21. Taber, Stephen "The Growth of Crystals Under External Pressure" Amer Jour Sci, Vol XLI, 1916
22. Taber, Stephen "Ice Formed in Clay Soils Will Lift Surface Weights" Engineering News-Record, Vol 80, Pages 262-263, 1918
23 Taber, Stephen "Frost Heave" Journal of Geology, Vol 37, No 5, July-August, 1929
24 Taber, Stephen "Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements" Public Roads, Vol 11, No 6, 1930
25 Toumey, J W "Foundation of Silviculture Upon Ecological Basis" Text Book, Vol 1, 1928
26. Watkins, W I, and Aaron, H "The Soil Profile and the Subgrade Survey" Public Roads, Vol 12, No 7, September 1931

DISCUSSION ON FROST HEAVING

ABSTRACTED

MR W. I WATKINS, *U S Bureau of Chemistry and Soils* The paper by Benkelman and Olmstead accomplishes much in solving the problem, but Mr Watkins does not feel that it offers a complete explanation, since the phenomena observed in some five or six hundred frozen soil cores taken from Minnesota subgrades during the winter of 1929 and 1930, by the Minnesota Highway Department in cooperation with the U S Bureau of Public Roads are not entirely explainable by this theory Ice layers no doubt will form in sands as described, but they may also form in sands which are not saturated, due to the formation of an artificially high water table caused by the rise, condensation and freezing of moisture vapor In stratified sands this vapor may cause ice layers between strata

Figure 1 represents a frost profile which was not uncommon in the structureless silts, silty clay loams, very fine sands, sandy clay loams, and in those highly calcareous soils having a uniform distribution of lime carbonate

Layers A, B and C in Figure 1 are explainable by the theory contained in Messrs Benkelman and Olmstead's paper However, the same explanation cannot be applied to the uniform spacing of the paper thin ice layers There seemed to be a difference in the spacing and thickness of the ice layers in the different soil textures Mr Watkins believes that the evenly spaced thin ice layers form during a uniform penetration of frost Observations during December, 1931, seem to strengthen this theory If the theory discussed in the paper explains these layers then the temperature penetration curve must have a recessional curve just slightly less than the penetration curve (See curves, Figure 1) This does not seem probable

It is thought that Figure 2 will serve to explain the formation of the thin evenly spaced ice layers In studying this diagram it must

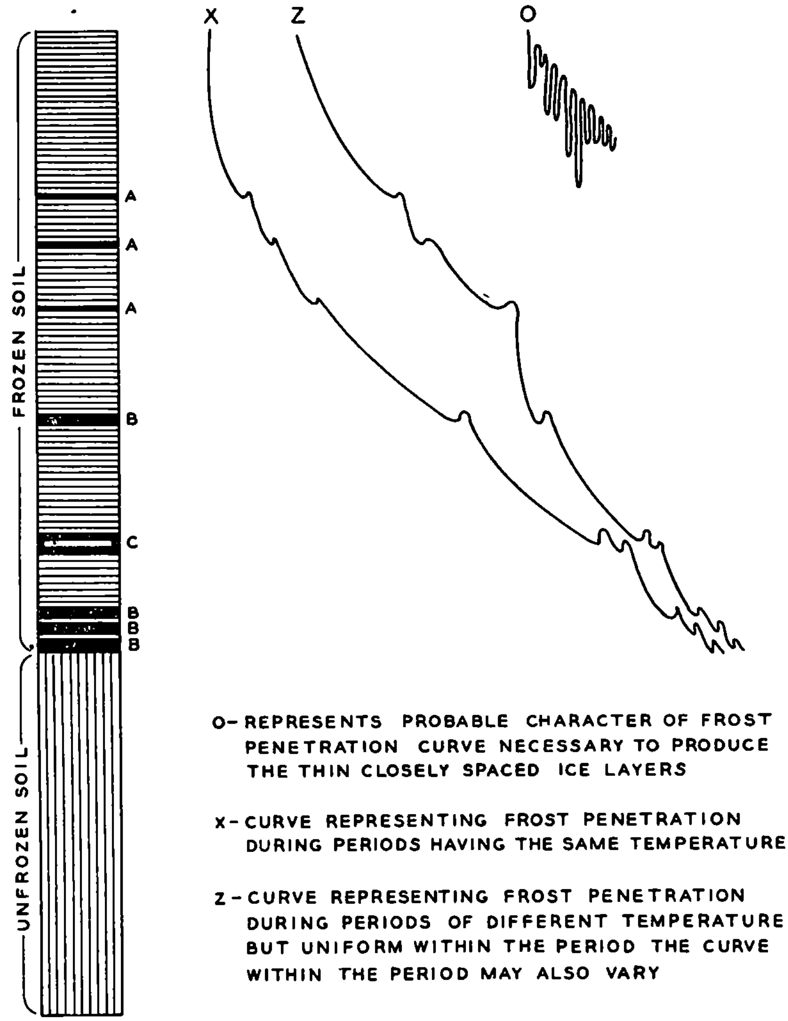

Figure 1 Frost Profile in Structureless Silts, Silty Clay Loams, Very Fine Sands, etc

be remembered that freezing conditions are usually preceded by several days or weeks of cool weather The cool weather serves as a primer in establishing maximum capillary action and saturation of the upper subgrade

In Figure 2, A represents the frozen soil As the frost layer penetrates a supersaturated layer B is being formed just below The warmer capillary water is drawn up through the capillary tubes D, which act as direct hose connections The supersaturated condition

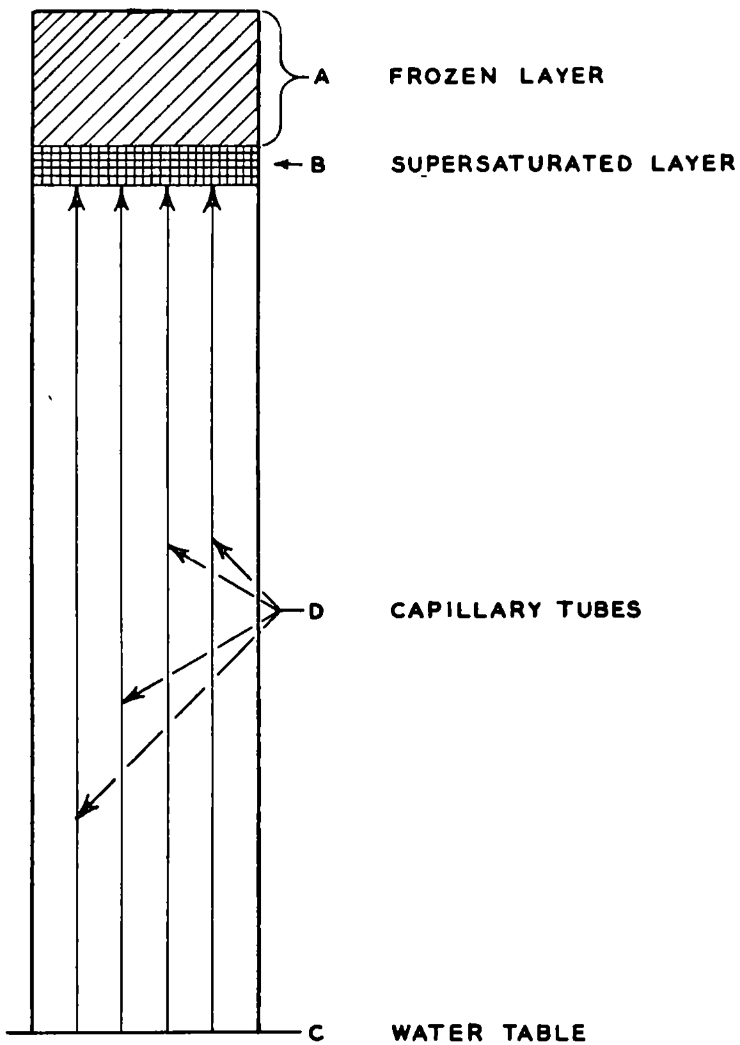

Figure 2 Formation of Thin Evenly Spaced Ice Layers

probably causes a slight expansion in layer B, and the soil has a tendency to settle The cooling of the water causes contraction and may accelerate settlement This would cause a thin water film to develop on the surface of B The freezing of this water film may cause a slight lag in temperature penetration As freezing progresses more rapidly than capillary water rises layer B freezes but the slight lag caused in freezing the water film may allow another supersaturated layer to develop It also seems possible that freezing might progress rapidly enough to dry out a thin layer at the surface of layer B This would cause a cleavage plane to develop which would become filled with moisture This would freeze and, while freezing, another layer B would form and the process be repeated This seems possible with the more rapid freezing and might produce a greater number of ice layers per inch of frost penetration The processes mentioned above will be broken by recessions of the frost line These theories may seem far fetched and are mentioned only as possible causes for the development of the numerous ice layers

Mr Watkins states that all his field studies indicate ice, except possibly horizontal ice layers, forms only in existing voids Therefore, he believes the formation of the horizontal void planes preceeds the formation of the ice layers, and the problem is to determine the causes developing these void planes The above is based upon observations made in different states and is covered in various reports

Mr Arthur Casa Grande, *Research Engineer, U S Bureau of Public Roads* Attention is called to the discrepancies which exist between the theory presented by Benkelman and Olmstead and that developed by other investigators and the hope expressed that the work will be continued so that the differences may be cleared up Two main points of difference are found (1) According to the new theory alternate freezing and thawing of the bottom of the frozen layer is necessary in order to produce excessive ice accumulation, according to the older theory this is accomplished by steady freezing action (2) According to the new theory ice layers can form in clean sand and gravel just as well as in fine grained soils, according to the older theory the presence of a certain amount of very fine grains is required in order to make the growth of ice layers possible under natural freezing conditions

In explanation of why the theory of alternate freezing and thawing explains correctly the process observed in the Michigan laboratory, and why it does not explain the freezing action observed in nature, the point is raised that if in a test cylinder a sample is frozen and then partially thawed from beneath, the frozen portion will adhere to the wall of the cylinder and cannot follow the subsidence of the thawing portion, whereas in nature the frozen layer must follow every subsidence due to melting at the bottom

This point is illustrated by the behavior of eight, three foot square slabs laid on two kinds of soil and exposed outdoors at the Massachusetts Institute of Technology during the winter of 1928-29 (See

Figure 1.)[1] The special soils underneath the slabs were arranged within side walls for a depth of three feet in such a way that friction between the walls and the soil was reduced to a minimum and thus the soil mass was allowed to heave or settle almost as freely as in nature. The soils used were a sandy silt with a small clay content and a clean, fine, uniform sand. The soils came from New Hampshire where the silt had caused heaving and the sand had not. Accurate measurements of all movements were made and records taken of temperatures and other pertinent data.

Figure 2 shows the heaving and frost penetration record of a four inch concrete slab on the New Hampshire silt, together with the prevailing temperatures.

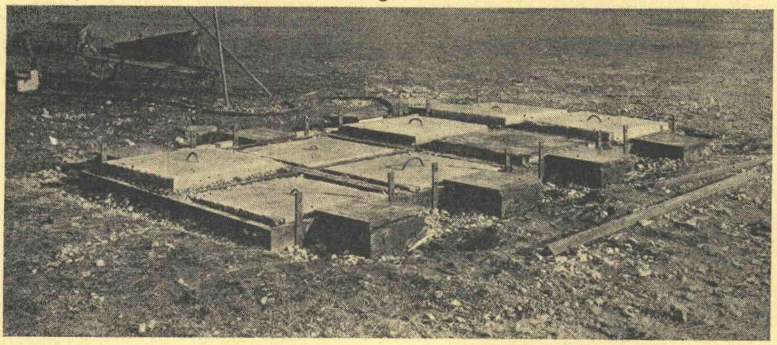

Figure 1. Layout for Frost Heaving Experiments. Massachusetts Institute of Technology

Figure 3 shows the heaving curves of four types of pavement on the silt and of a four inch concrete slab on the sand.

In Figure 4 is shown the heaving record and soil conditions along 2,000 feet of concrete pavement in New Hampshire taken during the winter of 1927-28.

The study of the data secured at the Massachusetts Institute of Technology and of similar information from many sections of New Hampshire lead to the conclusion that:

" Under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than three per cent of grains smaller than 0.02 mm., and in very uniform soils containing more than ten per cent smaller than 0.02 mm. No ice segregation was observed in soils containing less than one per cent of grains smaller than 0.02 mm., even if the ground water level was as high as the frost line.

[1] A complete report of this investigation will be published in *Public Roads.*

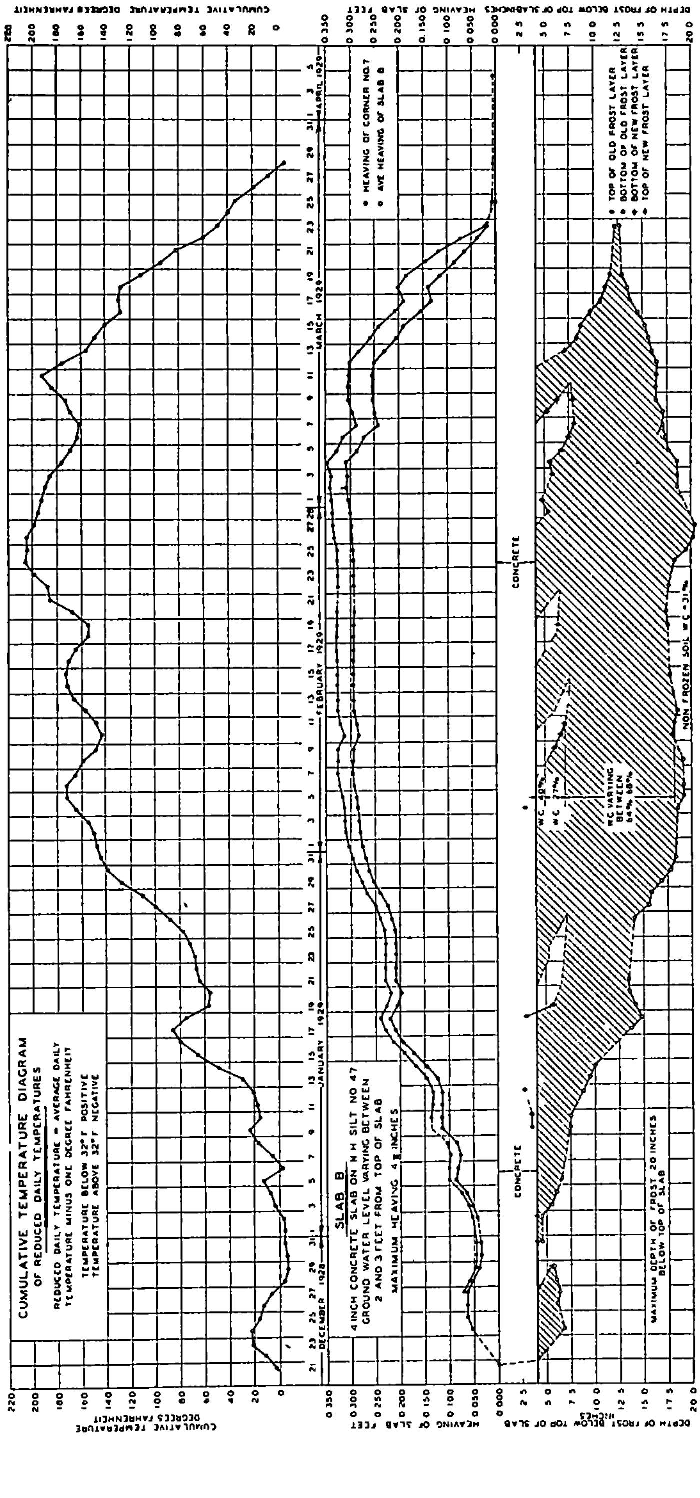
CUMULATIVE TEMPERATURE DIAGRAM
OF REDUCED DAILY TEMPERATURES
REDUCED DAILY TEMPERATURE = AVERAGE DAILY TEMPERATURE MINUS ONE DEGREE FAHRENHEIT
TEMPERATURE BELOW 32°F POSITIVE
TEMPERATURE ABOVE 32°F NEGATIVE
SLAB B
4 INCH CONCRETE SLAB ON N H SILT NO 47
GROUND WATER LEVEL VARYING BETWEEN 2 AND 3 FEET FROM TOP OF SLAB
HEAVING OF CORNER NO. 7
AVE HEAVING OF SLAB B
TOP OF OLD FROST LAYER
BOTTOM OF OLD FROST LAYER
BOTTOM OF NEW FROST LAYER
TOP OF NEW FROST LAYER
CONCRETE
NON FROZEN SOIL
CUMULATIVE TEMPERATURE DEGREES FAHRENHEIT
HEAVING OF SLAB FEET
DEPTH OF FROST BELOW TOP OF SLAB INCHES

Figure 2

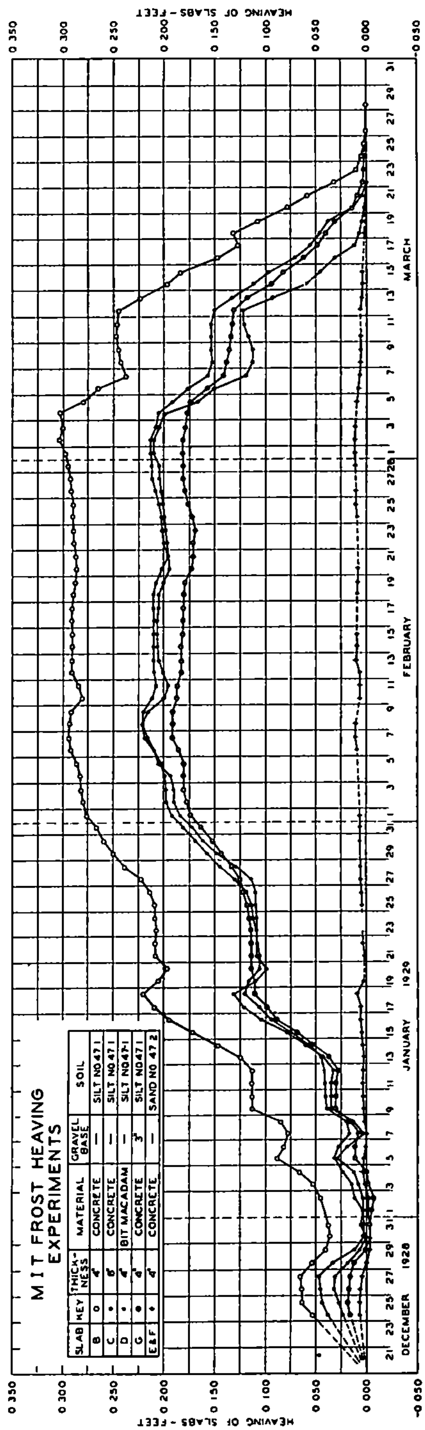
M I T FROST HEAVING EXPERIMENTS
SLAB | KEY | THICKNESS | MATERIAL | GRAVEL BASE | SOIL
B | ○ | 4" | CONCRETE | — | SILT NO 47 1
C | • | 6" | CONCRETE | — | SILT NO 47 1
D | • | 4" | BIT MACADAM | — | SILT NO 47-1
G | ● | 4" | CONCRETE | 3" | SILT NO 47 1
E & F | • | 4" | CONCRETE | — | SAND NO 47 2
HEAVING OF SLABS - FEET
0 350
0 300
0 250
0 200
0 150
0 100
0 050
0 000
-0 050
DECEMBER 1928
JANUARY 1929
FEBRUARY
MARCH

Figure 3

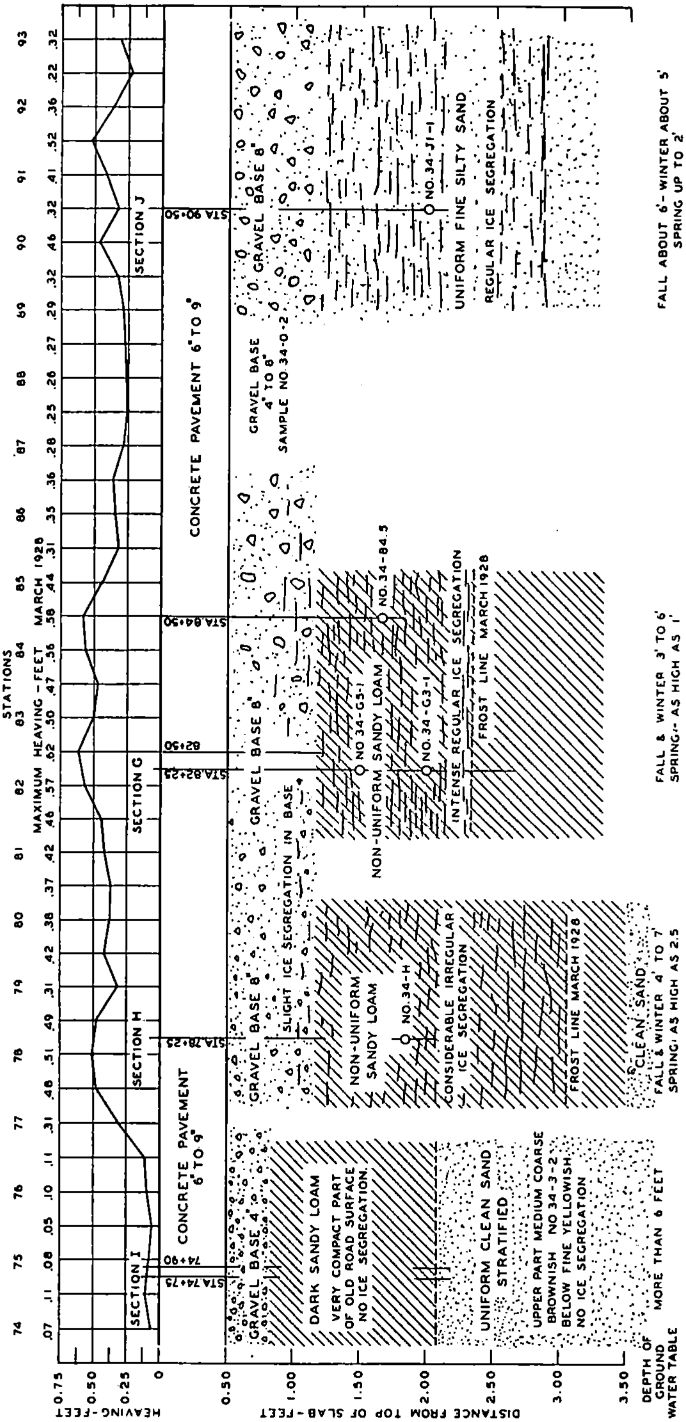
STATIONS
MAXIMUM HEAVING - FEET MARCH 1928
HEAVING - FEET
DISTANCE FROM TOP OF SLAB - FEET
SECTION I
SECTION H
SECTION G
SECTION J
CONCRETE PAVEMENT 6" TO 9"
STA 74+75
74+90
STA 78+25
STA 82+25
82+50
STA 84+50
STA 90+50
GRAVEL BASE 4"
DARK SANDY LOAM
VERY COMPACT PART OF OLD ROAD SURFACE NO ICE SEGREGATION.
UNIFORM CLEAN SAND STRATIFIED
UPPER PART MEDIUM COARSE BROWNISH NO 34-3-2 BELOW FINE YELLOWISH NO ICE SEGREGATION
MORE THAN 6 FEET
DEPTH OF GROUND WATER TABLE
GRAVEL BASE 8"
SLIGHT ICE SEGREGATION IN BASE
NON-UNIFORM SANDY LOAM
NO.34-H
CONSIDERABLE IRREGULAR ICE SEGREGATION
FROST LINE MARCH 1928
CLEAN SAND
FALL & WINTER 4' TO 7' SPRING AS HIGH AS 2.5
NO 34-G3-1
NO.34-G3-1
NON-UNIFORM SANDY LOAM
NO.34-84.5
INTENSE REGULAR ICE SEGREGATION
FROST LINE MARCH 1928
FALL & WINTER 3' TO 6' SPRING AS HIGH AS 1'
GRAVEL BASE 4" TO 8" SAMPLE NO.34-0-2
NO.34-J1-1
UNIFORM FINE SILTY SAND
REGULAR ICE SEGREGATION
FALL ABOUT 6' - WINTER ABOUT 5' SPRING UP TO 2'

Figure 4

Professor Stephen Taber, *State Geologist and Head of the Geology Department, University of South Carolina*. "For many years engineers have explained frost heaving, and all other pressure effects that accompany the freezing of water, as due to increase in volume of the water frozen. But, on many soils the uplift observed is greater than could be explained in this way. On the basis of experiments in which excessive heaving was observed when test samples were subjected to fluctuating temperature, Mr. Benkelman and Mr. Olmstead have advocated the modification of this old theory of frost heaving described in their paper."

A very different theory of frost heaving to that presented by Benkelman and Olmstead has been developed by Professor Taber, and presented in a series of papers (see list at end). Briefly stated it is as follows:

"Frost heaving is due to the growth of ice crystals and not to change in volume. Pressure is developed in the direction of crystal growth which is usually determined chiefly by the direction of cooling. Excessive heaving results when water is pulled up through the soil to build up layers or lenticular masses of segregated ice, which grow in thickness because water molecules are pulled into the thin film that separates the growing columnar ice crystals from the underlying, soil particles."

This theory has been criticized by Benkelman and Olmstead on the grounds that the experiments did not include tests on certain soils from states in the "frost area" and that freezing was conducted at a uniform rate. Professor Taber states that this criticism is apparently due to a misunderstanding of the purpose of his investigations which has been the determination of the fundamental physical processes associated with the freezing of water in soils. The effects of different factors have been studied by varying only one factor at a time. A considerable number of soil samples from northern states have been tested but the results have not yet been published.

Early in Professor Taber's investigations soils were subjected to repeated cycles of freezing and thawing, and it was found that prompt refreezing after thawing resulted in greater ice segregation and heaving than occurred on the first freezing. Since other experiments showed that freezing tends to concentrate water near the surface, and that segregation is accentuated by a high water content, the increased heaving that accompanied re-freezing was attributed to these two factors. Another factor should have been mentioned. The first freeze breaks up a consolidated soil, increasing permeability and reducing its tensile strength so that less resistance to heaving is offered when refreezing occurs.

If refreezing is delayed too long the excess water concentrated near the surface tends to drain downward out of the freezing zone. In the experiments described by Benkelman and Olmstead, downward drainage of water was prevented, for friction kept the frozen soil column from descending and air could not enter through the frozen plug to displace the water Friction would not be an appreciable factor when large areas of ground are frozen under natural conditions In some of Professor Taber's laboratory experiments an attempt was made to overcome this friction between soil and container by loading the surface of the soil column, but if the load is not removed before refreezing it increases the resistance to heaving and therefore decreases the uplift

Refreezing is not necessary to explain the formation of ice layers and excessive heaving, for a surface uplift amounting to over 60 per cent of the depth of freezing has been obtained as a result of only one freeze When ice layers are obtained from a single freezing of clay columns in the laboratory, thin wedges of the clay frequently project into clear ice and small lenses may be entirely surrounded by ice (see Figure 1) Because of lack of support such structures could not have developed through the freezing of the water *in situ* as described in the Benkelman-Olmstead experiments A careful examination of ice layers that develop in frozen ground under natural conditions shows similar peculiarities in the distribution of ice and soil (see Figure 2)

Perhaps the strongest evidence that increase in volume is not a factor in frost heaving, when freezing takes place in open systems, is furnished by substituting for water other liquids which solidify with decrease in volume The results obtained from freezing a clay column that stood in sand saturated with nitrobenzene is shown in Figure 3 During this test the clay column was under a surface load of 110 pounds per square inch and the friction between soil and container was high The frozen cylinder was sawed in half before the photograph was made

Burton and Benkelman stated in their paper on " The Relation of Certain Frost Phenomena to the Subgrade " (Tenth Proceedings, Highway Research Board) that Taber's experiments had quite definitely indicated that " ice segregation in soils was restricted to clays or materials of a similar particle size," while their " field investigations on the other hand had disclosed the fact that by far the most serious disturbances occurred in silts."

According to Professor Taber this was not a correct interpretation of his experiments, for in laboratory tests ice segregation was obtained in materials having a particle diameter of 0 07 millimeter, and with slower cooling or less frictional resistance to heaving, segregated ice would form in soils having a larger particle diameter In some of the tests the resistance to heaving, due to friction between frozen soil and container, was equivalent to a surface load of over seventy-five pounds per square inch

The amount of ice segregation and frost heaving in soils is controlled not only by particle size, but also by other factors, such as shape of soil particles, composition, amount of water available, size

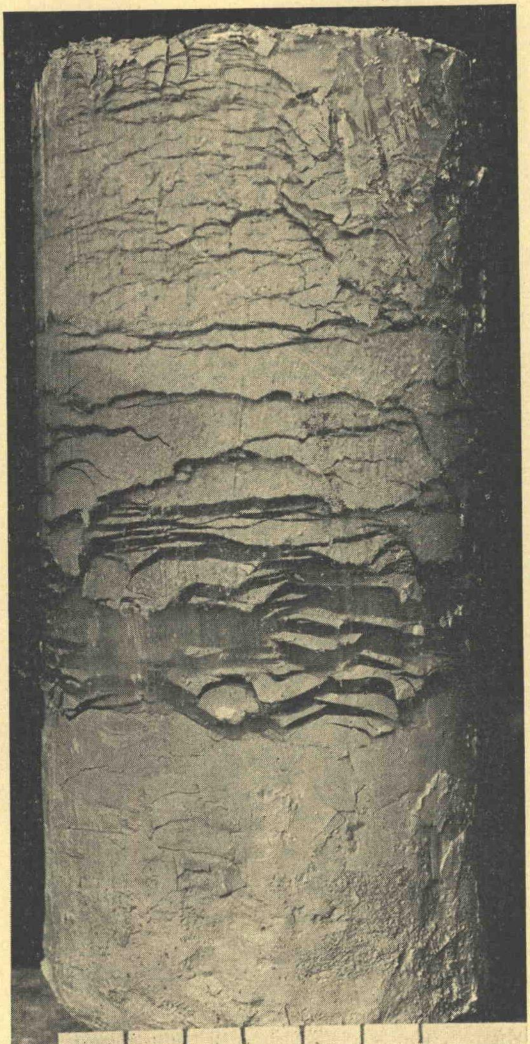

Figure 1. Clay Cylinder, Frozen by Cooling from the Top Down While Standing in Wet Sand. Note the Fragments of Clay That Occur as Inclusions within the Ice

and percentage of voids, rate of cooling and minimum temperature, tensile strength, and the surface load or resistance to heaving. Repeated cycles of freezing and thawing introduce no new factors and do not alter the mechanics of frost heaving.

Experiments show that within certain limits excessive heaving tends to increase as the particle size decreases, but that the presence of much colloidal material prevents excessive heaving by reducing the permeability, even though ice segregation occurs as in the tests with bentonite mixtures.

The materials tested, in which ice segregation and heaving were found to be excessive (and this includes the South Carolina kaolin), all have certain properties that are more apt to be associated with silts than with clays. For example, the shrinkage limits for lithopone, kadox, the clay from St. Peter, Minnesota, and the South Carolina

Figure 2. Clay Containing Ice Layers from under a Badly Heaved Street in St. Peter, Minnesota. Note the Fragments of Clay That Occur as Inclusions Within the Ice. Photograph Furnished by Prof. F. C. Lang

kaolin, as determined by the U. S. Bureau of Public Roads, were 22, 31, 30 and 36 respectively; while for average clay soils with a normal amount of colloids, the shrinkage limit would not be more than half of these amounts.

ARTICLES ON FROST HEAVING BY PROFESSOR STEPHEN TABER

Surface Heaving Caused by Segregation of Water Forming Ice Crystals. Eng. News-Record, Vol. 81, 1918, pp. 683-684.

The Mechanics of Frost Heaving. Journal of Geology. Vol. 38, 1930. pp. 303-317.

Also see Nos. 21, 22, 23, and 24 of the bibliography on page 165.

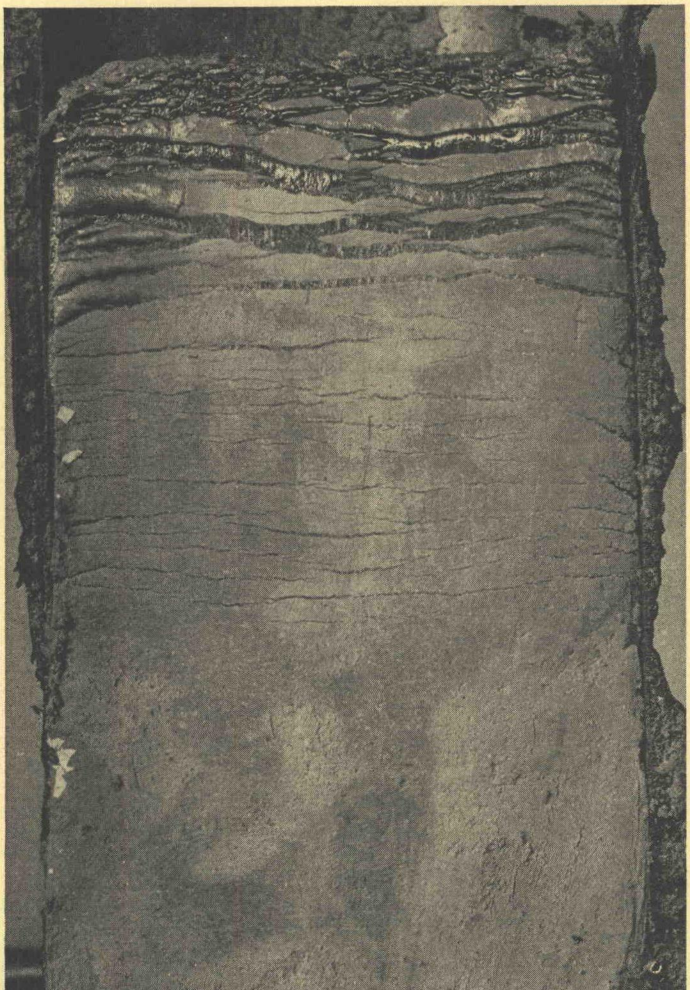

Figure 3. One Half of a Clay Cylinder Frozen under a Surface Load of 110 Pounds Per Square Inch While Standing in Sand Kept Saturated with Nitrobenzene. Note the Layers of Solid Nitrobenzene, a Substance That Freezes with Increase of Density