The Soil Freezing Experiment

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The purpose of this article is to present in as convenient and simple a form as possible a discussion of fundamental concepts and theories as a basis for frost action research, particularly with reference to the phenomenon of the upward flow of moisture in soil in the soil freezing experiment. A pilot soil freezing experiment relative to suction measurement is described and its results presented.

The improvised apparatus used in the freezing experiment demonstrates vividly where and how the ground-water is transferred and convinces one that upon freezing of the soil sample the ground-water is sucked up vertically into the soil.

Subpressure or suction values, as obtained analytically by means of the hydrodynamic and thermodynamic theories, are compared with those obtained experimentally.

Although much research work is still to be done along these lines, it is hoped, however, that this presentation will partially fill the existing gap in the present literature in respect to methodological organization and help to range this subject into a discipline supported on a theoretical basis.

● THE paving of the relatively narrow and yet expensive highway and railway ribbon, as well as that of airports, has a comparatively shallow foundation as contrasted with larger and heavier structures, the foundations of which are usually set well below the frost penetration depth line. This fact, as well as the fact that they are fully exposed to the weather makes their pavements especially vulnerable to climatic influences. Earthwork soils in particular are subjected to periodic temperature and moisture variations. For example, frost action may cause differential heaves on roads, but variation in soil moisture content as a consequence of frost action may affect the strength of the soil, particularly during a thawing period after frost has left the ground. This causes loss of bearing capacity of soil and so-called "spring breakups" on roads built on and of improper soil. The resulting affect of such conditions usually is damage to roads and their pavements. Thus it can be inferred that frost action imposes difficulties in design, construction, exploitation, and maintenance of highways. It also impairs traffic safety. In addition, repairs of roads damaged by frost usually cost huge sums.

It becomes necessary, therefore, in highway and airport engineering, to estimate, among other factors, the frost penetration depth in soil. By a correct estimate of this penetration, it is possible to provide either proper insulation or adequate drainage courses underneath the pavement to take care of the thawing waters, and to determine the necessary amount by which the ground-water table should be lowered. If the ground-water table is sufficiently low, upon freezing the suction height of the upward-sucked soil moisture from the ground-water will not be intercepted by the depth of the maximum frost penetration which is known to prevail in the region under consideration. Hence, we conclude that data on frost penetration and upward suction of soil moisture, which contributes to the thickening and to the downward progress of the frozen layer of soil along with soil properties, are useful in arriving at adequate design of highways and and runways.

A sketch illustrating the concept of unidimensional upward flow of soil moisture toward the frost boundary (or ice lenses) upon freezing is shown in Figure 1 (5).

Unfortunately the interrelationship of the various factors involved in damaging roads is very complex. A variation in any one of the factors influences to a greater or lesser extent the others, the properties of the soil, as well as the whole thermal system "soil-moisture-temperature." Soil, because of the variation in properties effectuated by moisture variations in it, is a difficult engineering material to deal with and to study. It is nonhomogenous, possessing many properties. Such studies become particularly difficult when soil is subjected to temperature potentials, temperature cycles, and moisture transfer.

Because in the freezing process the soil properties vary with the variation in its moisture content which, in turn, is associated with temperature variations, the study

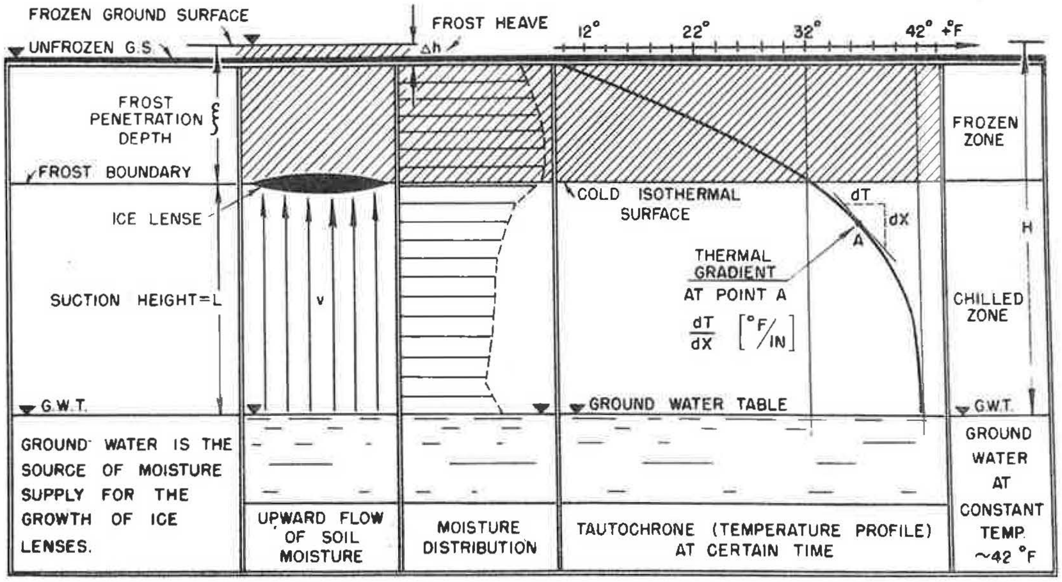

Figure 1. Sketch illustrating the concept of unidimensional upward flow of soil moisture toward the frost boundary (or ice lenses) upon freezing. Open system.

of frost penetration and moisture migration upon freezing and thawing in soil is simultaneously a geotechnical and heat transfer problem, a problem of considerable difficulty. This explains why soil studies under thermal conditions have in general never been highly popular or attractive. One of the reasons is that the process of heat transfer takes place slowly. Also, there are no convenient, simple, and handy laboratory means available for experimentation in order to confine the flow of heat and the migrating moisture along some well defined path. Consequently, little progress was made in arriving at more effective methods for evaluating the thermal system "soil-moisture-temperature." Researchers have avoided such studies simply because they are cumbersome, involved and unattractive.

However, because of the economic and national importance of the performance of highways under freeze-thaw conditions and in order to understand better the complex freezing process in soil where temperature differences, heat transfer and moisture migration are involved, it is necessary to familiarize and refresh ones thinking with some basic concepts pertaining to this subject. It is believed that familiarity with these concepts will be a great aid in methodological organization of the subject as well as in supporting a discipline to be built on basic knowledge already available.

GENERAL CONCEPTS

In the study of the complex frost problems associated with soil moisture migration, it is necessary to establish, as in any other field of physics and research, a so-called working system. The latter aids one to avoid some difficulties that may arise in research work and helps to develop the subject. A working system can be considered as a useful means by which to organize and orient the subject and the set of ideas, essential principles, and facts within a certain frame of general concepts. The following is a short description of some of the general concepts.

System. A system is generally understood to be the quantity of matter under consideration. More specifically, a system is a separated region of space or a finite part of matter set apart from its surroundings. Attention is focused on the system; in the system, changes in the state of matter and transfer of energy and/or mass can be studied. When energy transfer between the system and its surroundings takes place only under the influence of temperature difference, the transferred energy is called heat. As known from physics, heat possesses only one measurable property, temperature.

In the soil freezing experiment an effort was made to simulate field conditions as nearly as possible. For example, a vertically supported cylindrical soil sample (imagined to be a part of the soil in the ground) with a simulated ground-water table distant H below the ground surface is frozen from the top downward (Figure 1). This means that in the soil sample, upon freezing, changes in temperature, moisture content, phase (water is converted to ice), and volume (frost heaves) take place. The changes in the existing factors are usually effectuated by a temperature potential as a driving force in energy (heat) and mass (water) transfer. All these changes taking place in a physical body of matter under consideration are to be included in the region of study. Hence, a region where transfer of heat and soil moisture can be studied is defined as a system. In this sense, the concept of a system in thermal soil mechanics can be compared with the free body diagram as it is utilized in analyzing problems in technical mechanics, for example, statics (7), or it is analogous to the concept of "system" as used in studies of thermodynamics (6). Because of its nature, the particular system in the soil freezing experiment and its prototype in the field can be termed "soil-moisture-temperature."

The concept of a system is illustrated in Figure 2. This is an open system, that is, one where water can enter from below from the ground-water freely, and, after thawing of the frozen soil, leave it again. Also, energy (heat) can cross the lower and upper boundaries of the system. Thus exchange of energy and mass is possible with the surroundings.

Surroundings. The region outside the thermal system is called the surroundings. In Figure 2, the system is shown surrounded laterally by an insulating substance (impregnated cardboard tube and vermiculite) through which, it is assumed, no heat or moisture flow. However, internal energy in the form of heat can be transferred to the surroundings vertically across the horizontal unfrozen and frozen boundaries of the system. The prerequisite for the transmission of heat, in turn, is the temperature difference or potential between the system and its surroundings. A potential is popularly called a "driving force" causing changes in the state of a system. Hence, proper temperatures, as one of the several possible potentials, are one of the necessary factors in the freezing process.

Process. In a broad sense, a process is any event in nature in which a redistribution or transformation of energy occurs (1). Whenever a system undergoes a physical change of any kind from one state to another, this change is termed a physical process. In thermodynamics, a distinction is made between two kinds of processes, namely, reversible and irreversible ones.

According to Weber (10) a reversible process is defined as one where, at any stage, a differential decrease in the driving force causes the process to proceed in the opposite direction. After a reversible change, both the system and surroundings may attain their

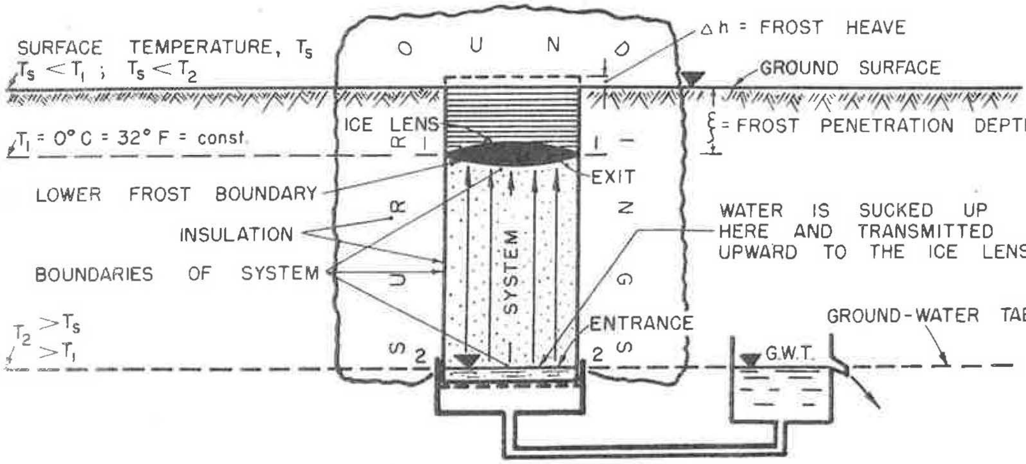

Figure 2. System, boundaries and surroundings.

original condition. An irreversible process is defined as one in which the system and surroundings can never be completely restored.

Aside from the concepts of system and surroundings, it is advantageous to attach to the system certain simple and idealized properties. For example, it might be assumed that the matter of the system is a uniform and homogeneous soil through the moisture films of which a perfect and easily mobile soil moisture flows, and through the soil of which, upon freezing the top surface of the soil sample, heat and moisture are transferred upward from a warmer region (ground-water table) to a colder one (lower boundary of the freezing ice lenses). The freezing lenses are connected with the ground-water table by a communicating system of soil-moisture films (Figure 3), and moisture is moved upwards against gravity (3).

Hence, the processes of moisture and heat flow within this thermal system are of the nature of soil mechanics, hydrodynamics, heat transfer and thermodynamics. From this discussion one realizes the complexity of the freezing process associated with heat and moisture transfer in a porous medium such as soil. Here heat is transferred by the soil particles in contact as well as by the moisture flowing upward through moisture films toward the freezing ice lenses. Very little is known as to what is the proportion of heat transfer through the soil particles as compared with that through the soil moisture. In addition, other factors must be taken into account, such as variation in water affinity to soil and changes in the viscosity of water effected by temperature variations, the amount of specific surfaces of soil, the various types and sizes of the constituent parts of the soil particles, as well as the soil void ratio. All these and other factors are to be recognized as constituting some of the difficulties in confining the flow of heat and moisture in a porous medium and thermal system like soil along or within some well-defined paths or channels. Therefore, certain assumptions are necessary to simplify studies.

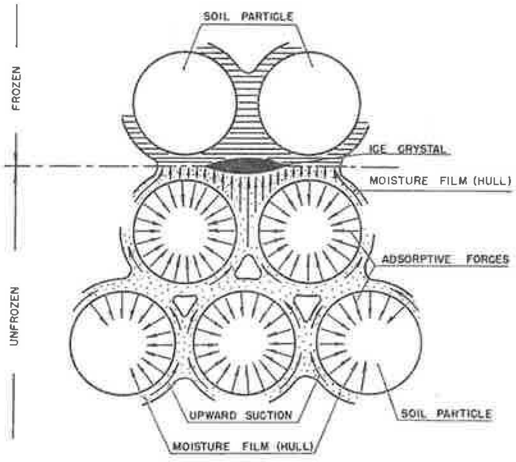

Figure 3. Sketch illustrating the concept of the upward flow of soil moisture toward an ice crystal.

Assumptions. From the previous discussion one gathers that the system in the soil-freezing experiment is by no means a simple one. It is a complex, multiple-component system where heat transfer is associated with the transfer of soil moisture in a porous medium. Therefore, in order to study physical processes and to obtain a general insight into them, it is necessary, as in almost every other branch of knowledge, to simplify the actual process considerably. Factors which are of minor importance are usually eliminated, and attention is focused on only the major phenomenon in the particular process. For these and other reasons, as well as for constructing a soil freezing apparatus, certain assumptions are to be made at the outset for agreement on certain facts.

In making assumptions, attention is focused on the interior of the system.

1. It is assumed that in the system under consideration there is a ground-water source present at a certain distance below the ground or pavement surface.
2. The freezing ice lenses are connected freely with the ground-water table, by means of moisture films which are adsorbed to the soil particles.
3. The temperature conditions in soil are such that the moisture films are uninterrupted.
4. Upon the application of a freezing temperature gradient, a suction within the moisture films is inaugurated, causing an upward flow of soil moisture in the liquid phase toward the forming ice lenses.
5. For reasons of simplicity, a laminar, unidimensional upward flow of soil moisture and heat transfer is assumed. The transference of mass and energy takes plac

upward unidimensionally and parallel to the longitudinal, vertical axis of the cylindrical system. Because of the large areal extent of the soil in the field, it is further assumed that no lateral transfer of heat and moisture takes place. In the laboratory, the upward direction of the flow, it is believed, can be achieved by isolating the soil system from its surroundings with insulation.

6. The system under consideration is an open system, that is, one such as is found in the field where additional moisture can enter and be sucked up vertically into an imaginary vertical soil cylinder as a result of freezing.

7. The film moisture and the soil particles are the medium between the ground-water table (entrance) at a temperature above freezing and the forming ice lenses (exit) at freezing temperature, and serves as a means of free communication for the transfer of energy.

8. No "eddies" or turbulence in the process of transfer of soil moisture and heat through the system take place.

9. The vapor movement in the soil is negligible, and therefore ignored.

10. The moisture transfer between the soil and the air is negligible.

11. The temperature underneath the ice lenses is regulated by the supply of cold from above, and the temperature of the upward flow of soil moisture from below. However, for simplicity, it is assumed that moisture in soil freezes at a theoretical freezing point, namely, 0 deg C = 32 deg F. This is done because the true freezing in soil cannot satisfactorily be determined. Factors which may affect the freezing point of soil moisture, such as salinity, are ignored.

These assumptions for the approximation of the problem oversimplify the actual process considerably. However, they have the advantage of being explicit, and can be justified as a means of approach to a better understanding of the processes partaking in the soil freezing experiment.

THEORETICAL BASIS

In studies of processes associated with freezing of soil, both kinds of approaches can be employed, namely, theoretical and experimental.

In theoretical studies, the hydrodynamic (also known as the suction force theory) and the thermodynamic methods usually are considered. Although different in nature, both methods of study, however, have one common feature. This is the fact that it is possible by means of them to calculate the magnitude of the subpressure or suction necessary to cause, upon freezing, the upward flow of soil moisture from ground-water to the growing ice lenses. It is simply a question as to how these suction values compare with each other.

Hydrodynamic Considerations. The suction force theory based on hydrodynamic considerations (8, 4) gives the following expression for the calculation of subpressure:

$$P_s = \frac{(\gamma_w).(\Delta h).(H - \xi)}{(1.09).(k_s).(t)} , \qquad (1)$$

where

P_s = subpressure or suction,
γ_w = unit weight of water,
Δh = allowable amount of frost heave relative to a certain riding length,
H = position or distance of the ground-water table below ground or road surface,
ξ = frost penetration depth,
$H - \xi = L$ = suction length,
1.09 = coefficient to take care of the expansion of water by an amount of 9 percent upon freezing,
k_s = suction coefficient of upward-sucked soil moisture, and
t = duration of freezing period in the field or freezing experiment.

By suction is understood the maximum possible subpressure, P_s, to which the pore moisture of the soil, upon freezing, is subjected in order to cause an upward flow towards the ice lenses.

In this theory the type of experimental system is a hydraulic one. The potential inaugurating the freezing process is temperature. A hydraulic gradient is present, causing a current flow of soil moisture, the current density of which is a volume of moisture flowing through a unit area in a unit of time and having for its conductivity a volume of moisture flowing through a unit area in a unit of time under a unit pressure gradient.

Thermodynamic Considerations. The study of a simplified thermal system "soil-moisture-temperature" can be based also on thermodynamic considerations. In the discipline of thermodynamics, there are two ways by which a thermal system may interact with its surroundings; namely, they are by the performance of work, and by heat transfer. As shown by Dr. Winterkorn, the difference in the amount of heat of a certain volume of water is equal to the amount of (heat) energy transferred in the upward suction process from a region of higher temperature (ground-water) to that of lower temperature (forming ice lenses). According to the second law of thermodynamics, the free energy or maximum theoretical work available in an ideal, mechanically reversible process, where the heat is being exchanged at two constant temperature levels only, can be calculated as follows (9, 11):

$$W_{max} = P_{max} \cdot V = Q \cdot \frac{T_2 - T_1}{T_2} , \qquad (2)$$

where

$P_{max} \cdot V$ = work of the steady flow process (or displacement energy),
P_{max} = maximum absolute pressure difference,
V = specific volume,
W_{max} = maximum work available or free energy that can be obtained from conversion of heat,
Q = total amount of heat transferred from a temperature level of T_2 (ground-water temperature) to a temperature level of T_1 (temperature of freezing ice lenses).

This amount of heat consists of latent heat of fusion of water, Q_L, and the difference in the amount of heat of the transferred matter at the two boundary temperatures without change in phase, Q_P. Because Q_L is relatively large as compared with Q_P, the latter is omitted from the derivation of the subpressure or suction function.

Assuming that V = 1 cm; that the unit weight of water is $\gamma_W = 1$ g/cm^3; that 1 cm^3 of water and 1 cm^3 of ice weigh approximately lg; that $Q_L = 80$ calories, and that 1 calorie = 42,700 g-cm = (4.27) · (10^4) g-cm, the maximum theoretical subpressure, P_{max}, or the difference in pressure due to the work function between the ground-water table and the forming ice lense (for finite difference in temperature between the temperature levels T_2 and T_1 or constant temperature gradients with depth) is

$$P_{max} = \frac{Q_L}{V} \left(1 - \frac{T_1}{T_2}\right) , \qquad (3)$$

or

$$P_{max} = 3.42 \times 10^6 \left(1 - \frac{T_1}{T_2}\right) \left(\frac{g}{cm^2}\right) \qquad (4)$$

The term

$$Q_L \frac{T_1}{T_2}$$

is the amount of heat unavailable for producing work.

When the temperature gradient varies as the depth coordinate in soil increases, then for the calculation of subpressure for a differential process the following differential equation is in order

$$dW = Q_L \frac{dT}{T} , \qquad (5)$$

or

$$P_{max} = \frac{W_{max}}{V} = 3.42 \times 10^6 \ \ln \left(\frac{T_1}{T_2}\right) \left(\frac{g}{cm^2}\right) \qquad (6)$$

In the thermodynamic theory in the suction process the acting potential is temperature. The conductivity is the thermal conductivity. The temperatures operated within this theory are in the absolute thermodynamic temperature system, in Kelvin degrees. The second law of thermodynamics applies to every case of practical importance where heat is converted to work.

Both theories, the hydrodynamic as well as the thermodynamic, presuppose that at the entrance of the system all properties which fix the state of the fluid maintain fixed values, that is, they do not vary with respect to time.

This presupposition concerning the ground-water in soil or the simulated "ground-water" in the experimental device can be approved, particularly relative to temperatures. Ground-water temperature measurements by the author through several winters showed that the temperatures vary from 6 deg C to 10 deg C, the average of which, 8 deg C, for a whole freezing season can be considered as constant. Hence, the viscosity of water can practically be considered as constant also. Thus during the laboratory soil freezing experiment it is possible to maintain the state, at the entrance of the system, at constant or fixed values.

Furthermore, in these theories, the conditions should be such that at the exit (ice lens) from the system fluid properties and velocity do not vary. When moisture molecules have reached the forming ice lens and freeze, the velocity of the upward flow of moisture is zero. Thus, the velocity condition can be considered as satisfied. However, the condition that fluid properties should not vary is not satisfied because just at the exit of the system (ice lens) water upon freezing is converted into ice — in other words, a change in phase takes place accompanied by changes in properties. However, assuming the simplest conditions, in other words, the properties just before converting the water into ice, this condition also can practically be considered as satisfied. It is to be noted, however, that the exit properties, because of the complex porous system, may be and usually are quite different from the entrance properties. Between the two points of reference, the properties might even be unsteady. The latter point becomes particularly obvious when we observe the work-energy Equation 2. This equation merely fixes the entrance and exit temperatures. It says nothing about what happens and how the process takes place within the system between its entrance and exit. This fact can be considered a disadvantage. On the other hand, it also can be considered an advantage, as it gives the final effect of the system, masking out processes between entrance and exit.

Theory, in general, also requires that the flow of soil moisture at the exit must be equal to the flow at the entrance (condition of continuity of flow). This requirement is satisfactorily fulfilled in the hydrodynamic or suction force theory (3) and indirectly in the thermodynamic theory. The latter, however, does not consider the resistance to flow of soil moisture through the system. It treats the process with a 100 percent efficiency and gives maximum possible suction values for every type of material and length of duration, which does not correspond to what can be observed in nature.

In the hydrodynamic theory the resistance to flow of moisture is reflected in the suction coefficient, k_s. It does not, however, consider temperatures directly. Their effect is masked out. Indirectly they are reflected in the suction process itself, as well as in the suction coefficient, and the amount of frost heave.

Because the thermal system "soil-moisture-temperature" in nature does not work with 100 percent efficiency, it is a practical necessity to ascertain the subpressure or suction values in soil upon freezing experimentally.

VALUE OF EXPERIMENTS

Studies of a complex system like that of "soil-moisture-temperature" can, according to the author's belief, be readily and most effectively studied experimentally in the laboratory on a small scale. The purpose of a small scale soil freezing experiment is (1) to gain a better understanding and knowledge of the freezing phenomenon, its process and its resulting effect; (2) to try, through observation, to explain the nature of frost penetration into soil with its associated heat and moisture transmission, with particular reference to the measurements of suction values of soil moisture; (3) to establish the

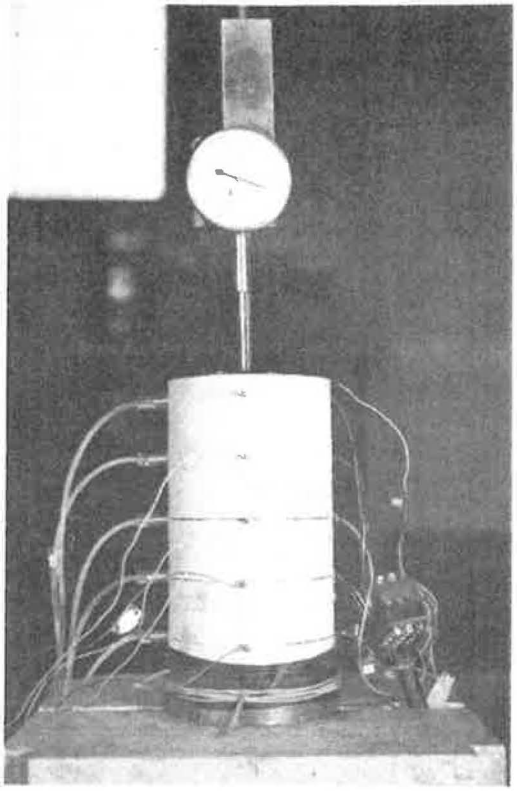

Figure 4. Photograph of the improvised soil freezing apparatus.

frost penetration problem in soil on a somewhat satisfactory scientific basis, and (4) to obtain qualitative experimental data for checking the theories and derivations of physical laws pertaining to this subject, as well as for calculating frost penetration depths in highway soils.

Because almost all physical laws are derived or obtained from experiment, so it is hoped that small scale soil freezing experiments might lead to a formulation of some physical relationships in this discipline.

Small scale laboratory research has the following advantages over full or natural scale field studies: (1) easy handling of experimental apparatus; (2) less expense than incurred in field studies; (3) independence from the mercy of the climate; (4) simulation and reproduction of freezing processes in soil in the frost research laboratory at any time, of any duration and variation; (5) simplification and reduction of a complex system into a less complex one; (6) elimination of extraneous factors and concentration on the elements of interest under investigation; (7) close observation of the processes; and (8) making of exact measurements, thus obtaining reliable data for evaluation and correlation.

After the small scale research is over, the findings can be checked in the field.

THE SUCTION PROCESS OF THE SOIL MOISTURE

During freezing the suction process of soil moisture takes place at a slow rate, and does not attain a state of equilibrium. Although the suction process is slow, a considerable amount of soil moisture can be transmitted during a relatively long period of time. However, it is the slow process of flow which often is overlooked and forgotten. This is the main factor where the danger of damage to roads and runways lies. The suction process continues until all of the soil moisture is consumed, or until the constantly freezing soil layer has grown in thickness and reached the ground-water table, or when the freezing process is checked by an increase in temperature, that is, the moisture in the soil redistributes and a new state of suction equilibrium is again attained. Upon the application of a new freezing thermal gradient, the state of equilibrium is interrupted, and upward flow of soil moisture towards the cold isothermal surface starts again.

When the soil moisture reaches the cold isothermal surface the film water is converted to ice, and gives up heat. The definite amount of heat which is released in the freezing process without change in temperature is called the latent heat of fusion of water. The magnitude of such a heat is 80 calories for one gram of water.

The attachment of the water molecules to the ice crystals induces suction in the soil moisture films. Hence, the lower, cold isothermal surface of the frozen layer (exit of the system) can be assumed to be an acceptor of the prevailing subpressure in the moisture films. Therefore, the subpressures or suction in soil freezing experiments are to be measured at the downwards progressing, ice-forming isothermal boundary.

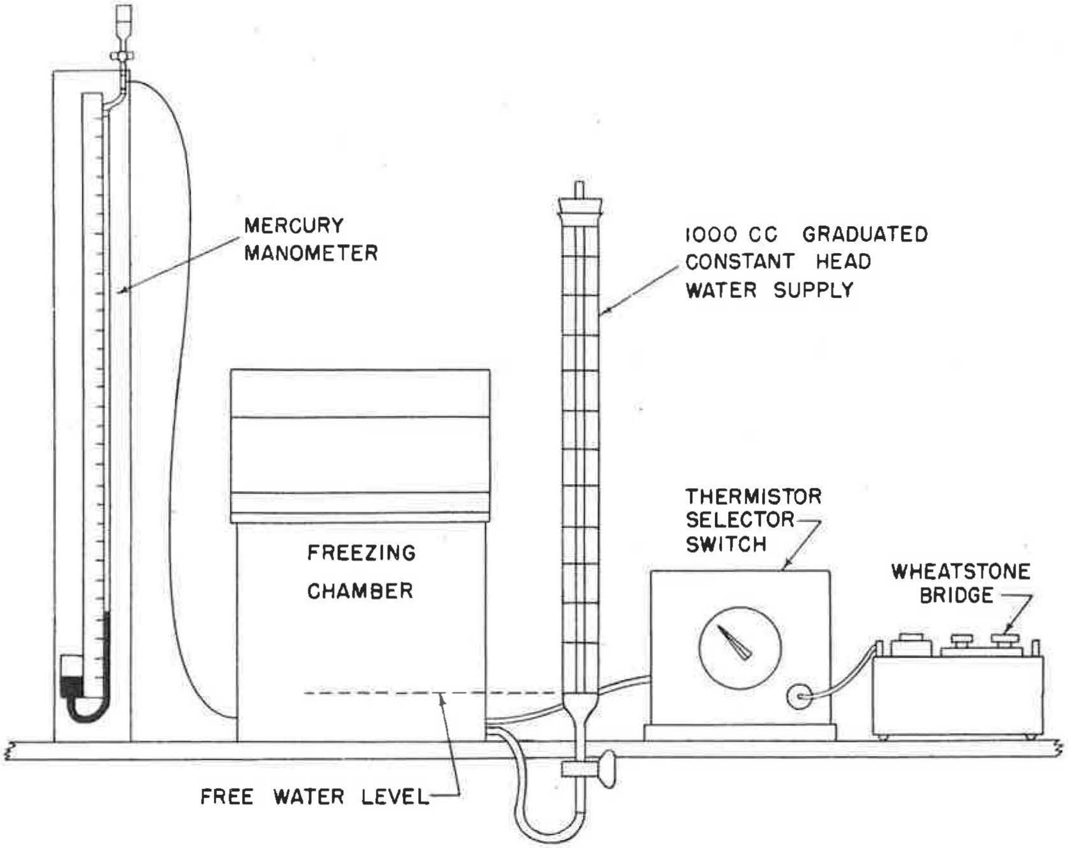

Figure 5. Apparatus used for freezing test.

THE SOIL FREEZING EXPERIMENT

General Notes. The processes in a soil freezing experiment correspond very nearly to those occurring in nature. Under the action of freezing temperatures the soil and soil moisture freeze. The frost penetrates the soil from the ground surface downward. Also, volume changes in the soil sample in the form of frost heaves are produced in the freezing process.

First, water freezes in the larger voids of the soil. The nuclei of ice crystals so formed start to grow, sucking up soil moisture from the surrounding soil and from ground-water or proximity of other water sources until the soil underneath the cold isothermal boundary of ice lenses freezes. This frozen layer of soil underneath the so-called ice line interrupts the supply of moisture to the ice lenses. The same process then starts deeper, forming in silty soils parallel layers of segregated ice layers.

Objectives. The main objectives of the improvised soil freezing experiment here described are to demonstrate the upward sucked soil moisture from the "ground-water table" towards the freezing ice lenses upon freezing the soil sample from the top downwards, that is, upon the application of a thermal potential, and to report on subpressure or suction measurements in the freezing soil.

No attempt was made in the experiment to simulate any particular climatic freezing condition. The main purpose was to see whether suction can be measured. It is hoped that after perfection of the freezing apparatus, there will be provided enough observation and test data to establish a method or criterion index for the evaluation of frost-susceptible soils as well as for the calculation of frost penetration depth.

Apparatus. The improvised soil freezing apparatus was constructed mainly for the demonstration of the upward motion of soil moisture from "ground-water" upon freezing as well as for the purpose of trying to measure suction in soil upon freezing. Figure 4 is a photograph of the equipment. Figure 5 illustrates the complete apparatus in line drawing. The apparatus consists of a freezing chamber (Figure 6). The soil specimen to be frozen is contained in an open-ended $4\frac{1}{8}$ in. inside diameter by $8\frac{1}{2}$ in. long waterproofed cardboard tube, the inside of which was greased with technical vaseline. The base of the soil sample is inserted in a perforated brass receptable or cup which is in communication with a constant level water supply, adjusted to give a free water level, specifically, ground-water table in the soil sample.

The soil specimen, when positioned for freezing, is enclosed within an insulated box made from Celotex. During a freezing experiment the space between the soil specimen and the sides of the box is filled with vermiculite insulating material.

Freezing is done by means of dry ice contained in a sidewise insulated can. There is a space provided between the top of the soil specimen and the ice can to permit heaving of the frozen soil. An Ames dial indicator indicates the amount of heaving. The temperatures within the soil specimen during freezing are measured in terms of electrical resistance by means of six helically spaced thermistors. A thermistor unit is illus-

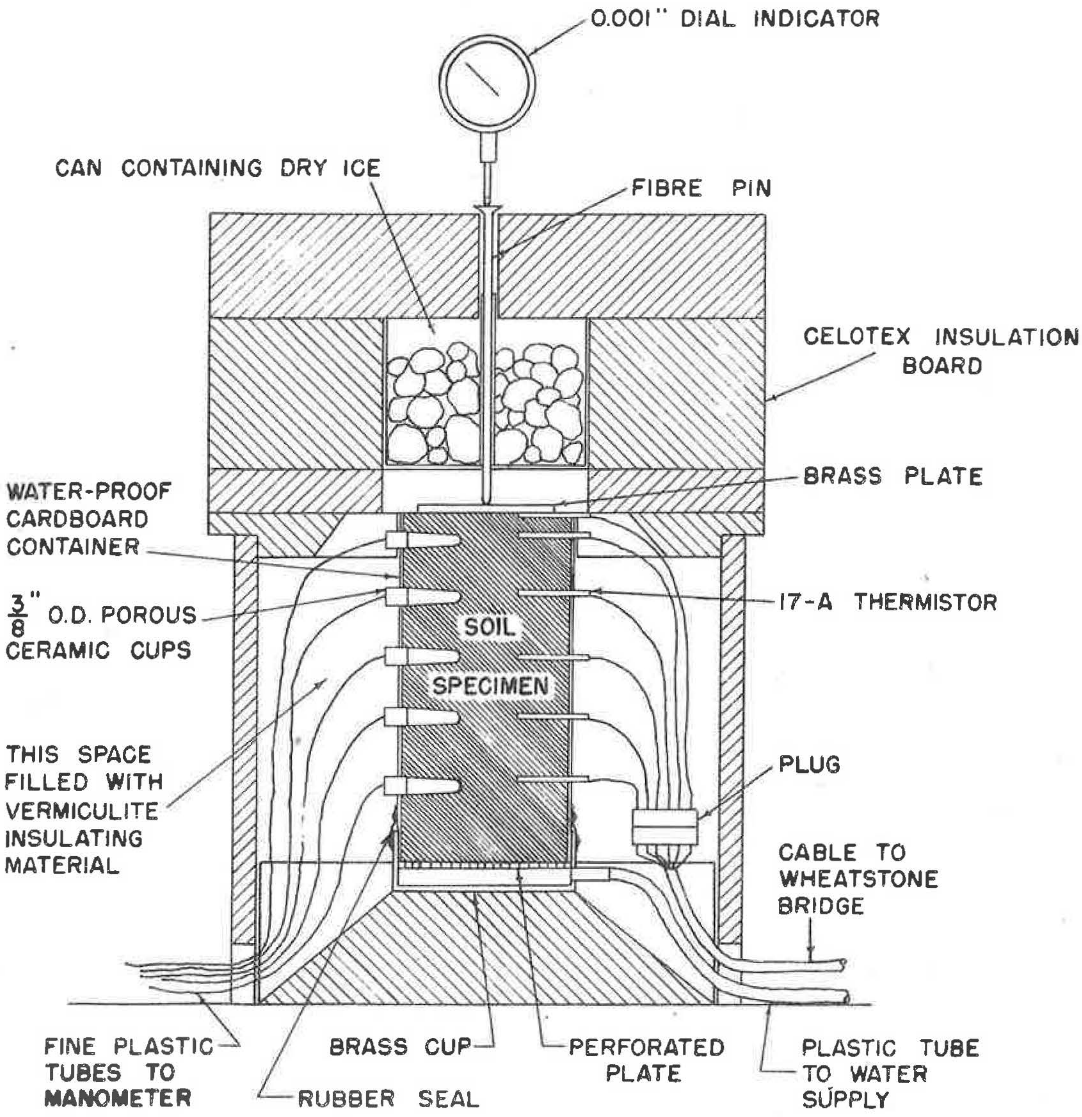

Figure 6. Freezing chamber.

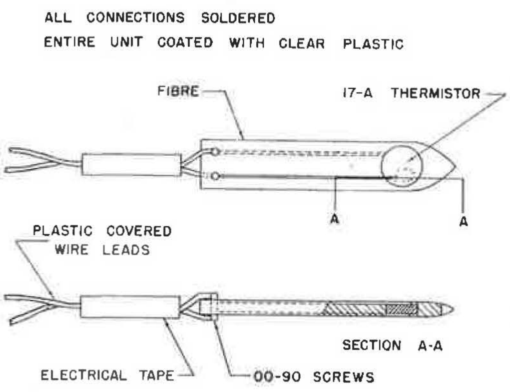

Figure 7. Thermistor unit.

trated in Figure 7. The thermistors were spaced from surface down, at 0, ½, 2, 3½, 5 and 6½ in. depths, respectively.

Subpressures were measured by a mercury manometer connected to the system by means of a suction cup at a depth of 3½ in. from the top of the specimen. The latter provides a connecting link or continuity between the moisture films in the soil specimen and the suction-measuring manometer. Any number of suction cups, as the system permits, can be inserted to learn the variation in subpressure along the height of the soil specimen. The mercury-water manometer was justified because the freezing and suction processes are relatively slow. It permitted accurate subpressure measurements. It was constructed with as small a core as possible in order to minimize the amount of water in the manometer that was consumed as an additional moisture supply for the growth of the ice lenses in the freezing soil specimen.

Soil. The soil used in this freezing experiment was a Dunellen soil, the grain size distribution of which is shown in Figure 8. The soil is a silty glacial outwash material. Its consistency limits are liquid limit, 16 percent, and non-plastic. The maximum dry density and optimum moisture content of this soil, determined according to the standard Proctor compaction method, are 120 pcf and 12 percent, respectively. The soil at a moisture content of 12 percent was compacted into a cardboard tube in five layers, applying ten blows per layer of a 5.5-lb compaction rammer falling 12 in. The soil specimen prepared in this way had a dry density of 120.9 pcf.

Freezing Test. The soil specimen, before freezing, was allowed to absorb water from the ground-water supply. This was done partly to simulate field conditions and partly to establish the moisture films within the specimen. Forty-four cm^3 of water

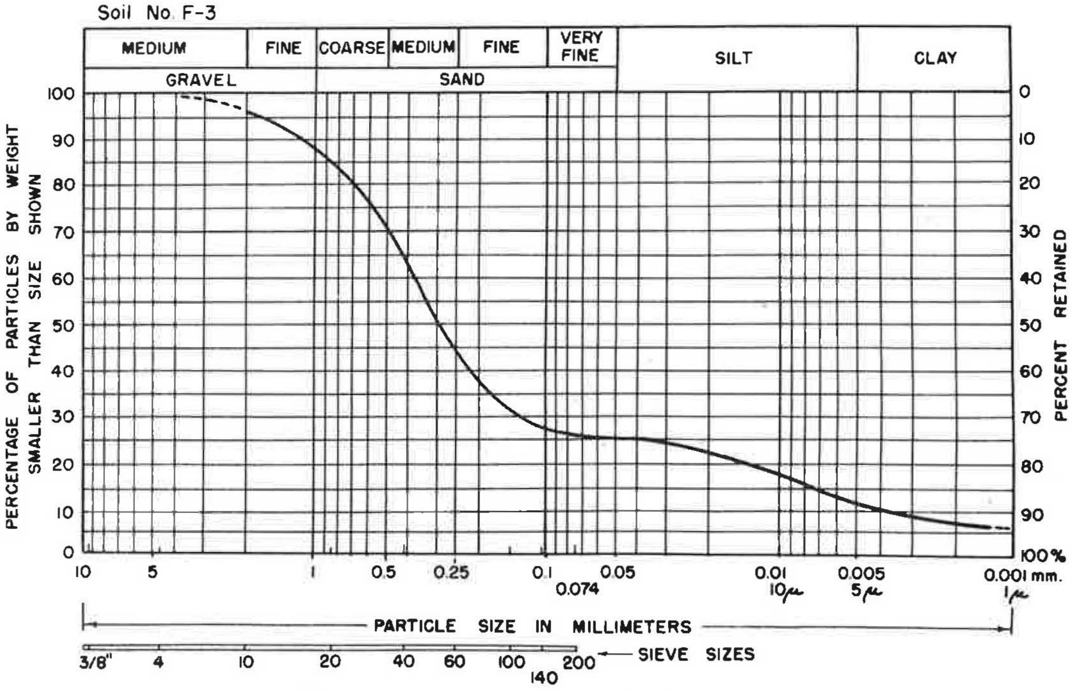

Figure 8. Grain size distribution curve.

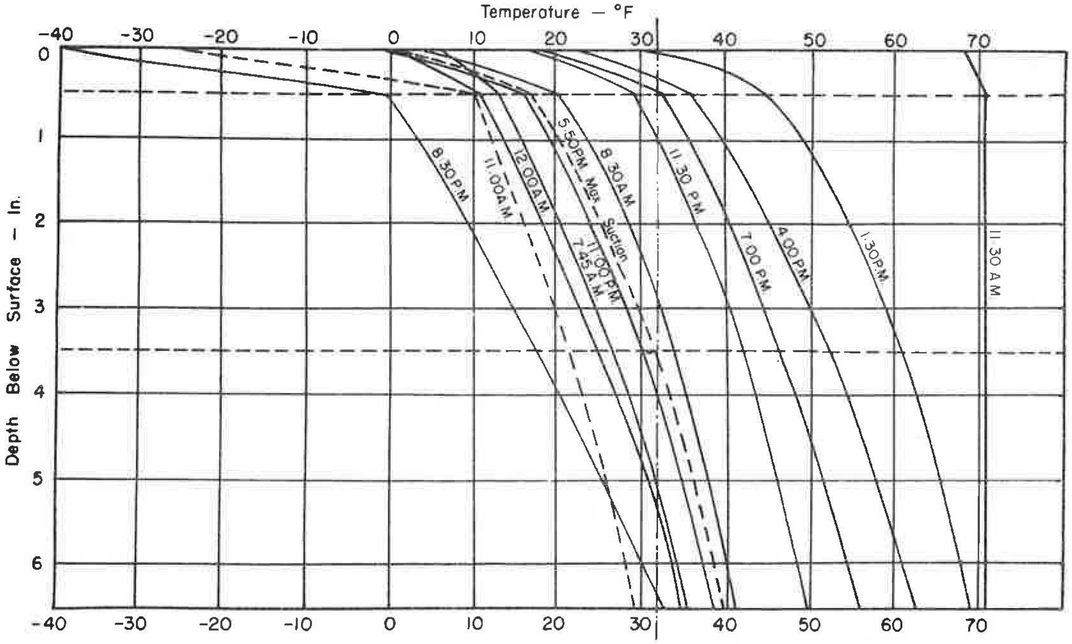

Figure 9. Temperature - depth curves (Tautochrones).

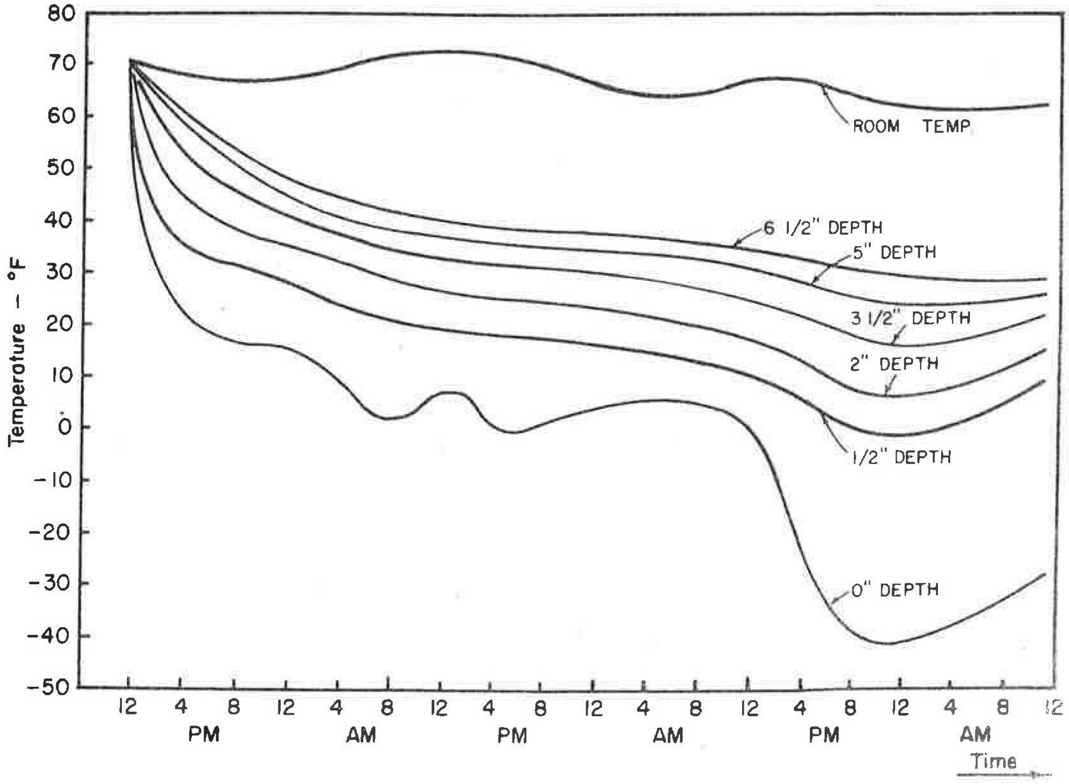

Figure 10. Time - temperature curves.

were absorbed during a 40-hour period, increasing the moisture content in the specimen to approximately 13.5 percent. The manometer indicated a slight moisture tension which reduced as absorption progressed.

The freezing chamber was then assembled, the dry ice can filled and observations started. Freezing was started at 11:30 a.m., April 22, 1954. The last readings were taken at 11:20 a.m., April 25, 1954. Soil temperatures, subpressures, volumes of upward-sucked ground-water and amounts of frost heaves were measured during the freezing process. Room temperatures were also noted. These data were recorded at 15-minute intervals for one and a half hours. This time interval was then extended to two hours.

Results. The results of a certain soil freezing experiment (Test No. 4), undertaken with illustrative purposes in mind, are shown here in a graphical form. Figure 9 represents some of the temperature-depth curves or tautochrones of the soil, the shapes of which agree with theoretical ones. They show the depth of frost penetration and indicate, indirectly, the rate at which the theoretical freezing temperature of 0 deg C = 32 deg F penetrated the soil specimen. The curved tautochrones indicate that after the frost had penetrated approximately half-way down (3½ in.) into the soil specimen, the tautochrone in the unfrozen part of the soil can practically be assumed to be straight lines, and thus the temperature gradient constant.

It can be noted from this graph that the soil specimen was subjected to an intense cold. At the start of the freezing experiment, 11:30 a.m., the temperature of the soil specimen was still at room temperature (note vertical, constant tautochrone). The colder the surface temperatures, the deeper the frost penetration (intersection of tautochrones with the 32 deg F-line). Because of the thermal properties of the soil (for example, heat capacity, latent heat of fusion and conductivity), the frost penetration into the soil suffered a time lag and retardation. The deeper the soil specimen was frozen, the more the tautochrones moved to the colder side on the graphs.

The dashed tautochrone marked at 5:50 p.m. corresponds to temperature conditions

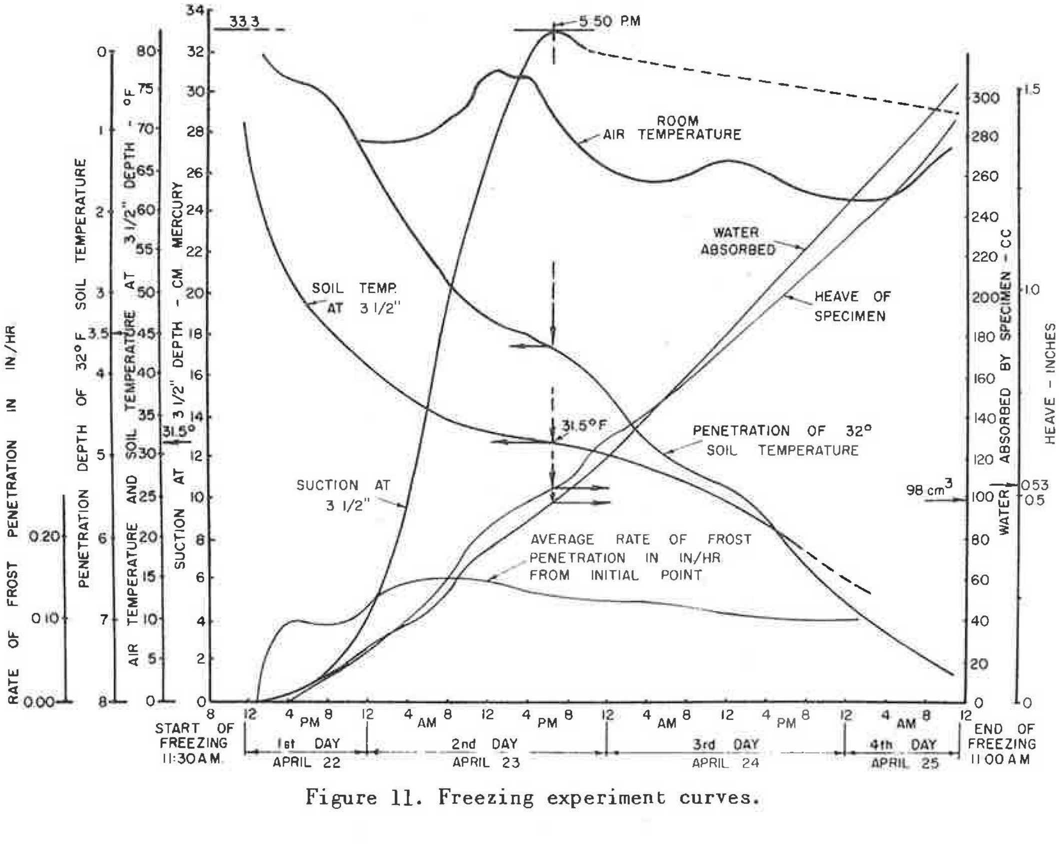

Figure 11. Freezing experiment curves.

when frost penetrated the soil specimen $3\frac{1}{2}$ in. deep, reaching the suction point, and where and when the maximum subpressure or suction for that point was measured.

The soil specimen was then frozen all the way down to the ground-water table $6\frac{1}{2}$ in. below the top of the specimen. The dashed line tautochrone marked 11: 00 a. m. indicates the last tautochrone in the freezing process. Note that the lower branch of this tautochrone approaches assymptotically the 32 deg F-line.

Figure 10 shows the time-soil temperature curves at the positions of the thermistors. The fluctuation of the soil surface temperature is a result of fluctuating room air temperature and the removal of the top of the chamber for inspection and replenishing of dry ice. This figure illustrates well the influence of the surrounding temperatures on the freezing process within the thermal system, and indicates the need, in soil freezing studies, for a controllable constant temperature room in order to keep, as nearly as possible, the ground-water and the suction manometers at constant temperatures. Such a room is desirable likewise for housing the actual soil freezing chambers, and to provide automatically controllable soil freezing equipment for freezing soil specimens either at constant temperatures or under cyclic variations.

In Figure 11 are shown the following relationships with time as observed in this experiment: (1) air room temperature as a function of time; (2) penetration depth in soil of the 32 deg F temperature; (3) rate of frost penetration; (4) water absorbed from ground-water by upward suction into soil upon freezing; (5) soil temperature at $3\frac{1}{2}$ in. depth during the whole freezing process; (6) subpressure or suction in soil upon freezing at $3\frac{1}{2}$ in. depth; and (7) frost heave.

The adverse influence of the room air temperature on the freezing process of the soil specimen is clearly reflected.

The rate of penetration of frost into the soil specimen decreases with time. This can be explained by the fact that the heat conduction of the growing ice lenses, or frozen layers, is considerably less than that of water. Besides, heat is transferred upward from a warmer region to a colder one, releasing heat to the surface and thus retarding the rate of frost penetration. Also, the rate of frost penetration in the soil decreased at each peak of the air temperature.

Frost penetration started at 1: 00 p. m. , heaving at 4: 00 p. m. on the same day. By the time frost penetrated the soil $3\frac{1}{2}$ in. (at 5: 50 p. m. next day), the amount of water "sucked up" from the burette was 98 cm^3, and frost heave was measured at 0. 53 in. The measured head of the subpressure or suction at the $3\frac{1}{2}$ in. depth reached a maximum of 33. 3 cm mercury = 14. 85 ft of water or 0. 462 t/ft^2 vacuum when the soil temperature at that suction measuring point was 31. 5 deg F, indicating that this soil medium froze at a temperature of less than 32 deg F.

After the frost passed below the suction point, its manometer was no longer operative. After the whole specimen was frozen through, the manometer indicated a slight drop in subpressure. At the end of the experiment the manometer showed 29. 2 cm mercury (see the dashed part of the suction curve in Figure 11).

COMPARISON OF THEORETICAL AND MEASURED SUCTION VALUES

1. The suction value, P_S, calculated for the described experimental conditions by means of the hydrodynamic Equation 1 with $k_S = 0.0000028$ ft/min and for $t = 1820$ min, is $P_{SN} = 0\ 083\ \text{t/ft}^2$.

2. The thermodynamic theory, assuming a linear temperature gradient (chord method), by Equation 2 or 3 gives an average maximum theoretical suction value of $P_{STc} = 0.523\ \text{t/ft}^2$.

For a variable course of temperature gradient, the maximum theoretical suction value (by Equation 6)is approximately $P_{STv} = 0.529\ \text{t/ft}^2$.

3. The suction value measured in the experiment was $P_{Se} = 0.462\ \text{t/ft}^2$.

A comparison of these values shows that the hydrodynamic suction value is about 15. 9 percent of that obtained from the thermodynamic expression. Of course, much of the suction value, P_{SH}, depends upon the accurate determination of the suction coefficient, k_S. Besides, more experiments are needed before any conclusion may be drawn.