SUB-SECTION Ic

PHYSICAL AND PHYSICO-CHEMICAL PROPERTIES OF SOILS.

Ic 4

SOME FUNDAMENTAL FACTORS INFLUENCING THE PROPERTIES OF SOIL MATERIALS x)

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INTRODUCTION

The important factors of composition controlling the properties of soil materials may be classified as follows: 4)

1) Clay-mineral composition - the relative abundance of the clay-mineral components and their particle-size distribution.
2) Nonclay-mineral composition - the relative abundance of each mineral and the size-grade distribution of its particles.
3) Electrolyte content - the amount and kind of exchangeable bases and any water-soluble salts.
4) Organic content - the amount and kind.
5) Miscellaneous textural characteristics such as shape of quartz grains, degree of parallel orientation of clay-mineral particles, silicification, etc.

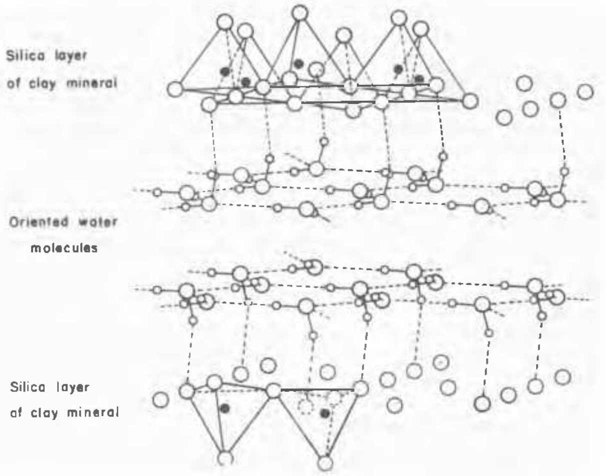
Not all of these factors apply in any given soil material, and their relative importance is not always the same. Current researches in the writer's laboratory and elsewhere have shown that certain components which may be present in soil materials frequently exert a tremendous influence on properties, even though they are present in very small amounts. The addition or subtraction of such components by weathering processes, groundwater movement, or construction activities can therefore change greatly the properties of soil material.

This paper considers some of these components and offers an explanation of their action on the basis of present concepts of the structure of soil materials. It will serve our purpose best to start with a theory of the structure of soil materials in the plastic condition.

THEORY OF THE STRUCTURE OF SOIL MATERIALS IN THE PLASTIC CONDITION

Water added to dry soil materials is adsorbed by the clay minerals and perhaps some other components. The important clay minerals are made up of flake-shaped units that occur both as unit flakes and as aggregates of book-like masses of flakes 4). Much of the water is adsorbed on the basal plane surfaces of such units.

Hendricks and Jefferson 7) have suggested that the water molecules have a definite orientation (figure 1) in the first layers adsorbed on the plane surfaces of the clay minerals. The first water molecules are oriented because their configuration fits with that of the oxygen layers in the surface of the clay mineral units. The orientation tends to propagate itself through layers of water some molecules in thickness outward from the surfaces of the clay minerals. Starting with this concept of the structure of the adsorbed water, a satisfactory theory of the structure of soil materials in the plastic state can be evolved.



Schematic sketch of orientation of water molecules absorbed on the basal surfaces of the clay minerals. Large circles represent oxygen atoms; small circles hydrogen atoms; small black or shaded circles silicon atoms (after Hendricks and Jefferson).

FIG.1

A mass or sheet of oriented water molecules would be rigid like ice rather than fluid, and therefore the initial adsorbed water would not be fluid. But as larger amounts of water are added to dry clay, the layers of oriented water molecules become thicker and thicker. Because the force orienting the water molecules is the structure of the surface of the clay minerals, it is not reasonable that oriented water would grow to an indefinite thickness on the clay mineral surfaces. Further the presence of adsorbed ions and molecules on the clay mineral surfaces would tend to restrict the growth of the oriented water. Therefore, at some distance from the clay mineral surfaces, the water molecules would not be oriented, that is, they would be fluid. xa)

Oriented water would develop from about

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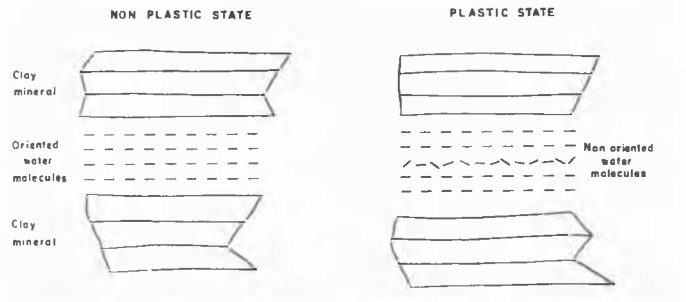
xa) A residual partial orientation of water, of course, exists in liquid water. 12) all basal plane surfaces of the clay minerals and the rigid adsorbed water of one surface would meet that of another surface. The rigid water would serve as a bond to hold the clay mineral units rigidly in place. With increasing amounts of water the adsorbed layers would become thicker until a thickness was reached at which orientation was nil or imperfect. Such water, having fluid properties, could act as a lubricant between the flakes. According to this concept, the plastic condition develops in a clay-water system when there is enough water to supply all the rigid water that can develop on available surfaces <u>and a little more water</u> that has poor or no <u>orientation to act as a</u> lubricant between flakes (figure 2). Large amounts of additional water provide much fluid water and give the system the properties of a fluid.



Schematic presentation of character of water in nonplastic and plastic state.

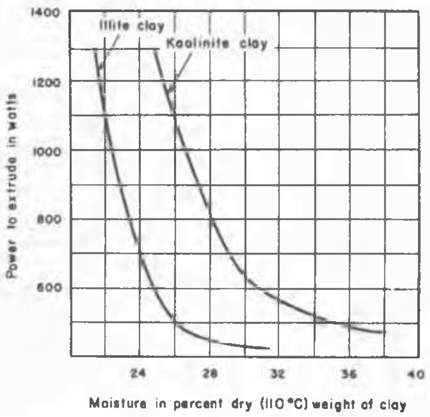
FIG.2

In soil materials the transition from oriented to nonoriented water molecules (that is, from rigid to fluid water), may be abrupt or somewhat gradual, but usually it is rather abrupt. If this is true there should be a sharp break in the plastic properties at a given moisture content when increasing amounts of water are added to a dry soil material. Experimental data (figures 3 and 4) show this. Figure 3 shows that there is an abrupt reduction in power required to extrude clay through a die when a certain moisture content is reached. Extrusion is exceedingly difficult until some fluid water is present. Curves that show compression strength of sand-clay-water mixtures in figure 4 show that maximum strength is developed within extremely narrow moisture limits which probably correspond to the maximum amount of rigid water that can be adsorbed. Additional amounts of adsorbed water are at least partially unoriented with attendant large decrease in compressive strength.

A time factor may be involved in the development of some plastic properties. For example, the compressive strength of some sand-clay-water mixtures increases gradually within short periods of time in compacted masses. 5) The explanation is that a certain amount of time is required for the water molecules to become oriented completely.

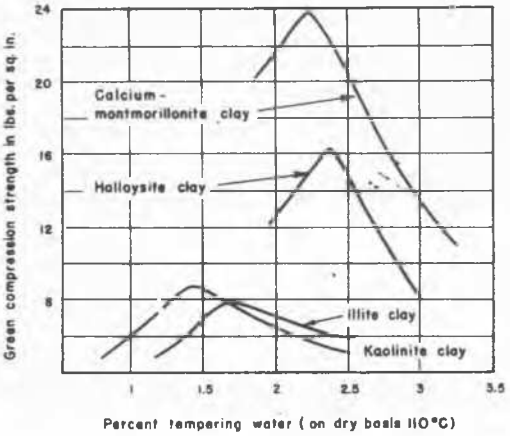
EFFECT OF MINOR AMOUNTS OF CERTAIN COMPONENTS ON THE PROPERTIES OF SOIL-WATER SYSTEMS

Extremely small amounts of certain chemicals have a tremendous influence on the properties of soil materials. This has been known for some time but the explanation has been obscure. An example is the large change in viscosity of sodium montmorillonite-water slurries caused by the addition of traces of sodium hexametaphosphate 13) (table 1).



Relation of tempering water in clay and the ower necessary to extrude clays through an auger machine.

FIG.3



Relation of compression strength to tempering water of sand-clay mixtures containing 6 percent clay.

FIG.4

Table 1 - Effect of $(NaPO_3)_6$ on viscosity of sodium montmorillonite-water suspensions

	$(NaPO_3)_6$ percent	Viscosity in centipoises
Sodium montmorillonite 8 percent water "slurry"		48
	0.2	23
	0.4	18

Not all the components which can have such an effect are known, but in addition to phosphates small amounts of magnesium and boron are known to alter clay-bonding properties. Small amounts of sodium, hydrogen, and aluminum as exchangeable bases greatly alter certain plastic properties.

Table 2 presents Atterberg Limits for natural clays 14) and for some clays treated with various chemicals. The latter data are preliminary and were obtained in a detailed study underway in the writer's laboratory. The data show the tremendous effect of the Na^+ ion in montmorillonite clays as compared to that of Ca^{++} or H^+, and the large effect of some chemicals on the "Limits" of Na-montmorillonite. The precise effects of the treating agents on illite and kaolinite remains to be determined, but the present data indicate that it is small.

This is to be expected since the "Limits" for these natural clays are low and the exchange capacity for illite and kaolinite are also low (20-40 and 3-15 respectively).

A satisfactory explanation for the action of most of these components is that they influence the orientation of the adsorbed water molecules. The influence may be in the perfection of the orientation, the thickness to which good orientation can develop, or the abruptness of the transition from oriented to nonoriented water.

In the case of phosphates, the configuration of the phosphate unit 1) is such that it would about fit into the configuration of the water molecules. The phosphate itself tends to leave a donor surface so that any water associated with it would not tend to fit into the oriented water associated with the clay surfaces. The result would be to disrupt the orientation of the water molecules without completely destroying it and thereby to increase the fluidity of the water between flakes which in turn would reduce viscosity.

In the case of small amounts of exchangeable sodium, for some reason not completely understood, the exchangeable Na$^+$ favors the development of thick layers of oriented water with gradual transition to nonoriented water. In sodium montmorillonites good orientation may extend through at least 100 molecular layers. When calcium is the exchangeable ion the oriented water hull is very thin (a few molecular layers) and the transition to nonoriented water molecules is abrupt 5). Calcium is the most frequent exchangeable base in soil materials, hence an abrupt transition of character of adsorbed water and resulting properties is usually encountered.

The application of the foregoing to engineering problems is clear. If one is dealing with a soil material with a moisture content about equal to that which can be held in a rigid form, any change in either amount of water or in chemical component might cause a tremendous effect on the properties of the soil. In general terms, it appears that soil materials and their environments are in equilibrium, but even slight changes may destroy the balance causing great changes of properties. For instance, equilibrium would be destroyed by changes in amount or movement of groundwater, and by changes in the amount of adsorbed Ca^{++} that would follow construction using portland cement in a soil material originally containing Na$^+$. The possibility of tremendous effects on the properties of soil materials adjacent to concrete structures because of base-exchange provided by the concrete itself appears to have been over looked.

INFLUENCE OF CLAY MINERALS

The plastic properties of soil materials are largely determined by the kind of clay minerals that compose them, 3) and White 14) has recently carefully measured the Atterberg Limits of pure clay-mineral samples (table 2).

TABLE 2

Atterberg Limits

Materials studied	Plastic Limit				Liquid Limit				Plastic Index			
	Untreated	H_3PO_4 x)	H_2SO_4 x)	$Na_6(PO_3)_6$ x)	Untreated	H_3PO_4	H_2SO_4	$Na_6(PO_3)_6$	Untreated	H_3PO_4	H_2SO_4	$Na_6(PO_3)_6$
Montmorillonite												
1. Na$^+$ exchangeable base Wyoming	97	54	50	48	700	340	250	395	603	286	200	347
2. Ca^{++} exchangeable base Arizona	72	63	77		124	119	142		52	56	65	
3. Ca^{++}H$^+$ exchangeable base Mississippi	82				118				36			
Illite												
4. LaSalle County, Ill.	25	23	26	21	36	35	36	31	11	12	10	10
5. Vermilion County, Ill.	24				29				5			
Kaolinite												
6. Georgia	30				35				5			
7. Union County, Ill.	37	35	32		58	68	68		21	33	36	
Natural mixtures												
8. Illite plus 10% montmorillonite Greene County, Ill.	26	27	28	25	58	52	61	48	32	25	33	23
9. Illite plus 5% montmorillonite Grundy County, Ill.	36	34	35		61	61	62		25	27	27	
10. Kaolinite plus 10% montmorillonite Georgia	33	31	31	39	65	65	74	67	32	34	43	28

x) Chemical added to tempering water in such quantity that the acid radical equalled the base-exchange capacity.

The Atterberg Limits of Kaolinite and illite are roughly the same. Sample 7 is relatively finer grained than sample 6 indicating the order of magnitude of the increase in the "Limits", particularly the Liquid Limit, as the particle size of kaolinite or illite decreases.

The Plastic Limit for montmorillonite is about three times that of kaolinite or illite. The Liquid Limit for montmorillonites carrying Ca^{++} and/or H^{+} is about three to four times that of the other clay minerals, whereas that of Na^{+} montmorillonite is five to six times that of the Ca^{++} or H^{+} montmorillonite and as much as twenty times that of kaolinite or illite. Clearly montmorillonite is the component, particularly when Na is present, with the tremendous plastic properties.

Samples 8 and 9 (table 2) contain 5 to 10 percent montmorillonite in addition to illite. Sample 10 contains 10 percent montmorillonite in addition to kaolinite. The presence of montmorillonite causes little change in the Plastic Limit, but increases the Liquid Limit about twofold so that the Plastic Index is increased four to six times by only 5 percent montmorillonite.

Montmorillonite has a peculiar lattice structure 9) which permits water to penetrate between the individual unit layers about 9.5Å thick, thereby separating them. The separation can be substantially complete in the presence of considerable amounts of water, particularly when sodium is the exchangeable base. Both basal plane surfaces of the montmorillonite units are composed of oxygens so arranged as to foster the growth of oriented water molecules. In addition montmorillonite has high base-exchange capacity (about 100 milliequivalents per 100 grams) so that montmorillonite surfaces are apt to carry adsorbed ions that favor the adsorption of water. The high plastic properties of soil materials composed of montmorillonite are due to its property of breaking down into exceedingly small flake-shape units with a consequent tremendous surface with particular ability to adsorb water.

Where soil materials are composed of a mixture of montmorillonite and other clay minerals, the components may be present either as mixtures of discrete aggregate particles of the individual clay minerals or as very intimate interlayerings of one or a few unit layers of montmorillonite with several unit layers of the other clay minerals. In the former case the effect on properties is about proportional to the amount of montmorillonite present. In the latter case, the effect is much greater as shown in table 2. The explanation is as follows: Illite and kaolinite occur in soil materials in aggregate particles which do not come apart into much smaller units in the presence of water. If, however, layers of montmorillonite are interspersed through the kaolinite or illite aggregates, the montmorillonite forms planes of weakness along which the aggregates can break up in the presence of water. Obviously, under such conditions, relatively few such planes would cause relatively great breaking up of the clay mineral particles with attendant great increase in plastic properties.

ORGANIC MATERIAL IN SOILS

Organic material can be present in soils in two forms: (a) as discrete particles such as fragments of wood, bits of leaves, spores, etc., and (b) as exceedingly fine material that is in the colloidal or molecular state.

It has long been known that organic material, particularly in the colloidal form, can increase the plastic properties of clay. The exact nature of the organic material in soils is still not known, but recent work in several laboratories has provided basic data on the adsorption of organic molecules by the clay minerals. The finings go a long way in explaining the manner in which organic material is present in soils and its influence on soil properties.

Gieseking 2) and later Hendricks 8) showed that some organic molecules were adsorbed on the basal plane surfaces of the montmorillonite clay mineral units, that is on the same surfaces that adsorb water. MacEwan 11) investigating the kind of organics adsorbed, has shown that those with polar groups are favored and that both montmorillonite and halloysite may adsorb organics between the unit cells. Grim, Allaway, and Cuthbert 6) have shown that the clay minerals illite and kaolinite also have some adsorption capacity for organics.

Since the organic molecules are adsorbed on the same surfaces that can adsorb water, a decrease or elimination of water adsorbing capacity would be an expected result of the adsorption of organics. This has been found to be true 6) 8) and is one of the effects on soil properties of the adsorbed organics.

Jordan 10) has recently shown that certain clay minerals, notably montmorillonite, when carrying adsorbed organic molecules of particular kinds are organophilic toward other organics. Such clay mineral-organic complexes do not swell in water, but they do swell tremendously in the presence of suitable organic liquids forming gels. Such gels are very stable, show almost no air-drying, and have very low bearing power. Organic-clay mineral complexes are undoubtedly to be found in nature. Swamps, bogs, and slough fillings would be probable places, and soils containing them would have striking and unusual properties.

SUMMARY AND CONCLUSIONS

A theory of the structure of soil materials in the plastic state is presented that is based on the oriented configuration of the water molecules initially adsorbed by the clay mineral components of such materials. It is shown that the plastic properties, particularly the Atterberg Limits, may very greatly because of the presence of small amounts of certain chemical components, and an explanation is offered based on the effect of such components on the orientation of the water molecules.

It is shown that relatively small amounts of montmorillonite may cause a relatively great increase in the plastic properties of soil materials. The structure of montmorillonite is such that when it is interlayered with other clay minerals, it forms planes of weakness that permit relatively great break-down of the clay mineral particles with attendant great increases in plasticity.

Certain kinds of organic molecules and some clay mineral may form gels. Such components probably explain the unusual and extreme properties in some peculiar soil materials.

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THERMAL CONDUCTIVITY OF SOIL

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SUMMARY.

Thermal conductivity tests have been conducted on fourteen different soils at a wide range of densities, moisture contents, and mean temperatures. The effect of the various factors upon the thermal conductivity is discussed. In general, it is found that the thermal conductivity of soil varies in the following ways:

1. Above freesing, increases for an increase in mean temperature;
2. Below freezing, shows very little change;
3. From below to above freezing, varies according to the moisture content;
4. At a constant density, increases with an increase in moisture content;
5. At a constant moisture content, increases with an increase in density;
6. Is dependent upon the grading and particle shape of the soil;
7. Differs appreciably with respect to different soil minerals.

INTRODUCTION.

During the past two years a research program for determining the thermal conductivity of soil has been in progress at the Engineering Experiment Station of the University of Minnesota. This work has been sponsored by the Corps of Engineers, Department of the Army, as a part of their research study of construction problems in regions of permafrost, or permanently frozen ground.

The purpose of the study was to determine the effect of such items as temperature, density, moisture content, and mineral composition upon the thermal conductivity of soil, as well as to obtain coefficients of conductivity of soils from test installations in Arctic regions. The data serve as a basis for predicting thermal conductivities of other soils.

The tests were made with apparatus designed and built for the investigation at the University 1). The soil was packed into the tubular soil container of this apparatus at various densities and moisture contents, the densities varying from that obtained by loose pouring to the modified maximum density obtained by heavy ramming 2) and the moisture contents varying from air-dry to a few per cent above the optimum moisture content. Tests were made at mean temperatures ranging from 70 to -20° F.

The units used in this report are as follows:

Thermal conductivity, k, represents the amount of heat expressed in British thermal units transmitted per hour through one square foot of soil one inch thick with a 1° F temperature difference between the two surfaces;

All temperatures are Fahrenheit;

Density is the weight of dry soil in pounds per cubic foot;

Moisture content is expressed as a percentage of the dry weight of the soil.

The thermal conductivity tests were made with a temperature differential of 10° between the hot and cold faces. A test with a hot temperature of 75° and a cold temperature of 65° is reported as having a mean of 70°; a test with 45 and 35 is reported as having a mean of 40°, etc.