RELATION OF FROST ACTION TO THE CLAY-MINERAL COMPOSITION OF SOIL MATERIALS

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Within the last 25 years the occurrences and properties of the clay-mineral components of soil materials and the characteristics of clay-mineral-water systems have been the subject of many researches. It is the object of the present paper to analyze the data and concepts that have come out of recent clay-mineral researches that are pertinent to the matter of frost action and frost heaving.

Factors Involved in Frost Action

There are two factors regarding frost action in clay materials particularly pertinent to a consideration of the influence of the clay minerals:

1. Taber (1) has shown that frost heaving is due to the growth of ice crystals rather than to a volume change accompanying a change in state. An increase in the size of ice crystals requires that the growing crystal be fed by a supply of water, i. e., there must be movement of water through the soil material. On freezing, soil material frequently shows segregation of ice masses into layers which require movement of water to the point of segregation.
2. Very fine colloid-sized clay materials show very little or no segregation of ice on freezing (1). Further it is well known that certain clays, e. g., some of the bentonites from Wyoming, are substantially impervious to water movement. Students of agricultural soils have shown that a certain percentage of water held by soils does not freeze at moderately low temperatures (2). Those and other considerations suggest that water held in soil pores of all sizes and in soils of all kinds may not all have the same characteristics. Water directly adjacent to an adsorption surface, e. g., a clay-mineral surface, in a soil is likely to be in a different physical state than the water in the center of a fairly large pore.

Winterkorn (3) has attempted to summarize ideas on the character of a pore water in soil material:

"Directly adjacent to the adsorbing soil solidly adsorbed water is to be found, the center of a pore space is occupied by ordinary water, freezing at about 0 C., and between the ordinary water and the solidly adsorbed water there is a zone of liquid water possessing a melting point down to -22 C. which serves as a passageway for the conduction of water to freezing centers."

Composition of Soil Materials

It is generally agreed by almost all students of soils that most soil materials are composed essentially of extremely small, usually colloid-sized, crystalline particles of one or more minerals that have been called "clay minerals" (4). Some clay minerals are equidimensional and flake-shaped, others are elongate and lath- or needle-shaped, and some seem to be tubular. The clay mineral composition is the major factor controlling the properties of most soils. The surface of the clay minerals provides the major adsorption surface in soil materials, and the adsorption characteristics towards water and various ions and organic molecules vary for the different clay minerals.

Montmorillonite Soils

It is preferable to begin an analysis of the relation of clay-mineral composition to frost action by considering a soil composed solely of montmorillonite. In montmorillonite, adsorption water penetrates between the individual molecular layers, and as a consequence such material has tremendous adsoption surface and enormous water-

TABLE 1

CLAY MINERALS

Kaolinite	$(OH)_8Si_4Al_4O_{10}$
Halloysite - high hydrate form	$(OH)_8Si_4Al_4O_{10}\cdot 2H_2O$
low hydrate form	$(OH)_8Si_4Al_4O_{10}$
Montmorillonite	$(OH)_4Si_8Al_4O_{20}\cdot xH_2O$ *
Illite - muscovite type	$(OH)_4K_y(Si_{8-y}\cdot Al_y)(Mg_4\cdot Al_4\cdot Fe_4)O_{20}$
biotite type	$(OH)_4K_y(Si_{8-y}\cdot Al_y)(Mg\cdot Fe)_6O_{20}$
Vermiculite	$(OH)_4(Si\cdot Al)_8(Mg\cdot Fe)_6O_{20}\cdot 4H_2O$
Chlorite	$(OH)_4(Si\cdot Al)_8(Mg\cdot Fe)_6O_{20}\cdot(OH)_{12}Mg_6$
Attapulgite-Palygorskite **	

* In montmorillonite some magnesium always replaces aluminum, and the replacement may be substantially complete. Iron in varying amounts may also replace the aluminum.

** The attapulgite-palygorskite clay minerals are not well known and no general formula can yet be written for the group. The minerals are hydrous magnesium silicates, with some replacement of magnesium by aluminum and with a hornblende-type crystal structure.

adsorption capacity. The theoretical total adsorption surface of montmorillonite is computed as 800 sq. m. per gram.

Hendricks and Jefferson (5) have presented structural evidence that the water molecules adsorbed on montmorillonite surfaces show a crystalline configuration and have suggested a concept of the actual configuration, which is reproduced in Figure 1. MacKenzie (6), and Barshad (7), while agreeing that the initially adsorbed water shows a definite configuration, have presented alternative concepts of the actual structure to the one suggested by Hendricks and Jefferson. In montmorillonite, all the basal plane surfaces, which provide almost all the surface area, possess structural characteristics which seem to favor particularly the development of a crystalline configuration in the water molecules immediately adjacent to it.

There seems to be little doubt that the water adsorbed on the surface of montmorillonite particles would consist of water molecules in a definite pattern and, therefore, the water would not be fluid or mobile. Grim (8) has presented an analysis of certain properties of clay-water mixtures which provided convincing evidence that the water initially adsorbed is rigid rather than mobile or fluid and that at varying distances from the adsorbed surface the rigid water changes to liquid water. Figure 2 presents a diagrammatic sketch of the condition of the water in the plastic and nonplastic states.

Montmorillonite has high adsorption capacity for certain cations, anions, and organic molecules. In ordinary soils the usual adsorbed cations (exchangeable bases) are alkaline earths, alkalies, and/or hydrogen, and it can be computed on the basis of cation-exchange capacity that an adsorbed cation is present for about every 140 sq. Angstrom units of total surface. The adsorbed ions are held on the adsorbing water surfaces. The tremendously significant fact is that the character of the adsorbed ion to a very considerable extent controls the perfection of orientation of the water mole-

cules and the thickness of the water layers, showing a definite configuration, and as a consequence exerts an enormous influence on the properties of clay-water systems (8).

In montmorillonite carrying sodium as the adsorbed ion, water can enter easily between all the unit layers, and in the presence of an abundance of water, adsorbed water layers with a definite configuration of water molecules can build up to great thicknesses (probably with thicknesses of the order of at least 100 Angstrom units). Thus even in the presence of large amounts of water in which the water content would be in excess of the clay-mineral content, there would be no fluid water. Such clays are, therefore, substantially impervious, and on freezing there is little or no concentration of ice in layers.

In montmorillonite carrying calcium, magnesium, or hydrogen as the exchangeable ion, the situation would be quite different than for a sodium montmorillonite. When the alkaline earths or hydrogen are present as adsorbed ions, water enters between the unit layers with some difficulty, and forms relatively thin layers of rigid adsorbed water. In such clays, water present beyond a certain relatively small amount (about 40 percent of the dry clay), in comparison with Na+ montmorillonite clay, is fluid. In such clays, therefore, concentration of ice in layers may develop on freezing only if the moisture content is fairly high.

In montmorillonite clays containing potassium, there is very little adsorption of water with a definite configuration. Therefore, in the presence of even small amounts of water, some fluid water would be present.

It should be emphasized that the adsorbed ions are exchangeable, and therefore a

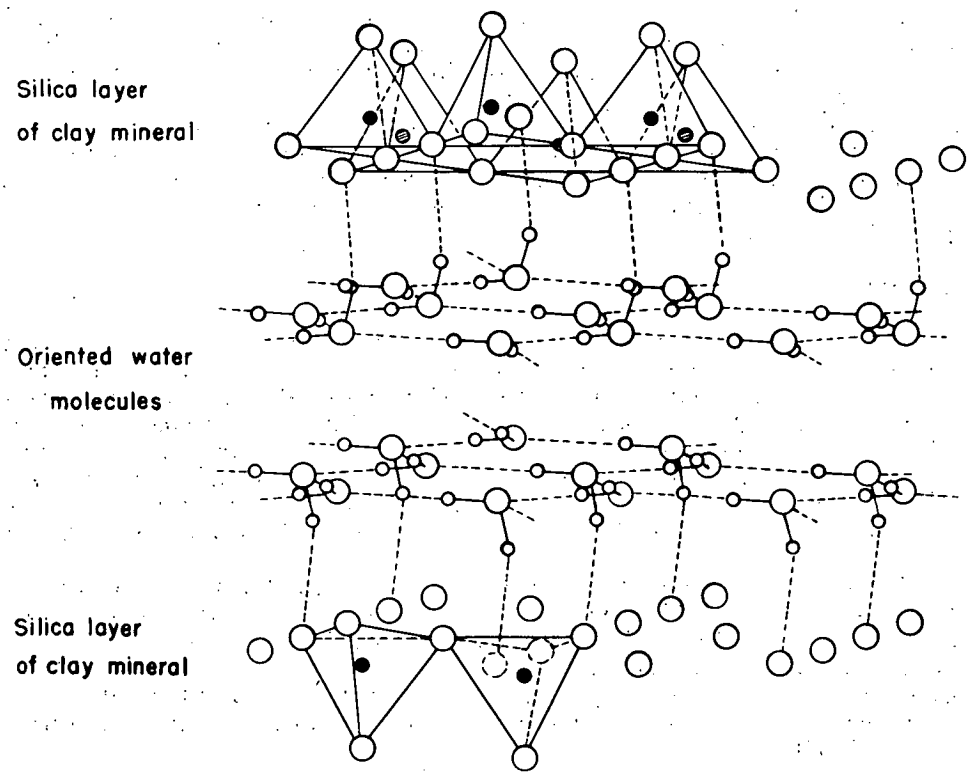

Figure 1. Configuration Proposed by Hendricks and Jefferson of the Water Adsorbed Directly Adjacent to Basal Plane Surfaces of Montmorillonite.

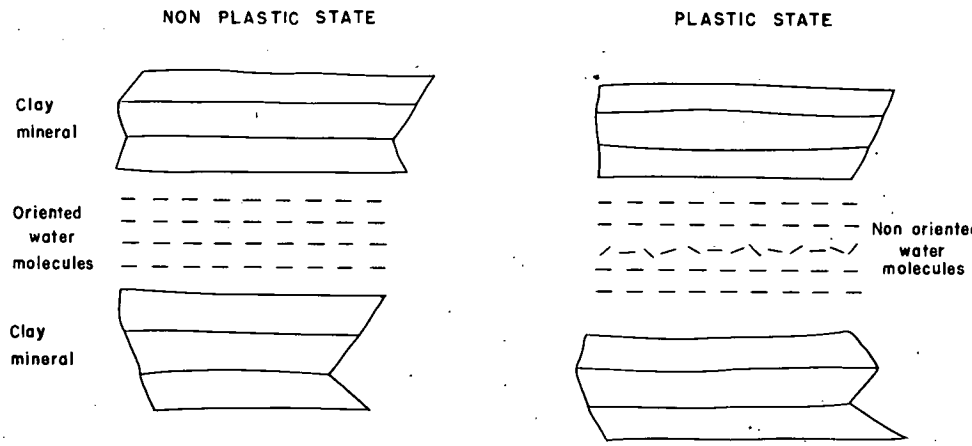

Figure 2. Diagrammatic Sketch of the Character of the Water in the Plastic and Non-Plastic States.

soil composed of Na+ montmorillonite could have its properties changed greatly by replacing the Na+ with Ca++. Such an exchange can be carried out by suitable treatment or may take place, sometimes unexpectedly, during manipulation of a soil in the process of construction, by a change of groundwater circulation, emplacement of masses of concrete, and perhaps for other reasons.

Montmorillonite also will adsorb certain organic molecules, particularly those that have high polarity (9); such organic molecules are held on the water adsorbing surfaces. The presence of these organic molecules destroys the water-adsorbing power of the montmorillonite so that no water with a definite configuration develops on the clay mineral surfaces.

Kaolinite Soils

In soil materials composed of kaolinite, the kaolinite particles occur in relatively large units, 100 to 1000 times the size of the montmorillonite units in a montmorillonite soil, and consequently the surface area is relatively small. Because of the nature of the crystalline structure of kaolinite, only about half the total surface seems particularly likely to develop adsorbed water with a definite configuration, i. e., rigid water. It may therefore be concluded that at even relatively small water contents kaolinite soils would contain some fluid water. Kaolinite soils therefore are not particularly impervious, and should readily show a concentration of water in ice layers on freezing.

Kaolinite has relatively low ion exchange capacity, about 10 percent of that of montmorillonite. Because of the small capacity to hold ions of various kinds, the characteristics of kaolinite soils are much less influenced by variations in the kind of cations present than are montmorillonite soils.

Only small amounts of organic molecules can be expected to be adsorbed by kaolinite soils. However, the effect of the adsorbed organics would be the same as that noted for montmorillonite soils.

Illite Soils

Many soil materials are primarily composed of the mica type of clay minerals like

illite and chlorite. The characteristics of such soils range between those of kaolinite soils and montmorillonite soils but usually are closer to the former than the latter. Illite soils contain adsorption surfaces of the same order of magnitude as kaolinite soils; however, in illite all the adsorption surface (rather than half as in kaolinite) has a structure configuration likely to foster the development of orientation in adjacent water molecules. Somewhat more adsorbed water would be immobilized in illite clays than in kaolinite clays, but the total quantity would still be relatively small, and at relatively low water content illite clays would be expected to contain fluid water. Illite clays are not impervious and should show readily the concentration of water in ice layers on freezing.

Soil materials composed of illite and chlorite clay-minerals have an ion exchange capacity about 2 to 5 times that of kaolinite soils but still only about 1/4 to 1/2 that of montmorillonite soils. The influence of various cations would be expected to be less than that for montmorillonite but considerably more than that for kaolinite. The influence of the particular cations would be the same as that stated for the previous soils.

Many illite soils contain small amounts of montmorillonite interlaminated with the illite layers. It has been pointed out previously (8) that small amounts of such montmorillonite can have an effect on physical properties out of all proportion to the amount actually present. This conclusion should also apply to frost action. A small amount of montmorillonite would greatly increase the amount of water immobilized, particularly if adsorbed sodium ions were present and as a consequence increase the imperviousness and decrease the tendency for water to concentrate in ice layers on freezing.

Halloysite Soils

Recent investigations by the author (10) have shown that halloysite soils are likely to have unusual and troublesome properties for the engineer. However, because of structural similarities to kaolinite so far as frost action is concerned, halloysite soils should act similarly to kaolinite soils.

Vermiculite Soils

Soils containing vermiculite are not yet known to be very common. Vermiculite appears to have somewhat similar water adsorbing properties to those of calcium montmorillonite. It has about the same ion-exchange capacity as montmorillonite, and therefore, vermiculite soils would be expected to react to freezing similarly to calcium montmorillonite soils.

Attapulgite-palygorskite Soils

Soils composed of these clay minerals appear to be relatively rare. It is noteworthy that the present known occurrences seem to be limited to dry areas of high temperature where frost action would not be encountered. The scant data regarding the structure and properties of these minerals permit only the tentative suggestion that soils containing them would act like montmorillonite soils except insofar as the influence of adsorbed cations is concerned. Clay water systems of these clay minerals show considerably less variation because of cation variation than do montmorillonite soils.

Influence of Salts added to Soils

Salts added to soils may produce cations which will be adsorbed by the clay minerals or cause base-exchange reactions with resulting effects, such as previously described. Salts added in large quantities than required for adsorption, or of a kind or under conditions where there is no ion exchange reaction, may act otherwise on frost properties. It is not the purpose of the present paper to analyze the effect of such added salts, but

it is obvious that one of the effects of some such salts may be to hydrate. On hydration the salt would develop a hydration structure, which in effect would immobilize the water involved in the hydration. An effect of the addition of the salt is, therefore, to tie up some water in an immobile form.

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ICE-BLOCKED DRAINAGE AS A PRINCIPAL FACTOR IN FROST HEAVE, SLUMP, AND SOLIFLUCTION

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Synopsis

Frost heave is caused by the freezing expansion of excess water accumulation either in the active zone above permafrost, or in the "vernal active zone" above the horizon of winter frozen ground. Normal gravitational drainage is blocked by an impervious ice horizon below the active zone. Water from melted snow cover, rain, and low evaporative rate in cool weather causes the soil of the active zone to become saturated; and as the excess accumulates, it increases the hydrostatic head. Expansive action of diurnal freezing in the active zone deforms the soils and permits formation of pockets, lenses, and layers which refill with free water or ice. The thicker these free-water layers become the greater becomes the expansive or frost heave force, disrupting the active soils above them. Frost heave under highways is intensified because winter freezing is abnormally deep due both to high conductivity of pavement and diurnal ("vernal active zone") activity. It is also more violent because of deep thawing due to solar heating of the pavement in daytime and unrestricted radiant cooling at night which results in rapid and deep freezing. Ice horizons may also block drainage and create water accumulation troughs. Control measures must either insulate pavement areas to neutralize these anomalies, or must provide positive drainage.

In sloping land, water accumulates at the base of the active zone, lying on the impermeable frozen layers which, of course, may also slope. Grav-