Soil Moisture Movement During Ice Segregation

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This paper reports the initial results of a continuing research study of frost action processes in soil undertaken recently by the Division of Building Research of the National Research Council of Canada.

Moisture flow to the freezing zone of small soil specimens has been measured under controlled laboratory conditions. The experimental findings agree with the now generally accepted concept of frost heaving outlined by Taber and Beskow.

In soil systems where a free water surface exists near but below the freezing zone, the results indicate that moisture flow is dependent on the unsaturated permeability and soil moisture tension characteristics. Both these soil properties integrate the effect of grain size structure, clay composition, and exchange ions among others.

Critical desaturation beneath the frost line in some soils appears to act as a barrier to liquid moisture transmission. Since in the heavier-textured soils, rapid moisture transmission continues to much higher tension values, greater heave rates are observed.

●SOME soils when subjected to naturally occurring freezing temperatures display certain features undesirable from an engineering standpoint. Uniform and differential heaving due to ice segregation and loss of strength upon thawing are perhaps the most notable. This behavior often results in the deterioration of road and airport surfaces, destructive action on railroad grades, and bad effects upon building foundations.

Much of the knowledge about frost action processes stems from the early work of Taber (1) and Beskow (2). More recently Haley et al (3), Ruckli (4) and Jumikis (5, 6) have made notable contributions. In his review of literature, Johnson (7) has drawn attention to the mass of useful information in allied fields, particularly soil science, available to the student of frost action.

The general concept of the frost action phenomenon in soils appears to be well established and is available in the literature. To a large extent frost action criteria now used in engineering have developed from this general concept. In view of this, it appears that if any improvement in frost action criteria is to be expected, more detailed information on the relationship between the physico-chemical properties of the soil and destructive frost action is required.

As part of a long-term study of frost action in soils by the Division of Building Research of the National Research Council of Canada, some initial laboratory studies are concerned with the nature of the moisture flow to the freezing zone. Soil moisture potentials and subsequent moisture flow are known to result from the phase change of soil moisture during ice segregation. In nature, this process is complicated by the heterogeneity of the soil, the complex heat flow pattern, and the unknown status of the water supply. Except in its simplest form, it does not lend itself to easy simulation in the laboratory.

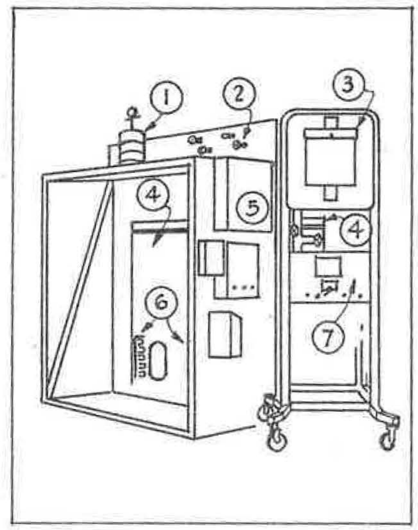
The amount of moisture available for ice segregation may be "limited" and this is commonly referred to in the literature as a "closed" system. In the "open" system water is supplied continuously from a shallow water table to the freezing zone by the mechanism of "unsaturated" liquid flow. It is with the latter condition, that is, the open system, under which extremely serious heaving may occur, that this paper is concerned.

The term "unsaturated" is defined in a number of ways in the literature. As used here it does not refer to the completeness with which the soil pores are filled with water but rather denotes that a state of soil water tension exists. At "saturation" the tension is zero, although in the case of light textured soils the soil pores may be partially filled with air. Heavy clay soils may remain completely filled with water, even when subjected to relatively high tensions, but are accordingly "unsaturated". To avoid any ambiguity, the degree to which the soil pores are filled with air may be expressed in terms of airvoid volume (8). Although "saturation" is not used here in the usual engineering sense it is necessary to base the definition on conditions of soil water tension in order to explain water movements by energy concepts.

METHODS AND MATERIALS

Description of Frost Action Apparatus

The apparatus shown in Figure 1 consists of two insulated metal tanks which are independently mounted on portable frames. Each tank contains approximately 25 gallons of ethylene-glycol water mixture which is pumped at a constant rate to the headers on the frost cell frame. A series of adjustable valves on the headers permits the conditioning liquid to serve four independent frost cells. The rate of liquid flow through the



(1) FROST CELL
(2) HEADERS
(3) MILLIVOLT RECORDER
(4) CONSTANT TEMPERATURE TANK
(5) CONTROL PANEL
(6) CONDENSING UNIT
(7) PREAMPLIFIER

Figure 1. Frost cell apparatus.

headers far exceeds the withdrawal for the frost cells. Thus additional frost cells may be mounted without greatly affecting the flow through others in which tests are already in progress. In addition, the rapid flow acts as a self-stirrer in the liquid bath. A separate condensing unit mounted beneath the tank is capable of keeping the liquid mix below the operating temperature. The desired liquid temperature in the tanks is achieve by heating the chilled liquid. The amount of reheat required (a function of the ambient temperature and the number of frost cells withdrawing conditioned liquid from the system is controlled by an electronic temperature controller. The main thermostat, consisting of two 500-ohm sensing elements, is placed in the flow path at the outlet from the tank. One 500-ohm thermostat is mounted after the heater to prevent overshooting of the operating temperature. Any unbalance in the electronic controller due to a temperature change of the liquid causes the operation of a modutrol motor which is attached to a variac for control of the electrical current supply to the immersion heater. With this arrangement it has been possible to maintain the desired temperature within ± 0.10 deg C for long periods. For short periods of twelve hours the temperatures can easily be maintained within ± 0.05 deg C.

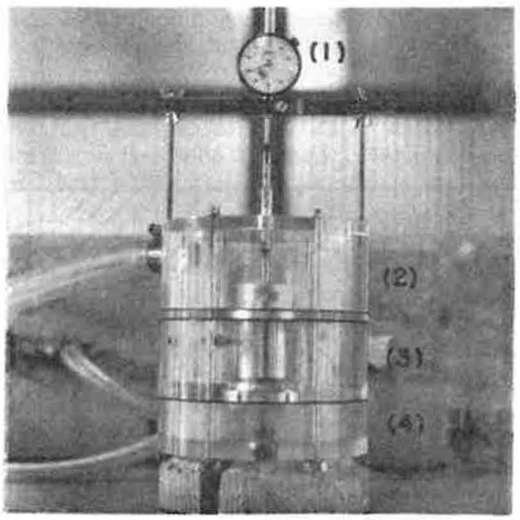


Figure 2. Frost cell in operation, (1) extensometer, (2) compartment 1, (3) compartment 2, (4) compartment 3.

The frost cell shown in Figure 2 and diagrammatically in Figure 3, which contains the soil specimen, consists essentially of three compartments. The liquid in compartment 1 conditions the upper one-third of the soil specimen and is the cold section of the specimen. Compartments 2 and 3 condition the lower two-thirds of the specimen and make up the warm section. The sample rests on a porous ceramic plate which permits control of the water tension in the specimen. A horizontal conduit through compartment 2 permits thermocouple placement in the specimen below the freezing zone. For temperature measurement in the frozen portion, thermocouples enter compartment 1 through the stem of the brass plunger. An extensometer is mounted on the cell that measures the relative movement of the plunger during ice lens growth. The frost cell is made of lucite except for the brass plate which holds the porous plate and the brass inner wall supporting the lower portion of the specimen. The inlets and outlets to the compartment are set oblique to the periphery of the cell but parallel to each other to facilitate even liquid circulation and good heat exchange.

A continuous temperature record was obtained with a specially built, high precision millivolt recorder. Copper-constantan thermocouples and ice water reference junctions were used in these experiments. The accuracy of the temperature measurements with the above arrangement was much greater than the degree of temperature control over the conditioning fluid. The frost cell was designed to give a sharp temperature gradient across the freezing zone with a constant temperature spanning the main body of the specimen. This was desirable if flow rates caused only by tension gradients were to be evaluated.

Soils and Specimen Preparation

The soils used in these experiments consisted of artificially blended mixes. Leda clay, a local marine deposit, was modified with silt obtained from natural deposits at Whitehorse and Uranium City. Leda clay and Whitehorse silt were air-dried, crushed, passed through a 200 sieve and mixed in arbitrary proportions for samples 1 and 2. Samples 3, 4 and 5 were mixtures of Leda clay (minus 200) and Uranium City silt (minus 325) pretreated in the same way. Sample 6 was Uranium City silt (minus 325).

The frost cell was designed to hold a cylindrical specimen $1\frac{5}{16}$ inch in diameter and 2.816 inches long. This is the size of a sample when molded in the Miniature Harvard Compaction Apparatus (9). Some difficulty was encountered however, with satisfactory thermocouple placement in a premolded specimen. In practice the soil specimens were compacted in the frost cell in $\frac{1}{2}$-inch layers to a density of 1.33 gm/cm^3. A thermocouple was placed between each layer. After placing the first two layers, a silicone-coated thin lucite sleeve, $1\frac{1}{4}$ inch inside diameter and 2 inches long, was lowered into

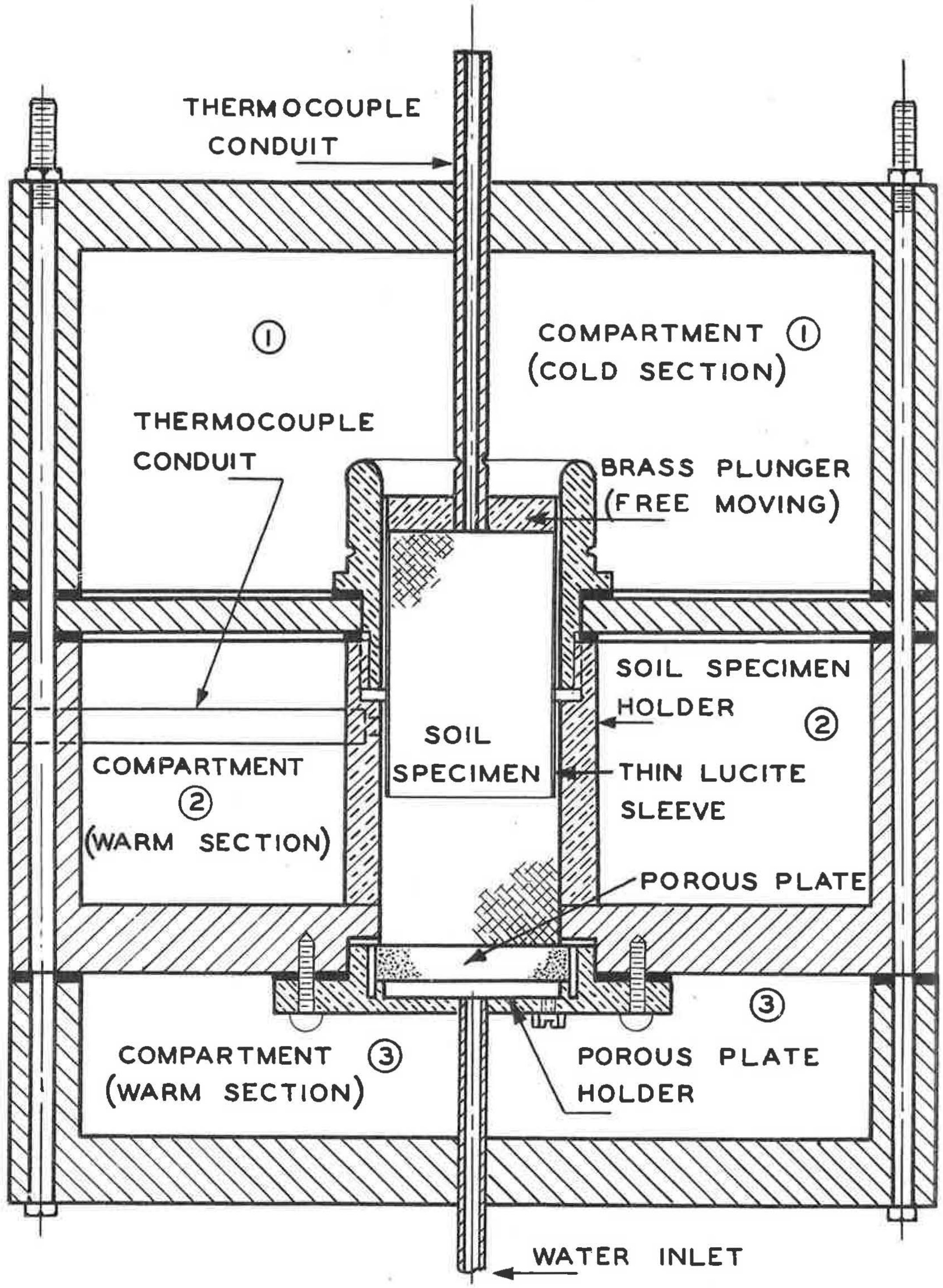


Figure 3. Section through frost cell.

the specimen holder. The soil specimen was permitted to freeze to this sleeve but heaving was restricted only by the friction between the outside walls of the sleeve and the inside wall of the specimen holder. The friction plus the load of the extensometer stem and brass plunger amounted to approximately 30 gm/cm^2 and was constant for all tests. The remaining four layers of soil were placed inside the sleeve to bring the specimen height to 3 inches.

In these experiments distilled water was allowed to enter the base of the specimen at room temperature and zero tension from a constant head device before freezing was begun. When no further water was withdrawn, it was considered that the equilibrium condition had been attained. Normally this took about twelve hours for the heavier-textured soils.

Soil Freezing Procedure

Upon completion of the saturating process, the conditioning fluid was circulated through the two compartments that condition the lower two-thirds of the specimen until an equilibrium temperature was reached. For these experiments an arbitrary temperature of approximately + 1.3 deg C was used which took some two hours to attain. Circulation of the cold liquid at a temperature of -6 deg C was then begun through compartment 1, conditioning the top inch of the 3-inch specimen. The temperature of the conditioning liquids was held constant (within the limits of the temperature control system) throughout the experiment. Supercooling was always evident but particularly in the heavier-textured soils. In the first few experiments crystallization was permitted to begin naturally but better reproducibility was attained by inducing crystallization at a fixed temperature. As stated before, a continuous temperature record made it possible to follow the progress of the freezing zone in the specimen. The amount of moisture flow into the sample and extent of heaving were measured at frequent intervals. In all the experiments reported here a free water surface was maintained level with the base of the specimen. The small hydraulic head loss caused by the porous plate at the base of the specimen in these experiments was considered to be negligible.

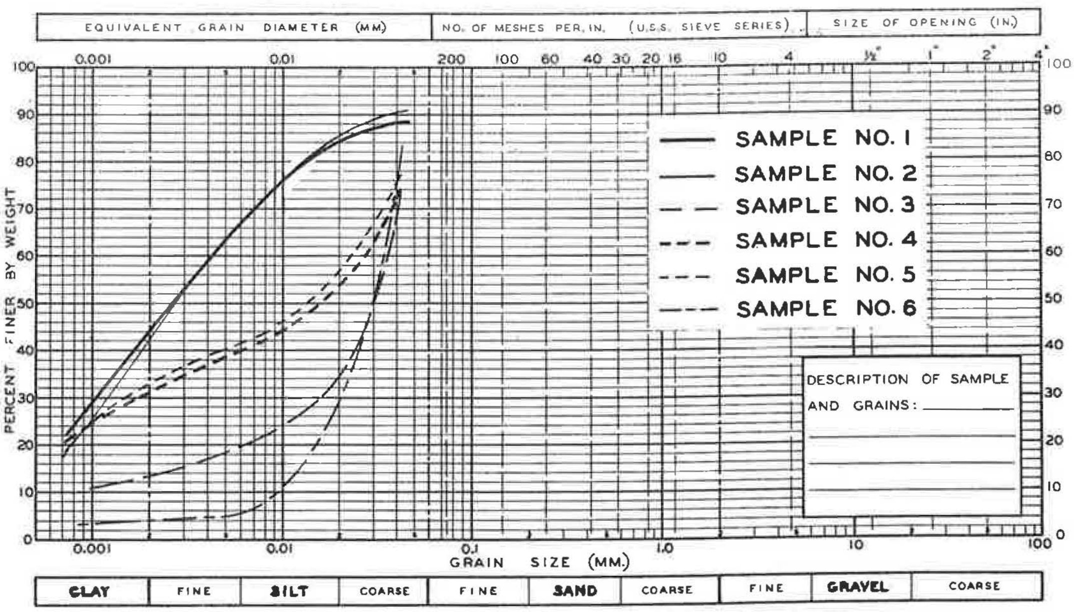


Figure 4. Mechanical analysis of soils.

Unsaturated Permeability and Moisture-Content/Tension Determinations

The general characteristics of the relationship between moisture content and moisture suction or tension for soils and their significance are well known. It has been shown in

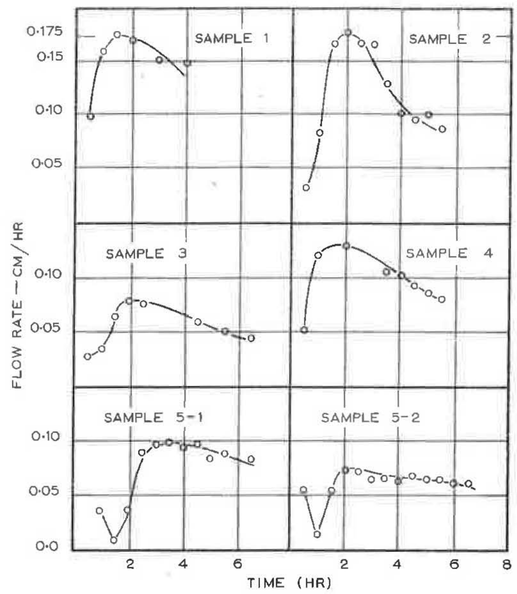


Figure 5. Rate of moisture flow induced by ice segregation as a function of time.

the past that there is hysteresis between the wetting and drying conditions, the sample being drier at a given suction when that suction is approached from the wet condition than when it is approached from the dry condition.

The freezing process, carried out according to the method described above, is essentially a drying process. Therefore it was necessary to determine only the drying moisture-content/tension relationship. This was done by the usual porous plate method. A soil is first permitted to wet against zero water tension on a porous ceramic plate. The plate is then conditioned to various tensions using air pressure. Moisture contents were determined by oven drying at 110 deg F after equilibrium conditions had been attained at the desired moisture tensions.

A modified method of the technique described by Richards (10) was used to determine the unsaturated permeability of the soil. Briefly the procedure is to create known moisture-tension gradients in a small soil specimen and to measure the flow rates under steady-state conditions. Darcy's law, $v = ki$, which has been shown to apply also to unsaturated flow, permits the calculation of saturated permeability coefficients k_u[1]. These are usually presented graphically as a function of either tension or moisture content.

EXPERIMENTAL RESULTS AND DISCUSSION

The hydrometer analyses for the soils are shown in Figure **4**. The grain-size distribution curves are fairly similar for samples 1 and 2 and for samples 4 and 5. These curves illustrate the reproducibility of sample pretreatment such as crushing, sieving, and mixing.

Figure 5 gives the rate of moisture movement into the sample versus time in hours induced by ice segregation for samples 1 to 5. No heaving occurred in sample 6. The curves all have the same general form although the starting times

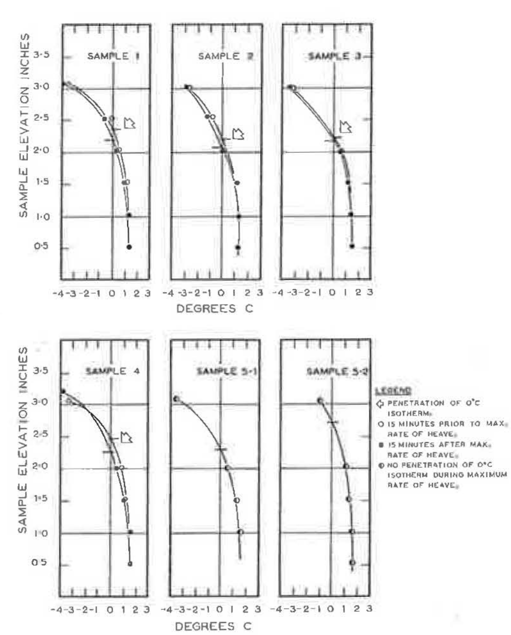


Figure 6. Temperature distribution in the soil 15 minutes prior to and 15 minutes after the maximum heave rate.

[1] $k_u = v\left(\frac{L}{S_1 - S_2}\right)$

v = linear velocity of flow in cm/hr.

L = length of sample in cm.

S_1 and S_2 = the respective tensions at the two faces of the specimen expressed in cm of water

k_u = unsaturated permeability coefficient in cm/hr.

vary. This is largely due to the lack of control over the amount of supercooling and the initiation of crystallization. The reduction in rate of heave with time is caused by many factors, some of them not fully understood. One of these is the reduction in heat flow as the zero isotherm penetrates the soil specimen. Temperature distributions in the soil specimens that existed 15 minutes prior to and 15 minutes following the maximum heave rate are shown in Figure 6. These graphs also show the penetration (if any) of the 0 deg C isotherm during this time.

A comparison of the grain-size distribution curves with the maximum rate of heave shows that the heavy textured soils heaved at the greatest rate. In heavy soils such as sample 5 the limiting factor appears to be the rate of heat removal. Further evidence was obtained on this point when sample 5-2 was treated similarly in all respects to sample 5-1 with the exception of the temperature on the cold side. This was increased from -6 deg to -3 deg C on the sample 5-2 which reduced the maximum heaving rate from0.1 to 0.75 cm/hr (Figure 5).

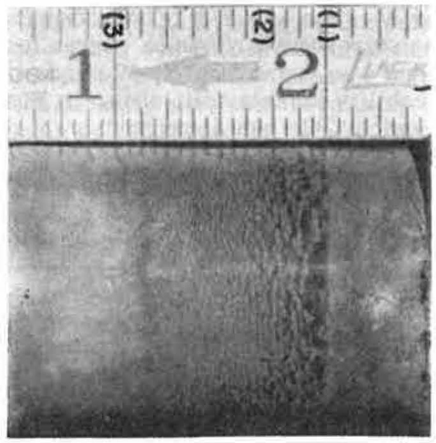


Figure 7. Sample 2, showing ice segregation beginning with no evidence of soil separation and progressing to almost continuous ice. (Total heave for 12 hour period was 1/2 in.) (1) top of sample, (2) point of maximum rate of heave, and (3) final frost line.

Examination of the frozen samples showed that for all samples no discrete ice lensing was evident at the position of the zero isotherm during the maximum heaving rate. As the frost line penetrated the sample, the separation of soil particles increased, gradually blending into solid ice. At the stage where a clear ice lens was growing, the rate did not become completely constant but progressed at a decreasing rate. The general nature of the distribution of ice is shown in Figure 7.

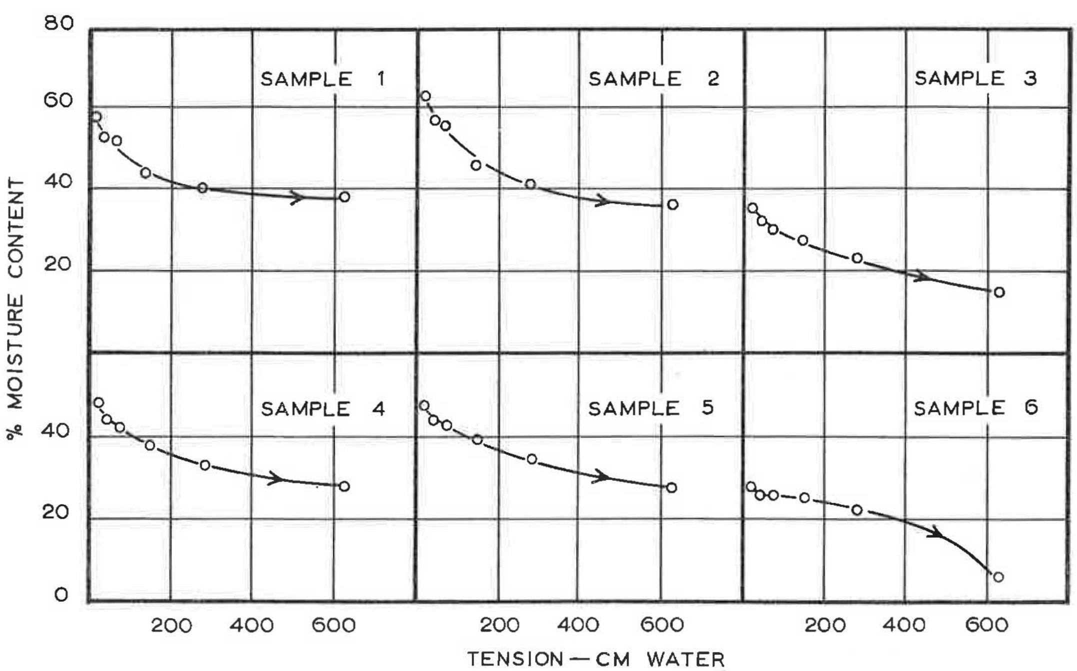


Figure 8. Relationship between moisture tension and moisture content for all samples.

The question arises why no heaving occurred in sample 6. Figure 8, which gives the moisture-content/tension curves for all soils, shows that the moisture content of sample 6 was approximately 30 percent when freezing was initiated. The unsaturated permeability for this soil, shown in Figure 9, demonstrates its ability to pass water at low tensions. In fact a comparison of the unsaturated permeability coefficients at low tensions with the flow rates in the freezing experiments shows that an inverse correlation exists for the soils studied. These experiments suggest that the crystallization of the soil moisture is able to create a sufficient tension to cause a high degree of desat-

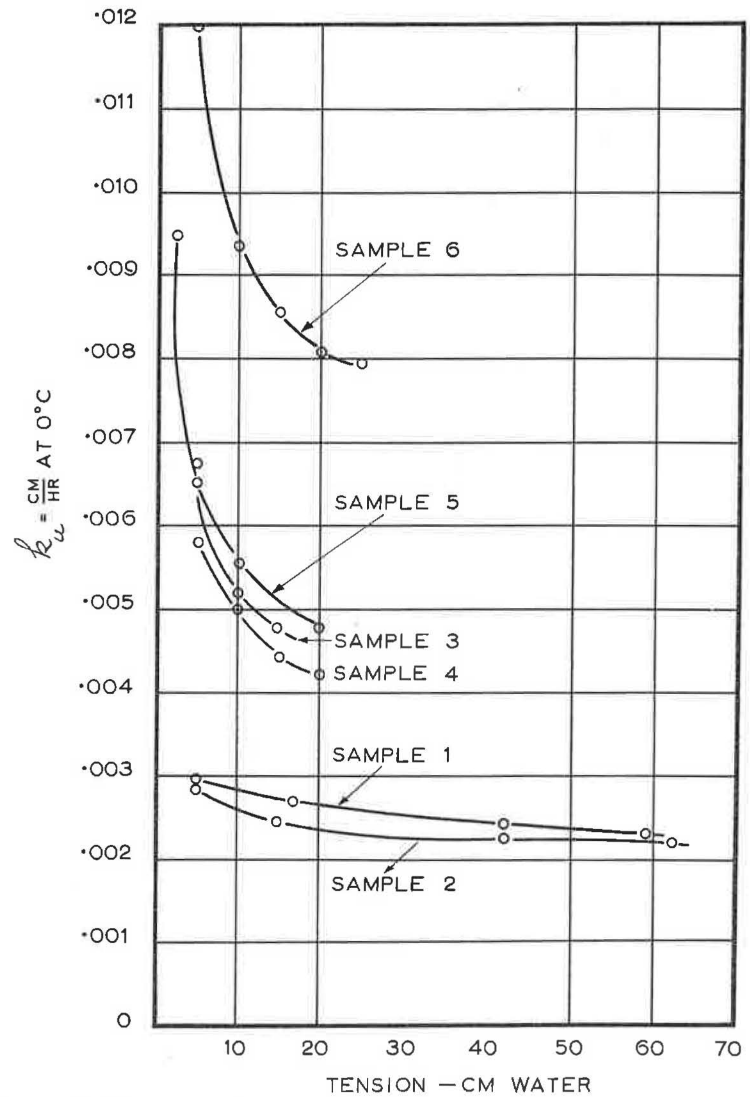


Figure 9. Unsaturated permeability coefficients as a function of tension.

uration immediately beneath the freezing zone. For the lighter textured soils (such as samples 3 and 6) this means a great reduction in moisture content (Figure 8), therefore, a low unsaturated permeability, and consequently a small heaving rate as in sample 3 or no heaving as in sample 6.

Other studies support the belief that critical desaturation beneath the frost line may act as a barrier to moisture movement in lighter textured soils. Research workers in soil science have shown the inverse relationship of unsaturated permeability coefficients and soil moisture tension (10). In moisture flow studies of the Division of Building Research, the soil moisture at one face of a soil specimen was held at zero tension(S_2) and the rate of flow was measured with increasing tension up to 1000 cm water on the opposite face (S_1). Figure 10 shows that for a predominantly silty soil there is an increase of flow with tension which rises to a maximum and then rapidly reduces to a low value. For clays the maximum flow rate is lower but the ability to transmit water extends to higher tension values. This appears to be the explanation for the higher rate of heave observed in these experiments for clayey soils as compared to coarser grained soils. It also explains how a no-heaving condition may occur even though high initial moisture contents exist.

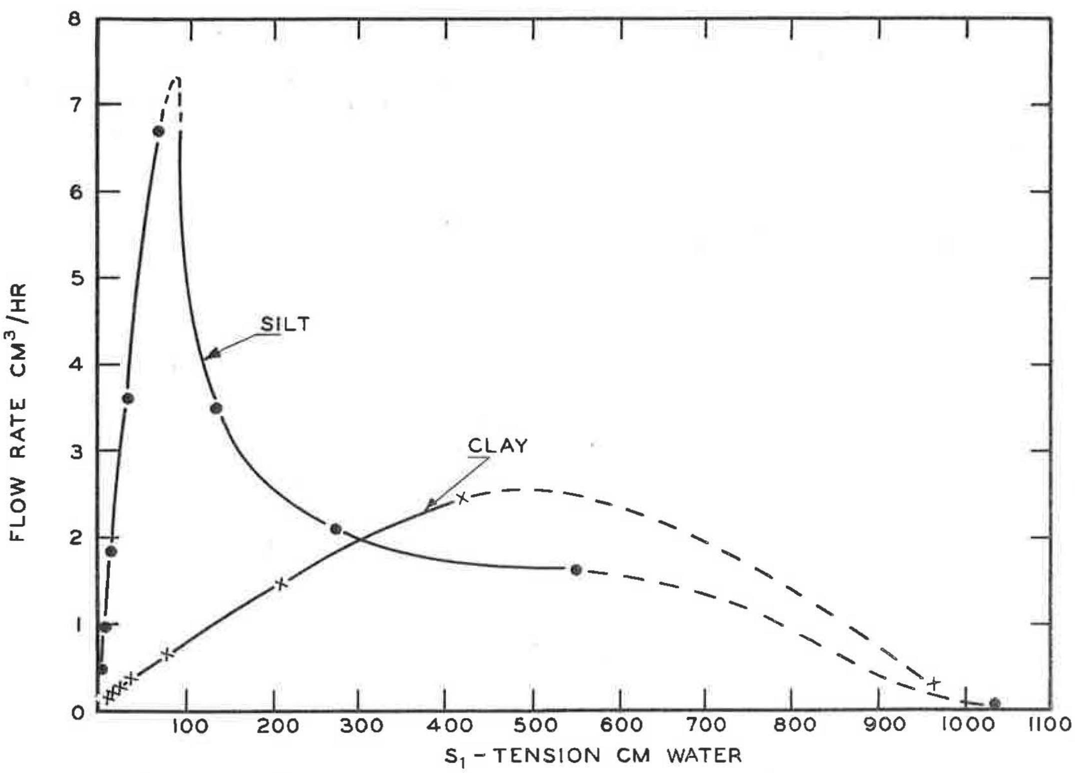


Figure 10. Flow rate as a function of S_1 with S_2 held at zero.

CONCLUSION

This paper is not a report on a completed study but rather describes the general approach and gives the initial experimental results.

The freezing experiments described were designed to measure moisture flow rates to the freezing zone for a number of soils under similar but arbitrary conditions. The results can best be understood in terms of unsaturated permeability characteristics and moisture-content/tension relationships.

The use of these concepts has the advantage of integrating all the factors, such as grain size, structure, clay composition, and exchange ions, which together result in a heaving rate peculiar to a given soil.

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