Importance of Water in Formation of Soil Structure

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Introductory Remarks by the Chairman

Modern science is based on observation either of naturally occurring phenomena or under the controlled conditions of the experiment. Interestingly, the French word for experiment is the same as for experience. The first step in natural science is to determine the "how" by observation; then follows the second step of finding out the "why," and of establishing a logical theoretical system that allows prediction of natural phenomena as functions of pertinent factors. Czeratzki and Frese have greatly enriched this symposium by careful and ingenious photographic studies of the morphology of soil structure formation as a result of wetting and drying and of freezing and thawing of moist soil systems. The mechanisms of soil structure formation, so beautifully demonstrated by the work of these authors, can be easily tied to physico-chemical and geometric factors brought out by other contributors to this symposium. As a matter of fact, these morphological studies aid in the recognition of those of the numerous physico-chemical factors involved that are the most significant with respect to the actual behavior of natural soils and of those that play only secondary and lesser roles. Giving morphology its just due in this area of interest, it is not amiss to do the same to some of the great morphologists to whom this science is deeply indebted, but whose names are largely unknown to the present engineering generation. First, should be mentioned D'Arcy Wentworth Thompson, the father of Biophysics and his magnum opus "On Growth and Form." With respect to the morphology of natural ice formations, honors are justly due to Elliot (1827), Herschel (1833), Le Conte (1850), von Mohl (1860) and Sachs (1860-61). May we learn again the art of observation which these men possessed and may we utilize to the utmost the newer, better and easier means of recording.

● THE SIGNIFICANCE of soil structure for the growth of plants and proper development of animal life in soil and also for many problems of soil and hydraulic engineering gives special importance to the problem of the causes and mechanism of structure formation. In view of the numerous factors involved and their mutual interrelations which often can be discerned only with difficulty, it is indicated to treat this problem in separate parts. Accordingly, this contribution is limited to the presentation of phenomena that in the formation of soil structure can be observed with the unaided eye.

In these dimensions, the soil structure may appear as coherent, that is, without specific structural units that are separated from each other, or it may be subdivided into individual structural units or elements. The latter are called aggregates. However, this name is correct only in the case that primary soil particles are aggregated to form a larger unit. In macroscopic dimensions, this aggregation differs from flocculation insofar as it is the result of fragmentation and splitting of a coherent soil mass rather than due to primary particles approaching each other closely and subsequently sticking together. Such a phenomenon can be caused essentially only by forces that act on the soil from the outside. The respective forces can originate from human activity in soil cultivation, from the boring and digging of soil animals, from the root activity of plants and from metereological influences. In a cultivated soil, the above named factors act independently and with varied intensities. They aid each other in structure formation, but they may also destroy structure formed by other factors. Most of the soil animals and also the plant roots affect soil structure favorably; on the other hand, human activity, depending on the cultivation system, chosen mainly from economical considerations, may destroy or improve soil structure.

Of widely varying importance for the soil structure is the climate since it is composed of factors that act in markedly different ways. Neglecting the extremes of wind and water erosion, which usually destroy the soil itself, and considering only the phenomena taking place in the much milder processes of structure formation, the following main climatic factors are found: temperature, precipitation and evaporation. The importance of these factors with respect to soil structure derives from their effect on the amount and condition of soil water. The main effect of temperature on soil water is the change of its physical state. Since in this presentation the change of water from liquid to vapor is included in the evaporation factor, the treatment of the temperature effect shall be restricted to change of soil water to ice and vice versa, as in freezing and thawing. Precipitation and evaporation increase or decrease the water content; hence, they are two important counter-players in the water economy of the soil.

The changes in amount and condition of soil water caused by the continuous change of the climate or meteorological factors influence the structure of soils susceptible to these factors. They are the cause of a more or less well marked dynamics of soil structure, understanding of which is of great importance in soil research. This dynamics of structure formation leads to a better explanation of morphological phenomena in soils, which latter permit the drawing of conclusions with respect to the physical properties of soils. Knowledge of the dynamics of soil structure is also an important basis for agricultural research, especially with regard to tillage operations. Soil structure obtained by working with agricultural implements is closely related to the structure formed naturally in the soil; hence, understanding of soil structure dynamics is an essential prerequisite for rational soil working, especially under difficult circumstances. Of course, economic reasons limit the cultivator to enter actively in the interplay of these relationships. As a rule, he must try to adapt his measures to the natural phenomena in the soil in a manner that the effect on the soil structure of his own efforts is aided by the action of the natural forces. Even though the dynamics of the structure of a given soil is markedly determined by meteorological and climatic influences, it is of great importance that the soil be worked in a suitable manner and that a large specific soil surface is brought into direct contact with the atmosphere.

PROBLEMS POSED AND METHODS EMPLOYED

The investigation of dynamic phenomena in soils is difficult, because of their relatively slow rate. With conventional methods of investigation, the difficulties can be overcome only when longer time intervals between observations do not affect the results in an essential manner. However, in cases in which intensity as well as direction of the reaction are subject to frequent changes, single observations at extended time intervals give unsatisfactory results and may even lead to contradictory conclusions. This is true for the phenomena of structure formation under consideration. Fortunately, they occur in macroscopic dimensions and can be recorded photographically. For this, fixation by means of single pictures is not always sufficient. While it makes possible diagrammatic presentation of structural changes as a function of time, it suffers from the disadvantage that the dynamic features of the phenomena cannot be shown in their continuity as is possible with moving pictures. Moving pictures possess the advantage that they can be run off as often as desired and that by repeated viewing, details can be discovered which often remain hidden in still pictures, because they cannot betray themselves by motion. These advantages of motion pictures can be utilized by means of fast or slow action photography even for phenomena whose rate of change as in the present case lies outside of the detection range of the human eye. Numerous investigations have been reported concerning the effect on soil structure of changes in moisture content. They show that this effect is bound to swelling and shrinkage phenomena. Haines (8) made the important observation in his swelling and shrinkage studies that in re-wetting the soil increases its volume beyond that of the original moist soil. This shows that a loosening of the soil has taken place during the experiment. Of special importance for the soil structure is, according to many authors (10, 15), the behavior of the soil air during the moistening process. Since water is more strongly absorbed by soil than air, the latter is pushed out during the moistening process. However, often air becomes occluded at elevated pressures in pores that have not yet been moistened and explodes the soil when its pressure exceeds the cohesion of the soil particles.

Figure 1. Layered edge structure of a soil clod after repeated wetting and drying.

It is known that a clay soil develops cracks in shrinking, especially in vertical direction, which subdivide it often into relatively large clods. In addition to this rough fissuration, a considerable number of smaller aggregates is observed in places especially exposed to weathering action which must be attributed to the same causes as the formation of the coarse fragments (Fig. 1). Aggregate formation as a result of swelling and shrinking due to meteorological influences occurs, therefore, in several orders of magnitude; differentiation is impossible without a further analysis of the involved processes. In the investigations reported so far, little consideration has been given to the formation of aggregates by swelling and shrinkage phenomena. Also, little information is found concerning the shape of the resulting aggregates. In view of the importance ascribed to the aggregate shape with respect to the macro-morphology and the physical properties of soils, there exists a definite need for obtaining additional facts that bear on this important question. This is especially evident from the large number of attempts to make the aggregate shapes the starting point of visual methods for judging the physical condition of agricultural soils and to use them for following and checking the effects of certain methods of cultivation (12).

For the reasons given above, the usual methods for swelling and shrinkage investigations, such as determination of linear expansion on test specimens, were abandoned; in their place cinematographic methods with time compression were used. This method combines the advantages of moving pictures with the possibility of evaluation by measurement.

STUDY OF THE FORMATION OF AGGREGATES AS A RESULT OF ALTERNATE MOISTENING AND DRYING BY MEANS OF MOVING PICTURES[1]

After several preliminary experiments, a soil developed on Opalinus clay of the Brown Jura near Schwäbisch Gmünd (Württemberg) was chosen for this investigation. This soil covers a large area and offers many agricultural difficulties. Because of the large swelling capacity of this soil, a great influence of moisture changes on aggregate formation was expected. Mechanical analysis of the soil gave:

Coarse sand	(2 - 0.2 mm)	= 1.2 percent
Fine sand	(0.2 - 0.02 mm)	= 9.2 percent
Silt	(0.02 - 0.002 mm)	= 36.5 percent
Clay	(<0.002 mm)	= 53.1 percent

The soil was first stirred mechanically with water until its aggregates were destroyed. Subsequently, a brick of 30 cm length, 20 cm width and 4 - 5 cm thickness

[1] The movie was made in cooperation with the "Institut für den wissenschaftlichen Film, Göttingen, (Director: Dr. Ing. G. Wolff, Specialist: Ober-Ing. H. Schladerbusch). It can be obtained from this Institute or from the "Institut für Bodenbearbeitung, Braunschweig-Völkenrode."

Figure 2. Formation of vertical fissures by alternating wetting and drying--after first drying.

Figure 3. Formation of vertical fissures by alternating wetting and drying--after second moistening.

Figure 4. Formation of vertical fissures by alternating wetting and drying--after third drying.

Figure 5. Formation of vertical fissures by alternating wetting and drying--after fourth moistening.

was molded from the tough slip. The alternating wetting and drying of the soil during the taking of the motion pictures was effected by spraying with fine water drops and subsequent drying at 30 to 40 C under a heating lamp. By these means, five wetting and drying sequences of increasing durations were made in the total time of 24 hours. At the first experiment, the movie camera was fixed in a way that it took a picture of 9 by 14 cm of the soil surface viewed at an angle from above. During the wetting period, four pictures were taken per second, during the drying period, one picture was taken per minute. During the first very short moistening, the previously smooth surface of the dry soil becomes rough and coarse-grained. The film shows that one of the causes for this phenomenon is the air replaced by the spray water. The emergence of the air from the soil surface is manifested by the formation and bursting of blisterlike excrescences. The first wetting phase takes only a short time since the soil is not yet able to take in a larger amount of water. In the

Figure 6. Formation of vertical fissures by alternating wetting and drying--after fifth drying.

Figure 7. Angular view of the top surface and of a vertical surface. Depth penetration of vertical fissures and formation of fine horizontal fissures after the second drying.

Figure 8. Angular view of the top surface and of a vertical surface. Depth penetration of vertical fissures and formation of fine horizontal fissures after the fourth drying.

Figure 9. Angular view of the top surface and of a vertical surface. Depth penetration of vertical fissures and formation of fine horizontal fissures after the sixth drying.

subsequent drying phase, a network of fine fissures is formed soon after the start of the drying. These fissures grow in size for a while, but after a short time no further changes are observed. This short shrinking period shows that the water has penetrated the soil only to a very shallow depth during the first moistening phase.

The first moistening and drying sequence shows already the essence of the fundamental phenomena occurring in the later sequences. These phenomena, however, become more marked with increasing number of sequences. This shows the great importance which extended repetition of the wetting and drying sequence has for aggregate formation.

During the second moistening, the soil can take already considerably more water because of the originally open fissures and the rough surface. Already after short spraying, the fissures begin to close while the edges of the fissures swell strongly in contact with the vertically moving water and form scar-like excrescences. In addition to this phenomenon caused by swelling, the movie also shows that very fine micro-aggregates are detached from the surface and carried along by the water. During the next drying, only a portion of the fissures open at the old locations. The following moistening and drying phases become increasingly longer since each time deeper layers are affected by the water. However, the observed phenomena remain the same as previously described. The fissures open and close at the same places and the edges bulge like pock-marks. During the opening of the fissures, jerking movements are observed at some places in the soil. These movements show that, as a result of the increasing fissuration of the soil, the moistening and drying proceed in a non-uniform manner and cause an irregular distribution of capillary tensions. Figures 2 to 6 show the final condition of the soil surface after several wetting and drying sequences.

The moving pictures that have been described so far depict the course of the events in two dimensions only. Since swelling and shrinkage of a soil take place in three dimensions, the camera was placed so that the picture would show both the surface and a plane at a right angle to it. A heavy alluvial valley loam was chosen for this experiment; it had the following grain size composition:

Coarse sand (2 - 0.2 mm) = 0.9 %
Fine sand (0.2 - 0.02 mm) = 27.5 %
Silt (0.02 - 0.002 mm) = 29.5 %
Clay (<0.002 mm) = 42.1 %

Figure 10. Fracture, after termination of movie-taking, with horizontal layers inside the soil.

The moving pictures taken show very impressively the swelling of the soil in vertical direction in addition to the previously described phenomena. During the spraying, the water was added in separate dosages. Hence, the swelling was also discontinuous and gave the impression of seismic movements on the surface which were propagated downward in a wavelike fashion as the water penetrated deeper into the soil. During the succeeding drying phases, the depth progression of the surface fissures can be followed on the vertical face. These fissures run irregularly in a zigzag manner and form lateral branches in their advanced stages of development. In addition to this phenomenon, one observes at a certain time the formation of fine horizontal fissures, the number of which increases slowly with time. They lie closely below each other and form a zone of horizontal layer-structure. Figures 7 to 9 show the progressive formation of vertical and horizontal fissures; Figure 10 shows a fracture-surface at the end of the experiment, and Figure 11 shows crumbling into flake-like aggregates. To be sure, the zone of horizontal layer formation does not reach the full depth of the vertical fissures, but is restricted to a shallow layer. Thus, it seems to represent a form of aggregation typical for the soil surface. This process is of greatest consequence for soil structure, since it creates small aggregates that are important for most physical properties of a soil and which, therefore, must also be present in a soil in which the aggregates have been formed by mechanical breakdown with agricultural implements. In heavy soil in which these fine aggregates can be produced artificially only by means of a large amount of power, this natural process of aggregate formation by wetting and drying is of utmost importance for rational soil cultivation.

THE EFFECT OF FREEZING ON SOIL STRUCTURE

Moving Pictures Investigations

The essential features of the effect of frost on soil structure are known and the morphology of frost structure has been described in numerous publications (2, 3, 7, 9, 11, 13, 14). However, it appears that no observations are available on the course of soil freezing or on the start and development of ice crystal formation immediately at the freezing front. To be sure, the penetration of frost in soil can be recorded photographically by means of suitable experimental arrangement; however, by these means it cannot be reproduced as a rate reaction. It was, therefore, attempted to study and record the freezing of soil using the same cinematographic methods as employed in the case of wetting and drying phenomena.

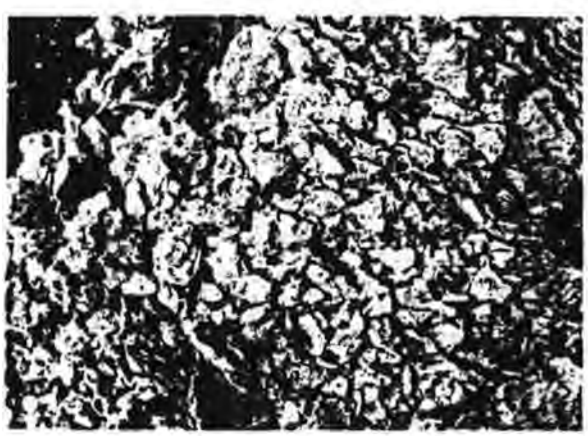

Figure 11. Break-up of horizontal layers shown in Figure 10 into flake-like aggregates.

During the cooling below 0 C of a water saturated soil and the resulting change of

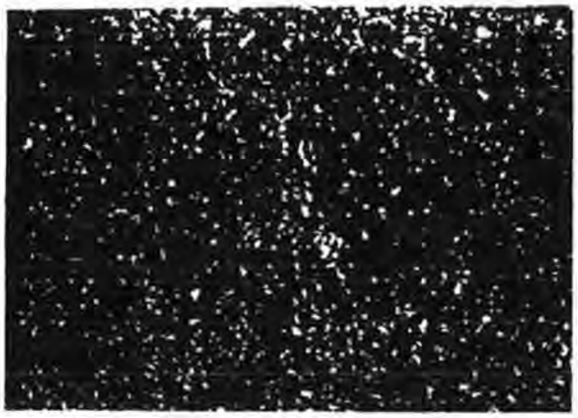

Figure 12. Homogeneous frost structure in sandy soil. Freezing front marked by line.

Figure 13. Formation of frost structure in a black earth on loess. Figures 13 to 16 were photographed at intervals of approximately seven hours.

water into ice, two phenomena take place which differ in intensity depending upon the type of soil and the freezing conditions, viz.:

1. Movement of the capillary water to the freezing front, and
2. Incorporation of this water as ice in intermittent layers in the soil.

If the frost penetrates into the soil then this ice segregation leads to frost structures which can be differentiated into "homogeneous" and "heterogeneous" structures. In the case of homogeneous frost structure, practically no change in appearance as compared with the unfrozen soil can be recognized macroscopically. The heterogeneous frost structure, however, may occur in markedly different forms depending on soil type, rate of freezing and water movement to the freezing zone. In soils containing fine sands and silts, the ice formation is predominantly in horizontal layers, while in clay soils polygonal structures are formed as a result of moisture loss and shrinkage of the clay which accompany the freezing process. Since every soil freezes homogeneously if its water content is below a certain limit determined by the soil type and the freezing temperature, a sufficient supply of water or the possibility of easy movement of water to the freezing zone is an important prerequisite for a strong formation of frost structures.

These relationships had to be taken into account in the experimental arrangement for the taking of the motion pictures in order to show the phenomena occurring in soil freezing as clearly and as true to nature as possible. Most suitable for this appeared to be the method employed in soil mechanics research in which the frost penetrates from one side and in which the soil is treated as an open system with respect to water

Figure 14. Formation of frost structure in a black earth on loess.

Figure 15. Formation of frost structure in a black earth on loess.

Figure 16. Formation of frost structure in a black earth on loess.

Figure 17. Thickening of ice layer at the freezing front at low penetration rate of the front.

supply; this means that during freezing, the soil is supplies with an artificial ground water level.

In order to fulfill these conditions, the soil samples were placed in a modified kitchen refrigerator in a way that the frost could penetrate only from the top, and the bottom was connected with a ground water level by means of a ceramic filter plate. To permit the photographing of the frost structure, a vertical area was cut out on the front side of each specimen. As a rule, one picture was taken per minute. The refrigerator was so regulated that the temperature on the surface of the soil specimen was between -1 and -1.5 C. Movies were made with different soils and yielded the following results:

Sandy Soil. Grain size composition:

Coarse sand	:	37.7 percent
Fine sand	:	50.3 percent
Silt	:	8.5 percent
Clay	:	3.5 percent

The penetration of the frost into the soil can be recognized only by the slow movement of a shadow in the picture. This shadow is caused by an ice film formed by the water which, because of volume increase in freezing, is forced out of the soil pores. No macroscopic change can be observed in the structure of the specimen surface; this means that the soil freezes homogeneously. Figure 12 shows a photograph in which the extent of frost penetration is marked by a line.

Soil from the A-Horizon of a Black Earth on Loess. Grain size composition:

Coarse sand	:	5.2 percent
Fine sand	:	40.1 percent
Silt	:	35.7 percent
Clay	:	19.0 percent

Humus content : 2.3 percent

Figure 18. Thickening of ice layer at the freezing front at low penetration rate of the front.

Frost penetration from the top surface results in this soil in the formation of horizontally oriented ice lenses placed in intermittent layers below each other. Many of the ice lenses are touched by the upwards bent ends of the ice layers underneath in a manner that during the freezing process a characteristic and in many places almost net-like frost structure is formed. The originally thin ice lenses form much faster in the beginning than toward the end of the experiment where the freezing rate decreases more and more while the ice lenses increase in thickness. The increase in thickness of different ice lenses continues even after the freezing front has passed the specific ice lens and has already formed a new one below. At the end of the experiment, the soil shows the horizontal frost structure which is characteristic for loess soil; however, in the vicinity of the water source, some polygonal structures are also found. Figures 13 to 16 give an insight into the course of the freezing process in this soil.

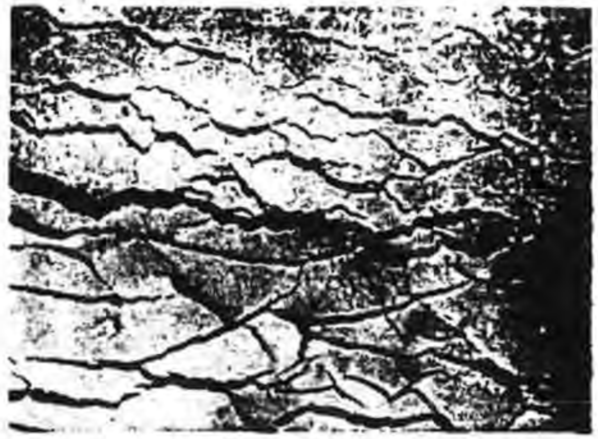

Figure 19. Thickening of ice layer at the freezing front at low penetration rate of the front.

A_3-Horizon of a Para-Brown Earth on Loess. Grain size composition:

Coarse sand	:	1.7 percent
Fine sand	:	55.5 percent
Silt	:	29.9 percent
Clay	:	12.9 percent

The freezing process shows initially the same course as in the case of the Brown Earth (2) and results also in a horizontally layered frost structure which, however, possesses more strongly broken contours. During the experiment, the freezing process was arrested for a while by decreasing the refrigeration. During this time, the amount of refrigeration surpassed the heat gain from the change of water to ice only to such an extent that it just sufficed to form a thick ice lens at the freezing front. This approximate equilibrium condition was terminated by returning to the original refrigeration and the experiment was concluded. Figures 17 to 19 show very clearly the growth in thickness of the ice lenses at the freezing front. The frost structure below the ice lens is coarser than above, probably because the soil had become enriched in water while the advance of the freezing front was arrested.

Chalk Clay. Grain size composition:

Coarse sand	:	7.7 percent
Fine sand	:	29.2 percent
Silt	:	37.4 percent
Clay	:	25.7 percent

Because of the low water conductivity of this clay soil, it was not possible to feed the formation of ice from an artificial ground water reservoir. Therefore, the soil specimen was made up with sufficient water that ice layers could be formed from its

Figure 20. Course of the freezing process in clay soil.

Figure 21. Course of the freezing process in clay soil.

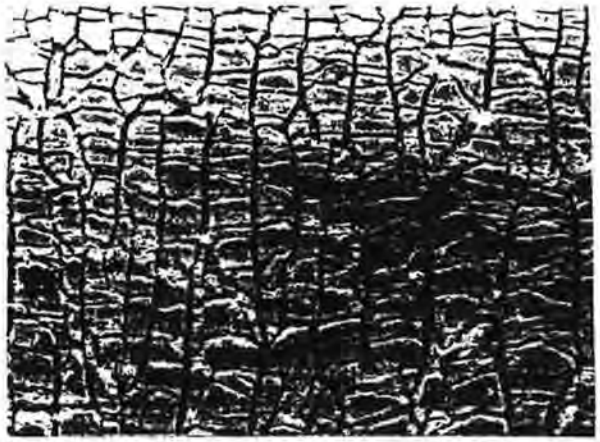

Figure 22. Vertical section through frozen Ca-montmorillonite.

Figure 23. Advance of the vertical ice layers at the freezing front into the unfrozen zone (montmorillonite).

own supply in the immediate vicinity of the freezing front. This, however, leads to soil shrinkage in the immediate vicinity of the freezing front and cracks are formed which become filled with ice already during their formation. This companion phenomenon of soil freezing results in frost structures that differ essentially from those in loess soil. As against the horizontal layer orientation of the ice lenses in the loess, parallel needle-pointed almost vertical ice layers are at first formed from the surface down into the clay soil. These needles increase in thickness during the freezing process to well developed ice bands and only later are joined to relatively coarse polygonal frost structures by means of horizontal ice lenses (Figs. 20 and 21).

Form of the Frost Aggregates in Clay

In the case of the freezing experiments—in contrast to that of the wetting and drying experiments—the freezing process could be photographed only in the vertical plane. Hence, the moving pictures alone do not give a complete presentation of the form of the aggregate structures. They were, therefore, complemented by experiments in which a large number of soil specimens were frozen in the described manner and then cut into vertical and horizontal slices. This way, very informative pictures were obtained concerning the geometric features of frost structures in clay-rich agricultural soils and also in montmorillonite clay.

In montmorillonite, especially regular frost structures were found because of its large and uniform shrinkage. Figure 22 shows a vertical section through a frozen Ca-

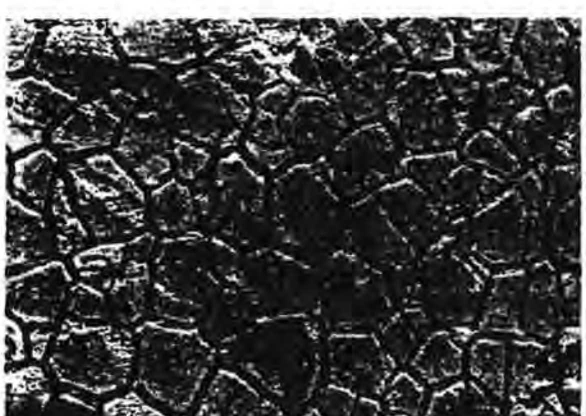

Figure 24. Horizontal section through frozen Ca-montmorillonite showing polygonal bases of the frost aggregates.

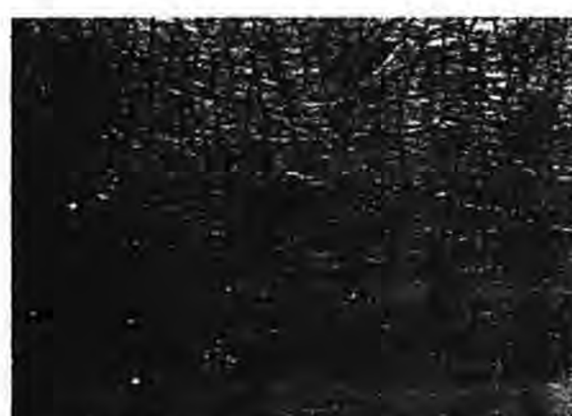

Figure 25. Frost structure of the Ca-modification of a sandy-clayey loam, vertical section.

Figure 26. Frost structure of the Ca-modification of a sandy-clayey loam, horizontal section.

Figure 27. Frost structure of the Na-modification of a sandy-clayey loam (see Fig. 24), vertical section.

montmorillonite: the vertical ice layers are especially marked since they run through the picture in a straight course. The horizontal ice layers, however, are relatively thin and seldom extend over two vertical layers. Since both ice formations are almost normal to each other, rectangular aggregate edges are obtained. The stronger formation of the vertical ice layers is explained, as shown in Figure 23, from their advance ahead of the freezing front into the shrinkage fissures of the unfrozen soil. These fissures provide a stress-free space into which the easily moving water can crystallize. The later occurring horizontal ice formation produces only relatively thin ice lenses since the water must be pulled against an ever increasing suction tension.

The frost structure of a horizontal section, taken parallel to the freezing front, is shown in Figure 24. This structure does not show the rectangular features of the vertical section, but hexagons and pentagons in cell-like arrangement. Formations of this kind are widely found in nature, for example, in basalt, whose polygonal forms are also the result of shrinkage phenomena.

Since swelling capacity and intensity of water binding of a clay is influenced by its exchangeable cations, an influence of the adsorbed cations on the frost structure can be expected. While Na-montmorillonite under the same experimental conditions showed the same aggregate forms as Ca-montmorillonite, the aggregates were smaller and more irregular than those of the latter. Additional experiments with a sandy-clayey loam showed, under the same experimental conditions and at the same plasticity as the comparison samples, that the soil with Ca-exchange ions formed the soil struc-

Figure 28. Frost structure of the Na-modification of a sandy-clayey loam (see Fig. 24), horizontal section.

Figure 29. Streaked course of shrinkage fissures in the Na-modification of a clay soil.

ture characteristic for this soil modification (Figs. 25 and 26). The Na-ion modification, however, showed in the vertical section an irregular and streaked frost structure (Fig. 27) and in the horizontal section an arrangement of ice lenses looking like a set of fine parallel lines (Fig. 28).

Aggregate formation in clayey soils as a result of frost action or of wetting and drying are related processes, since both are connected with swelling and shrinkage phenomena in the soil. This is why the resulting aggregate forms show great similarities and why, when both factors have acted on a soil, the specific cause can hardly be recognized. An example of this is the pattern of shrinkage fissures in a Na-soil modification (Fig. 29) which is similar to the frost structure in Figure 27. Although both patterns may be influenced in part by unavoidable flow structures, formed during preparation of the soil specimens, they prove the similarity of the effect of the factors involved. The same can be said for the layered structures and aggregates whose formation, according to the motion picture evidence, may be due either to wetting and drying or to freezing action.

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