

# Measuring Negative Pore Water Pressures in a Freezing Environment

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The measurement of negative pore water pressures is essential to the study of soil behavior in a freezing environment. Various devices are now available for suction measurements in unfrozen, unsaturated soils. The possibility of using these devices in the measurement of negative pore water pressures under freezing conditions is discussed. The thermal conductivity sensor appears to be a promising device for suction measurement. The thermal conductivity method of suction measurement in a freezing environment is examined. The theory of freezing soil and the thermal properties of soil are presented. Suction measurements in a freezing environment using thermal conductivity sensors from recent tests conducted at the University of Saskatchewan are also presented. The results are interpreted using the theory of freezing soil and the thermal properties of soil. The latent heat of fusion associated with the water phase transformation of water has significant influence on the thermal conductivity reading of the sensor during freezing and thawing. The formation of ice on freezing makes the interpretation of sensor reading difficult because of the significantly higher thermal conductivity of ice than that of water.

The negative pore water pressures in a soil or soil suctions affect the moisture flow, volume change, shear strength, and frost-heaving characteristics of a soil as it freezes. There is therefore a need for reliable techniques to measure negative pore water pressures in a freezing environment. Various techniques are now available for measuring soil suction in unfrozen soils. Of these techniques, the thermal conductivity sensor appears to be one of the most promising devices. The suitability of the thermal conductivity sensor for in situ suction measurements in a freezing environment is evaluated.

## PHYSICS OF THE PROBLEM

As temperature drops below 0°C, some soil waters freeze producing ice in the soil. Consider the situation of a thermal gradient with the coldest temperature at the ground surface. Figure 1 (1) shows a typical temperature gradient in a soil under freezing conditions. Water moves from the unfrozen zone to the frozen zone through a thin partially frozen fringe. The frozen zone slowly advances to a greater depth below the ground surface.

The ability of water to move upward to the freezing fringe is attributed to the development of a negative pore water pressure (suction) gradient through the frozen fringe as shown in Figure 1 (1). The suction can be negligible in sands, but

more significant in silts and clays depending on the temperature gradients and the rate of freezing (2). The suction just below the frost front can range from 6 kPa in silt to 400 kPa in Leda clay (3). The suction values in the frozen zone increase with decreasing temperatures below 0°C.

Water can exist in three phases as shown by a phase diagram (Figure 2). The fusion curve, *OC*, is associated with the freezing and thawing processes. At a given temperature, *T*, ice and water can coexist under a specified pressure as determined by the fusion curve, *OC*. The slopes of the curves on the phase diagram in Figure 2 are described by the Clausius-Clapeyron equation (4). For the fusion curve, *OC*, the slope has the following relation:

$$\frac{dP}{dT} = - \frac{L}{T v_w} \quad (1)$$

where

$dP$  = change in pressure;

$dT$  = change in temperature;

$L$  = latent heat of fusion, which is the heat liberated when water turns to ice or the heat absorbed when ice turns to water (i.e., 333 kJ/kg);

$T$  = temperature (°Kelvin); and

$v_w$  = specific volume of water [i.e.,  $1/\rho_w$  where  $\rho_w$  is the water density (1,000 kg/m<sup>3</sup>)].

Equation 1 has commonly been used to calculate the suction developed in the freezing fringe. Williams (2) defined the suction in the frozen soil as the difference between the ice and the pore water pressures ( $u_i - u_w$ ), where  $u_i$  = ice pressure and  $u_w$  = pore water pressure. The ice pressure,  $u_i$ , is usually assumed to be constant (e.g., atmospheric pressure, or  $u_i = 0$  gauge). This definition of suction is analogous to the matric suction definition in an unsaturated soil. The presence of suction results in a lower freezing temperature from that of the normal freezing temperature of 0°C or 273.15°K (5). The suction in the frozen soil can be related to the lowering of the freezing temperature below 0°C (i.e.,  $dT_0$ ) using Equation 1.

$$\frac{d(u_i - u_w)}{dT_0} = - \frac{L}{T_0 v_w} \quad (2)$$

where

$T_0$  = normal freezing temperature in Kelvin (i.e., 273.15°K or point O in Figure 2); and

$dT_0$  = freezing point depression, either in degrees Celsius or Kelvin.

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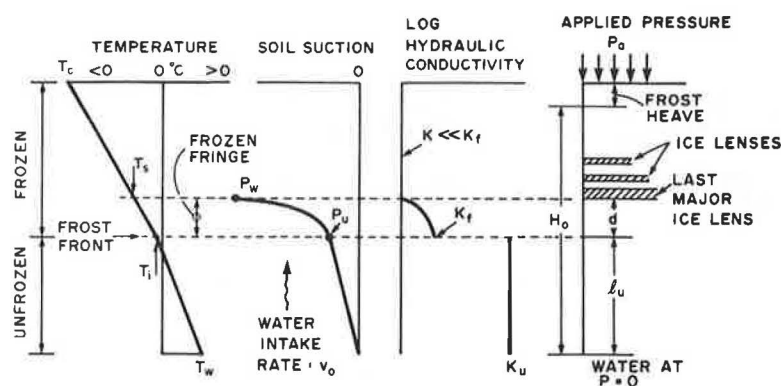


FIGURE 1 Schematic description of a freezing system (I).

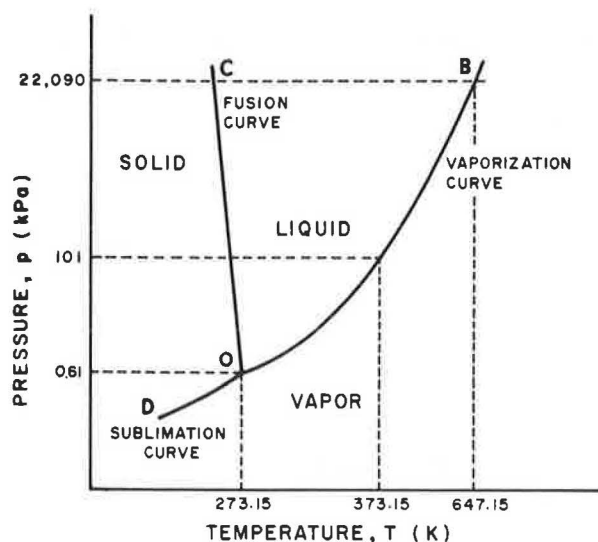


FIGURE 2 Phase diagram for water (not to scale).

Considering a constant ice pressure (i.e.  $u_i = 0$ ) and rearranging Equation 2 yields an equation for the suction in the frozen soil:

$$d(-u_w) = -\frac{L}{T_0 v_w} dT_0 \quad (3)$$

The  $d(-u_w)$  term in Equation 3 refers to an increase in suction as the freezing temperature is lowered by  $dT_0$  from  $0^\circ\text{C}$ . In other words, the suction increases as the temperature decreases below  $0^\circ\text{C}$ . Equation 3 is plotted in Figure 3 together with typical experimental data (2).

#### RELEVANT PROPERTIES OF PARTIALLY FROZEN SOILS

Water in a porous medium, such as soil, does not all freeze at a single freezing temperature (Figure 4) (6). The freezing characteristics of the pore water are dependent on many factors. Among these factors are (a) mineralogical composition, (b) specific surface area of soil solids, (c) surface forces, (d) osmotic potential of soil solution, (e) grain size and grain size

distribution, and (f) surface charged density. Generally, the smaller the particles, the greater the amount of unfrozen water present at any temperature below freezing (Figure 4). As freezing progresses, it becomes increasingly more difficult to freeze the remaining water. The freezing point depression is caused by the increasing surface forces on the water as the freezing advances closer to the particle surface.

#### Thermal Conductivity

In a soil, heat is transferred by direct thermal conductivity,  $k$ , which is defined as the amount of heat that is transferred in a unit time through a unit length of the soil with a unit cross-sectional area under a unit temperature gradient. The thermal conductivities of the various constituents in a soil are different and must be combined to give the apparent thermal conductivity of the soil. As the proportions of the constituents are changed, the apparent thermal conductivity of the soil will also change. Typical values of thermal conductivities of various constituents of a partially frozen soil are given in Tables 1–3 (7). For a given soil, the bulk density of the soil particles remains fairly constant. However, there are significant changes in the proportion of the frozen and unfrozen water contents as the water freezes.

The thermal conductivity of ice is approximately four times greater than that of water (Figure 5). As the ice content in a soil increases, the unfrozen water content decreases. During freezing, it is anticipated that the apparent thermal conductivity of the soil will increase.

#### Heat Capacity

The heat capacity of a soil refers to the quantity of heat that is required to raise the temperature of a unit mass of the soil by  $1^\circ\text{C}$ . The heat capacity of a partly frozen soil is simply the sum of the heat capacities of its constituents. When freezing occurs, the heat capacity appears to increase significantly because of the latent heat of fusion that is required in the water-ice phase transformation. The specific heat capacity,  $c$ , is the heat capacity of the soil per unit weight. Typical values of specific heat capacities of soil constituents are presented in Tables 1–3 (7).

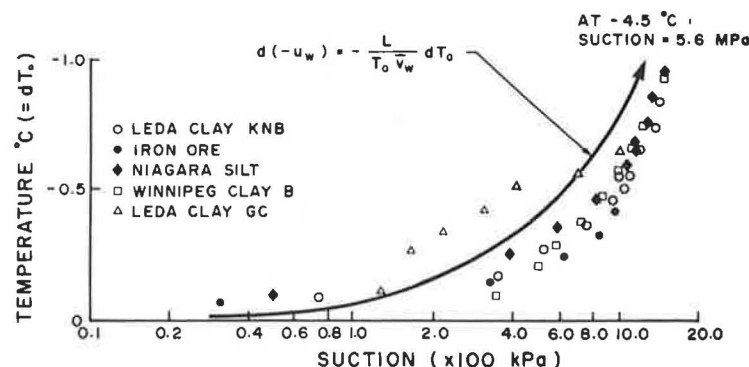


FIGURE 3 Theoretical and experimental relationships between temperature and suction at atmospheric pressure (2).

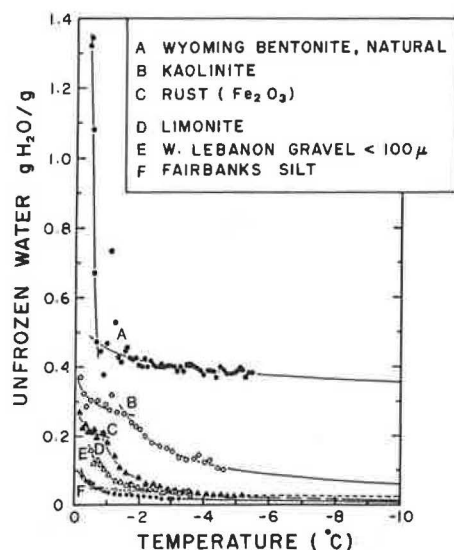


FIGURE 4 Variation of unfrozen water content with temperature for six representative soils and soils constituents (6).

TABLE 1 THERMAL PROPERTIES OF SOIL CONSTITUENTS AT 20°C AND 1 atm (7)

Material	Density $\rho$ (kg/m <sup>3</sup> )	Specific Heat $c$ (kJ/kg°C)	Thermal Conductivity $k$ (W/m K)	Thermal Diffusivity $\alpha$ (10 <sup>-7</sup> m <sup>2</sup> /s)
Quartz	2650	0.732	8.4	43
Many soil minerals*	2650	0.732	2.9	43
Soil organic matter*	1300	1.925	0.25	15
Water	1000	4.184	0.6	1.42
Air	1.2	1.004	0.026	0.21

\* Approximate average values

TABLE 2 PHYSICAL PROPERTIES OF LIQUID WATER (7)

Temp (°C)	Density (kg/m <sup>3</sup> )	Specific Heat (kJ/kg°C)	Thermal Conductivity (W/m K)	Latent Heat of Evaporation (kJ/kg)
-10	997.94	4.268	-	2523
-5	999.18	-	-	-
0	999.87	4.2150	0.561	2499
4	100.00	-	-	-
5	999.99	4.1995	0.574	2487
10	999.73	4.1894	0.596	2476
15	999.13	4.1832	0.595	2464
20	998.23	4.1790	0.603	2452
25	997.08	4.1769	0.611	2440
30	995.68	4.1756	0.620	2428
35	994.06	4.1752	0.628	2417
40	992.25	4.1756	0.632	2405
45	990.24	4.1765	0.605	2393
50	988.07	4.1777	0.645	2381

The phase transformation takes place without any change in temperature.

### Thermal Diffusivity

The thermal diffusivity,  $\alpha$ , of a soil is given by

$$\alpha = \frac{k}{\rho c} \quad (4)$$

where

$k$  = thermal conductivity,  
 $c$  = specific heat capacity, and  
 $\rho$  = density.

Thermal diffusivity controls the rate at which a temperature change spreads through a mass. The thermal conductivity of ice is approximately four times that of water. The specific heat capacity of ice is approximately half that of water. Consequently, the diffusivity of ice is about eight times the diffusivity of water. Therefore, in a frozen soil, temperatures can change faster and to a greater extent than in an unfrozen soil.

### Latent Heat

The latent heat of fusion is the heat or energy that is required in a phase change (e.g., from a liquid to a solid phase, or vice versa). For water, the latent heat of fusion,  $L$ , is 333 kJ/kg. This means that 333 kJ of heat is liberated when 1 kg of water turns to ice, or is absorbed when 1 kg of ice turns to water.

TABLE 3 PHYSICAL PROPERTIES OF ICE (7)

Temp (°C)	Density (kg/cm <sup>3</sup> )	Specific Heat c (kJ/kg°C)	Thermal Conductivity (cal/cm s °C) (W/m K)	Latent Heat of Sublimation (kJ/kg)	Latent Heat of Fusion (kJ/kg)
-20	920	1.958	2.433	2836	289
-10	919	2.029	2.319	2835	312
0	917	2.105	2.240	2833	333

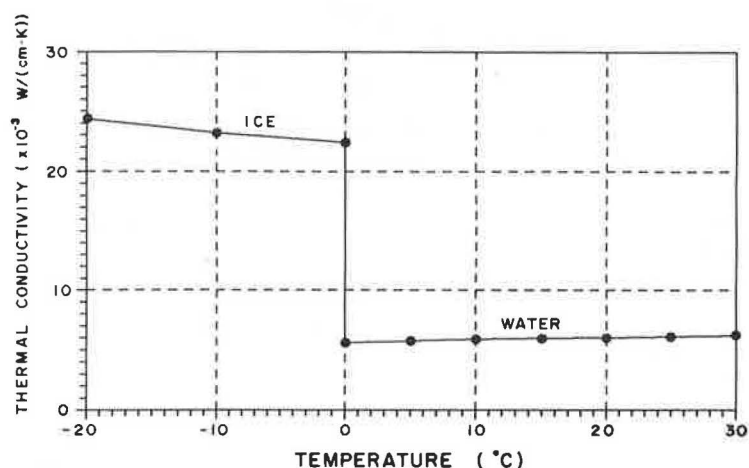


FIGURE 5 Thermal conductivity of ice and water at various temperatures.

In a fine-grained soil, the water in the pores freezes gradually. Its latent heat is therefore released in stages (Figure 6) (8). The rate of the heat released reduces with decreasing temperatures. The result of a release in latent heat is a sudden change in the specific heat immediately below the temperature at which freezing begins (Figure 7) (9). The latent heat acts similar to a large sink in which heat is released or absorbed without any change in temperature. This sudden change in the specific heat causes a corresponding sudden change in the diffusivity (e.g., Figure 8) (10).

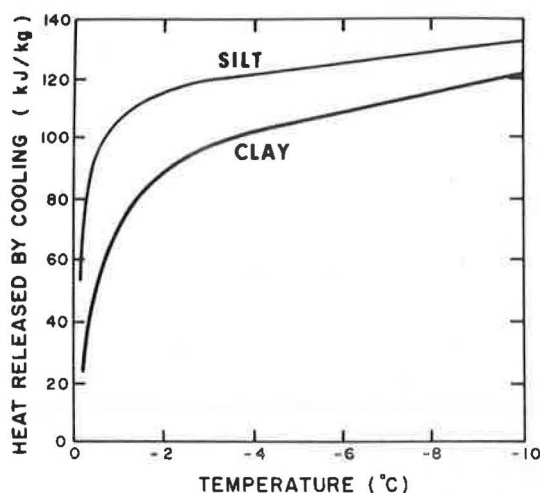


FIGURE 6 Latent heat released on cooling below 0°C (8).

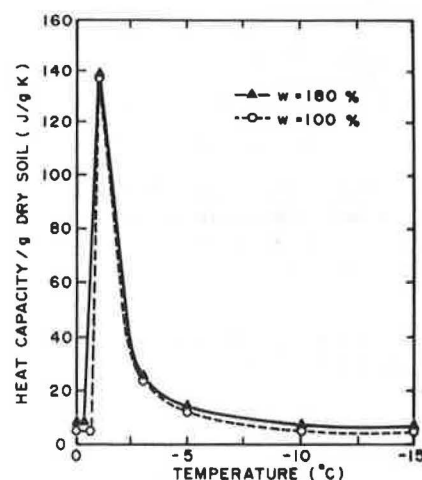


FIGURE 7 Relationship between heat capacity and temperature of a partially frozen bentonite (9).

### SUCTION MEASUREMENT TECHNIQUES

Several techniques are available for suction measurements in an unfrozen soil. These techniques include (a) tensiometers, (b) psychrometers, (c) filter paper methods, and (d) thermal conductivity sensors. Some of these techniques have also been used for frozen solids. The psychrometric and filter paper techniques do not require intimate contact with the soil. The other techniques require the use of a porous medium in intimate contact with the soil and allowing the suction in the medium

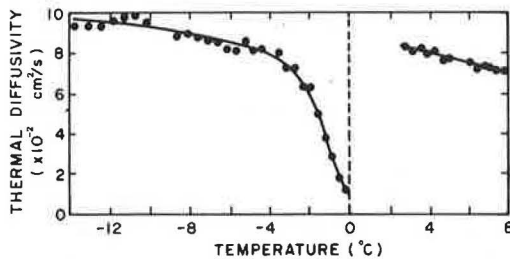


FIGURE 8 Variation of thermal diffusivity with temperatures for a kaolinite suspension (10).

to come to equilibrium with the suction in the soil. Water in the porous medium has different freezing characteristics from the water in the soil. Under subzero temperatures, the different freezing characteristics may present some problems in obtaining accurate suction measurement.

### Tensiometers

Tensiometers have commonly been used to measure the negative pore water pressures in an unsaturated soil. The tensiometer consists of a porous ceramic, high air entry cup connected to a pressure-measuring device through a small-bore capillary tube. The tube and the cup are filled with deaired water. The cup can be inserted into a precored hole until there is intimate contact with the soil. After equilibrium has been achieved, the water in the tensiometer will have the same negative pressure as the pore water in the soil. The water pressure that can be measured using a tensiometer is

limited to approximately  $-90$  kPa because of cavitation of water in the tensiometer.

Ingersoll and Berg (11) have used tensiometers for measuring negative pore water pressures under freezing conditions. The tensiometer cups were installed along a cylindrical soil column 1 m long and 14 cm in diameter. The tensiometer tube was filled in with a solution of ethylene glycol and water to lower the freezing point of the tensiometer fluid. The soil suctions increased as the temperature decreased below  $0^{\circ}\text{C}$ . Typical results are plotted in Figure 9 along with the corresponding temperatures. As freezing progresses, the measured suctions decreased abruptly, indicating a breakdown in the measuring system.

### Psychrometers

Thermocouple psychrometers are used to measure soil suction by measuring the relative humidity in the soil. Soil suction results in a decrease in the relative humidity. Measurements of soil suction are commonly conducted in the laboratory by placing a small soil specimen in a chamber together with the psychrometer. The relative humidity is then measured after equilibrium is attained between the air near the psychrometer and the pore air in the soil. The suction range that can be reliably measured by psychrometers in a controlled temperature environment is from 100 to 8,000 kPa.

Use of psychrometers in the measurements of soil suction in a freezing environment have not been cited. However, psychrometers have been used to measure relative humidity (and therefore suction) in snow (12). The results indicate a

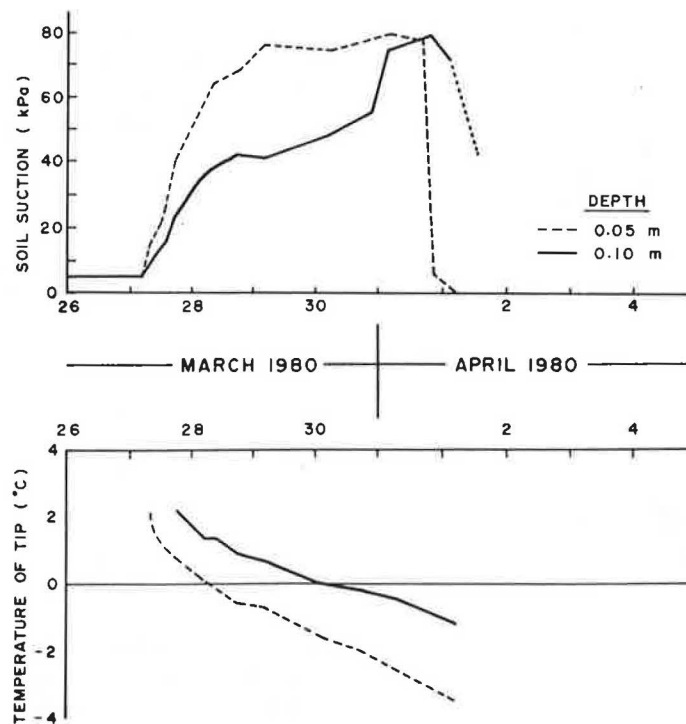


FIGURE 9 Suction measurements using tensiometers in a freezing environment (11).

reduction in the relative humidity with decreasing temperatures below 0°C.

### Filter Paper Technique

The filter paper technique has not been used to measure soil suction under frozen conditions. The vapor pressure associated with ice implies that there may be some possibility in using this technique for frozen soils. Research is needed in this area.

### Thermal Conductivity Sensor

The operation of a thermal conductivity sensor is based on the principle of heat dissipation in a porous material. The rate of heat dissipation is dependent on (a) the thermal conductivity of the solid material and of the water, and (b) the mass of the solid and the water. The thermal conductivity of air can be considered negligible. For a particular sensor, the mass of the solid is a constant and the rate of heat dissipated in the solid will be constant. Therefore, changes in the rate of heat dissipated in a sensor are directly related to the water content of the sensor.

When a sensor is inserted into a soil, water will move between the sensor and the soil. The movement of water takes place until stress equilibrium is attained between the soil and the sensor. The equilibrium water content of the sensor is an indication of the suction in the sensor and in the soil. The water content of the sensor can be calibrated against the applied suction using a modified pressure plate apparatus (13).

A typical sensor is made up of two parts, (a) a heating and heat sensing device enclosed within, (b) a porous block (Figure 10). The heater and the sensing devices are embedded within a porous ceramic of low thermal conductivity. The porous ceramic should be relatively small to ensure a rapid response. However, the porous ceramic must be sufficiently large so that the heat pulse generated is fully contained within the ceramic block. Otherwise, the thermal conductivity reading will be affected by the type of surrounding soil.

The reading operation consists of measuring the electrical output (current or voltage) before the heat pulse and the electrical output after a 60-sec heat pulse was applied. The heat pulse was then ended. The heat pulse is a precisely controlled amount of heat applied at a fixed rate. The change in

voltage output is a function of the electrical resistance, which in turn is a function of the temperature rise. The voltage outputs varies linearly with temperature and therefore the difference is not affected by the temperature of the sensor. A single calibration is therefore adequate for all temperatures.

In an unfrozen soil, a low water content in the sensor, or high soil suction, would result in a high temperature increase in the thermal conductivity sensor. This high temperature increase indicates a low apparent thermal conductivity of the sensor because of its low water content. In a frozen or partially frozen soil, the thermal conductivity of the sensor is not only a function of the unfrozen water content, but it also depends on the ice content. Thus, in a frozen soil at a low unfrozen water content, the temperature increase recorded by the sensor would be expected to be low because of the high thermal conductivity of ice.

### RESULTS OF SUCTION MEASUREMENTS USING THERMAL CONDUCTIVITY SENSORS

Lee (14) used heat dissipation sensors (MCS 6000) sensors both for in situ and for laboratory suction measurements. MCS 6000 sensors were manufactured by Moisture Control System Corporation, Findlay, Ohio. The results of in situ suction measurements conducted in a glacial till are shown in Figure 11. The results indicate that suction variations followed closely the daily temperature variation. The soil suction increased as the temperature approached 0°C. When the temperatures dropped below 0°C, the sensor was not able to record any suction reading.

Van der Raadt et al. (15) used AGWA-II thermal conductivity sensors for monitoring suction changes below railway subgrades. AGWA-II sensors were manufactured by Agwatronics Incorporated, Merced, California. Results of suction measurements using the AGWA-II sensors from one site are shown in Figure 12. The results also show that the suction readings increased as the temperature decreased below freezing. Several suction measurements were obtained for the soil in the frozen state.

### RECENT EXPERIENCE WITH THE AGWA-II SENSOR IN A FREEZING ENVIRONMENT

Suction measurements have been recently made in a freezing environment at the University of Saskatchewan. The measurements were made using AGWA-II thermal conductivity sensors. A soil column was prepared by compacting a glacial till into a PVC cylinder.

The cylinder had a height of 300 mm and a diameter of 150 mm. A thermal conductivity sensor together with a thermocouple were embedded near the top, middle, and bottom sections of the soil column (Figure 13). The thermocouple was used to measure the temperature in the soil at the proximity of each thermal conductivity sensor. The column was insulated on all sides except for the top face. The top of the column was subjected to temperatures ranging from 22°C down to -20°C inside a freezing chamber.

The suction and temperature measurements with respect to time are shown in Figures 14-16. All three sensors ap-

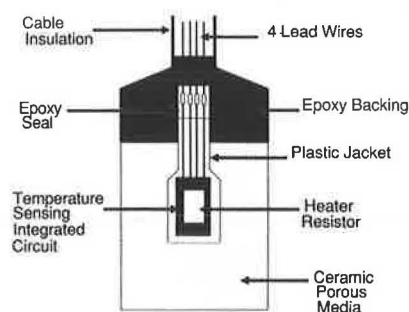


FIGURE 10 A cross-sectional diagram of the AGWA-II thermal conductivity sensor.



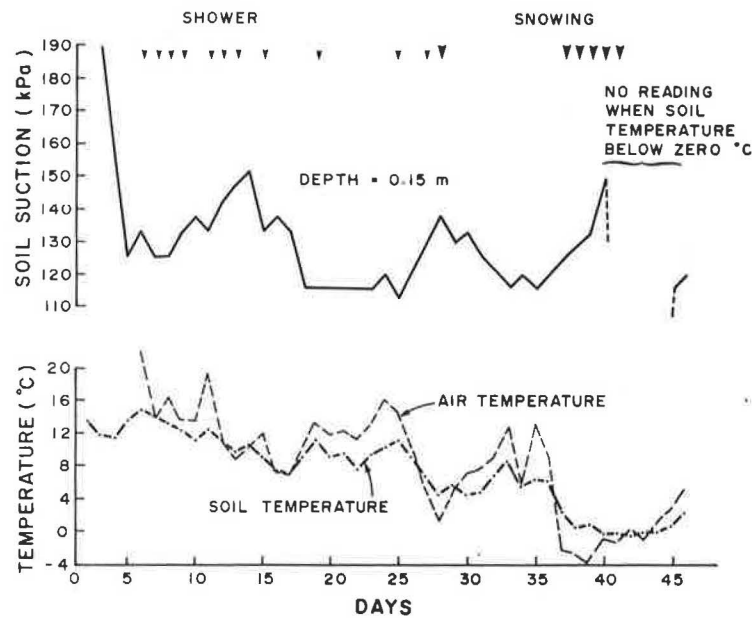


FIGURE 11 Field measurements of matric suction in a glacial till using the MCS 6000 thermal conductivity sensors (14).

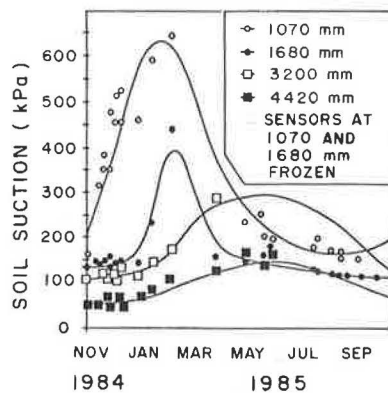


FIGURE 12 Variation of soil suction with time of year for various depths of Regina clay in Saskatchewan (15).

peared to respond in a similar manner. As the temperature decreased from above freezing to below freezing, the sensor readings dropped sharply. As freezing progresses, the sensor readings increased rapidly to approximately the same readings before freezing occurs. The same behavior was observed as the temperature was increased from below freezing to above freezing. All three sensors showed that after thawing, the soil suctions dropped to a range of 0 to 40 kPa.

## INTERPRETATION OF TEST RESULTS

As the water in the sensor begins to freeze, the apparent thermal conductivity of the sensor is affected by the latent heat of fusion. During the freezing process, the latent heat of fusion is released at a constant temperature. However, the water in the sensor does not freeze simultaneously, but rather it freezes in a gradual manner. As a result, the temperature

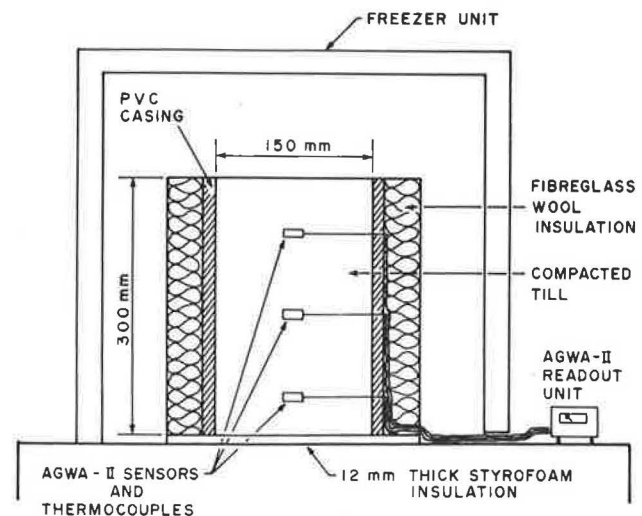


FIGURE 13 Setup for soil suction measurements using the AGWA-II sensor in a freezing test.

increase produced by the heat pulse will be smaller in a freezing sensor as compared to that registered in a nonfreezing sensor. This phenomenon could be attributed to the tendency of the water to maintain a constant temperature during the phase transformation. The reduced temperature increase in a freezing sensor would then be interpreted from the calibration curve as a decreasing soil suction. This situation is demonstrated by the drops in soil suction readings as the temperature decreases to 0°C.

After a major portion of the water in the sensor has frozen, the temperature increase measured because of the heat pulse depends on the proportion of ice and unfrozen water, and also on the quantity of air bubbles present. The higher sensor readings in the frozen state are probably because of the re-

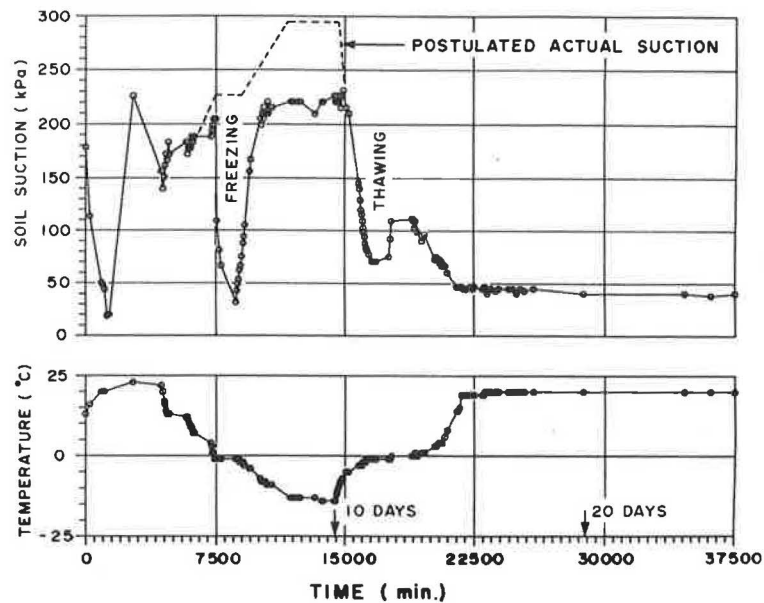


FIGURE 14 Suction and temperature measurements at the top section of the soil column.

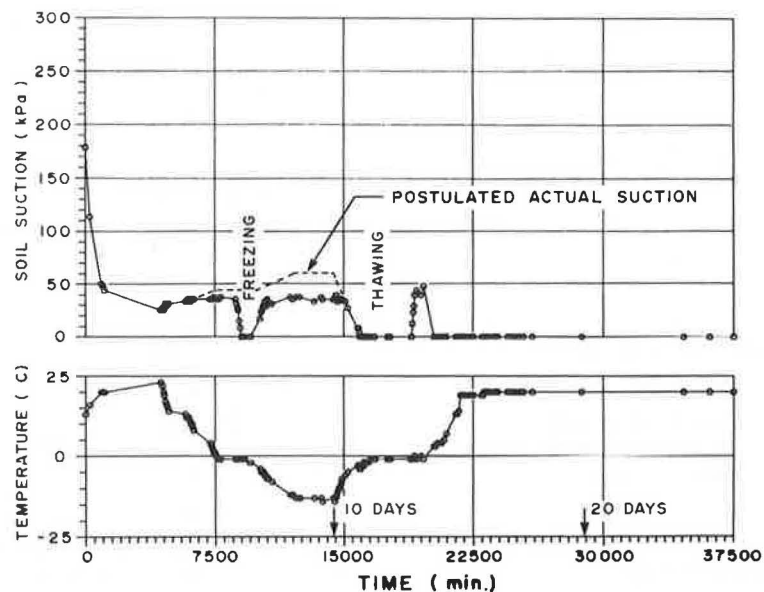


FIGURE 15 Suction and temperature measurements at the middle section of the soil column.

duced thermal conductivity caused by the presence of air bubbles.

As the water in the sensor begins to thaw, the heat pulse released in the sensor is again affected by the latent heat of fusion. During the thawing process, the latent heat of fusion is adsorbed at a constant temperature. The thawing process also occurs gradually within the sensor. The tendency to maintain a constant temperature will again reduce the temperature increase generated by the heat pulse. As a result, the suction readings will drop again as the temperature increases toward 0°C.

The reduction in the sensor reading after a complete thawing of the ice, is probably caused by the overwetting of the sensor, which is followed by separation from the soil. The separation of the sensor from the soil could be caused by the expansion of the frozen soil water and the migration of melting water upon thawing. In fact, the soil column was found to have expanded vertically by approximately 5 mm at the end of the test. When the water at the contact between the sensor and the soil thaws, a portion of the water may migrate into the sensor pores. As a result, a gap develops between the sensor and the soil. Once the sensor has separated from the



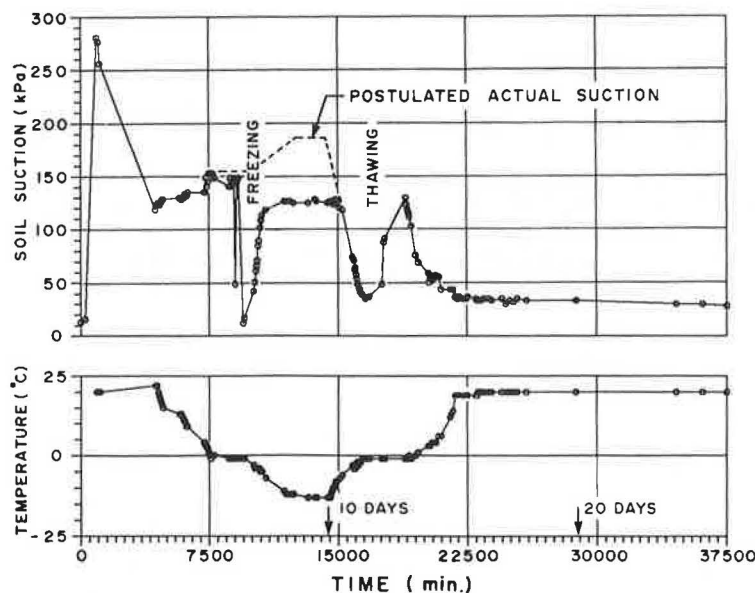


FIGURE 16 Suction and temperature measurements at the bottom section of the soil column.

soil, the sensor registers a suction reading depending on the remaining water content of the sensor.

## CONCLUSION

Experimental evidence has identified the difficulties associated with the measurement of negative pore water pressures in freezing soils. In particular, the use of thermal conductivity sensors in freezing environment is emphasized. Distinct drops in suction readings have been observed during the freezing and thawing processes. These drops are attributed to the effect of the latent heat of fusion on the thermal conductivity measurements. Also, as soil freezes, the proportions of unfrozen and frozen water change. Ice and water have different thermal conductivities. As a result, the sensor readings are difficult to interpret and to convert to soil suctions. In addition, the rigid, brittle ceramic used for the thermal conductivity sensors is susceptible to cracking caused by the expansion on freezing, especially under high water content conditions.

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