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MEASURING NEGATIVE PORE-WATER PRESSURES IN A FREEZING ENVIRONMENT

by

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ABSTRACT

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 in the paper.

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 in the light of 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 due to the significantly higher thermal conductivity of ice to that of water.

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INTRODUCTION

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. This paper evaluates the suitability of the thermal conductivity sensor for insitu suction measurements in a freezing environment.

PHYSICS OF THE PROBLEM

As temperature drops below 0° C, some soil water freeze producing ice in the soil. Let us consider the situation of a thermal gradient with the coldest temperature at the ground surface. Figure 1 [1] illustrates 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 [1]. 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 Fig. 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 increases with decreasing temperatures below 0° C.

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

$$\frac{dP}{dT} = -\frac{L}{Tv_w} \qquad [1]$$

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 in degrees Kelvin

v_w = specific volume of water (i.e., $1/\rho_w$ where: ρ_w = water density (1000 kg/m3)).

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_o) using Eq. 1.

$$\frac{d(u_i - u_w)}{dT_o} = -\frac{L}{T_o v_w} \qquad [2]$$

where:

T_o = normal freezing temperature in Kelvin (i.e., 273.15 K or point O in Fig. 2)

dT_o = freezing point depression, either in °C or K

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

$$d(-u_w) = -\frac{L}{T_o v_w} dT_o \qquad [3]$$

The $d(-u_w)$ term in Eq. 3 refers to an increase in suction as the freezing temperature is lowered by dT_0 from 0° C. In other words, the suction increases as the temperature decreases below 0° C. Equation 3 together with typical experimental data are plotted in Fig. 3 [2].

RELEVANT PROPERTIES OF PARTIALLY FROZEN SOILS

Water in a porous medium, such as soil, does not all freeze at a single freezing temperature (Fig. 4) [6]. The freezing characteristics of the pore-water are dependent on many factors. Among these factors are i) mineralogical composition, ii) specific surface area of soil solids, iii) surface forces, iv) osmotic potential of soil solution, v) grain size and grain size distribution, and vi) surface charged density. Generally, the smaller the particles, the greater the amount of unfrozen water present at any temperature below freezing (Fig. 4) [6]. As freezing progresses, it becomes increasingly more difficult to freeze the remaining water. The freezing point depression is due to the increasing surface forces on the water as the freezing advances closer to the particle surface.

THERMAL CONDUCTIVITY

In a soil, heat is transferred via direct conductivity, k. The thermal conductivity, k, of a soil 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, 2 and 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 (Fig. 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° 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 will appear to increase significantly due to 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 expressed on a unit weight basis. Typical values of specific heat capacities of soil constituents are presented in Tables 1, 2 and 3 [7].

LATENT HEAT

The latent heat of fusion is the heat or energy that is required in a phase change (e.g., from a liquid phase 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. The phase transformation takes place without any change in temperature.

THERMAL DIFFUSIVITY

The thermal diffusivity, α, of a soil is given by

$$\alpha = \frac{k}{\rho c} \qquad [4]$$

where:

k = thermal conductivity

c = specific heat capacity

ρ = 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.

In a fine-grained soil, the water in the pores freezes gradually. Its latent heat is therefore released in stages (Fig. 6) [8]. The rate of 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 (Fig. 7) [9]. The latent heat acts similar to a large sink where 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., Fig. 8) [10].

SUCTION MEASUREMENT TECHNIQUES

Several techniques are available for suction measurements in an unfrozen soil. These techniques include: i) tensiometers, ii) psychrometers, iii) filter paper methods, and iv) thermal conductivity sensors. Some of these techniques have also been used for frozen soils. The psychometric 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 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 sub-zero 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 de-aired water. The cup can be inserted into a pre-cored 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 negative 90 kPa due to 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 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° C. Typical results are plotted in Fig. 9 [11] 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 kPa to 8000 kPa.

The authors are not aware of the use of psychrometers in the measurements of soil suction in a freezing environment. However, psychrometers have been used to measure relative humidity (and therefore suction) in snow [12]. The results indicate a reduction in the relative humidity with decreasing temperatures below 0° C.

Filter Paper Technique

The authors are not aware of any attempts to use the filter paper technique to measure soil suction under frozen conditions. The vapor pressure associated with ice would lead one to believe 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 i) the thermal conductivity of the solid material and of the water, and ii) 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, i) a heating and heat sensing device enclosed within, ii) a porous block (Fig. 10). The heater and the sensing devices are embedded within a porous ceramic of low thermal conductivity. The porous ceramic should be relatively small in order 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 second 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 rise in the thermal conductivity sensor. The high temperature rise indicates a low apparent thermal conductivity of the sensor due to 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 rise recorded by the sensor would be expected to be low due to the high thermal conductivity of ice.

RESULTS OF SUCTION MEASUREMENTS USING THERMAL CONDUCTIVITY SENSORS

Lee [14] used heat dissipation sensors (MCS 6000 sensors) for both insitu and laboratory suction measurements. MCS 6000 sensors were manufactured by Moisture Control System Corporation, Findlay, OH. The results of insitu suction measurements conducted in a glacial till are presented in Fig. 11 [14]. The results show 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, CA. Results of suction measurements using the AGWA-II sensors from one site are presented in Fig. 12 [15]. 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 (Fig. 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° down to minus 20° C inside a freezing chamber.

The suction and temperature measurements with respect to time are presented in Figs. 14, 15 and 16. All three sensors appeared 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 rise produced by the heat pulse will be smaller in a freezing sensor as compared to that registered in a non-freezing sensor. This phenomenon could be attributed to the tendency of the water to maintain a constant temperature during the phase transformation. The reduced temperature rise 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 rise measured due to the heat pulse depends upon 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 due to the reduced 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 rise generated by the heat pulse. As a result, the suction readings will drop again as the temperature increases towards 0° C.

The reduction in the sensor reading after a complete thawing of the ice, is probably due to the over-wetting of the sensor which is followed by separation from the soil. The separation of the sensor from the soil could be due to 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 developed between the sensor and the soil. Once the sensor has separated from the soil, the sensor will register a suction reading depending upon the remaining water content of the sensor.

CONCLUSION

Experimental evidence presented in the paper has identified the difficulties associated with the measurement of negative pore-water pressures in freezing soils. In particular, the emphasis is on the use of thermal conductivity sensors in freezing environments. 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 are changing. Ice and water have very different thermal conductivities. As a result, the sensor readings are difficult to interpret and to convert to soil suctions. In addition, the rigid and brittle ceramic used for the thermal conductivity sensors are susceptible to cracking due to the expansion on freezing, especially under high water content conditions.

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Table 1

Thermal properties of soil constituents at 20°C and 1 atm [7]

Material	Density ρ (kg/m^3)	Specific Heat c (kJ/kg°C)	Thermal Conductivity k (W/m K)	Thermal Diffusivity α (10^{-7} m^2/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^3)	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

Table 3

Physical properties of ice [7]

Temp (°C)	Density (kg/cm^3)	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

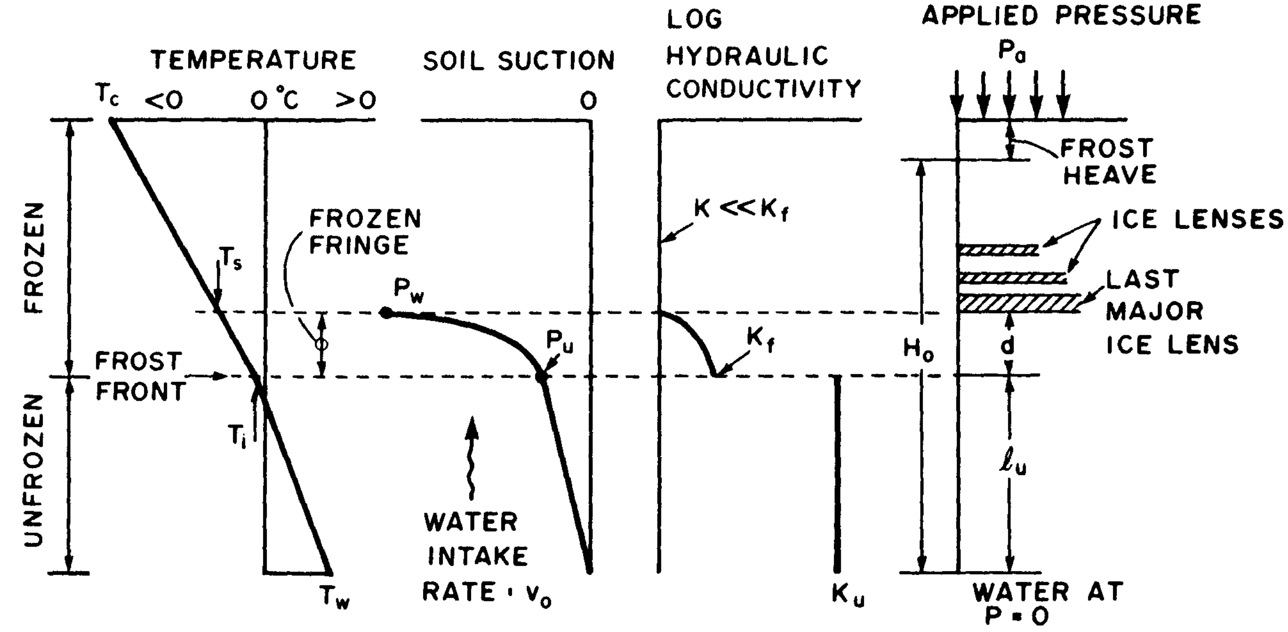


Figure 1 Schematic description of a freezing system [1].

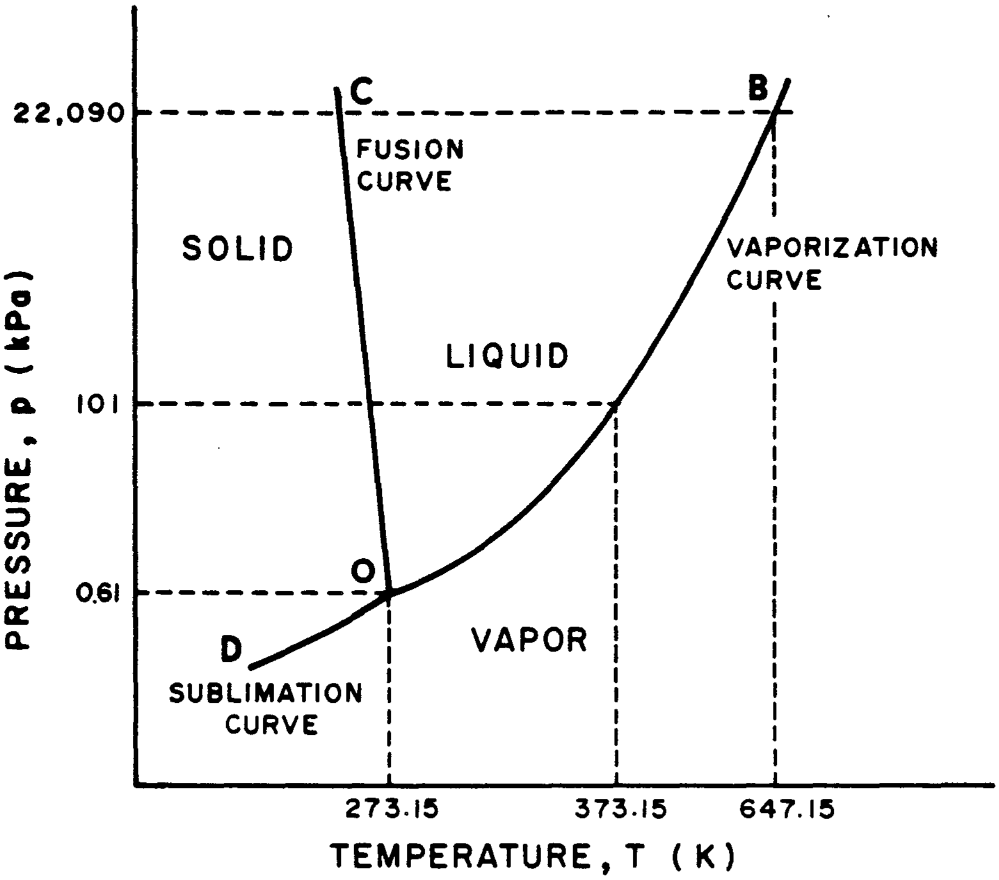
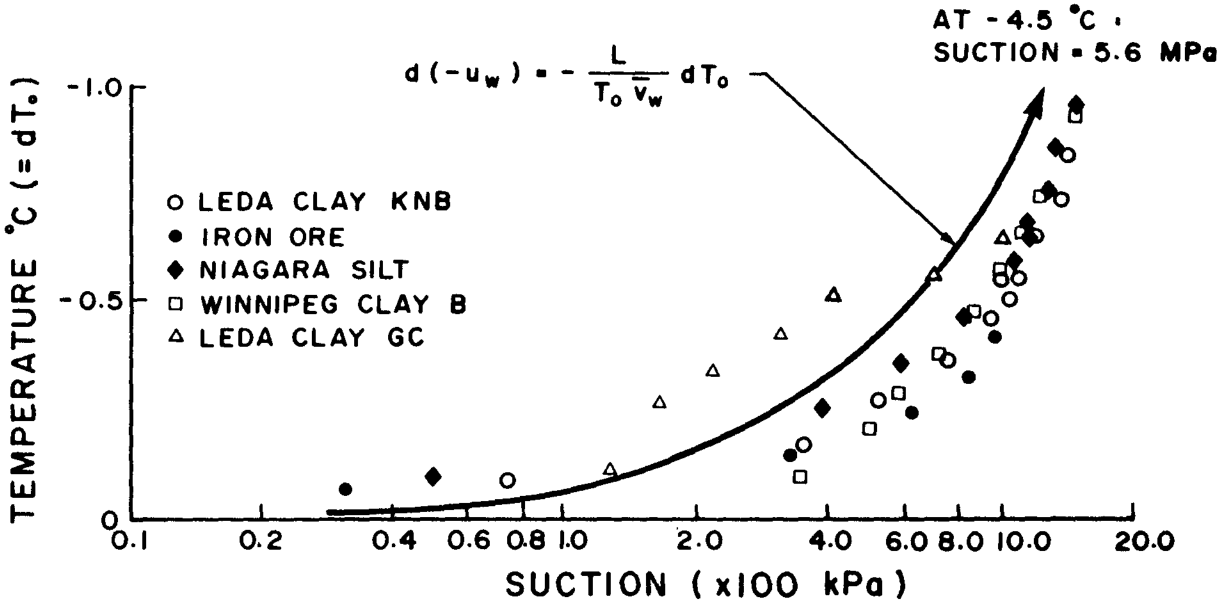


Figure 2 Phase diagram for water. (not to scale) [4].



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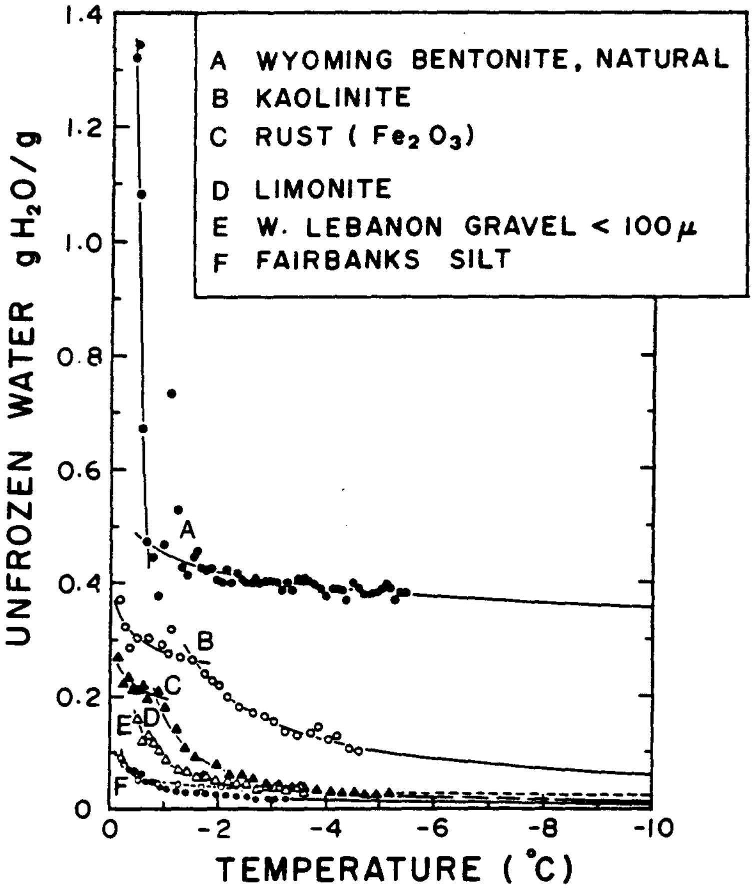

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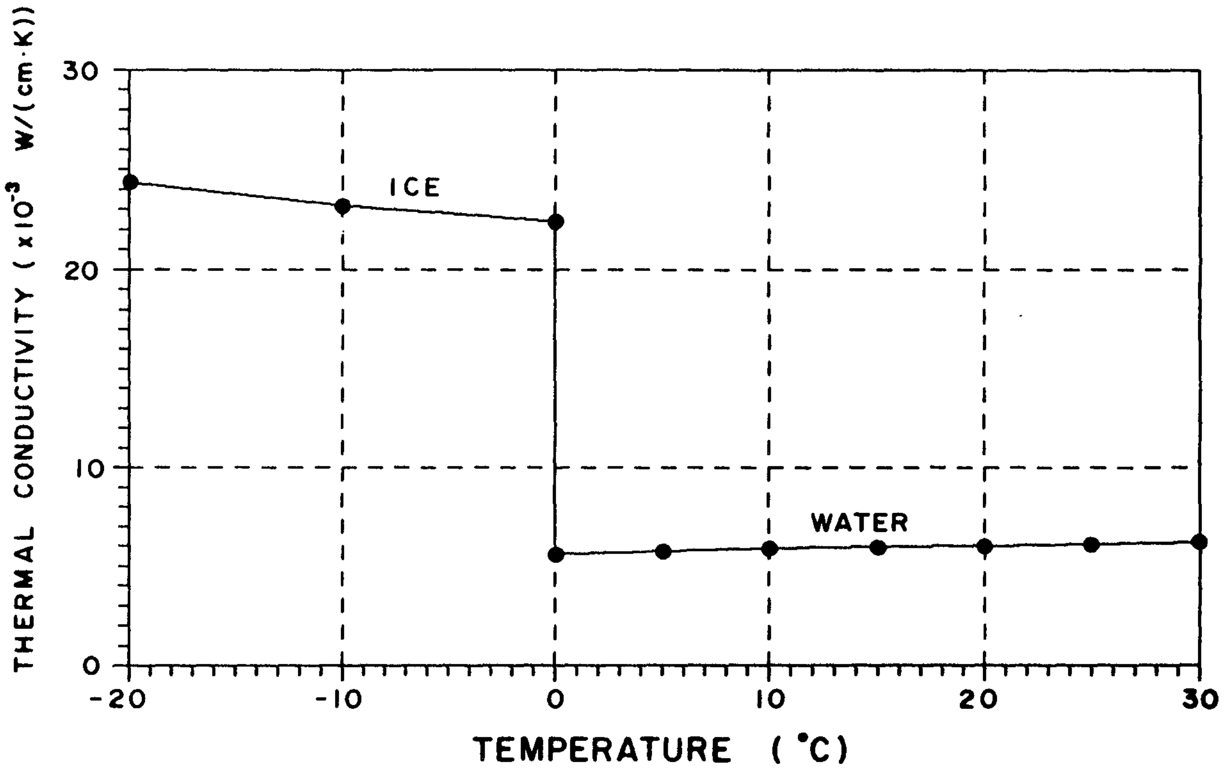

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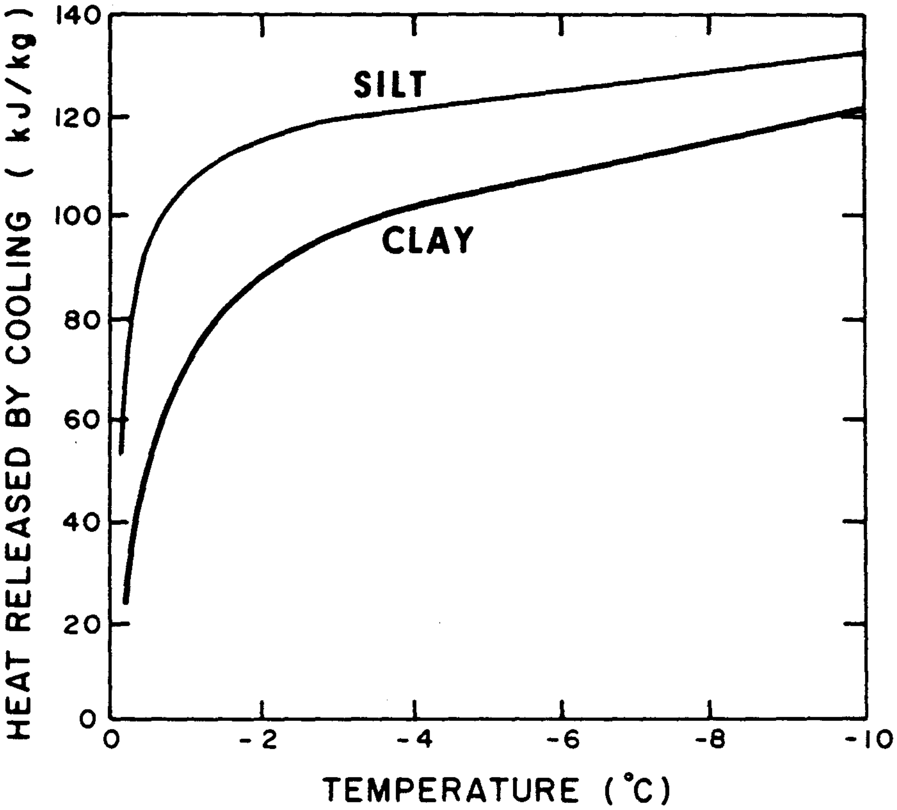

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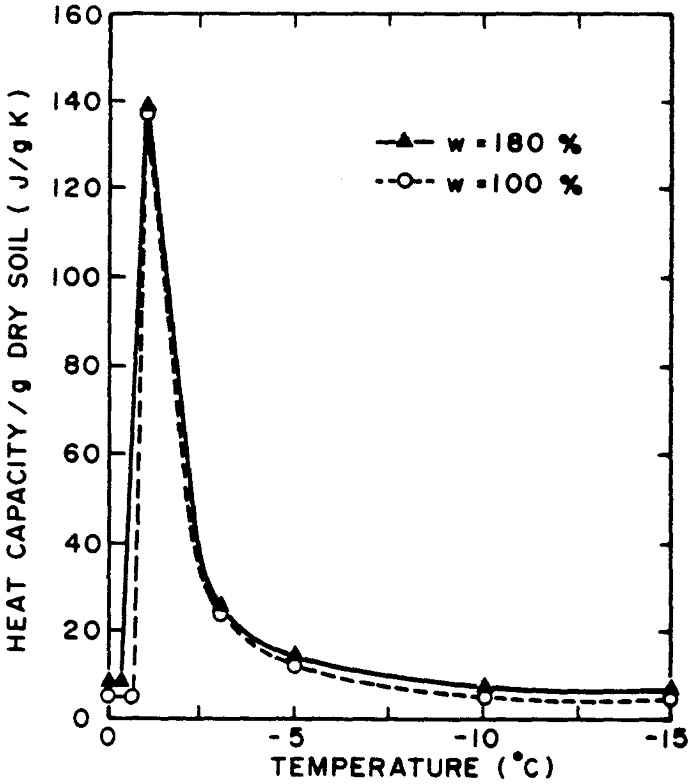

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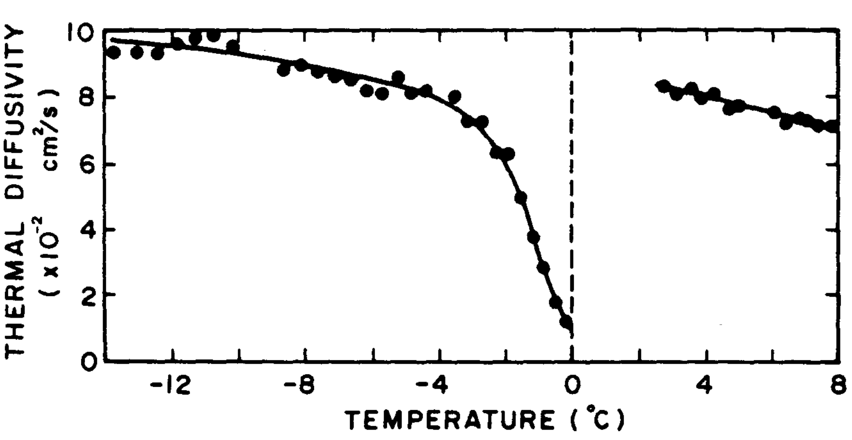

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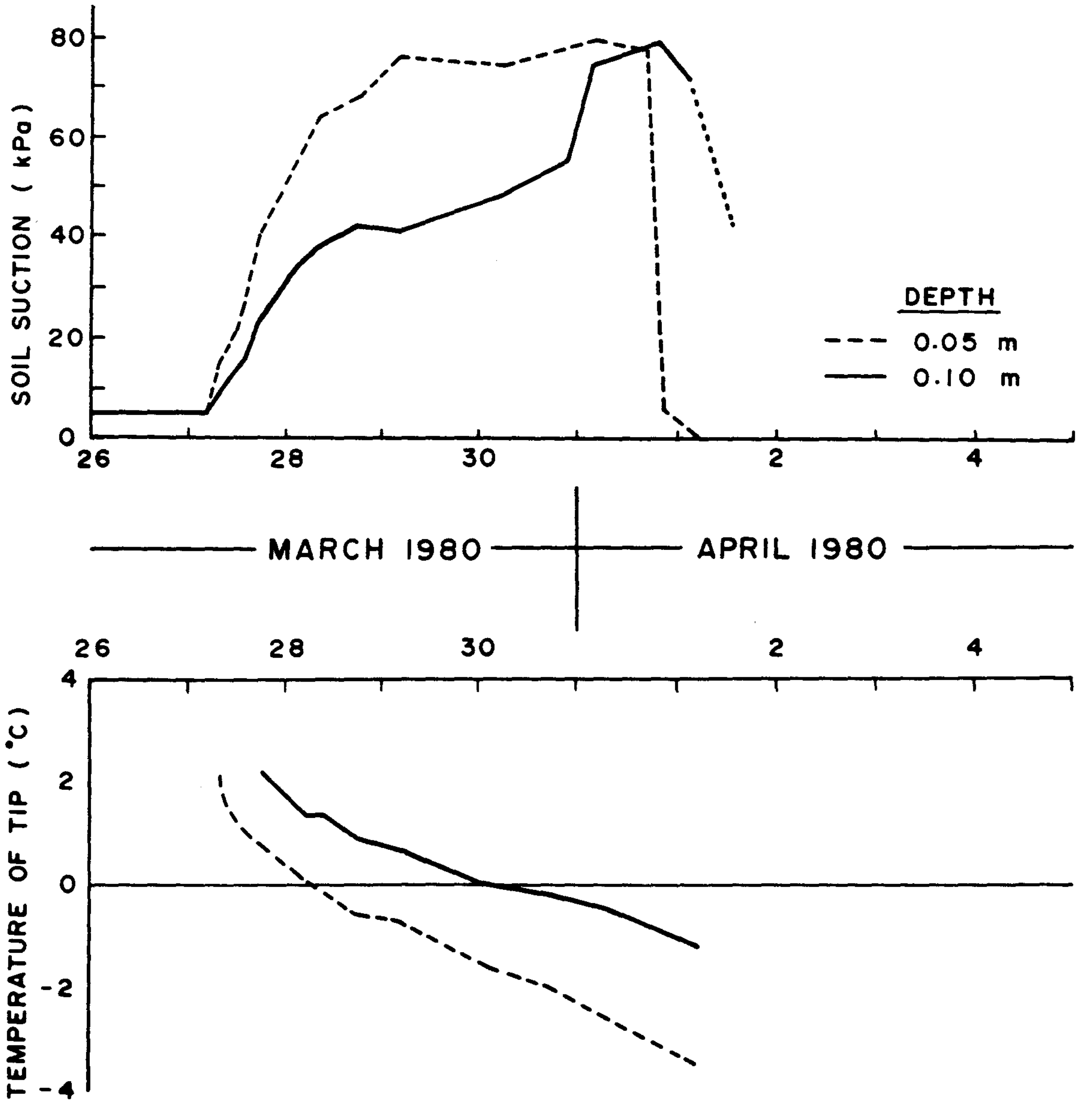

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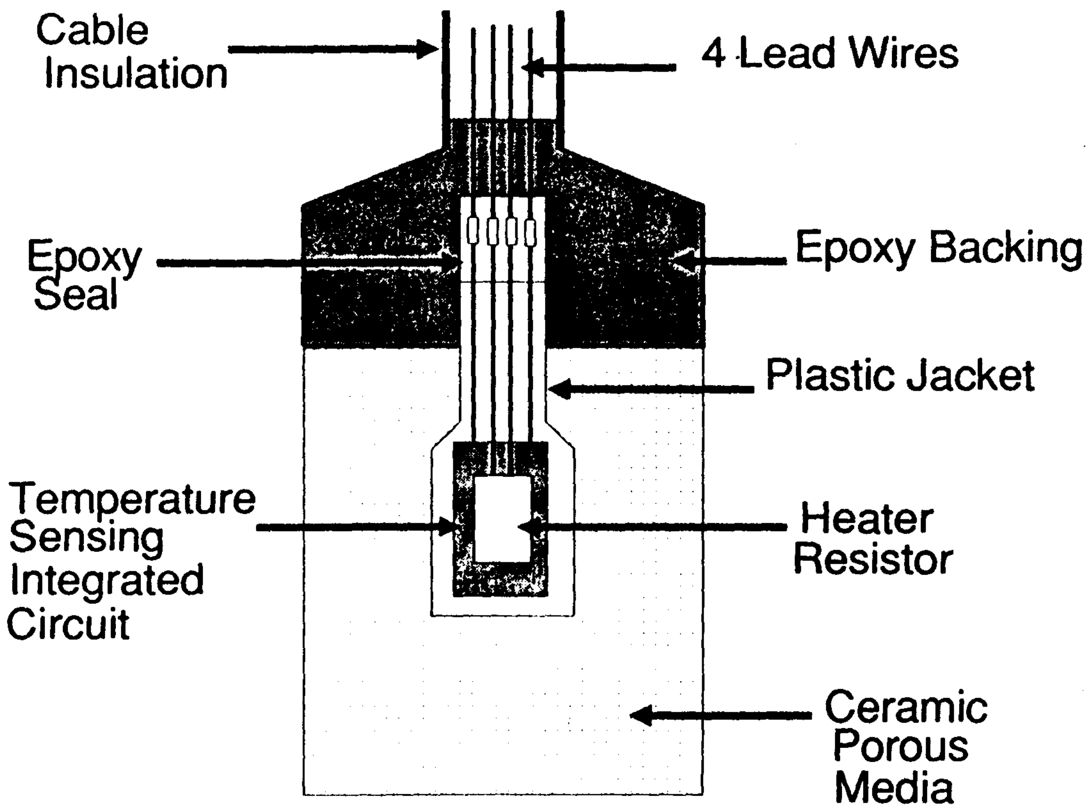
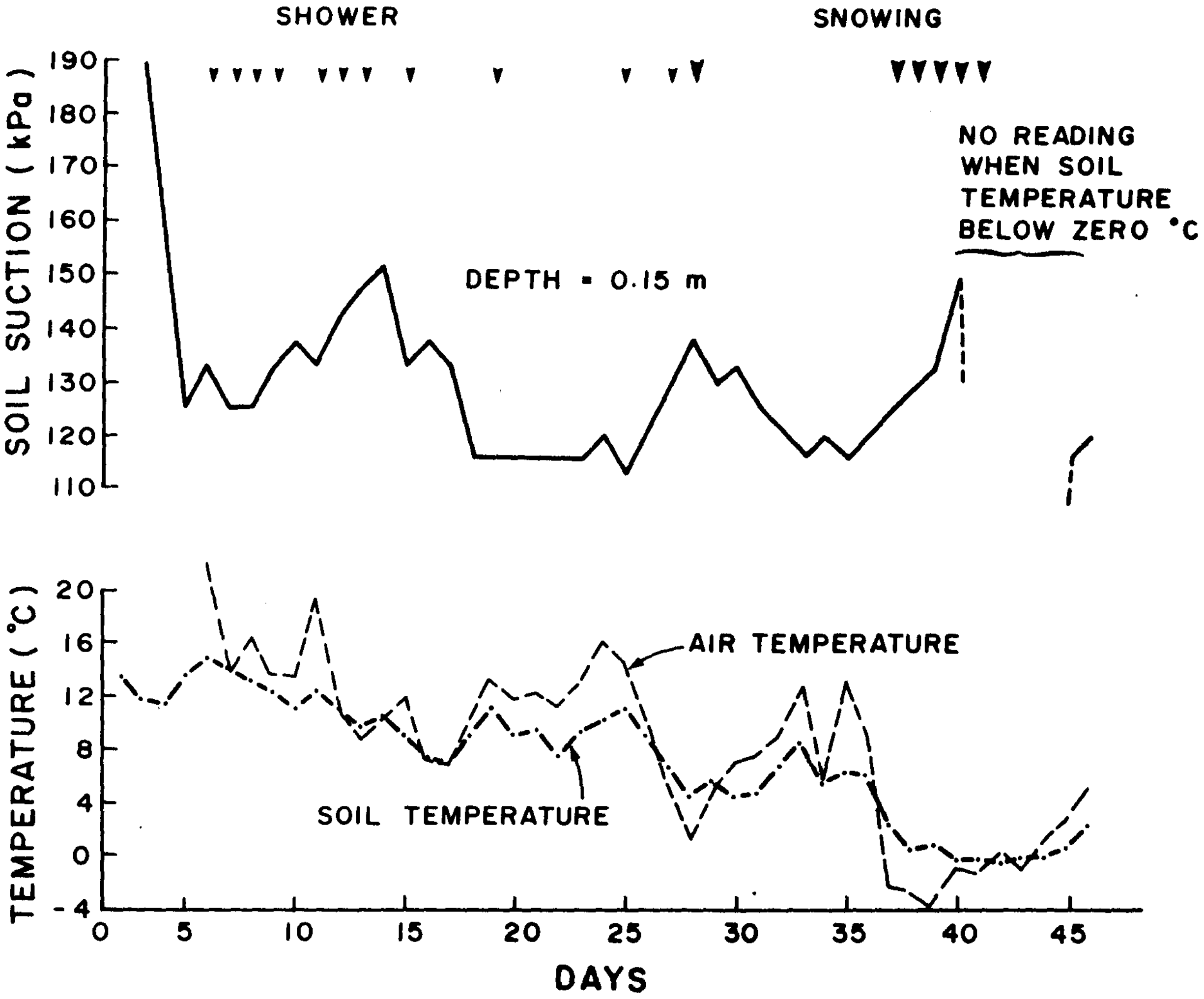


Figure 10 A cross-sectional diagram of the AGWA-II thermal conductivity sensor.



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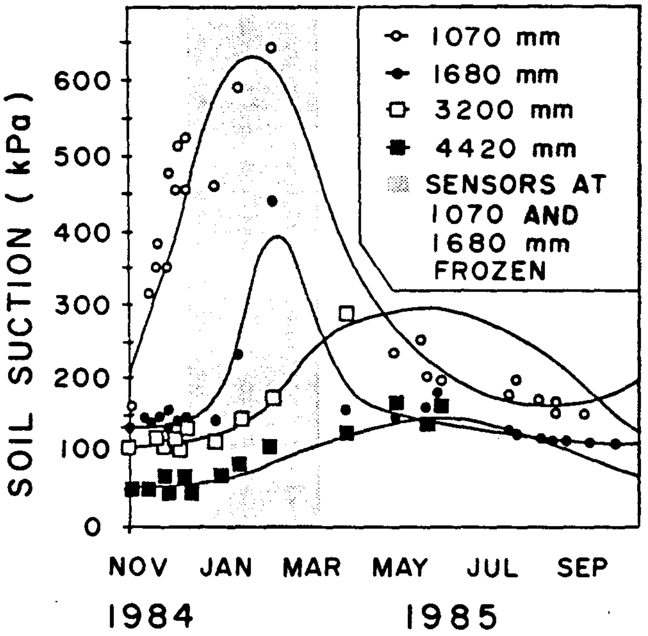

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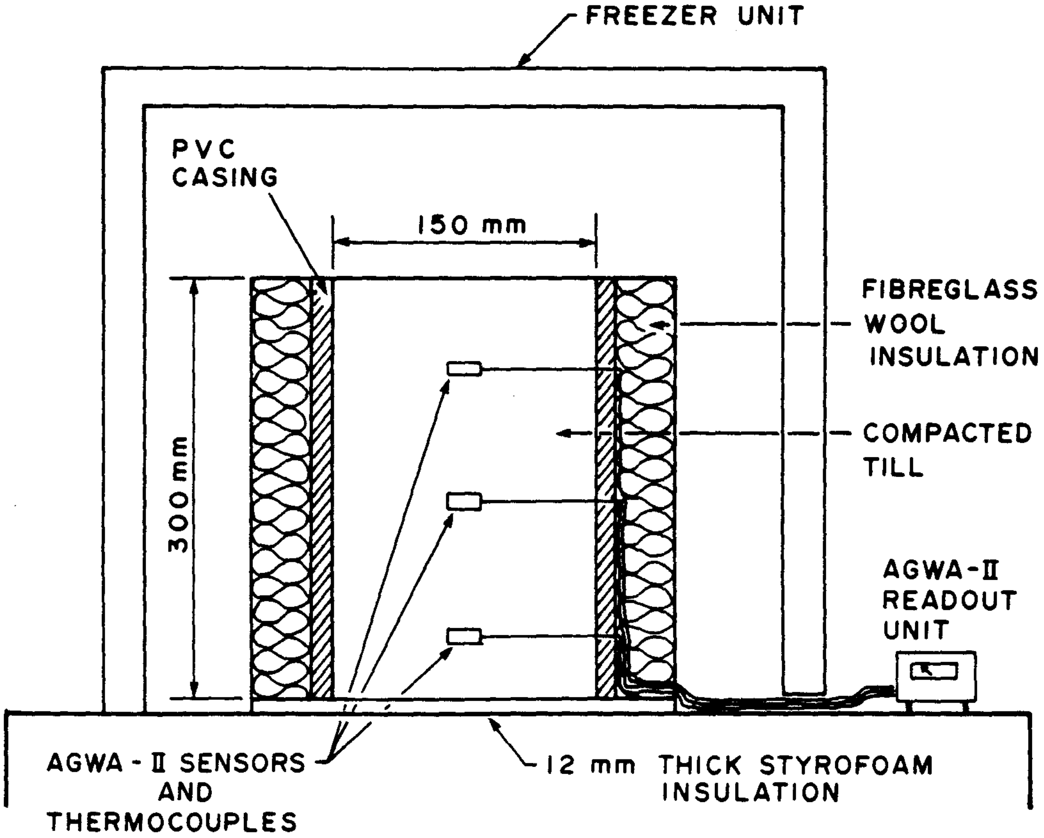

Figure 13 Setup for Soil Suction measurements using the AGWA-II sensor in a freezing test.

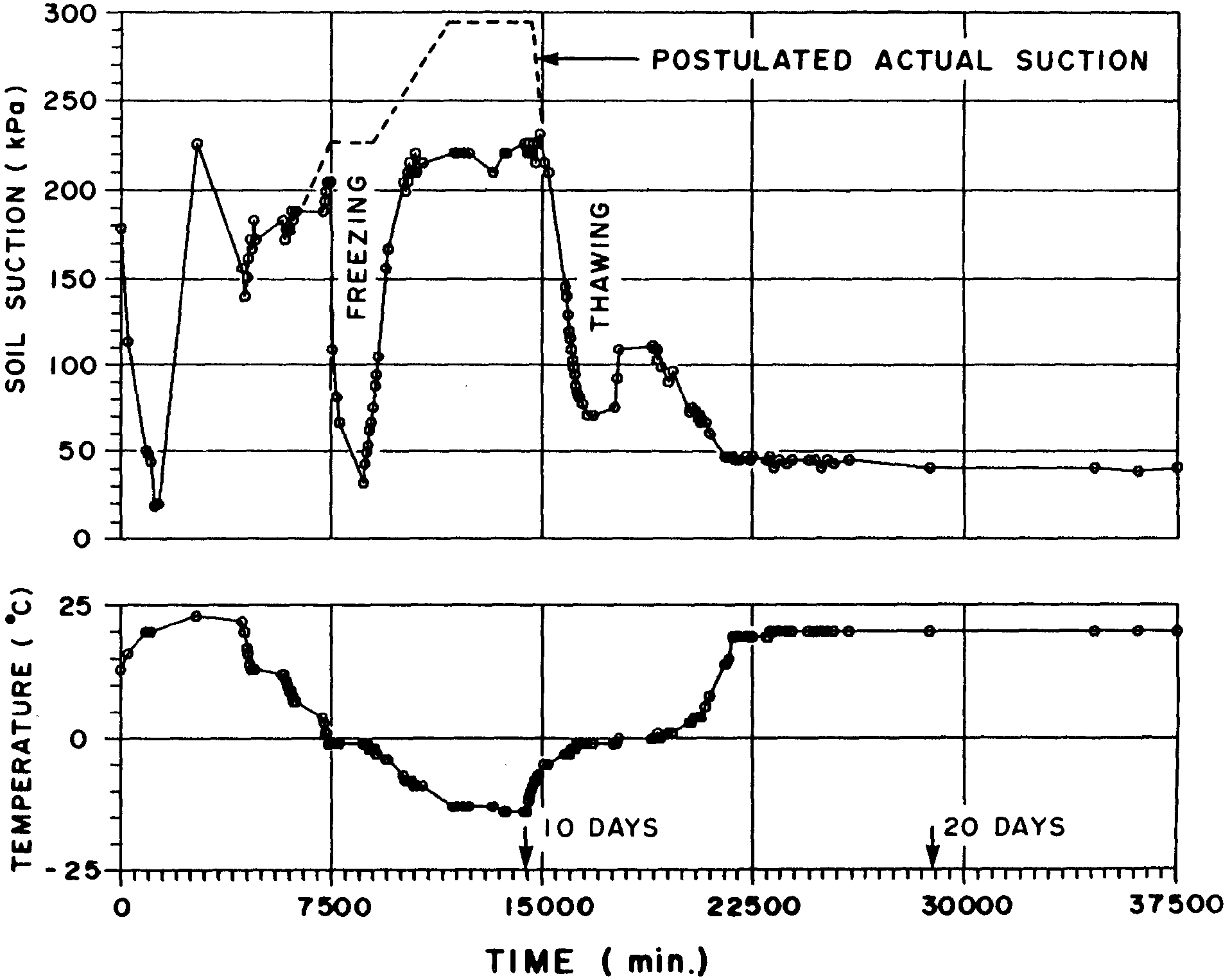

Figure 14 Suction and temperature measurements at the top section of the soil column.

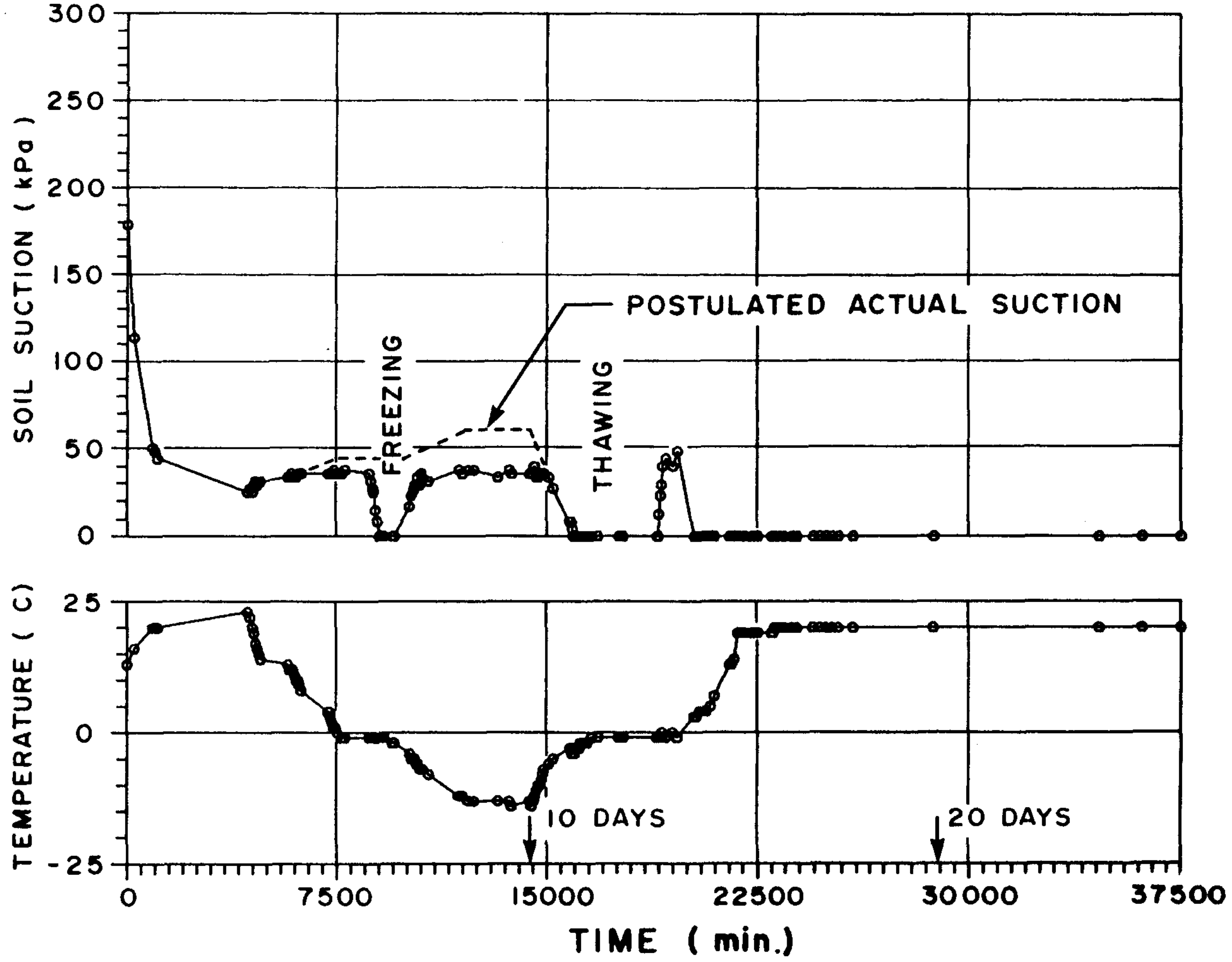

Figure 15 Suction and temperature measurements at the middle section of the soil column.

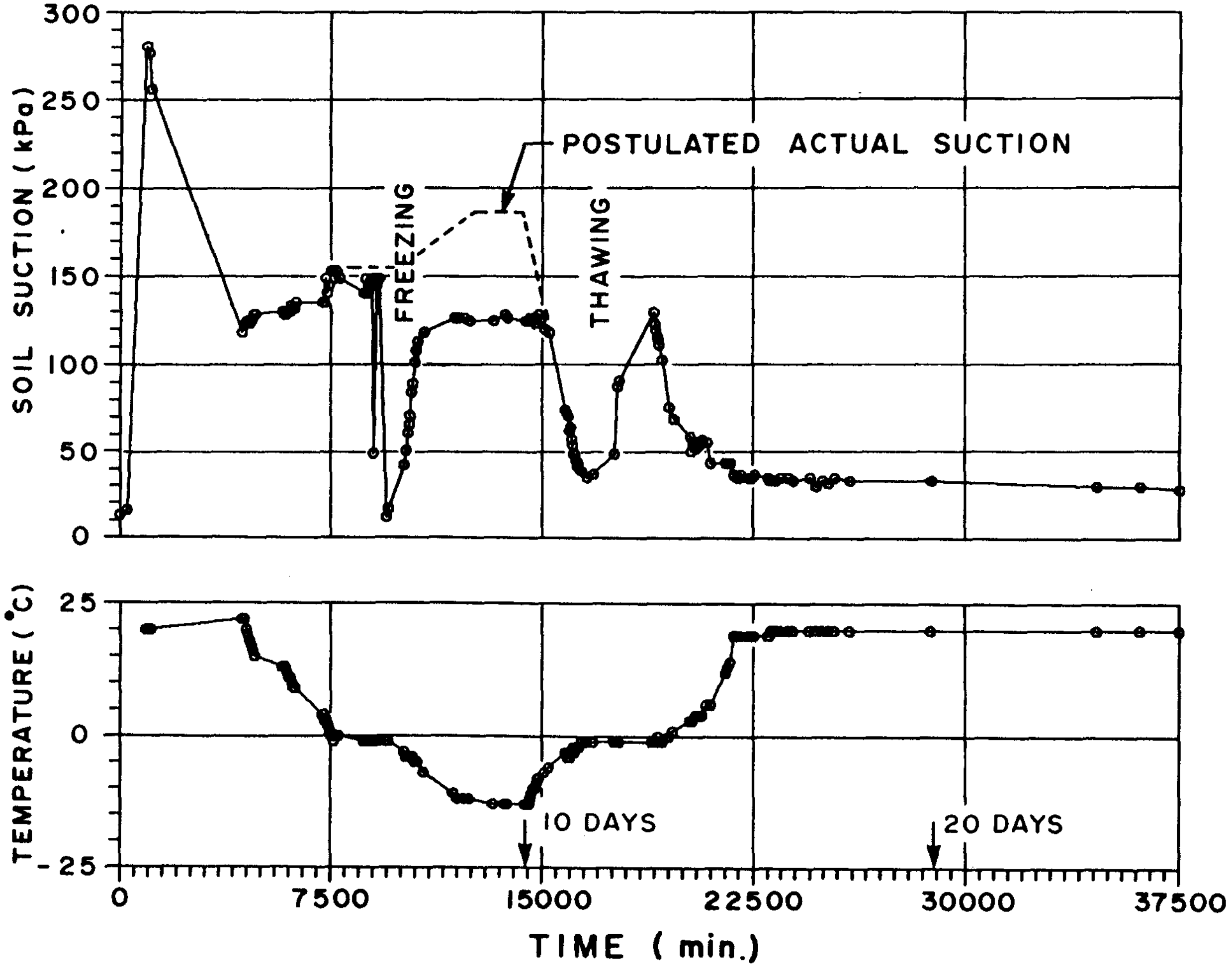

Figure 16 Suction and temperature measurements at the bottom section of the soil column.