Effective Soil Moisture Transfer Mechanisms Upon Freezing

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This paper describes the results obtained from freezing experiments on soil systems prepared at various porosities. The tensiometer theory, based on the mechanical principle of virtual work, underlying the subpressure measurement technique as applied to a freezing soil system reveals that the tensiometer measurements do not disclose in themselves the various soil moisture transfer mechanisms but indicate only the magnitude of the total pressure differences resulting from the simultaneous action of the various possible soil moisture transfer mechanisms in nature as well as in the laboratory.

These experimental studies clearly demonstrate that the soil moisture transfer in the vapor phase upon freezing is relatively ineffective as compared with soil moisture transferred by way of the film mechanism.

● IN PERFORMING RESEARCH on soil systems subjected to freezing one cannot escape the observation that the amount of soil moisture transferred upward from the ground-water table to the cold front, all other conditions being approximately the same, depends very much on the state of packing of the soil; namely, its porosity.

In the past, several authors (1, 2) have expressed the opinion, or showed by calculations (3), that soil moisture transfer in the vapor phase is an ineffective soil moisture transfer mechanism. In 1956, the author submitted to the Engineering Research Advisory Committee at Rutgers University College of Engineering, a frost action research memorandum, wherein the various upward soil moisture transfer mechanisms were formulated (4, 5, 6).

Tensiometer

Under the influence of a temperature gradient the soil moisture flows upward from the ground-water towards the cold front via the soil moisture films coated around the soil particles through poorly defined flow paths in a zigzag motion.

During the course of its upward migration, the flowing water loses some of its driving pressure. This means that the driving pressure in the system's flow performs some mechanical work that is lost. Thus, in doing external, over-all work, the entire freezing soil system loses some of its energy. The driving pressure (soil moisture tension) of the upward-flowing soil moisture in the porous medium of soil may be measured by means of so-called tensiometers (7, 8). The term "tensiometer" reflects literally the function of the device. Figure 1 shows the type of conical tensiometer developed from the author's studies and now used in his work for detecting soil moisture tensions in prepared soil systems subjected to freezing.

The tensiometer is a porous, thin-walled, ceramic moisture-tension sensing element of known porosity and known surface area (Table 1).

Virtual Work in a Freezing Soil System

The author (6, 9, 10) has described that in a freezing soil system several soil moisture transfer mechanisms may act simultaneously in translocating soil moisture upward from the ground-water (warm region) to the cold front. In such a case, all the partaking soil moisture transfer mechanisms contribute to a resultant driving pressure; namely, subpressure (or resultant soil moisture tension or pressure deficiency).

TABLE 1

Characteristic	Value
Effective surface area (sq cm)	30.52
No. of capillaries per sq cm	2325×10^5
Porosity (percent)	57
Average capillary radius	0.3μ
Bubbling gauge pressure (=air entry value) (at m)	2

Figure 2 shows an element of soil, abcd, into which a tensiometer is inserted. The freezing soil system is laterally insulated, so that a unidirectional upward flow of heat, soil moisture, and cations in the electric diffuse double layer can take place (9).

When a differential volume of water, dV, is transferred from the tensiometer to the soil, then the draw of water out of the tensiometer brings about a decrease in pressure in the tensiometer water and the mercury rise in the closed leg of the manometer, connected to the tensiometer, makes up the difference in volume. Thus, the adjusted difference in the mercury levels in both legs of the manometer may be considered a measure of the resultant tension forces prevailing in the soil-water-temperature system on the upward flow of soil moisture.

On drawing out a differential volume of water, dV, from the tensiometer, water in the tensiometer is subjected to a certain pressure, p. In doing so, the resultant water absorptive forces in the soil perform a differential mechanical work, dW, and the work performed by the pressure, p, in transferring a differential volume of water, dV, from the tensiometer to the soil is $p \cdot dV$.

When this differential volume of water, dV, leaves the tensiometer and enters through its porous walls into the soil, this volume of water, dV, displaces an equal volume of air that prevailed in the partially water-saturated voids of the soil. In this case, the displacement of a volume of air, dV, against atmospheric pressure, p_a, results in a differential mechanical work, the magnitude of which is $p_a \cdot dV$. Now, by the principle of virtual work, the total work done by all the forces on the system in any virtual displacement is equal to zero:

$$dW + p \cdot dV - p_a \cdot dV = 0 \tag{1}$$

The work per unit volume of water taken up by the porous soil system and thereby done by the resultant water absorptive forces prevailing in the soil-water-temperature system is

$$dW/dV = p_a - p \tag{2}$$

where

$p_a - p$ = pressure difference on the two sides of the porous wall of the tensiometer

Eq. 2 indicates that the mechanical work performed per absorbed unit volume of water by the soil is independent of the nature of forces that drive the water through the soil and holds for soils of all textures, such as sands, silts, and clays. Hence, this equation shows that the measurement of the water surface tension reveals only the magnitude of the total soil moisture driving pressure, $p_a - p$, as the resultant pressure available in the freezing dynamic soil system. The tensiometer measurements, thus,

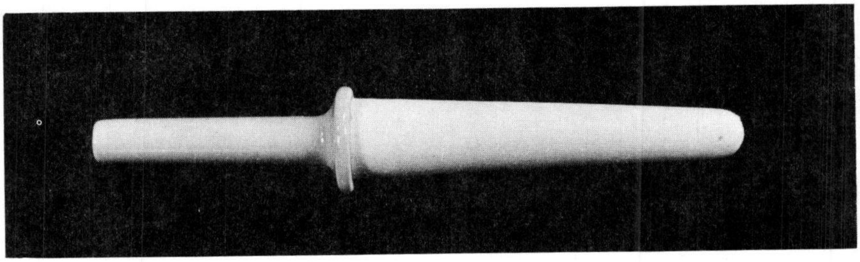


Figure 1. Conical tensiometer.

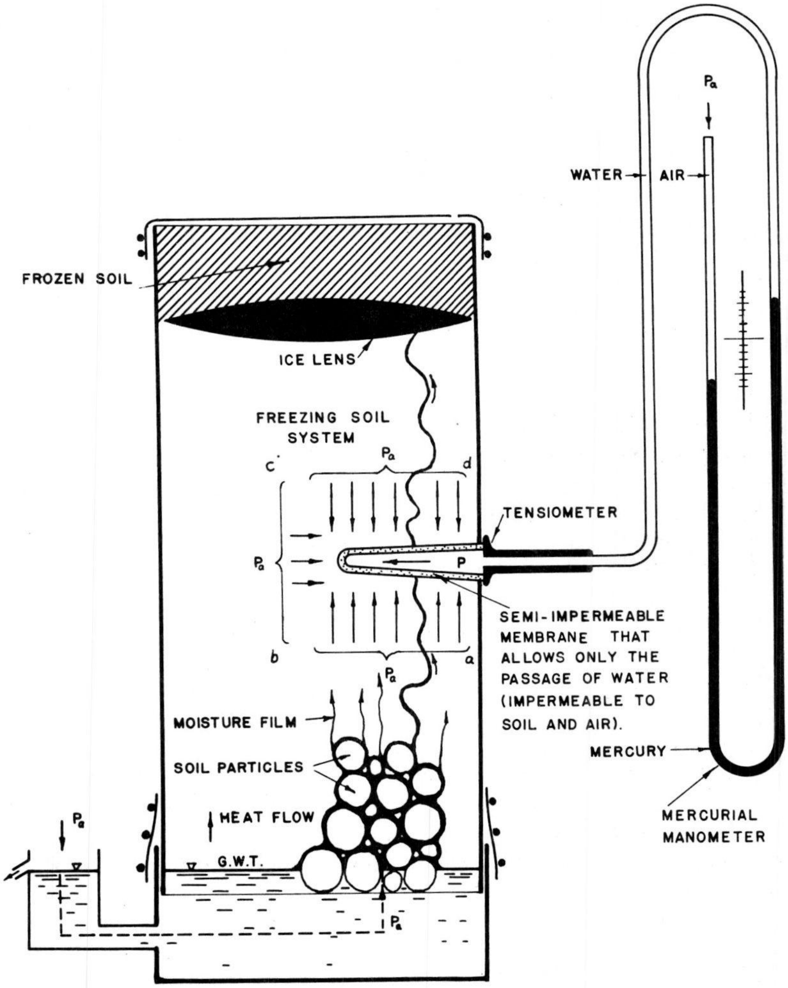


Figure 2. Soil-tensiometer-water system.

do not disclose in themselves the various soil moisture transport mechanisms resulting in the pressure difference p_a - p. As stated above, such (p_a - p) measurements indicate only the magnitude of the total pressure difference resulting from the simultaneous acting of the various soil moisture transfer mechanisms, as they may be present and acting in the freezing soil system in nature as well as in the laboratory.

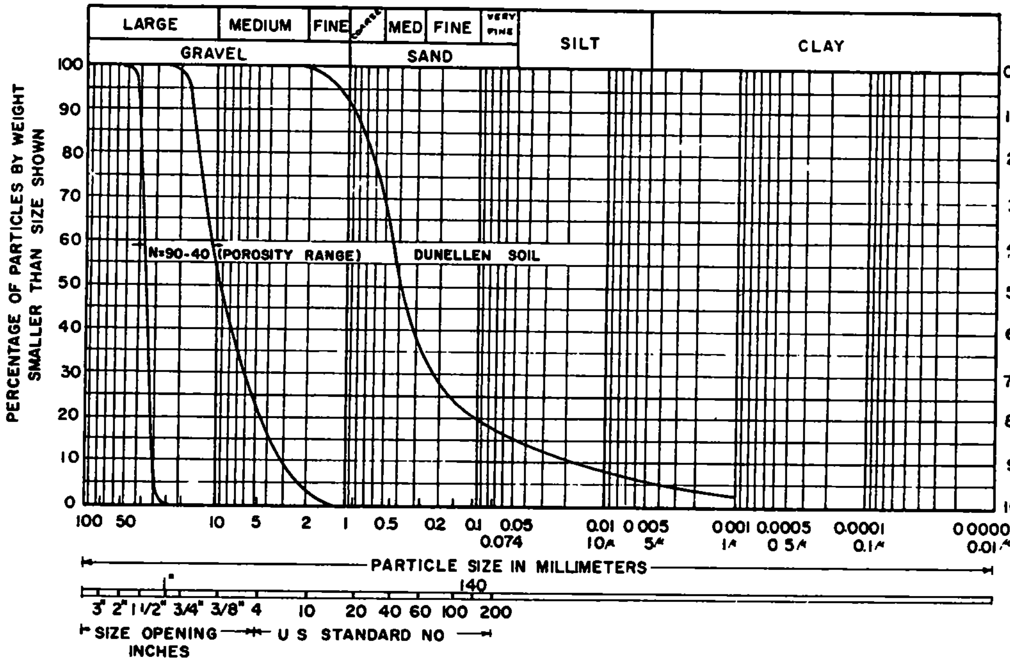


Figure 3. Soil particle size accumulation curves.

Rengmark's Publication on Vapor Transport in Soil

In 1953, Rengmark (11) published a paper on vapor transport in soil. The contents of that paper are that the vapor transport through an intermediary layer of sand or gravel upward to a "binder" has been investigated partly at a constant temperature (temperature gradient = 0/cm), and partly at a temperature gradient of 16 C per 30 cm during periods of 24, 240, and 720 hr. His temperature gradient was a non-freezing one, dropping from +20 C at the "ground-water" to +4 C at the surface. Rengmark concluded that the vapor transport decreases with the decreasing size of the soil particles in the intermediary layer.

Purpose of Paper

The purpose of this paper is to report on the author's studies of freezing soil systems. The object of the studies, in turn, was to make a scientific inquiry into the effect of soil porosities on the amounts of soil moisture transferred from the ground-water to the cold front. Another point of interest in this work was to make deductions from the results obtained in the soil freezing experiments as to within what ranges of porosity of the soil the film transport of soil moisture is more effective than the moisture transfer mechanism by vapor diffusion.

EXPERIMENTS

The soil used in the freezing experiments was a glacial outwash soil, called Dunellen soil, with a 14 percent silt and clay content, as shown in Figure 3, for porosities from n = 27.8 percent to n = 47.8 percent. The soil systems for freezing at porosities greater than n = 47.8 percent were prepared of the coarser particles of the soil under study. The particle size accumulation curves of the latter are shown in Figure 3 as a band of two steep curves and designated with n = 60-90 percent. Beginning with a porosity of about n = 60 percent, the particles are in no contact with each other. The size of the soil systems is 15.2 cm in diameter and 30.0 cm in height.

The freezing equipment used in these studies is shown in Figure 4. In the freezing chamber, the soil sample is placed with its lower end in the "ground-water," the tem-

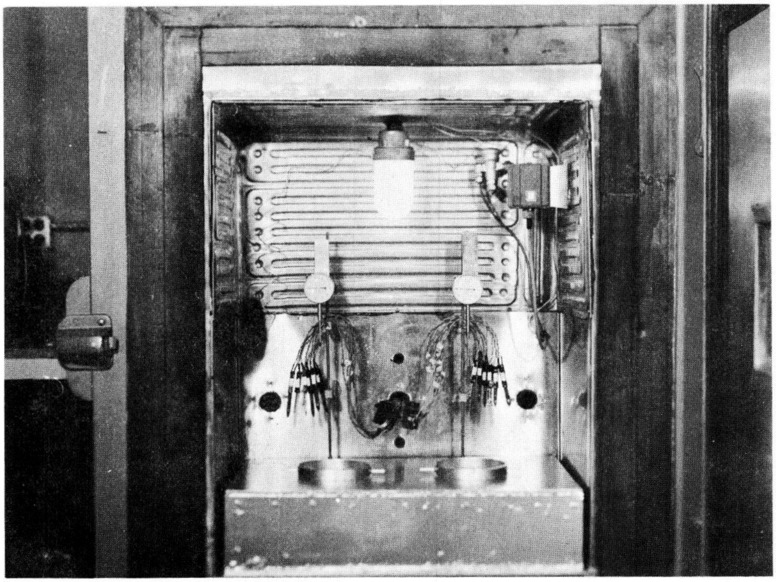


Figure 4. Soil-freezing compartment.

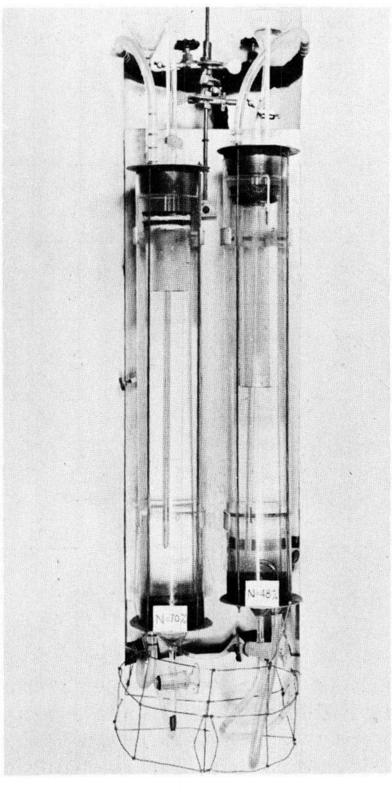
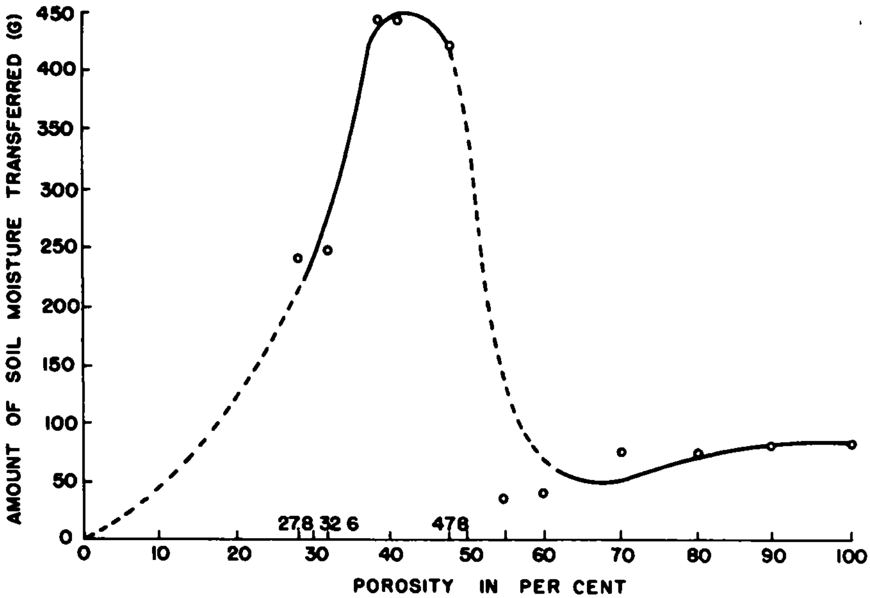


Figure 5. Device for maintaining a constant ground-water table and measuring the amount of soil moisture taken up to the freezing of soils.

perature of which is maintained constant at 8 C, which is an average annual temperature of the ground-water actually observed in the field. The ground-water level is maintained constant by means of a constant level device (Fig. 5). This device also permits one to observe at any time during the experiment the amounts of moisture transferred from the ground-water to the freezing soil system. To prevent lateral heat flux, the soil cylinders placed in the freezing chamber are laterally insulated with cork and vermiculite, so that, upon freezing of the soil samples from the top, a virtually unidimensional heat flow takes place from the ground-water upward through the soil system towards the cold front. Because of the upward direction of the dropping temperature gradient and unidirectional heat flow, the soil moisture in the soil sample is likewise transferred upward along the temperature gradient. For purposes of comparison all soil systems were studied under similar conditions; that is, at the same temperature and maximum temperature gradients, namely 0.53 C per cm and for a period of seven days = 168 hr.

Figure 6, compiling the results of these experiments, shows that the effective soil moisture transfer mechanism is by way of the film flow (unsaturated flow) within the porosity range between about n = 27.8 percent and n = 47.8 percent. In this range,



TEST NO.		B-6	B-9	B-4	B-7	B-5	A-8	A-6	A-5	A-3	A-4	A-7
EFFECTIVE MOISTURE TRANSFER MECHANISMS	LOWER POROSITIES THAN N = 27.8 % DIFFICULT TO ATTAIN IN PRACTICE	EFFECTIVE FILM FLOW					FILM AND VAPOR FLOW		PURE VAPOR TRANSFER			
OPTIMUM M C IN %		12.6	15.3	13.8	12.8	12.4	-	-	-	-	-	-
MAXIMUM DRY DENSITY IN LB/FT^3		119.8	119.7	102.1	97.7	86.7	71.2	63.0	46.5	29.9	13.4	0
VOID RATIO (e)		0.385	0.484	0.626	0.695	0.916	1.22	1.50	2.33	4.00	9.01	∞
AMOUNT OF MOISTURE TRANSFERRED: ABSOLUTE AMOUNT IN GRAMS		239.0	250.0	445.6	445.0	424.0	36.0	41.0	77.0	75.0	82.0	83.0
AMOUNT OF MOISTURE TRANSFERRED: RELATIVE TO MOISTURE TRANSFERRED AT 100 % POROSITY		2.88	3.01	5.47	5.46	5.11	0.43	0.49	0.93	0.90	0.99	1.00

Figure 6. Soil moisture transfer as a function of porosity of soil upon freezing.

because of the close packing of the soil particles and hence relatively great resistance for vapor movement, it can be deduced that the vapor diffusion is an effective soil moisture transfer mechanism. This figure also permits one to conclude that between porosities of about n = 60 and 100 percent the effective soil moisture transfer mechanism is by way of vapor diffusion. However, in this range, the amounts of soil moisture transferred are several (two to five) times less than by way of the film mechanism, so that even relative to other soil moisture transfer mechanisms the vapor transport mechanism can also be considered as ineffective, particularly if one considers the fact that the porosities, n, of soils in their natural or artificially compacted conditions are usually between about n = 30 and 40 percent.

As Figure 6 shows, there are no sharply defined boundaries between the various modes of soil moisture transport mechanisms and processes. It is, therefore, quite reasonable to assume that a transition from one mode to another (for example, the interval between porosities of about n = 50 percent and about n = 70 percent) constitutes a combination of various simultaneously-acting modes of transport. From these experimental studies one also deduces that in reporting research results on moisture transfer in soils upon freezing it is essential to report the porosity of the soil, because for each degree of packing there may be a different moisture transport mechanism in action.

CONCLUSIONS

This experimental study shows clearly that, all other conditions being the same, the following obtain:

1. The amount of soil moisture transferred upon freezing from "ground-water" to the cold front is the greater the less the porosity of the soil.
2. At a porosity from about n = 27 percent up to about n = 50 percent the most effective mechanism for the upward flow of moisture is the mechanism of film flow.
3. The porosity for the minimum amount of soil moisture transfer in these experiments is between about n = 60 percent to about n = 75 percent; in this range the effective moisture transfer mechanism is by way of vapor diffusion.
4. From a porosity of about n = 75 percent up to n = 100 percent, the moisture transfer takes place exclusively by vapor diffusion.
5. Although occurring in measurable quantities, the moisture transfer in the vapor phase at n = 100 percent constitutes only about one-fifth of the maximum amount of soil moisture transferred in the film phase, say at n = 40 percent (Fig. 6). In other words, the maximum moisture transfer in the film phase at n = 40 percent is five times as large as that at n = 100 percent.
6. The minimum amount of soil moisture transfer in the vapor phase at n = 65 percent constitutes about 50 percent of the maximum amount of soil moisture transferred by pure vapor diffusion at n = 100 percent.
7. Depending on the degree of porosity (namely, state of packing of the soil) one soil moisture transfer mechanism is more effective than another; at lower porosities the film mechanism predominates, whereas with high porosities the vapor transport mechanism governs. Further, between these two soil moisture transfer mechanisms there is an interval of transition in the soil porosities in which the film and vapor transfer mechanisms coexist simultaneously.
8. The least amount of moisture is transferred upward in the porosity range between about n = 60 percent and about n = 70 percent, porosities that are higher than those obtained for this soil in the standard compaction test (n = 32 percent).
9. Based on these observations it appears that in the soil studied, when compacted in the field at or nearly at its optimum moisture content (w = 12.0 percent) by standard compaction (maximum dry density W_d = 120 pcf), the amount of soil moisture transferred up to the cold front would be $\frac{2.66}{0.50} = 5.76$ times more than that transferred at the porosity of about n = 65 percent. The profound effect of porosity on the amount of soil moisture transferred from ground-water to the cold front is thereby demonstrated.

All in all, these experimental studies indicate that the soil moisture transfer in the vapor phase is relatively ineffective as compared with soil moisture transferred by way of the film mechanism.

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