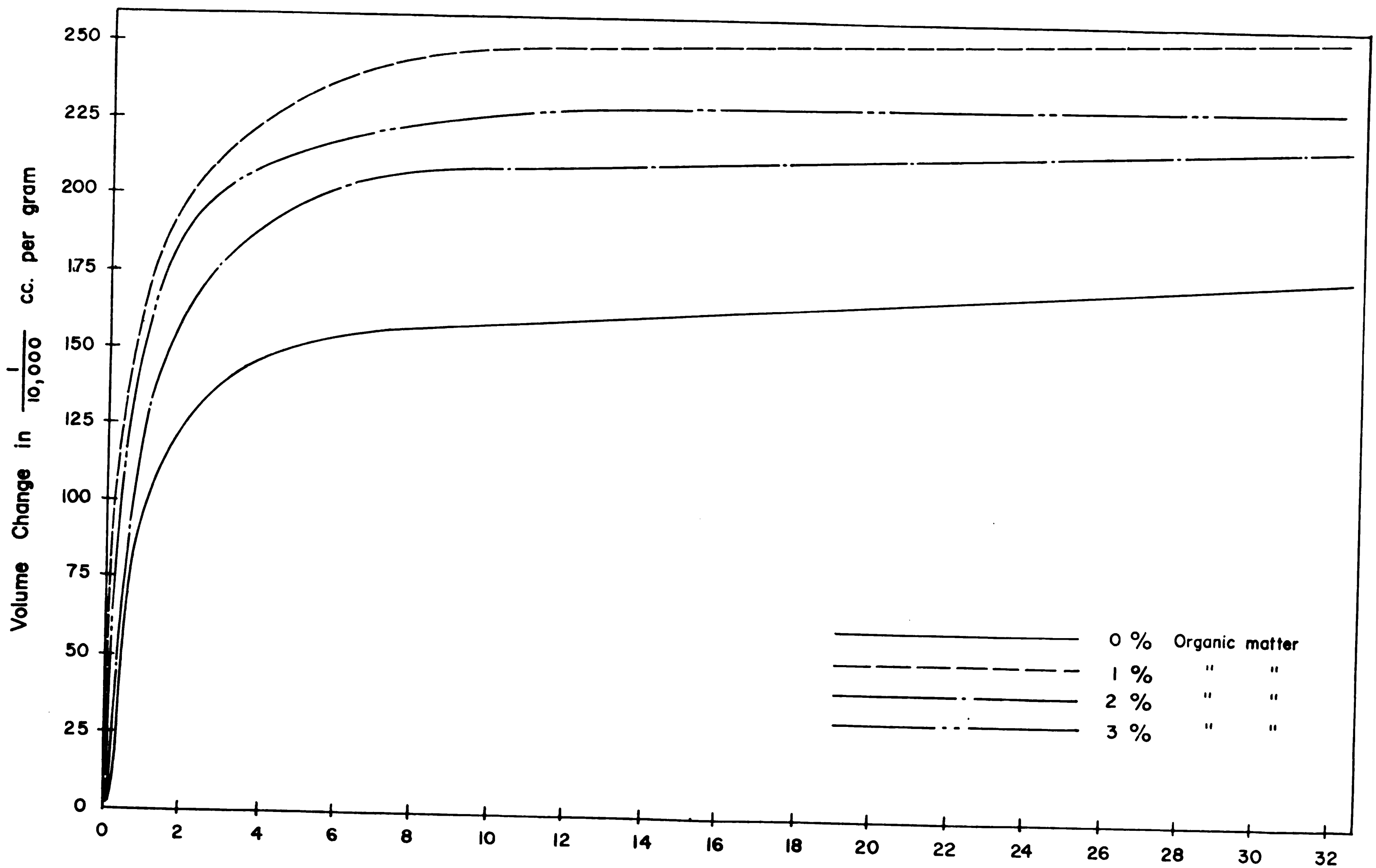

Fig. 19. — Swelling of "hydrogen" soil at various percentages of humic acid

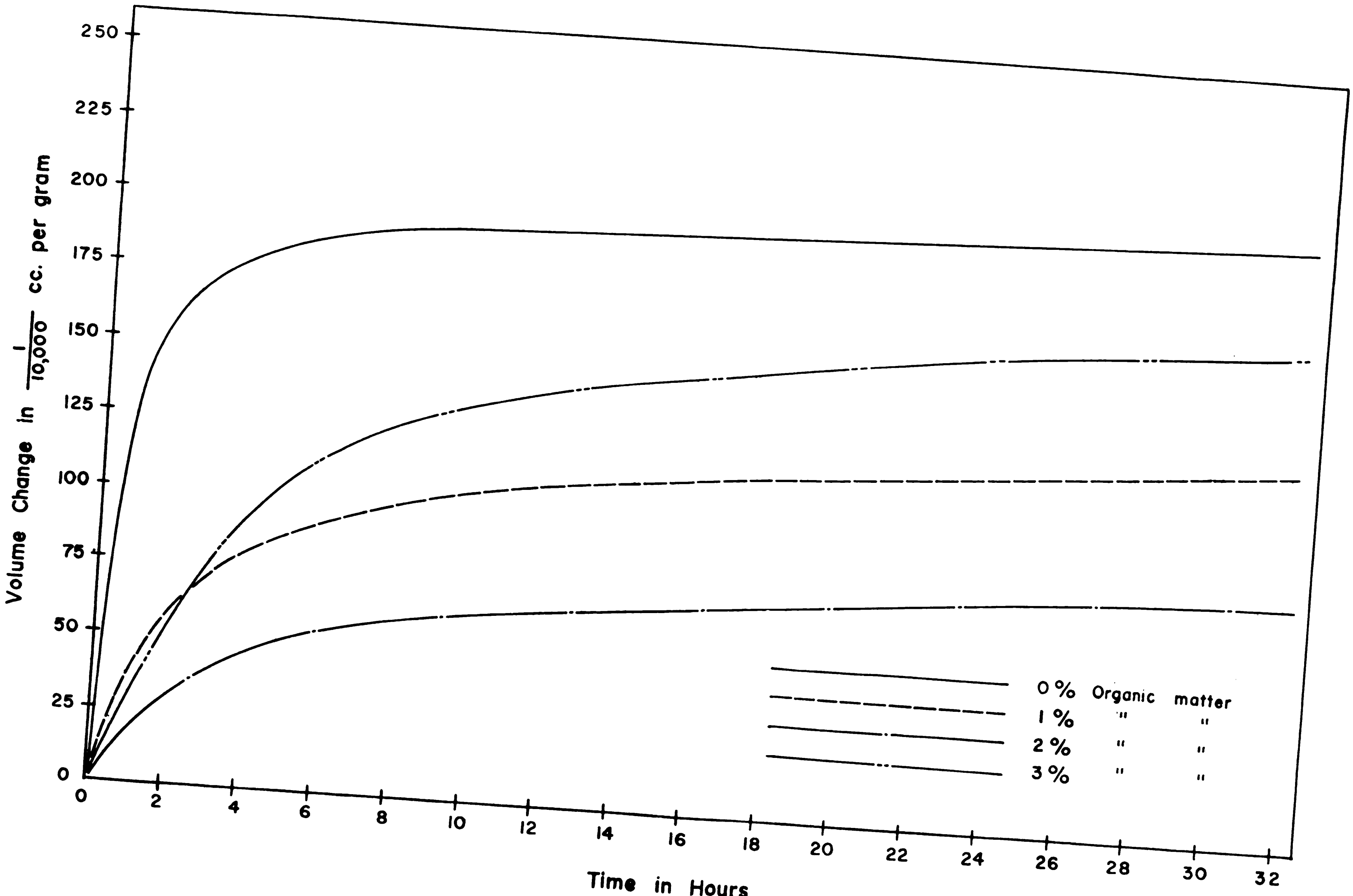

Fig. 20 – Swelling of "aluminum" soil at various percentages of lignin

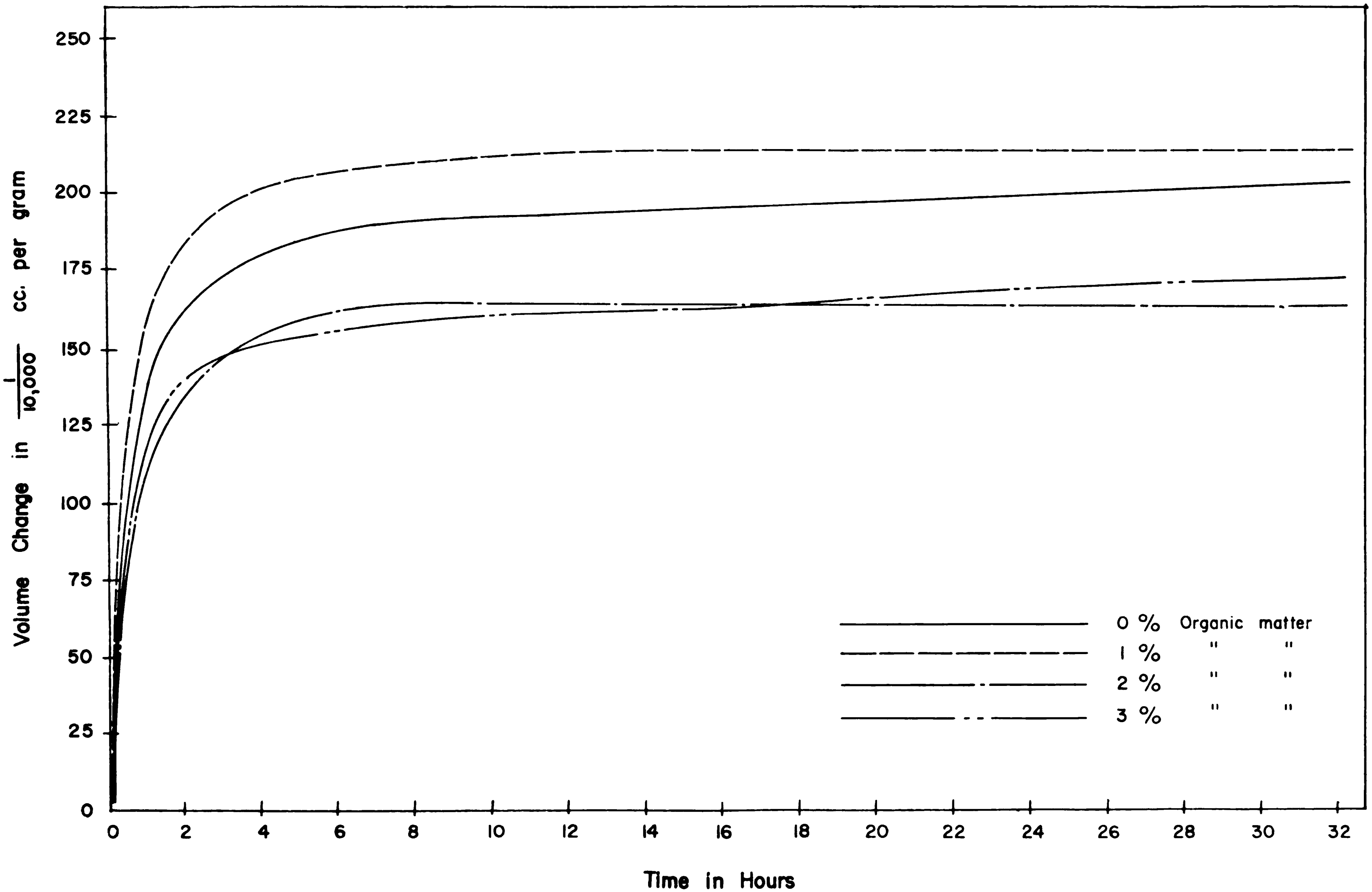

Fig. 21.— Swelling of "aluminum" soil at various percentages of humic acid

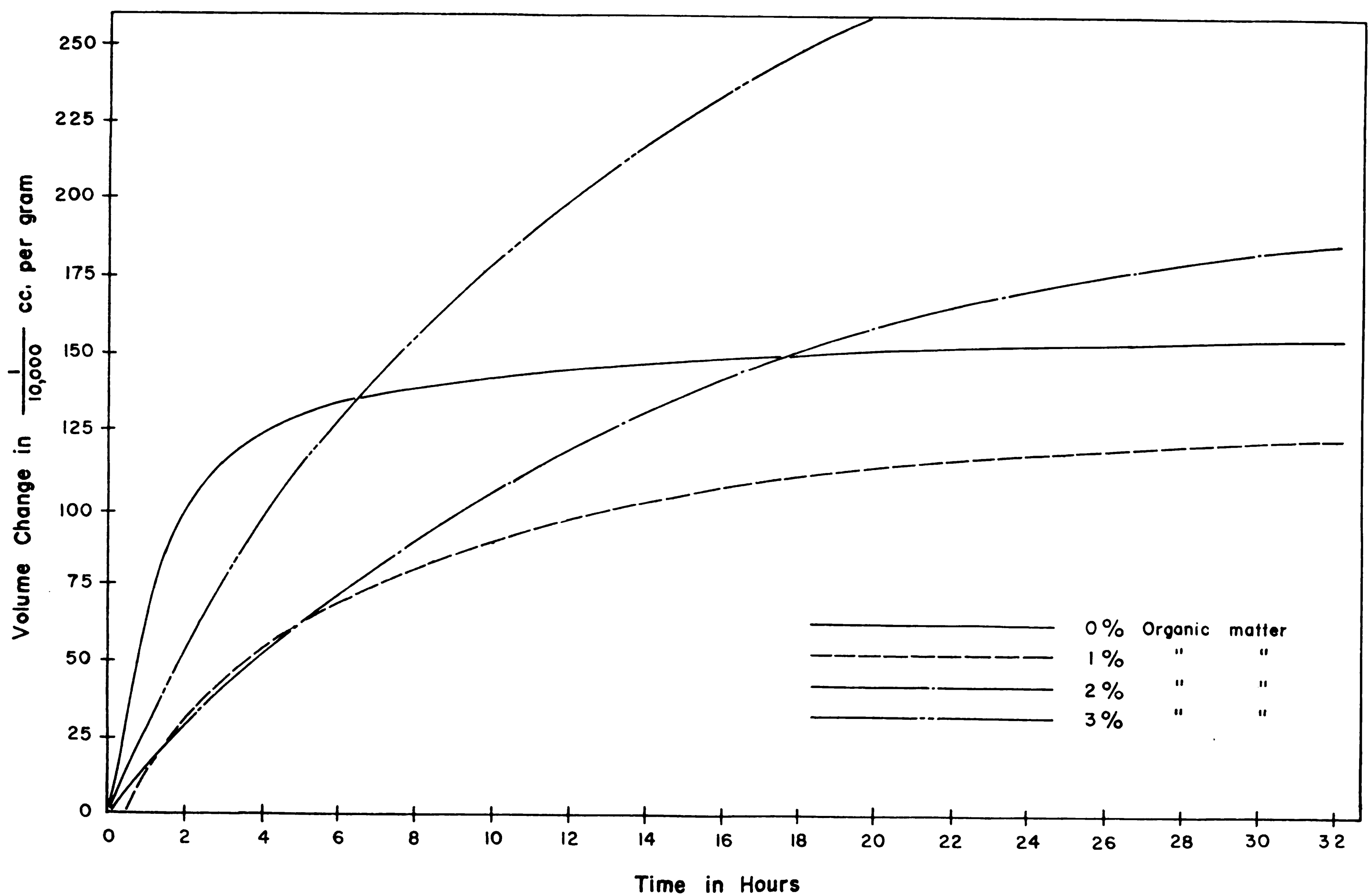

Fig. 22.- Swelling of "ferric" soil at various percentages of lignin

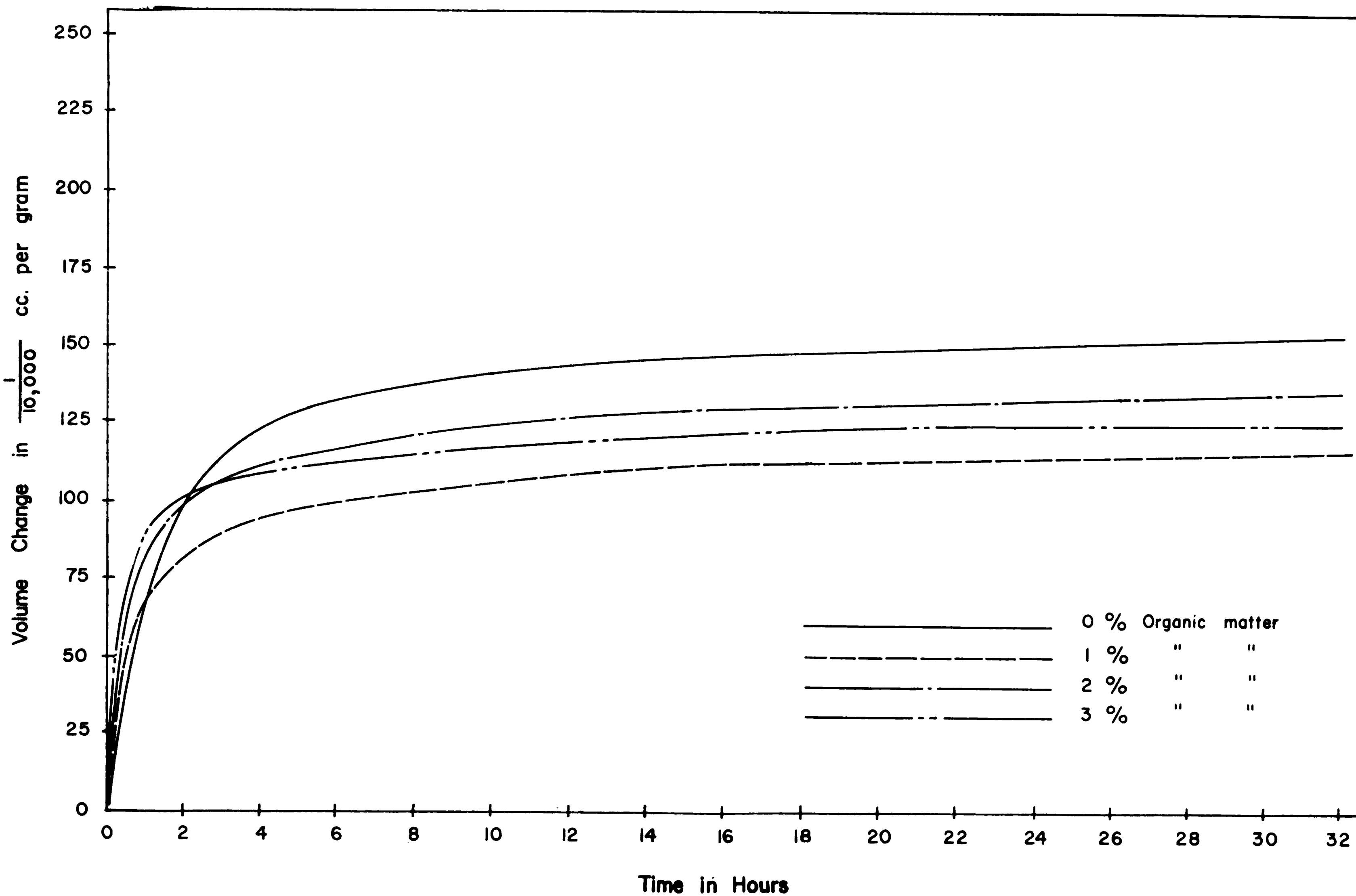

Fig. 23.– Swelling of "ferric" soil at various percentages of humic acid

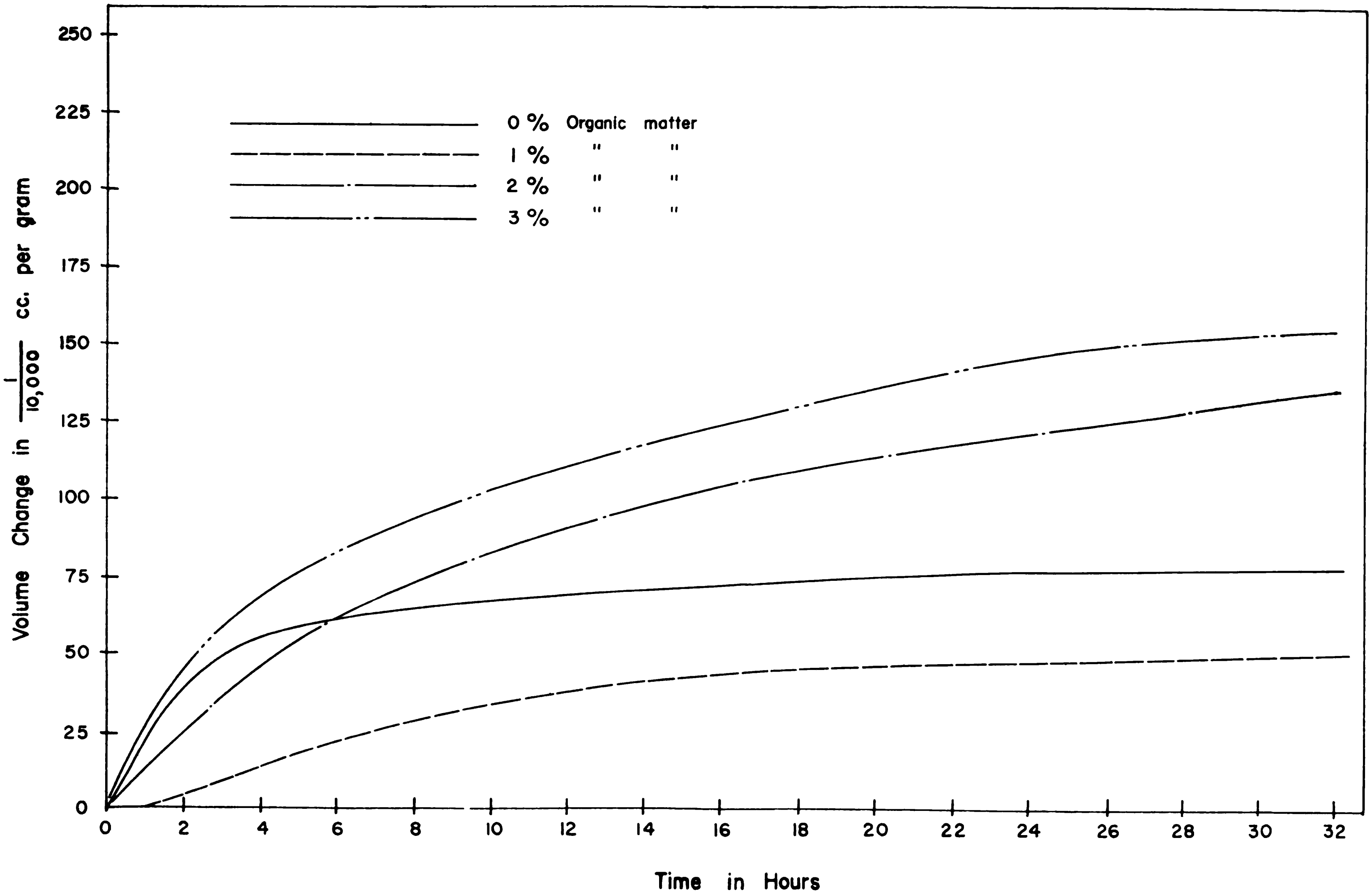

Fig. 24.– Swelling of "calcium" soil at various percentages of lignin

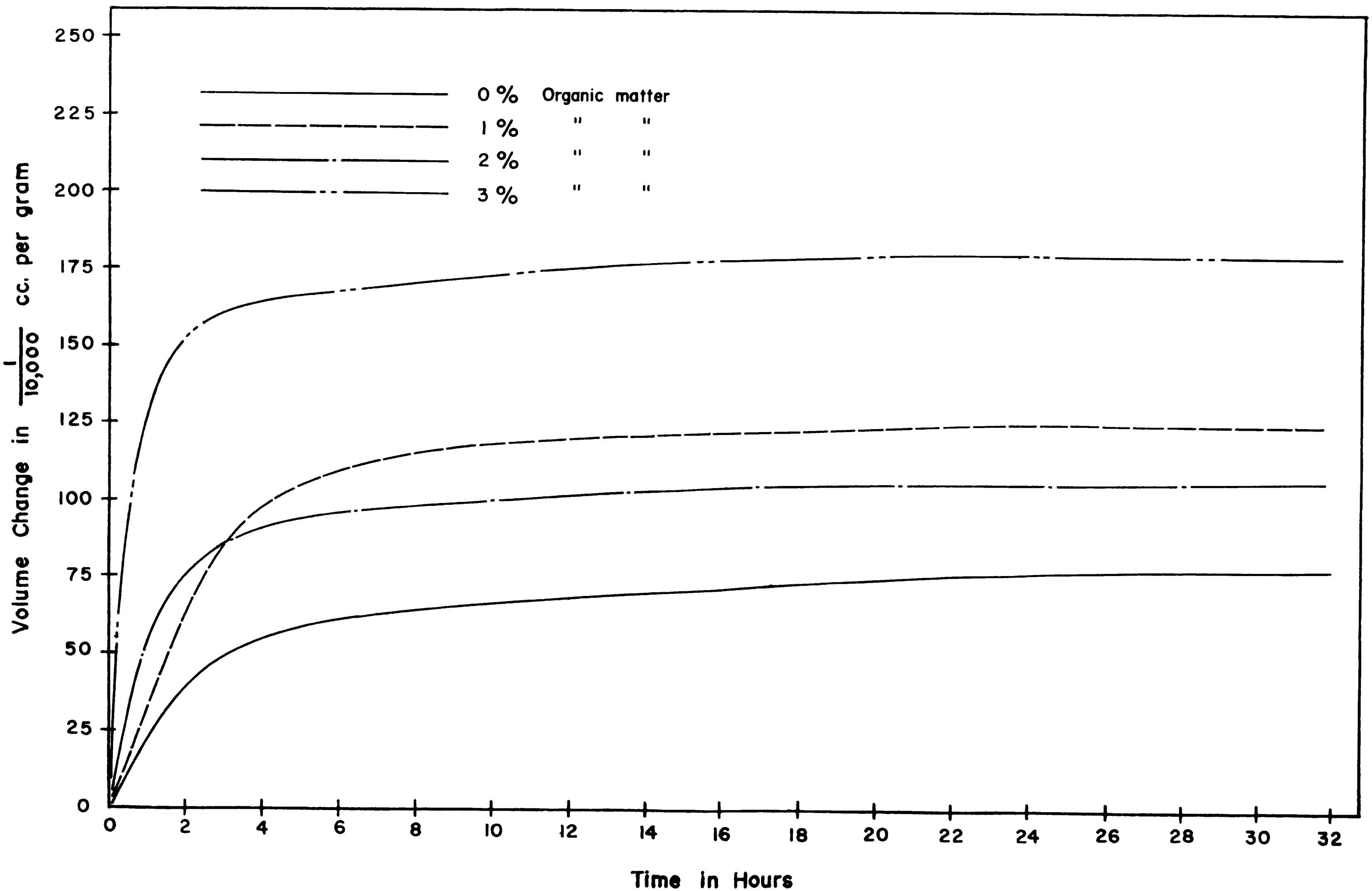

Fig. 25.- Swelling of "calcium" soil at various percentages of humic acid

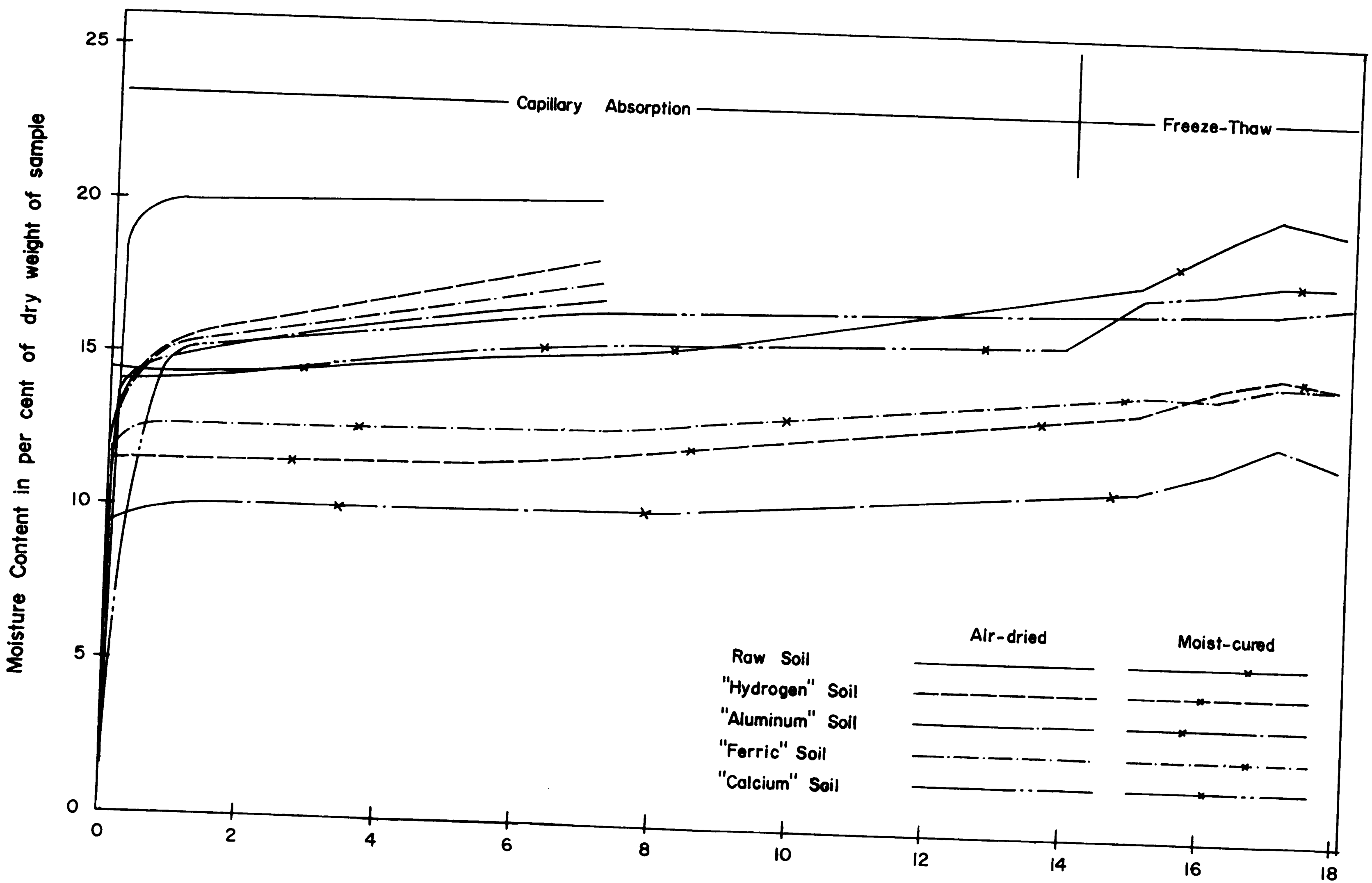

Fig. 26. Moisture absorption in weathering of homoionic soils containing no organic additive

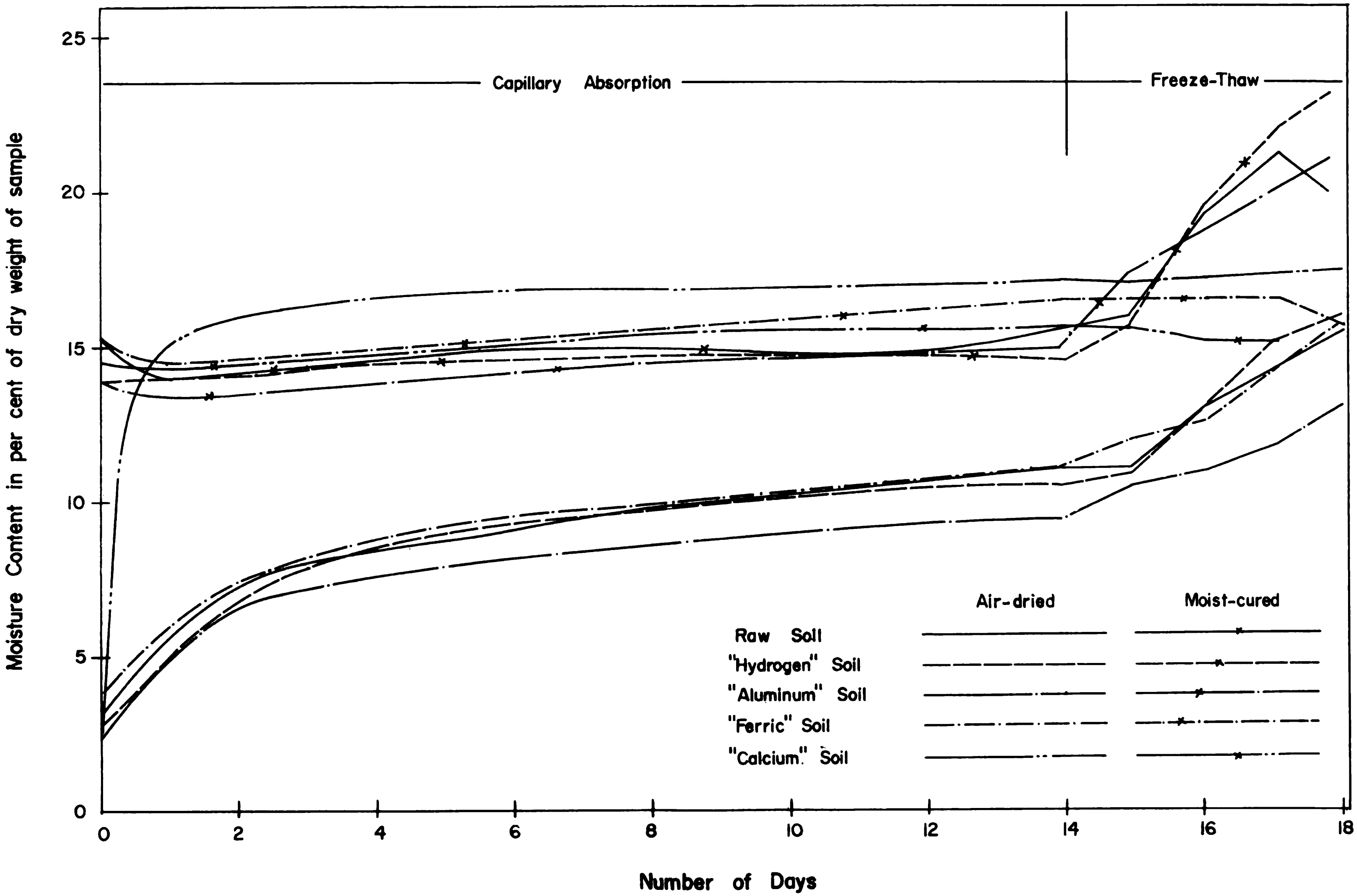

Fig. 27.-Moisture absorption in weathering of homoionic soils containing 1% lignin

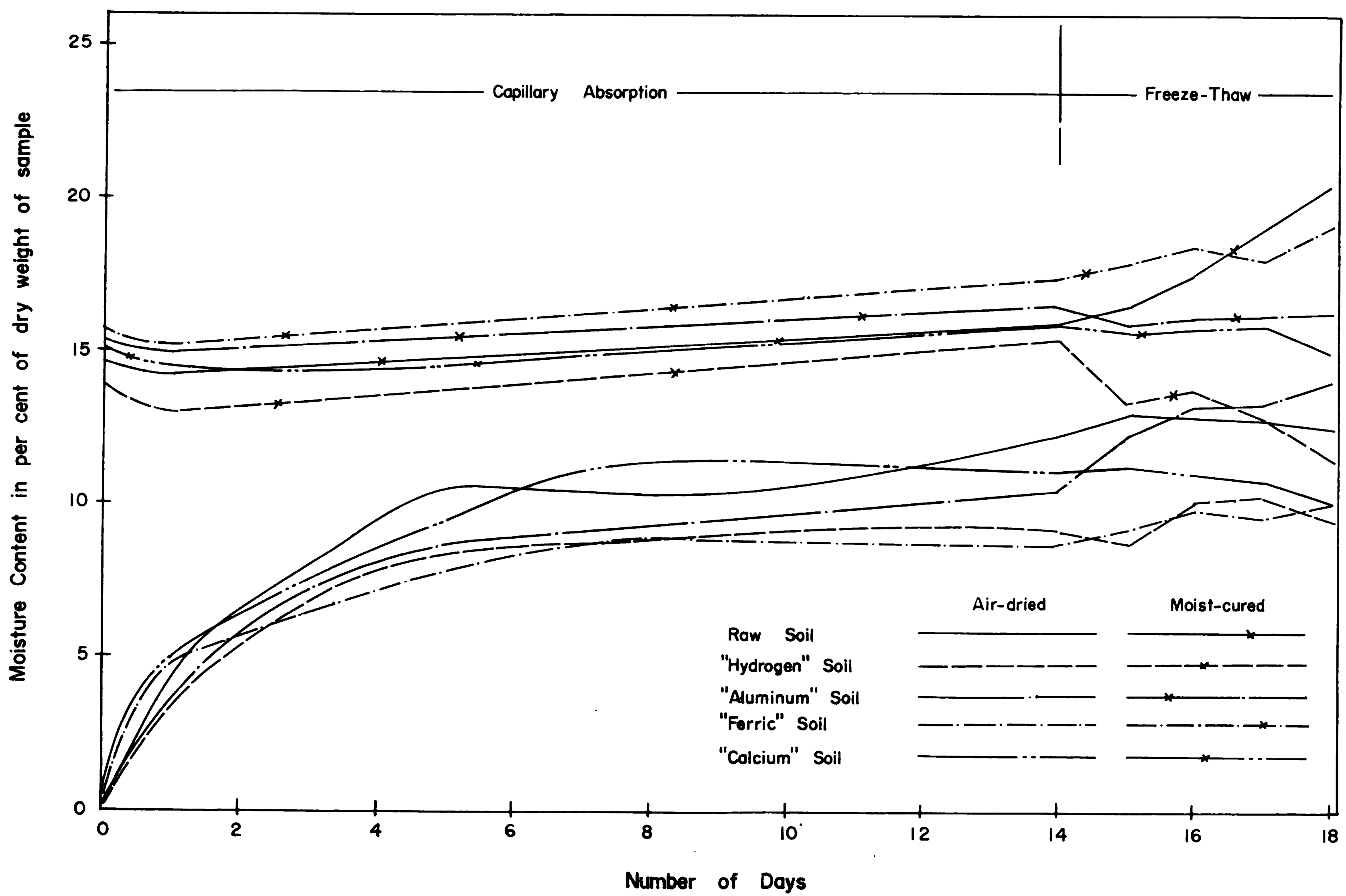

Fig. 28.-Moisture absorption in weathering of homoionic soils containing 2% lignin

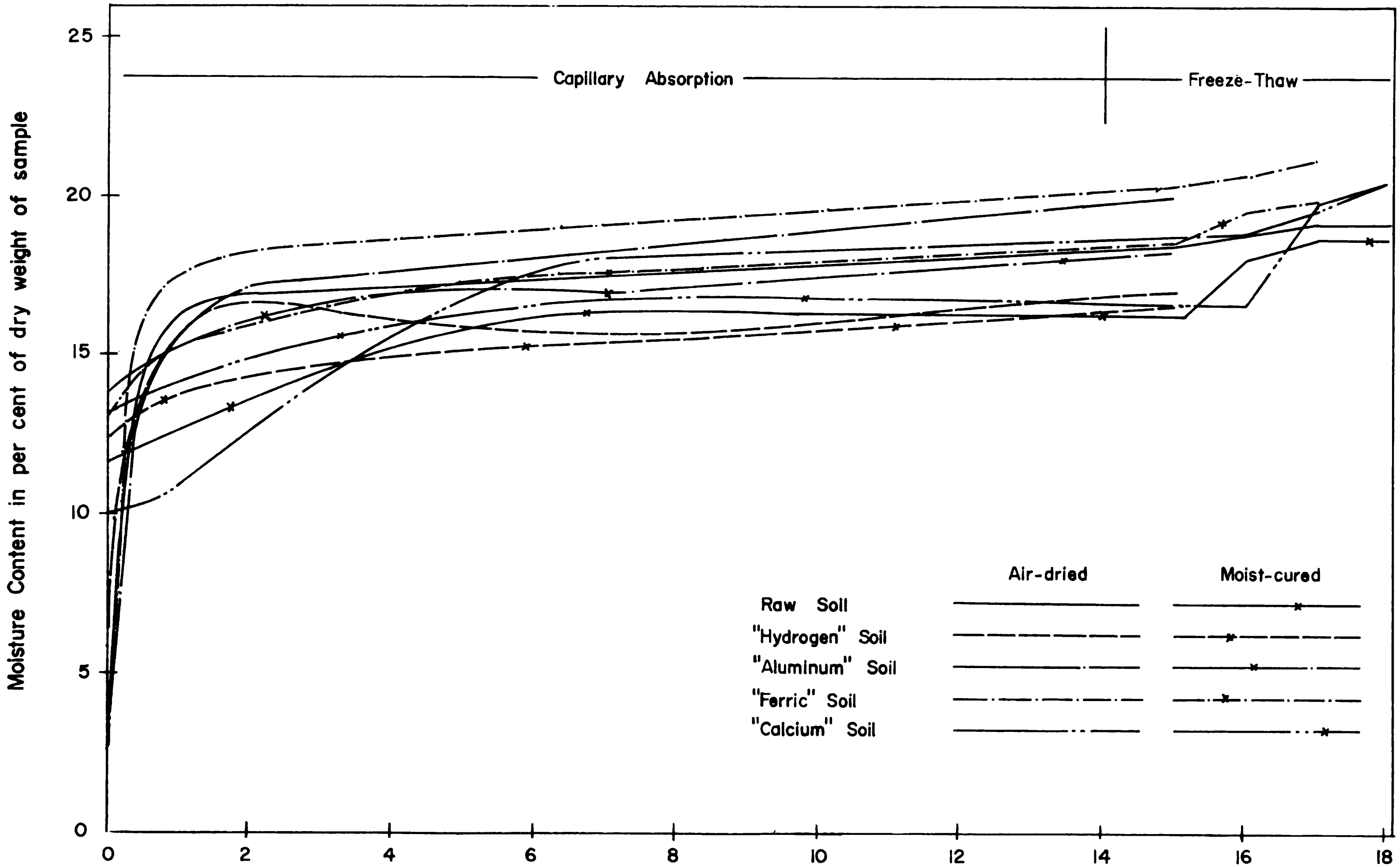

Fig. 29.-Moisture absorption in weathering of homoionic soils containing 1% humic acid

BIBLIOGRAPHY

Allen, H. "Report of Committee on Classification of Materials for Subgrades and Granular Type Roads," Highway Research Board Proceedings, XXV (1945).

Baver, L. D. Soil Physics. New York: John Wiley & Sons, Inc. 1940.

Baver, L. D. "The Relation of Exchangeable Cations to the Physical Properties of Soils," Journal of the American Society of Agronomists, XX (1928).

Belcher, D. J., McAlpin, G. W., and Woods, K. B. "Current Practices in Stabilization," Purdue Conference (1940), p. 166.

Bleck, A. T. "Pavements and Influences Affecting or Determining Their Performance," Highway Research Board Bulletin No. 20 (1949), p. 21.

Bremner, J. M. "Studies on Soil Organic Matter: I. The Chemical Nature of Soil Organic Matter," Journal of Agricultural Science, XXXIX (1949), pp.183-93.

Burton, V. R. and Benkelman, A. C. "The Relation of Certain Frost Phenomena to the Subgrade," Highway Research Board Proceedings, X (1930), pp. 259-75.

Casagrande, Arthur. "Classification and Identification of Soils," ASCE Transactions (1948), p. 922.

Catton, Miles D. "Research on the Physical Relations of Soil and Soil Cement Mixtures," Highway Research Board Proceedings, XX (1940), p. 821.

Davidson, Donald T. "Exploratory Evaluation of Some Organic Cations as Soil Stabilizing Agents," Highway Research Board Proceedings, XXIX (1949).

Davidson, D. T. and Glab, John E. "An Organic Compound as Stabilizing Agent for Two Soil-Aggregate Mixtures," Highway Research Board Proceedings, XLIX (1949).

Ensminger, L. E. and Gieseking, J. E. "Resistance of Clay-Adsorbed Proteins to Proteolytic Hydrolysis," Soil Science, LIII (1942), pp. 205-209.

Gieseking, J. E. "The Mechanism of Cation Exchange in the Montmorillonite-Beidellite-Nontronite Type of Clay Minerals," Soil Science, XLVII (1939), pp. 1-11.

Gillam, W. Sherman, "A Study on the Chemical Nature of Humic Acid," Soil Science, XLIX (1940),pp. 433-53.

di Gleria, John. "Laws of Apolar and Polar Adsorption," The Principles of Soil Science by A. A. J. de Sigmond. Trans. Arthur B. Yolland, ed. G. V. Jacks. London: Thomas Murby & Co., 1938.

di Gleria, J. and Dr. Fr. Zucker. "Soil Colloids," Colloid Chemistry. Ed. Jerome Alexander. Chemical Catalog Co., 1931, III.

Grim, Ralph E. Clay Mineralogy. New York: McGraw-Hill Book Co., Inc., 1953.

Grim, Ralph E. "Modern Concepts of Clay Minerals," Journal of Geology, L (1942), pp. 225-75.

Grim, Ralph E. "Ion Exchange in Relation to Some Properties of Soil-Water Systems," ASTM Special Publication No. 142 (1952).

Grim, Ralph E. "Organization of Water on Clay Mineral Surfaces and Its Implications for the Properties of Clay-Water Systems," Highway Research Board Special Report No. 40 (1958), pp. 17-23.

Grim, R. E., Allaway, W. H., and Cuthbert, F. L. "Reaction of Different Clay Minerals with Organic Cations," Journal of the American Ceramic Society, XXX (1950), pp. 137-142.

Grossi, Frank X. and Woolsey, John L. "Effect of Fatty Quaternary Ammonium Salts on Physical Properties of Certain Soils," Industrial and Engineering Chemistry, XLVII (1955).

Hauser, E. A. Colloidal Phenomena. Massachusetts: Massachusetts Institute of Technology Press, 1954.

Hendricks, S. B. "Base Exchange of the Clay Mineral Montmorillonite for Organic Cations and Its Dependence upon Adsorption due to Van der Waals Forces," Journal of Physical Chemistry, XLV (1941), pp. 65-81.

Hogentogler, C. A. "Report of Subcommittee on Subgrade Studies," Highway Research Board Proceedings, VII (1927), p. 97.

Hoover, James H. and Davidson, D. T. Preliminary Evaluation of Some Organic Cationic Chemicals as Stabilizing Agents for Iowa Loess. Proj. 283-S, Iowa Engineering Experiment Station, 1956.

Housel, W. S. "A Practical Method for the Selection of Foundations Based on Fundamental Research in Soil Mechanics," University of Michigan Engineering Research Bulletin, XIII (1929).

Jenny, Hans. Factors of Soil Formation. New York: McGraw-Hill Book Co., Inc., 1941.

Jenny, H. and Reitemeier, R. F. "Ionic Exchange in Relation to the Stability of Colloidal Systems," Journal of Physical Chemistry, XXXIX (1935), pp. 593-604.

Jones, P. C. T. "The Microbial Decomposition of Resinous Stabilizing Agents," Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering, IV (Rotterdam: 1948).

Jordan, John W. "Organophilic Bentonites Swelling in Organic Liquids." Journal of Physical and Colloid Chemistry, LIII (1949), pp. 294-306.

Kelley, W. P. and Jenny, H. "The Relation of Crystal Structure to Base Exchange and Its Bearing on Base Exchange in Soils," Soil Science, XLI (1936), p. 367.

Kelley, W. P., Jenny, H. and Brown, S. M. "The Hydration of Minerals and Soil Colloids in Relation to Crystal Structure," Soil Science, XLI (1936) p. 259.

Kelley, W. P., Dore, W. H., and Brown, S. M. "The Nature of the Base Exchange Material of Bentonite, Soils and Zeolites as Revealed by Chemical Investigations and X-Ray Analysis," Soil Science, XXXI (1931), p. 25.

Lang, F. C. "Practical Applications of Road Soil Science in the Construction of Flexible Surfaces," Highway Research Board Proceedings, XIV (Part II, 1934).

Mainfort, R. C. "A Laboratory Study of the Effectiveness of Various Chemicals as Soil Stabilizing Agents," Technical Development Note No. 40. C.A.A., U.S. Department of Commerce, October, 1945.

Mainfort, R. C., McAlpin, G. W., and Winterkorn, H. F. A Laboratory Study of the Soil Stabilizing Effectiveness of a Complex Salt of Abietic Acid. Technical Development Note No. 35. U.S. Department of Commerce, July, 1944.

Marshall, C. E. *The Colloid Chemistry of the Silicate Minerals*. New York: Academic Press, Inc., 1949.

Marshall, C. E. and Patnaik, N. "Ionization of Soils and Soil Colloids: IV. Humic and Hymatomelanic Acids and Their Salts," *Soil Science*, LXXV (1953), pp. 153-165.

McGeorge, W. T. "The Base Exchange Property of Organic Matter in Soils," *Arizona Experimental Station Technical Bulletin* No. 30 (1930).

Meunier, V. C., Williamson, G. J., and Hopkins, R. P. "Soil-Water Relationship in Calcium Acrylate Stabilized Soil," *Industrial and Engineering Chemistry*, XLVII (1955).

Meyers, H. E. "Physico-Chemical Reactions Between Organic and Inorganic Soil Colloids as Related to Aggregate Formation," *Soil Science*, XLIV (1937), p. 331.

Nicholls, R. L. and Davidson, D. T. "Polyacids and Lignin Used with Large Organic Cations for Soil Stabilization," *Highway Research Board Proceedings*, XXXVII (1958).

Olson, L. C. and Bray, R. H. "The Determination of the Organic Base Exchange Capacity of Soils," *Soil Science*, XLV (1938), pp. 483-496.

Parker, F. W. and Pate, W. W. "Base Exchange in Soil Colloids and the Availability of Exchangeable Calcium in Different Soils," *Journal of the American Society of Agronomists*, XVIII (1926).

Pauling, L. "The Structure of Chlorites," *Proceedings of the National Academy of Sciences*, XVI (1930) p. 578.

Peech, Michael. "Determination of Exchangeable Bases in Soils," *Industrial and Engineering Chemistry*, Analytical Edition, XIII (1941), pp. 436-441.

Procedures for Testing Soils, Sponsored by ASTM Committee D-18 on Soils for Engineering Purposes. Philadelphia: ASTM, July, 1950, pp. 131-135.

Russell, H. W., Worsham, W. B., and Andrews, R. K. "Influence of Initial Moisture and Density on the Volume Change and Strength Characteristics of Two Typical Illinois Soils," *Highway Research Board Proceedings*, XXVI (1946).

Searle, A.B. and Grimshaw, R. W. The Chemistry and Physics of Clays. 3d ed, New York: Interscience Publishers Inc., 1959).

Sheeler, J. B., Ogilvie, J. C., and Davidson, D. T. "Stabilization of Loess with Aniline-Furfural," Highway Research Board Proceedings, XXXVI (1957).

Sideri, D. I. "Soil Swelling: I. The Swelling of Soil in Water Considered in Connection with the Problem of Soil Structure," Soil Science, XLI (1936).

Sideri, D. I. "On the Formation of Structure in Soil: II. Synthesis of Aggregates; On the Bonds Uniting Clay with Sand and Clay with Humus," Soil Science XLII (1936).

de Sigmond, Alexius A. J. The Principles of Soil Science. Trans, A. B. Yolland, ed. G. V. Jacks. London: Thomas Murby & Co., 1938.

Smith, C. R. "Base Exchange Reactions of Bentonite and Salts of Organic Bases," Journal of the American Chemical Society, LVI (1934), p. 1561.

Sweet, H. S. and Woods, K. B. "Mapcracking in Concrete Pavements as Influenced by Soil Textures," Highway Research Board Proceedings, XXVI (1946).

Tittle, Robert H. "Salvaging Old Pavements by Resurfacing," Highway Research Board Bulletin No. 47 (1952).

Waksman, S. A. "Chemical Nature of Soil Organic Matter," Transactions, 2d Commission, International Society of Soil Scientists, Vol. A, p. 172.

Waksman, Selman A. and Hutchings, Imri J. "Decomposition of Lignin by Microorganisms," Soil Science, XLII (1936), pp. 119-130.

Winterkorn, Hans F. "Surface Chemical Factors Influencing the Engineering Properties of Soils," Highway Research Board Proceedings, XVI (1936) p. 293.

Winterkorn, H. F. "Physico-Chemical Soil Testing," Highway Research Board Proceedings, XX (1940) pp. 798-806.

Winterkorn, H. F. "Mechanism of Water Attack on Dry Cohesive Soil Systems," Soil Science, LIV (1942) p. 259.

Winterkorn, H. F. "Clay Research in Construction Engineering," Journal of Geology, L (1942), pp. 291-306.

Winterkorn, H. F. "Physico-Chemical Properties of Soils," Proceedings of the Second International Conference on Soil Mechanics and Foundation Design, I (Rotterdam, 1948).

Winterkorn, H. F. Homoionic Soil Study. May 31, 1946.

Winterkorn, H. F. A Laboratory Study of the Soil Stabilizing Effectiveness of Artificial Resins with Special Emphasis on the Aniline-Furfural Resins. Technical Development Note No. 43. U.S. Department of Commerce, January, 1947.

Winterkorn, H. F. and McAlpin, G. W. Soil Stabilization by the Use of Rosin. Technical Development Note No. 34. U.S. Department of Commerce, February, 1946.

Woods, K. B. and Havey, F. F. "Pumping of Subgrade through Paving Joints and Cracks," Technical Bulletin No. 103 (Washington, D.C.: American Road Builders Association, 1946).

Wooltorton, F. L. D. "Soil Structure and the Road Engineer," Proceedings of the Institution of Civil Engineers, No. 1 (February, 1952) Part II, p. 1.

Wooltorton, F. L. D. The Scientific Basis of Road Design. The Roadmaker's Library, Vol. 14 (London: Edward Arnold Ltd., 1954).

Yoder, E. J. "The Effect of Calcium Chloride on the Compactive Effort and Water Retention Characteristics of Soils," Highway Research Board Proceedings, XXVII (1947).