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INVESTIGATION OF RATES OF WATER MOVEMENT THROUGH FROZEN SOIL

P.J. Williams and E. Perfect
Geotechnical Science Laboratories
Carleton University, March 1979.

36 pages plus appendices

Price: $18.25

Earth Physics Branch Open File Number 79-15

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ABSTRACT

The presence of water along with ice in frozen ground has been recognized since the early sixties. However it was not until the 1970's that a deliberate attempt to determine the mobility of that water by measuring hydraulic conductivity of frozen soils was made. This report first reviews the theory and significance of the hydraulic conductivity of frozen soils and then describes a project designed to investigate the rates of water movement. This work, intended to contribute to the knowledge and accuracy of the measurement of hydraulic conductivity and to follow up questions raised by the original permeameter experiments, also involved the direct investigation of moisture content distribution and thus water migration in frozen soil columns. A novel approach to the freezing column was developed, which it is hoped will permit direct measurement of water migration as a function of temperature gradients in the frozen soil.

RESUME

La présence de l'eau avec la glace dans un sol gelé a été reconnue depuis les années soixante. Mais ce n'était que dans les années soixante-dix qu'on essaya de déterminer la mobilité de cet eau en mesurant la conductivité hydraulique des sols gelés. Ce rapport fait d'abord la revision de la théorie et de l'importance de la conductivité hydraulique des sols gelés et ensuite décrit un projet destiné à examiner le taux du mouvement de l'eau. Le but de ce travail est, de non seulement contribuer à la connaissance et à la précision de la mesure de la conductivité hydraulique et de poursuivre les questions posées par les expériences originales avec le perméamètre, mais aussi d'étudier directement la distribution de la teneur en humidité et ainsi la migration de l'eau dans les colonnes de sol gelé. Une approche nouvelle à la colonne de congélation fut développée. On espère que ceci permettra la mesure directe de la migration de l'eau en fonction des gradients thermiques dans le sol gelé.

FINAL REPORT

INVESTIGATION OF RATES OF WATER MOVEMENT THROUGH FROZEN SOILS

for the

Department of Energy, Mines and Resources
Earth Physics Branch

by

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Contract No. 02SU-KL229-7-1562
Serial No. ISU77-00269

31st March, 1979

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I INTRODUCTION

The presence of water along with ice in frozen ground has been recognised since the early sixties, when calorimetry showed that less heat was involved in freezing or thawing than was expected. Other studies showed the water to have a potential (or, equally, a Gibbs free energy), relative to free water, that was lower by an amount increasing as the temperature was lower. Concurrently investigations of frost heave were being pursued in various laboratories, but without explicit regard for the characteristics, outlined above, of soils at temperatures down to -1°C or -2°C.

It was not until 1973 that a deliberate attempt was made to determine the hydraulic conductivity of frozen soils, although Hoekstra (1966) had concluded some such permeability must exist very near to 0°C. Hoekstra had observed the continued growth of an ice lens _after_ it was _surrounded_ by frozen soil. Miller (1970) described an experiment in which a layer of ice (without soil) was involved in a transport process that included freezing on one face of the layer and thawing on the other.

An experimental apparatus was constructed by Burt (Burt and Williams, 1976) in the Geotechnical Science Laboratories, which permitted measurement of a hydraulic conductivity coefficient for frozen soils. As a result of these observations, coupled with the Laboratories long experience with freezing soils, Dr. Williams and his colleagues concluded in a report to the Mackenzie Valley Pipeline Inquiry that there were design problems in the then-current Arctic Gas Pipeline proposals. In essence it could be concluded that frost heave pressures would be greater than envisaged.

Although evidence to counter this was put forward, the Arctic Gas designs were subsequently withdrawn after a technical fault was found in their testing equipment. After the fault was corrected much greater heaving pressures were measured, and the design became invalid.

The significance in this context of the hydraulic conductivity of frozen ground, lies in the fact that water may travel <u>into</u> frozen ground, to freeze at temperatures substantially below 0°C. It moves to such regions under the influence of the temperature-determined potential, and this potential also determines the magnitude of the frost heave pressures generated when the water freezes. The theory is reviewed in this report.

The measurements of hydraulic conductivity made by Burt have been quite widely discussed. While they are such as to raise very serious questions concerning long-term frost heave of chilled gas pipelines, they are not yet acceptable as providing the answers. There is an urgent need for further knowledge, to which the project described in this report is intended to contribute. The contract proposal involved two approaches. Firstly, the work was to provide confirmation of the nature of Burt's findings, to improve the accuracy, and to follow up certain questions raised by the original experiments. Secondly, the work was to involve direct investigation of moisture content distribution, and thus water migration in frozen soil columns. This element would be an extension of earlier work carried out under contract through the Department of the Environment.

As the work progressed a novel approach to the freezing column was developed, which appears to have considerable advantage over the original form. This new approach has involved development of a special apparatus which it is hoped will permit direct measurement of water migration as a function of temperature gradients in the frozen soil.

In accordance with the terms of the contract, most of the work has been carried out by a graduate student, Mr. E. Perfect. He is a citizen of the United Kingdom. Mr. Perfect was selected for the position following wide advertising for a person at his level with appropriate background. In fact, he had no previous experience specifically with freezing soils but has proved thoroughly capable. A significant portion of the contract has involved technical work in the construction of the new apparatus. The undersigned has maintained an overall supervising role, as 'Principal Investigator'.

31 March 1979 P.J. Williams

II THEORY OF HYDRAULIC CONDUCTIVITY IN FROZEN SOILS

1. Unfrozen Water in Frozen Soils

It is well established that frozen soils contain highly significant amounts of unfrozen water coexisting with the ice phase (Bouyoucos, 1916; Nersesova and Tystovich, 1963). Miller and Koopmans (1966) and Williams (1967, 1976) have determined the amount of unfrozen water occurring at various negative temperatures. Examples are shown in Figure 1. The amount decreases as the temperature decreases and varies according to soil type. The amount of unfrozen water is essentially independent of the amount of ice, and thus of total moisture content. There is a slight dependence upon overburden pressure (Williams, 1976). It is also well established that the presence of the unfrozen water in frozen soil is due to capillarity and osmotic effects which reduce its freezing point, and to adsorption forces on particle surfaces. A clear and precise relationship has been identified between the unfrozen water content and the suction associated with the corresponding water content in an unfrozen soil.

2. Pressure State of the Unfrozen Water: Free Energy and Freezing Point

As the water content of an unfrozen soil is progressively reduced a suction of increasing magnitude occurs in the soil water. The dominant cause of this suction is the fall in pore pressure ascribable to air-water menisci in the soil pores. The suction is defined by the simple capillary equation:

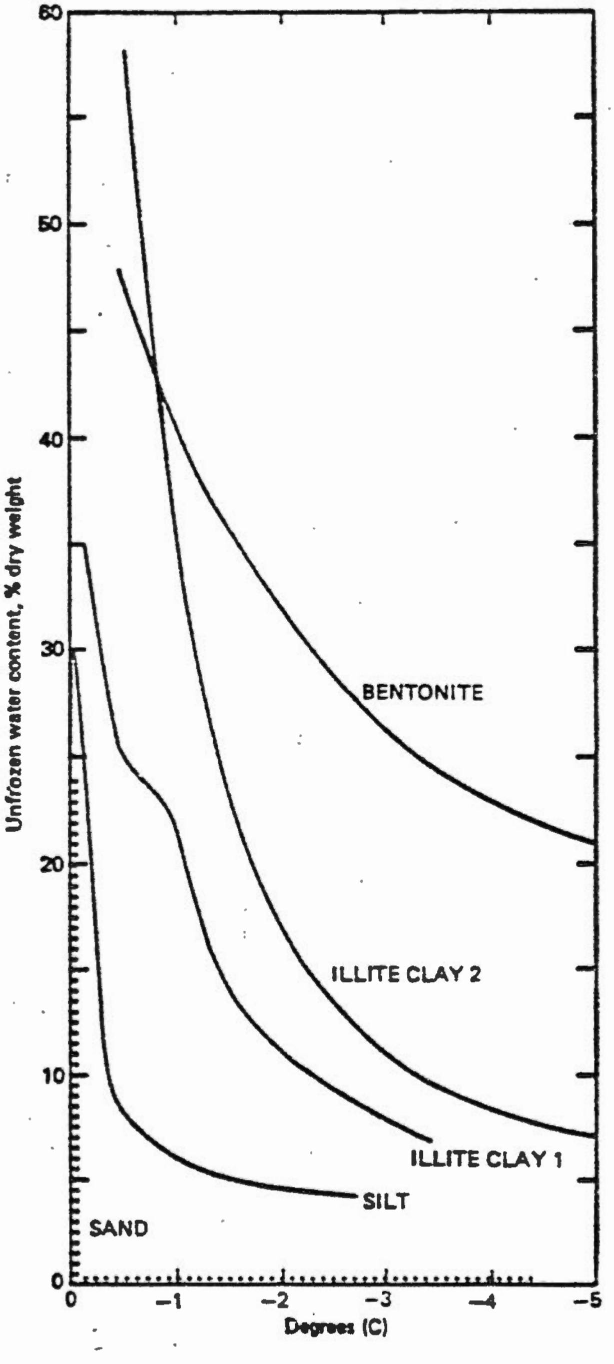


Figure 1. Unfrozen water contents of frozen soils as a function of temperature (Williams, 1967).

$$H = \frac{2\sigma_{aw}}{ry_w g} \qquad \text{Equation 1}$$

σ_{aw} = surface tension of water to air

y_w = density of water

g = gravitational acceleration

where H is the height of a column of water supported by a meniscus of radius, r. H may also be equated to the difference in pressure between the air surrounding a soil and the pore water, $P_a - P_w$ (Rose, 1966); while r can be considered the radius of the soil pores in which the air-water menisci reside.

The term 'suction' implies a pressure state. At low water contents other forces become more important, especially particle surface adsorption effects. For this reason it is preferable to refer to a more general thermodynamic function such as relative Gibbs free energy, ΔG (the term 'potential' as defined by the International Society for Soil Science (1963) is equivalent). Depending on how 'suction' is defined or measured it may be exactly equivalent to ΔG, but the use of the free energy function enables us to relate more clearly soil moisture studies to basic thermodynamic relationships.

The pressure state of the water in an unsaturated, unfrozen soil is essentially the same as that at the corresponding water content in a frozen soil. Regardless of whether the remainder of the pore space is filled with air (unfrozen soil) or ice (frozen soil) the free energy of the water is similar. Thus, the relative Gibbs free energy of the unfrozen water in frozen soil changes progressively as the quantity of water is reduced by ice formation. The Clausius-Clapeyron Equation relates Gibbs free energy, ΔG, to the freezing point of water:

$$\Delta G = \frac{(T_o - T)\,\ell}{T} \qquad \text{Equation 2}$$

where T = Temperature ^{o}K

$T_o - T$ = Freezing point depression relative to the freezing point of pure water

ℓ = Latent heat of fusion

The equation only applies in situations where the ice phase is pure (if T_o is $0^{o}C$) and under atmospheric pressure. It is the change of free energy as ice forms that explains the coexistence of the ice and water at lower temperatures; the free energies of the ice and water are equal. Another thermodynamic equation relates ΔG to a change in pressure, ΔP, alone:

$$\Delta G = V\,\Delta P \qquad \text{Equation 3}$$

where V = specific volume

These fundamental equations are considered with particular reference to frozen soils by Edlefsen and Anderson (1943).

There is a continuous liquid water phase extending from the frost-line to points within the frozen layer where temperatures are well below 0°C. Figure 2 shows the relative Gibbs free energy (suction) of the unfrozen water as a function of temperature. At the frost line, and at temperatures down to about -1.5°C, capillarity, in many soils is the dominant effect. Equations of the form of 1 and 3 apply here, but with σ_{iw} being the surface tension of ice to water. Consequently the suctions responsible for the movement of water through unfrozen ground towards the freezing layer - frost heaving - are usually relatively small. At colder points within the frozen zone, however, the relative Gibbs free energy (suction) of the unfrozen water changes in accordance with the Clausius-Clapeyron equation (Equation 2). As indicated by figure 2, the suctions that develop at such temperatures can be very large. It is these suctions that provide the driving force for water migration through the frozen soil - second frost heaving.

3. Permeability of Frozen Soils

The existence of continuous unfrozen water within frozen soils suggests a permeability; in other words the possibility of water movement. Hoekstra (1966) and Torrance and Williams (1976) have demonstrated migrations of water within frozen soils, in which there was a temperature gradient. The potential gradient can be assumed to result from the temperature gradient and the relationship between temperature and relative Gibbs free energy (suction). Burt (1974) developed a permeameter for measurement of water movement through frozen soils under essentially isothermal conditions. The apparatus was similar to that used to measure the hydraulic

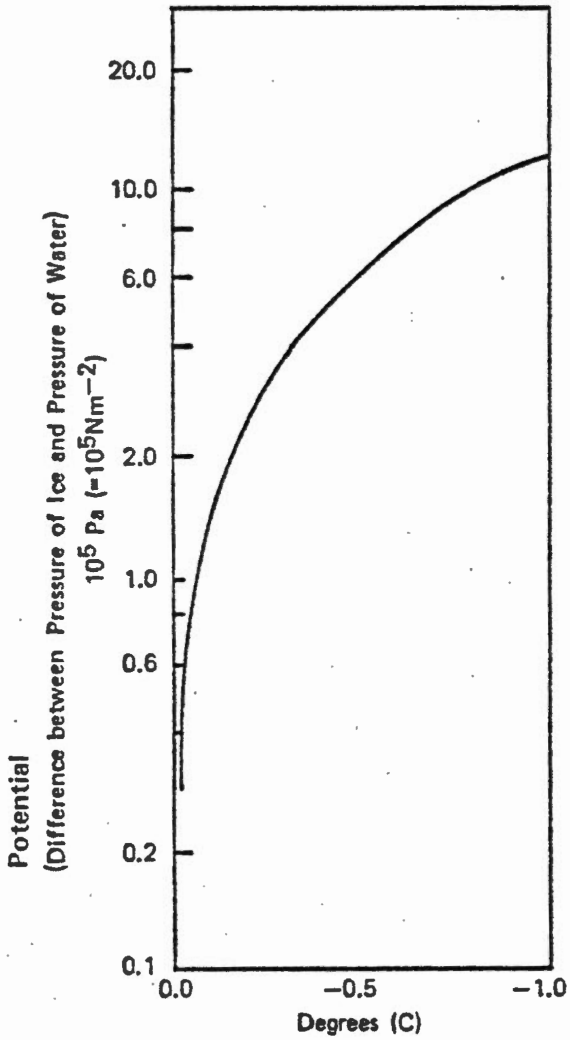


Figure 2. Relationship between temperature and potential (or free energy) in frozen soil.

conductivity of saturated unfrozen soils, but with various modifications to accommodate the presence of a frozen sample (Figure 3). The test procedure involved the passage of water from one reservoir through the frozen soil and into a second reservoir. The water in the reservoirs remained unfrozen because it contained dissolved lactose, such that its free energy was reduced to that of the unfrozen water in the soil. The potential gradient was supplied by application of hydrostatic pressure to one reservoir.

The interpretation of permeability and the construction of an appropriate experiment to measure it is made difficult by the complex thermodynamic situation in frozen soils. There is little doubt, however, that water, in one phase or another, is able to move through frozen soils in significant quantities, particularly at temperatures within a few tenths of 0°C. The latter is to be expected because of the large amounts of unfrozen water at these temperatures. Burt's results show the dominant influence of temperature on the hydraulic conductivity of frozen soils; commonly observed values ranged from 10^{-5} to 10^{-9} cms sec^{-1} (Figure 4).

Detailed experimental and theoretical work by Miller (1970) and Miller, Loch and Bresler (1975) suggests that in addition to water movement, the ice phase may also move, molecule by molecule through the frozen soil. Water molecules freeze on one side of ice lense and the latent heat liberated causes melting on the opposite side, with a consequent slow displacement of the ice body towards the 'melting' side. It follows that the presence of a

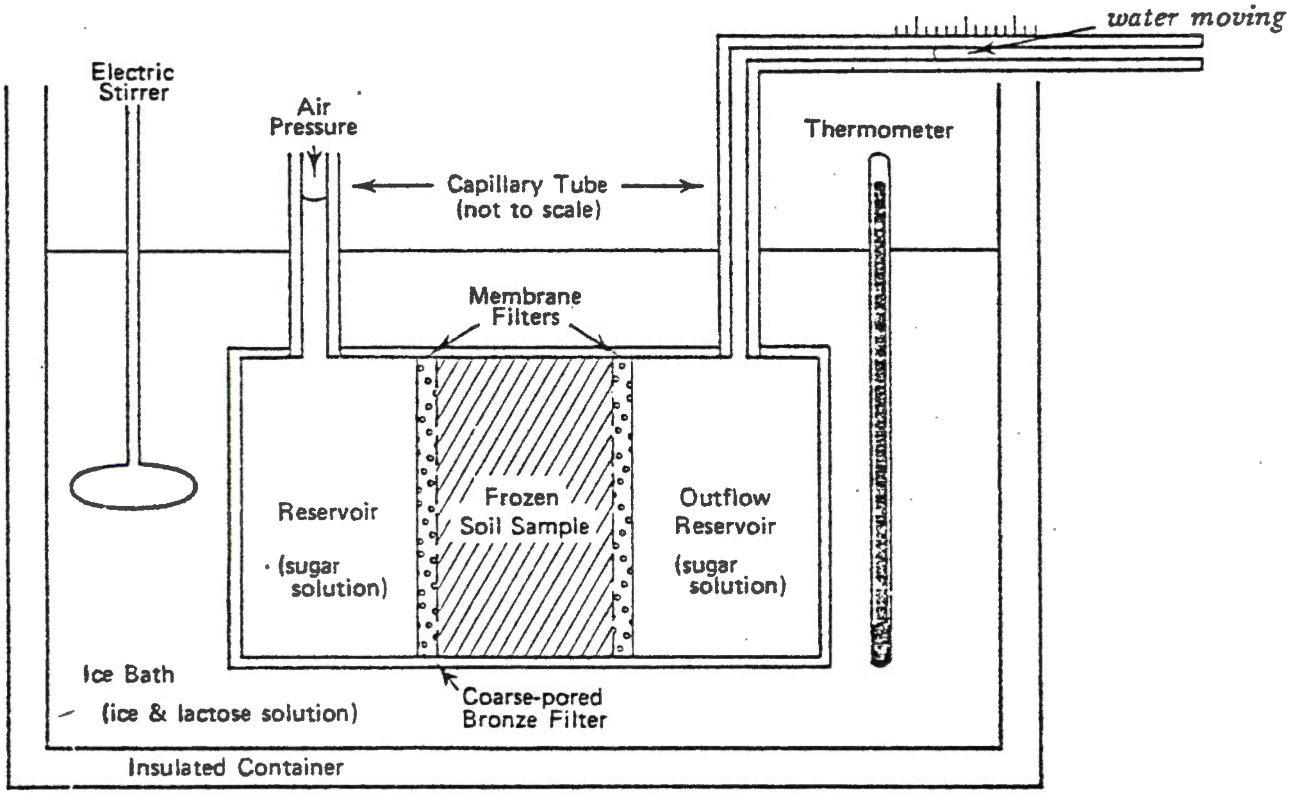


Figure 3. . A schematic diagram of the permeameter used by Burt (1974) to measure the hydraulic conductivity of frozen soils.

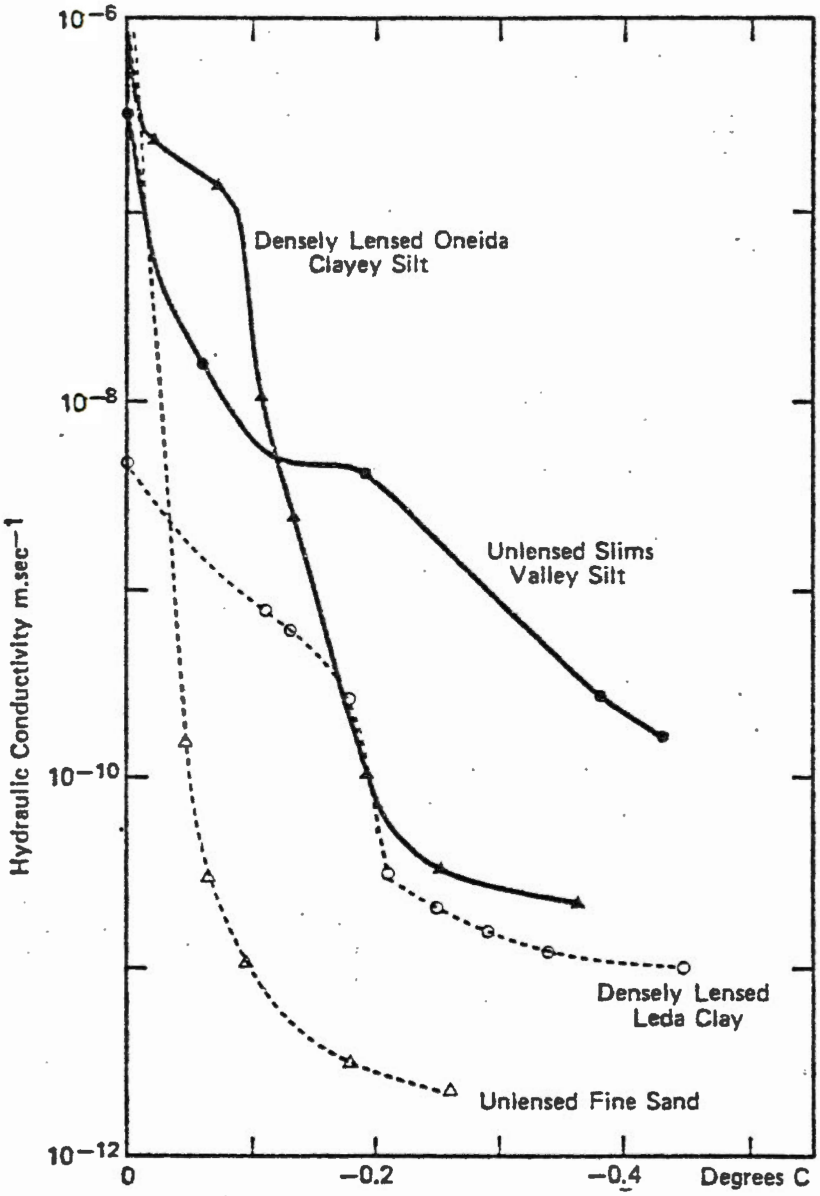


Figure 4. Hydraulic conductivity of frozen soils as a function of temperature. Experimental determinations from Burt (1974).

continuous transverse layer of ice does not reduce the permeability of the frozen soil very greatly. Experiments by Burt (1974) and Miller (1970) - Ice Sandwich Experiment - seem to confirm this hypothesis.

4. Water Migration in Frozen Soils Induced by a Temperature Gradient

Wherever there is a linear temperature gradient in frozen soil, a gradient of suction (or free energy) is implied by the relationship, Equation 2 and Figure 2. Consequently a flow of water, q, should occur in the direction of the temperature gradient. It should be remembered, however, that in a system with a temperature gradient, thermodynamic equilibrium in a precise sense does not exist; thus the clausius-clapeyron relationship is not strictly applicable.

If the temperature gradient is 0°C to -0.5°C, then the potential gradient is given by the difference in relative gibbs free energy over -0.5°C, which is 6.10^5 P_a or 6.10^3 cm of water head (see figure 2). The amount of water migration will also depend upon the permeability of the soil in the frozen state. If the permeability K, is taken as 10^{-9} cms sec^{-1} then we can obtain a value for q from the Darcy equation:

Equation 4

$$q = \frac{KiA}{L}$$

$$\therefore \quad q = \frac{10^{-9} \times 6.10^3 \times 10^4}{10^2} \quad cm^3\ sec^{-1}$$

$$\therefore \quad q = 6.10^{-4}\ cm^3\ sec^{-1}$$

where A = cross-sectional area = 1 m^2 or 10^4 cm^2

i = head = 60 m or 6.10^3 cm

L = length of sample = 1 m or 10^2 cm

As water accumulates within the frozen ground the gibbs free energy will tend to rise such that the ice and water are no longer in equilibrium. As a result freezing of the accumulated water will occur. Equation 4 implies the migration of an amount of water sufficient to produce a layer of ice approximately 50 cms thick in 25 years ($q \times 7.8894.10^9 \times 1.0904 = 5.16203442.10^5$).

The permeability of frozen soil decreases with temperature, as in figure 4, while the potential decreases linearly. Therefore ice accumulation will be favoured where the permeability is greatest and decreasing rapidly with temperature; that is, where the temperatures of the frozen ground are relatively warm. Over longer periods of time, however, water migration may result in ice accumulation at much colder temperatures.

III FURTHER INVESTIGATIONS WITH THE BURT PERMEAMETER

1. Problems with the Experiment

Burt's experiment was repeated a number of times in order to familiarize the author with the apparatus and test procedure used to measure the hydraulic conductivity characteristics of frozen soil samples. Running the experiment revealed a number of problems with the original permeameter:

(A) The Influence of Solutes

The gradual passage of lactose molecules through the dialysis membrane into the frozen soil upsets the equilibrium between the potential of the soil water, and that of the lactose solution. The lactose in the soil water adds an osmotic potential which further lowers the freezing point of the unfrozen water in the frozen soil. As a result some melting of ice occurs which gives rise to an increase in the hydraulic conductivity of the thawed part of the sample. At the end of each experiment a thawed layer, in some cases up to 0.5 cm thick, was consistently observed at the inflow end of each sample. Because of the existence of this thawed layer a correction must be made when calculating the conductivity coefficient using Darcy's Equation.

According to Burt (1974) the observed "agreement" when Carbowax (Polyethylene Glycol) and lactose were interchanged in an experiment with Leda Clay, indicates that the infusion of the lactose has only a minimal effect on the overall conductivity of the sample. As Miller (1976) points out, however, Leda Clay is a compressible soil, and as such, results obtained with it are not necessarily applicable to dominantly incompressible soils. Moreover, the comparison covered such a small range of temperatures that it is wrong to assume that the results are valid over a much larger range, especially when one considers the extremely high unfrozen water content for Leda Clay at the coldest temperature (-0.130°C) involved in the test (see Figure 1).

(B) Reduction in Flow Rates Over Time

Darcy's Law requires that a constant head produce a constant flow velocity. Like Burt (1974) the author has observed a pronounced time-decay of flow rates when pressure is applied over long periods of time. The occurrence shows no relationship to either temperature or size of head. The author is uncertain whether this means that some soils have a lower long term permeability or whether the time dependence is a result of experimental conditions. Possible causes for the decline in flow rates include:

1. Water flow into the frozen samples results in a local concentration of lactose at the inflow face; the inverse causes dilution in the outflow reservoir. This phenomenon coupled with the presence of dialysis membranes results in a counter osmotic potential gradient which induces flow in the opposite direction to the hydraulic gradient. The emergent layer of pure water (throughflow) is thus drawn back into the sample causing an apparent decline in hydraulic conductivity. This effect is accentuated by the high molecular weight of the solutes used (i.e.: carbowax and lactose). Miller (1976) has also observed this phenomenon when using dilute solutions of NaCl and $CaCl_2$ in the "Ice Sandwich" experiment. In his opinion the presence of solutes confounds the measurement of hydraulic conductivity "to an unknown degree". However, Burt (1974) has calculated that the reverse osmotic potential represents only 3 per cent of the total hydraulic gradient. For this

reason, Burt considers the effect insignificant so long as rapid diffusion of lactose molecules occurs in the reservoirs.

2. The imposed pressure gradient may induce a temperature gradient even though the permeameter is immersed in a stirred ice bath. Such a temperature gradient would approach zero only if the thermal impedancies of the end chambers of the apparatus were equal to zero. Since the end chambers contain a membrane, a porous bronze plate and a reservoir capable of enduring large pressures, this condition is not met. Although the induced temperature gradient might be small, it could well be critical. As in the case of the solute differential, it would be in such a direction as to diminish transport through the permeameter (Miller, 1976).
3. Because of the large heads used, ice may melt at the inflow end and refreeze preferentially on the outside of existing ice lenses. The resultant increase in lense sizes might reduce the permeability of the sample. This hypothesis is supported by the frequent appearance of continuous layers of ice across the outflow face of the sample.
4. Because the pressures applied were always over 500 cm water head it is possible that gradual consolidation of the samples occurred. Consolidation would give increased tortuosity to the ice free passages (i.e.: reduce r in equation 1), with a subsequent fall in conductivity. Hydraulic gradients induced by freezing, in the field might also produce consolidation of soils over time. If the samples do have a lower

long term permeability then this is the permeability which should be investigated, since it most closely resembles the natural situation. The short-term measurements which Burt's Permeameter permits, assume that this time dependence is a result of the experiment itself. Therefore, they may represent an overestimation in comparison with values that could be expected under field conditions.

(C) Pressure Induced Melting of the Sample

The large heads used to produce measureable flow may cause some melting of ice at the inflow face. For every 100 cm of water pressure exerted on water (in conjunction with ice) its freezing point is depressed by 0.007°C. Since the largest heads used were always below 2000 cm the maximum effect would be to cause a change equivalent to warming the sample by 0.14°C. This effect is not uniform on the sample, however, being greatest at the inflow end and decreasing linearly with the hydraulic gradient towards the outflow end, where no melting occurs. Because of this Burt (1974) considers the effect to be so small as to be insignificant.

(D) Measurement of Permeability at Low Temperatures

The existence of large amounts of unfrozen water in some clays, at very low temperatures implies a permeability for these soils even below -5.0°C. However, the most concentrated lactose solution only allows readings to be taken down to ≈-0.8°C. Consequently, Burt's permeameter only permits investigation of hydraulic conductivities at temperatures close to 0°C.

2. IMPROVEMENTS TO THE BURT PERMEAMETER

Because of the problems encountered with the original apparatus and test procedure a number of modifications have been investigated:

(A) The Use of Supercooled Water in the End Chambers

With reasonable care it is possible to perform Burt's experiment using supercooled water, instead of lactose solution in the end chambers. Barring punctures, the Dialysis membranes serve as effective phase barriers at temperatures as low as $-1^{\circ}C$, and possibly to -3 or $-4^{\circ}C$. It is not at all dificult to maintain water in a supercooled state down to $-1.0^{\circ}C$ (Dorsey, 1940), whereas lactose only produces freezing point depressions down to approximately $-0.8^{\circ}C$ (see Appendix A). Despite its theoretical disadvantage supercooled water eliminates the problems of infusion and reverse osmotic gradients encountered with lactose solution in the reservoirs. If the sample is confined, (which it is) then the supercooled water can be in mechanical equilibrium with the ice and unfrozen water in the soil. The tendency to "pull" water into the sample from both reservoirs vanishes as the ice pressure rises to its equilibrium valve. This may result in ice lensing on the ends of the sample, and thus a lower overall conductivity for the system. But, this situation is just as relevant to field conditions as the situation simulated by adding solutes to the end chambers.

(B) Increase in Cross-Sectional Area of the Sample Container

The diameter of the sample holder was enlarged so as to approximately double the cross-sectional area from 11.34 to 22.88 cm^2. Consequently hydraulic gradients established across the system yield greater volumes of throughflow. The increased discharge means that meniscus velocities can be measured more readily. Since cavities often occur at the interface between the sample and its perspex container (they appear to be an unavoidable product of packing and freezing) the increase in cross-sectional area should also reduce the significance of any flow lines arising from these edge-effects.

(C) A Thermistor Centered Within the Frozen Sample

This modification provides an internal temperature record. Continuous monitoring ensures that measurement of hydraulic conductivity does not commence until the sample is in thermal equilibrium with the lactose solution in the ice bath and reservoirs. The estimated limit of accuracy for temperature measurement was $\pm 0.01^{o}C$ (see Appendix B).

(D) Immersion of the Permeameter in a Refrigerated Methanol Bath

Burt (1974) has noted the need for an arrangement whereby the sample and reservoirs can be maintained at a constant temperature allowing the phenomenon of declining flow rates over time to be investigated:

> "Further research is required on this point, but since the present apparatus cannot allow constant temperatures to be maintained for long periods, especially at lower temperatures, the short term situation is all that can be investigated. Single tests lasting 7 or 8 hours are complicated by the fact that the temperature may have risen by 0.01°C by the end of the test".

The feasibility of such a modification has been examined by comparing the temperature control achieved with a stirred ice bath, to that obtained using a "Hotpack" bath circulator. Variations in the amount of electric current supplied caused significant temperature fluctuations in the Methanol bath, whereas the ice bath produced essentially isothermal conditions. For this reason it was decided to retain the ice bath in the experimental procedure.

(E) Instantaneous Freezing of Saturated Soil Samples

The method of freezing governs the type and pattern of ice lenses. Freezing samples in liquid Nitrogen would eliminate the influence of ice lensing on hydraulic conductivity. Pore water should freeze in situ; the temperature of the sample could then be brought into equilibrium with that of the ice bath. Consequently there would be a proportion of unfrozen water as well as ice within the soil pores. However, the almost instantaneous heave (9 per cent expansion caused by change of phase from water to ice) repeatedly fractured the perspex sample container.

A new permeameter has been constructed incorporating some of the modifications discussed above (plates 1 and 2).

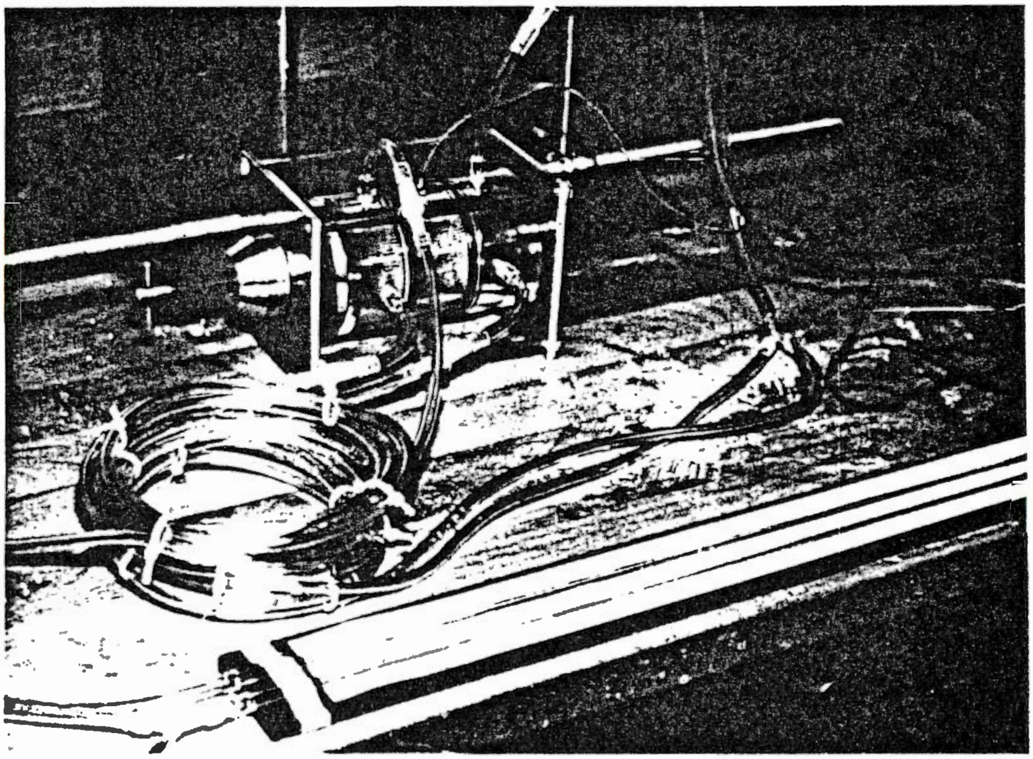


Plate 1. The modified permeameter; note capillary tubes used to measure throughflow and coils of tubing to supercool water in the ice bath before it enters the reservoirs.

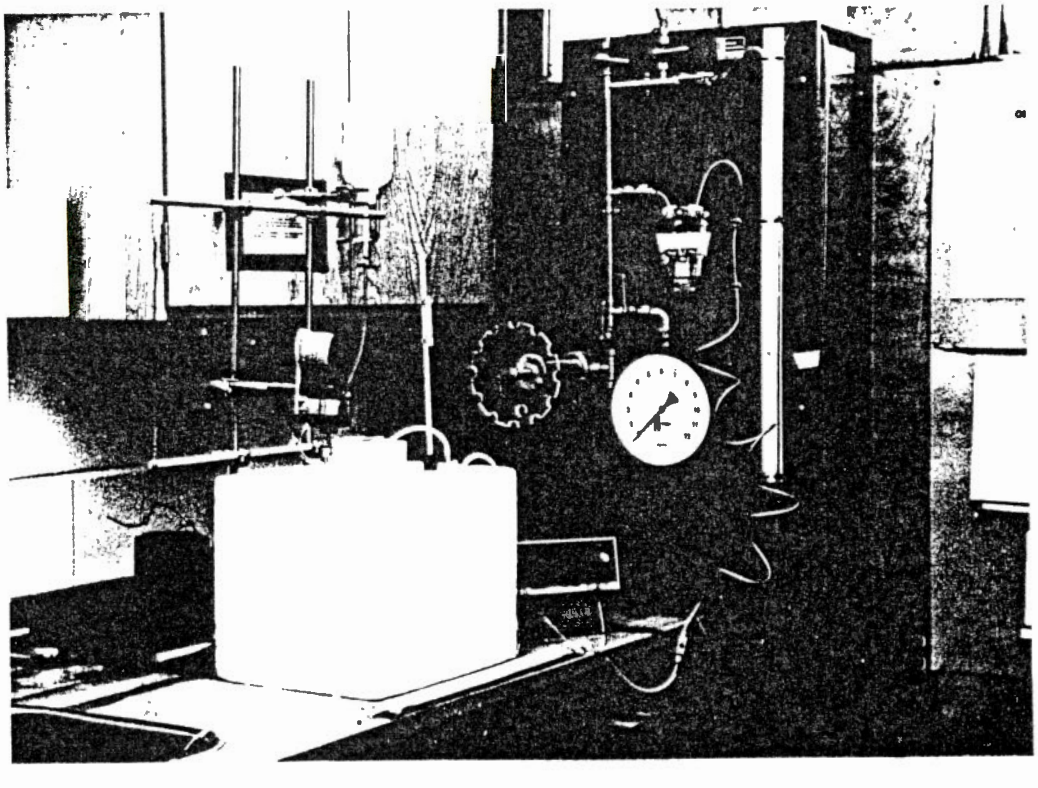


Plate 2. General view of the frozen hydraulic conductivity experiment; ice bath containing permeameter on left, manometer, and temperature measuring equipment on right.

This has been used to reproduce and improve on the hydraulic conductivity values achieved by Burt (1974). In the following section results obtained using the improved apparatus and test procedure are compared with those derived using the original permeameter.

3. RESULTS AND DISCUSSION

A comprehensive record of measurements obtained is presented in Appendix C. In this section a preliminary phenomenological evaluation of those results will be undertaken.

To the authors knowledge this study represents the first successful repetition of the frozen hydraulic conductivity experiment. Results derived appear to verify the conductivities obtained by Burt (1974), and thus the reproducibility of the test (compare Figure 8, Oneida Clayey silt and Figure 11, Slims Valley silt with the corresponding curves in Figure 4). All samples showed a general increase in permeability as the temperature rose towards $0^{\circ}C$ (see Figure 1). Figure 12 shows the hydraulic conductivity - temperature curve for a sample of castor silty loam, 1963. At temperatures close to zero the unfrozen water content - temperature relationship largely depends upon the pore-size distribution of the soil. Consequently, the steep slope of the curve from -0.240 to $0^{\circ}C$ indicates that the sample possesses a large number of pores which become ice-free over the temperature range in question; the gentle slope from -0.405 to $-0.240^{\circ}C$ implies the opposite. It follows that soil type exerts an important influence on the hydraulic conductivity of frozen samples (compare the permeability-temperature curves for three different soils, Figures 5, 11 and 13).

One test was run to simulate Millers' "Ice Sandwich" experiment; the results are presented in Figure 9. A transverse ice lense, approximately 5 mm thick developed across the outflow end of the sample container. The soil sample itself was not present. Supercooled water was used in the end chambers; on application of pressure to one reservoir flow was observed to take place 'through' the ice lense (water freezes on one side of the lense, and the latent heat liberated initiates thawing on the other side). The reduction in flow compared to a sample of frozen soil was suprisingly small ($K \simeq 6.10^{-11}$ cms sec^{-1}), although there was no observeable relationship to temperature. Close to zero, however, the 'apparent hydraulic conductivity' may be temperature dependent on account of flow in the unfrozen water surrounding individual crystals within the ice lense (Osterkamp, 1973).

Burt (1974) measured a single value of hydraulic conductivity at each temperature. In the present study, however, up to twelve readings were taken over a period of several minutes. From these a maximum, minimum and median value of hydraulic conductivity were derived for every temperature step. The curves plotted in Appendix C utilize these values. Because of the inherent variability of hydraulic conductivity tests it is important to stress the range over which measurements are obtained.

All samples showed a short-term decline in permeability, often by as much as an order of magnitude, over the period in which readings were taken. For example, the hydraulic conductivity of castor silty loam at -0.185°C dropped from 2.10^{-7} to 2.10^{-8} in just over thirty minutes:

Time (seconds)	Meniscus (Distance travelled, cms)	Head (cms)	Hydraulic conductivity (cms/sec)
51.70	50.00	1175.00	2.242539E-07
134.10	50.00	1180.00	8.609098E-08
142.90	50.00	1370.00	6.958500E-08
210.60	50.00	1385.00	4.670467E-08
200.20	50.00	1480.00	4.597721E-08
221.60	50.00	1485.00	4.139732E-08
261.60	50.00	1485.00	3.506745E-08
252.90	50.00	1580.00	3.409279E-08
295.20	50.00	1590.00	2.902385E-08
154.50	25.00	1595.00	2.764072E-08

The cause of this phenomenon is not fully understood at present, although Miller (1976) has noted a similar time dependence with his "Ice Sandwich" experiment, which he attributes to local accumulation of solutes at the inflow face. However, the phenomenon was also observed in tests where supercooled water was used. Since the permeameter does not allow constant temperatures to be maintained over long periods of time, it is uncertain whether the conductivity will stabilize at some lower, long term value, or continue to decrease until the sample becomes impermeable.

Samples also showed an initial drop in conductivity, irrespective of soil type, after an apparently high first measurement (see Figures 7, 8 and 12). The high initial permeability may be explained by re-adjustments occurring with the unfrozen water, to the pressure head applied. This hypothesis is somewhat confounded, however, by the non-occurrence of the phenomenon in Experiments 11, 12 and 13 (supercooled water in the end chambers).

IV. Experimental Determination of Temperature Induced Water Movement in Frozen Soils.

1. The Apparatus Design

A linear gradient of temperature in frozen soil will create a hydraulic gradient (potential) in the unfrozen water according to the relationship between Equation (2) and Figure (2). Therefore, given a frozen soil sample placed between two bodies of water, the application of a temperature gradient across the system should induce flow through the sample in the direction of decreasing temperature. Several important requirements must be met in the development of an experimental apparatus to simulate this situation:

A. The water must be at the same temperature as the frozen soil. However, the juxtaposition of ice and bulk water will cause freezing of the latter at any temperature below 0°C. Therefore, the potentials of the water in the reservoirs and the unfrozen water must be equalised before a temperature gradient is applied across the system.

B. The heat flow must be uniaxial. If this is not the case, then the temperature and moisture distribution will not be uniform (in cross-section) at any given length along the sample. It is necessary therefore, to avoid any lateral heat exchange between the sample and its surroundings.

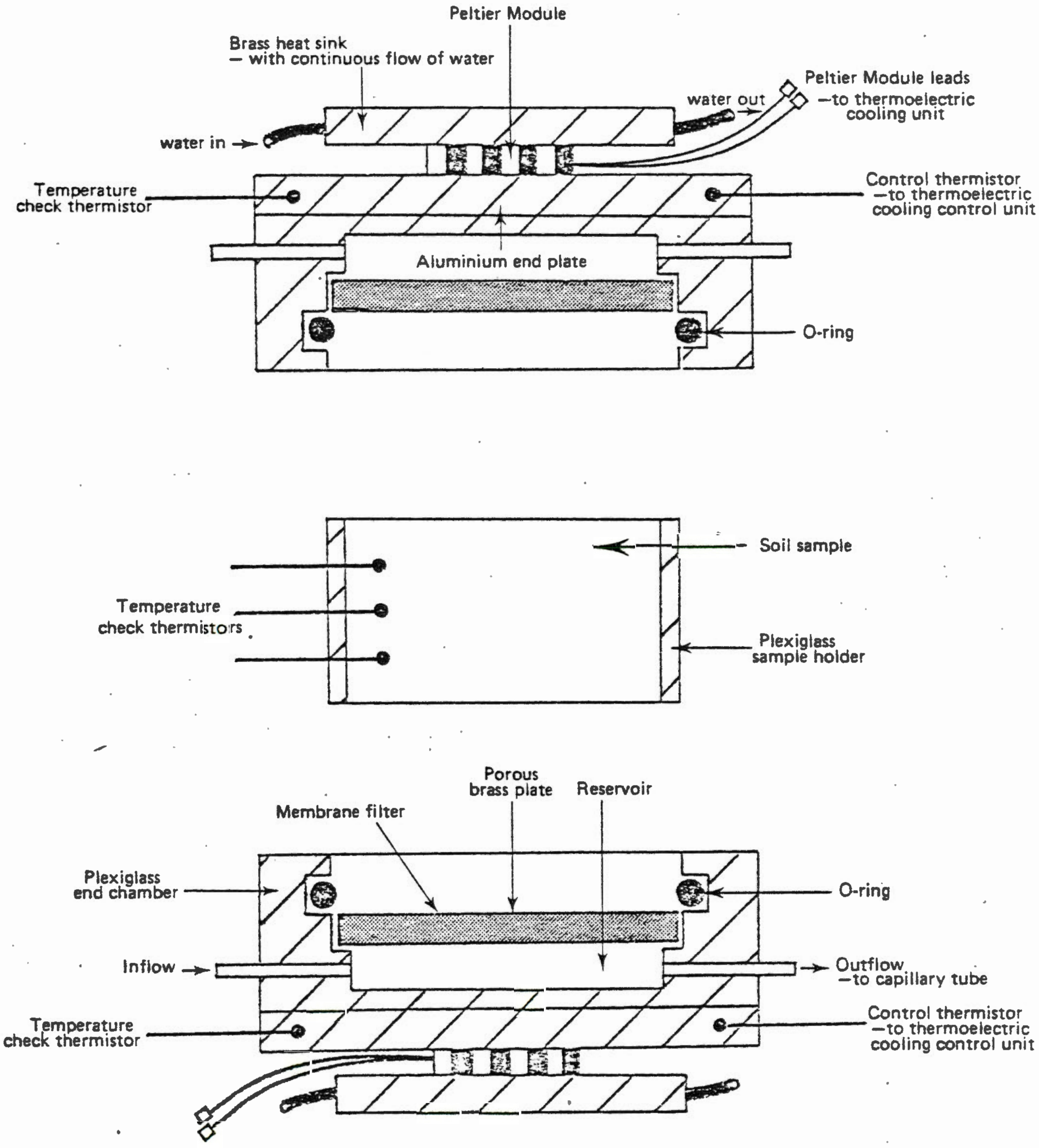
C. Both ends of the sample must be held at constant temperatures below 0°C. Because heat flow through the sample and end plates may be variable it is necessary to have the end plate temperatures controlled by a device which is able to maintain a steady state situation through rapid adjustment to fluctuations in cooling load.

The design of the experimental apparatus is shown in figure (5) and plates (3)-(4). It is essentially similar to that used by Burt to measure the hydraulic conductivity of frozen soil samples under isothermal conditions. The main difference is that the hydraulic potential is created by a temperature gradient incorporated into a steady state situation, rather than by a pressure differential. The frozen sample and reservoirs are sandwiched between two end plates containing Peltier modules. These cooling devices are controlled by a thermoelectric cooling control system which can maintain temperatures constant to within 0.02°C (Williams, 1968). Continuous monitoring of the temperature profile is provided by five thermistors and one thermocouple centred within the sample holder end plates (estimated limit of accuracy ± 0.01°C). To prevent lateral heat exchange between the frozen sample and air at room temperature the apparatus is enclosed in a box of 'styrofoam' insulation, packed with vermiculite granules. The entire assembly is then placed in a 'precision scientific' incubator which maintains a uniform air temperature, of approximately 0°C, within the box.

2. Experimental Procedure

The reservoirs contain either supercooled water or lactose solution. To prevent the possibility of ice nucleation a dialysis membrane (phase barrier) is fitted on each end of the sample, to separate soil ice from the end chambers. The membranes also serve to impede the entry of lactose molecules into the sample.

Figure 5 Scale drawing of the experimental apparatus. (Actual size)



(The Teflon screws used to hold the apparatus together are not shown).

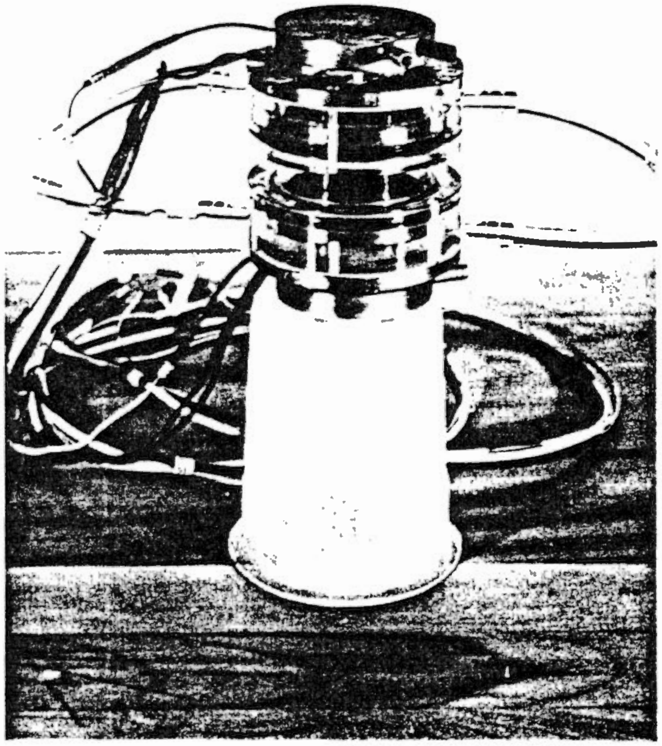


Plate 3. Apparatus used to measure water movement through frozen soil in response to a linear temperature gradient.

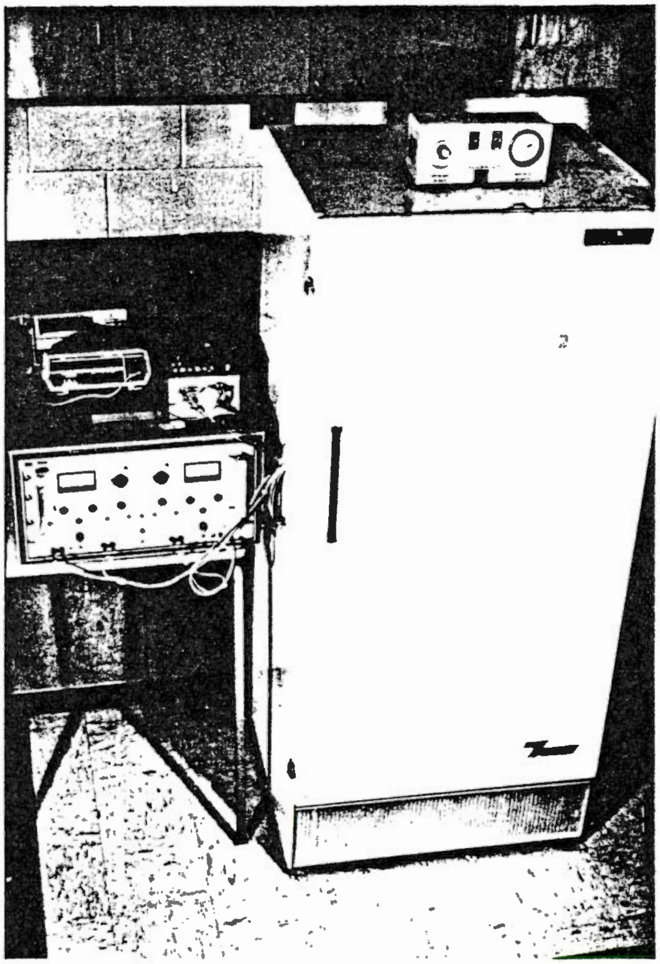


Plate 4. Incubator containing the experimental assembly, with switching box, multimeter and thermoelectric cooling control unit on the right.

Initially the potentials of the supercooled water and the unfrozen soil water are not equal. This differential establishes a tendency for water to be drawn into the sample from both reservoirs. However, this tendency disappears as the ice pressure in the sample reaches its equilibrium value. It follows that the potentials of the supercooled water and the unfrozen soil water also approach mechanical equilibrium.

When a temperature gradient is established across the system water passes from one reservoir, through the frozen sample into the second, colder reservoir. The discharge is measured in a capillary tube. The volume of throughflow represents a measure of the 'overall hydraulic conductivity' of the frozen soil (Loch and Kay, 1977). Under steady state conditions this equals the hydraulic conductivity integrated over the length of the frozen sample, in the form:

$$K = \frac{L}{\int_{X_1}^{X_2} \frac{1}{K(X)} \, d_X}$$

where L is the path length of flow

X_1, X_2 are the distance of coordinates coinciding with the boundaries of the flow path.

K is the overall hydraulic conductivity of the frozen soil.

K(X) is the hydraulic conductivity as a function of distance.

Thus, it is possible to calculate hydraulic conductivity as a function of distance and temperature by solving for K(X) with reference to the temperature profile. This permits comparison with the conductivities measured by Burt (1974).

Using the same apparatus it is proposed to conduct a second experiment in which the outflow face of the sample is covered by an impermeable rubber membrane. On application of a temperature gradient across the system, flow will take place through the frozen soil towards the outflow reservoir. However, water, is prevented from entering this reservoir by the impermeable membrane. As more and more water accumulates at the outflow face, ice lensing must occur. The amount of heave caused by the growing layer of ice should be measureable via the expansive rubber membrane; either with a pressure transducer or through displacement of water from the end chamber.

3. Results and Discussion

A preliminary freezing experiment, using a slims valley silt soil, has been completed with the new apparatus. All relevant data collected during the experiment are reported in Appendix D.

The sample was prepared as a slurry and then prefrozen in a refrigerator. On assembly, the top plate was brought to a temperature of about -0.67°C, while the bottom plate was maintained at approximately -0.17°C, giving a gradient of 0.5°C across the system. The temperatures of both plates were observed to be relatively stable, fluctuating by only 0.05°C throughout the duration of the experiment (12 hours). The end chambers of the apparatus were filled with lactose solution.

In general the results of the experiment were as expected, even though a linear temperature gradient was not achieved across the system. A steady flux of water ($\simeq 10^{-4}$ cm^3/min) was observed entering the reservoir at the 'cold' end of the sample (see Appendix D). Despite the presence of an unfrozen layer at the 'warm' end, it seems reasonable to attribute this flux to moisture migration occuring within the frozen portion of the sample. A temperature gradient in frozen soil implies a gradient of free energy (or Potential) within the unfrozen water according to the relationship Equation (2) and Figure (2). This relationship however, does not apply above $0^{\circ}C$; consequently temperature gradients in unfrozen soil do not induce the same potential for water movement. It follows that the observed flux was almost certainly due to migration of unfrozen water (and/or ice) through the frozen soil.

The results of the experiment are most encouraging. All major features in the experimental design appear to be functioning correctly, while only minor modifications are required to the test procedure. Work is underway on refinement of the temperature gradient. Provision is also being made for the continuous measurement of inflow.

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Appendix A

Freezing point depression, $\Delta^{o}C$ as a function of lactose concentration.

Reference: Handbook of chemistry and Physics, Page, D-218.

LACTOSE, $C_{12}H_{22}O_{11} \cdot 1H_2O$

Molecular weight = 342.30
Formula weight = 360.31

Anhydrous Solute Concentration g/l	Molar Concentration g-mol/l	Freezing Point Depression Δ°C
0.50	5.0	0.027
1.00	10.0	0.055
1.50	15.1	0.083
2.00	20.1	0.112
2.50	25.2	0.140
3.00	30.3	0.169
3.50	35.4	0.198
4.00	40.6	0.228
4.50	45.7	0.258
5.00	50.9	0.288
5.50	56.1	0.319
6.00	61.4	0.351
6.50	66.6	0.385
7.00	71.9	0.420
7.50	77.2	0.456
8.00	82.5	0.495
8.50	87.8	No value given
9.00	93.1	" " "
9.50	98.5	" " "
10.00	103.9	" " "

Appendix B

N.R.C. correction for thermometer used in the ice bath.

Note: Temperatures measured to an accuracy of ±0.01°C.

National Research Council Canada
Conseil national de recherches Canada

REPORT

Liquid-in-Glass Thermometer

Serial No.:	112213
Manufacturer:	Brooklyn Thermo Co.
Submitted By:	Carleton University Ottawa, Ontario
Description:	Mercury in Glass, 4 in. immersion
Range:	-6° to 0°C
Graduation:	0.01°C

The ABOVE DESCRIBED THERMOMETER HAS BEEN COMPARED WITH THE STANDARDS OF THE NATIONAL RESEARCH COUNCIL AND FOUND, AT THIS DATE, TO HAVE THE CORRECTIONS LISTED BELOW.

Thermometer Reading	Correction
-6°C	-0.086°C
-3°	-0.072°
0°	-0.055°

TO USE THE CORRECTIONS PROPERLY REFERENCE SHOULD BE MADE TO THE FOLLOWING NOTES ON THE REVERSE SIDE OF THIS SHEET: A & D

REMARKS:

The estimated limit of accuracy was ± 0.01°C.

for the Director, Division of Physics, Ottawa.

REPORT No. APH 2173

DATE 16 October 1978

Appendix C

Hydraulic Conductivity of Frozen Soils:

A record of results obtained.

Note: All experiments were conducted using the improved permeameter, except numbers 1 to 4, where the original apparatus was used. Lactose solution was used in all experiments, except numbers 4, 11, 12 and 13 where supercooled water was used. Refrigerator frozen samples were used throughout. All moisture contents are expressed as per cent dry weight.

1. Slims Valley Silt

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.160	1.331771E-08	1.122140E-08	1.122140E-08
-0.155	9.938956E-09	1.286778E-09	7.550400E-09
-0.145	1.257783E-08	2.885503E-09	8.635985E-09
-0.140	1.211911E-08	7.617729E-09	9.341706E-09
-0.135	9.738573E-08	5.119441E-09	8.106890E-09
0.000	4.624467E-05	8.065658E-06	1.778478E-05

2. Slims Valley Silt

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.730	4.328255E-09	6.492382E-10	3.787223E-09
-0.400	4.161784E-10	3.606879E-11	9.017199E-11
-0.360	-	-	3.606879E-11
-0.350	2.847536E-10	2.765658E-11	1.562051E-10
0.000	4.624467E-05	8.065658E-06	1.778478E-05

3. Oneida Clayey Silt

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.135	7.733149E-09	2.885503E-10	6.780933E-09
-0.130	7.588873E-09	8.656510E-11	3.751154E-10
-0.125	-	-	2.885503E-11
-0.115	1.154201E-09	1.442752E-10	1.731302E-10
-0.110	1.731302E-10	8.656510E-11	1.731302E-10
0.000	8.573731E-06	2.393244E-06	3.837826E-06
0.000	1.221736E-06	6.700085E-06	1.082064E-06
0.000	1.740877E-06	1.010291E-06	1.621322E-06
0.000	2.657548E-08	7.877424E-09	1.134003E-08
0.000	4.025277E-08	1.615882E-08	2.517602E-08

4. Continuous Transverse Ice Lense (≃ ½ cm thick)

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.180	7.551985E-11	6.338273E-11	7.079986E-11
-0.180	7.872270E-11	4.787419E-11	5.343704E-11
-0.175	7.383414E-11	6.034845E-11	6.776558E-11
-0.175	6.489987E-11	3.944564E-11	5.714560E-11
-0.175	6.405702E-11	4.821133E-11	6.203416E-11
-0.150	5.360561E-11	4.568277E-11	5.107704E-11
-0.145	-	-	5.899988E-11
-0.135	6.776558E-11	6.405702E-11	6.473130E-11
-0.125	6.843987E-11	5.495418E-11	5.866274E-11

5. Slims Valley Silt

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.230	2.284757E-06	2.087316E-06	2.154121E-06
-0.185	2.360573E-06	2.265380E-06	2.291483E-06
-0.175	3.138909E-06	2.574237E-06	2.750635E-06
-0.140	6.459395E-06	4.467245E-06	5.585976E-06
0.000	4.624467E-05	8.065658E-06	1.778478E-05

6. Slims Valley Silt

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.300	2.481862E-06	1.538092E-06	2.009977E-06
-0.295	5.799211E-06	1.132371E-06	3.308393E-06
-0.205	2.349048E-06	1.948561E-06	2.100168E-06
-0.195	1.305896E-06	2.338628E-07	1.265762E-06
-0.180	3.898103E-06	2.647770E-06	3.211444E-06
-0.060	8.210004E-06	7.487816E-06	7.501987E-06
0.000	4.624467E-05	8.065658E-06	1.778478E-05

7. Caster Silty Loam, 1963

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.405	4.671764E-07	1.832893E-08	7.281975E-08
-0.390	5.922890E-09	3.520533E-09	4.736114E-09
-0.285	1.240546E-08	3.475664E-09	7.940562E-09
-0.255	8.155055E-09	3.772426E-09	4.539675E-09
-0.240	1.846685E-08	1.481423E-08	1.709622E-08
-0.195	1.478946E-07	1.225629E-07	1.343963E-07
-0.155	2.793116E-07	2.214884E-07	2.589861E-07
0.000	1.021333E-07	2.632902E-08	4.382266E-08
0.000	8.840480E-06	5.681836E-06	6.510714E-06

8. Castor Silty Loam, 1963 (moisture content: 41.92%)

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.260	1.352082E-08	1.023194E-08	1.166786E-08
-0.235	8.737576E-09	7.042856E-09	7.504396E-09
-0.220	3.592812E-07	1.303935E-07	2.368411E-07
-0.185	1.224907E-07	1.051569E-07	1.122845E-07
-0.175	2.898555E-07	2.449010E-07	2.621903E-07
-0.135	5.616518E-07	4.033715E-07	4.303329E-07
-0.120	1.086006E-06	8.442006E-07	1.034622E-06
0.000	8.840480E-06	5.681836E-06	6.510714E-06
0.000	1.021333E-07	2.632902E-08	4.382266E-08

9. Castor Silty Loam, 1963 (moisture content: 29.90%)

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.305	3.901399E-08	2.142061E-08	2.713298E-08
-0.255	3.011383E-08	1.064735E-08	2.163894E-08
-0.235	3.026570E-08	1.973856E-08	2.115425E-08
-0.225	1.182561E-07	2.652876E-08	5.344936E-08
-0.195	-	-	2.677655E-08
-0.190	1.410877E-07	3.896979E-08	7.252521E-08
-0.160	9.368717E-08	2.223506E-08	3.140806E-08
-0.090	8.176450E-08	4.563315E-08	4.791489E-08
0.000	1.803523E-05	2.276760E-06	4.335065E-06

10. Castor Silty Loam, 1963 (moisture content: 34.68%)

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.225	2.237585E-07	9.527028E-09	2.550917E-08
-0.210	3.498640E-08	4.548703E-09	7.091567E-09
-0.185	2.242539E-07	2.764072E-08	4.368727E-08
-0.155	1.496048E-07	8.027900E-08	9.159923E-08
-0.125	2.743696E-07	2.227196E-07	2.400050E-07
0.000	3.478757E-05	2.352370E-05	2.734498E-05

11. Castor Silty Loam, 1963 (moisture content: 35.12%)

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.280	4.158498E-08	8.942608E-09	2.239376E-08
-0.280	1.521360E-08	1.651906E-09	2.579908E-09
-0.230	2.045205E-08	3.450204E-09	6.515755E-09
-0.230	3.781306E-09	2.214945E-09	3.282793E-09
0.000	1.021333E-07	2.632902E-08	4.382266E-08
0.000	8.840480E-06	5.681836E-06	6.510714E-06

12. Castor Silty Loam, 1963 (moisture content: 34.86%)

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.275	2.283106E-09	3.795425E-10	5.676194E-10
-0.245	9.642157E-09	2.941625E-09	5.115759E-09
-0.220	6.033850E-08	1.150368E-08	5.640062E-08
-0.120	3.252833E-07	7.203063E-08	1.256617E-07
0.000	1.887686E-05	1.405977E-05	1.558563E-05

13. Slims Valley Silt (moisture content: 28.36%)

Temperature (C)	Hydraulic Conductivity (cms/sec)		
	Max. Value	Min. Value	Median Value
-0.485	3.237400E-09	1.702858E-09	2.598911E-09
-0.415	4.812868E-09	1.343478E-09	2.883574E-09
-0.330	7.152746E-09	2.068956E-09	3.189480E-09
0.000	7.577268E-05	6.771833E-05	7.212607E-05

Figure 6. 1. Hydraulic conductivity of frozen Slims Valley silt.

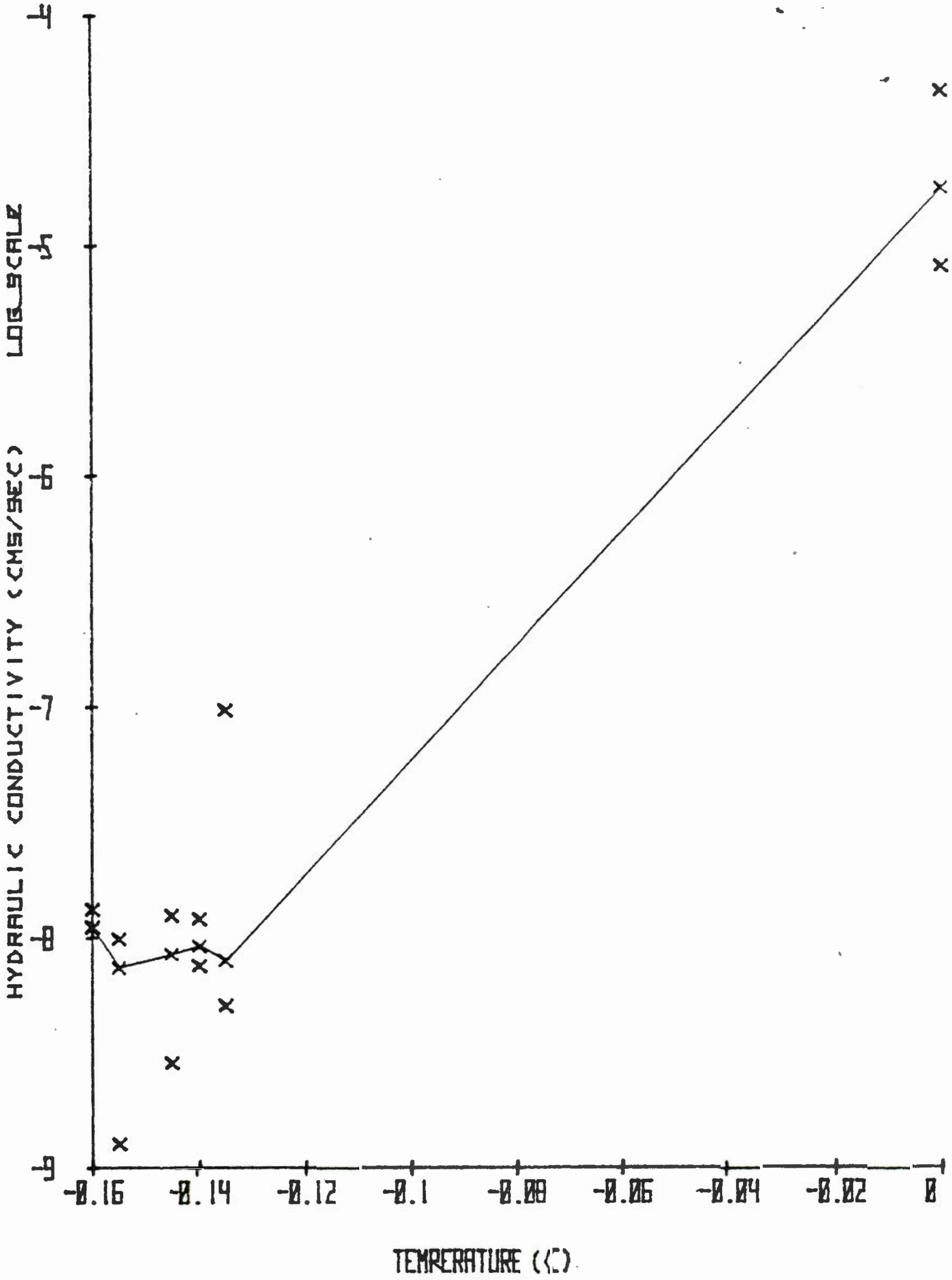


Figure 7. 2. Hydraulic conductivity of frozen Slims Valley silt.

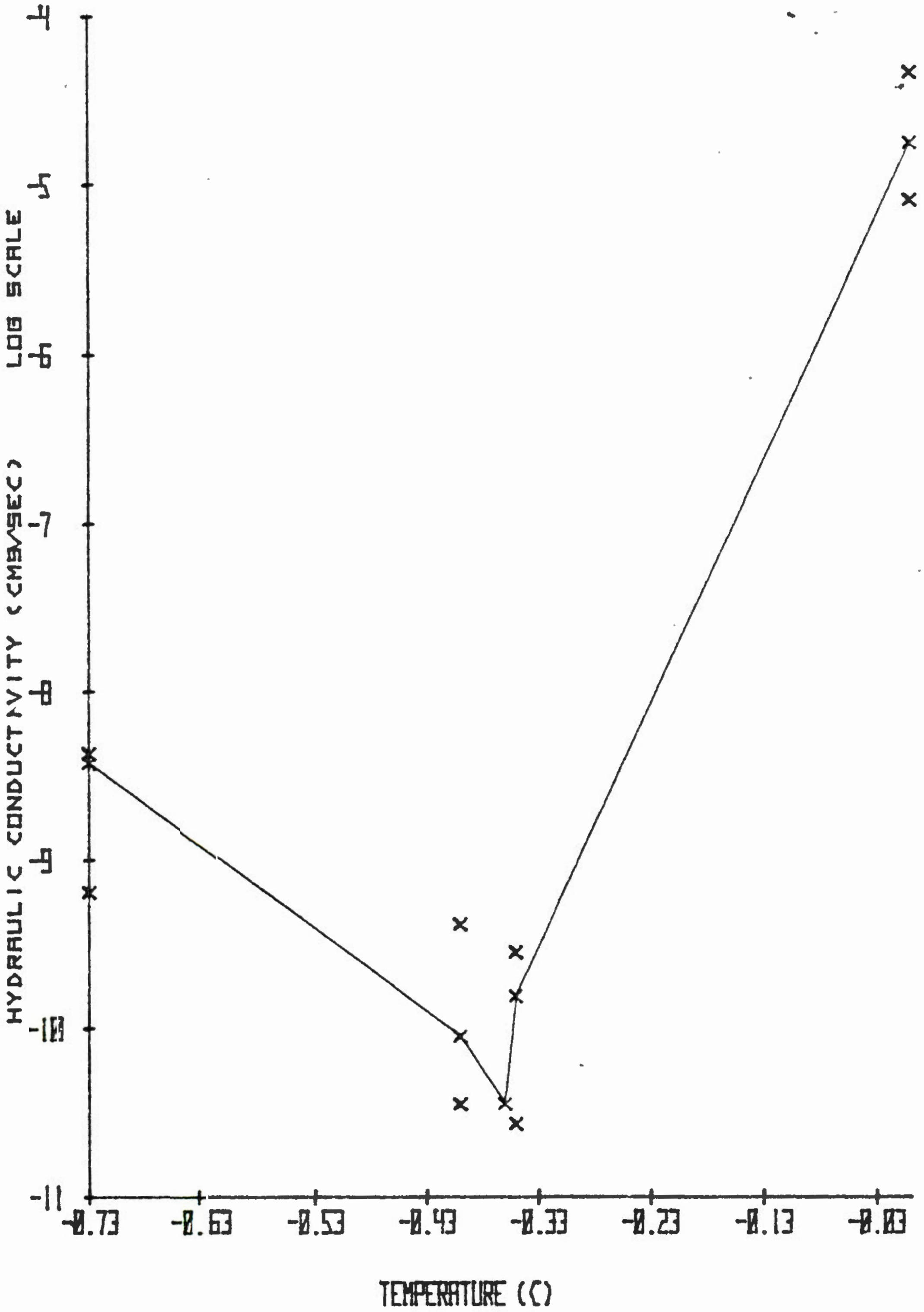


Figure 8. 3. Hydraulic conductivity of Oneida clayey silt.

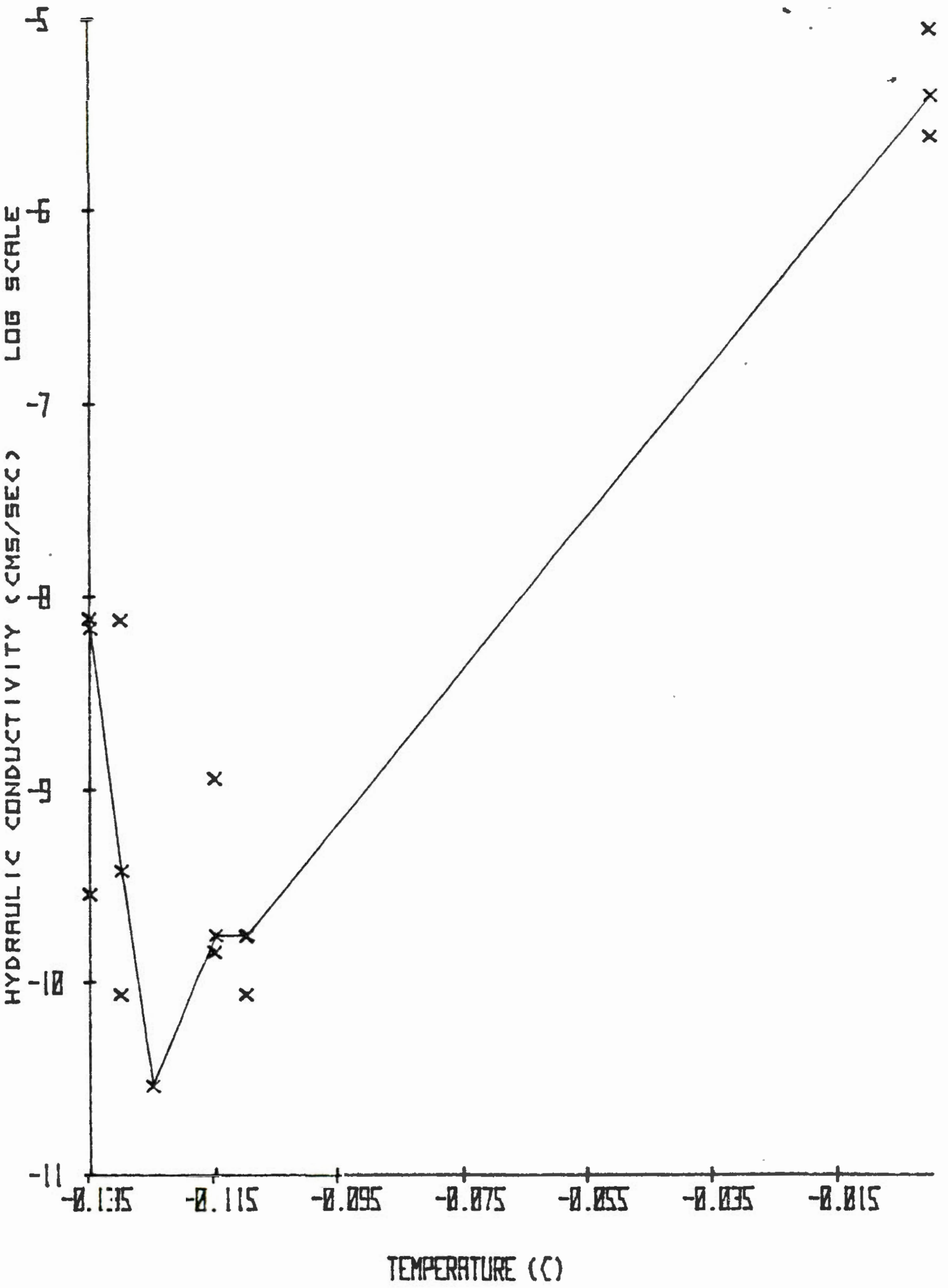


Figure 9. 4. Hydraulic conductivity of a continuous transverse ice lense.

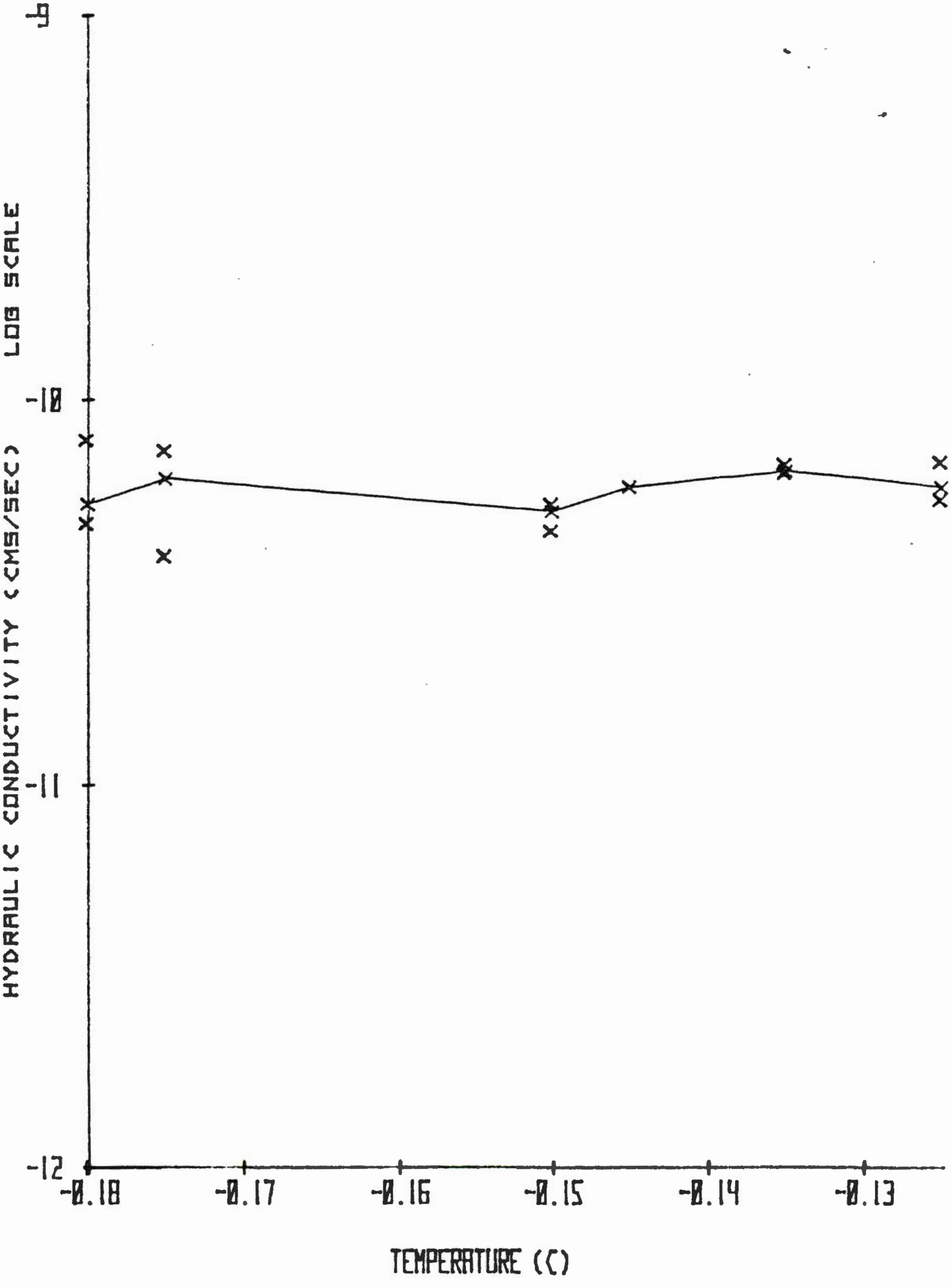


Figure 10. 5. Hydraulic conductivity of frozen Slims Valley silt.

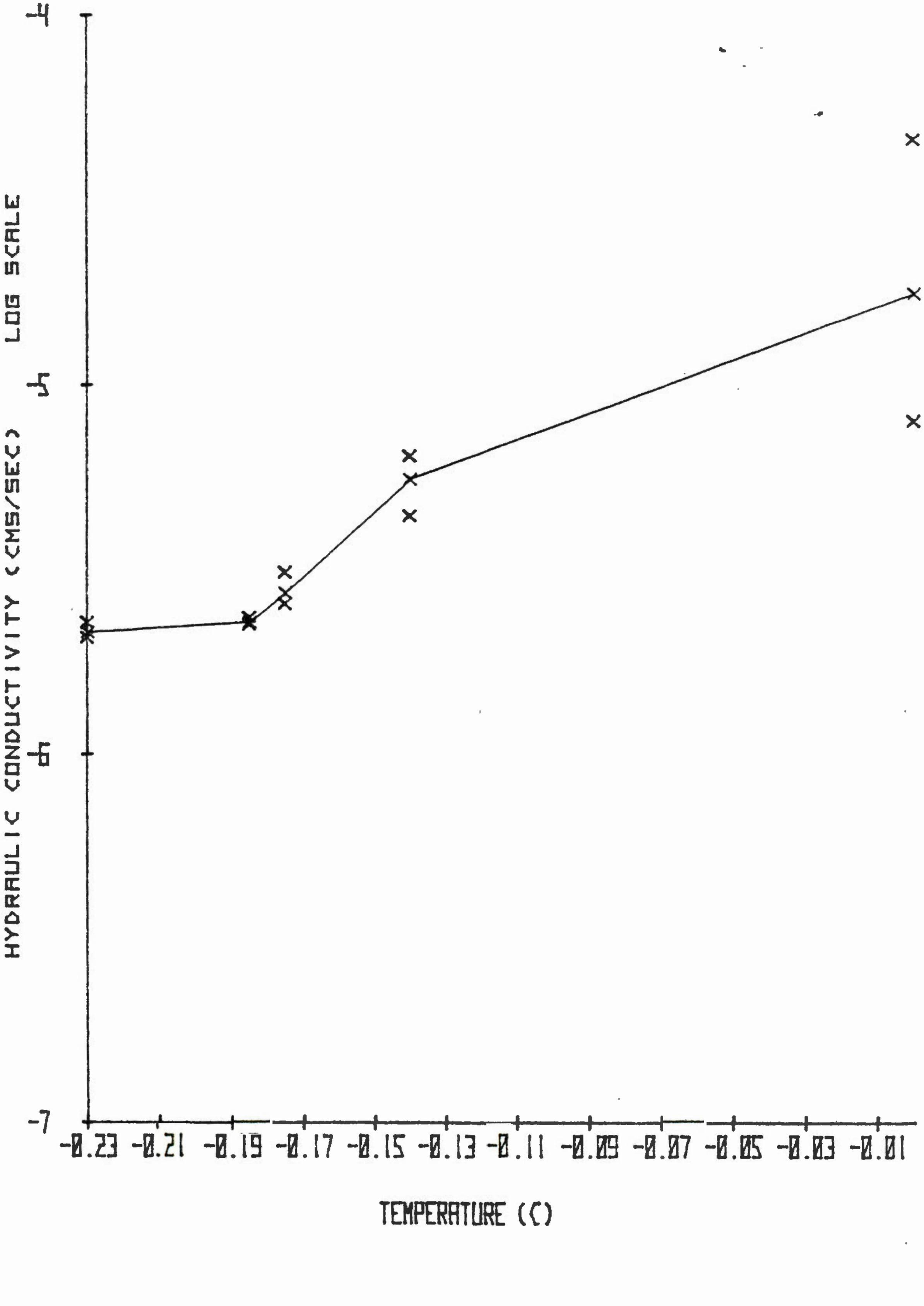


Figure 11. 6. Hydraulic conductivity of frozen Slims Valley silt.

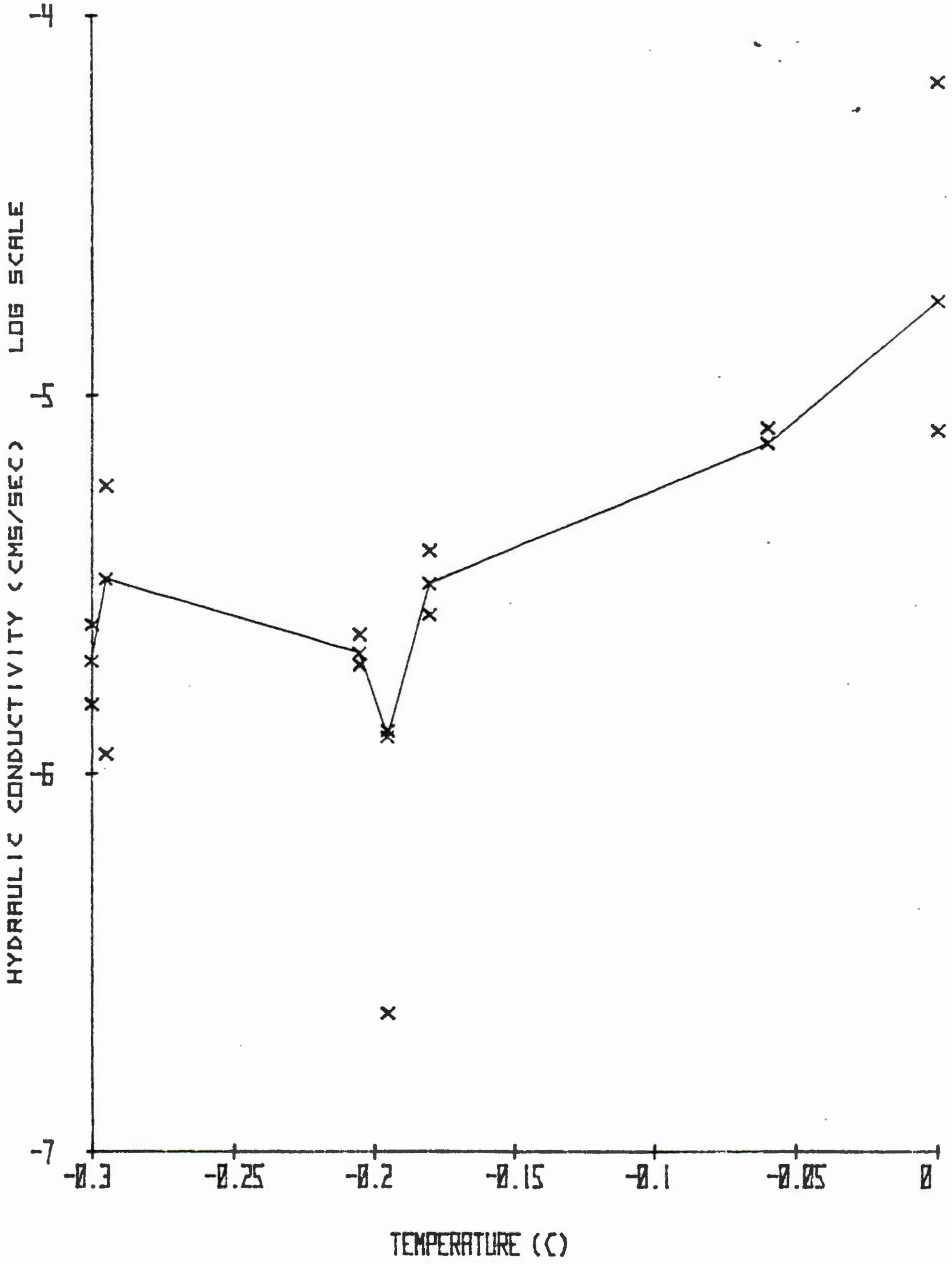


Figure 12. 7. Hydraulic conductivity of frozen Castor silty loam, 1963.

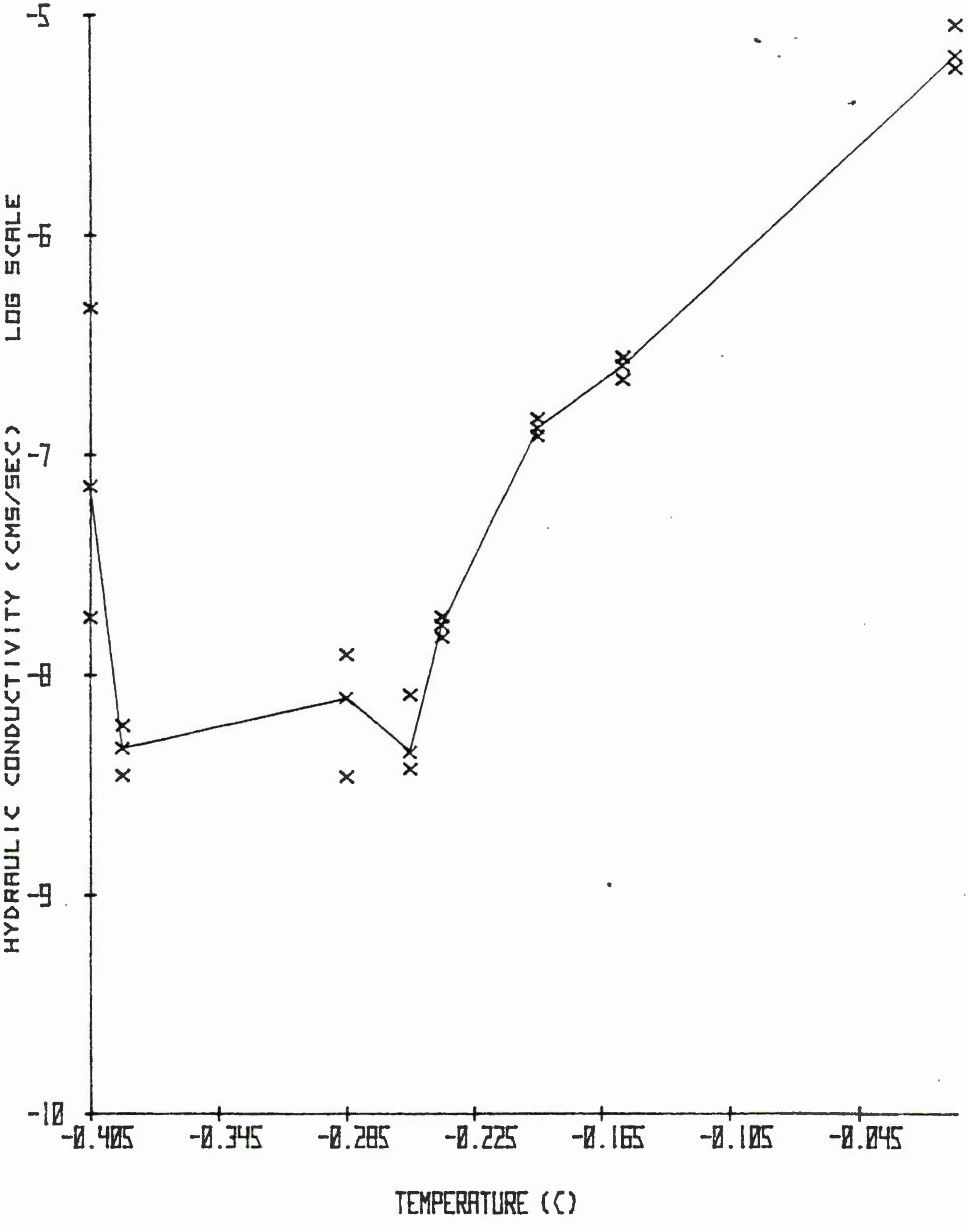


Figure 13. 8. Hydraulic conductivity of frozen Castor silty loam, 1963, (Moisture content: 41.92%).

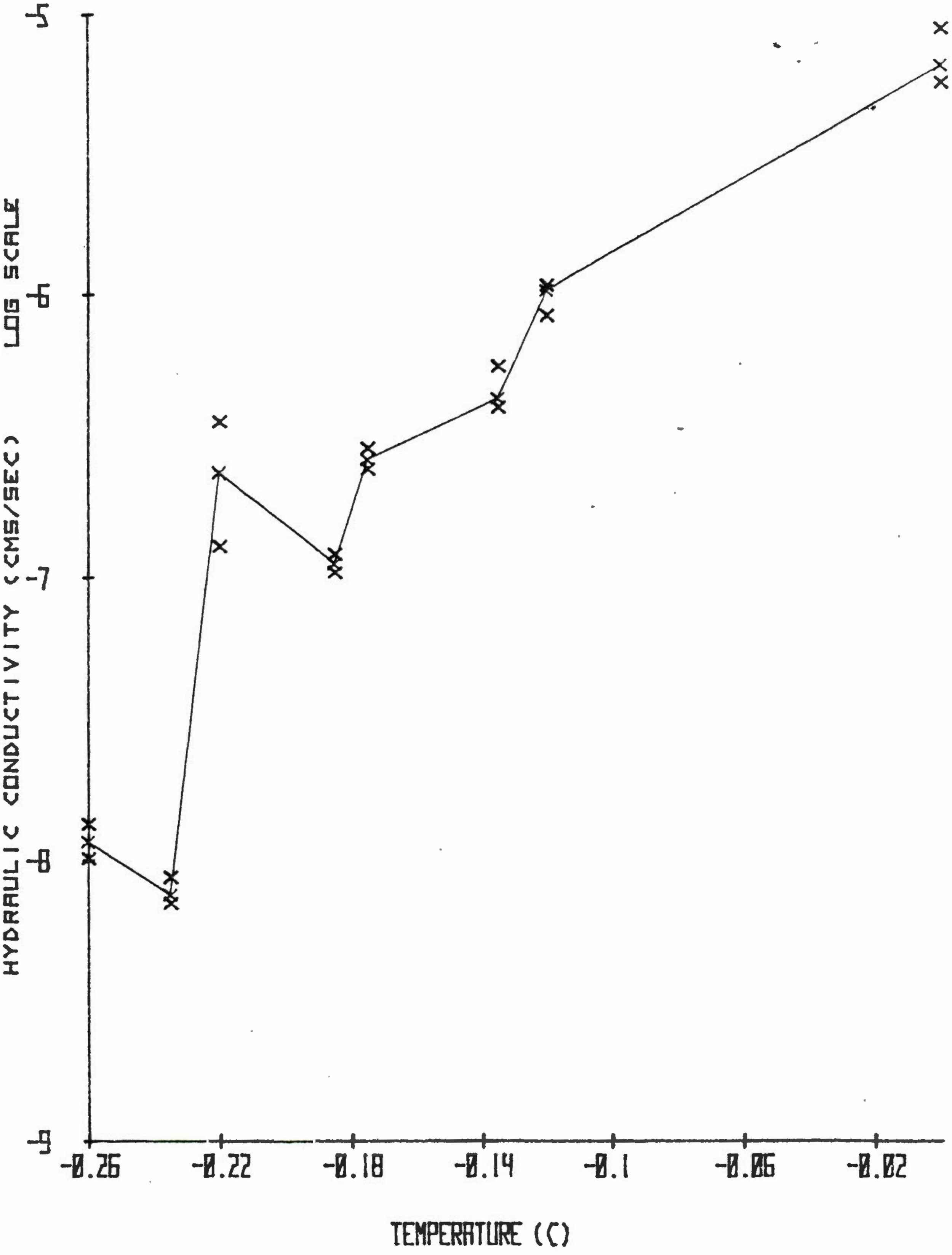


Figure 14. 9. Hydraulic conductivity of frozen Castor silty loam, 1963 (Moisture content: 29.90%).

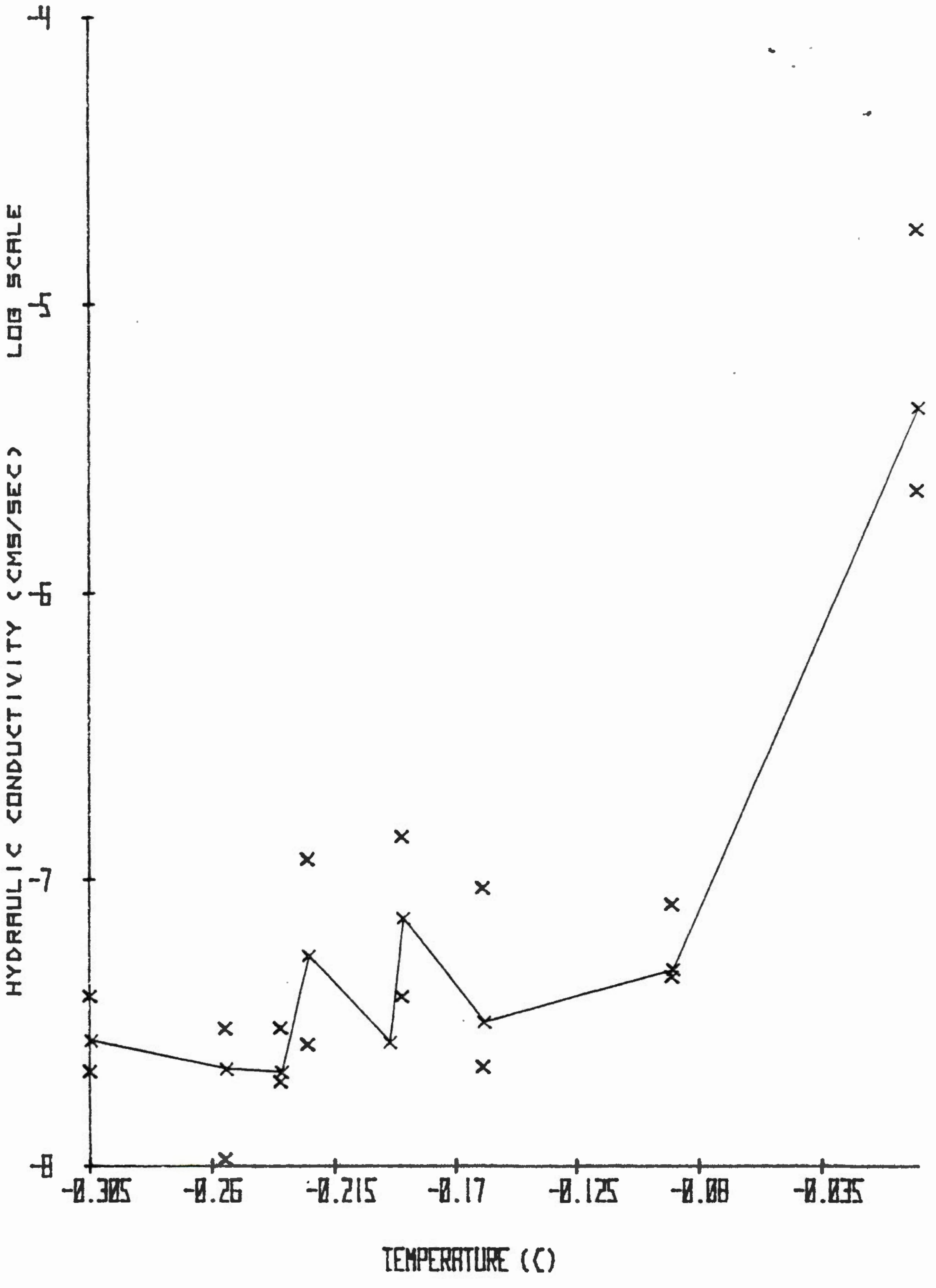


Figure 15. 10. Hydraulic conductivity of frozen Castor silty loam, 1963, (Moisture content: 34.68%).

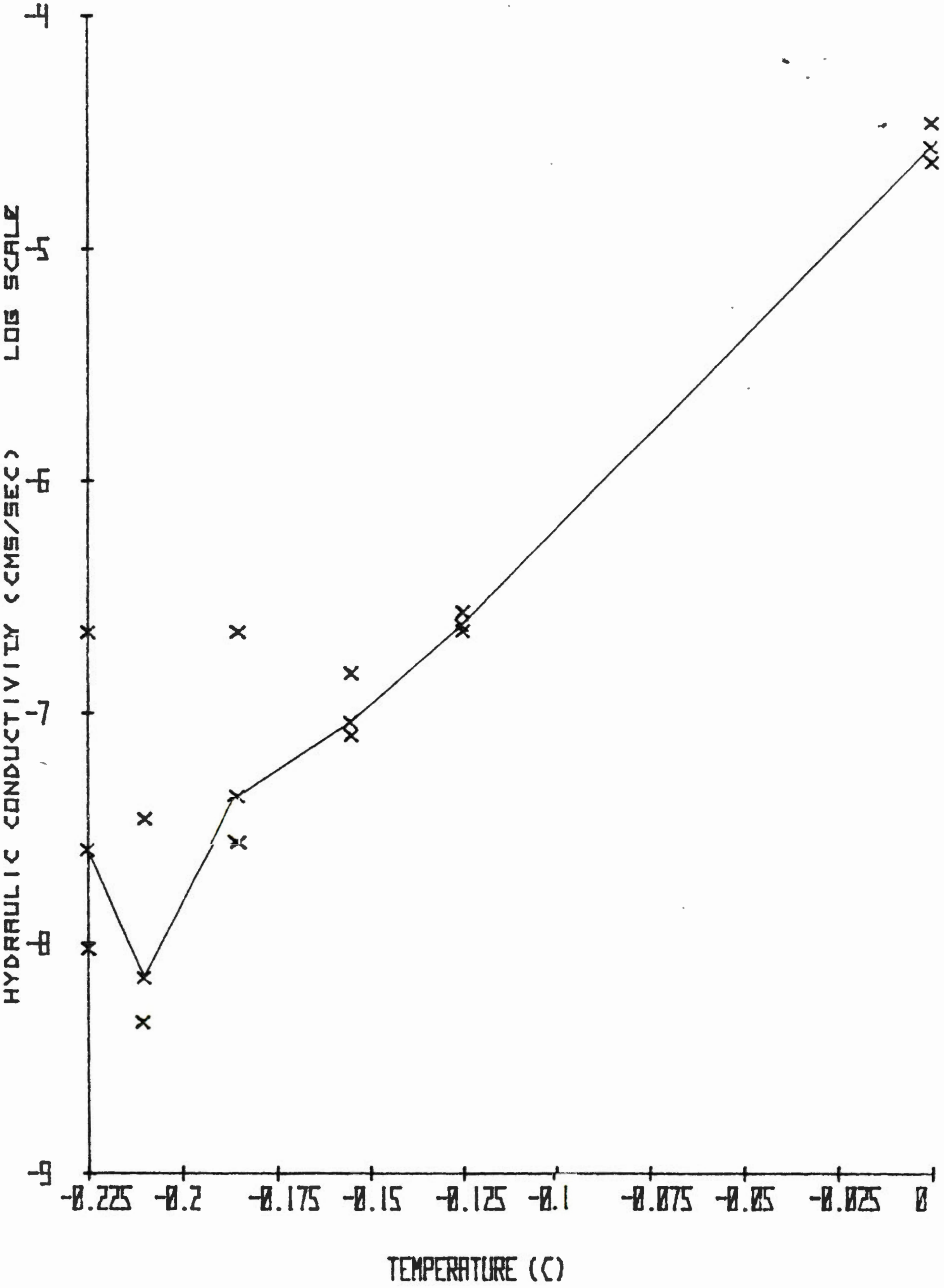


Figure 16. 11. Hydraulic conductivity of frozen Castor silty loam, 1963 (Moisture content: 35.12%).

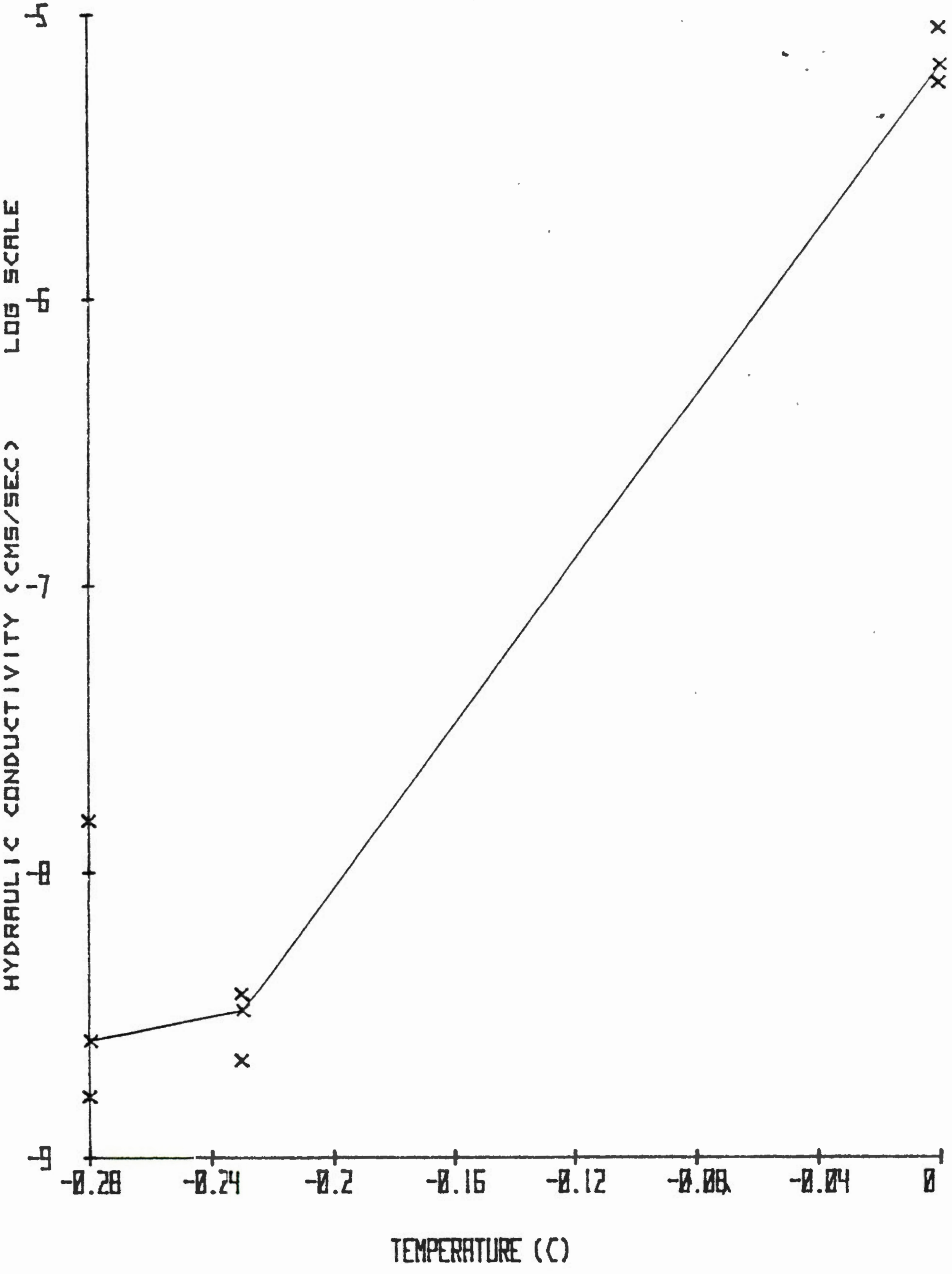


Figure 17. 12. Hydraulic conductivity of frozen castor silty loam, 1963 (Moisture content: 34.86%)

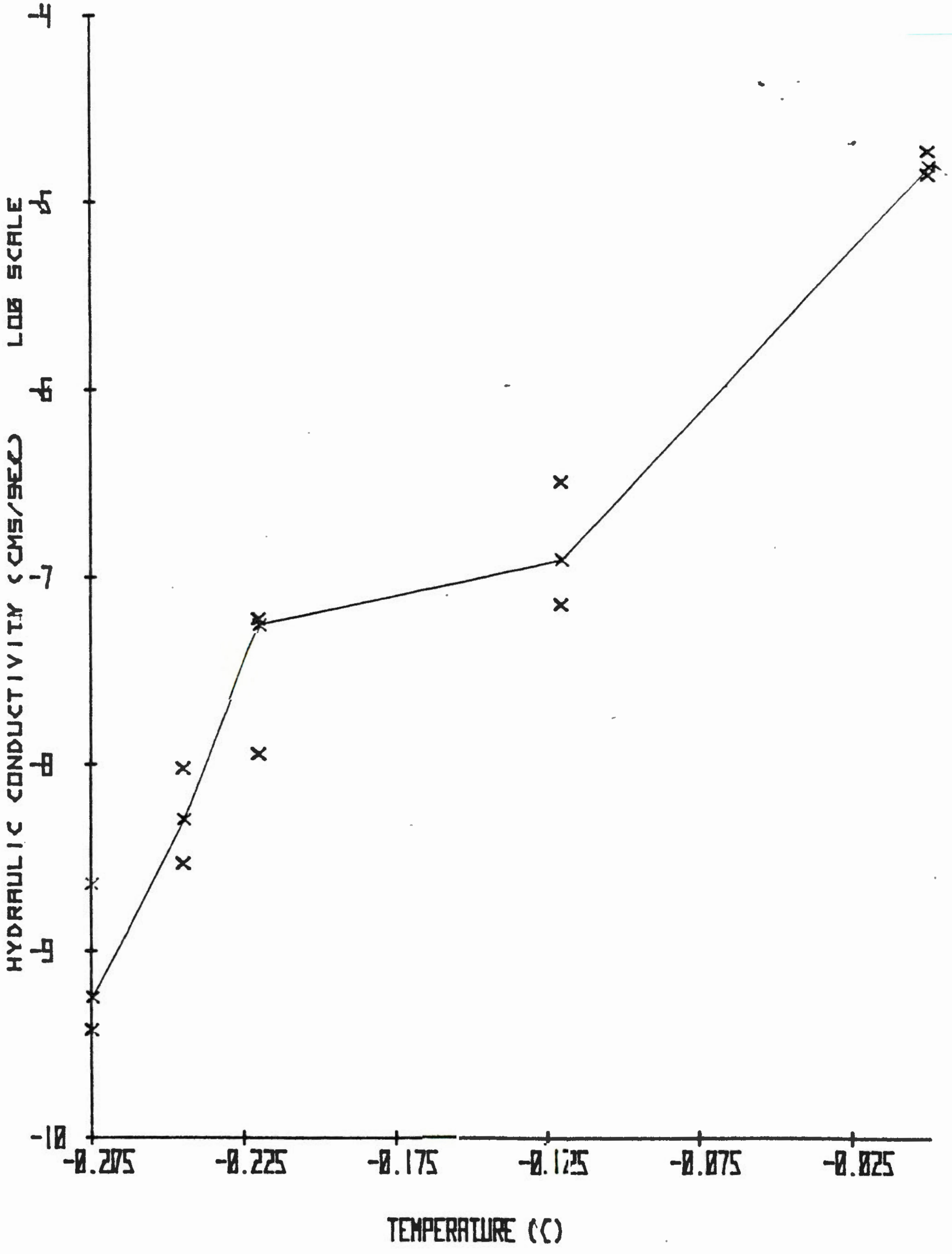
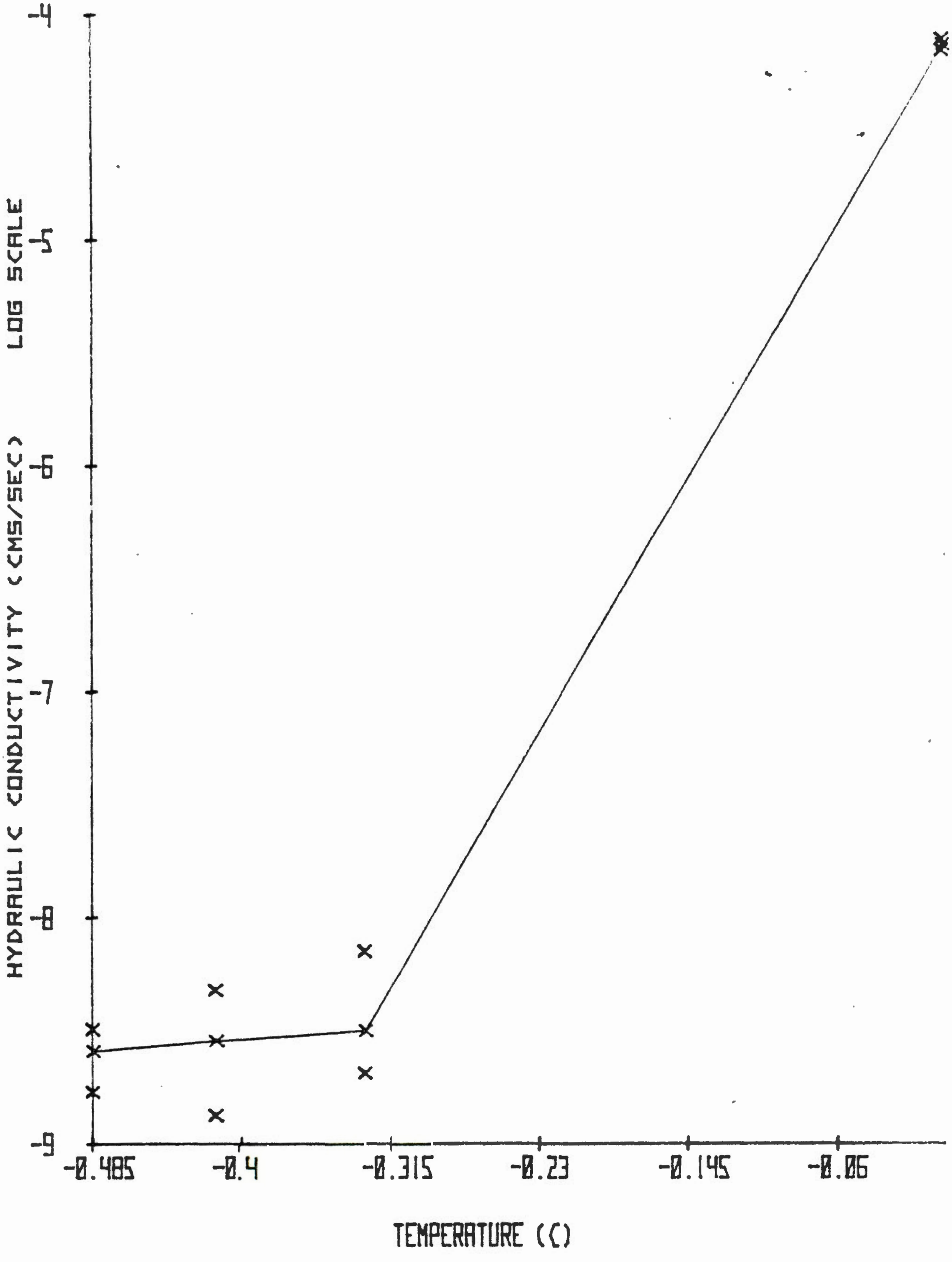


Figure 18. 13. Hydraulic conductivity of frozen Slims Valley Silt
(Moisture content: 28.36%)



Appendix D
Results of Preliminary Freezing Experiment

Note: A prefrozen sample of Slims Valley silt was used (moisture content: 30.41 per cent dry weight). The reservoirs contained lactose solution. Thermistor code:-

#13 - Cold plate temperature (top).
#14 - Temperature of sample 2 cms from top plate.
#16 - Temperature of sample 2.5 cms from top plate.
#15 - Cold plate temperature (bottom).

The estimated limit of accuracy for temperature measurements was ±0.01°C.

TEMPERATURE PROFILE AND FLUX OF WATER THROUGH FROZEN SLIMS VALLEY SILT OVER TIME

TIME INTERVAL (min)	TEMPERATURE GRADIENT (°C) #13	#14	#16	#15	MENISCUS* (Distance travelled cm)	THROUGHFLOW (cm^3/min)
0-30	0.59/-0.67	+0.09/+0.09	+0.17/+0.15	-0.07/0.17	3.5	$2.2910.10^{-4}$
30-38	-0.67	+0.07	+0.12	-0.17	2.1	$5.1548.10^{-4}$
38-56	-0.67	+0.01	+0.09	-0.17	4.3	$4.6912.10^{-4}$
56-67	-0.67	+0.01	+0.07	-0.17	1.0	$1.7852.10^{-4}$
67-80	-0.67	0.00	+0.07	-0.17	1.0	$1.5106.10^{-4}$
80-85	-0.67	-0.01	+0.04	-0.17	2.0	$7.8550.10^{-4}$
85-121	-0.67	-0.04	+0.04	-0.15	6.7	$3.6548.10^{-4}$
121-135	-0.67	-0.04	+0.02	-0.17	1.3	$1.8235.10^{-4}$
135-148	-0.67	-0.04	+0.01	-0.17	2.5	$3.7764.10^{-4}$
148-165	-0.67	-0.04	+0.01	-0.17	3.5	$4.0430.10^{-4}$
165-175	-0.67	-0.04	+0.01	-0.17	2.2	$4.3203.10^{-4}$
175-195	-0.68	-0.05	+0.01	-0.17	4.6	$4.5166.10^{-4}$
195-205	-0.68	-0.07	0.00	-0.17	3.3	$6.4804.10^{-4}$
207-235	-0.67	-0.07	0.00	-0.17	3.1	$2.1742.10^{-4}$
235-280	-0.67	-0.07	+0.01	-0.17	4.2	$1.8328.10^{-4}$
280-305	-0.69	-0.07	0.00	-0.18	6.1	$4.7916.10^{-4}$
305-335	-0.69	-0.07	-0.01	-0.20	7.1	$4.6475.10^{-4}$
335-365	-0.67	-0.07	-0.01	-0.17	4.5	$2.9456.10^{-4}$
365-395	-0.68	-0.07	-0.01	-0.20	8.6	$5.6294.10^{-4}$
395-425	-0.69	-0.07	-0.01	-0.20	6.5	$4.2548.10^{-4}$
425-455	-0.69	-0.07	-0.01	-0.20	3.2	$2.0947.10^{-4}$
485-515	-0.68/-0.69	-0.08/-0.07	-0.01/-0.01	-0.17/-0.20	4.3	$2.8147.10^{-4}$
515-535	-0.67	-0.07	-0.01	-0.17	3.2	$3.1421.10^{-4}$
535-605	-0.67	-0.07	0.00	-0.18	16.9	$4.7411.10^{-4}$
605-635	-0.67	-0.07	+0.01	-0.17	6.6	$4.3203.10^{-4}$
635-665	-0.67	-0.07	+0.01	-0.17	5.4	$3.5348.10^{-4}$
665-695	-0.67	-0.05	+0.01	-0.15	5.4	$3.5348.10^{-4}$
695-720	-0.62	-0.04	+0.04	-0.12	3.9	$3.0635.10^{-4}$

*Radius of capillary tube = 0.025 cm