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Determination of Some Frozen and Thawed Properties of Permafrost Soils

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Mackenzie Valley Pipe Line Research Limited has undertaken a significant amount of full-scale testing at its test site near Inuvik, N.W.T. Large diameter high ice content permafrost core samples were taken from this site to controlled laboratory conditions, and tested in both frozen and thawed states so that proposed predictive methods for pipeline performance could be evaluated.

This paper describes procedures for sampling, sample transportation at controlled temperatures, and sample preparation in the laboratory. Methods for thaw-settlement and thaw-strength are also described. The results of these tests are presented and analyzed.

La Mackenzie Valley Pipe Line Research Limited a entrepris un important programme d'essais en vrai grandeur à sa station d'essais près d'Inuvik, T.N.O. Des carottes de grand diamètre de permafrost à forte teneur en glace ont été prélevées sur ce site, et dans des conditions contrôlées de laboratoire, ont été soumises à des essais aussi bien à l'état gelé qu'après dégel dans le but d'évaluer les méthodes de prévision du comportement du pipeline.

L'article présente les procédures utilisées pour l'échantillonnage, la manutention des échantillons à température contrôlée et la préparation des échantillons en laboratoire. Les méthodes d'analyse des relations dégel-tassement et dégel-résistance sont décrites et les résultats des essais sont présentés et analysés. [Traduit par le journal]

Introduction

In conjunction with the various research projects undertaken by Mackenzie Valley Pipe Line Research Limited (M.V.P.L.) at their test facility site near Inuvik, N.W.T., a series of large diameter permafrost samples was obtained for laboratory testing. The principal objectives of this program were:

(*a*) To develop practical methods for coring, handling, transportation, and storage of frozen cores.

(*b*) To develop laboratory procedures for thaw-settlement and strength tests of permafrost subjected to temperatures above 32 °F (0 °C).

(*c*) To determine thaw-settlement and shear strength values (both frozen and thawed), for the Inuvik ice-rich silt.

(*d*) To obtain permeability and thermal conductivity values for correlation with existing *in situ* measurements.

Results of both the field and laboratory work are presented and discussed in this paper.

Sampling, Transportation, and Storage

Coring the permafrost was done during the summer months of 1971. Ambient air temperatures were as high as 80 °F (26 °C). The majority of the samples had a very high ice content and were thus susceptible to melting. Portable freezers, maintained at temperatures close to the *in situ* ground temperatures, were used to protect the samples.

Large-diameter frozen cores were required for the proposed laboratory testing program as this would minimize the effects of sample surface disturbance during coring and handling. To obtain these cores, three borings were made using a specially fabricated 5-ft (1.5-m)-long, single-wall core barrel having outside and inside diameters of 15 in. (38 cm) and 13 in. (33 cm), respectively (Fig. 1). The barrel was ad-

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FIG. 1. Barrel used for obtaining large diameter cores.

vanced by slowly rotating it under constant pressure using a Nodwell mounted Mayhew rig. After penetrating the desired amount, the barrel was extracted and the core rapidly freed and placed in the portable freezer. The diameter of the core recovered was approximately 11 to 12 in. (28 to 30.5 cm).

The portable freezer loaded with samples, was transported by plane to Norman Wells where a large walk-in freezer was available. The temperature inside the walk-in freezer was maintained at an average of 24 °F (−4.5 °C). There the cores were weighed, measured, and photographed. They were then wrapped in plastic sheeting and packed in canvas bags to facilitate handling. Samples were replaced in the portable freezer and transported by aircraft to Edmonton and then by truck to the permafrost laboratory, of the Division of Building Research, National Research Council of Canada, in Ottawa. The plane's electric system was used to supply power to the portable freezer using voltage and frequency converters to interface between the systems. A portable gasoline generator was used to provide power for the freezer while on the truck.

At the Division of Building Research, the permafrost cores were stored and prepared for testing in a large, walk-in, cold room having dimensions of approximately 15 × 22 × 9 ft high (4.6 × 6.7 × 2.7 m high).

Initial Sample Inspection and Measurement

After a photographic record of the samples had been made, frozen bulk densities were determined. Volumes were measured by placing the sample in a metal container of known volume, filling the container with Ottawa sand and measuring the volume of sand in the box. (The difference between the container volume and the volume of sand being the sample volume.)

It became apparent, after a preliminary examination of the 12-in. (0.3-m) diameter cores, that a visual examination from the outside would be of little value in determining the form and amount of ice present due to the smearing and thermal disturbance of the surface (Fig. 2 shows a typical core as received in Ottawa). Each of the samples was cut longitudinally

FIG. 2. Large diameter sample (15-CH-1, 5′8″–7′6″) as received at the laboratory.

along the center line with a band saw to: (*a*) obtain a better appreciation of ice content and its distribution, and (*b*) assist in the selection of samples for testing. After the loose shavings had been scraped off the cut face, the relative distribution of the ice and soil was clearly visible (Fig. 3).

Basic classification tests were then made on representative samples including frozen bulk unit weight, Atterberg limits, specific gravity, and grain size distribution. The values obtained are given in Table 1. Figure 4 shows a typical grain size distribution curve of the soil.

Sample Preparation and Preservation

To assess methods of preparing frozen specimens from large samples, a number of techniques such as hand trimming, forcing a cutting edge into the frozen soil, band sawing, and lathing were investigated. Hand trimming quickly proved to be inadequate due to slow progress and poor geometric control. Forcing a sharp cutting edge into the permafrost also proved to be unsatisfactory as the ice in front of the cutting edge would chip leaving voids in the sample. The use of a band saw and lathe proved very satisfactory for the silt and clay permafrost.

A band saw was used to make the initial cuts into

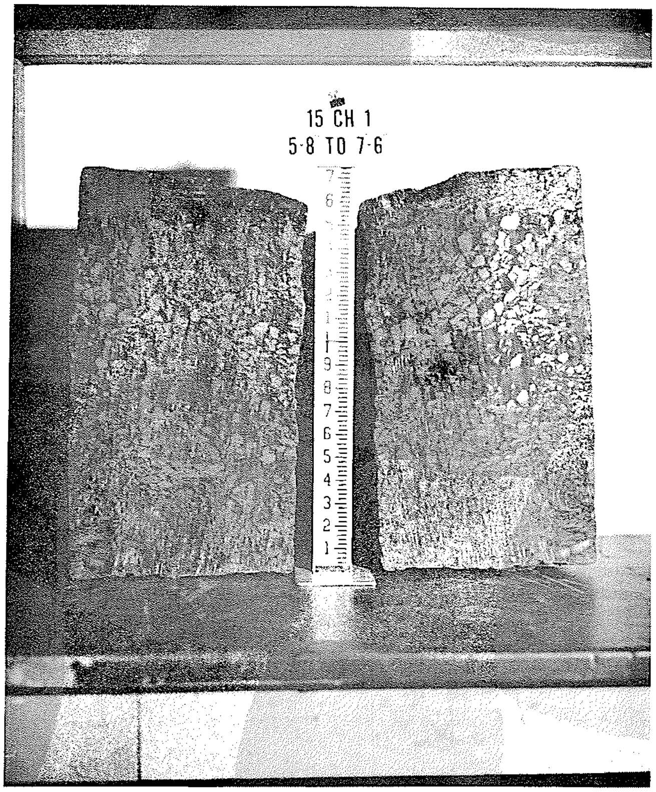

FIG. 3. Sample 15-CH-1 (5′8″–7′6″)—split core.

TABLE 1. Unit weight, Atterberg limits, water contents, and specific gravity values

Hole No.	Depth	Frozen bulk unit weight (p.c.f.)	Liquid limit	Plastic limit	Specific gravity	Water content (%)	N.R.C. classification
15-CH-1	4′0″–5′8″	65.3	—	—	—	244	V_r
15-CH-1	5′8″–7′6″	75.0	55.2	30.2	2.66	134	V_r
15-CH-1	7′6″–8′3″	88.5	63.0	28.8	2.66	76	V_r
15-CH-2	4′6″–6′0″	81.2	50.4	32.3	2.67	89	V_r
15-CH-3	5′6″–6′6″	72	*Core not tested due to disturbance*			149	V_r

NOTE: A gravel pad extended from ground surface to a depth of approximately 4 ft (1.2 m).

the large permafrost cores or blocks, and gave a fairly smooth surface. A 1/4 in. (0.64 cm) blade with 4 teeth/in. (1.6 teeth/cm) was used initially but this narrow blade tended to wander when cutting specimens that were 4–8 in. thick. A 1/2 in. (1.27 cm) blade with 2 teeth/in. (0.8 teeth/cm) was ultimately used. It gave a straighter surface but cut more slowly and dulled rapidly.

Cylindrical samples were turned on a metal working lathe. The sample was initially cut to rough dimensions on the band saw prior to mounting in the lathe. Good results were obtained on the lathe when the specimen was turned at 690 r.p.m. and with the carriage feed of the cutting tool set at 1 in. (2.54 cm)/36 revolutions. The sides and ends of the sample were trimmed on the lathe. The maximum depth of cut was limited to 0.015 in. (0.038 cm). For clean cuts the cutting tool had to be sharpened often as the abrasive action of the soil quickly dulled the edge. A sharp tool decreased the chipping of the ice in the sample. Long work samples had to be supported with the tailstock. The lathe produced a well finished sample which was ready for testing.

For rectangular specimens, a crosscut saw was used with a specially built miter box to give a relatively smooth and even surface. The crosscut saw produced a more regular surface than the band saw. If either the crosscut saw or band saw was used, however, the

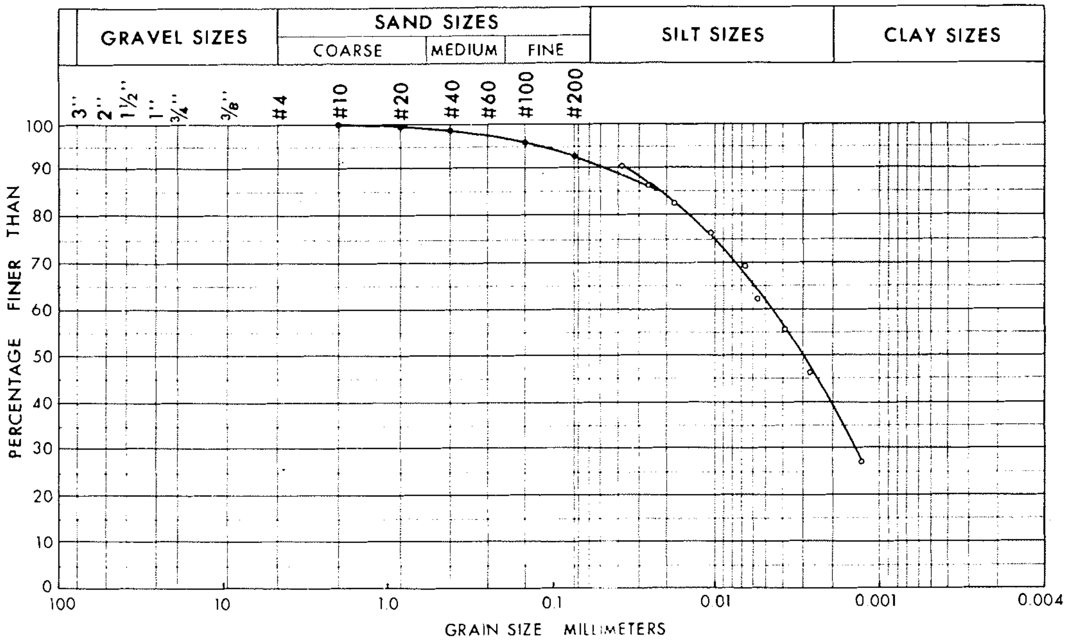

FIG. 4. Typical grain size curve.

surface was finished by hand shaving using a large, sharp, straight cutting edge with a guide.

The relative humidity in the cold room was low so the ice quickly sublimated at the edges of the sample when left exposed. Generally, the samples were prepared immediately prior to testing, thus avoiding sample preservation problems. If it was not possible to test the samples immediately after preparation, they were placed in a plastic bag and a vacuum pump was used to deair the bag. This caused the plastic to cling to the permafrost, minimizing the air gaps between the sample and the plastic. Where air gaps remained, ice crystals formed within a few hours on the inside surface of the plastic.

During handling and preparation of the frozen core samples, it was necessary to wear gloves to prevent localized melting. Also all equipment and tools used in sample preparation were cooled to the temperature of the cold room prior to use.

Laboratory Testing and Results

Thaw-settlement

It was desired to conduct a series of tests to determine total one-dimensional settlement of ice-rich permafrost when thawed under load. Although some work has been done in this field in North America (Crory 1964[4]; Luscher and Afifi 1970; Morgenstern and Nixon 1971; Shuster 1971; Smith 1972), and in the U.S.S.R. (Aberkov 1970; Shusherina 1954; Tsytovich and Sumgin 1937), a standard procedure for thaw-settlement tests had not been established. The selection of size of sample (length, diameter, length–diameter ratio), method of thawing (unidirectional, all around, rate), and method of load application (before or after thawing, number of load increments) are still somewhat arbitrary. All of the effects of these arbitrary selections on the results are not known.

For the thaw-settlement tests reported in this paper the sample holder was made from an acrylic cylinder, 3.5 in. (8.9 cm) I.D. with a 1/4 in. (0.64 cm) wall 4 in. (10.16 cm) high (Fig. 5). The bottom of the cell consisted of a porous stone sitting on an acrylic plate which was glued to the plastic cylinder. The plastic bottom plate had cross grooves in its top surface and these grooves were connected to a hole drilled in the plate through which the sample could drain. A valve was tapped into this hole. An overflow tube was connected to a hole drilled in the side of the cell approximately 3/4 in. (1.94 cm) from the top.

The samples were loaded by means of a center lever system. The load was placed at the end of a metal strap which was secured to the top of a small arc at the end of a lever arm. This permitted the arm to travel several inches

[1]Also personal communication, 1971.

FIG. 5. Thaw-settlement and permeability cell.

without changing the load applied to the sample. The load was transferred to the permafrost sample from the loading bar through a loading cap and a porous stone.

Initial tests were conducted with unrestrained movement of the loading cap and porous stone (a steel ball coupled the loading bar to the loading cap). The loading cap tilted by as much as 15–20° during a test which resulted in the loading cap and porous stone binding against the sides of the cell. To overcome this problem, a loading cap was machined to fit over the existing cap to limit tilting to a maximum of 4°. In addition, the sides of the porous stone were tapered so that some tilting could occur without binding.

The porous stones were vacuum saturated in place before a test commenced. The valve at the base was shut and surface water was removed from the top of the porous stone in the base. A prepared sample was placed in the cell, the saturated porous stone and loading cap were placed on top of the sample, and the assembly was positioned on the loading frame and loaded. The dial gauge was quickly zeroed and the sample was thawed at room temperature (70 °F, 21 °C). Melting of the permafrost sample occurred from all directions as no attempt was made to have unidirectional thawing. Because the valve at the base of the container was closed, only upward drainage took place.

The load on the samples during thawing varied from 22 to 800 p.s.f. (107 to 3905 kg/m^2). The low thawing pressures were used to simulate a no-load condition and the higher thawing pressures represented different overburden loads. After thawing was completed under the initial load additional loads were placed on the samples. For the samples thawed at low pressures, five incremental loads were applied while only two incremental loads were applied to the samples thawed at pressures of 400 p.s.f. (1955 kg/m^2) or greater. The results of these tests are shown in Figs. 6 and 7.

Figures 6 and 7 show that for these soils, the curves of relative settlement (Ap), (*i.e.* ratio of change in height of sample to height of original frozen sample) *versus* applied load are relatively straight for the range of pressures greater than 400 p.s.f. (1953 kg/m^2). Below this value the slope of the curve is constantly changing. When the straight line portion of the curve is extended back to meet the ordinate, a value for relative settlement is obtained and this value has been termed the "thaw-settlement parameter", (Fig. 8) *i.e.* the relative settlement of a permafrost sample upon thawing at the so called no-load condition. Values for the thaw-settlement parameter (A_o) and the slope of the straight line portion of the curve (m_v) are given in Table 2.

Thawed Strength

Several of the tests were conducted to obtain shear strength values of thawed samples. Laboratory vane tests were performed on material that had been consolidated to various pressures in the consolidated cell. Different areas of the sample were tested after the sample had consolidated under each load. Sample heights during these tests were between 1 and 1.5 in. (2.5 and 3.8 cm).

Unconfined compression tests were run on samples which had been thawed in a three-piece split mold under consolidation pressures of 400 and 900 p.s.f. (0.2 and 0.45 kg/cm^2). The mold was made in such a way as to allow both base and top movement during thawing

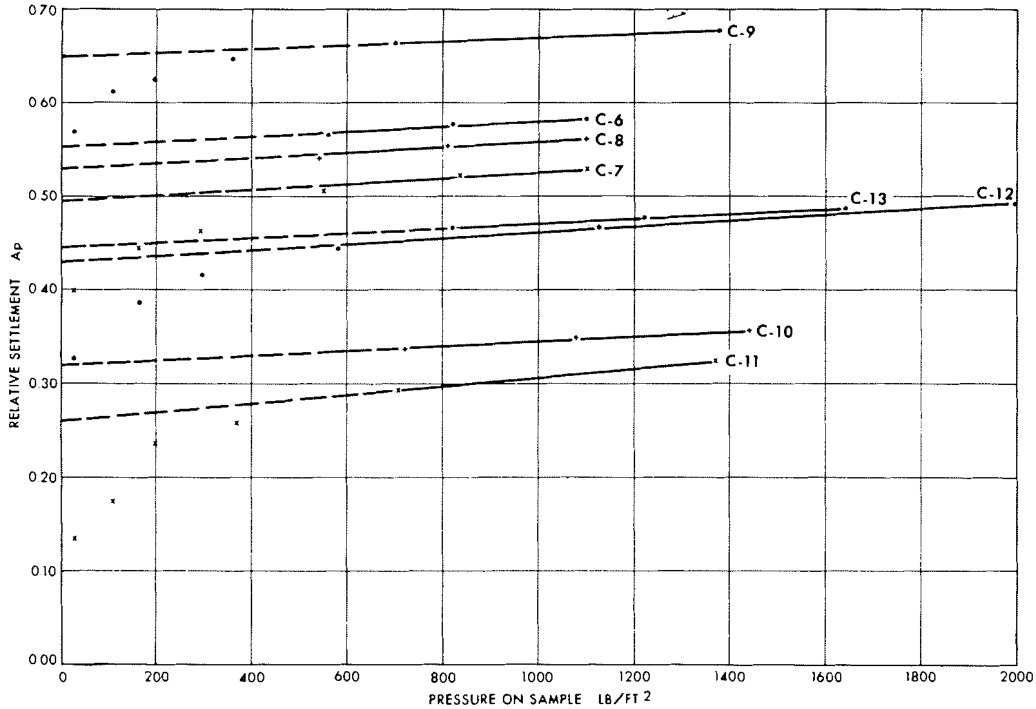

FIG. 6. Relative settlement *versus* pressure on sample (Tests C-6–C-13).

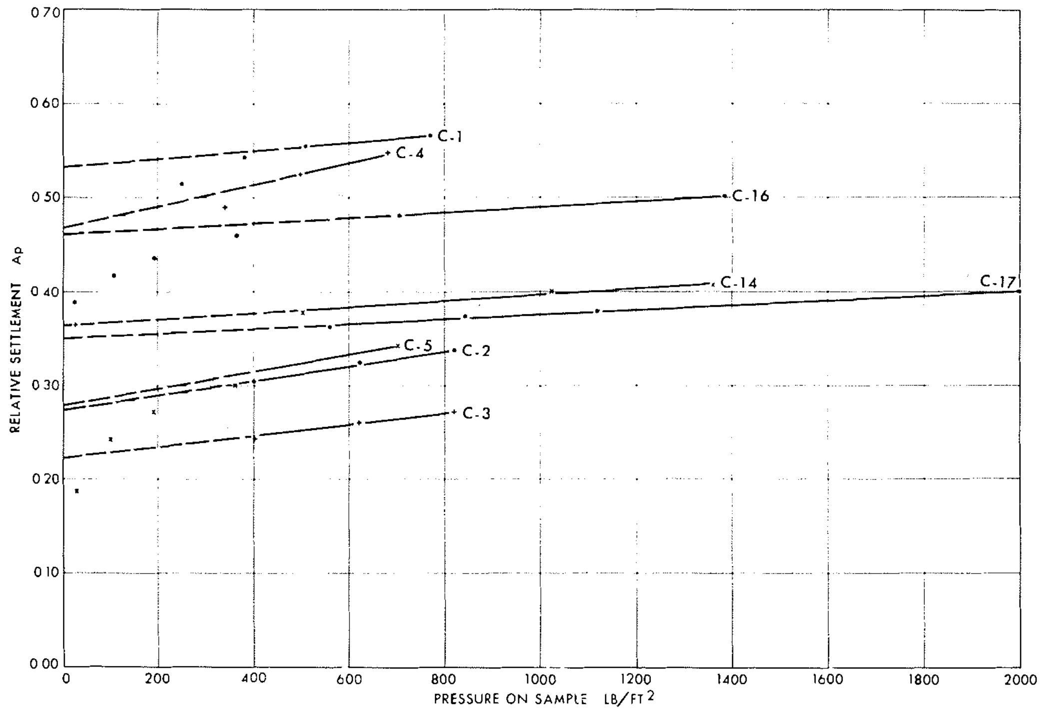

FIG. 7. Relative settlement *versus* pressure on sample (Tests C-1–C-5, C-14, C-16, and C-17).

TABLE 2. Thaw-settlement test results

Test No.	Sample	Depth	Initial conditions: Frozen bulk unit weight (p.c.f.)	Initial conditions: Water content (%)	Thaw-settlement: Thaw pressure (p.s.f.)	Thaw-settlement: Thaw-settlement parameter (A_o)	Thaw-settlement: Coefficient of volume compressibility (M_v) (ft²/lb(× 10^{-5}))	Conditions at end of test: Final pressure (p.s.f.)	Conditions at end of test: Final bulk unit weight (p.c.f.)	Conditions at end of test: Final water content (%)
C-1	15-CH-1	4′0″–5′8″	65.6	266.0	250	0.53	4.4	770	94.0	127.0
C-2	15-CH-1	4′0″–5′8″	69.4	189.0	400	0.27	8.3	820	78.6	127.0
C-3	15-CH-1	4′0″–5′8″	67.0	200.5	400	0.22	6.2	820	76.4	148.8
C-4	15-CH-1	4′0″–5′8″	61.8	348.0	26	0.47	11.4	680	66.0	169.0
C-5	15-CH-1	4′0″–5′8″	65.4	220.0	26	0.28	9.0	700	77.6	154.0
C-6	15-CH-1	5′8″–7′8″	78.5	125.0	550	0.55	2.5	1100	114.7	39.3
C-7	15-CH-1	5′8″–7′6″	83.2	100.2	23	0.49	3.0	1100	116.5	34.4
C-8	15-CH-1	5′8″–7′6″	77.6	117.5	550	0.53	2.9	1100	114.0	39.5
C-9	15-CH-1	5′8″–7′6″	70.6	196.0	23	0.65	2.2	1360	99.4	33.9
C-10	15-CH-1	7′6″–8′3″	94.5	63.2	710	0.32	2.6	1440	120.0	33.1
C-11	15-CH-1	7′6″–8′3″	95.2	59.6	24	0.26	4.6	1360	117.7	33.2
C-12	15-CH-1	7′6″–8′3″	82.2	96.4	24	0.43	3.2	2000	111.2	34.0
C-13	15-CH-1	7′6″–8′3″	85.6	85.1	800	0.45	2.5	1640	120.2	33.3
C-14	15-CH-2	4′6″–6′0″	88.4	78.8	510	0.36	3.4	1360	114.2	37.5
C-15	15-CH-2	4′6″–6′0″	81.2	98.8	22	—	—	2200	111.9	35.4
C-16	15-CH-2	4′6″–6′0″	80.0	106.9	24	0.46	3.0	1380	106.1	36.2
C-17	15-CH-2	4′6″–6′0″	90.3	71.2	550	0.35	2.5	2000	120.9	36.1

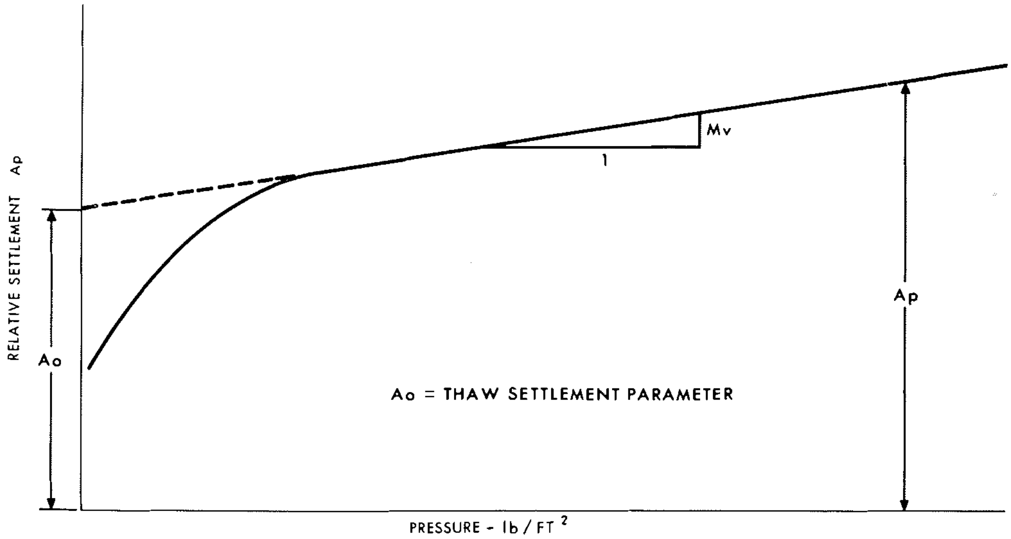

FIG. 8. Generalized thaw-settlement curve.

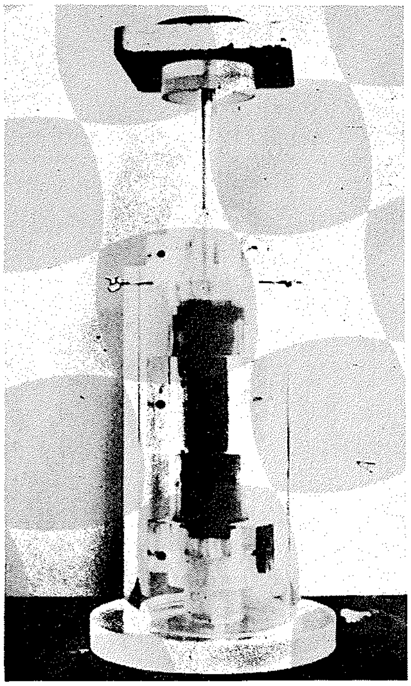

FIG. 9. Split mold used in forming samples.

(Fig. 9). An attempt to reduce side friction was made by lubricating the inside of the mold with silicone grease. The sample was thawed under water, allowing both top and bottom drainage. Prior to testing, the sample height was measured to 1/100 in. Samples consolidated at pressures less than 400 p.s.f. (0.2 kg/cm²) exhibited a very low strength. A summary of the results is shown in Fig. 10.

Two series of consolidated undrained triaxial tests were conducted on samples which had been thawed under loads of 400 and 800 p.s.f. (0.2 and 0.4 kg/cm²) with the following results:

Consolidating pressure (kg/cm²)	C' (kg/cm²)	ϕ' (degrees)
0.2	0.07	27.2
0.4	0.06	28.7

Frozen Strength

A series of unconfined compression tests was run of frozen core specimens 1.5 in. (3.8 cm) in diameter and approximately 3 in. (7.6 cm) in height. Failure occurred at relatively low axial strain (approximately 2%). Tests were run with a strain rate of 0.5–1% per minute. The strength built up rapidly to a maximum, leading to a 'plastic' type failure with substantial residual strength.

Unconfined compression strengths varied from 317 to 418 p.s.i. (22.19 to 29.26 kg/cm²), the low value, being obtained on a sample with a high organic content and a dry density of 9.9. p.c.f. (0.16 g/cm³). Excluding this result, the average strength was 393 p.s.i. (27.5 kg/cm²).

TABLE 3. Permeability and consolidation test data

Sample	Depth	Test No.	Load (p.s.f.)	Volume change (%)	Void ratio (e)	C_v (cm^2/s)	Δe	Permeability k (cm/s)	Bulk density (p.c.f.)	Moisture content (%)	Dry density (p.c.f.)	Sample condition
15-CH-2	4′6″–6′0″	1	0	0	3.10				82.4	102.5		Frozen
			380	46.0	1.265			2.47×10^{-5}				Thawed
			600	47.2	1.165			1.161×10^{-5}				
						0.0249	0.076	2.96×10^{-6}*				
			1200	49.5	1.070			6.89×10^{-6}				
						0.010	0.060	1.00×10^{-6}*				
			1800	50.8	1.019			4.28×10^{-6}	115.5	40.5	82.5	
15-CH-2	4′6″–6′0″	2	0	0	3.075				81.0	99.5		Frozen
			600	45.4	1.224			1.08×10^{-5}				Thawed
						0.74	0.137	1.60×10^{-5}*				
			1200	48.6	1.087			5.17×10.6				
						0.458	0.066	5.00×10^{-6}*				
			1800	50.5	1.021			2.72×10^{-6}	112.2	37.1	82.0	
15-CH-3	5′6″–6′6″	3	0	0	3.63				77.0	110.0		Frozen
			600	52.3	1.215			1.82×10^{-6}				Thawed
						0.146	0.084	3.36×10^{-6}*				
			1200	59.0	1.131			7.10×10^{-7}				
						0.109	0.061	1.20×10^{-6}				
			1800	55.3	1.070			3.77×10^{-7}	112.3	36.8	82.0	

*Calculated from consolidation time rate curves.

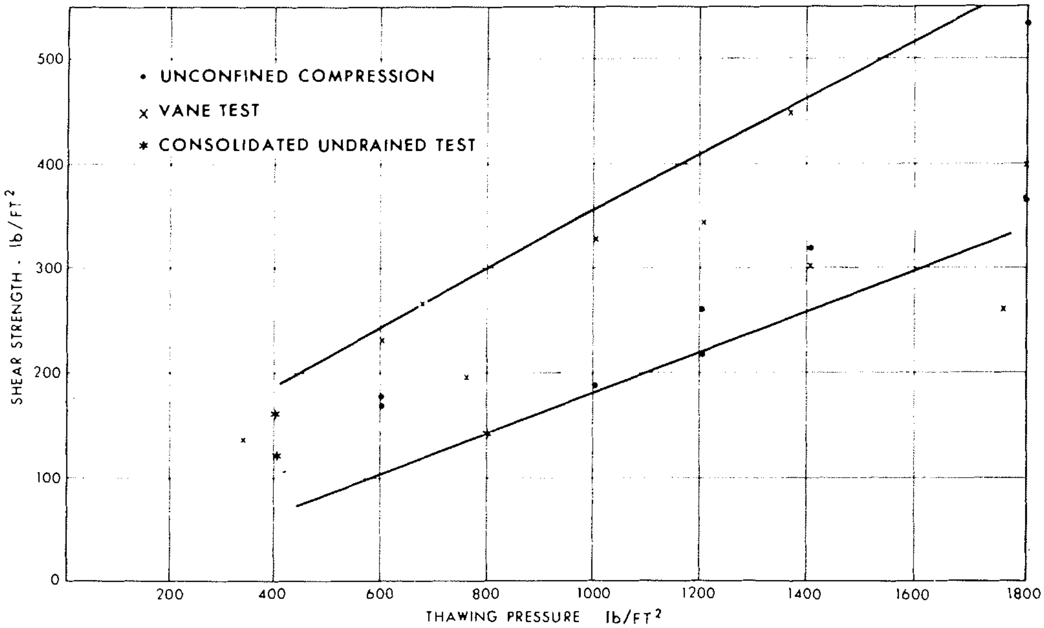

FIG. 10. Laboratory strength test results.

Permeability

Permeability tests were conducted on thawed samples during the consolidation phase of the thaw-settlement apparatus. Permeability coefficients were also calculated from the slope of the consolidation curves.

Figure 4 shows a typical grain size curve for the clayey silt. Falling head results gave values between 2×10^{-4} and 2×10^{-7} cm/s rather than the 10^{-6}–10^{-7} that would be anticipated from the grain size curve.

Table 3 shows the results of some of the permeability tests performed in the thaw-settlement apparatus under various loads. A relationship between permeability and dry density is shown in Figure 11.

Thermal Conductivity of Frozen Soil

Thermal conductivity tests were run on some large diameter cores and on some block samples taken from the same area. The samples were taken near the surface and contained considerable organic material. In total, two thermal conductivity probe tests, eight heat flow meter tests, and one guarded hot plate test were run. Probe tests (Slusarchuk 1972) were run on the samples before they were cut into rectangular slabs for heat flow meter and guarded hot plate tests. Heat flow meter tests were performed according to A.S.T.M. test method C518-67 and the guarded hot plate test followed A.S.T.M. test method C177-63. Heat flow meter and guarded hot plate samples had dimensions of $11 \times 11 \times 1\frac{1}{2}$ in. ($28 \times 28 \times 3.8$ cm).

The thermal conductivity values for the eight heat flow meter tests varied from 10.0 to 10.4 B.t.u.-in./ft²-h-°F (1.44 to 1.50 W/m-°C). All samples had a frozen bulk unit weight of approximately 67 lb/ft³, (1073 kg/m³), a dry unit weight of 31 lb/ft³ (497 kg/m³) and a water content of about 200%. The samples tested in the guarded hot plate gave a conductivity of 9.4 B.t.u.-in./ft²-h-°F (1.35 W/m-°C). The two probe tests gave values of 10^{-4} and 10^{-6} B.t.u.-in./ft²-h-°F (1.50 and 1.55 W/m-°C). Interpretation of the differences between these results is difficult at this time due to the limited amount of knowledge in determining thermal conductivity of ice-rich soil.

Thaw-settlement Analysis

In thaw-settlement analysis, when the A_o and m_v values for a permafrost soil have been determined and if the depth of thaw and loading conditions are known, total settlement can be calculated by the following equation (assuming

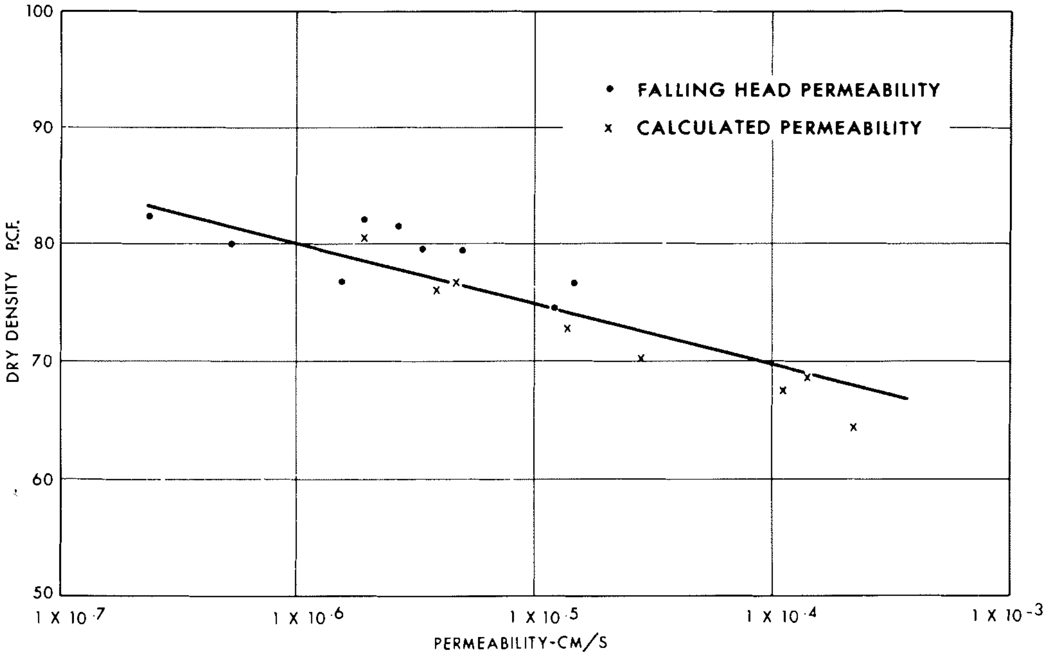

FIG. 11. Relationship between permeability and dry density.

that the water table in the thawed material is at the surface).

$$[1]\quad S = A_oX + m_v \int_0^X (P + \gamma'X)\,\mathrm{d}X$$

or

$$[2]\quad S = A_oX + m_vPX + \frac{m_v\gamma'X^2}{2}$$

where:

S = total settlement (ft),
A_o = thaw-settlement parameter,
X = depth to thaw front from original surface (ft),
m_v = coefficient of volume compressibility (ft^2/lb),
P = surcharge load (lb/ft^2), and
γ = submerged unit weight of thawed soil (lb/ft^3).

For the cases where several layers of soil are present, the settlement of each layer can be calculated separately and summed to obtain the total settlement. For these situations, in Eq. [2], X becomes the depth of thaw in any layer and P is the effective overburden pressure at the top of that layer.

As shown by Eq. [2], total settlement is affected by three terms; a thaw-settlement term and two volume compressibility terms (one due to a surcharge load and the other to self weight). For the ice-rich permafrost samples tested, the thaw-settlement term was dominant. For example, soils similar to those in tests C-6, C-12, and C-11 (relatively high, medium, and low settlement characteristics) were assumed to thaw to a depth of 20 ft (6.1 m) with an 800 p.s.f. (3905 kg/m^2) surcharge at the surface and the settlements were calculated. C-6, C-12, and C-11 type permafrost soils would settle 11.6, 9.4, and 6.4 ft, respectively, with 94, 91, and 81% of the settlement being derived from the thaw-settlement term.

The thaw-settlement parameter is plotted as a function of frozen dry unit weight in Fig. 12 and as a function of frozen bulk unit weight in Fig. 13. Excluding the results from tests C-1 through C-5 which contained considerable organic material, Figs. 12 and 13 show that a relationship appears to exist between the thaw-settlement parameter and both frozen bulk unit weight and frozen dry unit weight. To expand the range of this relationship, additional thaw-settlement data were obtained from tests by Speer *et al.* 1973 on soils with higher frozen bulk densities. Most of these data points fall within the band drawn in Fig. 14 with the value of the thaw-settlement parameter tending

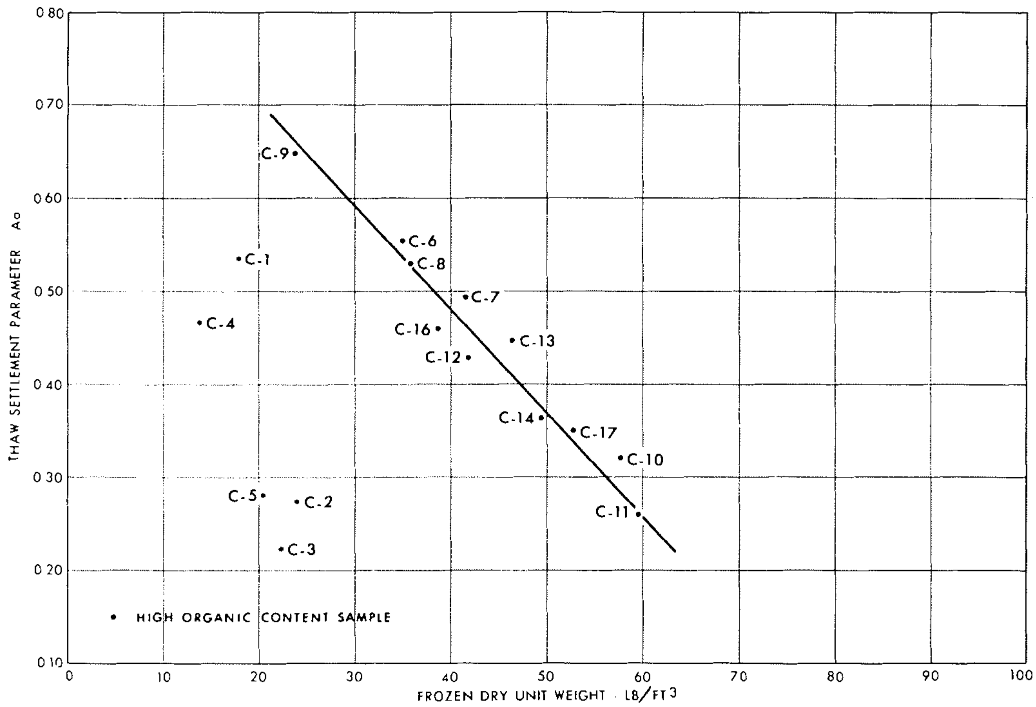

FIG. 12. Relationship between thaw-settlement parameter and frozen dry unit weight.

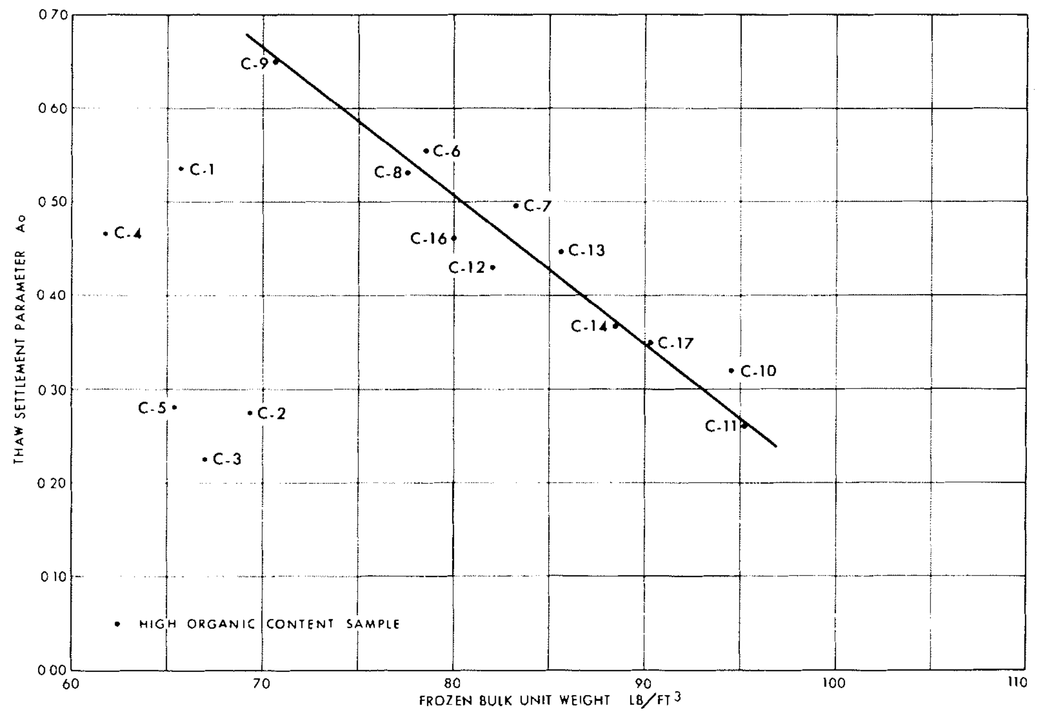

FIG. 13. Relationship between thaw-settlement parameter and frozen bulk unit weight (Results from Inuvik thaw-settlement tests).

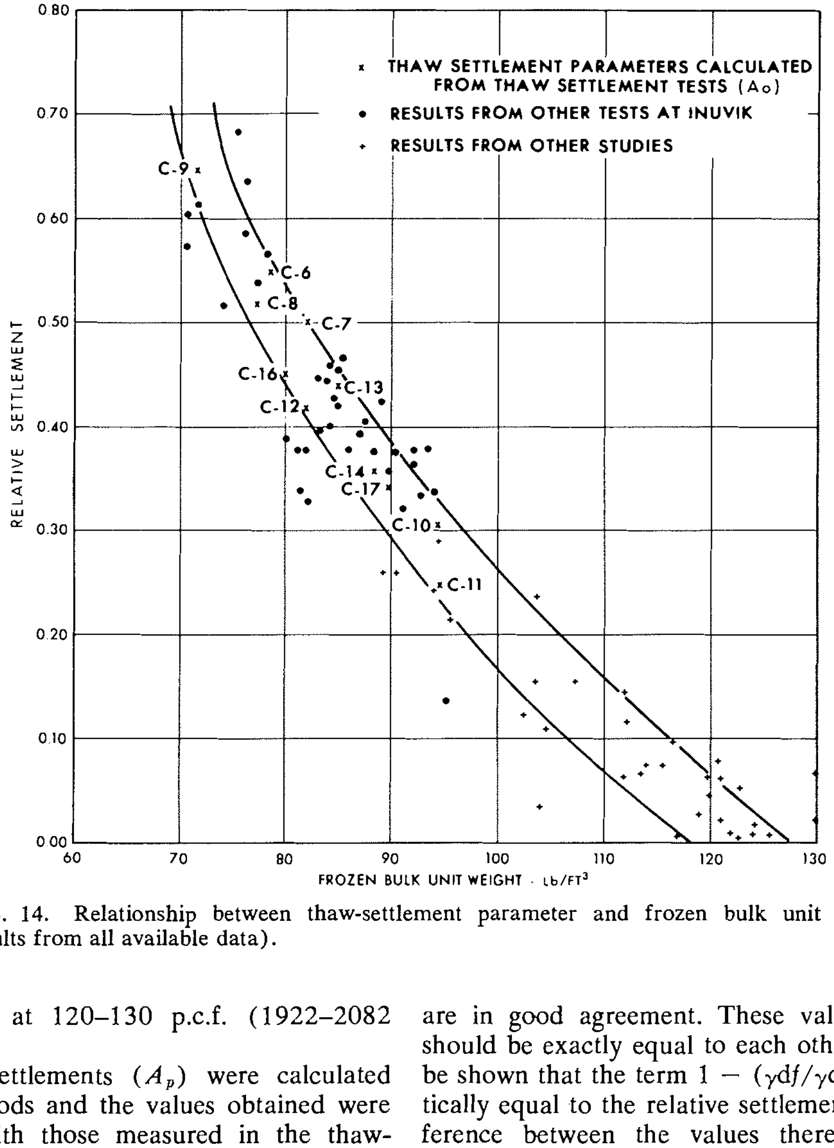

FIG. 14. Relationship between thaw-settlement parameter and frozen bulk unit weight (Results from all available data).

toward zero at 120–130 p.c.f. (1922–2082 kg/m³).

Relative settlements (A_p) were calculated by two methods and the values obtained were compared with those measured in the thaw-settlement tests. The results are given in Table 4.

In Method 1 (Crory 1964), relative settlement was calculated by the following equation

$$[3] \qquad A_{p1} = 1 - \frac{\gamma df}{\gamma du}$$

where:

A_{p1} = relative settlement at some pressure,
γ_{df} = dry unit weight of frozen material, and
γ_{du} = dry unit weight of unfrozen material.

As shown in Table 4, the measured values of settlement and those calculated by this method are in good agreement. These values in fact should be exactly equal to each other as it can be shown that the term $1 - (\gamma df/\gamma du)$ is identically equal to the relative settlement. The difference between the values therefore is an indication of the error associated with the weights and measures in the thaw-settlement test.

A second method was developed for calculating relative settlement from thaw-settlement tests. In this method, the difference in volume between the frozen and thawed state was equated to the change in volume associated with melting the ice plus the volume of water expelled from the sample. This relationship can be expressed as

$$[4] \qquad A_{p2} = \frac{w_f \gamma df}{90 \gamma w} + \frac{W_f - W_u}{\gamma w V}$$

TABLE 4. Comparison of measured and calculated settlements after thawing for final load condition

Test No.	Thaw settlement value (A_o)	Relative settlement measured (A_p)	Relative settlement calculated Method 1 (Crory 1964) (A_{p1})	Relative settlement calculated Method 2 (A_{p2})	Relative settlement ice change to water	Relative Settlement expelled water (A_{pw})	Expulsion ratio $\left(E = \frac{A_{pw}}{A_o}\right)$	Final load (p.s.f.)
C-1	0.53	0.56	0.57	0.48	0.08	0.40	0.75	760
C-2	0.27	0.34	0.31	0.32	0.08	0.24	0.89	800
C-3	0.22	0.27	0.27	0.26	0.08	0.18	0.82	800
C-4	0.47	0.55	0.44	0.48	0.09	0.39	0.83	680
C-5	0.28	0.34	0.33	0.29	0.08	0.21	0.75	680
C-6	0.55	0.58	0.57	0.56	0.08	0.48	0.87	1100
C-7	0.49	0.53	0.53	0.51	0.07	0.44	0.90	1100
C-8	0.53	0.56	0.56	0.52	0.07	0.45	0.85	1100
C-9	0.65	0.68	0.68	0.67	0.08	0.59	0.91	1360
C-10	0.32	0.36	0.36	0.34	0.06	0.28	0.88	1500
C-11	0.26	0.33	0.32	0.32	0.07	0.25	0.96	1360
C-12	0.43	0.49	0.50	0.50	0.07	0.43	1.00	2200
C-13	0.45	0.49	0.49	0.46	0.07	0.39	0.87	2200
C-14	0.36	0.40	0.41	0.40	0.07	0.33	0.92	1360
C-15	—	0.50	0.53	—	—	—	—	2200
C-16	0.46	0.51	0.50	0.51	0.07	0.44	0.96	1360
C-17	0.35	0.40	0.41	0.36	0.07	0.29	0.83	2200

where:

A_{p2} = relative settlement at some pressure,
w_f = percentage frozen water content,
γ_w = unit weight of water,
W_f = weight of frozen sample,
W_u = weight of unfrozen drained sample, and
V = volume of frozen sample.

If the sample is saturated or the volume of air voids does not change during thawing then the relative settlement calculated by this method should equal that determined by measurement or as calculated by method 1, *i.e.* $A_p = A_{p1} = A_{p2}$. The results of calculations using Eq. [4] are given in Table 4. The relative settlement due to both volume change of melting the ice and expelling the water is also given in Table 4.

In order to get an indication of the amount of water expelled from the soil as it thaws, in relation to the amount of settlement, an expression has been derived for a parameter E, the expulsion ratio. This term is defined by taking the final term in Eq. [4] and dividing it by the thaw settlement parameter, A_o.

$$E = \frac{W_f - W_u}{\gamma w V A_o}$$

This is similar to the concept proposed by Luscher and Afifi (1970). Values for this parameter are shown in Table 4.

Conclusions

1. Based on the results of the thaw-settlement tests undertaken during this program, a correlation between frozen bulk density and thaw-settlement parameter for mineral soils was shown to exist.

2. Figure 10 summarizes the results of the shear strength tests conducted on the thawed samples assuming that drainage occurred under overburden pressures. ϕ' and C' values of 28° and 0.06 kg/cm², respectively, were determined for these soils.

3. Permeability tests showed that samples thawed under low overburden pressures had a relatively high coefficient of permeability ($k = 1 \times 10^{-4}$–1×10^{-5} cm/s for loads up to 500 p.s.f.). Small increases in overburden pressure resulted in a rapid decrease in permeability ($k = 1 \times 10^{-7}$ cm/s for loads of approximately 2000 p.s.f.).

4. Thermal conductivity tests conducted on frozen samples from within the ice-rich organic clayey silt layer, using the cylindrical probe, guarded hot plate, and flow meter techniques, gave values for the coefficient of thermal con-

ductivity ranging from 9.4 to 10.7 B.t.u.-in./ft^2-h-°F (1.35 to 1.55 W/m-°C).

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